SECONDARY EMISSION BY POSITRONS

by

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CONTENTS

PREFACE

The material presented in Chapter I on secondary emission by electrons and positive ions has been obtained from the published literature, although an attempt had been made to bring out those aspects which are relavent to secondary emission by positrons.

In Chapter II the basic suggestion that positrons might liberate secondary electrons by a potential ejection process was due to Dr. S.C. Curran, who also suggested the use of an electron multiplier for detecting the secondary electrons. The more detailed discussion on potential ejection by positrons was an attempt, by the Author, to consider the mechanisms proposed by Hagstrum for positive ions in relation to positrons. In the remainder of Chapter II Part 1 the Author considers some known differences in the behaviour of positrons and electrons from the point of view of the secondary emission of these particles. The second part of Chapter II, dealing with the proposed experimental method for investigating secondary emission by positrons, is original.

The apparatus was designed by the Author and constructed with the co-operation of the Laboratory workshop Staff. Most of the electronics was of standard design, but the 8 KV power supply (Section III.2) and the special low frequency amplifier (Section V.5) were designed and constructed in the electronics Laboratory.

The preliminary experiments on the multiplier performance described in Chapter III were carried out by the Author.

The experiments on the relative secondary emission of electrons and positrons described in Chapter IV, and the first two experiments in the main experimental investigation using copper 64 sources, described in Chapter VI, were carried out by the Author with the assistance of Mr. P. Carmichael B.Sc. The remainder of the experimental work was carried out by the Author unassisted.

The tentative explanations for the results suggested in Chapter VII are due to the Author, although a number of discussions on the interpretation of the experiments have taken place, notably with Dr. S.C. Curran.

ACKNOWLEDGEMENTS.

The Author wishes to thank Mr. T.W. Pollok and Mr. J. Lindsay of the Electronics Laboratory, and Mr. R. Irvine of the Department Workshops, for assistance in their respective fields. Thanks are also due to Mr. J.T. Lloyd for valuable advice on techniques, especially in connection with high vacuum systems.

The Author would like to express his thanks to Mr. P. Carmichael for his co-operation in carrying out some of the experiments.

The Author wishes to record his appreciation of many fruitful discussions with Dr. S.C. Curran, who suggested the problem and supervised the research.

Finally the Author would like to thank Professor P.I. Dee for his continued interest and encouragement in the work, and in particular for a number of helpful discussions during the later stages of the research.

The Author wishes to acknowledge the receipt of a D.S.I.R. Maintenence Allowance during the period of the research, without which the work would not have taken place.

SUMMARY

In Chapter I the existing literature on secondary emission is reviewed from the point of view of possible effects which might be observed with positrons. Secondary emission by electrons of energy $\lesssim 2$ KeV has been extensively studied, and work on positive ions has been reported. No work at all on positrons has been published, and in the energy region covered by the present research ($\sim 5 - 500$ KeV) there has been no theoretical work and practically no experimental work on electrons.

Some simple theoretical ideas concerning secondary emission by positrons are put forward in Chapter II. Secondary emission by "Potential Ejection", which has been observed for positive ions but is impossible for electrons, is considered as a possible process for positrons; if such a process can occur for positrons it would only be predominent for particles with an energy $\lesssim 1$eV. Some known differences in the behaviour of positrons and electrons are then discussed, from the point of view of any effect these might have on the secondary emission of the particles. It is concluded that no large differences are to be expected in the energy range which can be investigated by experiments which are feasible at present. The second part of Chapter II outlines the basic principle of the experiment, which was to compare the secondary emission by positrons and electrons of the same energy

under identical conditions of geometry and target surface. A β^--spectrometer and a copper 64 source, which emitted positrons and electrons, provided focused beams of particles. The secondary electrons were detected with an Allen type electron multiplier, and the number of primary particles was counted with a thin windowed Geiger counter.

Chapter III describes the electron multiplier and the associated electronics, and discusses briefly some measurements on its performance.

In Chapter IV a preliminary experiment on secondary emission without using the spectrometer is described, which confirmed that there were no large differences in secondary emission by electrons and positrons at high energies.

Chapter V describes the β^--spectrometer and the rotating coil method used to measure the magnetic field.

Chapter VI describes the main experiments to determine η, the relative secondary emission of electrons to that of positrons. Some absolute measurements were also made. It was found that above $\sim$ 50 KeV η was about 1.04; as the energy was reduced η began to rise rapidly, exceeding 2 below 10 KeV. As such large values of η were not expected on any existing theory, a very thorough investigation was carried out to establish that the results were not due to any instrumental errors. The final results

for platinum, after all the corrections, none of which was very large, had been applied, were as follows:-

Energy KeV	6.5	10	20	50-500
η	3.25 ± 1.15	1.7 ± 0.3	1.2 ± 0.1	1.04 ± 0.025

A copper-beryllium target gave similar results.

In the final Chapter some tentative explanations for the results are put forward. For energies greater than 100 KeV a semi-quantitative theory is given. It was assumed that the secondary yield was proportional to the energy loss of the particles, and that a primary could produce a secondary as it entered the target, or as it left the target, if it did so as a result of scattering within the target. Using recent data on the energy loss of positrons and electrons, and the results of Seliger, who found that electrons were backscattered by $\sim$ 30% more than positrons, values of η of the right order of magnitude are predicted. Below $\sim$ 100 KeV the simple theory breaks down, but other factors which become important at lower energies enable this theory to be extended, so that it can possibly account for the results down to 20 KeV.

This extended theory does not seem adequate to explain the

large values of η observed below 20 KeV. Some very tentative ideas are put forward concerning processes by which positrons and electrons might liberate secondary electrons, which suggest qualitatively that electrons may be favoured. It is concluded that more experimental and theoretical work is required before the results at low energies can be understood.

PRINCIPLE SYMBOLS AND ABBREVIATIONS

S.E. ..... Secondary emission.

Primary ..... Primary particle.

Secondary ..... Secondary electron.

E_p ..... Energy of primary particle.

E_s ..... Energy of secondary electron.

S.E.C., δ ..... Secondary emission coefficient.

δ^-, δ^+ ..... δ for primary electrons and positrons respectively.

$\bar{\delta}$ ..... Average S.E.C. over a source spectrum.

$\bar{\delta}^-$, $\bar{\delta}^+$ ..... $\bar{\delta}$ for electron and positron sources, respectively.

R_p ..... Range of primary particle in target.

R_s ..... Mean range of secondary electron.

δ_R ..... Reflection coefficient.

δ_R^-, δ_R^+ ..... δ_R for electrons and positrons respectively.

E ..... The efficiency of the multiplier for primary electrons reflected from the first dynode.

$R = E/\delta$ ..... The ratio of the efficiency of the multiplier for primary electrons reflected from the first dynode, to its efficiency for detecting secondary electrons liberated at the first dynode.

ξ_M ..... The ratio of the count rate for an electron source to that for sodium 22 positrons; measured with the multiplier.

ξ_G	As ξ_M, but measured with the Geiger counter.
$\xi = \xi_M / \xi_G = \bar{\delta}^- / \bar{\delta}^+$	The ratio of $\bar{\delta}$ for an electron source to $\bar{\delta}$ for sodium 22 positrons.
B	The spectrometer magnetic field (gauss).
H	The standard field, produced by the Helmholtz coils (gauss).
p	The radius of curvature of particle paths in the spectrometer magnet.
I, I_H	The current through the Helmholtz coils.
η_M	The ratio of the electron count rate to the positron count rate at the same energy; measured with the multiplier.
η_G	As η_M, but measured with the Geiger counter.
$\eta = \eta_M / \eta_G = \frac{\delta^-}{\delta^+}$	The relative S.E. of electrons and positrons.

CHAPTER I

INTRODUCTORY REVIEW

I. 1 General

I. 1. (1) The Phenomenon of Secondary Emission. Secondary Emission (hereafter abbreviated to "S.E.") is the liberation of electrons when a surface is bombarded with particles. It was discovered by Austin and Starke [1] in 1902. Almost any incident particles can produce secondary electrons, which may be liberated from metals and non metals (both conductors and insulators). If the target is in the form of a thin foil secondaries are liberated on the exit side as well as on the entrance side.

I. 1. (2) Scope of previous work and aspects to be considered in the Introductory Review. Most existing measurements have been made on metals and for secondaries liberated on the entrance side. This review will be almost entirely restricted to these aspects of the subject.

S.E. has been extensively studied for primary electrons* of energy from ~ 50 - 2000 eV. Most work has been done in this region because, firstly, experiments are simplest and data

* Throughout this Thesis the term "electron" will only be used for a negative electron.

easiest to interpret, and, secondly, because the results have important applications to electron multipliers. A few measurements have been made on S.E. by electrons of energy less than 50 eV and greater than 2000 eV.

S.E. by positive ions has been studied by a number of workers, mainly in the energy range from a few KeV downwards.

There is a report by Berry [2] of S.E. by neutral atoms, and by Hereford [3] of S.E. by mesons. No work at all has been reported on S.E. by positrons.

In this Chapter the existing literature will be reviewed from the point of view of possible effects which might be observed with positrons. The important features of S.E. by electrons of primary energy $E_p \gtrsim 2$ KeV will be summarised briefly, as many of the basic properties of S.E. are relevent to any study of the subject. For further information about S.E. in this region there are several good reviews, such as by McKay [4], Pomerantz and Marshall [5], Curran [6], Massey and Burhop [7], who review the theoretical side in more detail, and a book by Bruining [8], which considers many aspects very fully. Measurements on electrons in the range of energy where positrons are easiest to obtain in the laboratory, i.e. 5 - 500 KeV, will be discussed as fully as possible. When the present research started there was only one report of work on

S.E. by electrons in this region, although some work had been done on the reflection of electrons, which is relevant. Work on positive ions will be discussed, because they can liberate secondary electrons by an entirely different process, which is impossible for electrons, but may under certain circumstances occur for positrons.

I. 1. (3) <u>The distinction between true secondary electrons and reflected primary electrons - Definition of the S.E. coefficient.</u>

For electrons as the primary particles it is necessary to consider carefully what is meant by the term "secondary electron". If the electrons which leave the target are examined as a function of their energy (denoted by E_s), there are three distinct, but not completely separate groups of particles. These are illustrated in Figure 1, due to Rudberg [9], and consist of (S), true secondaries with a mean energy of a few eV, (R), elastically scattered (or reflected) primary particles whose energy is equal to E_p, and (U), inelastically scattered primaries with an energy ranging from just less than E_p right down to E_s.

For $E_p \sim$ 100's of eV the number of true secondaries far exceeds the numbers in the other groups. However, as E_p is increased, the number of true secondaries falls off, while the number of reflected primaries rises, and for $E_p \gtrsim$ a few KeV the latter will greatly predominate. In fact these

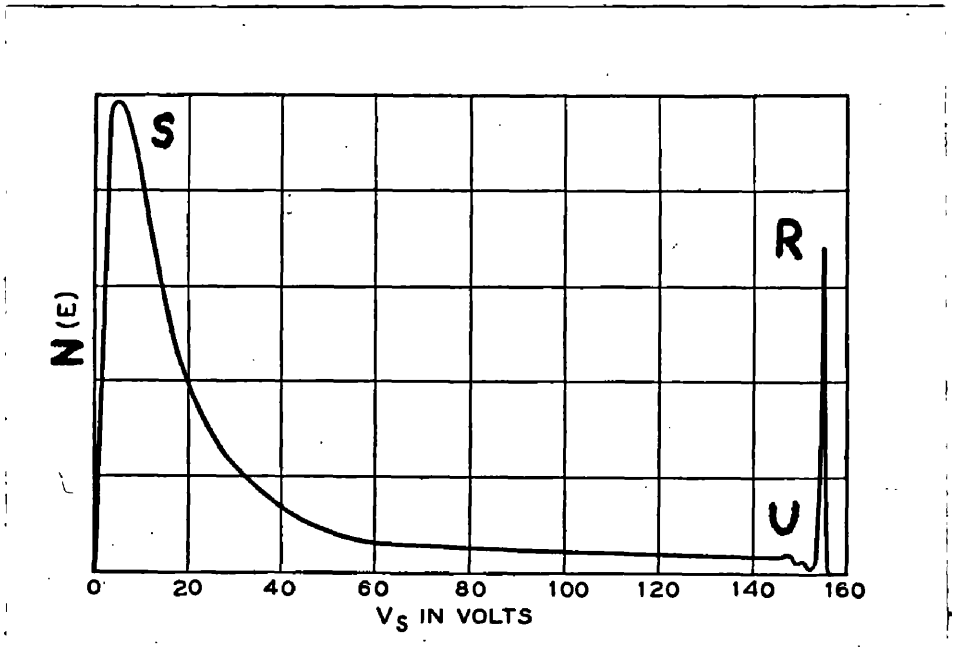


Figure 1. The energy distribution of the secondary electrons from silver, according to Rudberg [9]. The energy of the secondary electron is denoted by V_s.

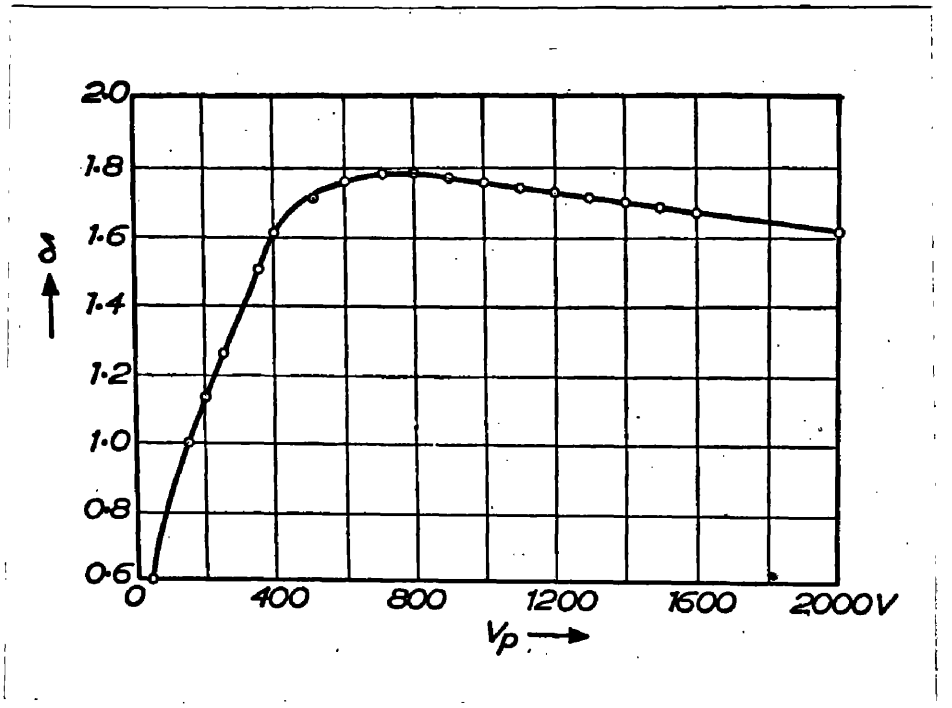


Figure 2. The yield for platinum as a function of primary energy, denoted by V_p; according to Copeland [10].

scattered primaries can themselves produce secondaries and the situation becomes rather complex. High energy primaries will also give X-rays, which will lead to secondary electrons, but this effect will be very small, because, as shown in Section III 3.(5), the production of secondaries by X-rays is an inefficient process.

If the primary particles are positively charged there is less confusion, as the true secondaries and reflected primaries have opposite signs. The scattered primaries can, however, still produce secondaries. Throughout this Thesis secondaries produced by scattered primaries are included in the secondary yield.

For primary particles of either sign the True Secondary Emission Coefficient, hereafter denoted by S.E.C., is defined as:

$$\delta = \frac{\text{Number of true secondary electrons emitted per sec.}}{\text{Number of primary particles incident per sec.}}$$

$$= \frac{\text{True Secondary Current}}{\text{Primary Current}}$$

1.2. The main aspects of work done on Secondary Emission by Electrons of energy less than 2 KeV.

1.2 (1) Experimental Methods used to investigate Secondary Emission. The basic principle of nearly all methods of determining the yield, i.e. the S.E.C. δ, is to allow electrons from an electron gun to fall on a target inside some kind of Faraday chamber arrangement, which will enable the primary and

secondary currents to be measured directly.

The energy distribution of the secondaries may be measured by a retarding electric field method, or by a magnetic method.

An important feature of all experiments is to have a very clean surface, as the presence of adsorbed gas atoms may have a considerable effect on the yield.

I.2 (2) Results of Experiments

I.2 (2a) The Yield. Figure 2 shows the variation of δ against E_p for platinum according to Copeland [10]. Platinum has the highest value of yield for a pure metal, but the yield curve for all other metals is very similar in shape. An interesting observation, first made by Baroody [11], is the existence of a "Universal Curve" for metals. If the yield curve is plotted in the form δ / δ_{max} against $E_p / E_{p\,max}$, where δ_{max} is the maximum value of δ, and $E_{p\,max}$ the primary energy at which δ_{max} occurs, it is found the points for all metals lie very close to one curve, called the Universal Curve. This is shown in Figure 3. Another observation is that with only two or three exceptions the maximum value of S.E.C. for all pure metals lies between 0.7 and 1.5, which is rather surprising in view of the fact that both density and work function vary widely over the periodic table.

The main features of the yield curve may be understood with the help of a simple physical picture. A primary electron loses

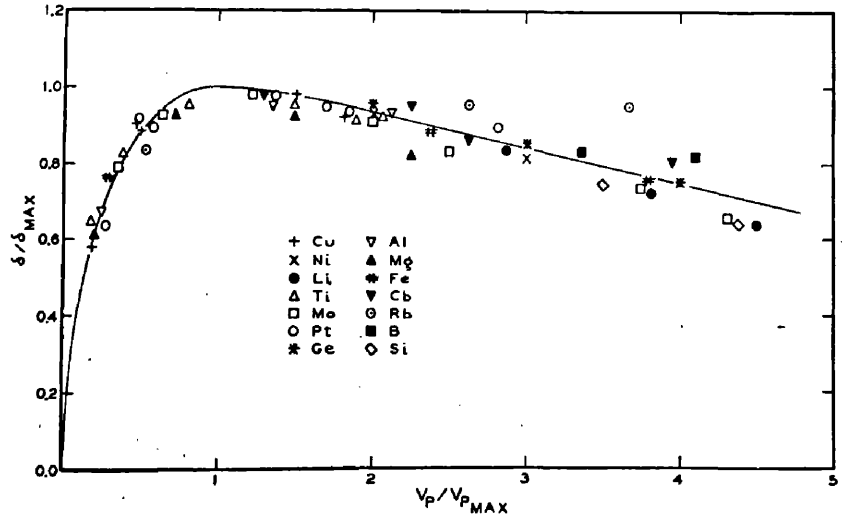


Figure 3. The "Universal Curve" for all metals, according to Baroody (24). The ratio E_p/E_p max. in the text is shown here as V_p/V_p max.

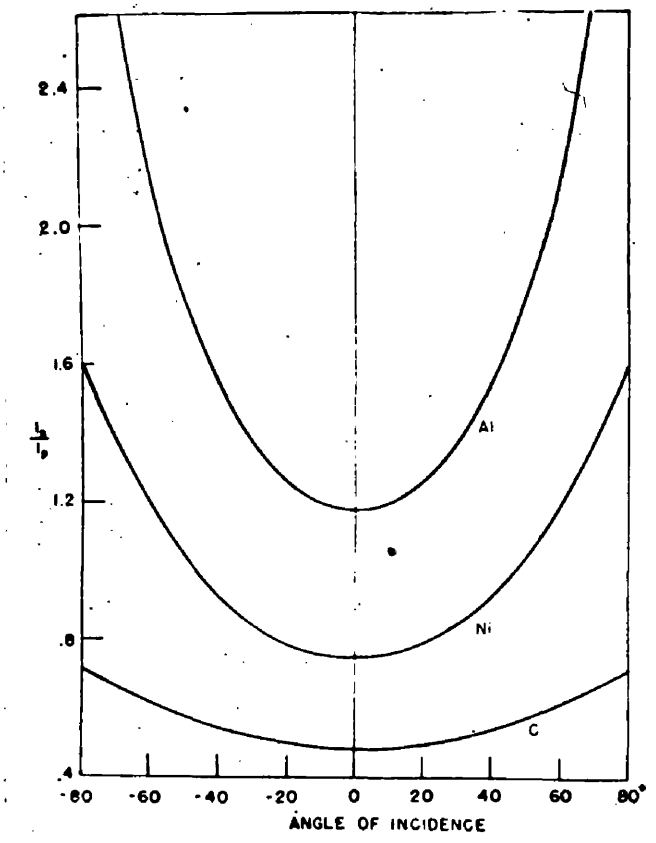


Figure 4. The variation of $\delta = \frac{i_s}{i_p}$ with the angle of incidence, measured from the normal; according to Müller (12).

energy by producing secondary electrons inside the metal, and those liberated near the surface are able to escape. For a very slow primary all the secondaries produced can escape, and, as E_p rises, so does the yield. A point is reached, however, when the primary range, R_p, exceeds the mean range of the secondaries, R_s, and these cannot all escape, but some are absorbed. As the number of secondaries produced per cm. of the primary path decreases when E_p increases, if $R_p \sim R_s$ the yield will be a maximum and will begin to fall if E_p is further increased. At high values of E_p ($\sim$ KeV) the yield will continue to fall slowly. The yield curve at high energies will be considered again in Section VI.5.(3b).

It seems reasonable to suppose that the above considerations would apply to S.E. by positrons, and that these particles would probably behave like electrons in producing secondary electrons, unless some other factors, not relevant for electrons, became important. This possibility is examined in Chapter II.

I.2. (2b) <u>Dependence of the yield on Angle of Incidence and Work Function.</u> The yield is strongly dependent on angle of incidence, as the curves in Figure 4, due to Müller [12], show. The rise in δ observed as the angle of incidence is increased occurs because the path of the primary electron inside the metal will lie nearer the surface, allowing more secondaries

to escape. These considerations also apply to high energy electrons, to high energy positive ions and presumably to positrons.

The dependence of S.E. on work function is interesting. McKay [4] has plotted δ_{max} against work function (See Figure 5), and observed that in general a metal with a high work function has a high S.E. This is surprising and one might have expected exactly the reverse; evidently other factors predominate in determining the yield. Bruining [13] has shown that for a given surface a decrease in the work function does in fact result in an increased yield, but to a very much lesser extent than for photo-electric emission. Sixtus [14] suggests that this is because a change in work function will probably be small compared to the mean energy of the secondaries.

According to Bruining [8] for very low primary energies ($E_p \lesssim 50$ eV) the work function is predominant in determining the yield, while at high energies ($E_p \gtrsim$ few KeV) density is probably more important.

As the work function is important in determining the escape of secondaries, rather than their rate of production, Bruining's considerations will probably apply to S.E. by positrons through any process similar to that which occurs for electrons, but not necessarily for any other process by which positrons might liberate secondary electrons.

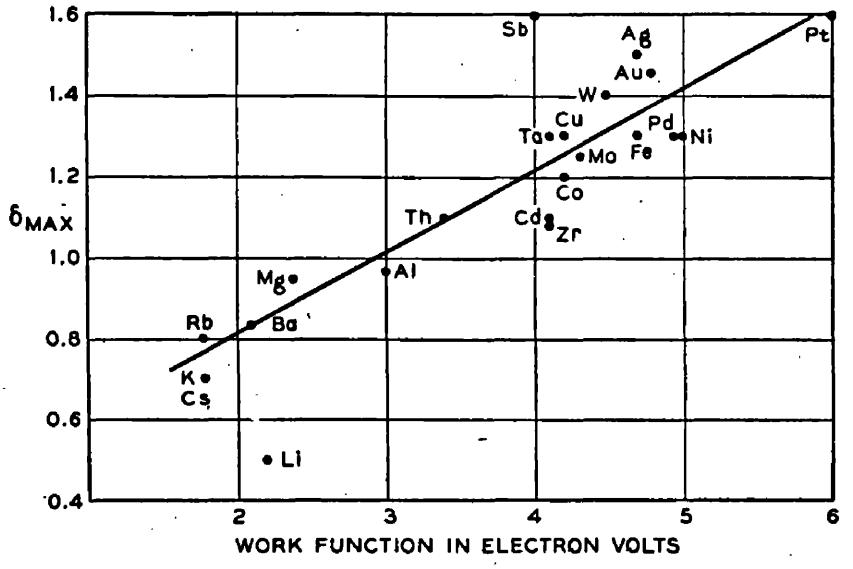


Figure 5. The variation of δ max. with work function over the periodic table; according to McKay (4).

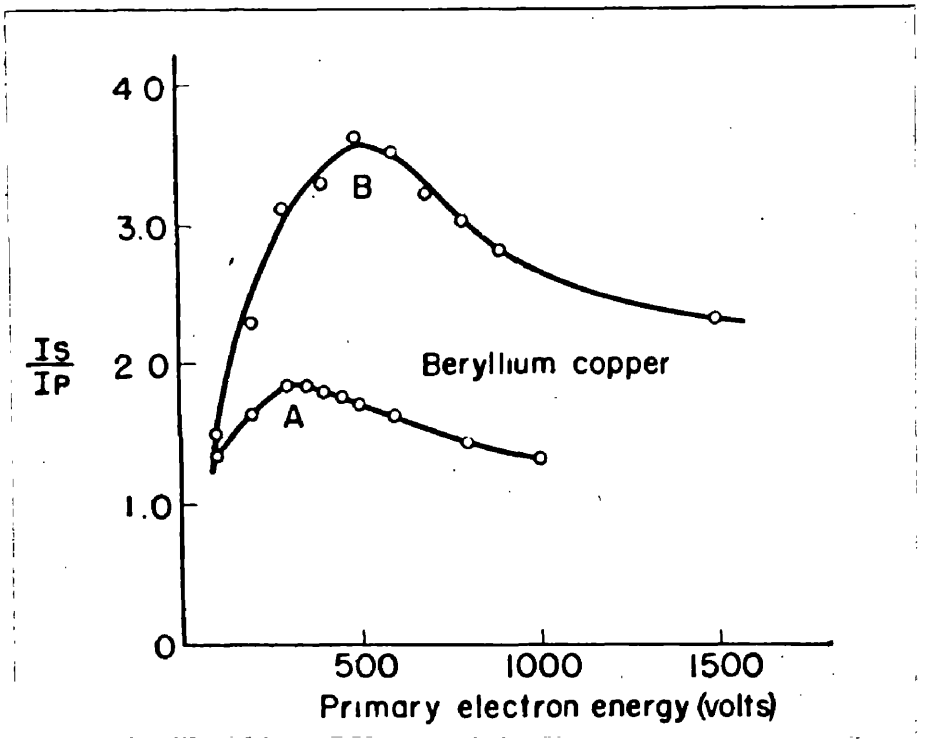


Figure 6. The yield curves for copper-beryllium before activation (curve A) and after activation (curve B); according to Allen (15).

I. 2 (2c) Influence of other factors on the yield. The S.E. yield seems remarkably insensitive to a great many factors e.g. the temperature of the target and whether the target is in the solid or liquid state. Most factors which do affect the yield can be shown to produce a change in the work function. Two further factors which are of importance will be mentioned here. The first of these is the effect of activation, which is of great importance in relation to electron multipliers, and much work has been done on this subject. Figure 6 due to Allen [15] shows the effect of activation on the yield from a copper-beryllium alloy (such an alloy was used by the Author). For further details on activation the works of Allen [15, 16] should be consulted. The second factor, which is relevant to the proposed experiments, is that the yield is independent of the primary current for metals. (This is not the case for insulators where local charging up of the surface can occur). It follows that the work of the Author using very small currents indeed may be linked up with other work where large currents (~ Ma's) were used.

I. 2. (2d) Properties of Secondary Electrons. The energy distribution of secondary electrons was mentioned in Section I. 1. (3). Further curves showing in more detail the energy distribution of the true secondaries are shown in Figure 7. These were obtained by Kollath [17], using a refined technique. He observed that all the maxima lay between 1.4 and 2.2 eV.

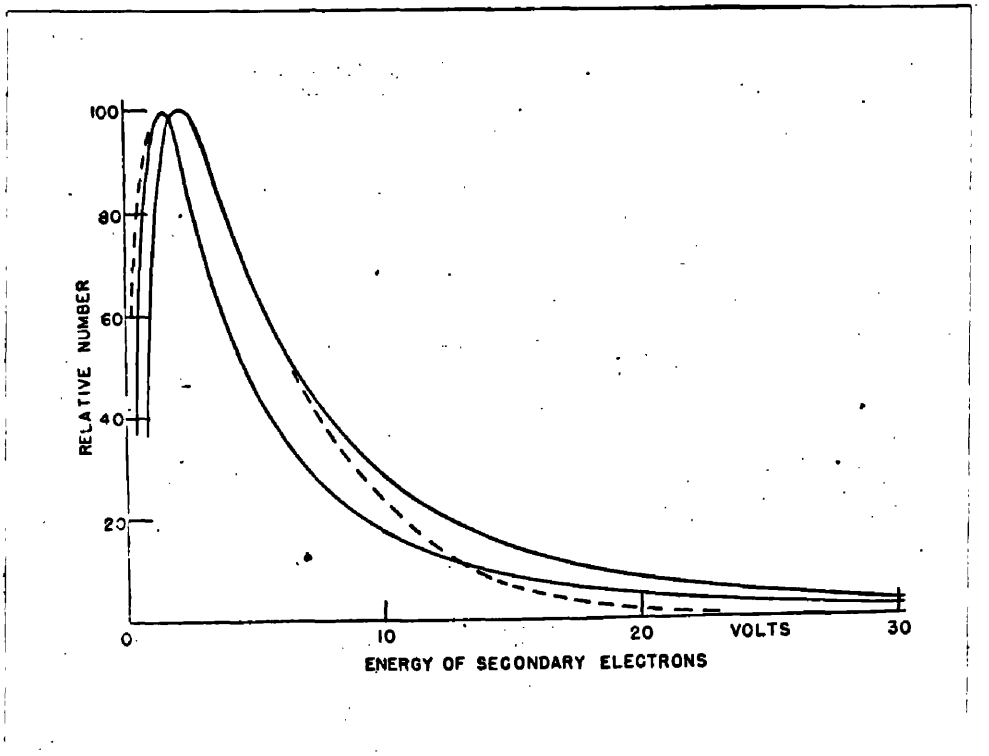


Figure 7. The energy distribution of the secondary electrons, according to Kollath (17). The experimental curves for different metals all lay between the two solid lines. The dotted line represents a Maxwellian distribution.

and, perhaps rather unexpectedly, the complete absence of any very low energy secondaries. Bruining [8] has suggested that the absence of any very slow secondaries may arise from the internal reflection of very slow electrons at the surface potential barrier of the metal. The distribution curves were almost independent of primary energy from $E_p \sim 20$ eV to 1000 eV. At greater values of E_p more high energy "secondaries" were observed, but these were probably inelastically reflected primary electrons.

The angular distribution of secondary electrons has been studied thoroughly by Jonker [18], and observed to follow a cosine law closely. The angular distribution of the emergent secondaries throws light on the angular distribution at the point of origin. Jonker concludes from these and other measurements that this is isotopic.

I.2.(2e) Secondary Emission for Primary Electrons of energy less than 50 eV. A certain amount of work has been done in this region on S.E. and on the reflection (elastic and inelastic) of electrons from surfaces. For very slow primaries no distinction is possible between a true secondary and a reflected primary, and presumably a value of E_p is reached where the primary has insufficient energy to liberate a secondary, and all outgoing particles are elastically or inelastically scattered primaries. This part of the subject

is reviewed by Bruining [8] and will not be considered further here.

I. 2. (3) Theories of Secondary Emission by electrons of energy less than 2 KeV.

Secondary Emission is a very complex phenomenon and it is worthwhile to outline briefly the sort of problems which have to be solved in any theoretical treatment. The complexity arises because S.E., unlike photo-electric emission, is a volume, rather than a surface, phenomenon. Secondary electrons are produced inside the metal, and must move through the lattice before escaping.

The first problem is the "Primary Interaction". The interaction between a primary particle and an electron inside the metal must be considered and momentum transferred to the latter must be calculated. It is also necessary to consider the "Primary Energy Loss," which determines the energy of a primary at any depth, on which depends the ability of the primary to produce secondary electrons. The last, and perhaps most complicated aspect of the process, is the interaction between the slow secondaries moving about inside the metal with conduction electrons. A secondary may be scattered or absorbed and finally it must retain sufficient energy to penetrate the surface barrier and escape.

Each of these problems is difficult to solve and at

present each lacks a satisfactory solution. Experimental data which would throw light on them is hard to obtain, in particular regarding the behaviour of both primary and secondary electrons inside a metal.

A number of theories of S.E. have been put forward. Bruining [19], and later Jonker [20], have developed a phenomenological theory, which is basically a mathematical formulation of the simple physical picture outlined in Section 1.2.(2a). It predicts the shape of the yield curve, the existence of a Universal Curve, and the effect of angle of incidence fairly well, but requires to assume a number of experimental parameters. This theory is important because it gives physical insight into the processes involved. Quantum mechanical theories have been developed by Fröhlich [21] Wooldridge [22], Dekker and Van der Ziel [23] and others, and theories using the free electron approach have been formulated by Baroody [11] and Kadyschevitsch [25]. Even these more rigorous theories usually require to assume experimental parameters in order to predict the magnitude of the yield. The general agreement between the observed yield curve and those predicted by the quantum mechanical and free electron theories are shown in Figure 8, due to Brophy [26]. Although most theories will predict some experimental results,

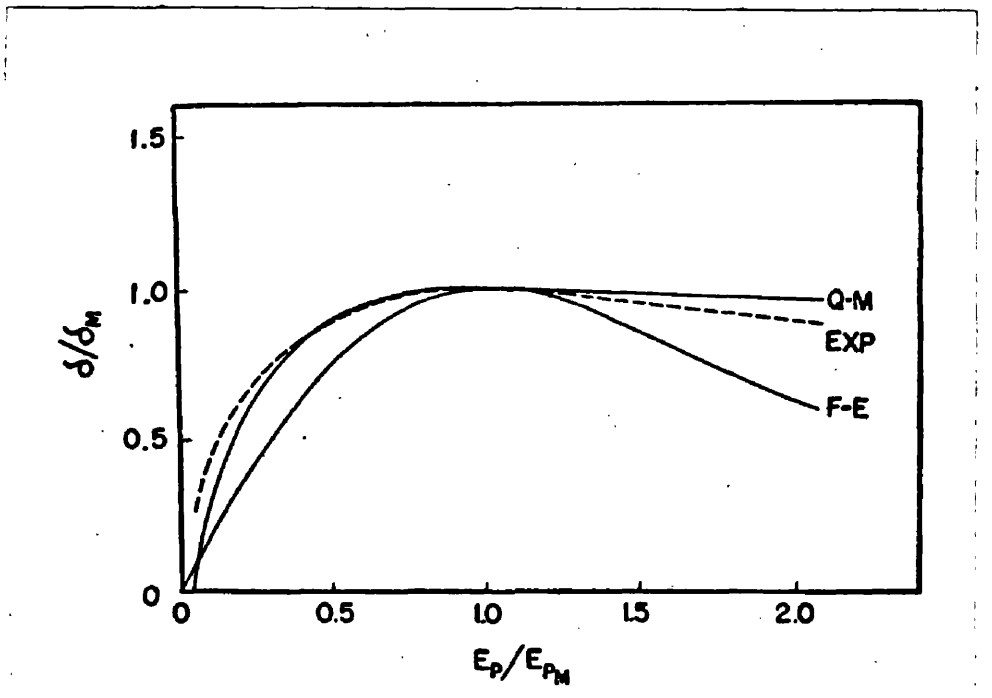


Figure 8. Comparison between theory and experiment, according to Brophy (26). Q.M. - Quantum Mechanical Theory; F.E. - Free Electron Theory; EXP - Experiment.

other data will often be in complete disagreement with theory. The best overall picture is probably obtained with a combination of different theories.

In conclusion it must be stated that the theoretical position is not yet very satisfactory and further reliable experimental data is required before this can be greatly improved.

I.3. Secondary Emission by Electrons of energy from a few KeV up to 500 KeV.

I.3. (1) General. This is the region where the Author's work on S.E. by positrons lies. The range was determined by the availability of positrons, rather than any considerations as to which region might be most interesting to study. In fact (See Chapter II, Part 1.) one would like to investigate S.E. by much lower energy positrons.

Most of the Author's measurements consisted of comparing S.E. by electrons and positrons, and in this section the existing date on electrons will be reviewed. Up to the time of the Author's work there was, apart from early investigations by Stehberger [27] and Schonland [28], only one report of S.E. by electrons in this region, by Trump and Van de Graaff [29]. They used primary electrons of energy from 20 - 300 KeV. Recently a further set of measurements was reported by Miller and Porter [30] from $\sim$ 20 KeV extending up to 1.2 MeV.

There is no theoretical work at all in this region, probably due to the increased complexity. The primary energy loss could be treated by means of the Bethe [31] ionization formula, which is well established in this region, but that would only be one step towards a theoretical treatment.

The experimental methods used in this region are basically the same as those outlined in Section I.2.(1) for lower primary energies, the electrons being obtained from an accelerator. It is important, however, to separate experimentally the different groups of "secondary" particles described in section I.1.(3). To do this a retarding potential method was used, which also enabled the energy distribution of the secondaries to be measured.

I.3.(2) Experimental Results. Figure 9, due to Trump and Van de Graaff [29], shows the variation with primary energy of the total secondary yield and the high energy component of the yield. Figure 10, which is a replot by Allen [16] of Figure 9 shows the variation with energy of the low energy component, assumed to be largely true secondary electrons. The high energy or reflected component increases with energy up to $E_p \sim 100 - 200$ KeV, after which it is practically independent of energy. The constant value reached depends on the material and is roughly proportional to density. The

Figure 9. The variation with primary energy (V_p) of the total yield and the fast secondary yield at high energies; according to Trump and Van de Graaff [29]

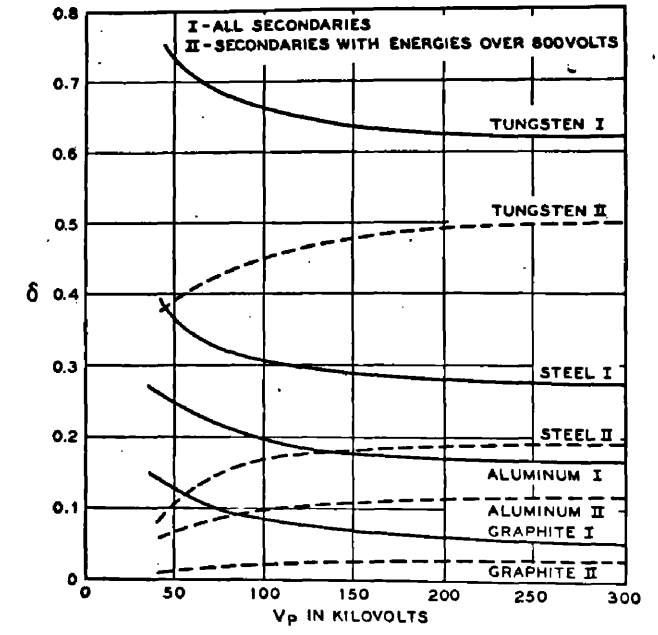
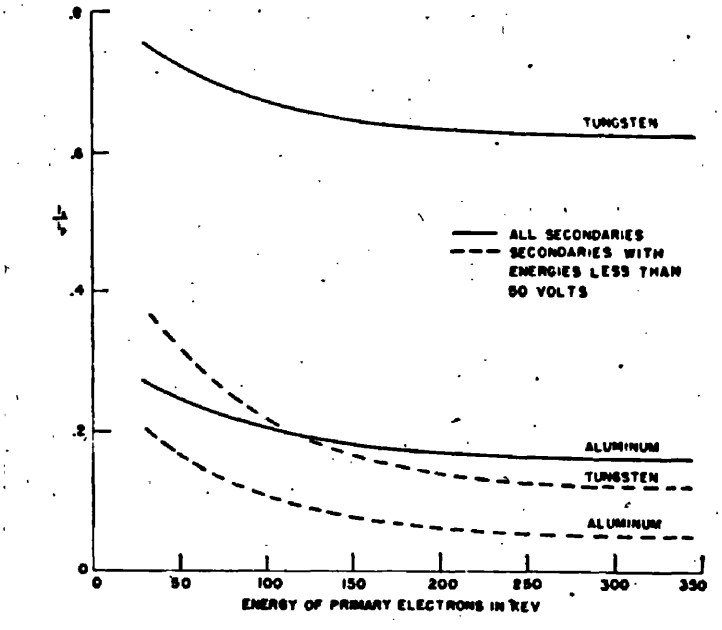


Figure 10. The variation with primary energy of the slow yield, at high energies. Replots by Allen [16] of Figure 9.



yield of true secondaries is a decreasing function of energy in the whole region, but falls more slowly at high primary energies until it also tends to become independent of energy between 200 and 300 KeV. Again the value reached is roughly proportional to the density of the material.

Trump and Van de Graaff observed that much of the low energy component of the yield had energies $\sim$ a few eV, and there were not many particles between 20 eV and 800 eV, the highest retarding potential used.

There are a few recent measurements of S.E. at very high primary energy, such as by Pomerantz et al.[32] at 1.3 MeV and Tautfest et al.[33] at 100 MeV. These are not really relevant to the present investigation, but did show that the energy distribution of the slow secondaries was similar to that observed at low primary energy, and that the yield was nearly independent of energy.

If a thin target is bombarded with electrons and the emergent particles are examined, two distinct groups are observed. There is a fast group of transmitted primaries and a slow group of secondaries. This was examined by Wecker[34], who observed that the yield of slow secondaries was of the same order of magnitude as that obtained for secondaries emerging on the entrance side. This is mentioned here because

some of the Author's results suggested that it might be interesting to observe the S.E. on the exit side produced by positrons.

I.4. Secondary Emission by Positive Ions

I.4.(1) Introduction. S.E. by positive ions is in general quite a different phenomenon to S.E. by electrons. Positive ions are able to liberate secondary electrons by an entirely different mechanism, the process of potential ejection. As such a process might occur for positrons, this section will largely be devoted to a consideration of the mechanism of potential ejection, and in Chapter II the conclusions reached here for positive ions will be considered in relation to positrons.

Before going on to discuss potential ejection a few general remarks will be made about S.E. by positive ions. The liberation of secondary electrons by positive ions is very important from the point of view of gas discharges, where electrons are produced at the cathode by positive ion bombardment. S.E. by positive ions has not been studied to nearly the same extent as electron induced S.E., largely due to the difficulty of obtaining homogeneous ion beams, and to the fact that the state of the surface is of even greater importance than in the case of electrons. This is because S.E. by low energy positive ions is more a surface effect than S.E. by electrons, due to the extremely short range of slow ions.

The general experimental methods are similar to those mentioned in Section I.2.(1) for electrons. Experimental investigations of S.E. by positive ions of energy from a few KeV downwards, where potential ejection is important, have been made by Penning [35], Jackson [36], Oliphant [37], Healea and Houtermans [38], and recently by Hagstrum [39], whose work is notable because of the care he took to obtain atomically clean targets. Theoretical work in this energy range has been done by Oliphant and Moon [40], Massey [41], Cobas and Lamb, [42], Shekhter [43], and Hagstrum. The work of Hagstrum forms the basis of the account given below.

I.4.(2) The Theory of Secondary Emission by Positive Ions

I.4.(2a) Processes by which secondary electrons may be liberated. Secondary electrons may be ejected by two processes. Firstly there is "kinetic ejection", in which the energy supplied to enable an electron to escape from the metal, comes from the kinetic energy of the incident particle. This process can occur for S.E. by any particle, and it is the only possible process for electrons. The second process is that of "potential ejection", and has been considered in relation to positive ions. In this process two conduction electrons in the metal are involved; one neutralises the ion, and the excess potential energy recovered by the ion on neutralisation is

available to eject a second conduction electron, which appears as a secondary electron. The ejection of an electron from the metal in this way may be considered as a collision of the second kind between the excited atom (i.e. the ion which has been neutralised) and a conduction electron, or as an Auger process by which the excited atom de-excites itself by particle emission. Oliphant and Moon considered the former while Hagstrum suggests that the latter is a better representation.

Kinetic ejection predominates for ion energies of more than a few KeV, and potential ejection is favoured at low ion energies, especially if the ion has a high ionization potential.

I.4.(2b). <u>The mechanism of the liberation of secondary electrons by potential ejection.</u> Hagstrum considers two processes of potential ejection. These are the "One Stage" or "Direct" process and the "Two Stage" process. Although the latter is more probable if energetically possible, the former is simpler and will be described in order to illustrate the basic mechanism of potential ejection. The two stage process, and one other possible process will then be mentioned.

<u>The one stage process.</u> The potential diagram of an atom with ionization potential Vi a distance d from a metal with work function ϕ is shown in Figure 11 (a). μ is the width of the conduction band and $W_a = \mu + \phi$. While the approaching ion is still outside the metal, a conduction electron e_2 with a potential energy β

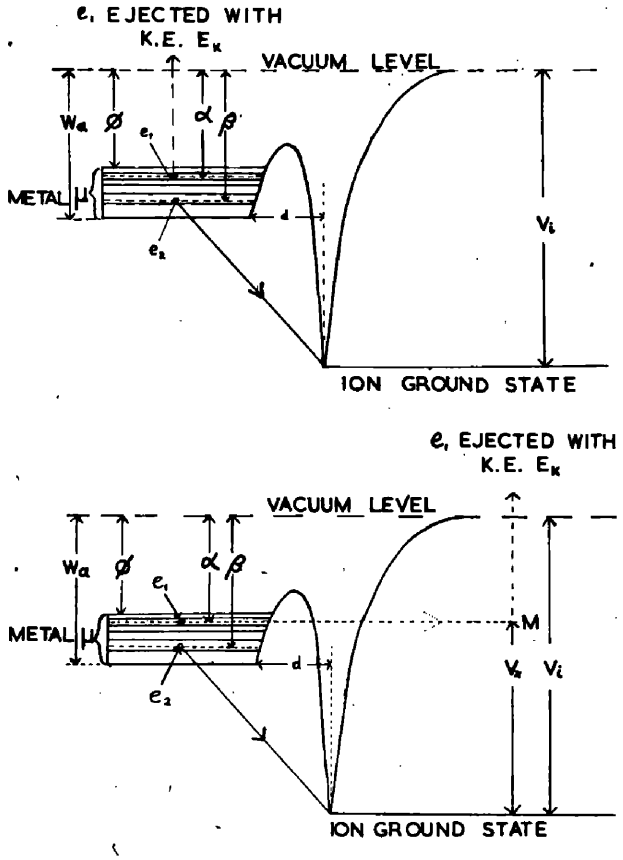


Figure 11. (a) (above) The potential diagram for the "one stage" process of potential ejection by positive ions.
(b) (below) The potential diagram for the "two stage" process.

below the vacuum level, penetrates the potential barrier and neutralises the ion by falling directly to the ground state. The excess potential energy of the atom (neutralised ion) is equal to $Vi - \beta$ and is available to eject a second conduction electron e_1 which requires an energy α to escape from the metal. The kinetic energy of e_1 outside the metal will be $E_k = Vi - \alpha - \beta$, with a maximum value E_k max. $= Vi - 2\,\phi$, when $\alpha = \beta = \phi$, and a minimum value E_k min. $= Vi - 2\,W_a$, when $\alpha = \beta = W_a$.

The Two Stage Process. In this process Hagstrum assumes that the electron, e_1, "tunnels" through the barrier to a metastable level M (excitation potential V_e), in the ion. This is the first stage and is illustrated in the potential diagram in Figure 11(b). It follows that this process can only occur if a suitable metastable level exists. In the second stage or "Auger de-excitation" a second conduction electron, e_2, falls directly into the ground state of the atom, and the excess potential energy recovered, $Vi - \beta$, causes e_1 to be ejected with a kinetic energy E_k, where E_k max. $= Vi - \alpha - \phi$, when $\beta = \phi$, and E_k min. $= Vi - \alpha - W_a$, when $\beta = W_a$.

In both these processes the excited atom may decay by radiation, but Shekhter [43] has shown the probability of this is very small. The actual yield of secondary electrons observed is limited by solid angle considerations.

A further process of potential ejection. Oliphant and Moon suggested an alternative process, in which a faster ion entered the metal before neutralisation. In this case the whole ionization potential would be available, and if a second conduction electron was ejected it would have a kinetic energy given by $E_k = Vi - \alpha$, where α is the energy required to extract the electron from the metal. Hagstrum's experimental results did not support this process and he suggested Oliphant's experimental evidence for it was due to He^{++} ions in the He^{+} beam. The process is included here because it might occur for positrons when no other process was energetically possible.

I. 4. (2c) Experimental evidence for potential ejection. Hagstrum's experiments yielded much data which supported the direct and two stage processes of potential ejection. The two most important results were as follows: (1) The observation that for low energy ions the yield was nearly independent of ion energy and was larger for ions with a high ionization potential. (2) Good agreement between the maximum energy of the ejected electrons, calculated from the expressions above, and the measured values.

I.4. (3) Secondary Emission by High Energy Positive Ions. A little work has been done on the S.E. by positive ions with energies more than a few KeV, notably by Allen [44], Hill et al. [45]

and Aarst et al.[46], The main features of the yield curve are a broad maximum at some 100's of KeV and high values of the yield, often from 10 - 15. Typical yield curves are shown in Figure 12, due to Allen.

I.5. Conclusion to Introductory Review

In this review an attempt has been made to outline the scope of the existing work and thus to indicate which aspects require further study. Of these, S.E. by positrons stands out, and the fact that no work at all has been done on this subject is itself sufficient justification for the proposed investigation. This investigation was largely a comparative study of S.E. by positrons and electrons of energy 500 KeV down to the lowest energy possible. (In practice this was ~5 KeV for positrons). Other reasons for such a study include the fact that there exist some interesting possibilities which might make positrons behave differently from electrons. Of these, one has already been discussed for the case of positive ions, and will be considered in relation to positrons in Chapter II. Some further considerations which might be relevant to S.E. by positrons are also discussed in that Chapter. A further reason for the proposed study is that there exists so little data on any aspects of S.E. in the energy region to be investigated. Also, the present theoretical position is not satisfactory and new data on positrons

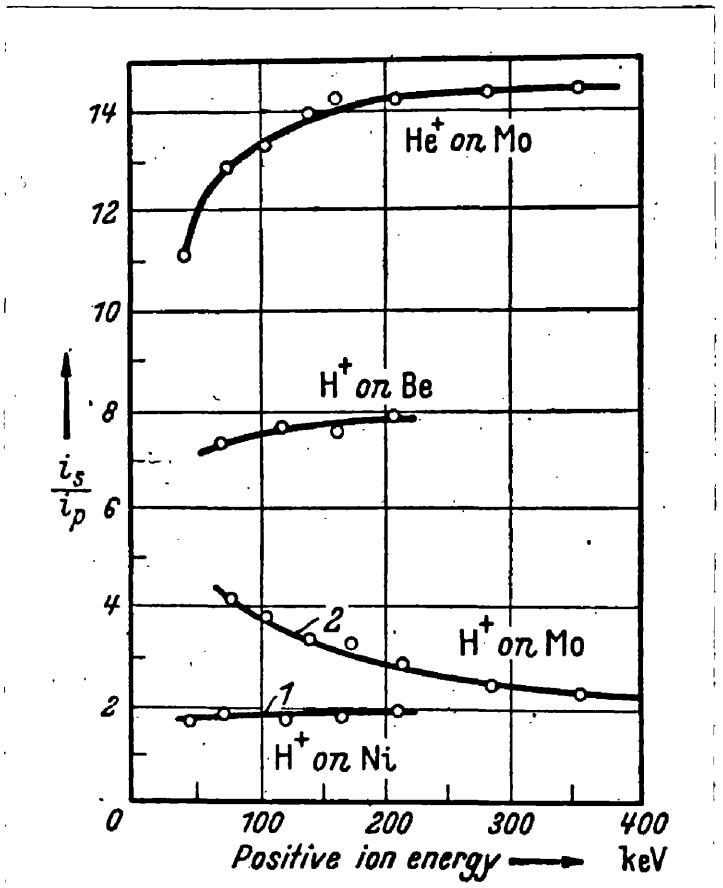


Figure 12. Yield curves for S.E. by high energy positive ions, according to Allen (44).

and also on electrons might throw some light on this, in particular, towards the formulation of a theory at higher energy.

The review has also attempted to bring out the aspects of the existing literature which might be relevant to S.E. by positrons. As there is no existing work on this it has only been possible to consider the subject in a general way, rather than specifically in relation to positrons.

Most of the basic properties of S.E. by electrons have been mentioned in the section dealing with lower primary energies. In the absence of any data on positrons it seems probable that these general considerations would also apply to S.E. by positrons, unless some other factors became important for these particles.

The section on high energy primary electrons was included in order to compare the results of the Author's experiments on electrons and positrons with existing data on electrons.

The section on positive ions outlined the mechanism of potential ejection, which is relevant because under certain conditions positrons might liberate secondary electrons by this process, and behave more like positive ions than electrons. Electrons are not able to eject secondaries by potential ejection. It must be pointed out, however, as stressed in Chapter II, that if the process of potential ejection occurs for positrons it

would only be predominant for very slow positrons of energy $\sim$ 1 eV or less. It is nevertheless important because it does illustrate one way in which S.E. by electrons and positrons could be quite different.

CHAPTER II

PART 1. SOME THEORETICAL IDEAS CONCERNING SECONDARY EMISSION BY POSITRONS

There is no existing theory on S.E. by positrons and in the first part of this Chapter a few simple theoretical considerations regarding S.E. by positrons will be given.

II. 1. (1). Potential Ejection as a possible process by which positrons might liberate secondary electrons.

An interesting possibility, first suggested by Curran (47), is that under certain conditions positrons might be able to liberate secondary electrons by a process of potential ejection similar to that known to occur for positive ions, which was described in Section I. 4. (2b). Such a process would be impossible for electrons.

If a positron, as it approaches a metal surface, draws out a conduction electron from the metal, it may capture this electron and be neutralised to form positronium. This is analogous to the case of a positive ion becoming neutralised at a metal surface and the considerations put forward below follow the same general lines as those which were given in Chapter I for positive ions. The formation of positronium will make available a potential energy $V = V_i - \alpha$ where V_i is the "ionization potential" of positronium and α is the energy required to extract the neutralising electron. This excess

potential energy may produce a radiating transition of the excited positronium, or cause a second conduction electron to be ejected from the metal and appear as a secondary electron with kinetic energy $V_k = V_i - \alpha - \beta$, where β is the energy required to remove the second electron from the metal. It must be assumed that the excess potential energy will be given up before the positronium annihilates, but this is probable, as most annihilations occur in the ground state.

It can be shown theoretically that positronium has energy levels like a hydrogen atom, except that the reduced mass in the spectral terms makes the energy levels, E_n, one half of those for hydrogen. Hence the value of V_i for positronium is $\frac{1}{2} \times 13.6 = 6.8$ eV, and $V_k = 6.8 - \alpha - \beta$.

The maximum and minimum values of V_k can be determined as described in Section I. 4. (2b) for the direct process of potential ejection by positive ions. For positrons the low value of V_i leads to the result that V_k min. = 0: V_k max. = $6.8 - 2\phi$, where ϕ is the work function of the metal. It follows from the value of V_k max. that if positrons can liberate secondary electrons by this process at all, they will only do so from metals with $\phi < 3.4$ eV.

It is possible that the further process of potential ejection suggested by Oliphant and Moon for a faster ion, which

was mentioned in Section I.4. (2b), might be favoured for S.E. by positrons. In such a process the positron is neutralised inside the metal and all the potential energy recovered is available to eject a secondary electron; the kinetic energy of the ejected secondary, V_k, is therefore $V_i - \beta$ i.e. $6.8 - \beta$. Thus all conduction electrons for which $\beta < 6.8$ eV are available for ejection, and this includes many electrons too deep down in the conduction band to take part in the other process. In that process the positron interacts with two conduction electrons for which $(\alpha + \beta) < 6.8$ eV. The maximum and minimum of V_k for the second process are given by V_k min $= 6.8 - W_a$ where $W_a = \mu + \phi$ and μ = the width of the conduction band and V_k max. $= 6.8 - \phi$. From the value of V_k max. it follows that this process can only occur for metals with $\phi < 6.8$ eV.

There is one very important consideration which applies to all the above discussion. In order to have a velocity comparable to that of a positive ion whose energy is less than $\sim$2 KeV, where potential ejection is known to occur, a positron would require to have an energy $\gtrsim 1$ eV. From this it follows that potential ejection will certainly not be predominant in any laboratory experiments which are feasible at present. It would be most interesting to examine the S.E. by very slow positrons and electrons, to see if the former gave a

greater yield than the latter, and a very convincing experiment would be to demonstrate the liberation of electrons when a surface was bombarded with positrons whose energy was too low for kinetic ejection to occur. No confusion between reflected primaries and true secondaries can arise in this case. A further important difference between S.E. by positrons and electrons which would be observed if potential ejection was important for positrons, arises in the energy distribution of the secondary electrons. It was shown that a potential ejection process can give secondaries with an energy distribution extending to zero, which is quite different case of S.E. by electrons for which there are no very slow secondaries (See Section I. 2(2d)). If feasible, experiments on the energy distribution of secondaries liberated by positrons should be fruitful. Potential ejection by positrons will certainly not be predominant for fast particles, because these spend too little time at the surface of the metal for the positron to have much change of being neutralised. There is, however, a possibility that even at higher energies positrons might be favoured slightly.

II. 1. (2) Further considerations regarding S.E. by positrons.

In this section other possible differences between the S.E. of electrons and positrons will be considered. Some known differences in the behaviour of these two types of particle will be examined from the point of view of any effect these differences

might have on their S.E.

One of the most striking differences between electrons and positrons (apart from the opposite sign of their charge) is that a positron when created e.g. in a β^+ emission processes or in pair production very quickly combines with an electron, and the electron-positron system so formed annihilates, usually to give two $\frac{1}{2}$ MeV. quanta. The life time of a positron in a metal is $\sim 10^{-10}$ sec., (See for example, Bell and Graham [24]) and there are two possible consequences which arise from the rapid disappearance of a positron by annihilation.

Firstly, a positron which entered a metal without giving a potentially ejected secondary electron might be lost, due to annihilation, before it was able to produce a secondary by the normal process of kinetic ejection. Only secondaries produced within a distance R_s of the metal surface can escape and contribute to the observed yield, where R_s is the mean range of a secondary electron. Thus the production of secondary electrons by a kinetic process probably always occurs while the positron is in flight. Most annihilations occur after thermalisation and Heitler [48] showed that only $\sim 10^{-2}$ positrons annihilate in flight at energies $\sim$ 100's of KeV, and fewer at lower energies. Thus the probability, P, of a positron being lost due to annihilation, before it was able to produce an observable secondary, is

approximately the probability of annihilation in a distance R_s. This is equal to the probability of annihilation in flight $x\ ^{R_s}/_{R_p}$ where R_p = the range of the positron, i.e. $P \sim 10^{-2}\ R_s/R_p$. This is negligible for positrons produced in the laboratory with energies $\lesssim$ a few KeV, as $R_p \gg R_s$. For slower positrons P may approach 10^{-2} as R_p tends to R_s and for very slow positrons the concepts of thermalisation and decay in flight become rather vague, and P can probably become an appreciable fraction.

The second possibility is that the annihilation radiation would give rise to a secondary electron. If the target is thick enough to stop the ppsitrons (this is generally the case for the Author's experiments), nearly every positron will give rise to two $\frac{1}{2}$ MeV γ-rays emitted in opposite directions inside the target. In order to produce a secondary electron, a γ-ray must first produce a fast electron by a photo-electric or Compton process, and this electron will actually eject the slow secondary electron. The mean free path of the γ-ray for these processes is long compared with the range of the fast electron produced, and the chance of this electron arising in the target so that it can emerge is only $\sim 1\%$. Only a fast electron which does emerge, or at least reaches a distance $\sim R_s$ from the surface, can produce a slow secondary electron which will escape. If it does, it will do so with a probability of the order the S.E.C.

at the energy of the fast electron, i.e. $\sim$ a few per cent. Thus the overall probability of a slow secondary arising from the annihilation radiation is $\sim 10^{-4}$.

There are some other differences in the behaviour of positrons and electrons, but these are usually small and in any case do not appear, on elementary grounds, very likely to have much effect on the S.E. of the particles. Among these Mott and Massey [49] point out theoretical differences which are predicted in the scattering of electrons and positrons in a coulomb field (of a nucleus); considerable differences are found for nuclii of high atomic number, positrons being scattered less. These authors also discuss collisions between electrons and positrons with a free electron, and again predict some difference, especially for large scattering angles. Some experimental results published after the present research began, for example by Bascova and Gorbachev [50] and by Seliger [51], showed that positrons were transmitted more readily through thin foils than electrons, the difference being small but not insignificant. These authors suggested this was in fact a consequence of the unequal nuclear scattering; electrons are scattered more and thus lost from the beam in greater numbers. Seliger [52] also found an excess of electron backscattering over that of positrons $\sim 30\%$, at energies $\sim$ 100's of KeV. This he attributed to an integrated effect of a large number of single scattering events in each of which the electrons were scattered

through a larger angle. As secondaries are produced by ingoing and outgoing particles (See Section I. 1. (3)) a large difference in the relative numbers of positrons and electrons which were backscattered would be expected to give a small difference in the secondary yield.

Summarising, it must be stated that it does not appear likely that any large difference in S.E. will be observed in the region of energy covered by the experiments about to be described. The position at very low primary energy might be quite different due to potential ejection, and there is the possibility of a small effect arising from this at high energy. The other factors, with the possible exception of the unequal backscattering do not seem likely to have an appreciable effect on the S.E. of the particles.

PART 2. THE BASIC PRINCIPLES OF THE EXPERIMENTAL METHOD TO BE USED TO STUDY S.E. BY POSITRONS

None of the existing techniques for studying S.E. was feasible for experiments with positrons. Positrons required to be obtained from a radio-active source, and it was necessary to adopt a counting method to determine the number of primary and secondary particles. The usual Faraday chamber arrangements used by other workers, which measured the primary and secondary

currents directly, were not nearly sensitive enough.

An electron multiplier seemed to be the only satisfactory arrangement to detect the slow secondary electrons and an Allen (53) type of multiplier was chosen for this purpose. The first dynode was used as the target, and the second dynode detected secondaries produced at this target with an efficiency approaching 100%. It should be noted that this arrangement involves the use of a curved target and a variable angle of incidence. However, as seen in Figure 14(a), the area of the first dynode which is bombarded by the primary beam is approximately flat and gives almost normal incidence. In any case the same target is used for both particles so comparative data should be reliable. The use of a flat target and normal incidence would destroy the focusing properties of the multiplier, and greatly reduce the efficiency of collection of secondaries produced at the target, by the second dynode.

An advantage of a multiplier for detecting the secondaries is that it automatically separates slow secondaries from reflected primaries, at the primary energies used by the Author. This is because the efficiency of the multiplier for detecting fast primaries reflected from the first dynode, is much less than its efficiency for detecting slow secondaries liberated at the first dynode. Measurements on the relative efficiency of the multiplier for detecting reflected primaries and slow secondaries will be

discussed in Section III. 3 (7).

The absolute number of primary particles was counted by means of a thin windowed Geiger counter. This had the advantages that its efficiency for particles transmitted by the window was 100%, that it was independent of particle energy, and that it was very insensitive to γ-rays. The later fact was important as there would be an appreciable flux of $\frac{1}{2}$ MeV γ-rays from the decay of positrons not focused on the counter.

The complete experimental arrangement consisted basically of a source and a β-spectrometer, to produce a beam of particles of the selected sign and energy. This beam either fell on the target or entered the Geiger counter, which could replace the target behind the final collimating slit. The whole arrangement is shown schematically in Figure 13.

In view of complications which might arise due to the state of the surface, it was decided that it would be very much better to concentrate on comparing the S.E. from positrons and electrons of the same energy, rather than to make measurements on positrons alone. The use of copper 64 as the source of positrons was ideal for this approach, as it also emitted electrons whose spectrum was similar to that of the positrons. The use of a comparison method, by means of which the S.E. of the two kinds of particle was measured under identical conditions of geometry, by reversing the magnetic field, had several other very attractive

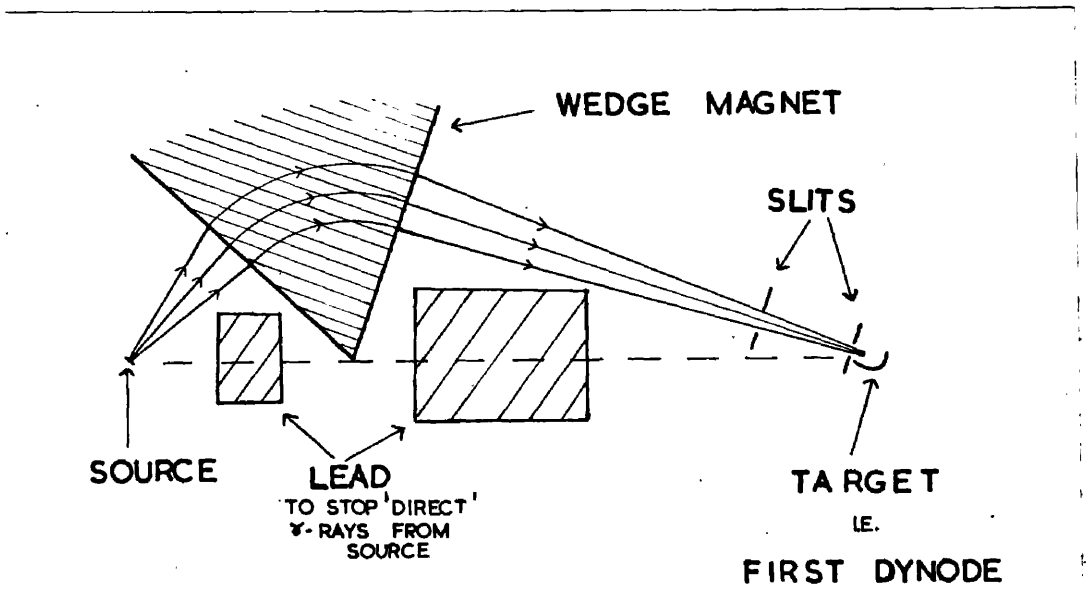


Figure 13. A schematic diagram of the experimental arrangement for investigating S.E. by electrons and positrons.

features. Absolute measurements could also be made, and for electrons, compared with existing date, where possible.

The energy distribution of the secondaries could be determined by placing a fine grid with a variable potential on it between the target and the second dynode. Although it would have been very interesting to compare the energy distribution of secondaries produced by positrons and electrons, in practice this turned out to be a very difficult experiment, and it was not carried out.

The method outlined above, essential when the primary particles come from a source, is much more involved than the usual methods mentioned in I.2 (1). In particular, when attempts were made to extend measurements to the lowest energy possible difficulties arose due, among other factors, to lack of particles and absorption in counter windows.

The use of an electron multiplier to detect electrons has been reported by Allen (53, 15, 16) but its use in conjunction with a Geiger counter as a device for measuring S.E. is original.

CHAPTER III

THE ELECTRON MULTIPLIER AND ASSOCIATED ELECTRONICS - EXPERIMENTS ON THE MULTIPLIER PERFORMANCE

III. 1. GENERAL

The electron multiplier was a 14 stage Allen type (First reported in 1939 by J.S. Allen [53]). The dynode assembly was obtained in kit form from Harwell and assembled by the Author. This Chapter describes the multiplier and associated equipment, and outlines briefly some preliminary experiments. These were important in order to obtain general data on the multiplier performance and to determine the best working conditions. Although Allen [53, 15, 16] has reported measurements on similar multipliers, no published characteristics are available, as for commercial photomultipliers.

III.2. Construction of the Electron Multiplier

III.2.(1) The Dynodes. The dynodes were made from a copper-beryllium alloy (2% beryllium) and activated at Harwell by R.F. heat treatment as described by Allen [15], whose curves showing the S.E.C. before and after activation were shown in Figure 6.

The dynodes were supported between two insulating plates by nickel wires which passed through holes in each plate. The layout is illustrated in Figure 14 (a).

III. 2.(2) The Multiplier Base. The multiplier base was a circular piece of brass $\frac{1}{4}$" thick and $4\frac{1}{2}$" in diameter; the

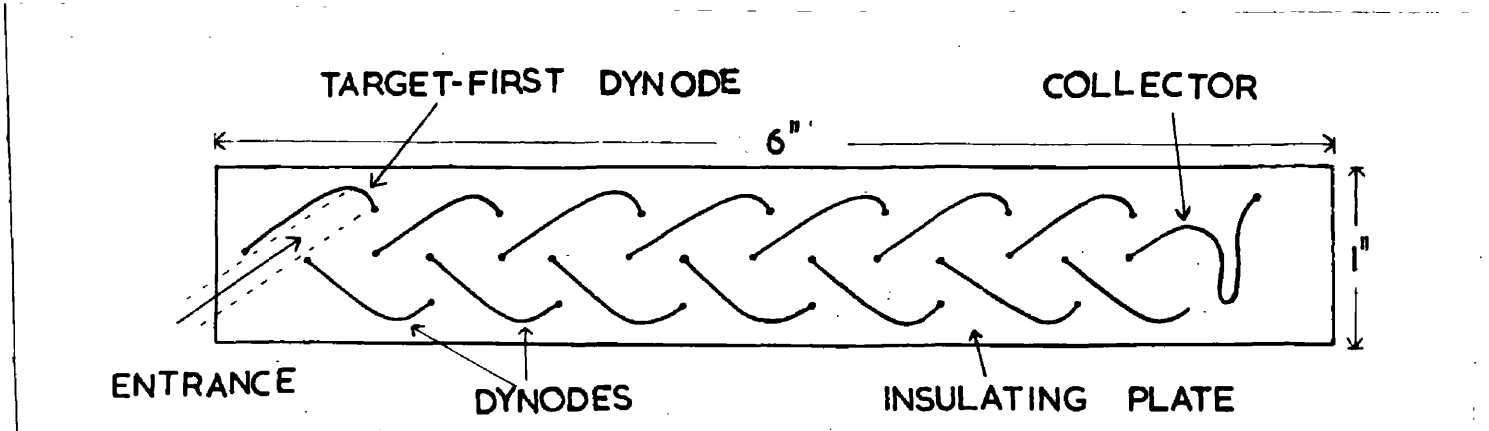


Figure 14 (a) A diagram of the layout of the electron multiplier dynode assembly.

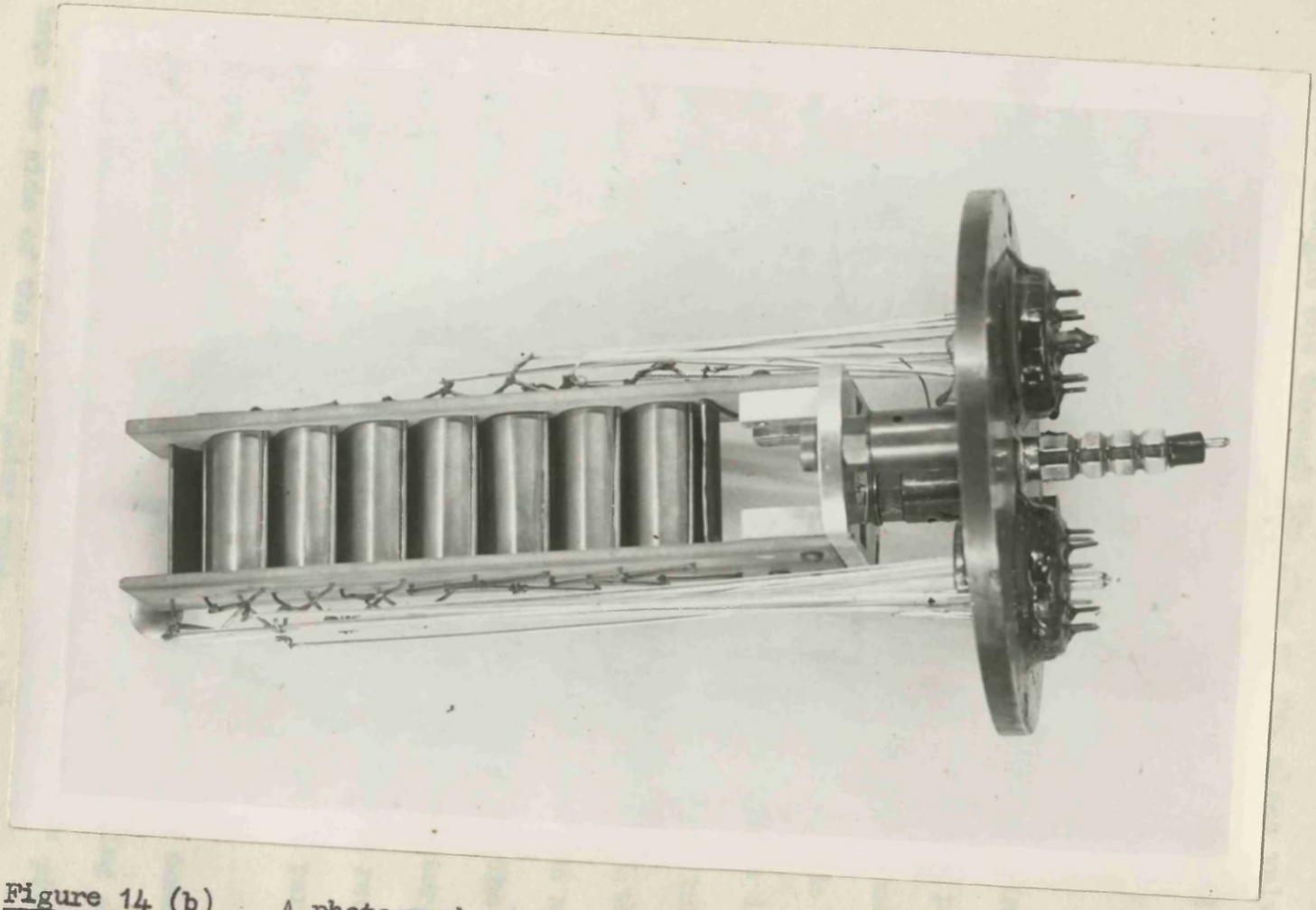


Figure 14 (b) A photograph of the dynode assembly.

insulating strips which supported the dynodes were fixed to this plate by suitable spacers. The wires from the dynodes were brought out through the pins of two glass valve bases, cut from VR 91 valves, and fixed by cold setting Araldite to holes in the base plate. Araldite was used because it made a good vacuum seal which had first class insulating properties. The collector was brought out through a $2\frac{1}{2}$" long Kovar seal passing through the centre of the plate. Care was taken to avoid the possibility of any electrical breakdown or "tracking" from the dynode connections, and, in particular, from the collector. The dynode assembly, mounted on the base plate, is shown in the photograph in Figure 14(b).

III. 2.(3) The Multiplier Case. This was an iron tube 3" in diameter and 8" long, which had a flange at one end through which the dynode assembly was inserted; a vacuum seal was made by an o-ring between the flange and the base plate. The other end of the case was closed with a brass plate $4\frac{1}{2}$" diameter, mounted at an angle of 45° to the tube axis, which contained a rectangular apperture opposite the first dynode, through which particles entered the multiplier.

The main vacuum system of the spectrometer was connected to the multiplier by this plate, an o-ring seal making a vacuum joint. The whole system was evacuated through a 2" pipe fixed into the side of the multiplier case. A diagram of the case is

shown in Figure 15 and the multiplier in position on the spectrometer is seen in the photograph in Figure 33 (Section VI. 2 (1)).

III. 2. (4) The Multiplier Electronics. A high voltage supply of 7 KV was required to operate the multiplier, as the gain of such a tube is nominally a maximum with 500 volts per stage. A suitable stabilised power unit was designed and built in the Electronics Laboratory.

It was essential that the first dynode was at earth potential and the collector at + 7 KV. If the first dynode was at - 7 KV, the primary beam would be accelerated (for positrons) or decelerated (for electrons) before hitting the target. Although this could be corrected for it would be very confusing, especially as much work was anticipated using primary energies ~ 10 KeV. It would also destroy one of the most favourable features of the proposed experiments, namely to make measurements with the electron multiplier and Geiger counter under identical conditions for both types of particle. This arrangement introduced a number of problems concerned with high voltage tracking and breakdown from components near the collector, which produced spurius counts. As many of the true multiplier pulses were only a few millivolts it was essential that such "artificial background" pulses should be much less than

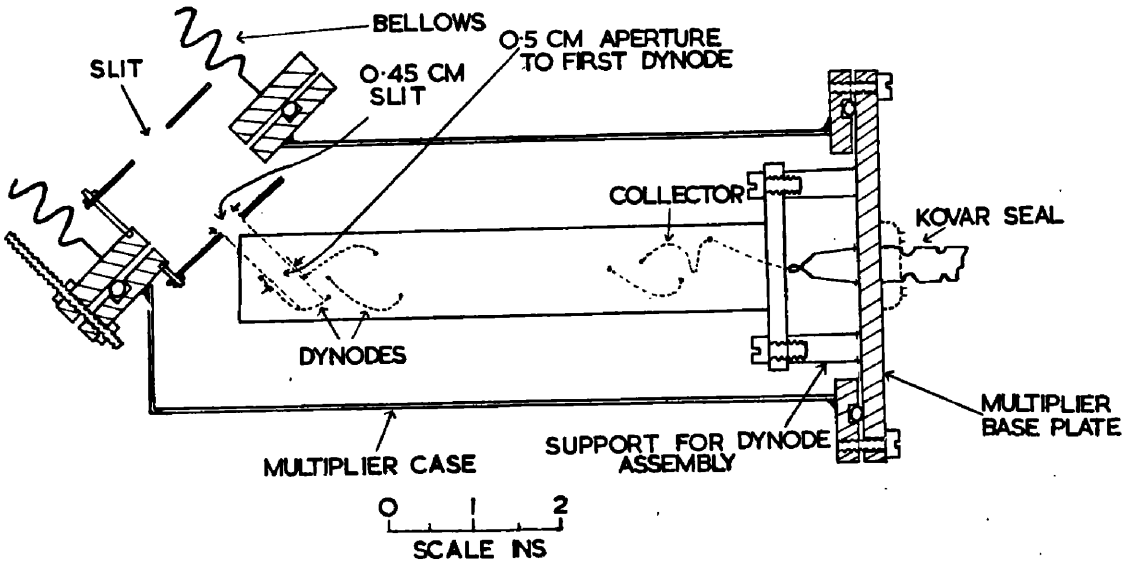


Figure 15. A diagram of the electron multiplier case, showing the collimating slits and the position of the dynodes.

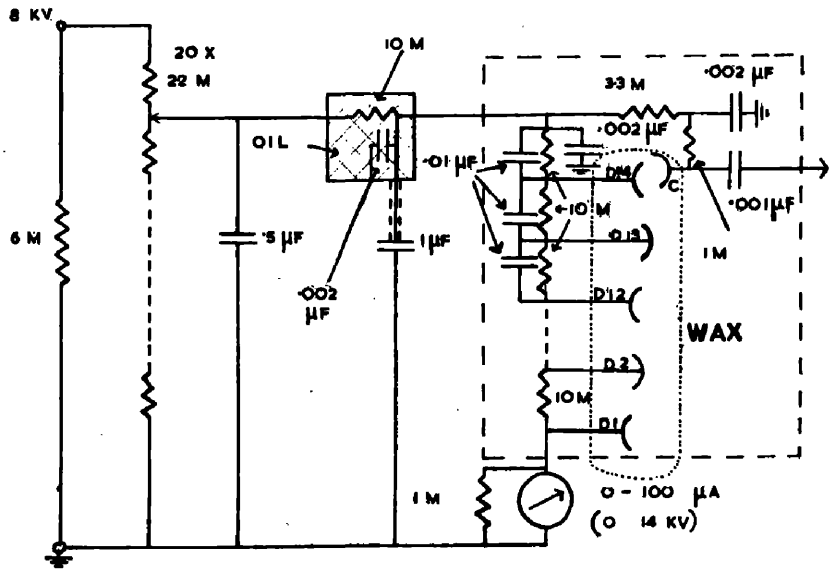


Figure 16. The circuit of the smoothing arrangement used to eliminate spurious pulses on the E.H.T. line at the multiplier.

1 millivolt. A considerable amount of time was devoted to obtaining the E.H.T. line at the collector free of unwanted pulses. The final arrangement is shown in Figure 16. In principle this consisted of removing any unwanted pulses produced in the power pack by decoupling with good quality high voltage condensers, and immersing these condensers and all the components following them, including the dynode resistor chain, collector load resistance and output condenser, in paraffin wax.

There were two main stages in the development of this part of the circuit. The first stage included experiments on the multiplier performance and the preliminary experiment on S.E. described in Chapter IV. During this stage of the work the artificial background, i.e. the count rate arising from high voltage breakdown, was some hundreds of counts per minute, compared with a natural background (due to thermal emission and cosmic rays) of 30 - 40 counts per minute. This was quite satisfactory for preliminary experiments but too high for work with the spectrometer, when count rates would often be very low. After the early experiments a systematic attempt to reduce the artificial background to a value suitable for measurements with the spectrometer was made. The final arrangement, which is shown in Figure 16, gave an artificial background of the order of 50% of the natural background, a workable value.

Most of the experiments were performed under these conditions, but later a few refinements, including the use of oil instead of wax, reduced the artificial background to zero. The improvement achieved in this respect is well illustrated in the curves of background against scaler bias in Figure 18.

The remainder of the electronics was of standard design, and consisted of a preamplifier and amplifier, (Type 1008), whose output pulses were displayed on an oscilloscope and counted on a scaler (Type 1009B). The control unit is shown in the photograph in Figure 17.

III.3. Experiments on the Electron Multiplier performance

III.3.(1) (1) Experimental arrangement. The spectrometer was not used for these experiments and the multiplier was connected directly to a glass tube 2" in diameter and 10" long, which contained an arrangement for inserting sources. The source holder was mounted on a rod which could slide in and out under vacuum by means of an o-ring seal, in order to let particles from the source reach the first dynode. When the rod was pushed in the source holder was held accurately a few cms. in front of this dynode by two guide rods. A sliding vacuum valve was incorporated so that sources could be changed without breaking the vacuum, and a shutter which closed the apperture into the multiplier when the source holder was withdrawn, enabled the background count rate to

Figure 17. A photograph of the control units for the multiplier.

be taken quickly. The arrangement for inserting sources was also used on the spectrometer and is shown in the diagram in Figure 25. (Section V.2.). The sources used for most of the early work were cobalt 60 and carbon 14 (electrons).

III. 3. (2) Variation of count rate with amplifier gain

III. 3.(2a) Fundamental considerations. It is important to understand what is happening in the multiplier when it is used, as in the Author's experiments, to investigate the S.E. from primary particles of energy from 5 to 500 KeV. Allen has shown that in this region the S.E.C. of copper-beryllium is less than 1. Hence primary electrons will liberate either one secondary or no secondaries at the first dynode. It follows that the pulse height distribution is determined largely by the second dynode and to a small extent by the subsequent dynodes. If a bias curve is plotted, i.e. a curve of count rate against scaler bias, a point should be reached where all primary particles which give an electron at the first dynode will be recorded, and a further decrease in the bias (or an increase in the amplifier gain) will not cause any increase in count rate. This is clearly the correct working position for the proposed experiments, and must be determined.

III. 3.(2b) Experiments. Count rates were recorded with the source in position and withdrawn (to give the background) at

different values of the amplifier gain and the scaler bias.

A typical bias curve is shown in Figure 18. The dotted line represents part of a bias curve due to Allen for a similar multiplier. Also shown in the figure is another bias curve, obtained later when the artificial background had been eliminated by using oil as an insulator instead of wax. This curve lies above the other because a slightly stronger source was used.

Measurements of the gain of the multiplier enabled an estimate of the average S.E. of the dynodes to be made. The value found was ~3. This was rather lower than the value given by Allen (see Figure 6), but the dynodes had been exposed to air for some years, and although Allen stated they were unaffected by exposure to air, a gradual deterioration did not seem unreasonable. A second multiplier tested had a slightly lower gain.

III. 3. (3) Variation of Multiplier Gain with E.H.T. Voltage.

Figure 19 shows the count rate as a function of E.H.T. voltage; the dotted line is from data by Allen using a similar multiplier. The curve rises to a broad maximum at 7 KV, corresponding to 500 volts per stage. The most suitable working voltage was 7 KV where a 5% change in E.H.T. produced a 1% change in count rate. The E.H.T. was stabilized to much better than 5%.

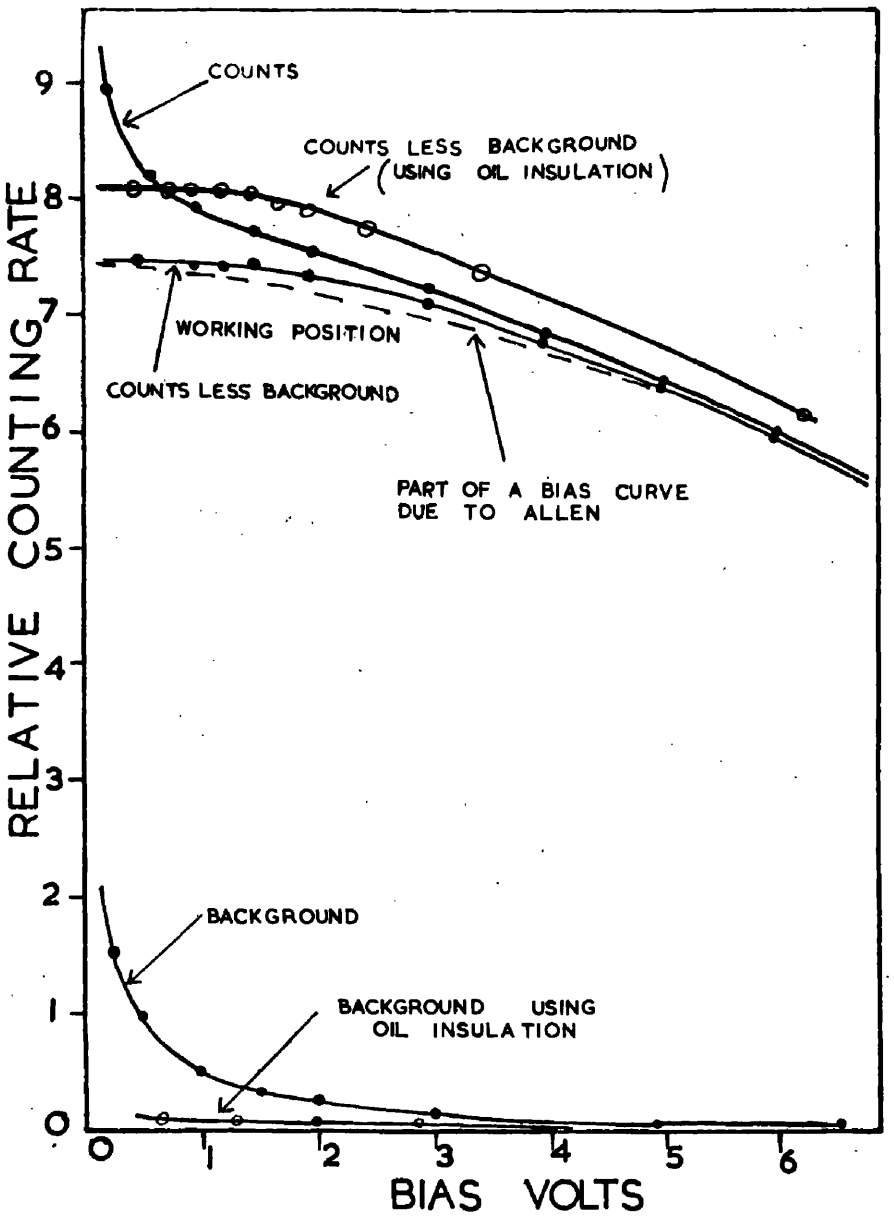


Figure 18. Bias curves obtained with the multiplier. Part of a curve due to Allen [15] is shown for comparison.

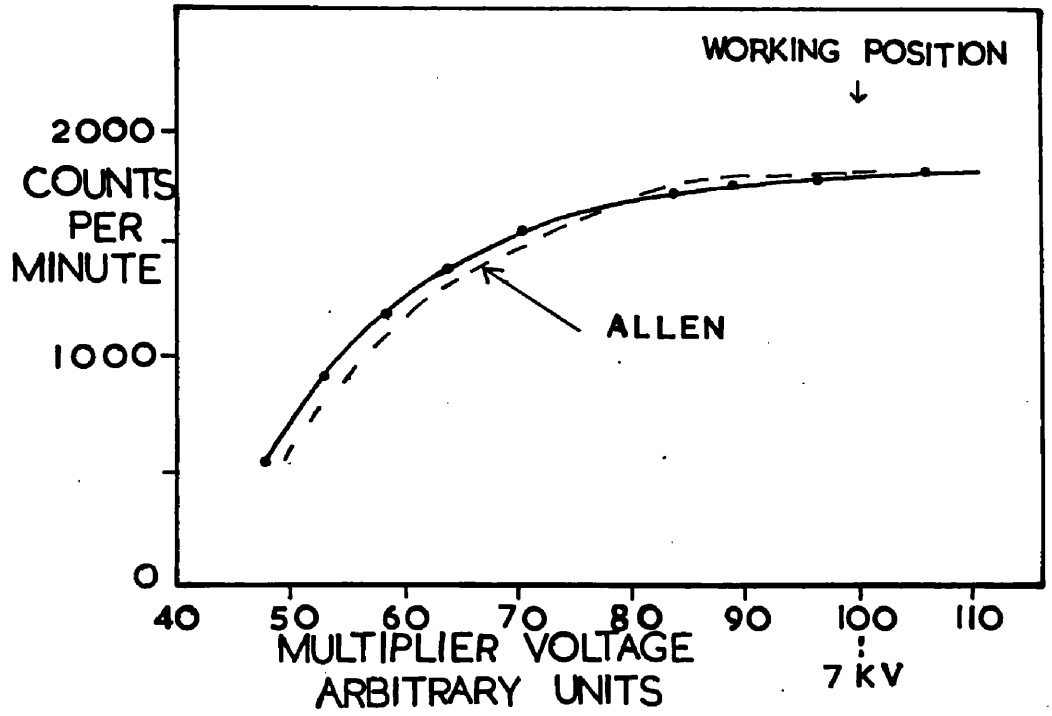


Figure 19. The variation of the multiplier gain with the E.H.T. voltage. Some data from Allen [15] are also shown.

It should be noted that varying the E.H.T. was equivalent to altering the gain of the whole system. The optimum working position corresponded to the lowest suitable E.H.T. (to minimise high voltage breakdown) and the gain corresponding to the working position indicated in Figure 18.

III. 3 (4) Decrease observed in Multiplier Gain after the E.H.T. was switched on. It was observed that the count rate for fixed amplifier gain, scaler bias and E.H.T. voltage, decreased with time after the E.H.T. was switched on. If the E.H.T. was turned off for some time, when it was switched on again the count rate had increased, but fell off with time as before. Exposing the multiplier to air (E.H.T. off) always caused the count rate to return to normal as soon as the multiplier had been evacuated and tested. Although the decrease with time became much slower after some hours, it never became constant, even during a continuous run of 30 hours. It was definitely established that this effect was due to the multiplier alone and not to any other part of the system. A curve showing the decrease of count rate with time is given in Figure 20.

This effect was not reported by Allen, although recently Barnett et al [54] observed a decrease in gain with time similar to that obtained by the Author. These workers, whose results are shown by a dashed line in Figure 20, found that an approxi-

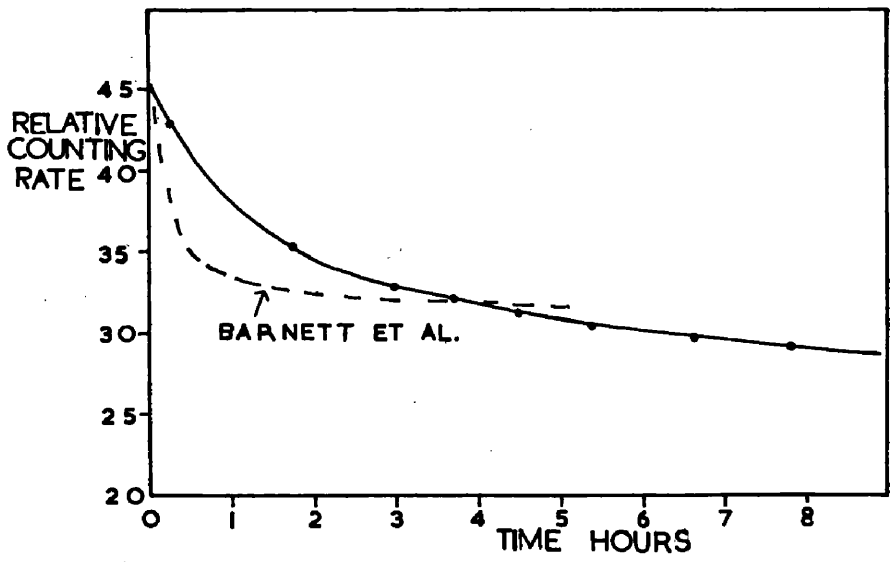


Figure 20. A curve showing the decrease in the multiplier gain observed as a function of the time after the E.H.T. was switched on. The dotted curve is from measurements on this effect by Barnett et al (54).

mately constant value of gain was reached. This was not so for the multiplier used by the Author.

The variation of multiplier gain with time was investigated in an attempt to eliminate this effect, which was unsuccessful. The explanation was probably that the insulating parts of the multiplier charged up slowly, or that local charging on the surface of the later dynodes, where the current was higher, lowered their S.E. The Author's observations favoured the second alternative.

This effect was troublesome in all the experiments, as corrections required to be made to standardise data to the initial measurements. All the results included in this Thesis have been corrected for the decrease in multiplier gain. The presence of this variation in gain was a further factor in support of the original intention to make measurements on the S.E. of electrons and positrons by a comparison method.

III. 3. (5) The efficiency of the Multiplier for γ-rays.

In many of the experiments which will be described the multiplier was subject to a flux of γ-rays, either directly from the source or from positrons which annihilated in and around the multiplier. It was therefore necessary to determine the efficiency of the multiplier for γ-rays. This was done by comparing the efficiency for γ-rays of the multiplier, to that

of one of the Geiger counters used for later work. Assuming a Geiger counter efficiency ~ 1%, and correcting for geometry, the efficiency of the multiplier for $\frac{1}{2}$ MeV γ-rays was $\sim 10^{-4}$. This value was quoted by Allen for a similar multiplier. It should be noted that the efficiency of the multiplier for γ-rays is not the same as the secondary electron yield arising from γ-rays produced by positrons which annihilate in the target. (See Section II. 1. (2)). For the former, counts arising from γ-rays striking any dynode are included, although the first dynode will give the maximum contribution; for the latter only counts which are produced by γ-rays which hit the target should be included in the yield.

III. 3. (6) Attempts to increase the efficiency of the Multiplier by increasing the size of the first dynode. In order to be able to use a larger target (first dynode) the effect of altering the size and position of this dynode was investigated. Snell and Miller (55) have reported obtaining a considerable increase in the efficiency by this means, although no figures were given. The Author investigated the type of arrangement reported by these workers, but found that the collection efficiency by the second dynode, of electrons liberated at the first dynode, was critically dependent on the position of this dynode. The existing dynode layout was the optimum.

III. 3. (7) The efficiency of the Multiplier for primary electrons scattered from the target. In Chapter II it was stated that the multiplier had a low efficiency for the detection of primaries scattered from the first dynode, compared with its efficiency for detecting true secondaries. It thus separated these two groups of particles. The efficiency for the detection of particles scattered from the first dynode is $E = \delta' \delta_r g f$ where δ' is the S.E.C. of the second dynode i.e. of copper-beryllium for primary particles, and δ_r is the reflection coefficient of the first dynode, i.e. the ratio of reflected primaries to incident primaries; g is a geometrical factor which determines how many of the scattered primaries reach the second dynode (due to their comparatively high energy they are unaffected by the electrostatic focusing field of the multiplier); f is a fraction arising from the decrease in the gain of the multiplier system which detects the reflected primaries at the second dynode - there is effectively one less stage of multiplication. By considering the dynode layout g was found to be about 0.33 The value of f, determined from a bias curve was 0.9; as the bias curve was roughly flat at the working position, the effect of the multiplier having one less stage was small. Thus $E \simeq 0.3 \delta' \delta_r$, and the ratio of the efficiency for the detection of primaries scattered from the first dynode, to that for

secondaries liberated at the first dynode is $R = {}^{E}/_{\varsigma} = 0.3\,\varsigma\,\delta'/\delta$

secondaries liberated at the first dynode is $R = {}^{E}/_{\delta} = 0.3\,\delta_R\,\delta'/\delta$

where δ is the S.E.C. of the first dynode.

δ_R may be estimated from the results of Trump and Van de Graaff [29], and the values of δ for copper-beryllium and platinum were measured (See Section VI.5.(2)). It was found that at high energies $R \gtrsim 11\%$ for platinum and $R \gtrsim 8\%$ for copper-beryllium. For all materials R varies approximately as δ_R, because δ'/δ is nearly independent of energy (See Section IV.6.(1)); thus R is roughly constant above 50-100 KeV; below $\sim$ 50 KeV δ_R falls and R becomes smaller. An upper limit for R was measured using a strong gold 198 source (electrons) in the spectrometer. The first two multiplier dynodes were joined together to remove the electric field between them (all other voltages being the same) and the count rate taken. The count rate obtained was due to secondaries produced at the second dynode by primaries scattered from the first dynode, together with a small contribution from secondaries produced at the first dynode which were drawn to the third dynode. This dynode was at a potential of 500 volts relative to the first two. R is given by the ratio of the count rate with the first two dynodes joined together to that when the multiplier was connected normally. The values obtained for R when the first dynode was made of platinum and copper-beryllium were 13% and 9% respectively, measured at 500 KeV. It is difficult to know what contribution came from

secondaries produced at the first dynode, but this is likely to be small. The true value of R was almost certainly between the calculated and the experimental values, if anything nearer the latter. Thus the probable values of R at high energy were, for platinum, 12%, and for copper-beryllium, 9%.

III. 3. (8). Other Factors investigated. Some other factors were examined. The effect of light on the multiplier was practically zero. The variation of background with pressure was measured and found to be insignificant below 2×10^{-5} mms. Hg. from 2×10^{-5} - 3 or 4 x 10^{-5} mms. Hg. a slight increase was observed. Breakdown began to occur at $\sim 10^{-4}$ mms. Hg.

III. 4. Conclusion. Apart from the background difficulties the multiplier was working satisfactorily. The general performance was very similar to that reported by Allen, except for the decrease in gain with the time, and the slightly low value of gain.

CHAPTER IV

DETERMINATION OF THE RELATIVE SECONDARY EMISSION OF ELECTRONS AND POSITRONS BY COMPARING THE AVERAGE SECONDARY EMISSION OVER THE WHOLE SPECTRUM FROM FOUR ELECTRON SOURCES AND ONE POSITRON SOURCE.

IV. 1. Introduction

As soon as the electron multiplier was working satisfactorily and preliminary experiments completed, it was decided to make a series of measurements on the relative S.E. of electrons and positrons using the existing experimental arrangement, and without the spectrometer.

Such an experiment was undertaken because it was considered important to obtain some data on the relative S.E. by electrons and positrons as soon as possible, and this approach would be much simpler and quicker than the method using the spectrometer. In particular, adequate count rates would be easy to obtain in such an experiment, and difficulties arising from the multiplier background would be minimised. Due to the rather small transmission of the spectrometer, (See Section V.1. (2)) low counting rates were anticipated when using it. A further advantage was that sodium 22 (Half-life 2.2 years) could supply positrons for this experiment. For measurements using the spectrometer copper 64 (Half-life 12.8 hours) was the only source available in

sufficient strength and only a limited amount of data could be obtained from one source.

It was realised that the proposed experiment would not yield such valuable data as measurements made using the spectrometer, and some of the limitations will be discussed later. Nevertheless, it would be a good guide to future work and certainly show if there were any large differences in the S.E. by electrons and positrons at higher energy.

IV. 2. The Basic Principle of the Experiment. In principle, the method was to compare the count rate for each source, when placed a few cms. in front of the first multiplier dynode, (the target), with that obtained when the source was placed inside a Geiger counter. Identical "geometry" was used for each source. The multiplier count rate gave the number of secondaries liberated at the target, and the Geiger counter count rate was proportional to the absolute number of particles reaching the target. The constant of proportionality depended only on the geometry of the two counters and was the same for each source. The ratio of the multiplier count rate to Geiger count rate was thus proportional to the average S.E.C., $\bar{\delta}$, over the whole spectrum, for each source. Values of $\bar{\delta}$ for the electron sources were plotted against the mean energy of the source spectrum. The value of $\bar{\delta}$ for electrons corresponding to a mean energy equal to that of sodium 22

positrons could then be compared with the value of $\bar{\delta}$ obtained for these particles.

IV. 3. The Experimental Arrangement

IV. 3. (1) The Electron Multiplier - Source Mounting. The multiplier was set up as described in Section III. 2, with a number of small refinements to ensure that identical geometry was maintained for all the sources. The source material was deposited over an area of 3 mms. x 2 mms. on a piece of aluminium foil 1/64" thick. For caesium 137, sodium 22 and phosphorus 32 a drop of solution was dried on the foil. The carbon 14 was deposited in the form of finely divided barium carbonate powder, which adhered to the foil by means of a very thin film of Silicone grease. The cobalt 60 was prepared by evaporating a metal nodule in vacuo. The sources prepared by these methods should, with the possible exception of carbon 14, be "thin" sources.

An activated copper-beryllium target was used, which has a low work function. As pointed out in Chapter II Part 1 a low work function is essential for any process of potential ejection by positrons.

IV. 3. (2) The Geiger Counter. A simple Geiger counter was constructed in order to determine the absolute number of particles emitted by each source. The sources were mounted on a source holder, which was placed inside the counter, to avoid

the use of thin windows. As the Geiger counter was ~ 100% efficient compared to 5 - 20% for the multiplier, a collimating arrangement which reduced the solid angle was employed. The collimator was transparent to γ-rays, and as several of the sources emitted γ radiation, a correction required to be made. This was done by inserting a stop which was opaque to β particles and almost transparent to γ-rays; the counting rate from γ-rays alone was thus found. The geometry in the multiplier was identical for γ-rays and electrons so that no correction was necessary, because of its very low ($\sim 10^{-4}$) efficiency for high energy quanta.

The Geiger counter, which is illustrated in Figure 21, consisted basically of a 1" diameter copper tube 20 cms. long, which was cleaned, out-gassed and passivised. About 6 cms. of this composed the counting volume, and contained a 0.008" diameter tungsten wire. The remainder was occupied by the collimating arrangement and source holder.

The counter was filled with argon to a pressure of 5 cms. Hg. and alcohol to a pressure of $\frac{1}{2}$ cm. Hg. It had a plateau of 100 - 150 volts at about 1 KV. The consistancy of the counter was shown by the fact that over six or eight different runs with sodium 22 (re-inserting the source and refilling each time) the count rates did not vary by more than 1%.

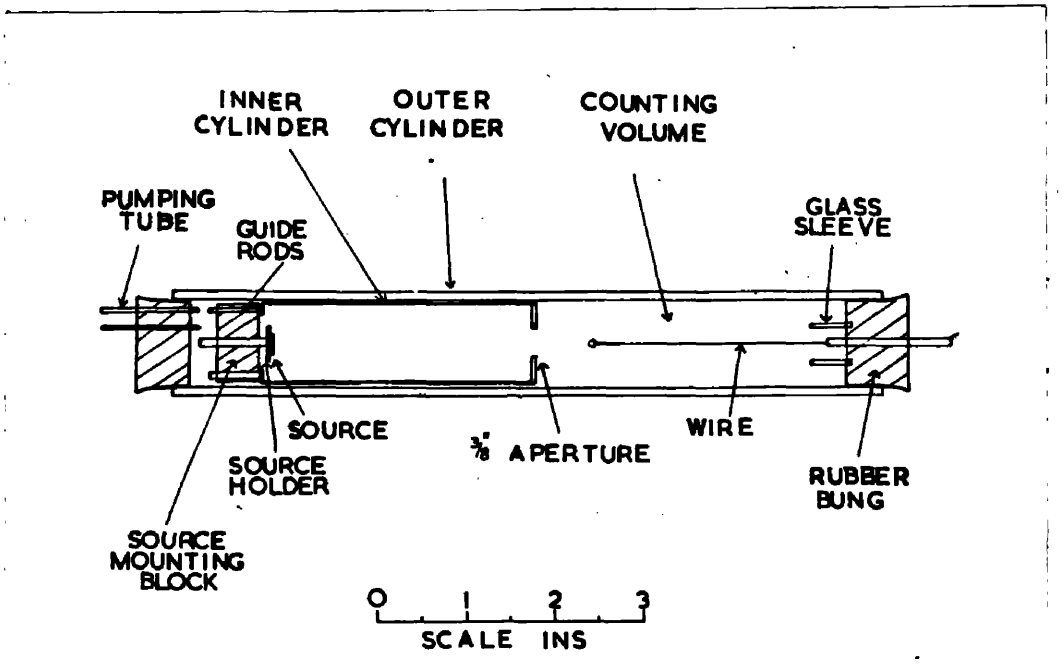


Figure 21. A diagram of the simple Geiger Counter used in the experiments described in Chapter IV.

IV. 4. The Experimental Method

IV. 4. (1) Measurements with the Multiplier. A comparison method was adopted for recording the multiplier data, and the count rate for each electron source was compared to that obtained for sodium 22 positrons. It must be emphasised that the positron source was chosen as the standard for convenience, and the ratio ξ_M = multiplier β^- count rate/multiplier β^+ count rate, does not, as it stands, have any significance regarding the relative S.E. of electrons and positrons.

In practice runs of the same total time were recorded alternately with the electron and positron sources, an equal interval separating each run. Values of ξ_M were obtained by comparing a positron count with the average value of the electron count before and after it. This method yielded fairly consistent results which were independent of the change in multiplier gain with time.

IV. 4. (2) Measurements with the Geiger counter. A number of runs were made with each source in the Geiger counter. The results were expressed in terms of ξ_G = β^- count rate/ β^+ count rate as measured with the Geiger counter. The Cobalt 60, sodium 22 and caesium 137 data required to be corrected for γ-rays, as described above. In general count rates were sufficiently high to justify a correction for dead time, and this was measured

in a separate experiment. A value of the dead time of 120 μ sec. was found.

IV. 5 Results

IV. 5. (1) Electron Multiplier Data. Values of ξ_M were obtained as explained above, for each electron source. In order to find the mean values, histograms were plotted. These showed an approximately Gaussian distribution. The final results for ξ_M, including the statistical errors, which were taken as the half widths at half maximum, are shown in Table 1. A correction for the count rate produced by primary particles reflected from the first dynode was subtracted from the observed count rates. It was shown in Section III 3. (7) that at high energies and for a copper-beryllium target about 9% of the count rate for electrons was due to scattered primaries. Seliger [52] found that electrons were backscattered by about 30% more than positrons at high energies; thus the correction for sodium 22 was 3% less than that for the electron sources. The effect of this was to decrease ξ_M for the electron sources except carbon 14 by 3%. For carbon 14, because of its lower mean energy, the decrease was 2%. These corrections were small compared to the final probable error in the value of the relative S.E. of electrons and positrons found in this experiment. (See Section IV. 5. (4)).

IV. 5. (2) Geiger Counter Data. Table 2 shows the results

TABLE 1

Values of ε_M obtained for the electron sources. The statistical errors are given.

Source	C^{14}	Co^{60}	Cs^{137}	P^{32}
ε_M	1.41 ± 0.03	0.54 ± 0.01	1.78 ± 0.04	0.96 ± 0.02

TABLE 2

Values of ε_G obtained for the electron sources. The correction for absorbtion inside the Geiger counter, which has been applied, is also shown. The statistical errors are given.

Source	C^{14}	Co^{60}	Cs^{137}	P^{32}
ε_G	0.557 ± 0.024	0.396 ± 0.022	1.87 ± 0.09	1.38 ± 0.03
Abs.Cor.	30%	17%	3.6%	2.5%

obtained with the Geiger counter. The correction for absorbtion inside the counter requires some explanation. The particles from each source have to pass through 8 cms. of counter filling (1 Mg/cm^2) before entering the counting volume. (See Figure 21). It follows that those particles whose range is less than 1 Mg/cm^2 will not be recorded. This corresponds to all particles of energy less than 23 KeV, according to the range-energy data given by Glendenin [56]. Hence, in order to obtain the true number of particles emitted by the source, a correction must be added to the measured count rate for that fraction of the spectrum with energies less than 23 KeV. This correction was determined graphically from published spectra. For the electron multiplier there is no absorbtion correction as the source and multiplier were both in a high vacuum.

IV. 5. (3) Results for Relative Secondary Emission. In this section the multiplier and Geiger counter results will be combined and the value of relative S.E. obtained. Firstly it is necessary to derive the relation between δ_M, δ_G and the average S.E.C., $\bar{\delta}$.

If N_M^- and N_G^- are the count rates obtained in the multiplier and Geiger counter respectively for one of the electron sources, say cobalt 60, and N_M^+, N_G^+, are the corresponding count rates for sodium 22 positrons, then the mean S.E.C. over the spectrum

for cobalt 60 electrons, $\bar{\delta}^-$, and for the positrons, are given by

$$\bar{\delta}^- = K \frac{N_M^-}{N_G^-} \qquad \bar{\delta}^+ = K \frac{N_M^+}{N_G^+} \qquad (4-1)$$

where K is a constant depending only on the geometry in both counters,

One may write:

$$\zeta_\xi = \frac{\bar{\delta}^-}{\bar{\delta}^+} = \frac{N_M^- / N_G^-}{N_M^+ / N_G^+} = \frac{N^- \; N^+}{M / M} \Big/ \frac{}{N_G^- / N_G^+} = \frac{\zeta_{\xi M}}{\zeta_{\xi G}}$$

where $\zeta_{\xi M} = N_M^- / N_M^+$, $\zeta_{\xi G} = N_G^- / N_G^+$ and ζ_ξ is, by definition, the S.E.C. of cobalt 60 electrons relative to that of sodium 22 positrons. In order to obtain a value for the relative S.E. of electrons and positrons, the S.E. coefficients must be compared at the same energy. To do this a value of ξ was obtained for each electron source and plotted against the mean energy of the source spectrum. This gave a curve showing the variation of the electron S.E.C. with energy on a scale which makes the S.E.C. of sodium 22 positrons equal to unity. The value $\zeta_\xi = 1$ was therefore marked on the graph at the mean energy of the positrons, and its position relative to the curve for the electron sources determined the relative S.E. of the two types of particles at this energy. Table 3 shows the final values of ζ_ξ. The mean energy of the spectra are also given in the table; these are approximately one third of the maximum energy for the electron sources and slightly less for sodium 22.

TABLE 3

Values of ξ and the mean energy of the source spectrum $\bar{E}$, for the sources. The statistical errors are given

Source	C^{14}	Co^{60}	Cs^{137}	P^{32}	Na^{22}
$\xi = \frac{\xi_M}{\xi_{Sc}}$	2.54 ± 0.15	1.36 ± 0.08	0.95 ± 0.06	0.7 ± 0.02	1
$\bar{E}$(KeV)	40	100	235	680	200

The curve showing the variation of ζ against energy for the electron sources is reproduced in Figure 22, curve A. The point for sodium 22 is marked, and within the experimental error it lies exactly on the curve. From this it was concluded that within the limits of the experiment, in which average values of S.E. coefficients and mean energies were considered, the S.E.C. of electrons and positrons was the same at high energies.

The absolute values of S.E. coefficients were obtained approximately by evaluating the constant K in Equation (4-1). This was done by measuring the solid angles subtended at the source in the two counters. The results for $\bar{\delta}$ are also shown in Figure 22.

IV. 5.(4) Errors. In this section some possible experimental errors will be considered. In particular some of the basic approximations and assumptions implicit in the method will be examined, in order to obtain an overall assessment of the accuracy of the results. There are two principal systematic errors which may be present. The first is an error arising from the correction for absorbtion inside the Geiger counter, and the second an error in the assignment of the mean energy of the spectra. These both depend on the agreement between the actual spectra emitted by the sources and the published spectra, which have been assumed. Differences in spectral shape are most probable at low energies, and

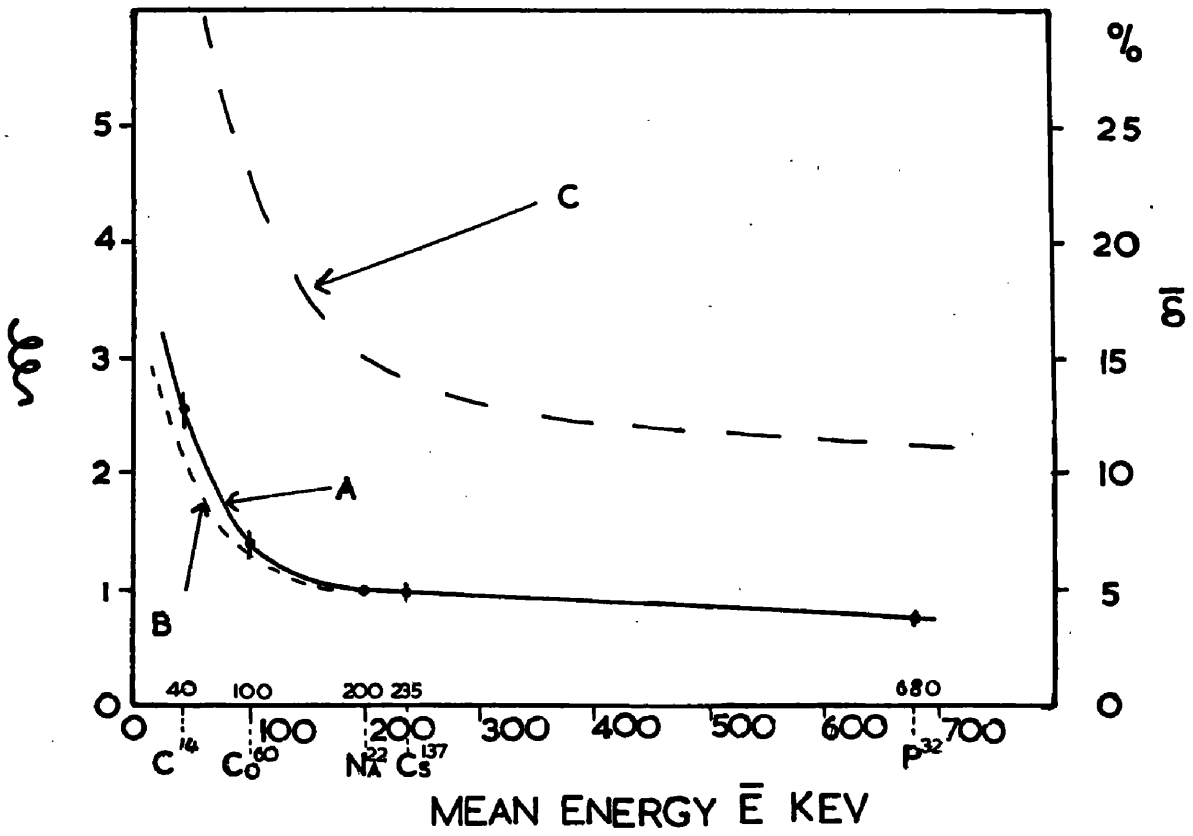


Figure 22. The variation with mean source energy $\bar{E}$, of ε (left hand scale) and $\bar{\delta}$ (right hand scale). Curve A is uncorrected for systematic errors, and shows the statistical errors. Curve B is corrected for systematic errors. Curve C shows the variation of δ with primary energy for tungsten, according to Trump and Van de Graaff [29].

so the errors are likely to be largest for the two lower energy sources, carbon 14 and cobalt 60. Detailed considerations, which will not be given here, show that the overall effect of these errors would be to displace the curve of ξ against energy at lower energies. A correction was estimated and the corrected curve, B, is shown in Figure 22. An important observation is that, although curve B is probably a better representation of the variation of the S.E.C. of electrons with energy, curve A had hardly been affected in the neighbourhood of the point representing the S.E.C. of positrons. The uncertainties arising from these errors were therefore not important when considering relative S.E.

It is necessary to examine the basic and approximate assumption underlying this whole experiment, which is that the average S.E.C. over a continuous β spectrum is equal to the S.E.C. of particles having an energy equal to the mean energy of the spectrum. As the S.E.C. is a function of energy, rising rapidly as energy is decreased, the contribution from a few low energy particles may be comparable to that from the rest of the spectrum. It follows that the average S.E. may correspond to an energy less than the values used for $\bar{E}$. Detailed considerations, which again will not be given here, show that a correction for this would displace the curve at lower energies, and to a lesser

extent at higher energies, to the left. As before, a curve which was a better representation of the variation of S.E. by electrons with energy would be obtained, but the position of the positron point, with respect to that curve, would remain almost the same. As the correction would be rather complicated to make and would require a knowledge of the actual source spectra, it was not considered worthwhile to determine it.

The overall probable error in the relative S.E., including the statistical error and the uncertainties outlined above was estimated to be $\pm$ 10%.

IV. 6. Discussion

IV. 6. (1) Results for Electrons. Although this experiment was not primarily intended to yield absolute data on the variation of the S.E.C. of electrons with energy, it is worthwhile to compare the curve in Figure 22 with existing data. Curve C in the figure shows the measurements of Trump and Van de Graff[29] for tungsten. There are no detailed measurements for copper-beryllium, although Allen[16] stated that at high energies the S.E.C. was probably ~ 5-10%, in approximate agreement with the value of 5% found.

The shape of curves B and C is very similar, which is satisfactory, because, as will be shown later, one would expect the yield curve for all metals to be of the same shape. It was

pointed out in Section I.2.(2a) that this was so at low energy, and the little existing data at high energy indicates that it is probably true in that region also. This will be considered further in Section VI. 5.(3b) when more data has been obtained. It will be shown in that section that the shape of the yield curve at high energy can be predicted quite simply from the Bethe ionization formula.

The curve for the variation of S.E.C. with energy for copper-beryllium lies below that for tungsten, which would be expected on Bruining's postulate (See Section I.2. (2b)) that at high energy the density rather than the work function is predominant in determining the yield. Copper-beryllium has a lower work function than tungsten, but it also has a lower density.

The general agreement with Trump and Van de Graaff in the shape of the yield curves showed that the method used by the Author to measure S.E. was reliable for comparative measurements. The numerical value of the S.E.C. was perhaps rather low, but of the right order.

IV. 6. (2) <u>The Relative S.E.C. of Electrons and Positrons.</u>

This is the first report of a measurement of S.E. by positrons, and it shows that at high energy the S.E.C. of positrons is approximately equal to that of electrons. This bears out

the considerations outlined in Chapter II. Large differences, if any, must exist only at low energy, or at very high energy. It would have been fruitful to extend the method of comparing the average S.E. coefficients, by using a lower energy positron source, but no suitable source was available.

The results showed that it was important to proceed at once to measurements with the spectrometer, in which the S.E.C. of particles at the same energy was compared, and it could be established whether there were any small differences in S.E. at high energy or significant differences at low energy.

The remainder of this Thesis gives a brief description of the β^- spectrometer, and an account of the main experiments using it.

CHAPTER V

DESIGN AND CONSTRUCTION OF THE β-SPECTROMETER AND THE MAGNETIC FIELD MEASURING SYSTEM.

V. 1. Design of the β-Spectrometer

V. 1. (1) Requirements for the Spectrometer. The β-spectrometer, which had to be constructed from an existing magnet, was required to focus electrons and positrons of energy from a few KeV up to ~500 KeV. As S.E. is a steadily varying function of energy a high resolution was not essential, and it was decided to design the instrument to have the maximum transmission consistant with a resolution of 5 - 10%.

There were two further factors which were important. Firstly, it was necessary that the focus was outside the magnetic field, so that the electron multiplier would be in a field free region. Secondly, it was desirable that the source and focus should be some distance apart. This would enable the space between them to be filled with lead to stop γ-rays produced in the source, or near it, due to positron annihilation, from reaching the detector.

In view of the above considerations it was decided that a "Wedge Spectrometer" was the optimum type.

V. 1.(2) The theory of a Wedge Spectrometer. The full theory of such a spectrometer was given by Stephens (57), and only the results will be considered here. If OP, OQ, in Figure 23 (a).

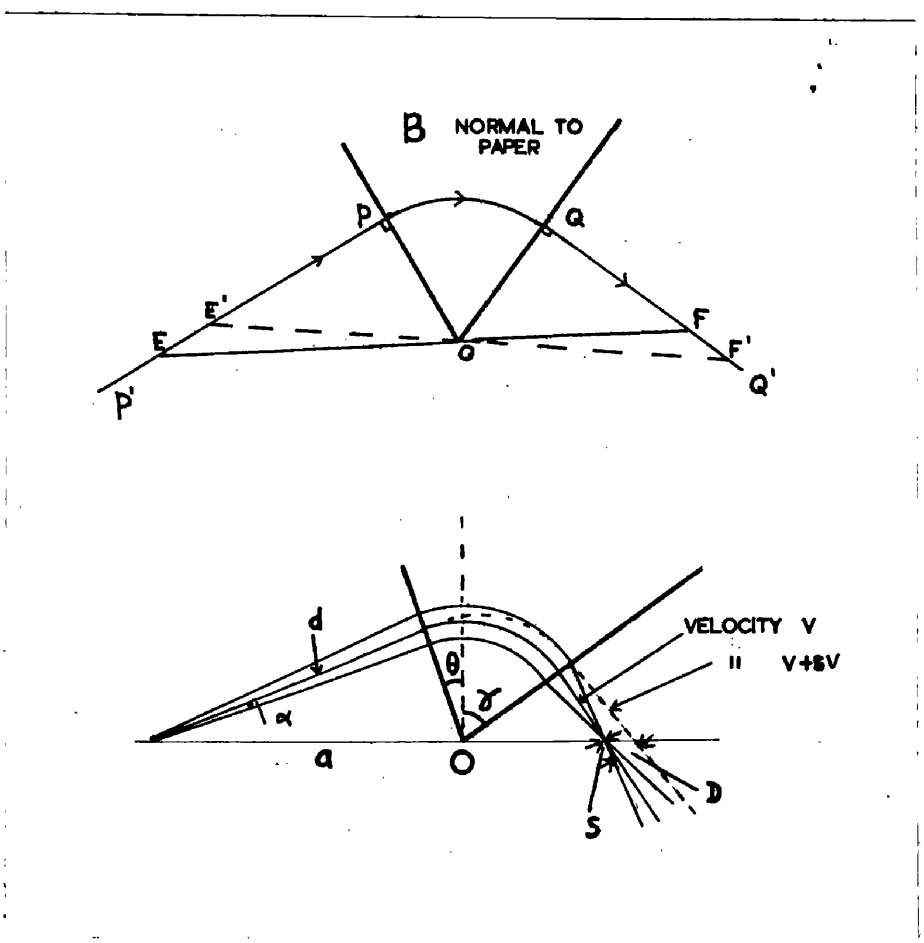


Figure 23. (a) (above) The geometry of a wedge magnet.

(b) (below) A diagram illustrating the parameters which determine the focusing properties of a wedge magnet.

represent the boundaries of a magnetic field perpendicular to the paper, and of such magnitude that a particle with velocity v incident normally at P will also emerge normally, at Q, then all particles with velocity v diverging from any point E on PP' will be brought to a focus at F, where the line EO through the vertex, O, of the wedge, meets QQ'.

For a given source position the focus is thus fixed for all velocities, and the magnetic field, B gauss, required to focus particles of mass m and velocity v is given by

$$Bp = \frac{mv}{e}$$

where p = radius of curvature = OP = OQ, and e = the particle charge in e.m.u.

There are three important results from the theory. Firstly, there is the spread, S, which measures the width of the focus for a homogenous beam. Secondly, there is the velocity dispersion, D, which is the distance from the focus of particles with velocity v that a particle with velocity $v + \delta v$ will pass. Both S and D are illustrated in Figure 23(b). The third quantity is the transmission, t, of the arrangement. These three parameters are determined by geometry, but the expressions are rather cumbersome and therefore will be given in Appendix I.

The resolution is determined by $\frac{D}{S}$, and the velocity resolution is $\frac{\delta v}{v}$ where δv is such that D = S.

The arrangement which best satisfied the criteria set out in Section V. 1.(1) was a 65° wedge with $\theta = 45°$, $\gamma = 20°$ (θ, γ are illustrated in Figure 23(b)). It was not found possible to increase the transmission at the expense of the resolution and still satisfy the other conditions set out in Section V. 1.(1). The other parameters are given in Table 4. In the experiments using copper 64 sources the number of particles focused onto the final slit was increased at the expense of the resolution by using a larger area of source. The resolution for these experiments was ~ 7%. It must be pointed out that these figures are for the hypothetical case when there is no fringing field. The effect of the fringing field will be mentioned later. The table also shows the experimental and theoretical values of the parameters obtained when the effect of the fringing field is included.

V. 1.(3). Construction of Pole Pieces and Description of Magnet.

The pole pieces were made of mild steel, 3" thick and shaped as shown in the diagram in Figure 25, which also indicates their position relative to the circular poles of the magnet. The choice of magnet gap required care. A large gap, which was desirable in order to obtain the maximum transmission, produced a fringing field which completely altered the focusing characteristics of the magnet. A suitable compromise was

TABLE 4

The wedge parameters for a line source. U and V are the object and image distances, measured to the nearest pole face.

	U cms.	V cms.	t %	S cms.	D cms.	Resolution %
Theory, no fringing field	10	18	0.16	1.5	$36\frac{\Delta v}{v}$	4
Theory, with fringing field	10	53	0.16	1	$30\frac{\Delta v}{v}$	3
Experimental	10	~53	0.12	$\sim\frac{1}{2}$	--	~2

found with a 2 cms. gap.

The magnet, which was originally designed to produce fields much stronger than those required for the proposed experiments, is illustrated in the photograph in Figure 24. The current for the magnet coils, which was in the range 0 - 1 amp, was supplied by a 6 volt accumulator.

V. 1.(4) Field Measurements. A number of field measurements were made with a search coil and fluxmeter. The most important of these was a measurement of the fringing field, which determined the actual position of the focus. This will be mentioned in Appendix II. A hystersis curve was obtained, which showed that at low magnetic fields ($\lesssim 100$ gauss) it was impossible to obtain even an order of magnitude of the field from a knowledge of the magnet current. It followed that an accurate method of measuring low fields would be required.

V.2. The Spectrometer Vacuum System

The vacuum system is shown in the diagram in Figure 25. It consisted basically of a brass chamber specially constructed to fit between the magnet poles, and two limbs each consisting of two pyrex tubes ($\sim$ 2" diam.), one sliding inside the other by an o-ring seal to allow the length of either arm to be varied easily without breaking the vacuum. A 2" length of flexible bellows was inserted between the chamber and the first pyrex

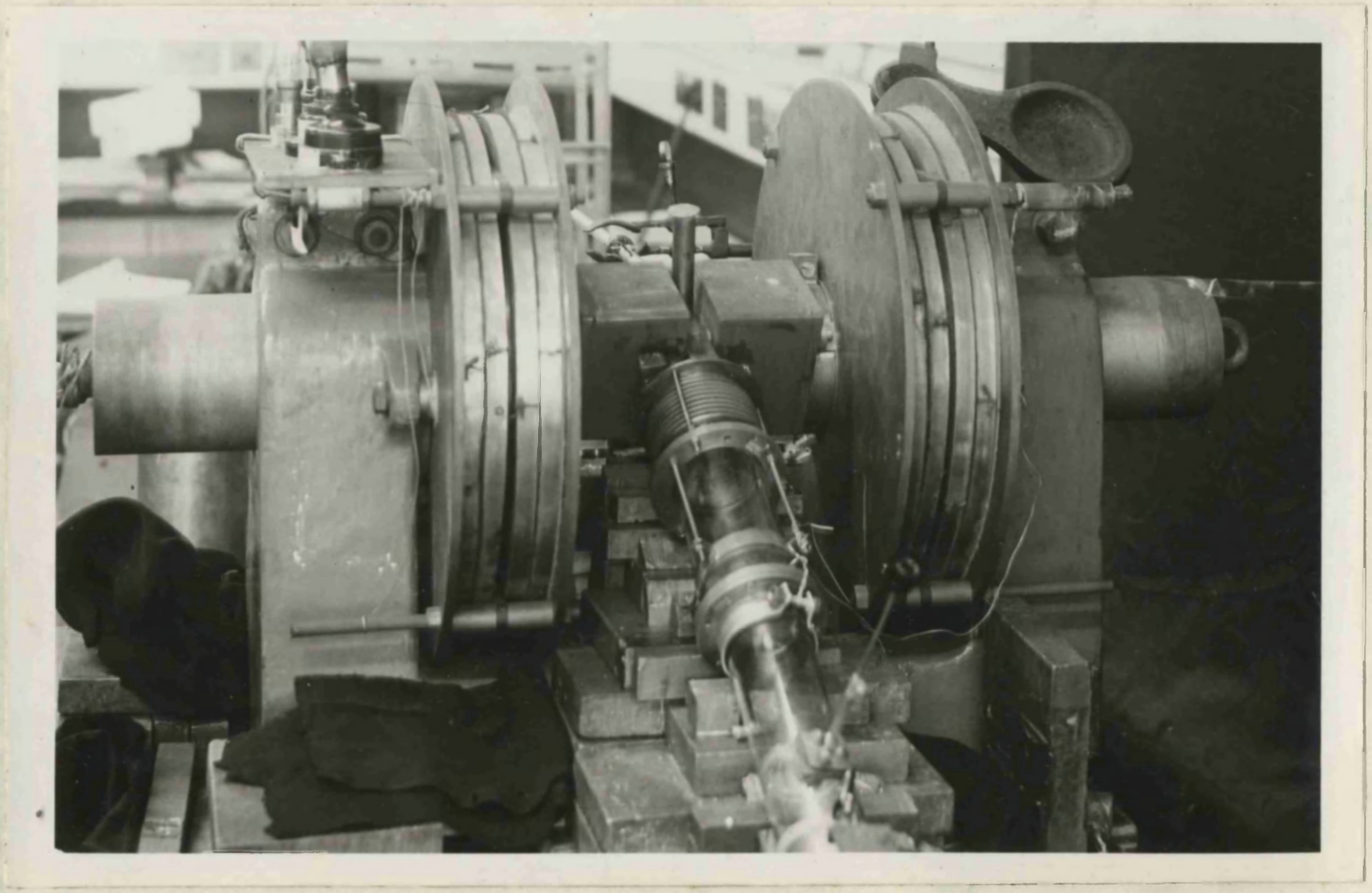


Figure 24. A photograph of the spectrometer.

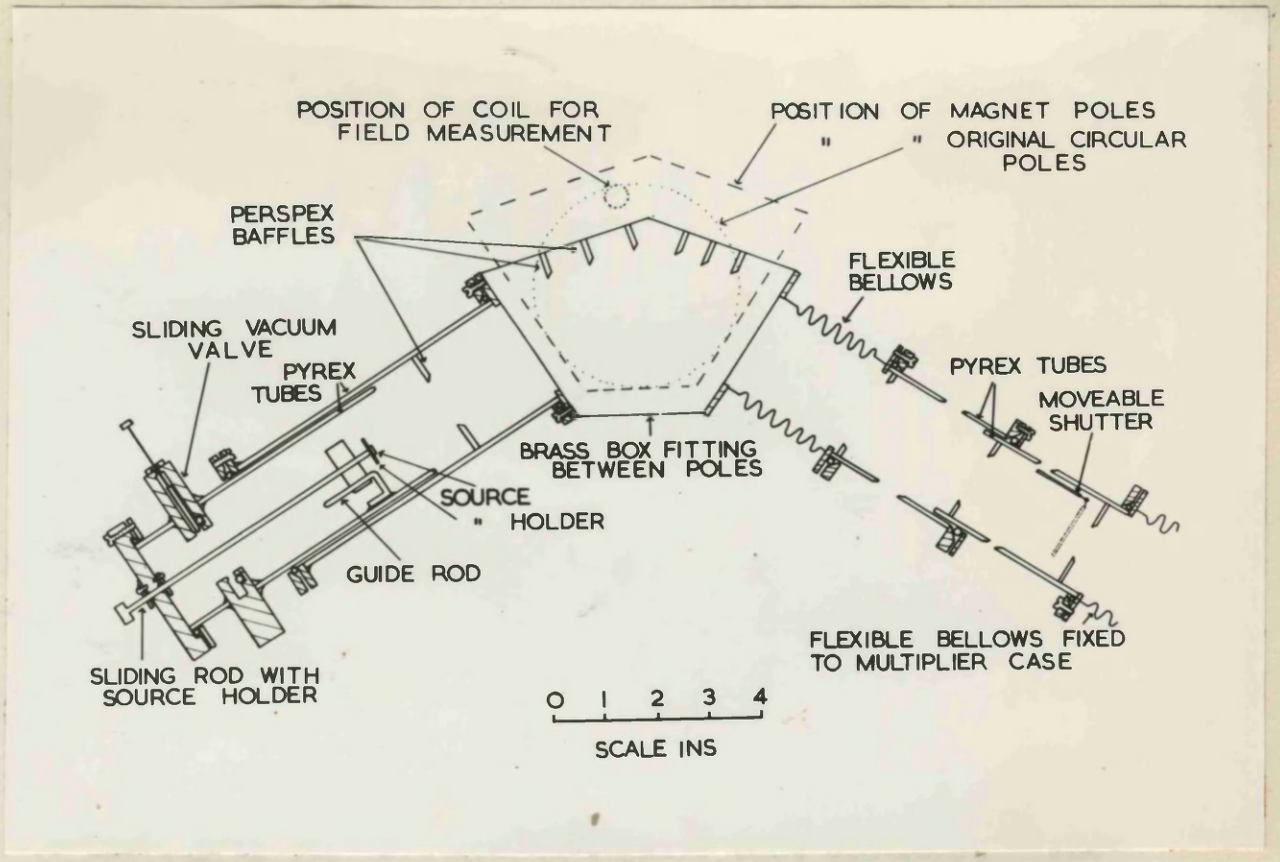


Figure 25. A diagram of the spectrometer vacuum system.

Figure 26. A photograph of the focused beam from the electron gun on a fluorescent screen. (Approximately actual size). The dark vertical band is a scale on the screen.

tube on the detector limb, to enable the spectrometer to be aligned easily. All demountable metal to glass seals were made with o-rings, and permanent seals were made with cold setting Araldite.

The source mounting arrangement was fixed inside the second pyrex tube in the shorter arm, and the sliding vacuum valve mentioned in Section III 3.(1). was again used to insert sources without breaking the vacuum. Care was taken to ensure that sources were supported accurately in the correct position relative to the pole face of the magnet.

The second pyrex tube of the longer arm was fixed directly to the top of the electron multiplier case assembly. The whole system was evacuated through a pipe entering the side of the multiplier case by a Metrovac 03B oil diffusion pump, with an internal liquid air trap. The pressure, which was measured on a hot cathode ionization gauge, was maintained at a few times 10^{-6} Mm. Hg.

The inside of the chamber and the pyrex limbs of the spectrometer were fitted with perspex baffles to reduce scattering from the walls.

V. 3. Measurements on the spectrometer using an Electron Gun

As already pointed out, the actual position of the focus would be determined by the fringing field, and it was necessary to find

the true focus. Elementary considerations suggested that the required correction might be appreciable, and so it was decided to measure it experimentally.

This was done by replacing the source with a simple electron gun, which gave a thin line source. The focus was examined visually on a fluorescent screen which could be moved about inside the spectrometer. Such an experiment also enabled some useful data on the variation of the size and position of the focus with other parameters to be obtained, and enabled the best arrangement to be found. No details of these measurements will be given except for the case of the fringing field correction, which is outlined in Appendix II. The result was that the magnet behaved as a wedge, which had poles parallel to and extending ~ 1.7 cms. beyond the actual faces of the wedge. The measured correction agreed with that estimated from the observed fringing field. Table 4 shows the measured values of the wedge parameters. Figure 26 shows a photograph of the focused beam on the fluorescent screen. The width of the beam at the focus was just equal to the width of the slit at the entrance to the first multiplier dynode. This gave the maximum transmission. Any attempt to further increase the transmission resulted in a beam width at the focus which was wider than the slit. Therefore all the particles in the beam would not be able to enter the

multiplier and the transmission would not be significantly increased.

V. 4. The method of measuring the spectrometer magnetic field.

V. 4.(1) The requirements for the field measuring system and the basic principles of the method to be used. There were three main factors which had to be considered when designing the field measuring system, which were as follows:

(a) It was important to be able to reverse the field accurately. This was to ensure that the S.E. by positrons and electrons of identical energy was compared.

(b) The field must be measured or set up to any given value quickly. Due to the short half-life of the copper 64 sources it was desirable to measure or adjust the field with the minimum delay.

(c) The field measuring system must be accurate for low fields ($\simeq$ 100 gauss). Such fields would often be required, in order to focus particles of energy less than $\sim$ 20 KeV.

A search coil and fluxmeter did not satisfy (a) and (b). The spectrometer construction did not permit the use of a sufficiently large search coil for this method to fulfil (c) adequately.

It was decided, therefore, to construct a system with which the spectrometer field, B, was measured by balancing the

e.m.f. produced across a small coil rotating in this field against the e.m.f. developed across a similar coil rotating in a standard field, H, produced by a pair of Helmholtz coils. This system, although taking longer to construct than a simple search coil arrangement, fully justified itself later by the simplicity and effectiveness of its operation.

V. 4. (2). Theory of the Field Measuring Arrangement. If the e.m.f's produced by the two rotating coils (out of phase by π) are connected in series and fed into an amplifier, the condition for "balance", i.e. minimum amplifier output, is

$$B = H \frac{S_2}{S_1} \text{ --- } (V - 1)$$

where S_1 and S_2 are the number of maxwell turns on the rotating coils in the spectrometer and Helmholtz fields respectively.

As there was no iron associated with the Helmholtz coils, H was exactly proportional to I, the current through these coils. One may write $H = k I$ ---(V - 2)

where k is a constant. It follows that if S_1 and S_2 are known, and k determined, B may be obtained from a knowledge of I. In order to set the spectrometer field to any given value, I was set to the appropriate current, and the spectrometer magnet current adjusted until a balance was found. To reverse a given field I, was reversed and the spectrometer current

reversed and varied until a balance was reached. Due to hysteresis the numerical value of the new spectrometer current was often quite different from the value for the original direction of field.

In practice values of Bp, rather than B, were required, where p is the radius of curvature of particle paths in the spectrometer. The Helmholtz coils were therefore calibrated directly in terms of Bp, using a source which emitted a monoenergic electron line by internal conversion. If I_o, H_o are the values of I and H corresponding to a certain value $B_o p$ of Bp, then by (V - 1) and (V - 2).

$$\frac{Bp}{B_o p} = \frac{H \frac{S_2}{S_1}}{H_o \frac{S_2}{S_1}} = \frac{KI}{KI_o} = \frac{I}{I_o}$$

$$\text{and so } Bp = \frac{B_o p}{I_o} I \quad \ldots\ldots\ldots\ldots (V - 3)$$

Thus any value of Bp is determined by noting I.

The method of field measurement described above followed the same general lines as that used by Seigbahn [58].

V. 5. The construction of the field measuring system

V.5.(1) The Helmholtz coils. The Helmholtz coils were spare coils which had been removed from the spectrometer. These were mounted on a rigid frame of aluminium dexion, with the spacing equal to the inner diameter of the coils. It can be shown that such an arrangement produces the most homogeneous field between

the coils. The Helmholtz coils and their mounting are shown in the photograph in Figure 27. This arrangement gave H $\sim$ 50 gauss per amp, and, as the maximum spectrometer field was $\sim$ 500 gauss it was desirable to make $S2/S1 \sim 10$. It would then be possible to run the Helmholtz coils at a current of $\sim$ 1 amp, supplied by an accumulator, rather than at 10 - 20 amps from the D.C. mains. An accumulator had the advantages that it gave a more constant voltage and was free from "ripple"; there would also be no cooling problems. One consequence of using a low Helmholtz field was that a compensating coil required to be fitted to the Helmholtz coils to correct for H_v, the vertical component of the earth's magnetic field. Although H_v was negligible compared with the spectrometer field, it was not insignificant compared with the field in the Helmholtz coils, at low values of I.

V. 5(2) <u>The Rotating Coil Assembly.</u> The rotating coils were both mounted on the same shaft, which was made of $\frac{3}{8}$" diam. aluminium tube. The coils were two meters apart so that the spectrometer and Helmholtz fields did not influence one another. This was checked experimentally. The design and construction of the rotating shaft required considerable care to obtain smooth rotation. The inclusion of a flexible coupling, and a phase adjuster were found to be essential. The commutator consisted of platinum wires pressing on brass rings. The shaft was

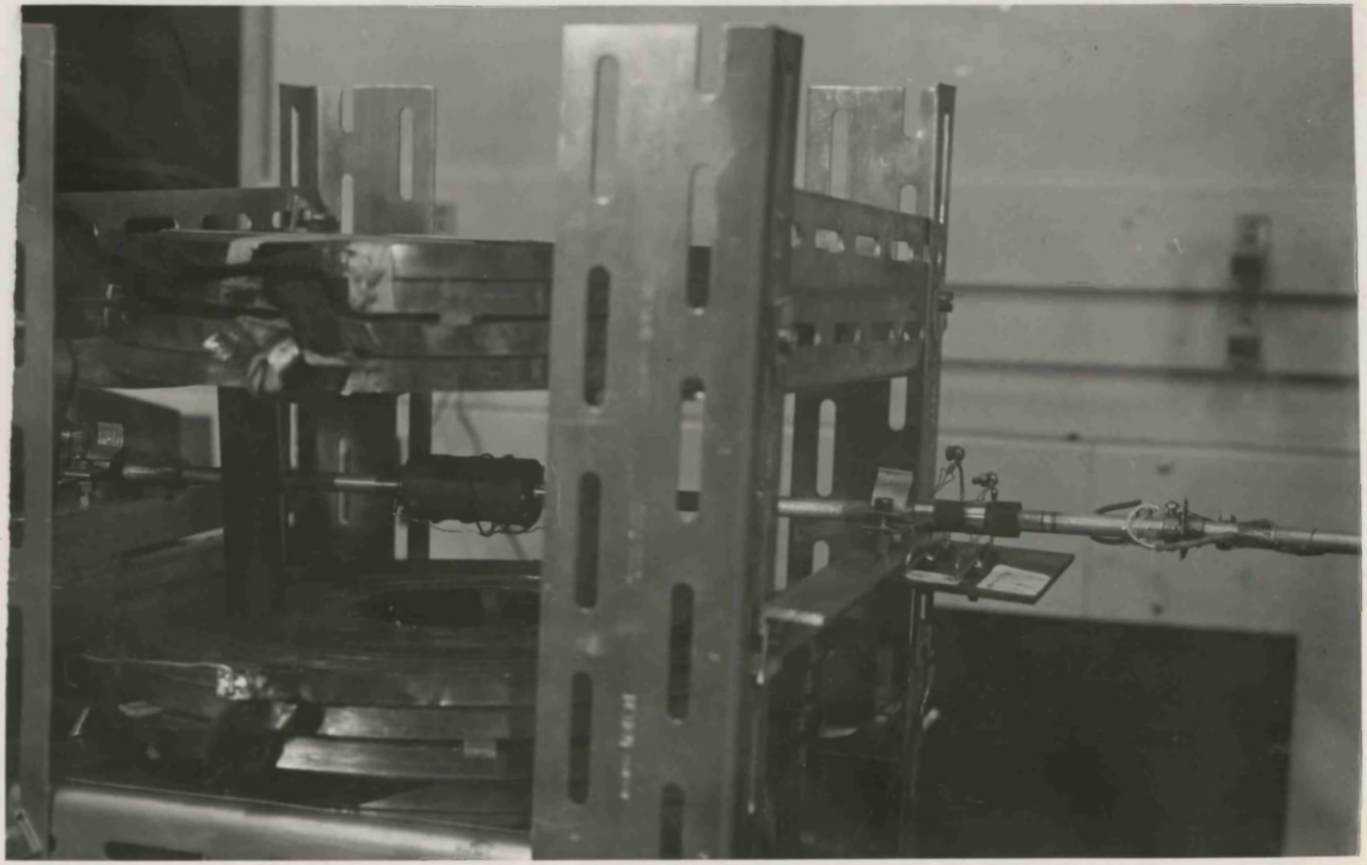


Figure 27. A photograph of the Helmholtz coils including the Helmholtz rotating coil, the commutator and the flexible coupling.

rotated through reduction gears at 37 c.p.s. by a small 50 c.p.s. induction motor. It was important to choose a frequency away from the 50 c.p.s. mains, and a slower rotation made the shaft mounting simpler.

The rotating coils were wound with 48 s.w.g. enamelled wire on small perspex formers supported in tufnol blocks. The number of turns and maxwell turns for the Helmholtz and spectrometer rotating coils were respectively 55,000; 28,000 turns and 115,000; 17,000 cms.^{2} turns. This gave $S2/S1 \sim 6.7$, rather than 10, which was considered to be suitable.

V. 5.(3). <u>The Amplifier.</u> A 37 cycle, high gain, high stability tuned amplifier was designed and constructed in the Electronics Laboratory by T.W. Pollok and J. Lindsay.

The amplifier was designed along lines similar to that described by Sturtevant (59). It consisted of two identical tuned stages, each of which was basically a two valve amplifier tuned by means of R - C controlled selective negative feedback. The frequency was determined by a 'Twin T' network. One stage of this amplifier is shown in Figure 28.

The maximum gain of the amplifier was measured and found to be $\sim$ 7000. An attenuator was fitted to the input so that lower values of gain could be used until the balance was almost reached

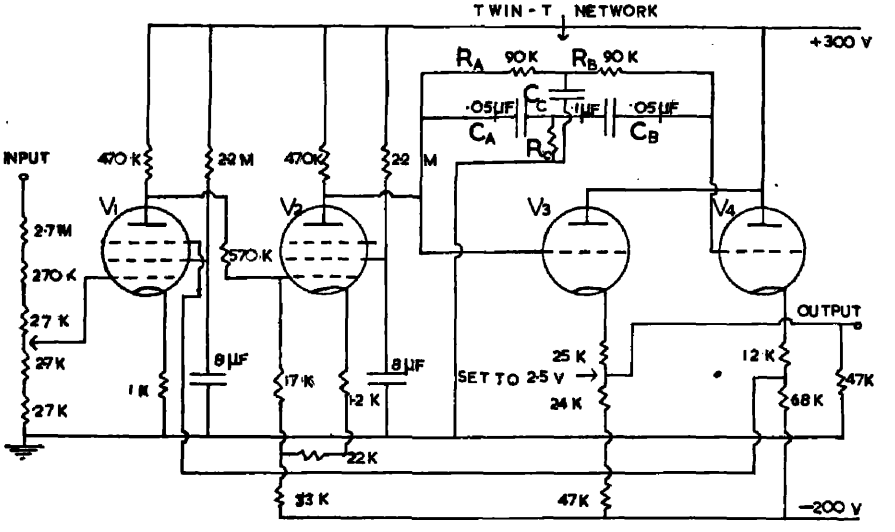


Figure 28 The circuit of one stage of the 37 c.p.s. high gain, high stability, tuned amplifier. The conditions for best tuning are:-

$$R_A = R_B = 2R_C, \quad C_A = C_B = \tfrac{1}{2} C_C$$

and then $\omega_0 = \dfrac{1}{R_A C_A}$

The selectivity was good, giving a half width ~6 c.p.s. in 37 c.p.s. which is, if anything, slightly better than 4 c.p.s. in 22 c.p.s., as obtained by Sturtevant.

The excellent performance of the field measuring system was largely due to this amplifier. The high gain, associated with a frequency response which eliminated interference from the 50 c.p.s. mains and high frequency components produced by the commutator, enabled a very accurate balance to be obtained.

V. 6. <u>The performance of the complete Field Measuring System used with the spectrometer</u>.

The complete apparatus, including the field measuring system and the spectrometer are shown in the photograph in Figure 29. The field measuring control panel is illustrated in the photograph in Figure 30. A number of measurements were made on the performance of the whole system, of which only two will be mentioned here. Both are important from the point of view of the S.E. experiments.

The first is a measurement of the accuracy with which the field can be set to a given value. This also gives the accuracy with which it can be reversed. The amplifier output was displayed on a voltmeter, and a curve of the output against the Helmholtz coil current near balance, was obtained. This is shown for the second most sensitive range of the amplifier

Figure 29. A photograph of the complete apparatus.

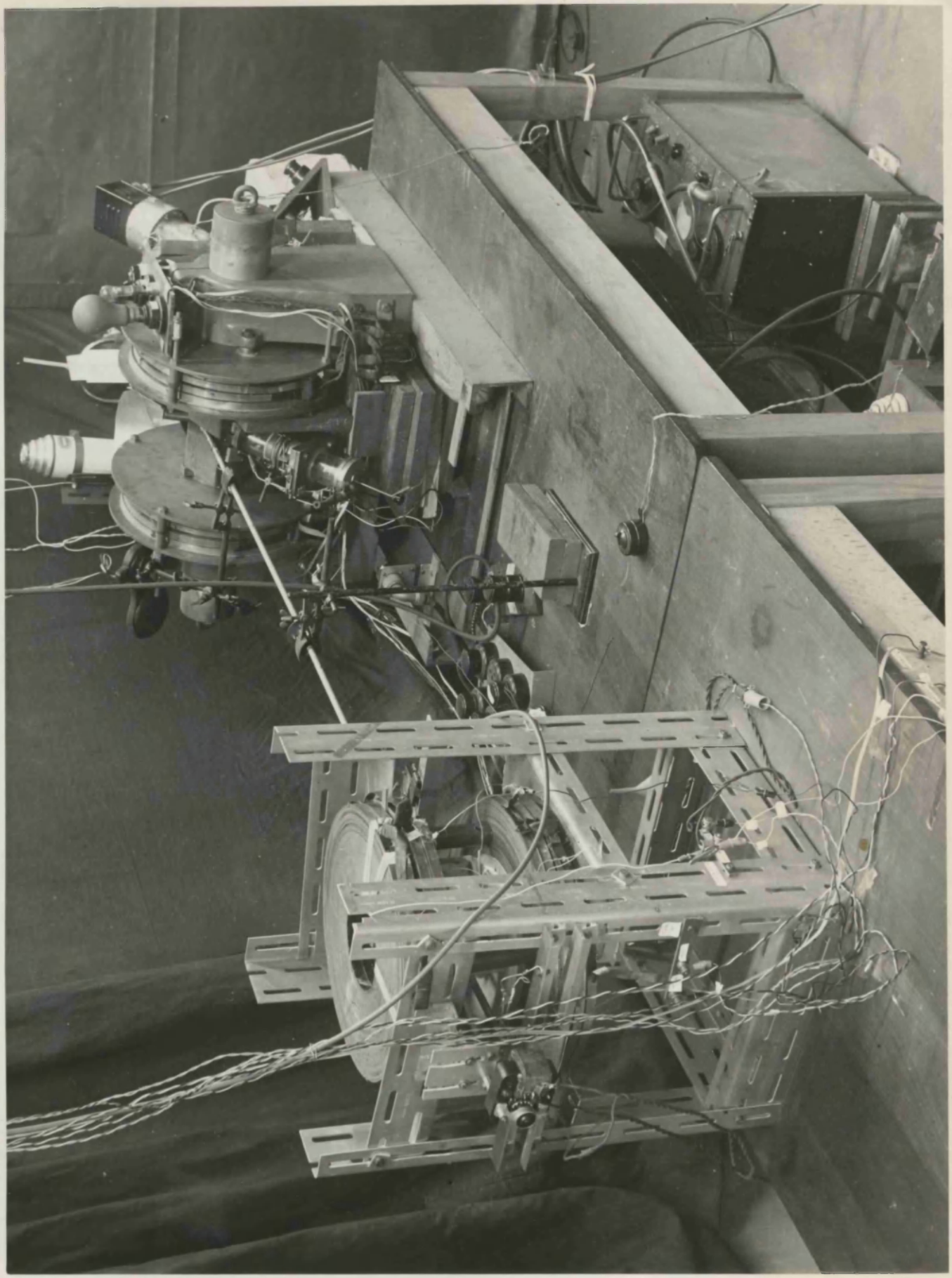


Figure 30. A photograph of the magnetic field control units.

in Figure 31. A 10% change in output, which was just detectable, corresponded to a change in I of 1.5%. For maximum sensitivity a similar change in output corresponded to a 0.15% change in I. An accuracy of this order was therefore possible in the field setting. It is seen in the figure that at balance the amplifier output was a minimum rather than zero. This was due partly to a small output, due to noise, from the amplifier with no input signal, and to a lesser extent to a slight error in the phase of the two rotating coil e.m.f's.

The second measurement was a check between the field measuring system and an accurately set up search coil and ballistic galvanometer. It was found that when I was reversed and a new balance obtained the spectrometer field was exactly reversed. This was true over the whole range of fields which would be used for the S.E. experiments.

V. 7. Calibration of the Field Measuring System in terms of Bp

The spectrometer was set up with a thin windowed Geiger counter (See Section VI. 2(2)) at the focus and the spectrum of the K and L conversion lines of the 411 KeV γ-ray from gold 198 obtained as a function of Bp. A very thin line source was used to get maximum resolution. The spectrum is reproduced in Figure 32 and shows a sharp K peak and a distinct L peak. The value of I correspondong to Bp for the K peak provided an

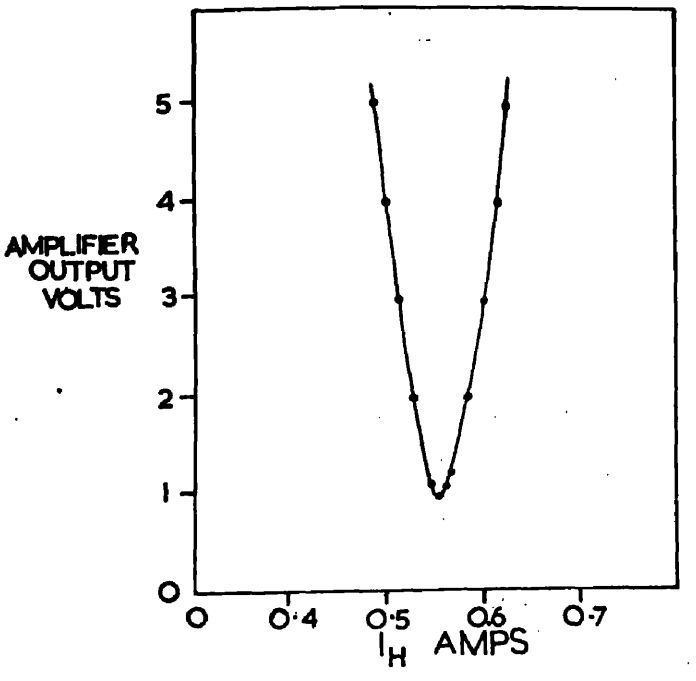


Figure 31. The output of the amplifier near balance as a function of the current, I_H, through the Helmholtz coils.

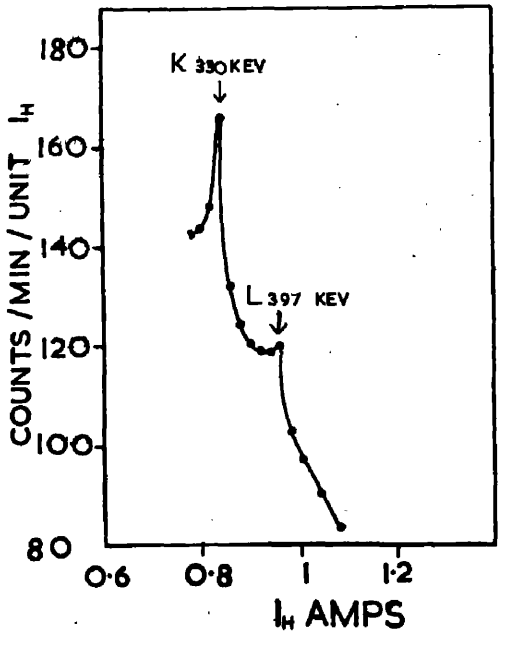


Figure 32. The momentum spectrum of gold 198, showing the K and L conversion peaks which were used to calibrate the field measuring system.

absolute calibration. The calibration constant $\frac{B_o p}{I_o}$ of Equation (V - 3) was 2800 gauss cms. per amp. The accuracy of this was checked by comparing the spacing observed between the two peaks with the calculated value. This yielded a probable error of $\pm$ 1.5%.

CHAPTER VI

EXPERIMENTS ON SECONDARY EMISSION BY ELECTRONS AND POSITRONS OF ENERGY FROM 5 - 500 KeV

VI. 1. Introduction

In this chapter the main series of experiments comparing S.E. by electrons and positrons will be described. Some data yielding an absolute value of the S.E.C. will also be presented and, where possible, compared with existing measurements. The final discussion of the results for the relative S.E. will be given in Chapter VII, although some comments on the results for the S.E.C. of electrons will be included in Section VI.5(3b)

Most of the apparatus has already been described, but a short section is included in this chapter which deals with the complete experimental arrangement. The design and construction of thin windowed Geiger counters, specially made for use in the spectrometer will be mentioned briefly.

The experimental method, the basic principles of which were outlined in Chapter II, will then be discussed. In particular, considerations which arose from the short half life of the copper 64 sources which were used, will be given. Measurements were made with seven different sources, as only a limited amount of data could be obtained from each one. After careful consideration, it has been decided that the best way

to present the results is to discuss each source separately, giving the results for a particular source, comparing them with those obtained from other sources, and hence showing what further measurements were required. It is felt that by presenting the data in this way a much better picture can be given of how the experimental investigation was carried out, bringing out the importance of some of the measurements more clearly.

After the section describing the results obtained with the sources, there is a final section in which systematic errors are discussed. It is necessary to say a little about systematic errors before going on to describe the results obtained from the experiments. When the measurements with the first three sources were complete the general form of the final result was clear. The final result was as follows:- In the energy range 50 KeV $\lesssim E_p \lesssim$ 500 KeV the ratio of the S.E.C. of electrons to that of positrons was a few per cent greater than unity. As the energy was reduced below 50 KeV this ratio began to increase, reaching a value of 1.25 at 15 KeV, 1.7 at 10 KeV and 3.25 at 6.5 KeV. This large difference in S.E. by electrons and positrons was not expected on any existing theory, and although lack of theory is certainly no reason for rejecting the results,. it was considered very important to establish that the observed difference was genuine and not due to any systematic or instrumental errors. This investigation into the possibility of such

errors was carried out very thoroughly, and the last section in this Chapter summarises the relevant experiments and attempts to determine the most probable result and to assess the final error.

It will be shown in Section VI.11. that there were two principle systematic errors for which corrections required to be made. The first of those, which was only important for energies greater than ~ 20 KeV., arose from the multiplier count rate produced by primary particles scattered from the first dynode. This has already been mentioned in Section IV.5.(1). The other systematic error, called the "background error", was rather involved and will not be discussed until Section VI.11.(6). (It should be noted that the background error was not connected with the difficulties described in Section III.2.(4), arising from spurious counts in the multiplier). This error only became appreciable at energies less than ~ 30 KeV., and was much less than the observed difference in the relative S.E. in that region. The correction, which was estimated from some subsidiary experiments, was applicable directly to the relative S.E., and the corresponding correction to the actual values of the S.E.C. of electrons and positrons was not determined. It will be shown, however, that the error in the relative S.E. arose almost entirely from the positron results, and so as a first approximation it was assumed that data for electrons was correct and that the

data for positrons had to be corrected by the same factor as the relative S.E. In practice the experiments designed to investigate systematic errors were mostly carried out at the same time as the other measurements and so a good idea of required corrections was obtained along with the main results. In all the results which are presented these corrections have been applied, but all reference to the accuracy or validity of the corrections themselves will be omitted until the final section.

VI.2. The Apparatus

VI.2. (1) The Complete Apparatus. The spectrometer was set up as described in Section V.2. The space between the source and the electron multiplier case was filled with lead blocks to shield the counter from direct γ-rays from the source. As strong sources of the order of tens of millicuries were used, the whole spectrometer was surrounded by lead shielding to screen the operator at the control panel a few yards away. A photograph of the apparatus, as used for the main series of experiments, is shown in Figure 33.

VI2.(2) Thin Windowed Geiger Counters

In order to determine the absolute number of particles reaching the first multiplier dynode, two special Geiger counters were constructed. Either of these could replace the dynode

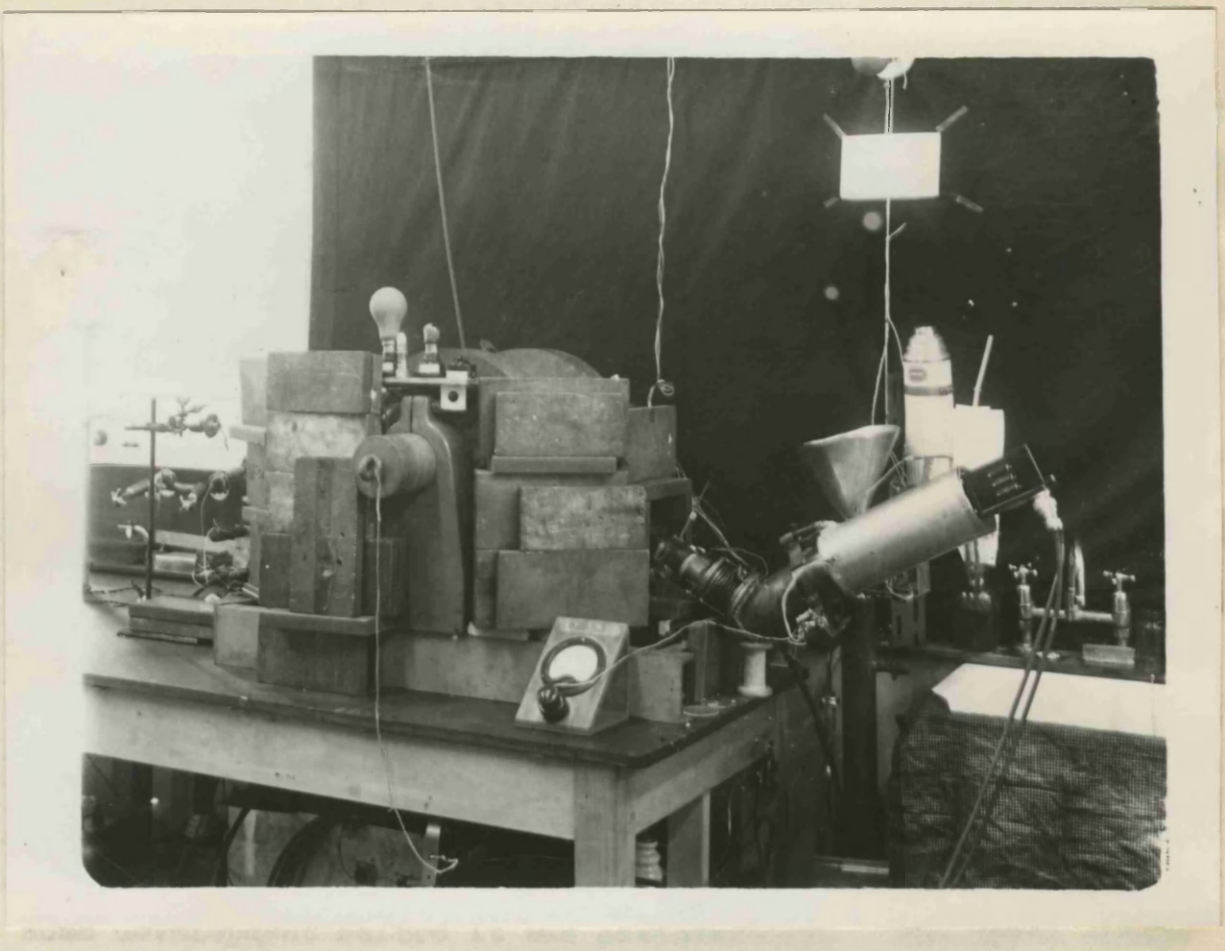


Figure 33 The complete spectrometer, with the electron multiplier in position; as used for the main experiments. The spectrometer was surrounded by lead to screen the operator.

assembly inside the multiplier case; the counter window was just behind the final collimating slit, which defined the beam falling on the first dynode. One of these counters had a 1.5mg/cm^2 mica window, which is equivalent to the range of 30 KeV electrons, according to curves published by Glendinin [56]. The other counter had a window made from a 50 μ g/cm^2 nylon film; Backus[60] found that a 50 μ g/cm^2 film transmitted all electrons with an energy greater than $\sim$ 3-5 KeV. A diagram of one Geiger counter in position inside the electron multiplier case is shown in Figure 34 (a), and a photograph of both counters is reproduced in Figure 34 (b). The counter with the mica window, which was fixed with cold setting Araldite, was quite straightforward and had a good plateau. It was filled differentially to a pressure of 8 cms. Hg. with argon and alcohol vapour in the ratio 8:1.

The other counter was not so straightforward and required some development before it was satisfactory. The nylon window was supported on a polished brass plate which contained a large number of 0.045" diameter holes, spaced very close together, which gave a transmission of 50%. This counter was also filled differentially, to a total pressure of 5 cms. Hg. It was connected to a 1 litre ballast flask, to compensate for any diffusion of the filling through the window. With this arrangement the counter lasted several days on one filling, and

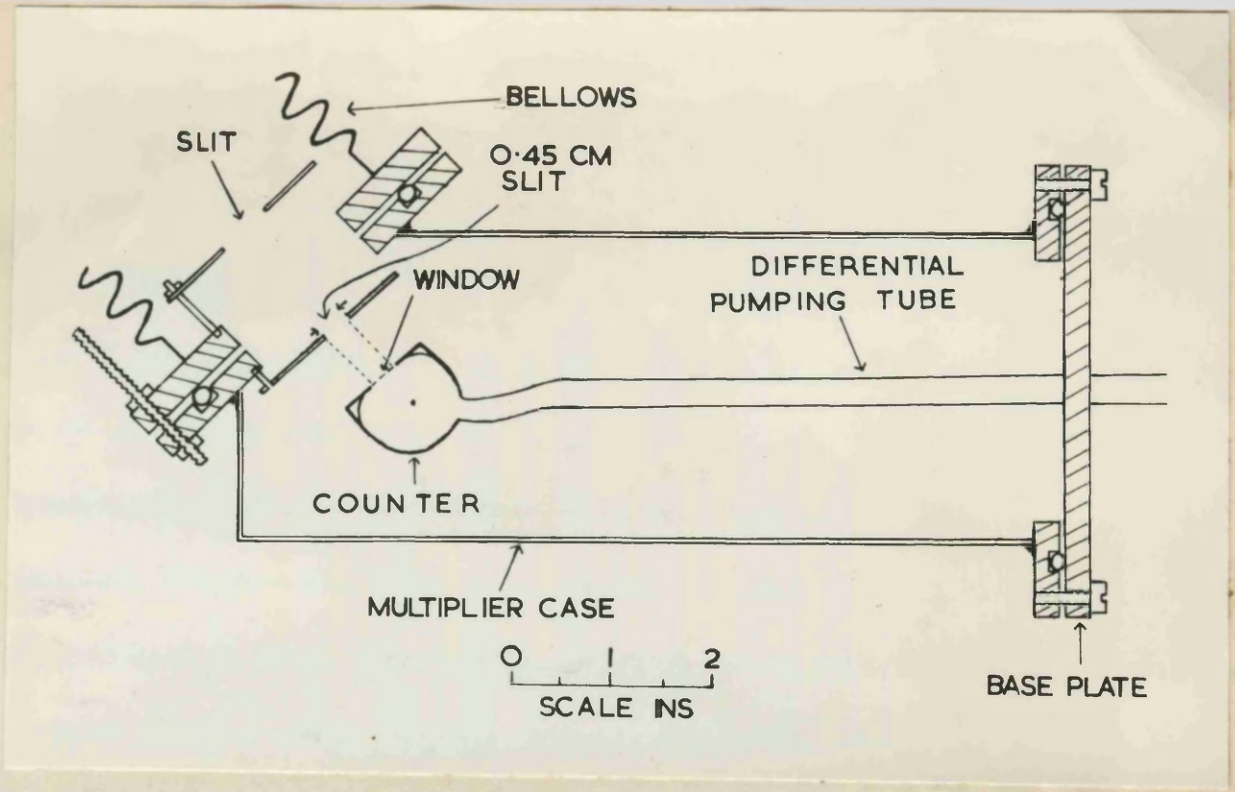


Figure 34 (a). A diagram of one Geiger counter replacing the dynode assembly inside the multiplier case.

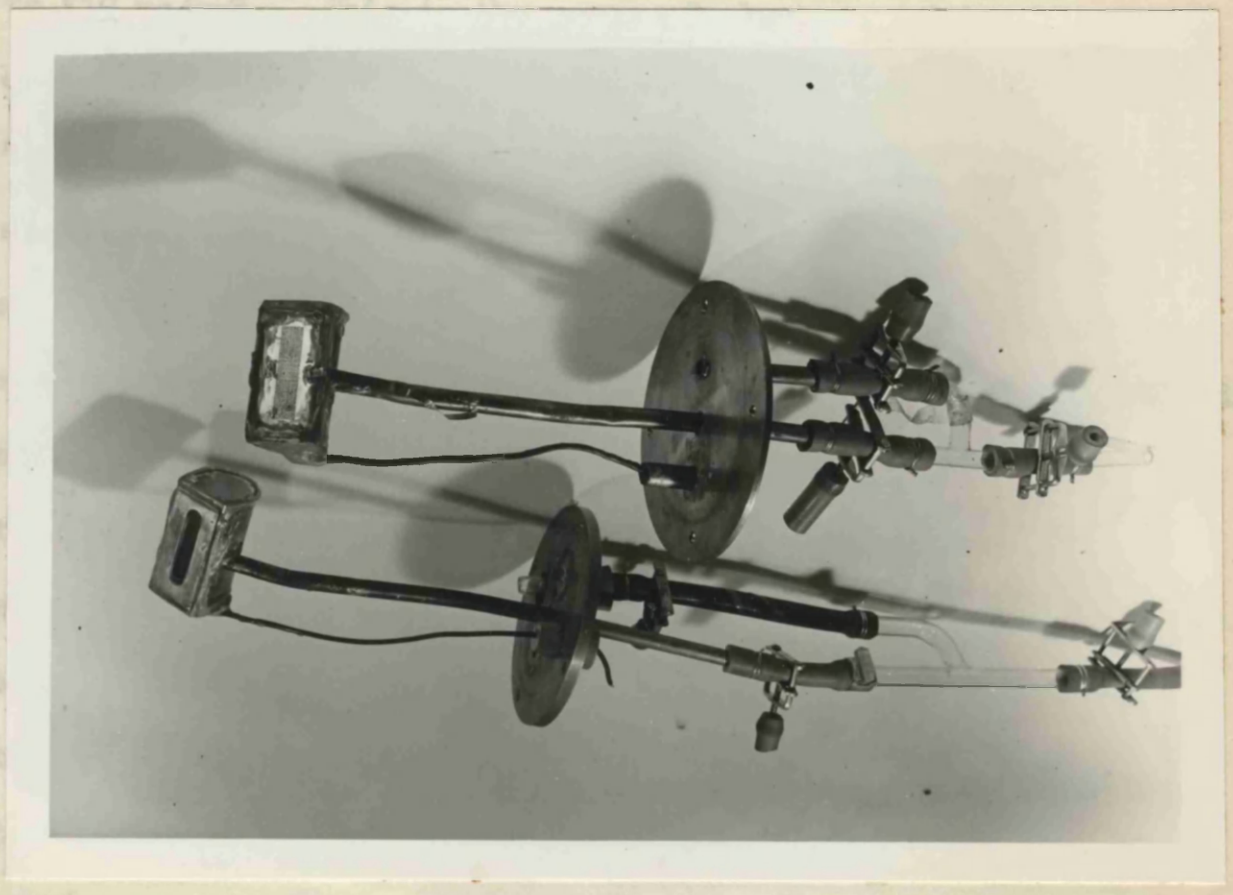


Figure 34 (b). A photograph of both counters. The nylon windowed counter is above.

particles in the spectrum emitted with medium and low energy.

A further important factor was that the end products of the β^- decay, zinc 64, and that of the β^+ (also K-capture) decay, nickel 64 were both stable. A disadvantage of copper 64, which has already been pointed out, was the short half-life.

VI. 3. The Method of Making Measurements

The basic principle of the method was outlined in Chapter II. Here the actual method of making the measurements will be described.

VI. 3.(1) General Features of the Method For reasons already given it was decided that the best method was to compare the S.E. by β^- and β^+ particles of the same energy under identical conditions of geometry. This also proved to be the simplest method, because of the decrease of the electron multiplier gain with time. Values of the S.E.C. were also obtained by standardising the multiplier, and correcting for the half-life of the source.

At each energy the electron and positron count rates were recorded alternately; the background count rate was taken after every count. This procedure was carried out for the multiplier and for the Geiger counter, and the following quantities determined at different energies.

$$\eta_M = \frac{\text{Electron count rate in multiplier}}{\text{Positron count rate in multiplier}}$$

$$\eta_G = \frac{\text{Electron count rate in Geiger counter}}{\text{Positron count rate in Geiger counter}}$$

and $$\eta = \frac{\eta_M}{\eta_G} = \frac{\text{S.E.C. of Electrons}}{\text{S.E.C. of Positrons}}$$

η_M, η_G and η were each plotted as a function of energy. To obtain the S.E. coefficients, the actual positron and electron count rates were determined, from which

$$\text{S.E.C. of electrons} = \delta^- = \frac{\text{Electron count rate in multiplier}}{\text{Electron count rate in Geiger counter}}$$

and similarly for δ^+, the S.E.C. of positrons; δ^- and δ^+ were plotted as functions of energy.

There were also many measurements made to investigate possible systematic errors, especially with the later sources. The importance of this has already been emphasised.

It was assumed that the background was the count rate with zero magnetic field in the spectrometer. This was only an approximation, and its validity will be examined in Section VI. 11.(6). It may be stated here that the approximation was valid at medium and high energies, where the count rate was much greater than the background.

VI.3.(2) Considerations arising from the short half-life of the source. Due to the short half-life of copper 64 a rather careful procedure was used to record results, in order to obtain the

maximum amount of data from each source. Sources arrived in Glasgow on a Monday afternoon or evening and were at once inserted in the spectrometer. Measurements were made firstly with the electron multiplier, which yielded lower counting rates than the Geiger counter, because of its lower efficiency. A continuous run of between 24 and 30 hours was usually made. On the following two or three days the Geiger counter data were recorded. Measurements with each counter were made first at low energy, where there were fewest particles in the source spectrum.

One of the major difficulties in all the experiments was to obtain sufficient data at low energies to reduce the statistical error to a reasonable value, without having to restrict the number of energies at which measurements were made to two or three per source. This was especially true for low energy positron count rates in the multiplier, which were often very much less than the background. The total count rate (positrons + background) was often only $\sim$ 200 per minute when the source was strong.

VI. 4. Experiments with the First Source

VI. 4.(1) General - Experimental Details. As this was the first of the main series of experiments with the spectrometer, an attempt was made to obtain some data over a wide range of energies, rather than to make accurate measurements in a small

region. This would be a much better guide when deciding what measurements to make with subsequent sources. Data was recorded with the electron multiplier and the mica windowed Geiger counter from energies ~ 5 KeV up to ~ 500 KeV. Geiger counter measurements below ~ 30 KeV would be very unreliable with a 1.5 mg/cm^2 window, but it was hoped that in the low energy region at least the form of η_G, and hence of η could be obtained, by extrapolation, if necessary. The nylon windowed counter had not been developed at this stage. The multiplier was not corrected for gain variations and only relative measurements were made. The target (first dynode) was of copper-beryllium for this experiment. The copper foil of the source itself was 0.002" thick i.e. 45 mg/cm^2.

VI. 4.(2) Results. The ratios η_M and η_G which were obtained are plotted as functions of energy in Figure 35(a). The value of η is plotted against energy in Figure 35 (b). η_M and η have been corrected for the multiplier count rate arising from primaries reflected from the first dynode. The statistical errors are shown, and, as expected, are rather large because of the limited amount of data which was obtained.

VI.4. (3) Discussion of results from the first source.

The variation of relative S.E., η , with energy was important, as this was the first measurement comparing the S.E. of electrons and positrons of the same energy over a wide range of energies which

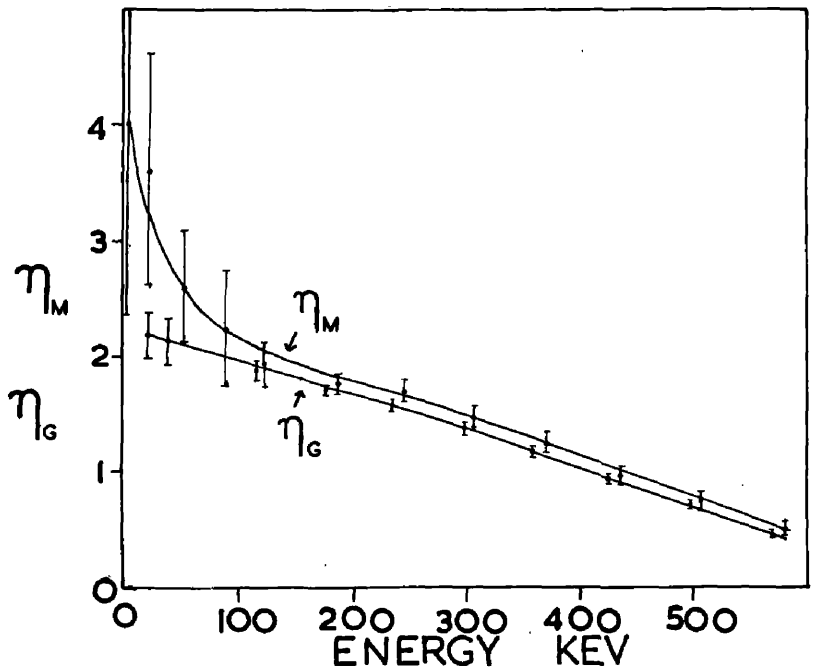


Figure 35 (a). The variation with primary energy of η_M for copper-beryllium, and η_G. (Source 1).

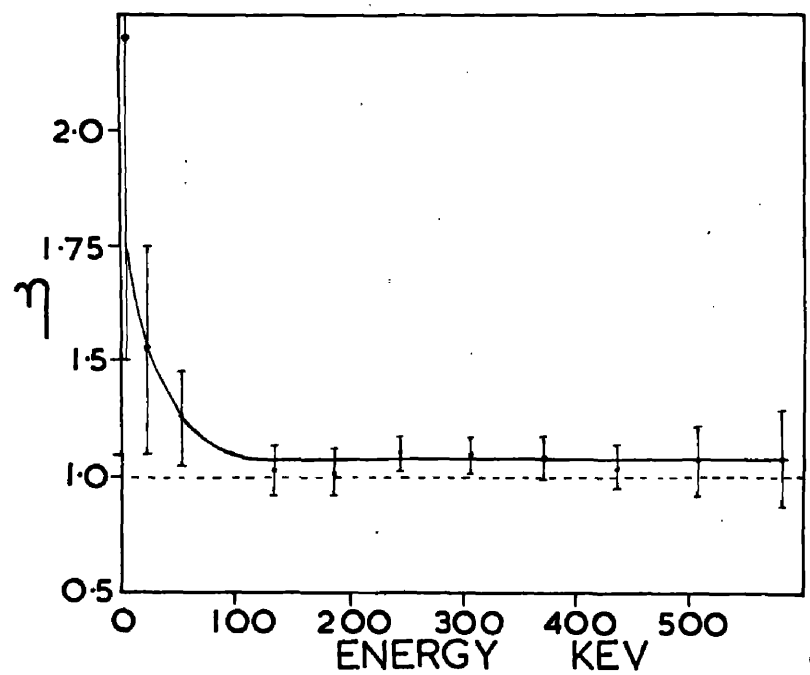


Figure 35 (b). The variation with primary energy of η, for copper-beryllium. (Source 1).

has been reported. The curve for energies greater than ~30 KeV will be considered first. Here it was found that η was slightly greater than unity, and fell to a roughly constant value of 1.07 at energies higher than ~ 100 KeV., i.e. electrons had a greater S.E.C. than positrons. Although the statistical error was too large to be certain about the high energy value of η, it did appear that η was greater than unity, and probably did not tend to unity, but tended to remain approximately constant as the energy was further increased. The appearance of this small difference in S.E. at higher energies was not inconsistent with the preliminary experiment described in Chapter IV, as there was an uncertainty of ± 10% in that result.

At low energies the form of the curve of η against energy was both interesting and unexpected. It appeared that the S.E.C. of electrons began to exceed that of positrons by a large amount. The excess of electron S.E. observed was much greater than the statistical error and the uncertainty in the correction which had been applied. It must be pointed out that the results for low energies had to be regarded as tentative because of the unreliability of the Geiger counter measurements, due to absorbtion in the window. It was significant, however, that the rise in η seemed to come from a corresponding rise in η_M, which was reliable. η_G appeared to be approximately linear at low

energies in this experiment.

It was found with later sources, in which more accurate data was obtained, that the rise in η did not actually become rapid until lower energies were reached than those indicated in Figure 35. However, the general form of the later curves was the same as that shown in Figure 35.

From the results obtained with the first source it was clear that subsequent investigations should consist of (a) a further experiment at high energy in which a reduced statistical error would be obtained, in order to confirm or otherwise the existence of the small excess of electron S.E. over positron S.E. in that region: (b) a detailed study of the phenomenon at low energy.

VI. 5. Experiments with the Second Source

VI. 5. (1) General - Experimental Details. This was one of the most fruitful sources and was devoted to an investigation of the high energy region only. Many measurements were made and the statistical error was considerably smaller than with the first source. Several improvements in the apparatus were incorporated. A stronger source was used, in order to achieve higher count rates, by increasing the thickness of copper foil by a factor of two. The use of a thicker source altered the the positron and electron spectra slightly and η_M and η_C could

not be compared with the values obtained with the first source. The relative S.E., η, is, of course, independent of source thickness. A platinum target was used instead of the copper-beryllium one. The reasons for this choice of target were threefold: Firstly, at energies greater than a few KeV platinum, because of its high density, should have a greater S.E. than copper-beryllium (See Section I. 2.(2b)). This would give larger count rates, which would be an advantage. Measurements showed that the S.E.C. of platinum was about 1.5 times that for copper-beryllium. The second factor in favour of the use of platinum was that a polished platinum surface, cleaned by heating, would be intrinsically a more reliable and consistent target than the activated copper-beryllium alloy. The third reason was that it would be interesting to see if a second material also gave an excess of electron S.E. over positron S.E. The use of a platinum target would rule out the possibility of any potential ejection mechanism, because of its high work function. However, no evidence for this had so far been obtained with a copper-beryllium target, which has a low work function, and it was considered important to follow up the difference in S.E. which had been observed. In fact the values of η for platinum and copper-beryllium at different energies turned out to be much the same, and except for one further experiment, (source seven), all other measurements were made with

platinum. The data obtained with the seventh source were much more accurate than those obtained with the first source, but the results were similar.

As well as measurements of η_M and η_C, the multiplier was standardised in this experiment in order to determine the absolute S.E.C. of electrons, δ^-. The S.E.C. of positrons, δ^+, was obtained from δ^- and η by the relation $\delta^+ = \delta^-/\eta$.

VI. 5. (2) Results. Values of η_M and η_C are shown as functions of energy from 30 KeV - 500 KeV in Figure 36 (a). As before η_M has been corrected for systematic errors. The values of η are plotted against energy in Figure 36 (b). For comparison the results for η obtained for copper-beryllium with the first source are also shown in the figure. The statistical errors are shown on both curves. These are greatest at high and low energies, where there are fewest particles in the positron and electron spectra. Usually counts were recorded for a longer period when the count rates were low, but it was not possible to reduce the statistical errors further at the extreme ends of the spectra without spending an undue proportion of time on these two regions.

The results for the S.E.C of positrons and electrons are shown in Figure 37. For comparison the curve obtained for the average S.E.C of copper beryllium as determined in Chapter IV

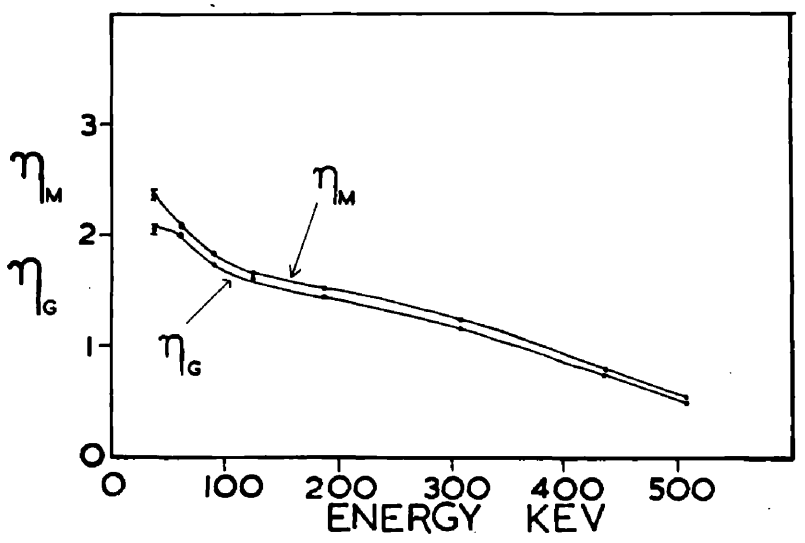


Figure 36 (a). The variation with primary energy of η_M for platinum and η_G. (Source 2).

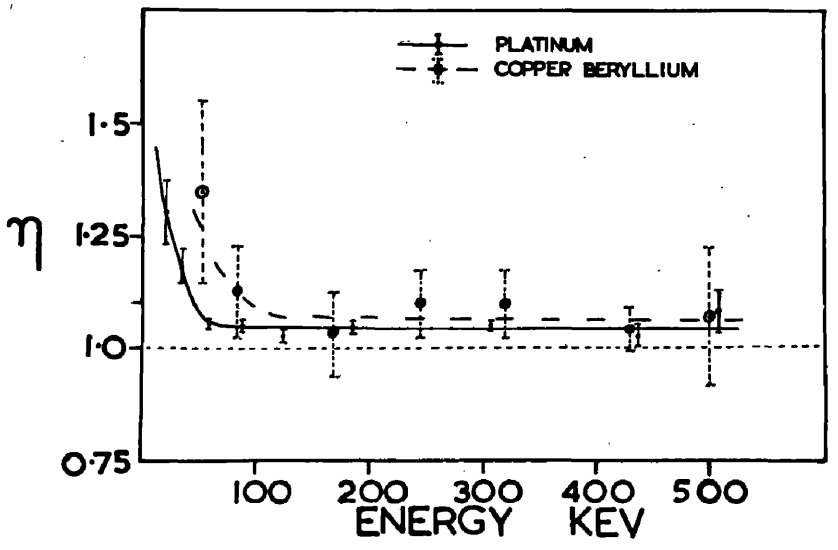


Figure 36 (b). The variation with primary energy of η, for platinum. (Source 2). The dotted line shows the results obtained for copper-beryllium with Source 1.

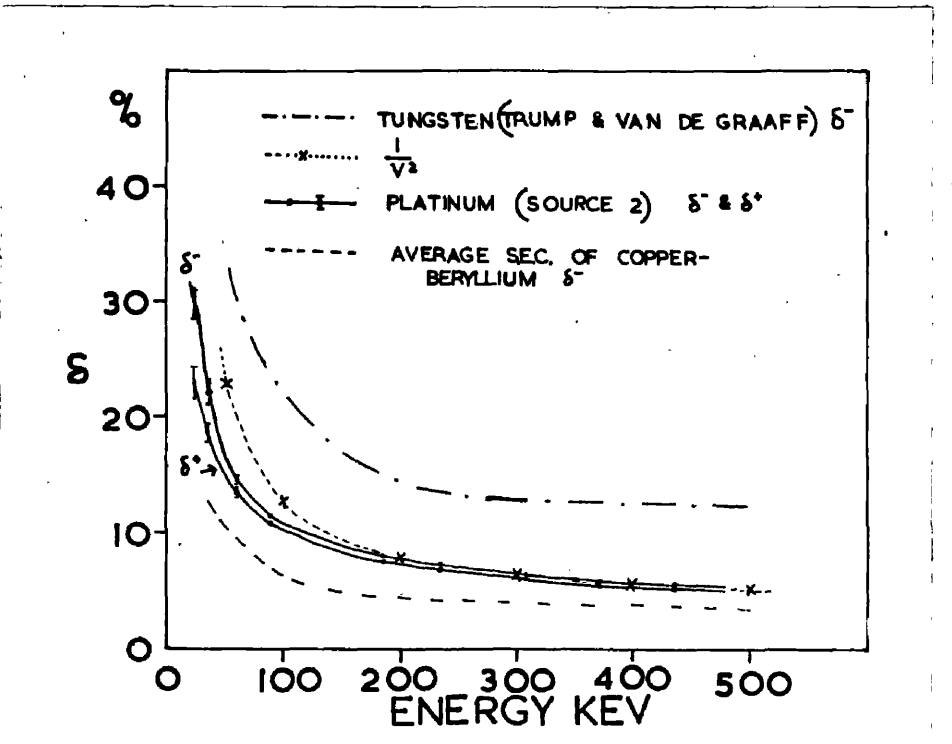


Figure 37. The variation of δ^- and δ^+ with primary energy for platinum. (Source 2). Some other curves are also shown for comparison

is shown, together with the results of Trump and Van de Graaff[29] for tungsten. It will be shown that at high energy the yield curve can be approximately represented by a $1/v^2$ law, where v is the velocity of the primary particle; the dotted line in Figure 37 shows the variation (in arbitrary units) of $1/v^2$ with energy, normalised to the yield curve for platinum at 200 KeV.

It should be noted that the standardisation of the electron multiplier, as done in this experiment, only enabled measurements made during one run to be compared. In order to compare the absolute values of the S.E.C. for platinum and copper-beryllium over different runs a further calibration was required. This was done in a separate experiment and the results given here are normalised to the values obtained in that experiment.

VI. 5 (3). Discussion of Results

VI. 5 (3a) The Relative Secondary Emission. The results for platinum were similar to those already obtained for copper-beryllium. Results in the energy range $50 < Ep < 500$ KeV will be discussed first. In this region η tended to a constant value of 1.04. The statistical error was much smaller than for the first source and most probable value of η for platinum was 1.04 ± 0.02. This was slightly lower than the value of η obtained for copper-beryllium with the first source but the statistical errors in that experiment were too large to enable quantitative comparisons to

be made. The observed small excess of S.E. by electrons over S.E. by positrons at high energy is an important result. It was pointed out in Chapter II Part 1 that a small excess of electron S.E. might arise due to the unequal backscattering; more detailed considerations, which will be given in the final chapter, did indicate that electrons would probably have a greater S.E.C. than positrons by a few per cent.

At lower energies η', for platinum, showed marked tendency to rise in a very unexpected way, as observed for copper-beryllium with the first source. The data at lower energies was not sufficiently accurate in either experiment to obtain a numerical value of η in that region.

Much more data was required in the low energy region, with a view to obtaining consistent numerical results and finding an explanation for them. The next three sources were used to investigate the phenomenon at low energies.

VI. 5 (3b). <u>The values of the S.E.C. of Electrons and Positrons.</u>

Values of the S.E.C. of electrons were obtained in order to compare measurements made using the Author's technique, with those of other workers, and to determine the S.E.C. of positrons, assuming the value of η which had been found.

The results for the S.E.C. of electrons will be considered first. The agreement between the two curves obtained using the

electron multiplier, that for platinum and for copper-beryllium as obtained in Chapter IV, was very satisfactory. The shape of the two curves is similar, in fact to a greater extent than might have been expected. As pointed out in Section IV. 5.(4), the curve showing the average S.E.C. of copper-beryllium would perhaps have tended to rise faster with decreasing energy than the true curve, due to the increased S.E.C. of relatively few low energy particles in the spectrum. It must be inferred that there were not enough particles of sufficiently low energy for this effect to be appreciable. The shape of both curves at higher energy approximated fairly well to the curve of $1/v^2$ against energy, thus supporting a $1/v^2$ law for the variation of the yield with energy. The magnitude of the S.E.C. of platinum was about 1.5 times the value for copper-beryllium, which is strong evidence in support of Bruining's [8] hypothesis that at high energy density rather than work function is predominant in determining the yield. Both the density and the work function of platinum are considerably greater than the values for copper-beryllium. The maximum value of the S.E.C. of activated copper-beryllium is $\sim$ 4 at an energy of 500 eV, according to Allen [15], and the maximum value for platinum is 1.8 at an energy of 700 eV, according to Copeland [10]. It follows that the yield curves must cross at some energy between $\sim$ 1 KeV. and

~20 KeV. Experiments with subsequent sources, which extended the S.E. measurements down to an energy of 5 KeV, produced no evidence for any tendency of the yield for copper-beryllium to increase faster with decreasing energy than that for platinum; it follows that the crossover must be at an energy much lower than 5 KeV.

Direct comparison of the results obtained in this experiment with the work of Trump and Van de Graaff was not possible as they did not study either platinum or copper-beryllium. The possibility of using tungsten was considered, but this metal was not available in a suitable form for constructing a dynode to act as the target. A later experiment on the S.E.C. of electrons using an aluminium target, did permit direct comparison. The S.E.C. of this material at 200 KeV was found to be 5% compared with 7% obtained by Trump and Van de Graaff. The two yield curves were similar.

As regards the measurements made with platinum, the best comparison should have been with tungsten, a metal of comparable density. Figure 38 shows that although the form of the yield curves were the same there was a considerable difference in the magnitude of the S.E.C. of the two materials. The other measurements by Trump and Van de Graaff, on iron and carbon, indicated that the yield was roughly proportional to density at

high energies, but there is too little data to say that this was a definite rule for most metals, to which platinum was an exception. Even if there was a definite density rule, there were differences in the experimental technique which would tend to make the value obtained by Trump and Van de Graaff greater. One such difference was that these workers included as secondaries all particles with an energy of less than 800 eV., while the present technique for detecting the secondary electrons was only efficient for secondaries with an energy of less than several tens of eV., as pointed out in Chapter II Part 1. However, other curves published by Trump and Van de Graaff indicated that most secondaries had energies of less than several tens of eV., so this effect is unlikely to be large. A more important difference in technique lies in the geometry of the electron multiplier. As shown in Section III. 3.(6) the efficiency of collection of secondary electrons liberated at the first dynode, by the second dynode, was critically dependent on the shape and position of the first dynode. Thus the electron multiplier technique was not accurate for absolute measurements and, if anything, would tend to yield low values of the S.E.C., unless the targets were made to very fine tolerances. As the experiment was not primarily designed to make absolute S.E. measurements it was not considered worthwhile to make the targets very

accurately. This would have been difficult in any case, with thin sheets of a metal like platinum. It is likely, however, that the platinum target was constructed sufficiently carefully to prevent geometrical errors which could produce differences in the yield of the order of a factor of two, and probably platinum does have a rather lower value of S.E.C. than tungsten. Another factor which could lead to differences was the state of the surface. This is very important for low energy primaries; at higher energy, however, where the work function is less important, it is unlikely that the yield was very sensitive to the state of the surface.

One further measurement of the absolute S.E.C., for silver, was made in another experiment; this yielded a value ~ 0.08 at 200 KeV, only $\sim 10\%$ less than the value found for platinum. This was the value to be expected for silver if Trump and Van de Graaff's value for tungsten was accepted, and a direct proportionality to density assumed. In conclusion, it may be said that with the electron multiplier method, metals with greatest density had in general the largest values of S.E.C. but that no clear cut proportionality between the yield and the density was observed.

It should be noted that this uncertainty in the absolute measurements did not affect the validity of the method for comparative measurements, which lead to the shape of the yield

curve, and the relative S.E. of electrons and positrons. For such experiments the target was identical over any one set of comparative measurements.

The agreement between the yield curves at high energy and a $1/v^2$ law has been pointed out. It can be shown that the shape of the S.E. yield curve for all materials at high energy should be approximately represented by a curve of $1/v^2$ against energy. This can be predicted directly from the Bethe [31] ionization formula. Bethe gives an expression for the energy loss, $-dE/dx$, of the primary particles as a function of their velocity, v, as follows

$$-\frac{dE}{dx} = \frac{2\pi e^4 n}{v^2 m} F(v, I)$$

where e, m are the charge and mass of the electron; n is the number of electrons per c.c. in the target and F (v, I) is a logarathmic function of v and I, where I is the mean ionization potential of the atoms in the target.

The rate of production of secondary electrons inside the metal is proportional to dE/dx, and is therefore approximately proportional to $1/v^2$. The agreement between the yield curve for platinum and the curve of $1/v^2$ against energy is quite good, especially at high energies. This is remarkable in view of the complexity of the full process of S.E., which was pointed out in Section I.2.(3). The shape of the yield curves for tungsten and

copper-beryllium also approximate to a $1/v^2$ variation.

Although some reference to the use of the Bethe formula to predict the form of the yield curve at high energy has been given, by Barut (61), no comparison between the shape of the yield curve and a $1/v^2$ law has been published. * (See footnote).

The S.E.C. of positrons at high energy also varied as $1/v^2$, although the value was slightly lower than for electrons. As the Bethe formula is expected to be valid for both types of particle, except for a small correction, the agreement in shape at high energy was to be expected. As already pointed out the small difference in magnitude does permit a simple explanation, which will be given in Chapter VII.

VI. 6. Experiments with the Third Source

VI. 6. (1). General - Experimental details. Measurements with this source were restricted entirely to the low energy region from 5 - 20 KeV, and the nylon windowed Geiger counter was used to determine the relative numbers of electrons and positrons. The third source was important because it gave the first reliable

* Recently, after the present research had been completed, a further publication on the S.E. by high energy electrons has appeared, by Miller and Porter (30), in which the $1/v2$ variation is mentioned.

results at low energy. Unfortunately Harwell were unable to supply a strong source on this occasion, as only a low pile factor was available, and the amount of data obtained was rather limited. Only relative measurements were made, and some data was recorded in order to investigate possible systematic errors.

VI. 6. (2) Results. The values of η_M, η_G, and η are shown in Figures 38 (a) and 38 (b), η_M and η have been corrected for the background errors. The statistical errors are shown, and due to the low source strength these were very large. However, the observed differences between the values of η_M and η_G, which is equivalent to the differences in the S.E. co-efficients of electrons and positrons, was much greater than the total uncertainty due to the background correction and the statistical error. The source was too weak to enable measurements to be extended to join up with the results of the second source, but a point obtained in that experiment is shown in Figure 38 (b), and the intervening region is marked in by a dotted line.

VI. 6. (3) Discussion - Comparison with the first two sources and summary of the position after three sources.

The rapid rise in η as energy was reduced which was indicated with the first two sources, was confirmed by the results obtained with the third source.

At this stage the general form of the result for the

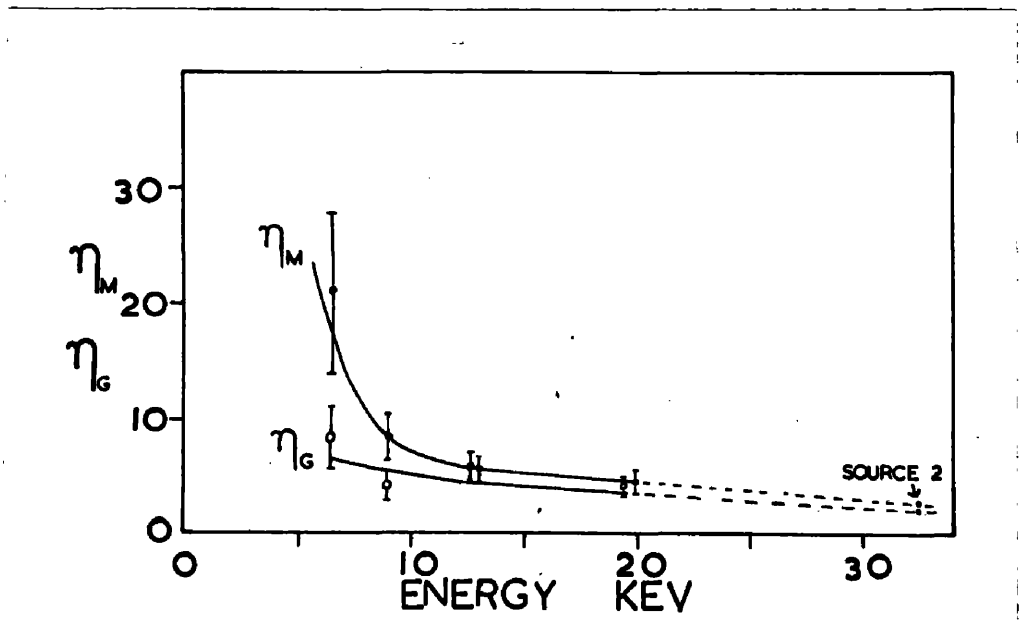


Figure 38 (a) The variation with primary energy of η_M, for platinum, and η_G, at low energies. (Source 3).

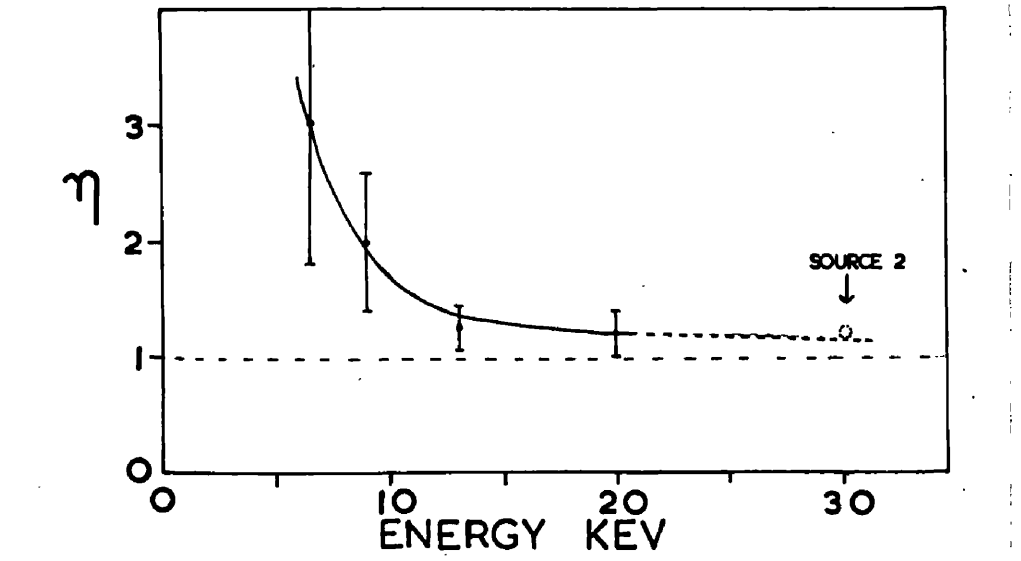


Figure 38 (b). The variation with primary energy of η, for platinum, at low energies (Source 3).

relative S.E. of electrons and positrons was apparent, and despite the large statistical error associated with the low energy measurements, the final result for η after much data had been obtained was quite close to that given in Figure 38. The unexpected magnitude of η at low energy required most careful investigation and a tentative programme for further work was drawn up in the light of the results already obtained. It was as follows:

(1) To obtain much more data from 5 - 20 KeV in order to reduce the statistical error.

(2) To make measurements in the intermediate energy region, to link up low energy measurements obtained with source three, with those at high energy obtained with the second source.

(3) To standardise the multiplier at low energy in order to obtain values for the actual S.E.C. of electrons and positrons. The shape of the positron yield curve would be of interest and there did not appear to be any existing data for electrons extending from 5 - 20 KeV.

(4) To make further measurements over the whole energy range with copper-beryllium.

(5) To investigate possible systematic errors.

VI. 7. Experiments with the Fourth Source

This experiment was effectively a repeat of that with the third source. A much stronger source was used and a few measurements were included which extended to higher energies; some data was recorded at 4.5 KeV, the lowest energy used in any experiment. A few measurements were also made to investigate systematic errors. The low energy limit was determined by four factors. The first of these was that the limit of the transmission of the nylon windowed Geiger counter was being approached; secondly, the positron count rate was so small and so close to background in both the Geiger counter and the multiplier that it was almost impossible to obtain a reasonable statistical error. The third reason was that the method as it stands, becomes basically unsound for particles with an energy of the order of a few KeV, because the electric field produced by the potential difference of 500 volts between the first and second dynodes will begin to affect the primary beam, which must pass through this field before reaching the first dynode. Positrons and electrons would be deflected in opposite directions by ~ 1 mm. or more and comparison between the S.E.C. of the two types of particles would become unreliable. This effect was studied as a possible source of systematic error and will be mentioned again in Section VI. 11.(3). The fourth

reason was, as will be shown later, that the S.E.C. of electrons was approaching unity at an energy of 5 KeV. As the technique used to detect the secondary electrons would not discriminate between a primary which gave a single secondary, and one which gave two, it was not valid for δ approaching unity. A primary which gave two secondaries would only give one output pulse from the multiplier, although this pulse would be much larger than that from a primary which only produced one secondary. To differentiate these a pulse height distribution from the multiplier would be necessary, and there were too few particles to do this in the time available.

Curves showing the variation with energy of η_M, η_c, and η are shown in Figures 39(a) and 39(b). For comparison the low energy results for η from the third source, and some high energy data from the second source are also shown. Agreement was within the statistical error.

As no basically new results were obtained with this source further space will not be given to it.

VI. 8. Experiments with the Fifth Source

VI. 8.(1) General. With this source an attempt was made to obtain reliable results in the low energy region only, and much data was recorded at only three or four different energies. The multiplier was standardised to enable values of the S.E.C. of

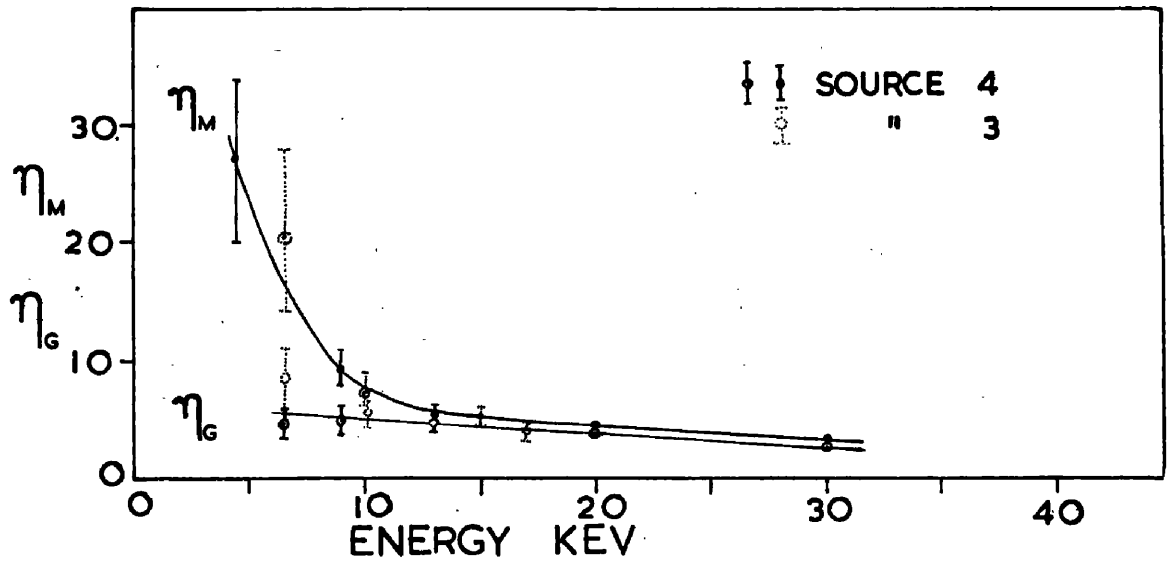


Figure 39 (a). The variation with primary energy of η_M, for platinum, and η_G. (Source 4).

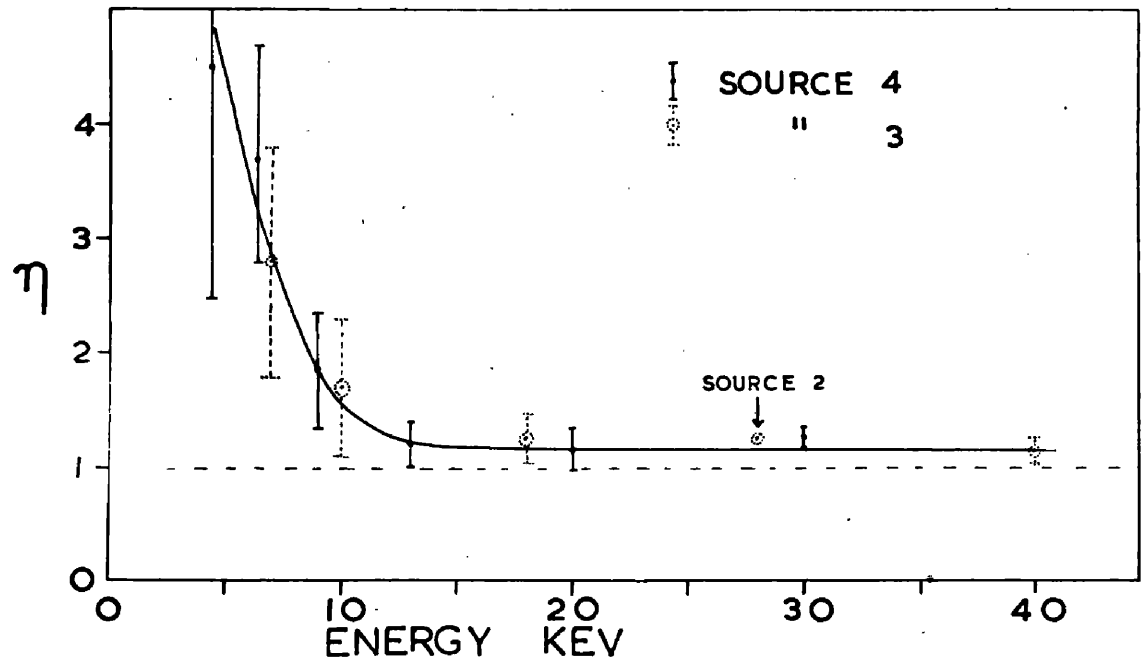


Figure 39 (b). The variation with primary energy of η, for platinum. (Source 4).

electrons and positrons to be obtained, in addition to relative measurements. In this experiment both δ^+ and δ^- were measured directly, instead of measuring δ^- only and finding δ^+ from δ^- and η, as done with the second source experiment. A fairly detailed investigation into some possible systematic errors was made in this experiment. The source strength was again increased by using a thicker copper foil. This will slightly alter the spectral shapes and therefore η_M and η_G may not be compared to the values found with previous sources; η is independent of source thickness.

VI. 8. (2) Results. The results for η_M, η_G, and η are shown as functions of energy in Figures 40 (a) and 40 (b). The values of η from the third and fourth sources are shown for comparison, and the agreement is surprisingly good considering the large statistical errors. The values of S.E.C. for electrons and positrons are plotted against energy in Figure 41. Some points from the second source results are shown for comparison and are joined to the present results by a dotted line. There does not appear to be any published data on electron S.E. extending from 5 to 20 KeV with which to compare these results.

VI. 8. (3). Discussion of Results. No new results were obtained from the relative S.E. measurements, which were

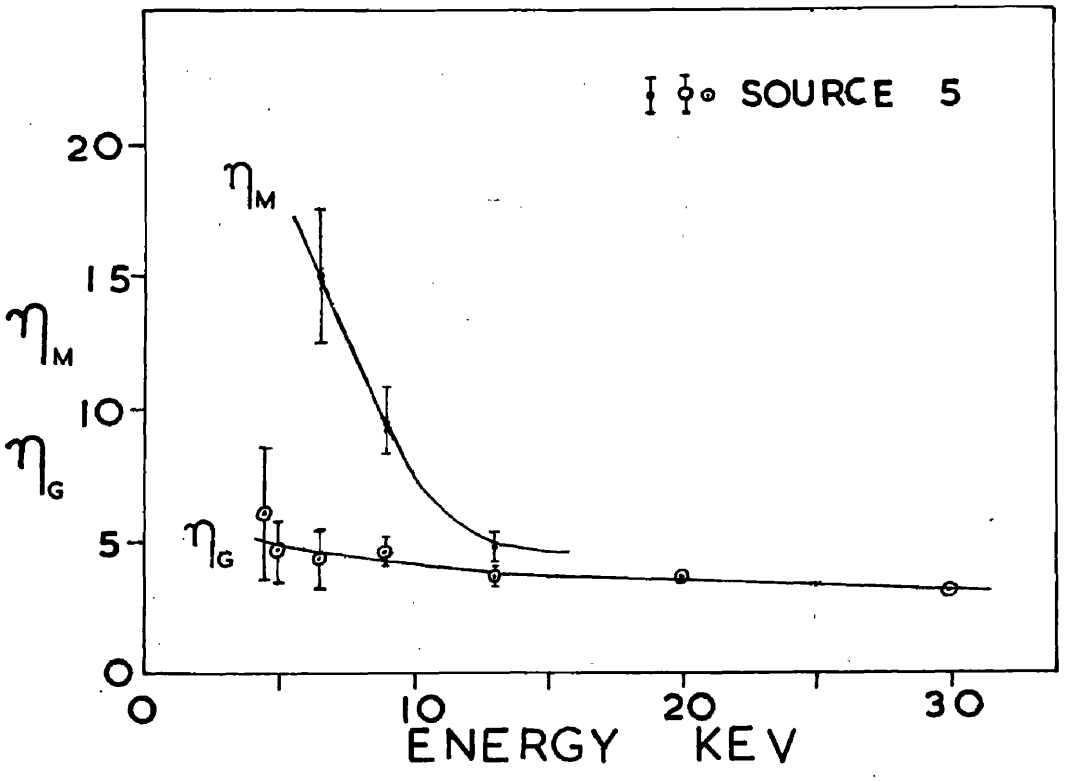


Figure 40 (a). The variation with primary energy of η_M, for platinum, and η_G. (Source 5).

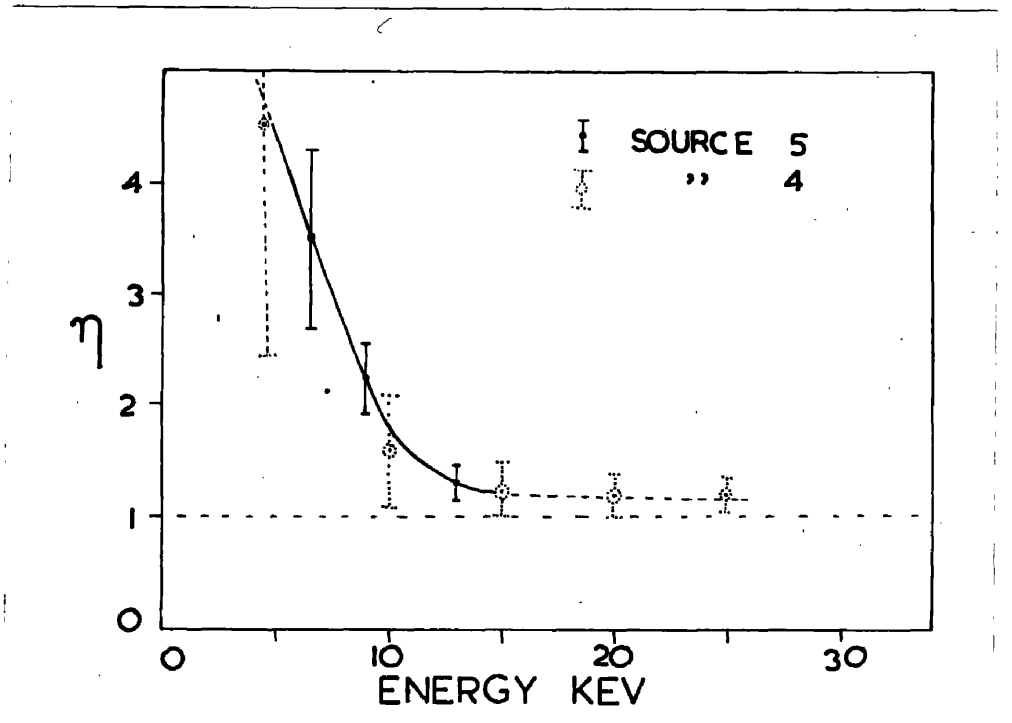


Figure 40 (b). The variation with primary energy of η, for platinum. (Source 5).

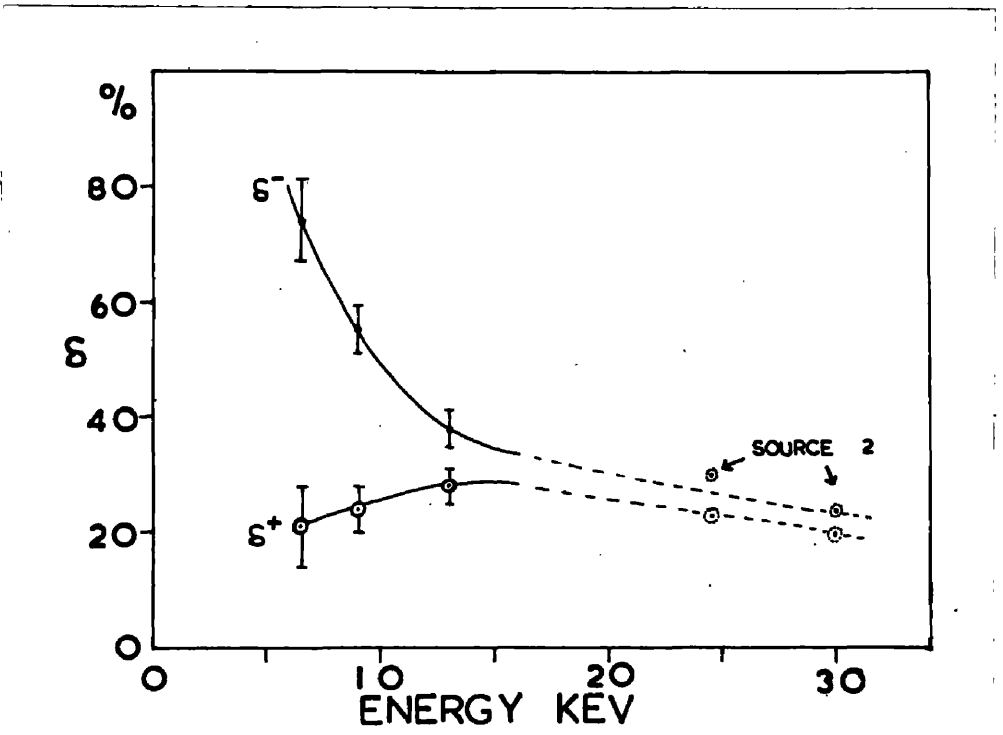


Figure 41. The variation of δ^- and δ^+ with primary energy for platinum. (Source 5).

important largely from the point of view of reducing the overall statistical error at low energy to a reasonable value. It was hoped to reduce the statistical errors to values of the same order, or less than, the estimated uncertainties in the corrections for systematic errors which have been applied. Excessive statistical errors were being found with the Geiger counter measurements. These arose because, by the time sufficient data had been obtained with the multiplier, the source was becoming very weak. Most of the experiments to investigate possible systematic errors involved the multiplier and not the Geiger counter, so the former used up a disproportionate fraction of the life of the source.

More data on the relative S.E. at intermediate energy was required as there was a discrepancy there. This was not very obvious from the curves of η against energy, due to the statistical error, and because there was such a wide interval between the lowest energy data obtained with the second source and the highest energy measurements made with the later sources. On close examination, however, it was found that from 20 - 30 KeV the value of η obtained with source two was larger than the mean value from the other sources.

The values of S.E.C. of the two kinds of particle are interesting, in particular those for positrons. The curve for

electrons was of the expected form. Although in this region there is no other data with which to compare the present results, by interpolating between measurements at 1 - 2 KeV, and at greater than 20 KeV it follows that δ^- is probably a steep function of decreasing energy. The positron yield curve showed that δ^+ is certainly not a sensitive function of energy, and may even decrease as the energy is reduced. This was, however, a matter of doubt because of the statistical error associated with the positron measurements.

VI. 9. Experiments with the Sixth Source

VI. 9. (1) General. This was the final experiment using a platinum target and measurements on the relative S.E. were made from 10 KeV, up to high energy, concentrating in particular on the intermediate region between the measurements made with the second source and with the low energy sources. The multiplier was again standardised in order to obtain values of δ^- and δ^+. As with the experiment with source five both δ^- and δ^+ were measured directly. Measurements to investigate instrumental errors were also made.

IV. 9. (2) Results. The values of η_G, η_M and η in the low energy region are shown plotted against energy in Figures 42 (a) and 42 (b). For comparison low energy data from sources four and five and high energy measurements made with the second source

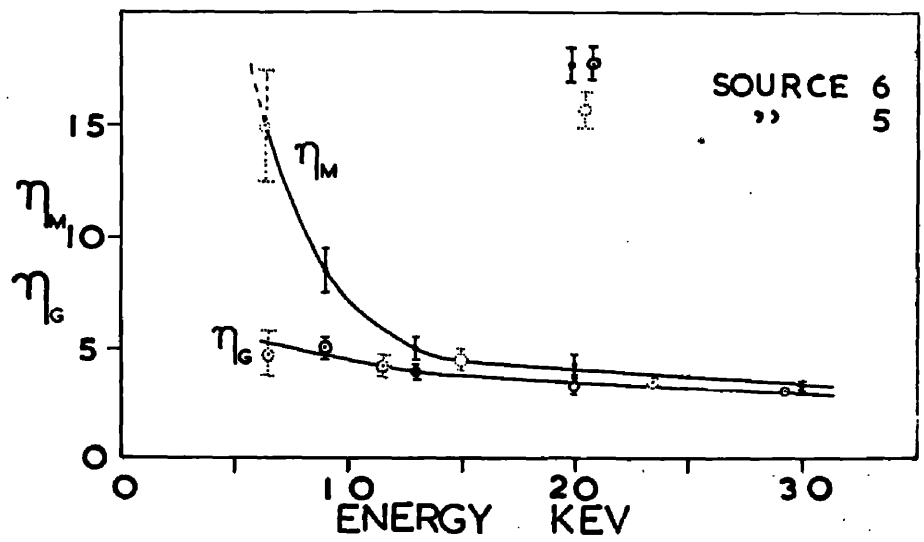


Figure 42 (a). The variation with primary energy of η_M, for platinum, and η_G at low energy. (Source 6).

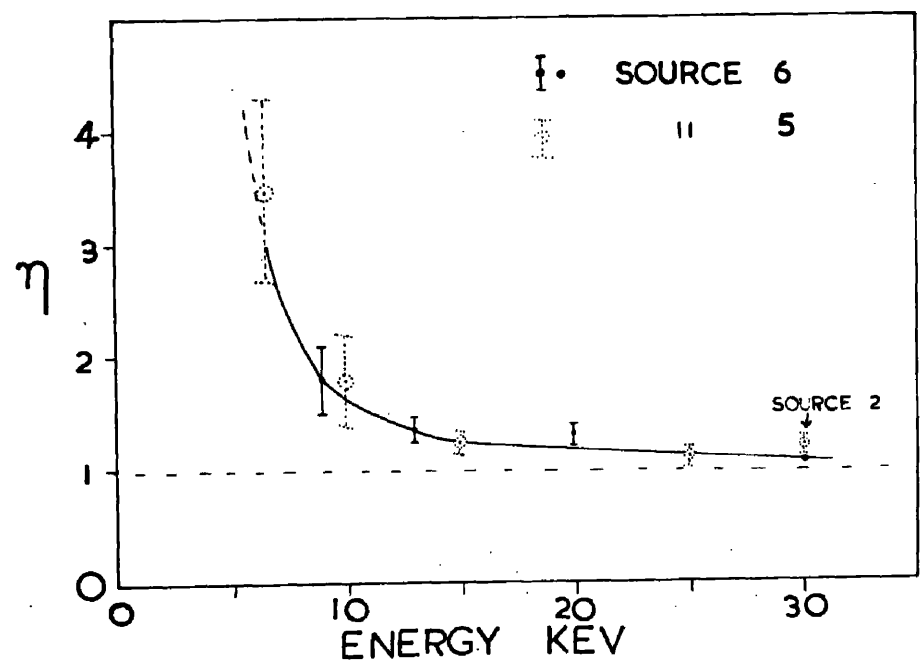


Figure 42 (b). The variation with primary energy of η, for platinum (Source 6).

are also shown. The results for η_M, η_G and η at high energies are shown in Figures 43 (a) and 43 (b). The variation of the S.E.C. of electrons and positrons with energy at low and high energies are shown in Figures 44 (a) and 44 (b), together with some results from other sources for comparison.

VI. 9. (3) Discussion of the results from the sixth source

The values of the relative S.E. were in good agreement with those obtained in the other experiments at low energy and at high energy, but not in the intermediate region. There was a definite discrepancy in that region, which was investigated. It was found that the discrepancy arose from small differences in the value of η_G obtained using the mica and nylon windowed Geiger counters. This is shown in Figure 43 (a). These differences in η_G were shown to arise from the unequal transmission of electrons and positrons through the mica window, when the particle range became of the order of the window thickness, and the transmission was strongly energy dependent. At higher energies the value of η_G was the same for both windows. The unequal transmission of electrons and positrons through thin targets has been observed by a number of workers, for example Bascova and Gorbachev [50], and Seliger [51]. No measurements on mica are reported. A detailed investigation of this phenomena was outside the scope of the present research.

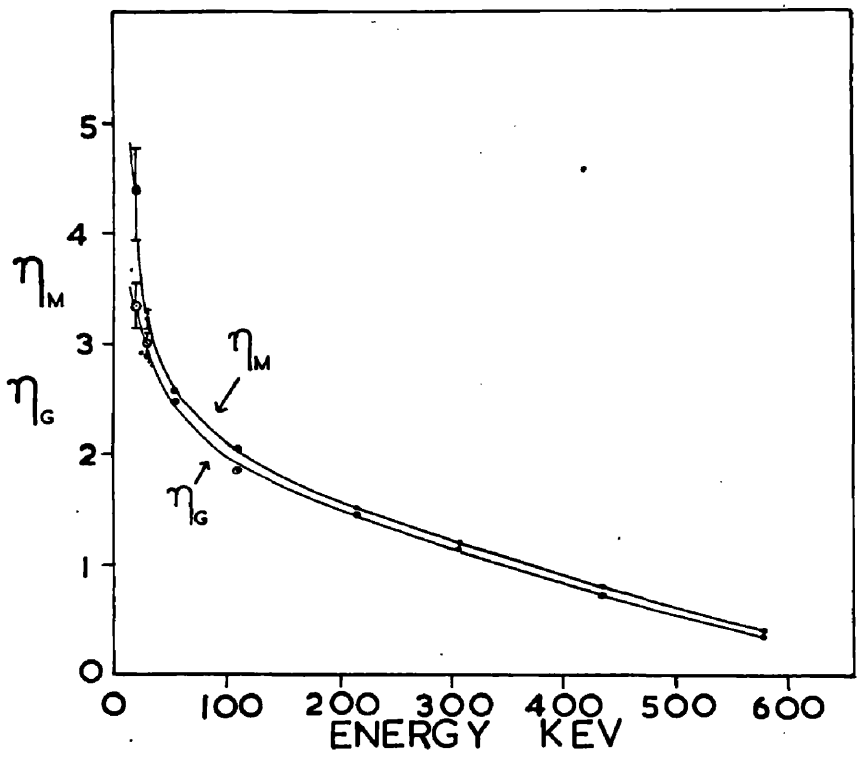


Figure 43 (a). The variation with primary energy of η_M, for platinum, and η_G at high energies (Source 6). The dotted line at energies ~ 20 - 30 KeV shows the value of η_G obtained with the mica windowed Geiger counter. The full line below ~ 40 KeV was obtained with the nylon window.

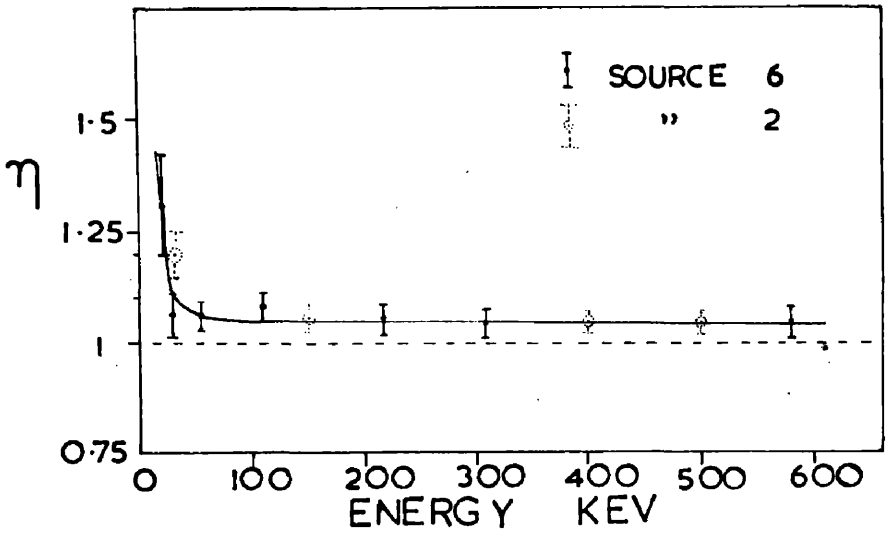


Figure 43 (b). The variation with primary energy of η, for platinum, at high energies. (Source 6).

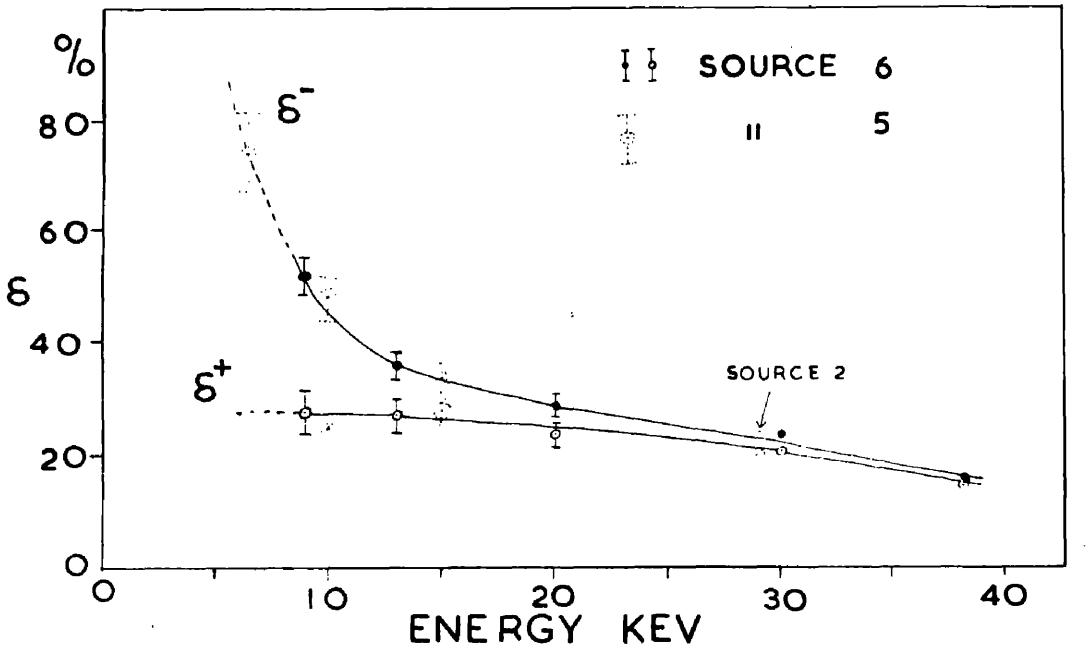


Figure 44 (a). The variation of δ^- and δ^+ with primary energy, for platinum, at low energies. (Source 6).

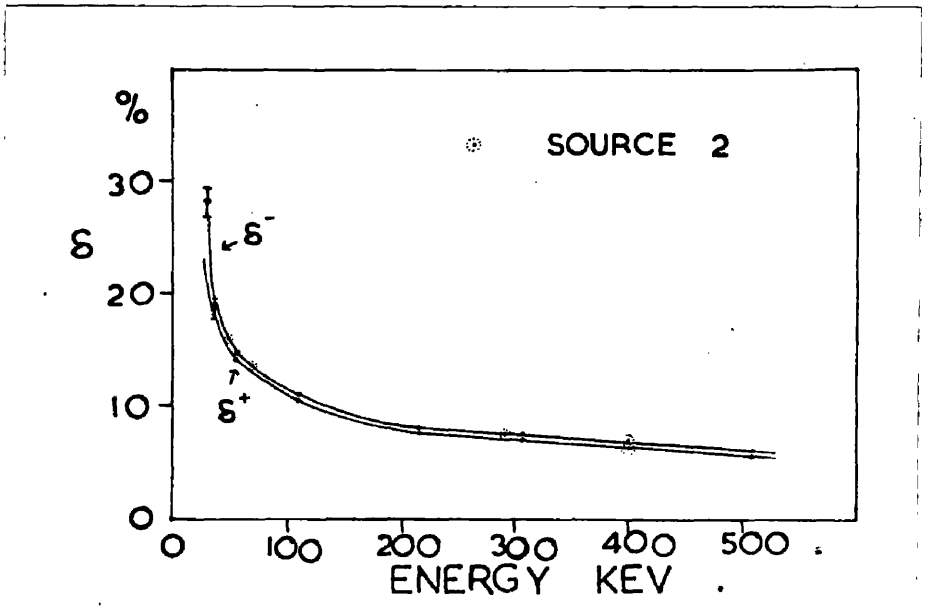


Figure 44 (b). The variation of δ^- and δ^+ with primary energy, for platinum, at high energies. (Source 6).

It has been assumed that the value of η_G obtained using the nylon window, which was thinner than the mica by a factor of the order of twenty, was correct below ~ 40 KeV. It was necessary to see if there was an error in η_G obtained using the nylon window at much lower energies, when the particle range was approaching the thickness of the nylon film. Two experimental observations did not indicate such an error. The first of these was the absence of any evidence for anomalous behaviour when using the nylon windowed counter, like that observed when using the mica window at energies in the range 20 - 30 KeV. The second observation was that the value of η_G at energies down to 4.5 KeV was the same within the statistical error for different thicknesses of nylon film. If there were any errors due to the unequal transmission of electrons and positrons this should lead to variations in η_G with window thickness.

The results for δ^- and δ^+ obtained with this source are in fair agreement with the earlier experiments. At low energy δ^+ appeared to be roughly constant, rather than a decreasing function of decreasing energy as indicated by the measurements made with the fifth source. The mean values for a platinum target of η, δ^- and δ^+ from all the sources at low energy will be given after the section on systematic errors. The final

curves at high energy are so close to those already shown in Figures 43 (b) and 44 (b) that they will not be reploted.

VI. 10. Experiments with the seventh source

VI. 10 (1) General. This was the last experiment, and measurements were made with a copper-beryllium target, in order to improve on the accuracy of results from the first source, and to extend measurements for this material to low energy. It was considered worthwhile to compare results from two different targets, even though it was realised that the statistical error on one experiment would be large and no small differences in the behaviour of the two materials could be detected. Values of $\delta -$ and $\delta +$ were obtained in addition to relative measurements. Data obtained with the seventh source did not extend to the high energy region, because of a breakdown in the field measuring system. The small rotating coil went open circuit, and it was not possible to wind a replacement before the source became too weak to use.

VI. 10 (2) Results. The variation of η with energy is shown in Figure 45, which includes some points obtained with the first source for comparison. There appeared to be a discrepency between the value of η obtained in this experiment, and the value found using source one. However, as the statistical errors associated with the results obtained with the first

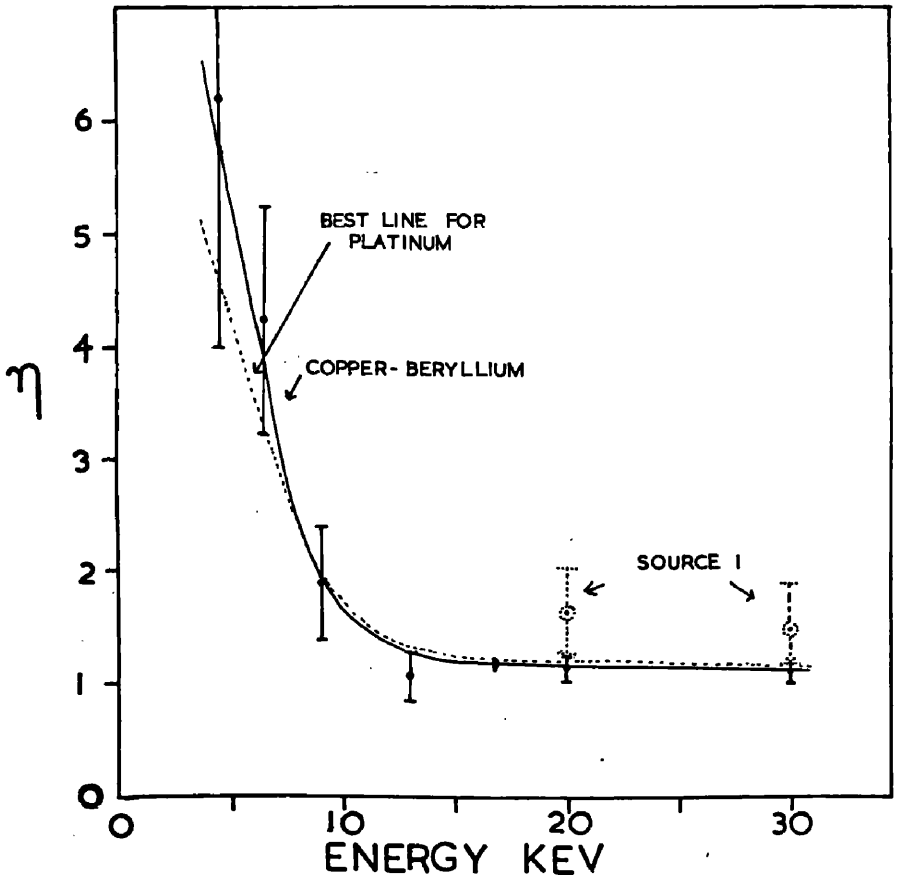


Figure 45 (a). The variation with primary energy of η, for copper-beryllium, at low energies. (Source 7).

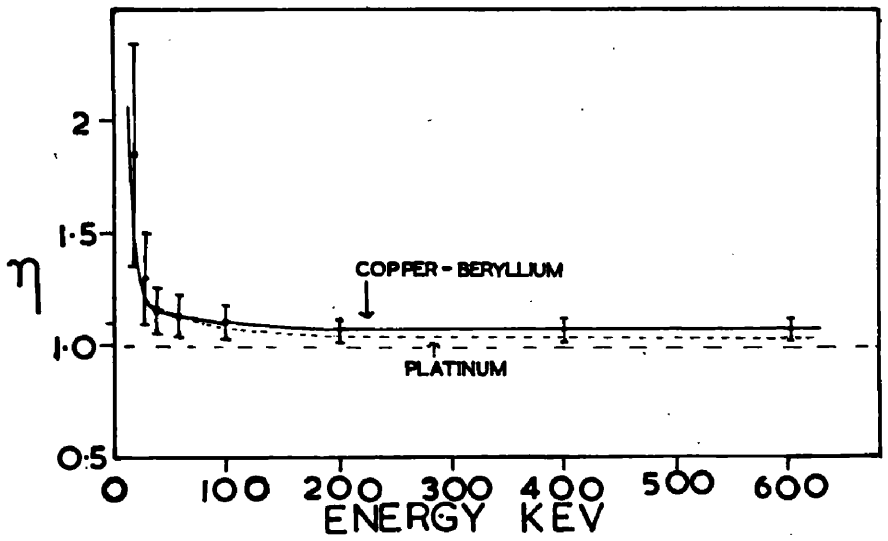


Figure 45 (b). The variation with primary energy of η, for copper-beryllium, in the high energy region. Obtained from Sources 1 and 7. The best line for platinum is shown dotted for comparison.

source were very large, and several improvements in technique were included after the first experiment, the values obtained with source seven were much more reliable. The best results for platinum are shown by a dotted curve. Figure 46 shows the values of the S.E.C. obtained; some data for platinum is also included for comparison.

VI. 10 (3) Discussion. The results for relative S.E. were the same for platinum and copper-beryllium within the statistical error. The significance of this from the point of view of the interpretation of the results will be discussed in Chapter VII.

The shape of the yield curve for copper-beryllium was also similar to that for platinum, although the value was lower. There was no tendency for the former curve to approach the latter as energy was decreased, and so the cross over mentioned in Section VI. 5. (3b) must occur at an energy less 5 KeV, probably 1 - 2 KeV.

VI. 11 Systematic Errors

VI. 11. (1) General Considerations. In the introduction to this Chapter the importance of examining the possibility of systematic errors was pointed out. The investigation was carried out with the last four sources and two additional sources. Many factors were examined, but only two were found to introduce any appreciable error. The first of these was

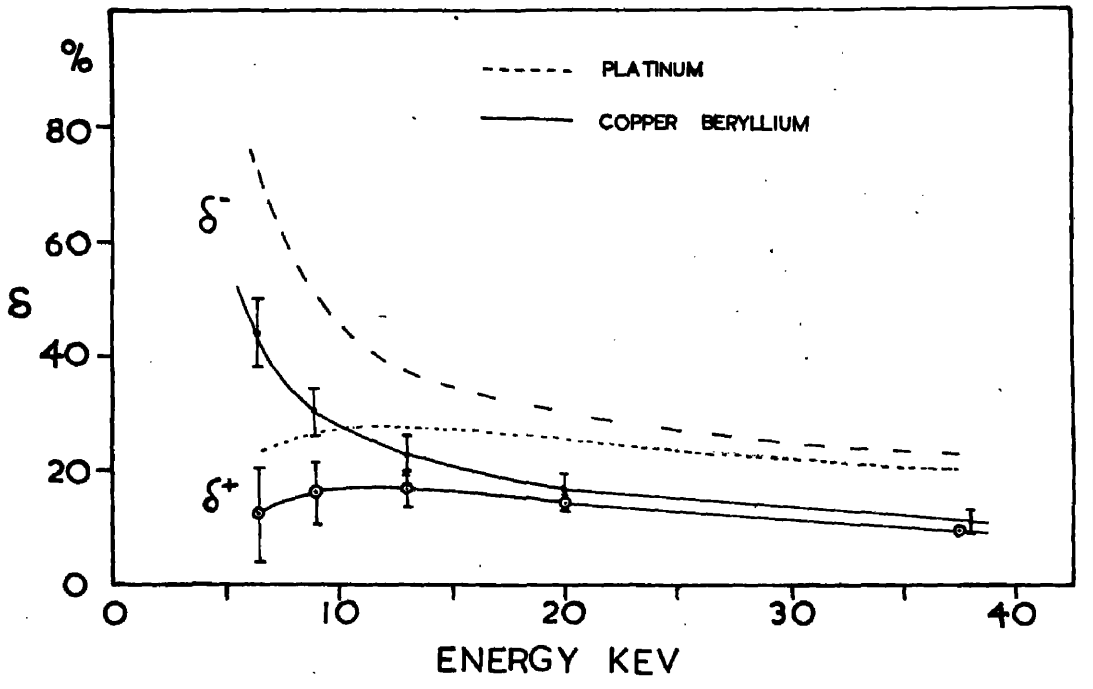


Figure 46. The variation of δ^- and δ^+ with primary energy at low energies for copper-beryllium. (Source 7). The best line for platinum is shown for comparison

the error which arose at high energies from primary particles scattered from the first dynode. This was quite straight-forward and was measured in the preliminary experiments described in Sections III. 3. (7), and IV. 5.(1). It will only be referred to very briefly in this section. The other error was the background error, which is rather involved and will be considered in some detail.

The use of a "comparison method", in which the relative S.E. of electrons and positrons was measured, caused most factors which might have introduced errors to cancel out. The search for errors was largely an investigation of any instrumental factors which would be different for the two types of particle. The corrections determined for the error arising from primaries reflected from the target was directly applicable to the values of the S.E.C. of electrons and positrons. For the background error, the correction was applicable to η, the relative S.E., but it will be shown that most of the error in fact arose in the positron measurements, so as a first approximation it was assumed that δ^- was correct and δ^+ was subject to the same error as η. This approximation does not affect the comparisons already made between the results of the Author and those of other workers, because in the region where the measurements were compared ($\gtrsim 20$ KeV), the background error was becoming small.

In the remainder of this section a very brief summary of the more important factors which were investigated will be given. This will be followed by a slightly more detailed account of the background error; in conclusion, the final corrected results and the estimated probable errors will be given.

VI. 11. (2). The possibility of an error in the magnetic field.

An error in the magnetic field was considered unlikely in view of the method of field measurement used. However, it was realised that, as the S.E.C. of electrons is a steeply rising function of decreasing energy, a small error in the magnetic field could produce an apparent excess of electron S.E. over positron S.E. Such an error would arise if, on reversing I, the magnetic field was not exactly reversed, but was weaker in the direction required to focus electrons. This would mean that the S.E.C. of electrons of a certain energy was being compared to that of positrons of a higher energy, and so the S.E.C. of electrons would appear to be greater.

Examination of the form of the curves of δ^- and δ^+ against energy at low energies did not suggest a magnetic field error. If there was such an error, in the direction necessary to produce large values of η, then the two yield curves should be approximately parallel, but with the positron curve displaced to lower energy relative to the electron curve. Therefore the

rapid rise in δ^- which was observed with decreasing energy should also be observed for δ^+, except at an apparently lower energy. Figures 41 and 44 (a) showed no evidence for such a rise in the positron yield curve, even at energies much lower than those at which the rise in the electron curve became steep. A further factor in favour of making a very careful check on the field measurement was the discrepency observed in η_G, pointed out in Section VI.9.(3). Such a discrepency would have been produced by a magnetic field error in the direction to make η appear too large.

A very careful experiment on the field reversal was carried out, in which the magnetic fields produced by reversing I were measured with a ballistic galvanometer; the spectrometer was removed from between the magnet poles and the ballistic galvanometer search coil placed in the centre of the gap. This experiment showed no significant discrepancy, and the result was quite independent of the previous history of the magnet, so no peculiar hysteresis effects could be present.

VI. 11. (2a) <u>The possibility of an error due to positron annihilation radiation.</u> A factor which might have introduced an error was the effect of the 0.51 MeV quanta produced by the comparatively large flux of positrons which annihilated in the vicinity of the counter e.g. on collimating slits, when these particles were

being focused. The effect of these quanta in the multiplier could be neglected as its efficiency for such radiation was only $\sim 10^{-4}$ (See Section III. 3. (5)). These γ-rays could, however, affect the Geiger counter, whose efficiency for such radiation was $\sim 10^{-2}$. This would have made the measured positron count rate larger than the true count rate, because a contribution would have been included due to the annihilation radiation from positrons which did not enter the counter. Thus the measured values of η_c would be smaller and η larger than the true values. An error which arose in this way would have been independent of energy, and so could not have produced the large values of η observed at low energy. It might have introduced a discrepancy at high energy.

An experiment was carried out to see if any appreciable error arose from the annihilation radiation. The Geiger counter count rate was measured for positrons of a fixed energy with the counter window covered by a brass plate 1/16" thick, and then as usual. In practice, to obtain comparable count rates the first measurement was made about seven source half-lives before the other, and corrected for the half-life. The count rate with the window covered arose from γ-rays which were produced by positrons which would normally have entered the counter, and also from γ-rays produced by positrons which annihilated in the spectrometer near

the counter. It was the latter group which would have contributed to an error. The measurements showed that the count rate with the window covered, was $\sim 0.6\%$ of the positron count with the window uncovered. This was just about the contribution to be expected from the positrons which would normally have entered the counter. The other contribution, which would have given an error, was certainly less than 0.2% and could be neglected compared to the lowest statistical error of 2% in η .

It should be noted, as shown in Chapter II, Part 1, that the actual secondary yield produced by the radiation which arose from positrons which annihilated in the target, without giving secondary electrons, was negligible. It was shown to be $\sim 10^{-4}$.

VI. 11. (3). <u>The possibility of an error produced by the electric field between the first and second multiplier dynodes.</u> The primary beam must pass through the electric field between the first and second dynodes before hitting the target. The potential, V, on the second dynode was 500 volts, and in the electric field produced by V slow positrons and electrons would be deflected, in opposite directions, before hitting the target. It was shown in Section III. 3.(6) that the position of the first dynode was critical, and so the point of impact might also be very important. Calculations gave a deflection $\sim$ 0.1 mm. in the energy region 10 - 20 KeV, which can probably be neglected. At energies $\sim$ 5 KeV, the

deflection would approach $\sim \frac{1}{2}$ mm., which might have an effect. If these deflections increased the efficiency of detection of secondaries produced by electrons or reduced that for positrons, values of η_M and therefore of η which were larger than the true values, would be obtained.

In order to examine this effect, values of η_M were measured in which V was 250 volts, 500 volts (normal) and 1,000 volts, all other potentials on the multiplier being unaltered. A correction was made for the resultant variation in the gain of the multiplier. If the high values of η_M were produced by the voltage V, then at V = 1,000 volts much greater values would be expected, and smaller values at V = 250 volts. A small effect showing exactly the opposite was found. It was thus established that the high values of η_M did not arise from errors introduced by the voltage V, but the variation of η_M with V remained to be explained. Other measurements showed that the change in V only affected the positron count rate, and not the electron count rate. This suggested that the observed effect might be associated with the background error and the probable explanation for it will be given later (Section VI. 11. (6c)).

VI. 11 (4) <u>The possibility of the spectrometer magnetic field affecting the multiplier.</u> Electron multipliers are sensitive to small magnetic fields, and so although the measured fringing

field at the multiplier was found to be negligible, even for the maximum spectrometer field, a control experiment was carried out to see if the spectrometer field affected the multiplier. No effect was found for fields of twice the maximum value which had been used.

VI. 11. (5). The error arising from primary particles scattered from the first dynode. A correction for this effect was worked out in Section IV. 5. (1) for the case of high energy primaries on a copper-beryllium target. In this section the correction for platinum will be found, and the correction for both targets extended to lower energies.

The correction for platinum at high energies was determined in exactly the same way as described in Section IV. 5. (1) for copper-beryllium. Again, the results of Seliger [52] on the relative backscattering of electrons and positrons were assumed, together with the data given in Section III.3.(7) on R, the ratio of the efficiency of the multiplier for reflected electrons to that for secondaries. The value of the corrections to be subtracted from η_m at high energies was 4%. The corrections to be subtracted from δ^- and δ^+ were determined in the same way.

The corrections varied with energy as R, and the values of the corrections to be applied to η at different energies, for platinum and copper-beryllium, are shown in Table 5. The

TABLE 5.

Corrections, which have been subtracted from the observed values of η_M and η, due to primary particles scattered from the first dynode. The estimated uncertainties in the corrections are given.

Energy KeV	Correction %	
	Platinum	Copper-Beryllium
<20	$\simeq 1 \pm 0.2$	$\simeq 0.5$
30	2 ± 0.25	1.5 ± 0.1
50	3 ± 0.5	2 ± 0.25
100	3.5 ± 0.5	2.5 ± 0.3
150	3.5 ± 0.5	2.5 ± 0.3
>200	4 ± 0.5	3 ± 0.3

uncertainties in the corrections to be applied to η at different energies are given in the table. These uncertainties were important, because, although the correction itself was small, it was comparable with the excess of electron S.E. over positron S.E. observed at high energies. The uncertainties mainly arose from the values of R; the accuracy of the value of R at high energy was considered in Section III. 3. (7), and the figure given there has been assumed. It was found that the maximum error in $\frac{N}{M}$ and hence in η which was likely to arise from these uncertainties was $\sim \frac{1}{2}\%$. This did not have much effect on the value of η. A further error in the correction could have arisen if the results of Seliger were inaccurate, but an error $\sim 30\%$ in these results would only introduce errors $\sim 1\%$ in the correction.

VI. 11. 6. The Background Error

VI. 11. (6a) How the background error arose. When the spectrometer was set up to focus electrons or positrons of a given energy, the following different groups of particles actually reached the detector:- (1) Electrons or positrons of the required energy, with a count rate denoted by N. (2) Particles of both signs from all the rest of the electron and positron spectra, which had been scattered from the walls of the spectrometer in order to reach the counter. This group was called the "scattered background" and is denoted by B_s. (3) The natural background, B_o.

This arose largely from cosmic rays and thermal emission at the first dynode, but also included the background produced by direct γ-rays from the source. The required count rate, N, was given by $N' - (B_o + B_s)$ where N' is the observed count rate for a given field setting, including the background. B_o was independent of magnetic field (this was checked experimentally) and could be measured and the appropriate correction made. B_s could not be measured directly, and varied with the magnetic field for the following reason. At any field, particles which had a radius of curvature in that field of the same order of the radius of the spectrometer tubes, would be curled up by the field and unable to reach the detector, even after being scattered from the walls. Thus the value of B_s would tend to decrease as the magnetic field was increased. A first approximation to $B_o + B_s$ was the background for zero magnetic field, but the true value at other fields was less. This approximation is valid if $N \gg B_s$, i.e. at medium and higher energies. At low energies, where $N \lesssim B_s$, errors in the count rate arose. As the energy was reduced, B_s tended to its value at zero field, but the count rate became much less than B_s, so a small error in B_s introduced an appreciable error in the count rate. An idea of the relative values of B_s, and the count rates at low energy can be obtained from Table 6 which shows values of γ; γ is defined above

TABLE 6

Values of γ at low energies. γ is defined as the ratio of the count rate (corrected for zero field background) to the scattered background, B_S, expressed as a percentage.

Energy	Multiplier		Geiger Counter	
KeV	Electrons γ^-_M %	Positrons γ^+_M %	Electrons γ^-_G %	Positrons γ^+_G %
6.5	490	30	130	20
10	475	60	185	35
15	700	120	300	70
20	960	193	390	118
30	2000	400	600	250

the table. The experimental method for separating B_o and B_s will be given later. The corrected count rate was less than B_s if $\gamma < 100$, and errors in B_s became important.

At first it might have appeared that any errors would have arisen in both the multiplier and Geiger counter data, and therefore have tended to cancel each other in the final ratio, $\eta = \eta_M/\eta_G$. This was not so and an error in η did arise. This error arose because the error in B_s was much more important for the multiplier positron measurements, than for any other measurements. If a comparable error had arisen in either the multiplier electron data, or the Geiger counter positron data, these errors would have tended to cancel and the final error would have been small. It will now be shown why the error due to B_s was only large for the positron measurements in the multiplier.

B_s contained particles of all energies, and the slowest particles, (largely electrons, as $\eta_G \sim 5$ at low energies) would be very efficiently recorded by the multiplier, but would not enter the Geiger counter at all, because of the nylon window. It was just this very slow component of B_s which was most likely to be affected by the magnetic fields required to focus low energy particles. Thus, at low energy, where it was shown that an error in B_s would have the most effect, such an error was

greatest for the multiplier measurements. For low energy multiplier data on positrons, γ^+ is small i.e. $N^+ \angle B_s$, and there was an appreciable error. For low energy electrons γ^- was large, and so there was only a small error, which tended to cancel the error in the positron measurements. For the low energy Geiger counter data, the window removed the particles most likely to introduce errors, but for positrons γ^+ was again small and there was some error, also tending to cancel the error in the multiplier positron measurements. At low energies the error in B_s would depend on how many very slow particles there were in B_s.

VI. 11. (6b). Some General considerations regarding the background error. Before considering experimental methods of determining the background correction, an estimate of the error in B_o required to account for the observed differences in the S.E.C. of electrons and positrons was made from the values of γ given in the table. It was found that below $\sim$ 20 KeV an error $\sim$ 50% in B_s was required; above $\sim$ 20 KeV a much greater error was necessary. Although the error in B_s increased with field, so did γ, and at $\sim$ 20 KeV γ became large and the effect of the error in B_s was small.

Some general considerations indicated that such a large error was improbable. Firstly, the Geiger counter spectrum

showed that only a few per cent of all the particles in the β^- and β^+ spectra have energies $\lesssim$20 KeV and therefore B_s was largely composed of high energy particles. Secondly, high energy particles had a greater chance of being reflected from the walls of the spectrometer, because the reflection co-efficient increased with energy (See Section I. 3. (2)). To offset these points it must be remembered that the multiplier was very sensitive to slow particles, and as measured by this counter an appreciable faction of B_s could have arisen from low energy particles.

Although it seemed unlikely that the large values of η which were observed arose from a background error, such an error would probably have some effect on the result, and it was important to investigate this experimentally and determine a correction. After the first source experiment, when the possibility of a background error was realised, the spectrometer was dismantled and fitted with much more efficient baffles to reduce scattering from the walls.

VI. 11. (6c). Experimental Investigation of the Background Error. Many experiments were considered, and some tried unsuccessfully. A basic drawback to most of the proposed methods was the lack of particles; three experiments yielded useful results. The object of these was basically to determine the

number of low energy particles in the scattered background and to estimate how B_s varied with energy. A correction was deduced from this. There did not seem to be any feasable experiment by which the correction could be measured directly.

The first experiment arose from an attempt to fit a 'gate' in the spectrometer, consisting of an electrostic lens which would stop particles of energy less than a given value from reaching the detector. This approach failed because the applied field in either direction caused the multiplier to behave very erractically, and the natural background increased by up to an order of magnitude, presumably due to stray ions, or to electrons (possibly produced by field emission) which were accelerated down the tube to the first dynode. A modification consisted of two electrostatic deflector plates outside the spectrometer glass tube, one above and one below, about 20 cms from the target; the electric field produced would bend the slow particles in B_s away from the collimating slit, while not affecting the high energy component. This experiment, although rather crude, did give results. It was found that an applied potential across the plates from 500 - 3,000 volts caused a greater decrease in the value of B_s when measured with the multiplier than with the nylon windowed Geiger counter. This indicated that a greater faction of the background arose from slow particles

for the multiplier than for the Geiger counter. By calculating the expected deflection of particles produced by the applied field (taking into account the fact the plates were outside the glass tube), an estimate of the low energy component of B_s in the multiplier was made. The figure obtained was between 5 and 25%, probably between 10 and 15%; there was some evidence that this component was of very low energy $\simeq$ a few KeV.

A very important addition to the apparatus for all the correction experiments was a moveable shutter in the spectrometer, just in front of the final slit. This could be operated without breaking the vacuum. When the shutter was closed no particles could pass down the tube and B_o was obtained. B_s is equal to the count rate with the shutter open, minus B_o.

The second method for estimating the low energy component of B_s consisted of using data already obtained to find the mean S.E.C. of B_s, and also to compare values of the B_s obtained with the two Geiger counters. The average S.E.C. of B_s was of the order of that of 30 KeV electrons. This suggested that an appreciable fraction of the multiplier background probably arose from low energy particles. A very rough estimate placed this fraction at between 10% and 30%. By comparing the values of B_s measured with the two Geiger counters it was found that

the nylon windowed counter detected ~ 40% more counts than the mica windowed counter. This suggested ~ 40% of B_s lay between a few KeV and ~ 30 KeV, which is higher than other experiments indicated, but included many particles whose energy was too high to contribute much to the background error.

The third and most fruitful method of investigating the background was, in principle, to examine the scattered background from a source which only emitted electrons, with the magnetic field in the direction required to focus positrons. A gold 198 source of comparable thickness to the copper 64 sources was used, and the scattered background measured with the multiplier and the nylon windowed Geiger counter. This gave at once fair estimate of the way B_s from the copper sources (assuming B_o was largely electrons at low energy) varied at low "positron fields". The gold spectrum was similar to the copper 64 electron spectrum but extended to rather higher energy. This means that the correction would be underestimated, because there will be relatively fewer slow particles in the gold spectrum. The curves obtained are shown in Figure 47; σ, which is defined under the figure, is effectively the value of B_s at "positron fields" expressed as a percentage of the value at zero field. It is seen that, as expected, the scattered background in the multiplier fell off faster than in the Geiger counter as the

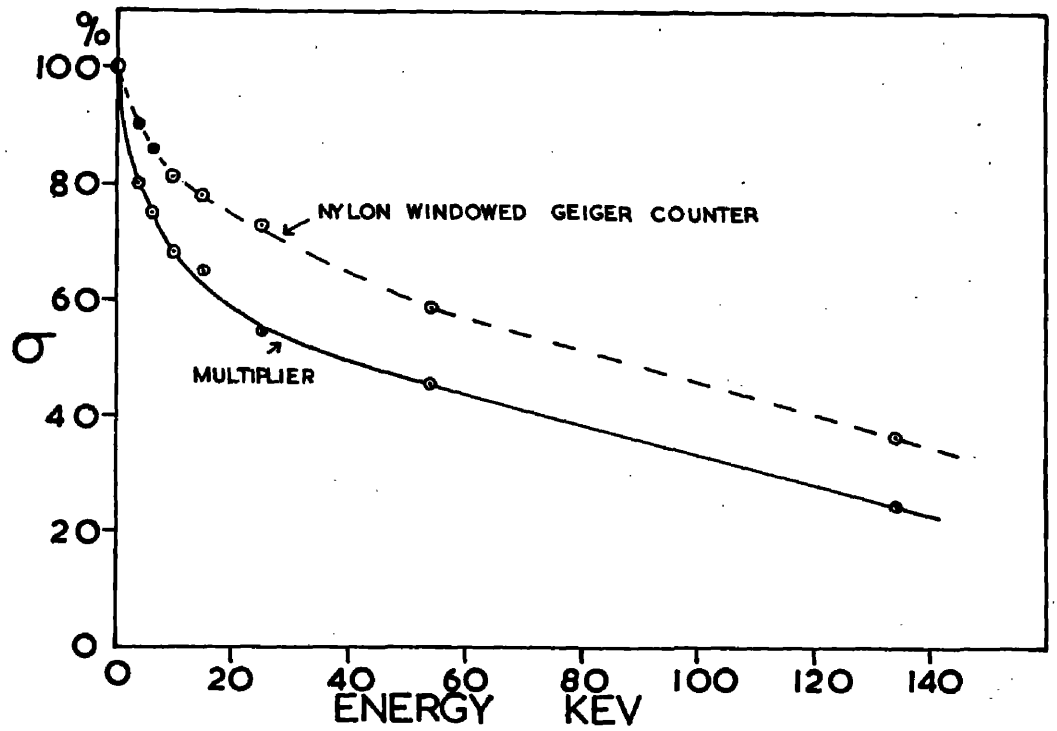


Figure 47. The variation with the "equivalent positron energy" of σ, for the multiplier and the nylon windowed Geiger counter; obtained using a gold 198 electron source. σ is defined as the ratio, expressed as a percentage, of the count rate at "positron fields" to that at zero field; the natural background is subtracted from each.

"positron field" was increased. The difference due to the low energy component was ~ 10-20% in the region of interest. Again there was some evidence that the difference was probably produced by very slow particles.

This measurement really gives the relative contribution of low energy particles to the multiplier background compared to the background in the nylon windowed Geiger counter. It was assumed that the error in B_s in the multiplier was approximately the difference between the two curves in Figure 47 and so any background error in the Geiger counter positron measurement was also taken into account.

In this discussion it has been assumed that the error in the background in the experiments with copper 64 arose largely from the electron component of the background. This assumption was justified, because the type of errors considered would arise largely from the slow particles in the background, and these were mostly electrons, because η_c was ~ 5 at low energies.

There was one further piece of evidence which agreed qualitatively with the above considerations on the background error. This was the discrepancy observed in η_H when the potential, V, between the first and second multiplier dynodes was varied (See Section VI. 11. (3)). It was found that η_H was smaller when V = 1,000 volts than when V = 500 volts and larger when V = 250 volts.

Further measurements established that this difference was produced by a variation in the positron count rate. This probably arose from a change in B_s produced by altering V. If V was increased the very slow component of B_s would be bent away and not fall on the target. This would make B_s at zero field with V = 1,000 volts smaller relative to the value at V = 500 volts. Hence at V = 1,000 volts the positron count would appear too large and η_M too small, as observed. Although there was insufficient data to confirm the variation of B_s with V, the above explanation leads to results for the variation of η_M with V of the order of magnitude observed.

VI. 11. (6d). Final Assessment of the Background Error.

All the evidence presented above, together with a few further considerations led to the values of the error in B_o, ε, at different energies given in Table 7. By considering all the different methods of obtaining a value of ε the estimated probable uncertainty in ε was found, and is given in the table. The corresponding correction, μ, to be subtracted from the measured values of η_M and η is also given in the table, together with the estimated probable uncertainty in η, $\delta\eta$, arising from the background correction. μ was equal to $100\,\varepsilon / \gamma_M^+$ where γ_M^+ was defined in Table 6.

It should again be stressed that the value of ε

TABLE 7

Values of the error in Bs, ϵ, together with the estimated uncertainty in ϵ. The appropriate corrections, μ, to be subtracted from the measured values of η are shown; μ is expressed as a percentage of the measured values of η. All the results have been corrected by μ, and the final column gives the estimated probable uncertainty in η, $\delta\eta$, arising from the background correction. $\delta\eta$ is expressed as a percentage of the final values of η; a minus sign indicates that the lower limit of η is obtained by subtracting $\delta\eta$.

Energy KeV	ϵ %	μ%	$\delta\eta$%
6.5	10 ± 4	33	± 20
10	13 ± 5	22	± 10
15	16 ± 6	13.5	± 6
20	18 ± 7	9.5	± 4
30	25 ± 15	6.3	± 3
50	~33	~2	-

determined assumed that the background error was largely important for the multiplier positron measurements. The basis for this assumption has been given. There was probably some error in the positron Geiger counter data, as δ_c^+ was small at low energies, but this has been taken into account by the way the correction was determined. The first and last methods described essentially measured the effect of the background error in the multiplier, compared with the Geiger counter. Any errors in the electron data will probably be small compared with the errors in the positron data, and in any case would tend to cancel in the final value of η. The background error was only invesitgated in detail for platinum target. However, as the general form of the results for platinum and copper-beryllium at low energies was similar the corrections would probably be approximately the same; the value found for platinum has been used for copper-beryllium.

VI. 11. (7). Systematic Errors - Conclusion. The Final Results.

The overall correction which has been applied was the sum of the corrections due to scattered particles at the first dynode and the background error. The total error was the sum of the statistical error and the probable uncertainties in the corrections; these have been added because the uncertainties in the corrections were not random errors.

Table 8 gives the final results for η with the errors, for a platinum target. The final curve of η against energy at low energies is given in Figure 48. Figure 49 gives the final results for the S.E. coefficients of electrons and positrons at low energy. The overall errors are shown, and as a first approximation it has been assumed, as pointed out in Section VI. 11. (6a), that the background error lies in the positron measurements, and δ^+ has been corrected by the same percentage as η ; the final error in δ^+ was found in the same way as for η. The shape of the curve of δ^- against energy was as expected; the shape of the δ^+ curve was rather strange, and indicated a slight fall in δ^+ with decreasing energy. It is not possible to say if this is genuine, as the corrections to δ^+ were only approximate estimates.

There were two main observations from the final results for η. The first of these was the existence of a small excess in the S.E. of electrons over that of positrons at high energy, which probably lies between 2% and 6%. In this energy region the difficulties associated with the low energy measurements were absent, and the background error was very small because B_s was only a few per cent of the count rate. Thus the observed difference in the S.E. of electrons and positrons was probably quite genuine. It is, of course, always hard to be

TABLE 8

The final results for the relative S.E. of platinum, from all sources; obtained from the graphs of η against energy. The overall statistical error (St.E.), the probable uncertainties in the corrections (U) and the total errors (T.E.) are shown.

Energy KeV	η	St.E.	U	T.E.
6.5	3.25	± 15% 0.5	± 20% 0.65	± 35% 1.15
10	1.68	± 9% 0.15	± 10% 0.17	± 19% 0.32
15	1.25	± 4% 0.05	± 6% 0.075	± 10% 0.125
20	1.20	± 4% 0.05	± 4% 0.05	± 8% 0.1
30	1.14	± 4.5% 0.05	± 3.5% 0.04	± 8% 0.09
50	1.07	± 3% 0.03	± 0.5% 0.005	± 4% 0.04
100	1.04	± 2% 0.02	± 0.5% 0.005	± 2.5% 0.025
200	1.04	± 2% 0.02	± 0.5% 0.005	± 2.5% 0.025
300	1.04	± 2% 0.02	± 0.5% 0.005	± 2.5% 0.025
400	1.04	± 2% 0.02	± 0.5% 0.005	± 2.5% 0.025
500	1.04	± 3% 0.03	± 0.5% 0.005	± 3.5% 0.035.

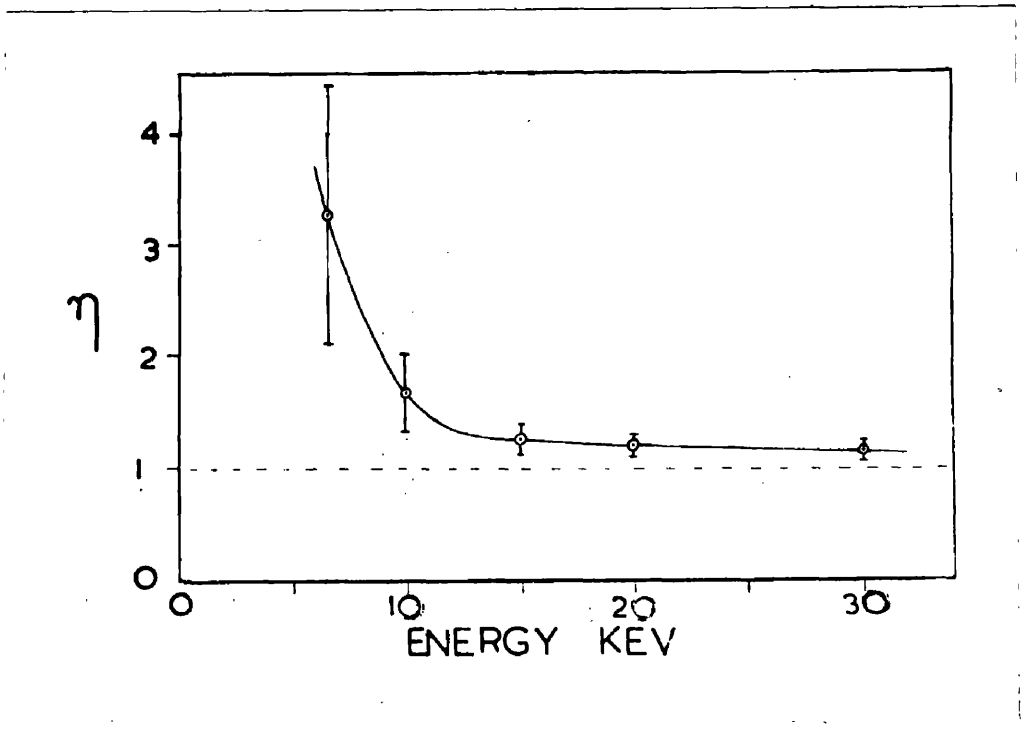


Figure 48. The variation with primary energy of the final value of η, for platinum, at low energies. (Obtained from all sources). The total errors are shown.

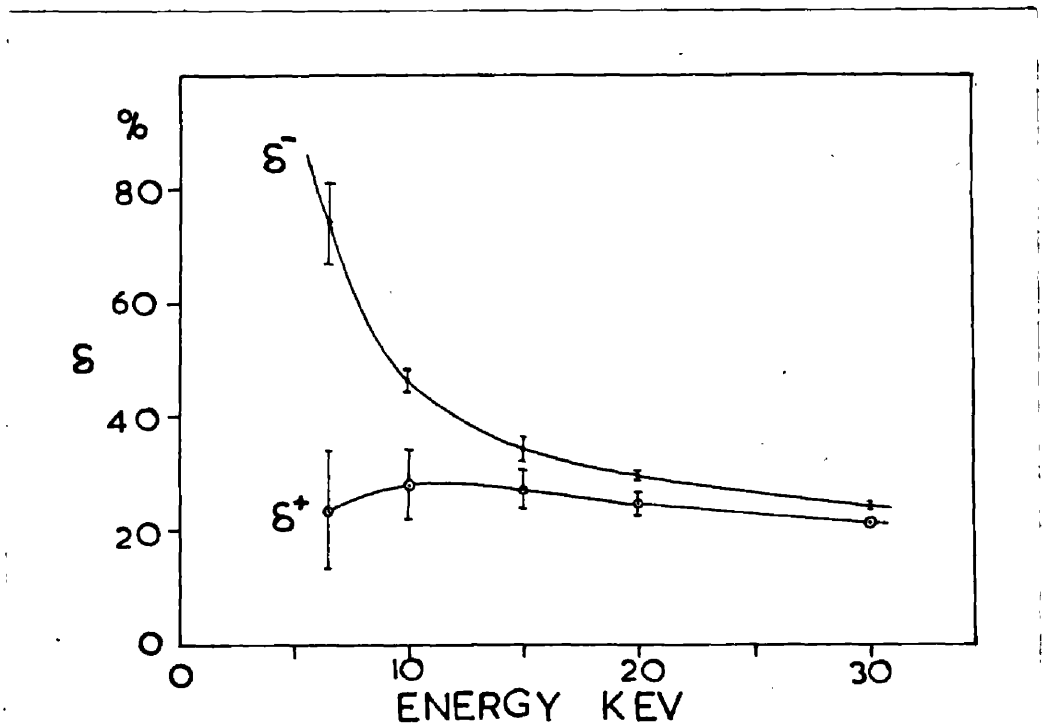


Figure 49. The variation with primary energy of the final values of δ^- and δ^+ for platinum at low energies. The total errors are shown.

certain of a small effect without repeating the measurements using a different experimental arrangement.

The second observation was that at low energy a substantial increase in η was found which was much greater than the maximum uncertainty in the results. In this region, however, there were many difficulties in the measurements; in particular the fact that the count rate was often much less than the background. The background error was investigated as thoroughly as possible, but it must be stressed the final correction was an estimate, and not an exact measurement. The estimate was made from four quite different experiments, all of which gave approximately the same values of the corrections, so it should be fairly good.

In the low energy range only the background error, of all the errors investigated, had an appreciable effect. It is not possible to say that there were no other factors which introduced errors, but the Author has attempted to carry out as thorough an investigation of instrumental errors as possible, and only a further experiment with a different geometry would finally settle the matter. The importance of repeating the measurements, especially at low energies, with a different experimental arrangement was fully realised, and some alternative approaches were considered. There was however, insufficient time to undertake a new experiment with a different method, and a few

hastily made measurements would not be of much value.

In any further experimental work, a spectrometer with the maximum transmission should be used, in which particular care is taken to eliminate scattering from the walls, so that no confusion between wanted and unwanted particles can arise. The use of a comparison method does seem to offer advantages, but it would be better to use two sources, one giving electrons only and one positrons only, which could be interchanged; this would remove any possibility of detecting electrons when examining positrons. The difficulty would be to obtain a sufficiently strong β^+ emitter. It is essential to use a very strong β^+ source in order to get sufficient positrons at low energies. Other possible improvements include the design of a multiplier with a larger first dynode, to increase the collection efficiency and the use of a coincidence method with the positron decay radiation, if copper 64 had to supply the positrons. As will be pointed out in Chapter VII, information on the energy distribution of the outgoing particles, both fast and slow would be extremely valuable, and future experiments should attempt to include such measurements.

CHAPTER VII

DISCUSSION AND TENTATIVE EXPLANATION

VII. 1. Introduction

In this Chapter the results for the relative S.E, η, of electrons and positrons will be discussed. Firstly, a simple theory to explain the small differences observed at high primary energies will be suggested; this is semi-quantitative and predicts values of η of the right order of magnitude. Some more tentative suggestions, which might perhaps qualitatively explain the results at low energies, will then be given.

At the time of writing there is no theoretical work on S.E. for primary energies of greater than $\sim$ 2 KeV, even for electrons, which might act as a guide in the interpretation of the results for positrons. For energies greater than $\sim$ 20 KeV work has been done on positrons, for example on scattering (both multiple and single), which has in general confirmed theory; with the exception of Seliger's [52] measurements on the backscattering of positrons, none of the other work seems relavent to the S.E. of the particles. At energies between $\sim$ 5 and 20 KeV there do not appear to be any relavent measurements on positrons, and practically none on electrons.

VII. 2. A Proposed Interpretation of the Results at Primary Energies from 50 to 500 KeV.

VII.2.(1) Theoretical Considerations. In the absence of any detialed theory on the mechanism of S.E. at high primary energies, it seems reasonable to suppose that the S.E.C. will be proportional to the energy loss of the particles, dE/dx. A secondary which can escape must be produced very near the surface of the target, so a primary normally produces observable secondaries as it enters the target; also, as pointed out in Section I.1.(3), primaries which are scattered inside the target, and emerge again, can liberate secondaries as they leave the target.

It follows that the S.E.C., as defined in Section I.1.(3) *(See footnote), is given by:

$$\delta = K(zE)\ (dE/dx)\ (1 + \delta_R) \quad \ldots\ldots\ldots\ldots \text{VII} - (1)$$

where δ_R is the reflection coefficient and K (zE) is a factor depending on the material and possibly on the primary energy.

$$\text{Thus } \eta = \frac{\delta^-}{\delta^+} = \frac{K^-}{K^+} \frac{(dE/dx)^-}{(dE/dx)^+} \frac{(1 + \delta_R^-)}{(1 + \delta_R^+)} \quad \ldots\ldots \text{VII} - (2)$$

Without any knowledge of K it will be assumed that $K^- = K^+$; physically this means only differences in S.E. arising from dE/dx and δ_R are included.

Recently Nelms (62) published tables of the energy loss and range of positrons and electrons in many materials. These tables

*Some Authors define the S.E.C. as the yield from ingoing primaries only

were compiled using the Bethe [31] formula for electrons, and the expression derived by Rohrlich and Carson [63] for the energy loss of positrons. There is, as yet, very little experimental support for the calculations on positrons. Seliger [52] has made measurements on the backscattering of electrons and positrons with energies ~ 100's of KeV, and found that electrons were backscattered by ~ 30% more than positrons, i.e. $\delta^-_R / \delta^+_R \sim 1.3$.

It is worthwhile to outline very briefly the mechanism proposed by Seliger to explain his results. He suggested that the unequal backscattering was a consequence of the integrated effect of a large number of inelastic single scattering events, for each of which the cross section for electrons (σ_e) exceeds the classical Rutherford cross section (σ_r), and that for positrons (σ_p) is less than σ_r. (See Mott and Massey [49]). Miller [63] calculated the approximate difference in the backscattering to be expected on the above basis, and found $\delta^-_R / \delta^+_R \sim 1.16$. This ratio would be expected to decrease at low energies and for small values of the atomic number, because σ_e and σ_p will both tend to σ_r; Seliger observed that the ratio was approximately independent of atomic number for $4 < Z < 80$.

In order to determine the variation of η with energy, values of δ^-_r at different energies were required. These were obtained from the results of Seliger [52] and Trump and Van de Graaff [29],

which were in approximate agreement with values estimated by the Author (See Section III.3.(7)). At high energy δ_R^- was $\sim$ 50% for platinum. Precise values of δ_R^-, and also of δ_R^+, could have been measured with the Author's apparatus, but this would have involved a complete further series of experiments, of a rather more difficult nature than the S.E. measurements. For the semi-quantative treatment given here accurate values were not essential. Table 9 gives, for platinum, the ratios of $(dE/dx)^-/(dE/dx)^+$ obtained from Nelms' results, and the values of $(1 + \delta_A^-)/(1 + \delta_R^+)$. The values of η are given by the product of these two quantities; the experimental values are also shown.

The above considerations lead to values of η for copper-beryllium roughly the same as those for platinum; the data for that material are not accurate enough to warrant quantitative comparisons.

From the table it is seen that at energies below $\sim$ 400 KeV electrons lose energy slower than positrons, so, on the proposed picture, they will produce fewer secondaries per unit path length. However, more electrons are reflected, and above an energy $\sim$ 100 KeV the extra yield from these particles exceeds the other effect, and electrons have a greater S.E.C. than positrons.

VII.2.(2) Agreement with Experiment For primary energies $\sim$ 100 - 400 KeV there is reasonable agreement with experiment, and therefore the proposed picture may be a reasonable representation of

TABLE 9.

Values of the quantities appearing in equasion VII (2), together with the values of η calculated for platinum from that equasion, and the experimental values.

E. KeV.	$(dE/dx)^{-}/(dE/dx)^{+}$	$\frac{1+\delta_R^-}{1+\delta_R^+}$	η Calc.	η Expt.
10	0.85	~1.02	0.87	1.68 ± 0.32
20	0.88	1.05	0.93	1.2 ± 0.1
50	0.92	1.06	0.98	1.07 ± 0.04
100	0.95	1.07	1.02	1.04 ± 0.025
200	0.98	1.08	1.06	1.04 ± 0.025
300	0.99	1.08	1.07	1.04 ± 0.025
400	0.99	1.08	1.07	1.04 ± 0.025
500	1.01	1.08	1.09	1.04 ± 0.035

the process. Above~500 KeV the value of η should rise as $(dE/dx)^-$ begins to exceed $(dE/dx)^+$. The experiments were not extended to sufficiently high energies for this to become marked. Below ~ 50 KeV the experimental value begins to rise and the calculated value to fall, so the simple picture breaks down.

More experimental and theoretical work, both on S.E. and the reflection of particles from surfaces, is required to fully illucidate the process. In particular, it would be very valuable to repeat Seliger's measurements of δ_R^- and δ_R^+ over a range of energies, using monoenergetic beams. (Seliger used sources, as was done in the S.E. experiment described in Chapter IV).

Another fruitful experiment would be to compare the S.E. coefficients of electrons and positrons from very thin and thick targets. With the former the reflected component will be greatly reduced, and positrons should give the larger yield because of (dE/dx). The targets used for the experiments described in Chapter VI were all thick, compared to the primary range. The Author attempted a hasty experiment to measure δ_R for electrons, using a thin aluminium target, alone, and backed by a thick target. There were a number of complications, however, and the results were inconclusive. Miller and Porter [30] examined the fast secondary yield from a gold foil, and found it was reduced; they did not observe any large change in the slow secondary yield, but, as

stated in their paper, these workers did not make any careful measurements on the true secondary yield from a thin target. It would be surprising if there was no reduction in the slow yield as the production of secondaries by reflected primaries seems to be generally accepted (See for example, Bruining [8], or Palluel [64]).

One further useful experiment would be to examine the secondary yield, both slow and fast, from the exit side of a thin target for electrons and positrons. Positrons, being reflected less are transmitted more (See Chapter II Part 1) and the true secondary yield on the exit side should be greater for positrons than electrons.

VII 3. Some tentative explanations for the results at primary energies less than 50 KeV.

VII. 3. (1) An extension of the theory proposed at high energies.

It was assumed in Section VII.2. that a scattered primary which emerged from the target had an equal chance of producing a secondary electron as it entered or left the surface. At high energies this was probably true, but at lower energies, where δ^- is increasing sharply with decreasing energy this may not be the case; an inelastically reflected primary, emerging with lower energy, would have a greater probability of producing a secondary when it left the surface. If there was an appreciable fraction of the reflected

primaries degraded in energy, especially if some particles emerged with much lower energy, these could make a substantial contribution to the yield.

A few measurements on the energy distribution of the fast secondary yield for electrons of energy between 20 and 40 KeV have been reported, by Kulenkampff and Spyra [66]. The distribution showed that, although most of the reflected particles had energies near E_p, there was a tail which included a significant number of particles with energies much less than E_p.

If Seliger's results can be extended to lower energies, rough estimates show that η could be of the order of 1.1 at 50 KeV and 1.05 - 1.1 at 20 KeV. The figure at 20 KeV assumed Palluel's[65] value for δ_R for platinum; this author found that δ_R reached its maximum and approximately constant value at lower energies than those indicated by the work of Trump and Van de Graaff [29].

There is an important corollary to the above discussion. On the basis of the assumptions which have been made, the correction which has been applied for primaries reflected from the first dynode, (See Section VI.11.(5)), would become greater and the true value of η smaller. There is insufficient data to make a qualitative reassessment of the correction, but in the energy region 20 - 50 KeV the experimental value of η might easily be reduced by several per cent, and become of the same order as the theoretical estimates.

The preceeding considerations do not seem adequate to explain the large values of η observed below 20 KeV. It should be noted, however, that if the energy distribution of the fast secondary yield from electrons and positrons was different, such that there were more slow electrons, values of η up to 1.5 could be explained between 10 and 20 KeV, even without assuming Seliger's result that $\delta_R^- / \delta_R^+ \sim 1.3$. Although no relevant work has been done, general considerations do not suggest that there is likely to be much difference between the two distributions.

VII. 3. (2) Further considerations regarding S.E. by electrons and positrons at energies less than 20 KeV. In order to account for the large values of η observed below 20 KeV some more basic difference in the mechanism of the production of secondary electrons is required. As yet the detailed processes occuring for electrons are not fully understood.

A physical picture showing how the secondary yield might be produced will be suggested; it will then be shown how positron - electron differences could perhaps arise. Primary particles which enter the target will soon loose their original sense of direction, and will meander about inside the metal, loosing energy as they go, producing secondary electrons within the metal. When the primaries pass near the surface, some of these electrons can escape, and appear as secondary electrons. The rate of production

of secondary electrons increases as the primary looses energy.

For primary positrons, conduction electrons near the surface, whose escape might be favoured, will often experience an inward force, which would impede their emission. This is similar in some respects to the process of Auto-emission by positrons, discussed in Chapter II, except that here the positron is inside the metal, and its field is opposing the escape of a secondary electron. Also, the positron may be moving much more slowly, having lost energy in the metal, so that it has a greater chance of affecting the conduction electron in the way described.
A further possibility is that a positron which had been slowed down might capture an electron, which otherwise would have appeared as a secondary.

VII. 4. Conclusion Although the excess of electron S.E. over positron S.E. can be accounted for at energies greater than 100 KeV and possibly greater than 20 KeV, the results below 20 KeV are not yet by any means fully understood; more experimental and theoretical work is required. The experimental method used is capable of extension, and some improvements were suggested at the end of Chapter VI; the lack of a suitable source of positrons with energies less than 20 KeV is at present the main drawback to making more extensive measurements on these particles.

APPENDIX I

The expressions from the theory of a wedge spectrometer. The symbols are explained in Section V.1.(2).

$$S = \frac{a \alpha^2}{2} \left\{ \frac{\sin^2 \theta}{\sin \gamma} + \frac{\sin^2 \gamma}{\sin \theta} \right\}$$

$$D = \frac{a \sin \theta}{\sin \gamma} \frac{\Delta v}{v} (\sin \theta + \sin \gamma)$$

$$t = \frac{25 x \sin \alpha (\cos \theta + \sin \theta [\theta + \gamma])}{\pi \cos \theta (\cos \theta + \sin \theta [\theta + \gamma] + \sin \theta \cot \gamma)}$$

Where x = magnet gap.

The expressions for S and D were given by Stephens (57)

APPENDIX II

The agreement between the observed position of the focus and the measured fringing field will be briefly discussed.

From the point of view of the focusing characteristics of the magnet the fringing field can be replaced by an "equivalent field", which is a step function of height equal to the field between the poles B_o, and extending a distance X_o from the poles. X_o is defined by the relation $\int_o^\infty H_f \, dx = H_o X_o$, where H_f is the true fringing field. The value of X_o found from the measured fringing field was 1.7 cms.

If a scale drawing is made of the wedge showing different source positions S_1 S_2 etc, and the corresponding experimentally observed foci F_1, F_2 etc, then the line joining S_1 F_1, S_2 F_2 etc should pass through the vertex of the "effective wedge" which has poles extending a distance X_o from the actual position of the poles. Figure 50 shows a photograph of such a scale drawing, and it is seen that S_1 F_1 etc all pass through O' the vertex of the effective wedge P' O' Q'. The real wedge is P O Q. The value of X_o found from this diagram was 1.7 cms, in good agreement with the measured fringing field.

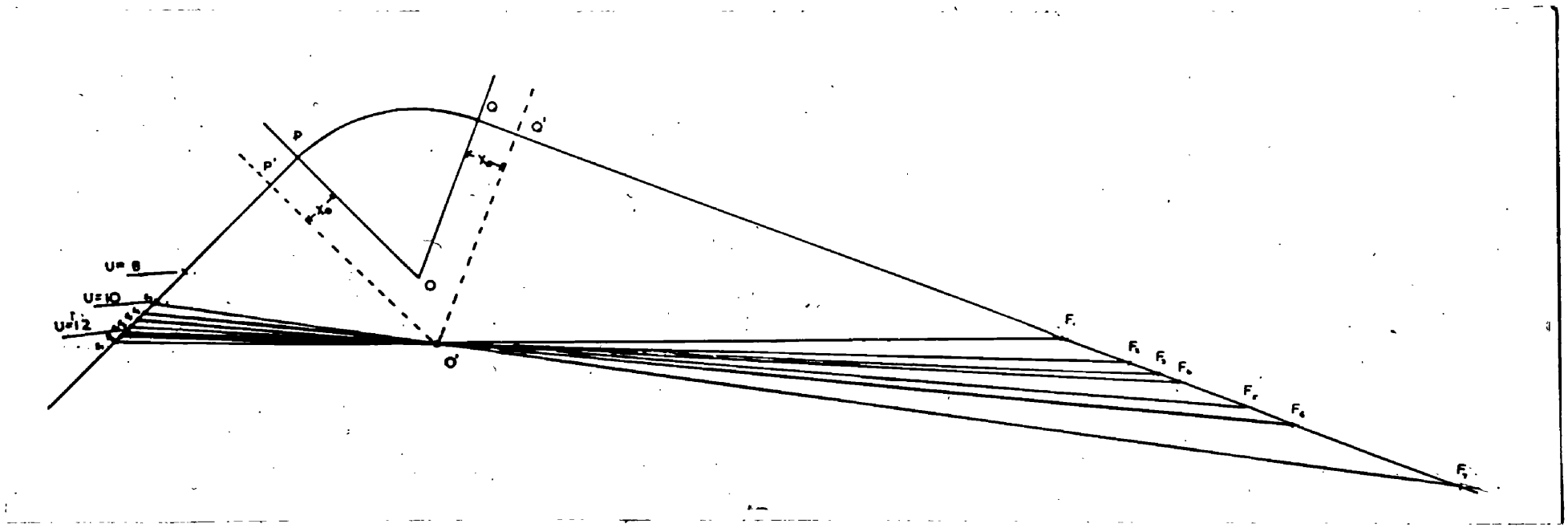


Figure 50. A photograph of a scale drawing showing that the lines joining source positrons S_1 S_2 etc., with the corresponding experimentally observed foci F_1, F_2 etc., pass through the vertex, O', of the "effective wedge" P'O'Q'. POQ represents the actual position of the poles, and x_o is determined by the fringing field.

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