THE SCATTERING OF ELECTRONS AND POSITRONS BY HEAVY NUCLEI

by

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PREFACE

This thesis describes an investigation into the scattering of electrons and positrons by the nuclei of xenon and mercury; except where otherwise stated, the work was carried out independently by the author.

There were two reasons for studying scattering in these elements. Firstly, the behaviour of positrons as compared with electrons in the presence of heavy nuclei is of particular interest to scattering theory. Secondly, in 1938 Champion had reported abnormally low scattering by mercury nuclei, and scattering by this element had not since been investigated although very full calculations had been carried out for mercury by Massey (1942).

Xenon, as the heaviest stable gas, was clearly ideally suited to an expansion chamber scattering experiment; while an examination of apparent alternatives made it clear that Champion's reason for choosing mercury in the form of mercury di-methyl as the heaviest available vapour was stil valid.

The photographs of xenon scattering were taken by J.R. Atkinson and A.F. Howatson, after a study of scattering in argon. The author assisted in part of this, and himself analysed the photographs of xenon scattering.

The expansion chamber used was not designed by the author, but was rebuilt in the light of the special problem

that arose from the use of mercury di-methyl in an expansion chamber. Owing to the scarcity and toxicity of mercury di-methyl it was not possible to carry out trial runs: a considerable amount of apparatus was therefore modified, designed, and in many cases constructed by the author in an endeavour to ensure that the expansion chamber could be safely and efficiently filled and operated.

In particular it is believed that the technique developed for injecting mercury di-methyl into a sealed chamber (a method since used by other workers in this department) is original.

It was found that existing methods of calculating plane projection distributions were only applicable to light elements. A new technique of calculating these distributions was therefore developed using existing published data, and tabulated constants were prepared enabling the plane projection distribution to be readily calculated for any heavy element. It is believed that these results will be of general application.

Contents of Thesis

I. Following an introduction showing the significance of electron/nuclear scattering, the implications of the quantum-mechanical Mott formula are considered, and the methods developed for evaluating it; experiments applied

to scattering are then reviewed and their results summarised, showing the importance of the Champion experiment with mercury di-methyl (1938).

II. In studying scattering in mercury di-methyl vapour, it was hoped to use this vapour alone without added water. Mercury di-methyl is scarce, highly toxic, and has a low gamma. These factors necessitated a careful study of many facts of chamber design and operation, and a number of experiments designed to throw light on the behaviour of an expansion chamber under various conditions are described, together with the apparatus and procedure finally evolved.

III. The filling procedure was successfully carried out, but tracks could not be obtained with mercury di-methyl and argon alone, so water was added. There was no evidence of abnormally low scattering, but further positron tracks were desired. After some alterations had been made to the chamber, a further run was carried out, using nitrogen in place of argon.

IV. While analysing photographs of scattering in xenon it had been found necessary to alter the techniques of reprojection, and alternative methods are reviewed.

The development of plane projection calculations applicable to heavy elements is also described. The scattering in xenon, and in mercury di-methyl with argon, is shown to be in agreement with Mott theory; but in the second run carried out with nitrogen, the mercury scattering was negligible.

V. A detailed study of the behaviour of mercury di-methyl vapour is described, and a low density of vapour is shown to be the cause of the anomolous scattering observed, both by Champion and by the author.

During these experiments and during the runs proper, few of the operations which involved handling or injecting mercury di-methyl were performed by the author; these were almost all carried out by Mr. J.T. Lloyd, to whom my thanks are also due for the use of facilities in the radio-active laboratory over the whole period that mercury di-methyl was in use.

It is a pleasure to record my thanks to Mr. J.R. Atkinson for suggesting this problem, and for his guidance on cloud chamber technique; to Dr. G.A.P. Wyllie for stimulating discussions and valuable criticism, and to Professor Dee for his sustained interest in the work.

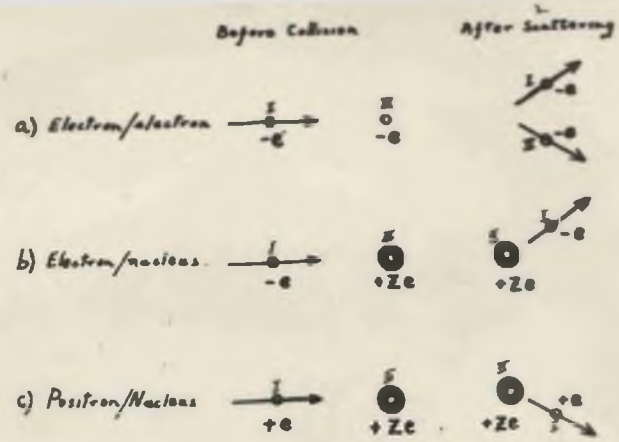


Fig. 1. Electron/electron scattering is identified by the existance of a recoil track, accompanied by loss of energy in the incident electron.

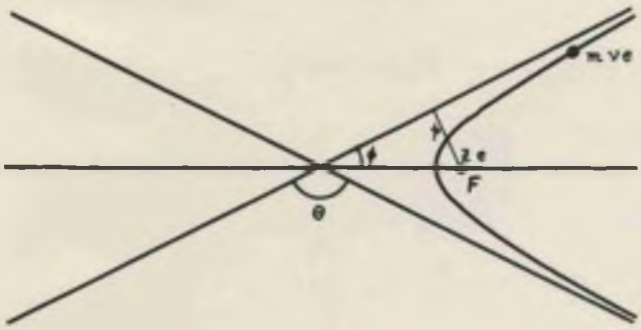


Fig. 2 Electron-Nuclear Scattering

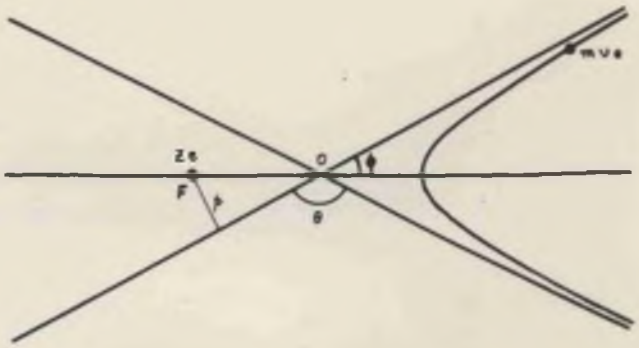
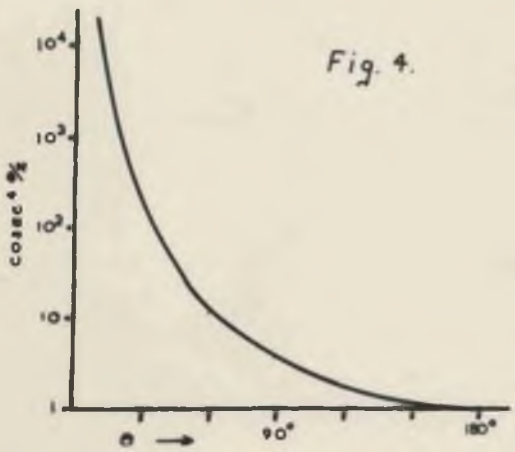
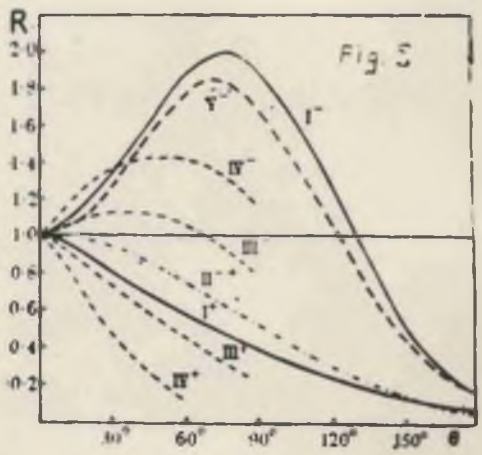


Fig 3 Positron-Nuclear Scattering.





Figs. 4 & 5. The $\mathrm{cosec}^4\theta$ term, common to Rutherford and Mott scattering formulae, results in a predominance of small angle scatters. It is therefore convenient to discuss evaluations by considering the ratio (R) between the cross-section predicted at any angle, and the corresponding "Relativistic Rutherford" cross-section. The curves shown are for Z = 80, E = 1·6 Mev.

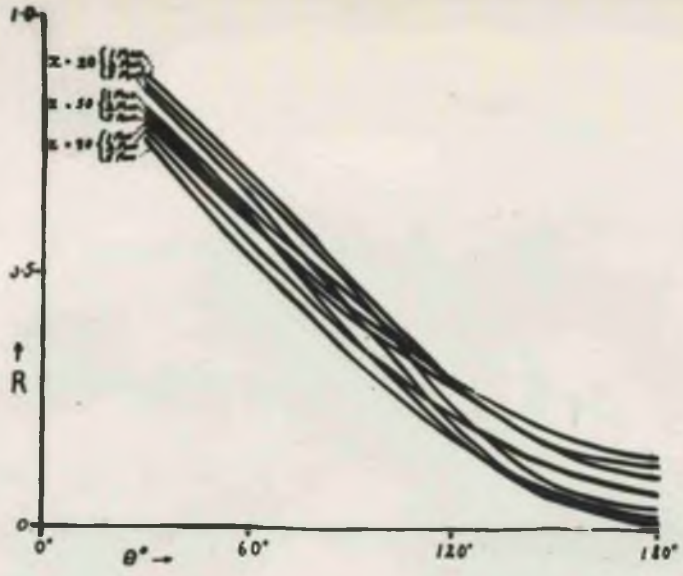


Fig. 6. The variation of cross-section with energy and atomic number is small for positrons. These curves are based on tables published by Yadav.

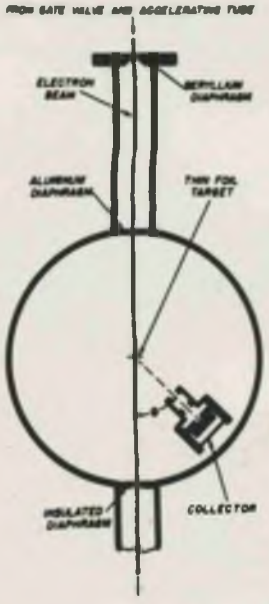


Fig. 7. The ionising chamber used by van de Graaf, Buechner & Feshbach.

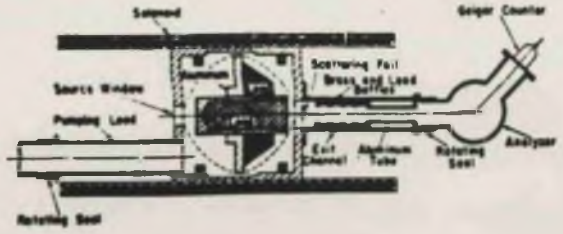


Fig. 8. The electron lens and geiger counter used by Lipkin.

I. SURVEY OF THEORY AND EXPERIMENTS

i) The Single Scattering of Electrons and Positrons

From a purely Newtonian standpoint, the path of a charged particle travelling through matter is made up of a series of localised single scattering events, between which it travels freely. We may accept the implications of this as applied to electrons or positrons.

If we regard the group of neutrons and protons in the nucleus as behaving like a single particle of charge Ze and mass A, there are two distinct and characteristic types of collision that may occur

a) electron-nuclear or positron-nuclear

b) electron-electron or positron-positron

As classical theory does not distinguish scattered positrons from electrons, we need consider only the latter. In each case the energy and momentum of the incident electron will be shared between the particles. but in the first case, the nuclear mass is so much larger than that of the electron that, in effect, the exchange will be one of momentum

only, the transfer of energy being negligible.

In the second case, assuming for the moment that it is possible to identify the incident electron at all times in the course of its passage through matter, it would be expected that at nearly every scattering event a change of direction of the electron would take place, but that this change of direction might sometimes be characterised by a definite loss of energy, and sometimes by no loss of energy at all.

Further, it will be noted that for an atom of atomic number Z we shall have Z electrons of negative charge -e available per atom, but only a single positive partice of charge Ze.

In general, then, there are Z times as many electrons as nuclei, and these might normally be expected to produce inelastic scattering, while we might expect the nuclear scattering to be elastic. These two types of collision may, still on a Newtonian picture, be represented as in Fig. 1.

It is clearly not difficult to distinguish between <u>single</u> scattering events of the two types; in the electron-electron case there is not only a loss of energy in the incident particle; there

is also a second electron, previously unobservable, and now detectable by virtue of its kinetic energy. In the electron nuclear case there should be no loss of energy, and no second particle observable.

The work of this paper is concerned solely with collisions between nuclei and electrons (or positrons), and it should be noted at this stage that, as all types of collision must occur along the track of a particle passing through matter, it is essential that any experiment, designed to investigate the statistics of either type of collision, be able to distinguish clearly and reliably between them. A discussion of this point will be found later (Sections II i and III i).

ii) Experimental Parameters

ENERGY

It will be shown that, in the classical case, the number of particles deflected is inversely proportional to the energy^2 of the incident particles, while an inverse dependence almost proportional to E^3 is obtained from quantum-mechanical theory. Thus a precise knowledge of incident energy is essential to the determination of absolute cross sections. The Mott-Massey

theory which is used throughout for comparison with experiments neglects a) the screening effect of electrons b) the effects of nuclear charge distributions. For mercury, these limitations are not significant a) above 100 Kev b) below 10 Mev. The experiment is carried out within these limits.

ATOMIC NUMBER

Classically, the number of scattered particles increases in proportion with the atomic number of the scattering nucleus. What is more important is that with heavy nuclei large departures from classical theory are predicted, and thus in this region it is easier to distinguish between alternative theories.

ANGULAR DISTRIBUTION

The difference between alternative theories is greatest when the scattered angle is large, as the angular distribution follows a $\mathrm{cosec}^4\theta$ law it is therefore necessary to consider a large number of small angle scatters in order to obtain a distribution with sufficient data on large deflections. In the experiments to be described the observed number of deflections falling within certain angular ranges is tabulated. Where, however, the behaviour of electrons and positrons is being compared, the ratio of the relative

number of electrons and positrons scattered under similar conditions is considered, as this ratio is much less energy dependent than the absolute cross-section.

iii) Theory of electron scattering

Assuming only Coulomb forces affect an electron of mass m and incident velocity v as it approaches a nucleus $Z\ e_1$ (Fig. 2), from considerations of conservation of energy and angular momentum, we have

$$\tfrac{1}{2}\ m\ v^2 = \tfrac{1}{2}\ m\ v_1^{\,2} - \frac{Ze^2}{FA}, \text{ and } p\ v = FA\ v_1$$

and thus Rutherford showed it will suffer a deflection Θ where

$$\cot \frac{\Theta}{2} = \frac{p\ m\ v^2}{Ze^2}$$

If we have a beam of n particles, and N nuclei per unit area, the number of particles with an impact parameter between p and p + dp will be

$(2\pi p\ \ dp)\ n\ N$

From above formula $p^2 = \dfrac{Z^2\ e^4}{m^2\ v^4\ \tan^2\ \Theta/2}$

and, differentiating, $p\ dp = \dfrac{Z^2\ e^4}{m^2\ v^4} \dfrac{-\ d\ \Theta}{2\ \tan^3\ \Theta/2\ \cos^2\ \Theta/2}$

Hence the number of particles per unit solid angle deflected between Θ and $\Theta + d\ \Theta$ is:-

$$n(\theta) = 2\pi n N \left(\frac{Z^2 e^4}{m^2 v^4}\right) \frac{d\theta}{2 \tan^3 \theta/2 \cos^2 \theta/2} \cdot \frac{1}{2\pi \sin\theta d\theta}$$

Hence,

$$n(\theta) = \frac{n N}{4 \sin^4 \theta/2} \left(\frac{Z e^2}{m v^2}\right)^2$$

the usual Rutherford formula.

From the last term it is clear that the number of particles scattered through a given angle will be proportional to the square of the atomic number, Z, and inversely proportional to the square of the energy, $\frac{1}{2} m v^2$, so that, according to this theory, if the energy of the incident particles, and the atomic number of the scattering material are increased in the same proportion, the number of particles scattered will remain unchanged. Also, owing to the $\text{cosec}^4 \theta/2$ term, the number scattered through large angles will be very much less than those scattered through small angles, as is evident from the curve (Fig. 4).

In early experiments (1931) Neher found this theory predicted three times the number of scattering events he observed, using electrons with energies up to 145 Kev, giving

$\beta = 0.6$, but he found very much closer agreement, towards his upper limit, when he added the empirical factor $(1 - \beta^2)$.

According to relativity, if a body is moving at a velocity v approaching that of light, its effective mass is increased by a factor $\frac{1}{\sqrt{(1 - \beta^2)}}$ where $\beta = \frac{v}{c}$. If then we substitute $\frac{m_o^2}{1 - \beta^2}$, if m_o is the rest mass, for m^2 in the Rutherford equation we have

$$n(\theta) = \frac{n N}{4 \sin^4 \theta/2} \left(\frac{Z e^2}{v^2}\right)^2 \frac{1 - \beta^2}{m_o^2}$$

This is exactly the form suggested by Neher, and has come to be known as The Relativistic Rutherford formulae, though this is a misnomer as the derivation of the formula is strictly classical and non-relativistic, and indeed was intended by Rutherford to be applied only to α-particles which, except at energies of the order of 100 MeV, are non-relativistic.

WAVE-MECHANICAL THEORIES

The Schrodinger wave equations for an electron are entirely classical in concept,

and do not take into consideration any of the effects arising from spin. The only forces recognised as occurring between the incident electron and the nucleus are electrostatic, and, if the particular case of a Coulomb field is considered, the formula obtained is

$$n(\theta) = \frac{n N}{4 \sin^4 \theta/2} \left(\frac{Z e^2}{m_o v^2}\right)^2$$

which is identical with the Classical Rutherford form, or in cross-section form

$$\sigma = \left(\frac{e^2}{2 m_o v^2}\right) \operatorname{cosec}^4 \theta/2$$

It has already been shown that this formula differs widely from the observed results, and it is thus necessary to consider whether there are any physical properties of the electron, not allowed for in the classical picture, which should be included.

Relativity It is clear from the improved agreement obtained by Neher that it is essential to allow for the relativistic rise of mass. It is, however, quite unjustifiable to insert a correction term in a classical

formula, and the whole equation must be derived according to relativistic quantum mechanics.

Screening So far we have considered only the interaction of an electron and a stripped nucleus. The K-energy for Mercury, for example, is 85 KeV, so for energies over 100 KeV, the electron being scattered will be well inside the K-shell and, in the range of several MeV, the screening can be completely neglected.

Spin If, in addition to translational velocity, the electron was capable of rotating about its own axis, it would then be the equivalent of a circulating current, and would possess magnetic moment. Under these conditions, even if the nucleus were assumed not to possess a magnetic moment, its electrostatic field would react with the moving magnetic moment of the electron to produce a non-central force, dependent in magnitude on the orbital velocity of the electron, as well as on the electron nuclear constants.

If relativistic theory is applied to the

Schrodinger equation, a more general form is obtained, giving four wave equations describing particles of electron mass and unit charge, of which two must be negative, and two positive.

Dirac suggested that if the electron possessed a spin, which had two possible orientations, this would complete the four possible cases, and already had confirmation from Pauli's earlier view that the degeneracy of the ground state of hydrogen could be thus explained.

Working from these Dirac equations, with all their inherent implications, Mott (1929) derived equations for the cross-section of scattering. These were in the form of a conditionally convergent infinite series, from which results are not readily accessible. For this reason a considerable amount of work has been done to obtain solutions, of varying accuracy, by numerical and other methods. For comparison, the precise numerical cross-section for mercury obtained by Bartlett and

Watson (Fig. 5) is given, for energies of 1 MeV, in heavy line. All the cross-sections are expressed as a ratio to the corresponding Relativistic Rutherford value, that is $\frac{Z^2 e^2}{m^2 v^4} \operatorname{cosec}^4 \theta/2 \, (1-\beta^2)$

Mott, himself, suggested the form

$$\frac{Z^2 e^4}{4 m^2 v^4} \operatorname{cosec}^4 \theta/2 \, (1 - \beta^2 \sin^2 \theta/2 + \pi\alpha\beta \cos^2 \theta/2 \sin \theta/2 + \text{terms in } \alpha^2) \, (1 - \beta^2)$$

which he further simplified to a form accurate for low atomic numbers

$$\frac{Z^2 e^4}{4 m^2 v^4} \operatorname{cosec}^4 \theta/2 \, (1 - \beta^2 \sin^2 \theta/2) \, (1 - \beta^2)$$

where $\alpha = \frac{Z e^2}{hc}$ and is much less than 1.

Any effect associated with magnetic coupling must contain a term in Z(or in α). The formula represented in Curve IIdiffers from Rutherford in that it contains a Relativistic mass term, $(1 - \beta^2)$ and the term

$$(1 - \beta^2 \sin^2 \theta/2)$$

This latter cannot be associated with normal spin coupling, as it is independent of Z. If it has a physical interpretation it is of a non-magnetic, non-electrostatic force resulting from electron spin.

The additional terms in α and α^2 (CurvesIV) are associated with spin orbital coupling.

In the process of deriving the exact numerical solutions for mercury Bartlett and Watson suggested the approximation

$$\frac{Z^2 e^4}{4 m^2 v^4} \cot^4 \theta/2 \sec^2 \theta/2 \, (1 - \pi\alpha\beta \sin^2 \theta 2 \cos\chi)$$

$$(1 - \beta^2),$$

where χ is defined by gamma functions of α and α/β. This (Curves III) is accurate for angles of less than 15°, but is otherwise inadequate.

McKinlay and Fesbach (1948) expanded the Mott series in a power series in α and α/β. They believed that this series is accurate for middle Z elements, and suggest that, by comparing the results obtained (Curve V) with particular cases calculated numerically by Bartlett and Watson (who have summed Mott's series for mercury), scattering cross-sections for all atomic numbers may be computed with errors of at most a few per cent. This comparison may be done quite justifiably as,

though the actual values are slightly different, the curves are of similar shape, and at the ends are asymptotic. On this basis, they have published families of curves giving, at 1, 2 and 4 MeV, the variations of cross-section with angle for atomic numbers from 0 to about 82.

It is interesting to note that, if α and β are small, all the above approximations reduce to the classical Rutherford form, except the Bartlett and Watson small angle formula.

It, however, becomes

$$\frac{Z^2 e^4}{4 m^2 v^4} \operatorname{cosec}^4 \theta/2 \cos^2 \theta/2$$

and, within the specified limit of 15° or less, $\cos^2 \theta/2 \simeq 1$.

iv) Positron Scattering

If we consider positrons with an incident energy in excess of 100 KeV, we may again neglect the effect of orbital electrons. On a classical basis then the Coulomb force on the positron will be equal and opposite to that on an electron.

If we consider the same figure as

before, but place the nucleus at the other focus, we can find the scattered angle by the same method. (Fig. 3)

The energy now becomes

$$\tfrac{1}{2}\, m\, v^2 = \tfrac{1}{2}\, m\, v_1^{\,2} \quad \frac{Z\, e^2}{FA}$$

and, from geometry, the distance FA = p cot $\theta/2$. The scattered angle ϕ is given by

$$\cot \theta/2 = \frac{p\, m\, v^2}{Z\, e^2}$$

Thus, for a given impact parameter, the positron will not approach the nucleus so closely, but will be scattered through the same angle as an electron.

This might also be deduced from the form of the Rutherford formula in which, as the term containing the product of the charges is squared, the sign is immaterial.

In the Mott approximation of Curve II (Fig. 5)

$$\frac{Z^2\, e^4}{4\, m^2\, v^4} \operatorname{cosec}^4 \theta/2\, (1 - \beta^2 \sin^2 \theta/2)\, (1 - \beta^2)$$

there is again no change if we substitute +e for -e, but in his form in Curve IV every odd power of α will change sign, and we get

$$\frac{Z^2 e^4}{4 m^2 v^2} \operatorname{cosec}^4 \theta/2 \; (1 - \beta^2 \sin^2 \theta/2 - \text{terms in } \alpha + \text{terms in } \alpha^2 \;).$$

One consequence of this alternating series is that, with a small number of terms, a very much better approximation is obtained than for the electron case.

The Bartlett and Watson "Small Angle" formula (Curve III) differentiates between positrons and electrons (one α term), and gives a fair curve shape, but underestimates the cross-sections of each at large angles.

MacKinlay and Fesbach have not applied their method to the case of positrons, but this has been carried out by Yadav (1952), and shows that, as expected, the variation of cross-section with energy and Z is not great (Fig.6).

As before, for low values of β and α the positron versions of these formulae reduce to the Rutherford positron/electron form.

v) Survey of Experiments

It has already been mentioned in the previous section that Neher (1931) found the purely classical Rutherford alpha-scattering

theory unsuitable except for the slowest electrons. In the five years that followed, innumerable experiments were reported, and from these there gradually emerged a picture which, despite frequent exceptions, was clear at least in outline: this was that, with atomic numbers less than twenty, and scattered angles not exceeding 60^{o}, reasonable agreement was found with Rutherford theory if this was modified by incorporating the relativistic term $(1 - \beta^{2})$ in the expression for the mass of the incident electrons. For larger scattered angles, however, and particularly for heavier nuclei, large departures were still found.

Treating the electron as a Dirac particle, Mott (1929) derived an expression for its nuclear scattering cross-section. This, unfortunately, is not in a form suitable for computation; but one of the first approximations of experimental value, the Mott light element formula, was applied by Champion (1935) to nitrogen scattering in the region of 1 Mev, and

was shown to give better agreement with experiment than the Relativistic Rutherford formula, particularly in the range 60^{o} - 180^{o}.

The work of Champion (nitrogen, 1936), of Borisov, Brailovski and Leipunski (nitrogen, 1940) and of Bleuler, Scherrer and Zunti (nitrogen, fluorine and argon, 1942) showed that the Mott light element formula was valid within the limits of experimental errors - which ranged from -15% to +50%. It is true that in 1936 Skobelyzyn and Stepanowa reported scattering in nitrogen greatly in excess of that predicted by Mott, while in the following year Stepanowa herself again found large cross-sections under similar conditions. No confirmation of this was however reported by other workers.

In the case of the heavier elements, on the other hand, the measure of agreement was not so marked. Even with argon, while Zuber and also Stepanowa in 1938 and 1939 found scattering normal up to 1 Mev, the

latter found over twice the predicted amount in the range 1.5 - 3 Mev. In Krypton, Klarmann and Bothe (1936) found one sixth the expected figure, and over the range 0.5 - 2.6 Mev, the same workers found a fifth of the predicted scattering in xenon; while Sen Gupta (1939) at 2.1 Mev found no significant departure from theory.

Again, Barber and Champion (1938) in observing electron scattering (0.5 - 1.1 Mev) by mercury nuclei found only a sixth of the scattering predicted by an early medium-Z Mott approximation. Van de Graaf, Beuchner and Fesbach (1946) found good agreement (1.27 - 2.27 Mev) with the Bartlett and Watson (1940) calculations for gold and platinum, while the ordinary Mott formula fitted their results for aluminium, copper and silver, with a slight deviation for aluminium (over 1 Mev). These results are important as the method used is capable of considerable accuracy. A beam of monochromatic electrons from a Van de Graaf generator is admitted (Fig. 7) through a slit to an evacuated chamber and impinges on a

metal foil. Those scattered in the direction of the ionisation chamber will pass through the guard foil into it, unless they have previously lost energy in an inelastic collision. Thus with a monochromatic source and a counter technique the scattering cross-section of any metallic element may be very accurately determined for any given angle. Nevertheless, the difficulty of obtaining an angular distribution, the restricted range of choice of suitable scattering elements, and the difficulty of adapting the method to direct comparison of electron and positron interactions severely limits its general applicability.

Although it begins to appear that the large departures from theory in early experiments were due to non-repeatable experimental factors, even the results of Randels, Chao and Crane (1945) - whose analysis was certainly the most critical and whose figures are probably the most reliable - though confirming the necessity for a relativistic mass correction, fail to show with certainty whether or not it is necessary

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It, however, becomes

$$\frac{Z^2 e^4}{4 m^2 v^4} \operatorname{cosec}^4 \theta/2 \cos^2 \theta/2$$

and, within the specified limit of 15° or less, $\cos^2 \theta/2 \simeq 1$.

iv) Positron Scattering

If we consider positrons with an incident energy in excess of 100 KeV, we may again neglect the effect of orbital electrons. On a classical basis then the Coulomb force on the positron will be equal and opposite to that on an electron.

If we consider the same figure as

before, but place the nucleus at the other focus, we can find the scattered angle by the same method. (Fig. 3)

The energy now becomes

$$\tfrac{1}{2}\, m\, v^2 = \tfrac{1}{2}\, m\, v_1^2 \quad \frac{Z\, e^2}{FA}$$

and, from geometry, the distance FA = p cot $\theta/2$. The scattered angle ϕ is given by

$$\cot \theta/2 = \frac{p\, m\, v^2}{Z\, e^2}$$

Thus, for a given impact parameter, the positron will not approach the nucleus so closely, but will be scattered through the same angle as an electron.

This might also be deduced from the form of the Rutherford formula in which, as the term containing the product of the charges is squared, the sign is immaterial.

In the Mott approximation of Curve II (Fig. 5)

$$\frac{Z^2\, e^4}{4\, m^2\, v^4} \operatorname{cosec}^4 \theta/2\, (1 - \beta^2 \sin^2 \theta/2)\, (1 - \beta^2)$$

there is again no change if we substitute +e for -e, but in his form in Curve IV every odd power of α will change sign, and we get

theory unsuitable except for the slowest electrons. In the five years that followed, innumerable experiments were reported, and from these there gradually emerged a picture which, despite frequent exceptions, was clear at least in outline: this was that, with atomic numbers less than twenty, and scattered angles not exceeding 60^{o}, reasonable agreement was found with Rutherford theory if this was modified by incorporating the relativistic term $(1 - \beta^{2})$ in the expression for the mass of the incident electrons. For larger scattered angles, however, and particularly for heavier nuclei, large departures were still found.

Treating the electron as a Dirac particle, Mott (1929) derived an expression for its nuclear scattering cross-section. This, unfortunately, is not in a form suitable for computation; but one of the first approximations of experimental value, the Mott light element formula, was applied by Champion (1935) to nitrogen scattering in the region of 1 Mev, and

was shown to give better agreement with experiment than the Relativistic Rutherford formula, particularly in the range 60^{o} - 180^{o}.

The work of Champion (nitrogen, 1936), of Borisov, Brailovski and Leipunski (nitrogen, 1940) and of Bleuler, Scherrer and Zunti (nitrogen, fluorine and argon, 1942) showed that the Mott light element formula was valid within the limits of experimental errors - which ranged from -15% to +50%. It is true that in 1936 Skobelyzyn and Stepanowa reported scattering in nitrogen greatly in excess of that predicted by Mott, while in the following year Stepanowa herself again found large cross-sections under similar conditions. No confirmation of this was however reported by other workers.

In the case of the heavier elements, on the other hand, the measure of agreement was not so marked. Even with argon, while Zuber and also Stepanowa in 1938 and 1939 found scattering normal up to 1 Mev, the

latter found over twice the predicted amount in the range 1.5 - 3 Mev. In Krypton, Klarmann and Bothe (1936) found one sixth the expected figure, and over the range 0.5 - 2.6 Mev, the same workers found a fifth of the predicted scattering in xenon; while Sen Gupta (1939) at 2.1 Mev found no significant departure from theory.

Again, Barber and Champion (1938) in observing electron scattering (0.5 - 1.1 Mev) by mercury nuclei found only a sixth of the scattering predicted by an early medium-Z Mott approximation. Van de Graaf, Beuchner and Fesbach (1946) found good agreement (1.27 - 2.27 Mev) with the Bartlett and Watson (1940) calculations for gold and platinum, while the ordinary Mott formula fitted their results for aluminium, copper and silver, with a slight deviation for aluminium (over 1 Mev). These results are important as the method used is capable of considerable accuracy. A beam of monochromatic electrons from a Van de Graaf generator is admitted (Fig. 7) through a slit to an evacuated chamber and impinges on a

metal foil. Those scattered in the direction of the ionisation chamber will pass through the guard foil into it, unless they have previously lost energy in an inelastic collision. Thus with a monochromatic source and a counter technique the scattering cross-section of any metallic element may be very accurately determined for any given angle. Nevertheless, the difficulty of obtaining an angular distribution, the restricted range of choice of suitable scattering elements, and the difficulty of adapting the method to direct comparison of electron and positron interactions severely limits its general applicability.

Although it begins to appear that the large departures from theory in early experiments were due to non-repeatable experimental factors, even the results of Randels, Chao and Crane (1945) - whose analysis was certainly the most critical and whose figures are probably the most reliable - though confirming the necessity for a relativistic mass correction, fail to show with certainty whether or not it is necessary

for the theory to consider the spin of the incident particle.

While for electrons the existence of a spin-orbital interaction may make the cross-section larger or smaller than the Rutherford value, (depending on angle, energy, and atomic number), for positrons (Fig5,6) the inclusion of a spin term always brings about a reduction in the cross-section at all angles; moreover the cross-section varies much less with atomic number than it does for electrons. If, then, only deflections of less than, say, 60° are considered, the Mott cross-section for positron scattering is markedly less than the Rutherford even for elements of moderate atomic number; the corresponding cross-section for electron scattering is never appreciably less but does become significantly greater (at 60°) for elements heavier than xenon. As increasing the atomic number of the scattering elements results in the electron cross-section becoming progressively greater than the Rutherford value at the same time as the positron cross-section

becomes less, it seems that the most conclusive tests will be carried out by comparing positron and electron scattering - equal according to Rutherford theory - for heavy elements.

That it is in practice more difficult to obtain numerically satisfactory results with positron than with electron sources may be deduced from the statement by Corson and Hanson (1953) that hitherto, with the exception of the copper and platinum foil experiments of Lipkin (1953), the number of positrons scattered through large angles was too small to show any definite difference from the scattering of electrons.

Nevertheless, although there has not yet been anything approaching the amount of work which has been done on electron scattering, what has been carried out suggests that the electron and positron behave as anti-particles governed by the Dirac equation.

In 1937 Fowler and Oppenheimer used electrons and positrons produced in a 0.13 mm. lead foil by a beam of 17 Mev. gamma rays obtained from a Li^7 target bombarded by

protons. The source foil together with the thin scattering foils was placed inside an expansion chamber, thus ensuring equal numbers of positrons and electrons. Though consistent with theory, results were sparse (9 deflections greater than $14\frac{1}{2}^{\circ}$) and it is doubtful if the technique is now of more than academic interest, as it is usually preferable to avoid the background of Compton electrons that result from passing a gamma beam through an expansion chamber.

More recently, Howatson and Atkinson (1951) showed that in argon positron scattering was less than the Rutherford value and in agreement with Mott, while the electron cross-section also agreed with that of Mott. Between 20° and 90°, 65.5 positron deflections were recorded. Using another light element, nitrogen, Cusack (1952) observed 114 deflections greater than 20°. This was 30% lower than predicted by theory, but followed a distribution in general agreement with Mott.

Apart from the experiment by Fowler and Oppenheimer already referred to, only two

papers have been published about the ratio of positron to electron scattering in nuclei heavy enough to provide a significant result. In 1948 Lasich reported on scattering by a gold foil in a cloud chamber. In three runs, the ratio of electrons to positrons was about 20% lower than predicted, with a total of 30 positron deflections greater than 17^{o}. As a complete contrast, Lipkin (1952) described an experiment using electron optical systems, both to produce a beam of monochromatic electrons (or positrons) and to select for elastic collisions (Fig. 8.). A geiger counter was used as detector. The ratio of e^{-}/e^{+} scattering was then studied for deflections of 60^{o} for foils of copper and platinum. The total number of deflections is not stated, but as the counting rates were of the order of hundreds a minute, it may be assumed to be large. The ratios observed were mostly 10% to 20% higher than theory. While the statistics obtained by such a method are excellent, the necessity for the preparation of a special source and the impossibility of studying an angular distribution are severe

disadvantages; but disadvantages which will undoubtedly be overcome in time.

CONCLUSIONS

It seems clear that in most cases where electron scattering by light nuclei has been studied, good agreement has been found with Mott theory. In many cases, however, reasonable agreement could also be shown with Relativistic Rutherford theory, for with such nuclei the difference between the theories is not great. This difference rises rapidly with the heavier nuclei, and here it would seem, results should be conclusive. True, all the heavy nuclei that have been investigated have been reported - at one time or another - to exhibit Mott scattering. Even to this very limited statement, however, this is an exception, and it occurs in the element which, after the detailed calculations of Massey, might appear the ideal subject of study - mercury.

In more recent years the availability of artificial positron emitters has made possible the very much more powerful approach of comparing directly the scattering of electrons

and positrons. This ratio is of particular interest because, while the classically founded theories predict no difference in the statistical behaviour of the two particles, the Mott theory, which treats them as Dirac particles, predicts that with heavy nuclei the number of large deflections suffered by electrons will, under the same conditions, be over twice that suffered by positrons.

While there is no longer any reasonable doubt about the validity of Mott's treatment of the electron as a Dirac particle, it is important that the implications of this theory on scattering should be verified, and in view of the manifest difficulty that had been experienced by previous workers in obtaining differentially conclusive results, it seemed to the author that this could best be achieved by comparing, as directly as possible, the angular distributions of electrons and positions scattered by heavy nuclei.

In this department photographs had been

taken of scattering of electrons and positrons in xenon, and these were to be analysed by the author; But for heavier nuclei the only published experimental work that included positron scattering had made use of foils, either in an expansion chamber or with a counter array. Neither is entirely satisfactory, as in the former case there is a tendency for tracks to disappear near a foil - apart from the difficulty of supporting in an expansion chamber foils thin enough to ensure single scattering. Again, with counters, it does not seem possible to construct electron lens assemblies which will eliminate inelastic events, and at the same time retain sufficient flexibility to study angular distributions.

These difficulties do not arise when studying dispersed scattering in a cloud chamber, and as a scattering medium for this purpose, the vapour of the volatile di-methyl of mercury seemed ideal. Massey has published full calculations for this element, and there was also a particular interest

attached to mercury di-methyl as this compound had been used by Champion (1938) when he observed the highly anomalous mercury scattering which, although frequently referred to, had never been repeated.

It was realised that the vapour of mercury di-methyl in an expansion chamber might affect track quality and hence ultimately statistics, but in view of the very limited positron scattering data already published for heavy nuclei, it was decided to concentrate on scattering in mercury di-methyl vapour, and use the techniques of analysis developed by Randels, Chao and Crane (1945) to obtain as much information as possible from the results.

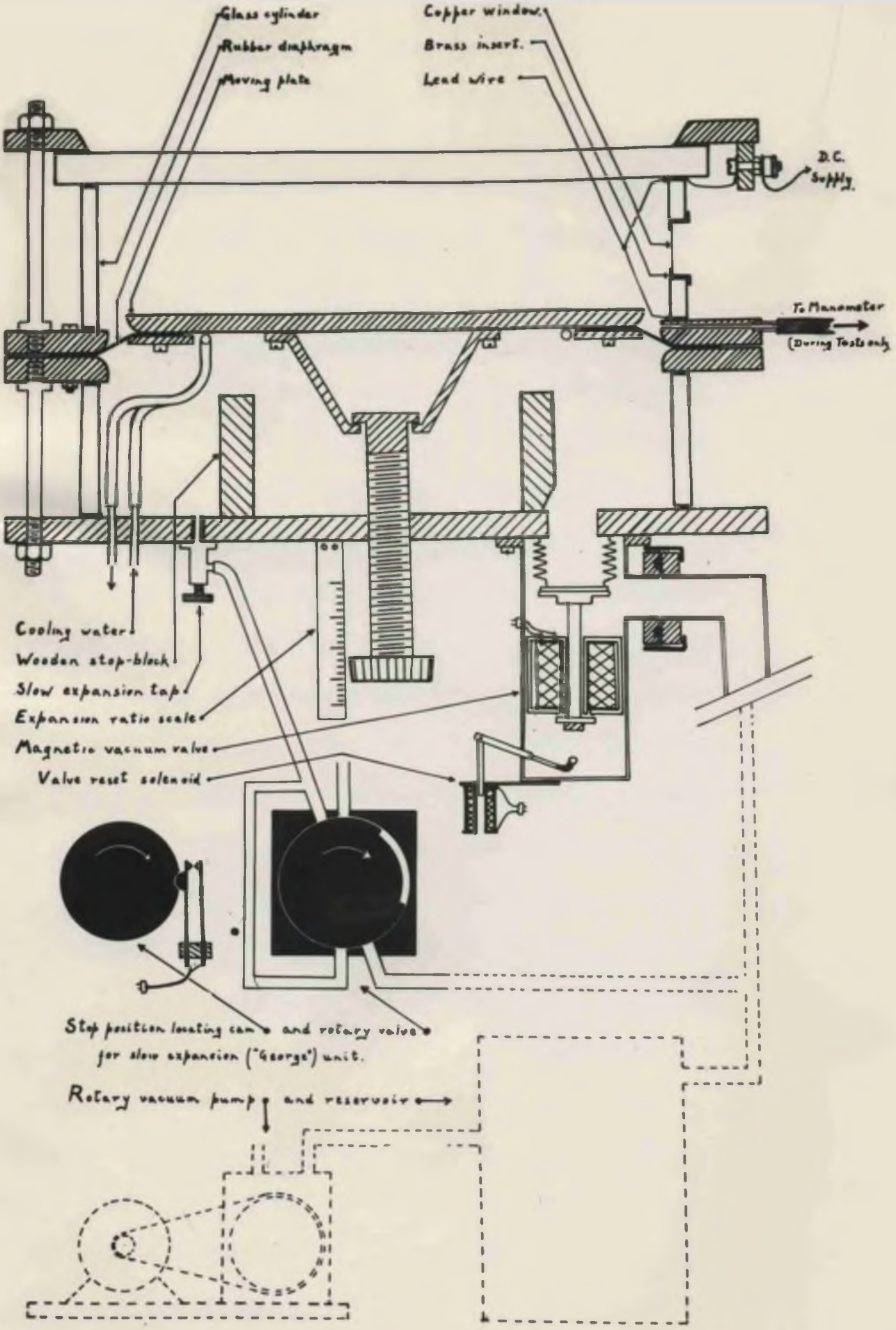
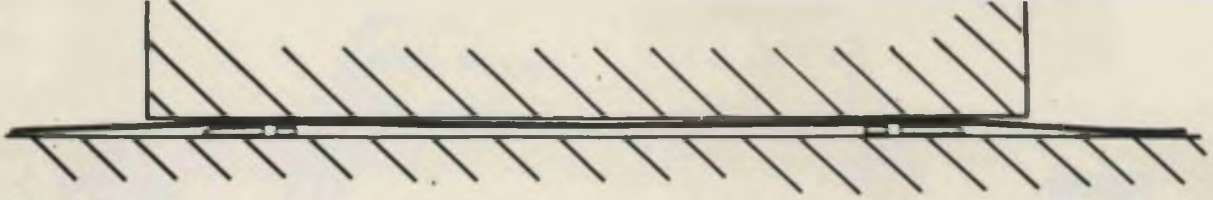
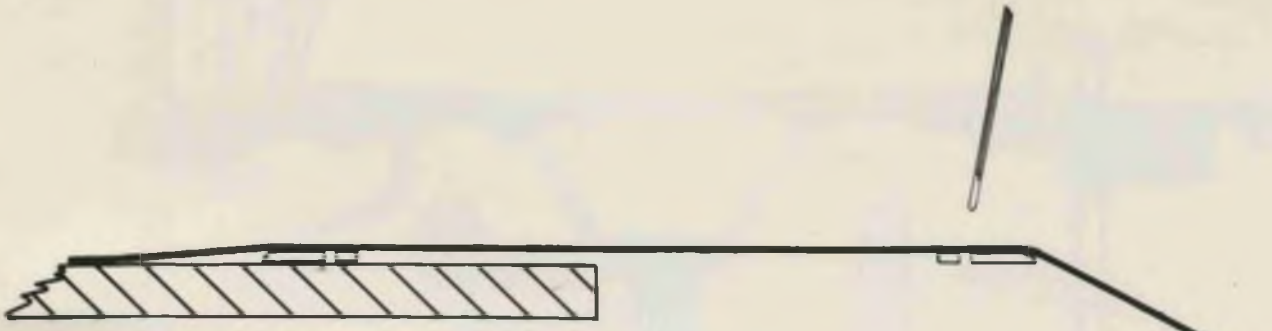


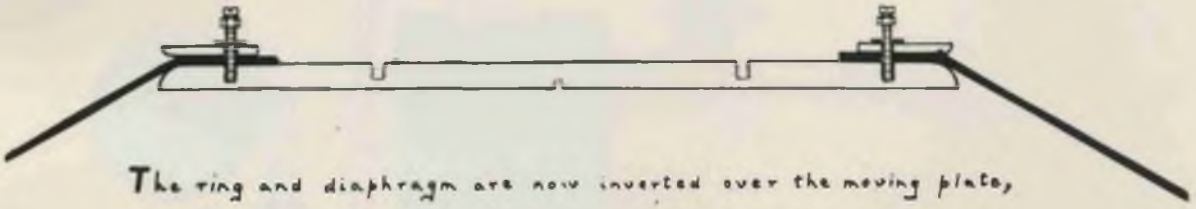
Fig 9. Section through Expansion Chamber (Parts shown dotted are not to scale)



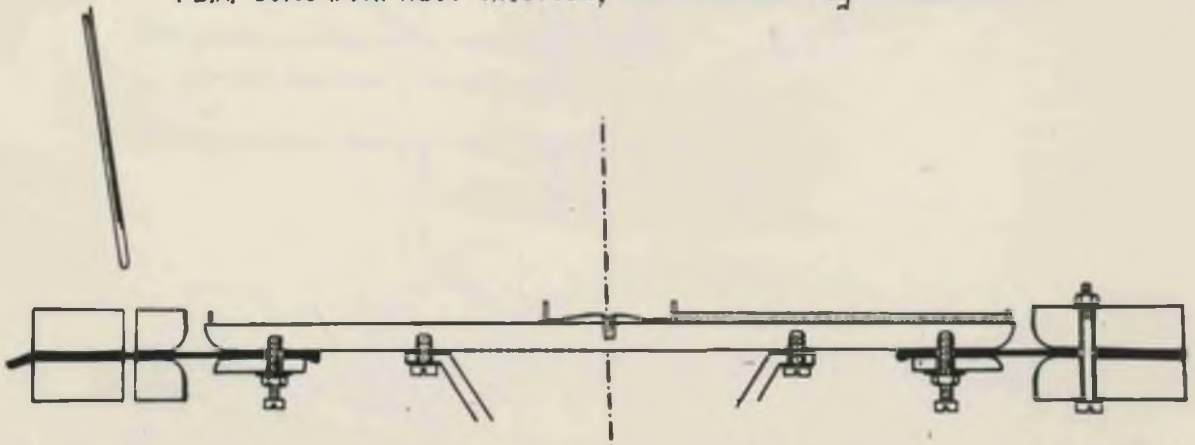
A selected piece of sheet rubber is cemented to the clamping-ring, using a water-soluble glue.



A hot iron wire is applied to the semi-translucent rubber to burn holes opposite those in the brass clamping-ring. The melted rubber is then cleaned off, and the centre of the diaphragm cut out.



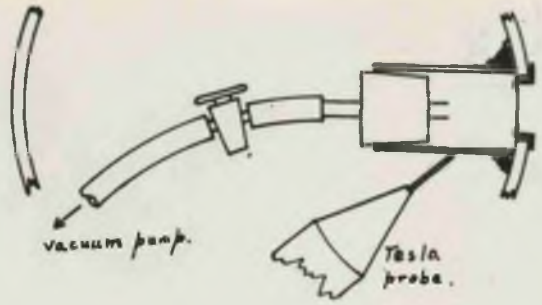
The ring and diaphragm are now inverted over the moving plate, 4 B.A. bolts with nuts inserted, and the nuts tightened down.



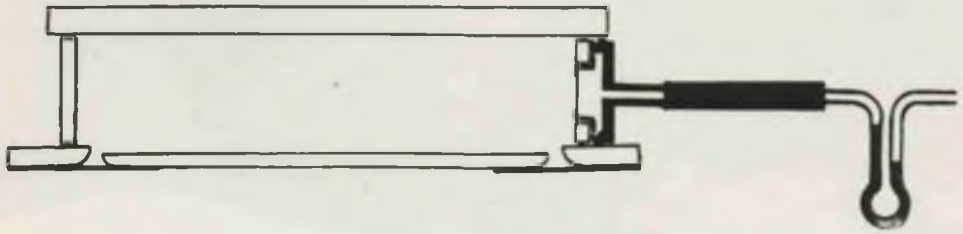
With the plate supported in the chamber, the outer clamping-ring is positioned, and holes burnt.

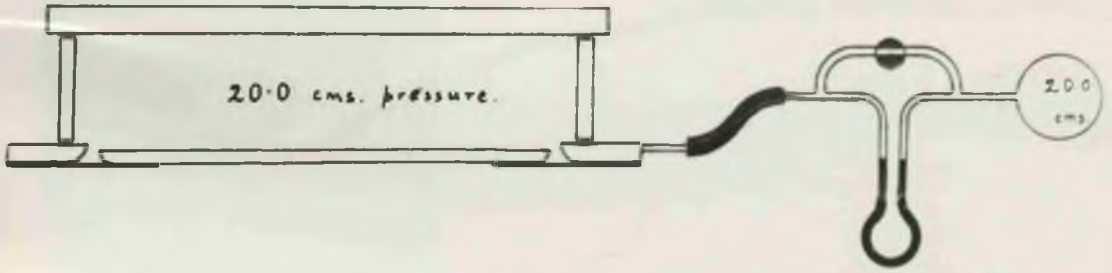
When the diaphragm is clamped, the plate is covered with gel, and the chamber assembled

Fig. 10.

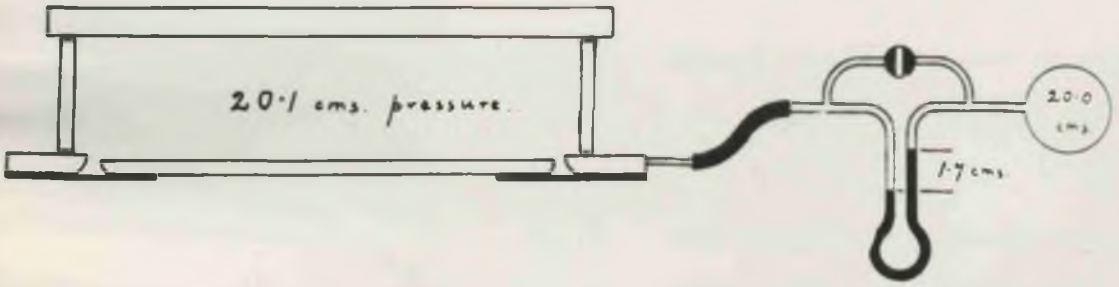


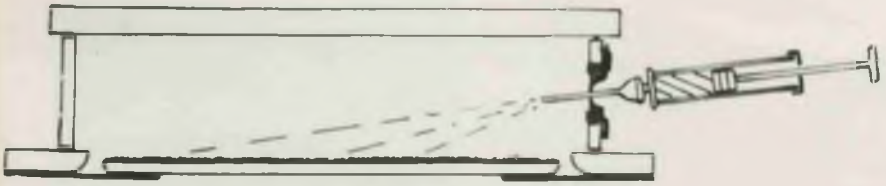
After cementing in place, windows are tested for leaks under vacuum with a Tesla coil. Window leaks developing after assembly can be found by the change on a spirit-filled manometer sealed to the outer surface.





Small changes in pressure resulting from other leaks may be measured rapidly by a differential manometer, independantly of atmospheric pressure.





At first the mercury di-methyl was sprayed over the bottom: later, to reduce chemical fog, a long needle was used to pour it into a central brass cup surrounded by a deep gel.

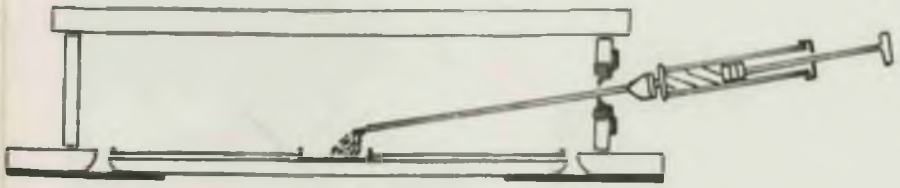


Fig 16 Leak-testing, and injection of mercury di-methyl.

Fig. 17.

Fig. 18.

Fig. 19.

Fig. 17. Methods of introducing mercury-di-methyl: (left) valve for admission of vapour alone; (centre) initial tests with a penicillin bottle, and the brass insert and locking ring later used; (right) the complete injection port, and the hypodermic syringe for injecting liquid mercury di-methyl.

Fig. 18. A 60mm. camera with automatic wind-on cam and microswitch.

Fig. 19. Exploded view of camera and demountable cassette.

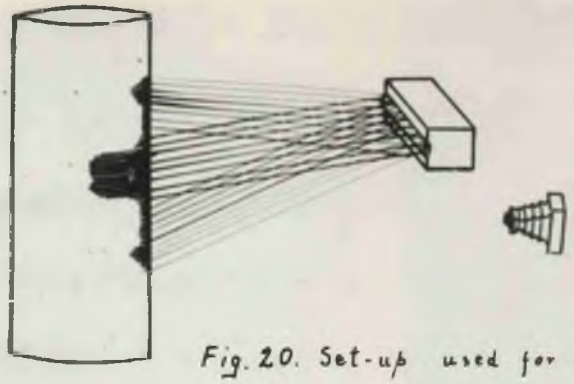
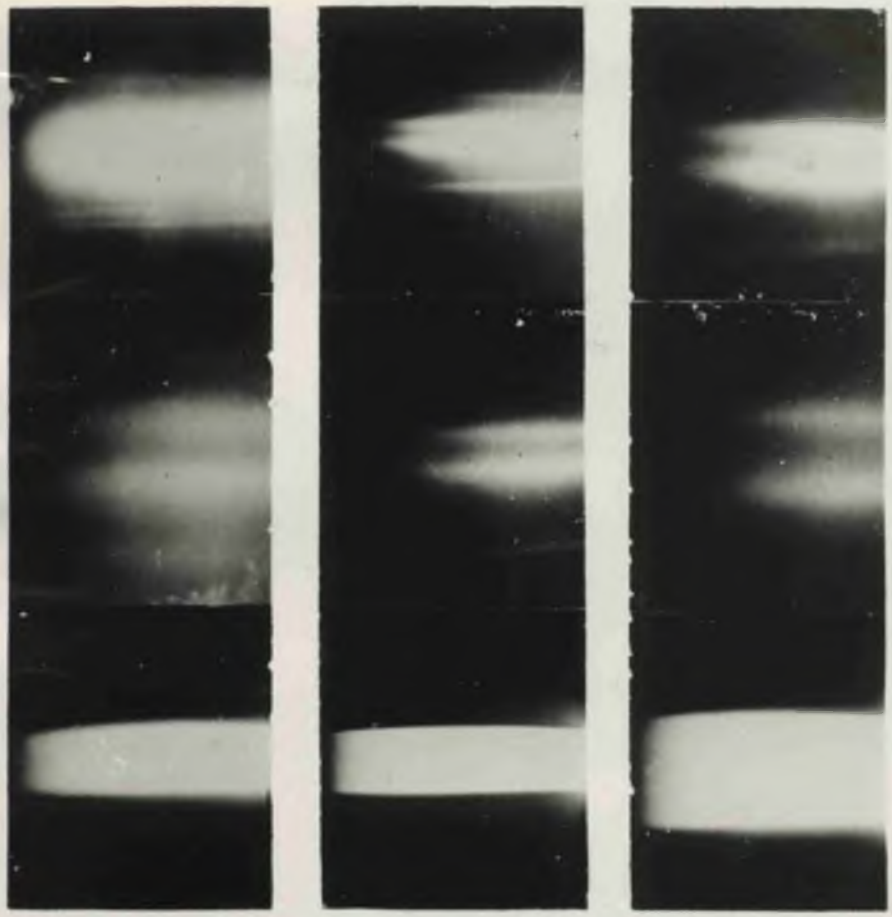


Fig. 20. Set-up used for observing intensity distributions of cylindrical lenses.

LENS:

Perspex. Optical Glass. Soda Glass. GEOMETRY:



a) Cylindrical screen at 10°: no masks.

b) Cylindrical screen at 20°: no masks.

c) Cylindrical screen at 20°: a slit ½" wide is mounted 1" in front of the lens: exposure increased.

d) Plane screen at 20°. The illuminated zone is 20" wide and would therefore cover a 10" dia. chamber with negligible scatter at the far side.

Perspex lens.

Optical glass lens.

II. MODIFICATIONS TO TECHNIQUES AND APPARATUS

i) Properties of Mercury di-Methyl.

One reason for the lack of more recent work on mercury, despite the very full calculations that have been carried out by Massey (1942) and others, rapidly became evident when we endeavoured to obtain the small quantity required for our purposes. Several mercury compounds are used industrially in seed dressing as fungicides, and for this purpose the single methyl of mercury is produced by Messrs. Lunevak Products Ltd., among others, in considerable quantity. Unfortunately it has a vapour pressure that is less than a third that of the di-methyl.

Enquiry at the department of chemistry at this University suggested that the difficulties of manufacture lay less in the process itself than in the highly toxic nature of the compound. As it therefore appeared unwise to attempt the manufacture ourselves, a second approach was made to Messrs. Lunevale Products Ltd., who agreed on this occasion only to make 10 ccs. for us; in fact the amount actually suppled was rather less than this.

In the meantime, despite the disadvantages of foils already referred to, some attempts were made to evaporate metallic mercury on to nylon film, and thus obtain comparative figures by a different technique. This, however, was abandoned as the evaporated mercury

formed minute globules which ruptured the nylon, and a uniform layer could not be obtained.

In addition to supplying us with the material, the manufacturers made a number of valuable suggestions for handling mercury di-methyl in the laboratory; this was particularly useful as the only literature available in the medical press, apart from containing a number of colourful case histories, was solely concerned with chronic poisoning in seed dressing factories, and its effects on the central nervous system. The only laboratory case referred to was the traditional one of the three lab boys who sniffed an unlabelled bottle - and of their sudden demise.

The comments of Messrs. Lunevale Products on handling were to the effect that the liquid could safely be poured from one vessel to another at arm's length in an ordinary room, although they strongly recommended the use of a forced draught fume cupboard when possible; the use of rubber gloves was essential as the compound has an action on the skin similar to fluorine; any liquid spilt, or any vessel contaminated, could be rendered immediately safe by swilling with a solution of sodium sulphite. It may be mentioned that the saturated solution prepared was somewhat unpleasantly caustic on the hands, so some quarter strength solution was kept for routine rinsing after handling apparatus exposed to the vapour.

The technique developed for filling the chamber will be discussed later, but it should be stressed at this stage that the meagre quantity of mercury di-methyl available and the lack of any further prospects rendered it necessary to conserve supplies until an actual run was being undertaken. This, coupled with the very limited information available about its physical and chemical properties, suggested to the author the general line of attack.

It was not clear from his paper whether Champion (1938) had used mercury di-methyl as the condensible vapour, or whether water had been added to fulfil this function. Calculations, referred to later, suggested that it might be possible to use mercury di-methyl alone, probably with a rather high expansion ratio. There would be distinct advantages in this, as the mere existence of tracks would be proof of the continued presence of mercury in the chamber, a point that Champion appeared to have been anxious to confirm.

For this purpose the chamber, after initial testing, would be assembled dry, and filled with dry gas so that no cloud appeared even on over-expansion. Mercury di-methyl would then be added, and if tracks could not be obtained, water could also be added in quantity sufficient to produce saturated conditions, it having

been confirmed that mercury di-methyl does not react with water.

Mercury di-methyl is a powerful solvent and, in general, reacts readily with organic materials; thus in designing a chamber with a suitably high expansion ratio, the scarce, toxic and reactive nature of the compound had to be continuously borne in mind. In addition, in order to make the best use of what might prove to be a rather limited run, a considerable amount of ancillary apparatus was redesigned, and more elegant techniques were evolved. In the following section, these preparations are considered in more detail.

ii) Increase in expansion ratio of chamber

It was hoped to be able to use mercury di-methyl as the condensible vapour, so some modifications were carried out to the moving parts of the chamber. In the absence of any detailed information in the paper published by Champion and Barber on their use of mercury di-methyl in an expansion chamber, some calculations were carried out by D.R. Morrison, based on the rather meagre data available on mercury di-methyl, to estimate the probable expansion ratio required in the presence of argon.

The value of surface tension of mercury di-methyl calculated from its parachor is in good agreement

with that observed experimentally, so a similar calculation was carried out for mercury di-methyl, giving a value of 33.5 dynes per cm. Since the mercury di-methyl molecule has the same number of degrees of freedom as has the ethyl alcohol molecule, the experimental, (rather than the calculated) gamma value for alcohol was taken for mercury di-methyl; again, from the similarity of the vapour pressure curves, it was assumed that, with slight modification, the critical supersaturation conditions for alcohol would also apply to the liquid under review. Thus, with a gamma for the argon/mercury di-methyl mixture of 1.35, and a critical supersaturation of 8.2, it was estimated that an expansion ratio of 1.52 would be required. As the largest expansion ration normally used in an expansion chamber is not greater than 1.31, it was clear that provision would have to be made for a diaphragm or moving plate excursion considerably greater than is normally required.

With a view to limiting the area of rubber exposed it was decided to use a moving plate type of chamber, so it seemed desirable to investigate with some care the best way of obtaining an expansion ratio which could be increased to over 1.5 without damage to the rubber, and which could easily be made much smaller if it became necessary or desirable to use water or some other condensible vapour as well

as the mercury di-methyl.

As a preliminary, attention was directed to the removal of any factors that appeared to have been the cause of rubber failure in the past. These appeared to be three in number; pinholes produced during manufacture, inadequate clamping of the edges, and softening of the rubber caused by exposure to certain cleaning solvents, such as alcohol, benzeneand amyl acetate.

After initial selection over a lamp, the ring of rubber was cut out then carefully stretched over a strong light, to locate any flaws which, especially in earlier supplies of rubber, typically took the form of minute bright spots apparently caused, not by actual holes, but by bubbles formed during manufacture.

It will be seen from the drawing (Fig. 9) that this rubber ring, about nine inches in diameter and two inches broad, provides a vacuum seal between the moving plate and the outside of the chamber, to each of which it is clamped.

As the tension on the rubber is considerable when the chamber is expanded, it is clearly necessary to ensure that the rubber is firmly held by the clamping plates; otherwise creep will occur causing elongation of the holes for the clamping screws. In the outer ring, this presents no problem, as the holes above and below are drilled

clear, and after a clean hole has been made with a burning wire, a bolt and nut will readily give adequate pressure. In the inside ring, however, which is normally assembled first, the clamping ring is secured by screws which are blind tapped into the underside of the moving plate. If the same procedure is used here, and the rubber followed by the clamping - ring is laid on top of the inverted moving-plate, the result is that when the burning wire is used to make the holes, the semi-liquid rubber runs into the tapped holes, and chokes the thread, in due course also fouling the threads of the inserted screws. During assembly, it thus becomes difficult to know when a screw is properly home, and when it is bottoming prematurely on a choked hole.

For the inner ring, then, the following procedure was adopted. First, the rubber was lightly attached to the clamping ring with some water soluble glue such as a seccotine. Once dry, this was mounted, rubber uppermost, with a light underneath (Fig. 10) to show the positions of the holes in the brass plate. A hot iron wire about $\frac{1}{8}$" diameter was now used to make the holes in the rubber, the liquid rubber being removed while still warm. (It was at this stage that the excessive use of solvents had been found deleterious). The rubber/clamping-plate assembly was now located on the inverted

moving-plate proper, and relatively long screws, with nuts previously screwed up to the heads, inserted and screwed home. A box spanner applied to the nuts on the screws enabled the rubber to be clamped uniformly all round, irrespective of the depth of the tapped holes, or of the exact length of the screws; the full depth of thread being utilised in each case.

Having thus taken reasonable precautions to avoid failure of the rubber, coupled, of course, with careful rounding and polishing of the edges of the clamping rings, it remained only to arrive at the best compromise of providing the required expansion ration with the minimum hazard to the rubber.

In the chamber in question, the expansion ratio is varied by altering the upper limit of travel of the moving plate, the lower limit being a wooden block which may be replaced during assembly, but is not otherwise variable. This latter is usually so chosen that, within the normal range of expansion ratios, if the plate is at the upper limit of travel, the rubber is stretched only very slightly, if at all. This permits the use of pressures in the top which, before expansion, are almost up to atmospheric.

As it was by no means certain that good tracks could be obtained with mercury di-methyl alone, and as the addition of water would reduce considerably the required ratio, it seemed most undesirable to

alter the lower "fixed" limit, as in the event of water being added, the rubber would be under a continuous strain. It seemed clear that the best compromise would be to increase the range of the upper, variable, limit, permitting the plate to move almost as far above the equilibrium position as, on expansion, it normally moves below. This would undoubtedly have the marked disadvantage that, in order to obtain a large expansion ratio, it would be necessary to use pressures well below atmospheric in the top half, or alternatively pressure in the bottom half of the chamber to force the plate up, followed at the moment of expansion by a partial vacuum. This was, however, felt to be more than outweighed by the advantages of having a large excursion of the plate obtainable for a minimum amount of strain in the rubber, and the ability to return the chamber to more or less normal working conditions, if it were decided to use added water as the principal condensible vapour.

iii) Increasing window area and eliminating leaks in chamber.

As the side wall of the chamber is a glass cylinder, about a quarter of an inch thick, and nine inches in diameter, it is necessary to provide "windows" which will permit the ingress of electrons without excessive energy loss. If turbulence is to be avoided,

it is also necessary for the inner surface to be flush with the inside of the glass cylinder. Normally this is achieved by drilling a circular hole of about an inch in diameter in the glass cylinder, and fitting into it a brass insert (Fig. 9) to which has been affixed, with beeswax, a disc of mica about .003" thick. The brass is sealed to the glass with some soft material, such as "Q" compound.

In this case, two problems arose. It was intended to use, as a source of positrons, Cu^{62} irradiated in the 30 Mev Glasgow Synchrotron. This is a very weak source, and it was therefore necessary to have as large an area of window as possible. Previous attempts in this Department at making a long continuous window has been unsuccessful, and it was therefore decided to make as many conventional circular windows as practicable. Drilling glass is at any time a rather tedious business, so it seemed a good opportunity to try and improve the technique.

The second problem was that it was known that mercury di-methyl attacked several of the waxes normally used in the laboratory, so some satisfactory alternative to "Q" compound and beeswax had to be found.

The drilling procedure was to clamp the cylinder, axis horizontal, against a vertical board. A dam of "Q" compound was built round the prospective hole, and filled with a mixture of water and carborundum powder. A thin-walled copper cylinder, of the appropriate diameter, was slowly rotated through a flexible drive from an electric drill wired to a Variac, and kept bearing against the cylinder by an axial spring. It was soon observed that grinding occurred rapidly for about a minute after lowering the copper cylinder on to the glass, but that very little happened thereafter, until the copper was raised and again lowered, carrying down fresh grinding mixture. This time could be slightly lengthened by cutting axial sawdrifts in the copper, and this in addition prevented the copper cylinder, which was closed at the top, from "floating" on the liquid. Provided the cutting face was kept well supplied with fresh grinding mixture, the cutting rate could also be increased by applying considerable pressure (released when the hole was almost through); but it was not closely dependent on speed, provided this was not too high.

The unit was therefore modified by fitting a motor, geared down to a suitable speed and using a belt drive with two 3" vee pulleys. This proved

satisfactory, as it permitted the cutter to be raised or lowered (Fig. 12) without using a splined shaft, while the belt (unlike the flexible drive) transmitted sufficient torque to ensure a uniform speed, independent of load. Finally, a worm drive taken off the motor rotated a crank which, via a pair of dogs, automatically raised the cutter clear of the work about once a minute.

The exact composition of the grinding mixture was varied, but a good basic mix was found to be water, light oil, and about 80 screen carborundum powder, with sufficient soap added to form an emulsion. Starting largely with water, which gave the most rapid cutting, the proportion of oil could be increased as drilling proceeded, especially if there was any tendency for the cutter to bind.

With this set-up, the drill could be left largely unattended, except for the occasional replenishment of abrasive, and would drill a one inch hole in four to five hours. A cutter an inch long was found to drill two to three holes in quarter inch glass.

In the absence of waxes, there did not appear to be any material suitable for cementing mica to brass, so it was decided to use copper windows, and soft solder them to the brass. Again "Q" compound

would be attacked by mercury di-methyl, so "cold" Araldite, a self polymerising synthetic resin was used. This necessitated heating the glass cylinder to 80°C for several hours curing, but this was done without mishap. When, however, the chamber was later assembled and vacuum-tested, several leaks were found in the araldite, and the whole surface was coated with vacuum sealing paint. Several months later when the chamber was re-assembled for a further run, leaks were again found in the araldite, and this time also in the copper. This latter was probably due in part to the sulphite "de-contamination" bath in which was immersed everything that had been in contact with mercury di-methyl.

Leak-testing in an expansion chamber is somewhat complicated by the fact that, while high-vacuum technique cannot normally be applied, the standard of sealing must be very high to prevent the ingress, even during the shock of expansion, of traces of unwanted gases or vapours. Normally, a very small hole, drilled through the brass assembly to allow the chamber to be filled with gases, permits the pressure inside to be measured with a mercury manometer, a correction being applied for the ambient atmospheric pressure. in this way a small leak is measurable after about a day. Where, however,

there are in effect six windows, each with the possibility of leaking through either solder or araldite, in addition to leaks through lead seals, the systematic location of leaks by this method is somewhat protracted, and a more direct method becomes necessary. It is unfortunately necessary, as a rule, to saturate the inside of the chamber with the required vapour before assembly; this, coupled with the very poor pumping rate obtainable through the small filling aperture, precludes the use of several otherwise eminently suitable techniques, such as the differential Pirani Gauge, or a Tesla coil and hydrogen jet.

Two techniques were finally developed by the author which were found satisfactory. The first, a high vacuum window tester, was applied to the windows mounted in the glass cylinder, immediately prior to assembly of the chamber. It consisted (Fig.16) of a brass tube, of bore slightly exceeding the hole in the glass, and with one end curved to fit the inside of the glass cylinder; the other end was connected, via a glass tube with a tap, to a vacuum system. This tube was placed over the inside of a window and sealed to the glass with "Q" compound. The unit was then evacuated and sealed off, any leak showing as a change in luminescence

on application of a Tesla coil to the glass tube. Owing to the small volume involved, this provided a fairly rapid test, while if a leak was observed, the window, or araldite, or both could be covered on the outside with "Q" compound for confirmation.

The second technique was intended for use when it was desired to test a window in a chamber already assembled. Here the previous method could not be applied, as windows are normally designed to withstand pressure in one direction only. A similar, but lighter unit was therefore made and stuck, again with "Q" compound to the outside of the window in question. This in turn is connected to an alcohol or water differential manometer (Fig.16). Again owing to the small volume involved, and the great sensitivity of such a manometer, any leak in the window rapidly appeared as a fall in pressure in the outside unit.

Some difficulties had previously been experienced with leaks occurring at the lead wire seals between the glass cylinder and the brass frame, so the use of rubber sealing rings of channel section was contemplated. After some trials, however, it was decided that, although they had many advantages, the non-availability of conducting rubber in this form would necessitate a conducting coating on the top plate of some such material as colloidal graphite in order to

establish an electrostatic clearing field across the chamber, and it was therefore felt that the completely inert lead wire was simpler and therefore preferable. It was found that if wire and glass were carefully cleaned, if the wire was smoothed with fine emery paper followed by a trace of vacuum grease, and if the top clamping plate was slowly and evenly clamped down, a half turn at a time on diametrical nuts, a good permanent seal was obtained.

iv) Temperature control of chamber

In order to maintain the gas in an expansion chamber saturated with vapour, it is necessary to have an excess of liquid. This liquid, or film of liquid, must however be restricted to the bottom of the chamber; if it is allowed to condense on either the top or walls, this will scatter light and prevent clear photography; while if it accumulates, it will run down the sides, and in the case of a moving-plate chamber may be thrown up in an atomised cloud by the rubber ring joining the moving plate to the edge of the chamber.

Purely from the standpoint of controlling the surplus liquid, undoubtedly the most satisfactory method is to circulate cooling water through

the bottom of the chamber. In practice, this is not without its disadvantages. If it is to serve its purpose, it must be left on continuously, and in a laboratory the water pressure rises considerably at night and fluctuates during the daytime. In addition the temperature is not constant - variations of several degrees can take place in a matter of minutes, and may seriously affect the consistency of track quality.

For these reasons alternative methods of maintaining a temperature gradient between the bottom and the rest of the chamber were explored. A warm pad on the top of the chamber was already in use between runs to prevent misting-up, so the logical step was to wind several turns of resistance wire round the glass cylinder, the wire being then cemented in place and leads brought out. This proved remarkably successful from a "storage" point of view, the expansion ratio remaining substantially constant even after lying for several days; but after the chamber had been running for an hour or so, the top began to mist over. Any treatment of the under surface of the glass plate forming the top of the chamber with proprietary ahti-mist preparations was not satisfactory as the improvement lasted only a few hours; moreover, the possibility of thereby introducing undesirable condensation nuclei into the

chamber could not be overlooked. A small hot-air blower - similar to the commercial hair-dryer - was therefore constructed, and mounted in such a way that it could be switched on if necessary while the chamber was in use without interfering with the operation of the cameras. This was used with success for some considerable time. When, however, it became possible to construct a ball-cock cistern for the sole use of the chamber, this, combined with the heating coils referred to, was perhaps ideal, as it provided water at a head of a few feet only, which could easily be controlled down to a trickle, and which, with several hours supply always in the cistern, was not subject to rapid temperature changes. Also, while the heating coils and blower alone had dealt effectively with the glass sides and top, there had been a tendency with a lot of liquid for some to condense on the exposed brass at the edge. While not normally serious, this could in a long run have accumulated enough to cause trouble.

Thus, with the chamber temperature effectively stabilised, it only remained to maintain a constant room temperature free from temperature gradients; this was attained by the use of radiators, draught screens, and deflectors over the ventilating air ducts.

Where a chamber with a considerable amount of liquid has to be left for a week or more between runs, present technique is always to leave on both water and heating, to prevent damage in the event of failure of either.

v) Forms of resevoir suitable for non-aqueous liquids and methods of injecting vapours and liquids.

Certain gases and vapours diffuse through rubber sufficiently rapdiy for the resultant loss to be a source of experimental error, while with others a slow chemical action takes place with the rubber causing the liberation of undesirable products. Where either of these effects is anticipated, the piston or moving-plate type of expansion chamber has the considerable advantage that the amount of rubber is reduced to an annular washer joining the moving plate to the side walls.

As it was supected that a reaction might occur between mercury di-methyl and rubber in view of its known affinity for certain other organic materials, the use of a moving plate expansion chamber seemed clearly indicated; this, however, raised in turn new problems.

When using a moving-plate expansion chamber with water as the condensible vapour, normally the most efficient method is to cover the bottom plate (consisting perhaps of black lacquered brass) with a

wet gel consisting of water, gelatine, and a bacteriostatic such as copper sulphate or acetyl-salicylic acid. Within its limitations such a bottom is excellent, as its glossy surface does not scatter light from the side lamps up towards the cameras, while the wet surface of the gel traps most effectively any dust or other condensation nuclei which may be present; finally, owing to the large volume of loosely-bound liquid distributed over the plate, there is never any doubt that the gas is maintained in a uniformly saturated condition.

It does, however, suffer from one very severe limitation; it can only be used when water is the condensible vapour. It is true that small quantities of alcohol may be added to the water, but more gelatine must be used; even so the gel becomes unstable and above one part of alcohol to two parts of water a curd begins to form, and the gel breaks up altogether.

Apart from the impracticability of making a gel with mercury di-methyl alone, the desirability (for other purposes) of being able to use mixes of alcohol and acetone as well as water (Beck, 1941) suggested investigating alternative forms of chamber bottom.

The first approach was to look for a direct alternative to gelatine, that is, some substance which would form a clear (or black) gel composed of the required liquid and such inert components as necessary.

It early became evident that there was no suitable gel which did not require the presence of water. The possibility of a thick emulsion was explored, but, while this might have possibilities for some mixes, nothing was found that would be sufficiently firm over a normal range of temperatures, and the project was dropped.

The third possibility was to use a wetting agent to maintain a film of liquid onablack glass plate secured to the moving plate. Usmg a proprietary anti-mist preparation with water was successful, and good tracks were obtained; but the amount of liquid which could thus be safely carried left rather a small margin, and again the problem of suitable wetting agents is one that would have to be solved afresh for each new liquid.

As it did not appear possible to provide inside the chamber a liquid reservoir of general utility, the possibility of using an external reservoir was explored. (The use of black velvet, as in rubber diaphragm chambers, was considered, but the idea was shelved pending an investigation into the effect, if any, of mercury di-methyl on velvet).

It was accepted as axiomatic that there must be no re-entrant cavities in the chamber walls such as might cause turbulence during an expansion;

equally it was clear that an aperture must be provided of size sufficient to permit of free entry of vapour, probably during clearing expansions. Thus the method used for admitting gas to the chamber, through a 1 mm. hole with a tap outside the chamber walls, could not be applied.

A valve was therefore developed to a design analogous with the mushroom valve used in petrol engines. When the valve is closed (Fig.17) the rubber-faced plate bears against the flange on the brass insert, almost flush with the inside surface of the glass wall and providing a vacuum-tight seal, while when open the effective cross-section is about 1 sq. cm. This valve, which was normally held closed by a return spring, was opened manually at intervals to allow vapour to be drawn into the chamber from liquid in a small glass flask.

With a dry, polished, black glass plate on the bottom and the valve closed, the chamber was evacuated and filled with dry nitrogen. With a 1.35 expansion ratio no cloud was obtained, confirming the absence of moisture, so the valve was opened, admitting a mixture of water and alcohol vapour. A normal cloud was now obtained but, as

might be expected, this failed to clear sufficiently to obtain tracks.

A thin layer of white vaseline was now run on to the glass plate, and the same procedure followed. The chamber now cleared almost as rapidly as with a gel on the bottom, and good tracks were obtained although a slightly milky appearance in the vaseline appeared as a background. It was, however, always necessary to use a slightly higher expansion ratio than normal, showing that the vapour pressure was slightly lower than saturation pressure. This, however, was not without its advantages, as the normal tendency for the liquid to condense on the sides and top was entirely absent. Although it might be expected that the expansion ratio would be more sensitive to temperature changes than with a saturated gas, no excessive drift was observed.

It had now been ascertained that there was no observable reaction between the velvet and mercury di-methyl, so a disc of black velvet was attached to the moving plate, and the previous procedure repeated, vapour only being admitted through the valve. Photographically this bottom was very good, the fact that, on expansion, it was pulled well down out of the illuminated field giving it a marked advantage over the same bottom in a fixed position in a rubber

diaphragm chamber. It was found less efficient in dust collection than vaseline, but provided care was taken to exclude dust when assembling the chamber, good tracks with little background fog were obtained.

The best method of mounting was found to be to stretch the (washed) velvet over a tight ring, to which it was stitched. The edges were now painted with cellulose lacquer to prevent fraying and then trimmed close. The ring carrying the velvet was secured to the bottom plate with four small screws.

In view of the rather slow clearing observed with dry velvet the chamber was opened, and approximately 5 ccs. of water/alcohol sprayed on the velvet with an atomiser. On assembly this was found to give much more rapid clearing and of course complete saturation with concomitant tendency to condensation on the walls.

If mercury di-methyl were to be used alone as the condensible vapour, there appeared to be two possible procedures,

(i) to use an external reservoir, and either dry velvet or a black glass plate with a film of some clear grease.

(ii) to spray the velvet with liquid before assembly.

The nature of the mercury di-methyl was also a factor to be considered; the quantity available was small, it is difficult to obtain, and its vapour is highly toxic. For all these reasons it seemed desirable to have the chamber assembled and leak tested before admitting mercury di-methyl. On the other hand it had already been observed that the presence of sufficient liquid to moisten the velvet improved the clearing considerably.

It therefore seemed desirable to cover the bottom of the chamber with dry velvet, assemble, leak-test, fill with the required gas at about 60 cms. pressure, then add the required quantity of liquid and seal off. While it appeared possible to add the liquid with the gas at atmospheric pressure, seal off and subsequently reduce pressure by connecting the normal aperture to a small evacuated vessel, it was clearly preferable to add the liquid without contaminating the gas inside, and if possible without altering the internal pressure.

A promising solution appeared to lie in the self-sealing rubber caps on the bottles in which antibiotics are frequently supplied, permitting small amounts to be withdrawn without contaminating the remainder. One of these bottles, of about 10 ccs. capacity, was obtained and partially evacuated by withdrawing water with a hypodermic syringe (Fig.17)

A hypodermic needle, connected to an open manometer, was inserted and, over several days, the pressure (initially about 20 cms. below atmospheric pressure) showed no tendency to increase. A later test with a cap that had been punctured twice, sealing an evacuated 50 cc. container showed that the leakage, if any, did not exceed 0.1 mm. per day. In addition, the shape in which the caps are moulded permitted the insertion of a rubber bung over the punctured portion, so this appeared entirely satisfactory.

A trial was made, with a suitably mounted cap, and a chamber filled with dry nitrogen to a pressure of 60 cms. With a hypodermic syringe 2 ccs. of a water/alcohol mix was injected, spraying the liquid in a fan-like shape over the velvet. After the chamber had settled down, and the rather well-defined lines of liquid had evaporated and re-condensed over the velvet, good tracks were obtained with a very satisfactory background.

As there appeared no point at which this process could not be repeated with mercury di-methyl, the procedure was adopted.

vi) Testing of cylindrical lenses, and design of lamps for chamber photography

The illumination of an expansion chamber for optimum photographic quality demands even intensity

over a layer of the chamber about two centimetres deep, and as little light as possible above or below this. Further, to enable high-contrast film to be used, the spectrum of the light should correspond reasonably with the rather blue-sensitive emulsion of most recording film.

With a view to the latter, early workers used very much over-run tungsten lamps, sometimes flashed at double voltage during an expansion. The earlier forms of mercury vapour discharge tubes represented a considerable improvement in that, apart from spectrum considerations, they provided a line source. This, used in conjunction with a cylindrical lens, is capable of providing a "sheet" of light which is almost ideal.

The more recent form of discharge lamps, filled with a rare gas, had been in use in this department for some time, but several different types of lamp and mounting were being used, and these were not in general interchangeable. In these lamps, the tube containing the gas and electrodes was enclosed in an outer tube, the scattered light from which, during a flash, effectively increased the size of the source to an inconvenient extent. Thus it was when the new range of Mullard

lamps, with no casing and a long narrow tube, became available, it was decided to standardise on them, and design a lamp-house which would accommodate any reasonable variations in pattern, and which could be fitted to any of the expansion chambers in present use.

The first step was the selection of a suitable lens. Three speciments were considered, of focal length between 1" and 2", and from one to two inches broad by three long. The exact length was not regarded as important as, unlike earlier versions, the lamps had a luminous length of some 10", and thus several lenses would have to be used end to end.

The first lens was concavo-convex, machined in perspex and polished; focal length 1½", breadth 2".

The second was optically ground glass, of focal length 2½" and breadth 2".

The third was a moulded soda glass lens, with a focal length of 1¼" and breadth of 1". The two latter were plano-convex.

In order to ascertain the suitability of these lenses under working conditions, a "mock-up" lamp was constructed by Mr. Lloyd, of this department. It consisted of a glass tube, of similar dimensions to that of the proposed lamps, and containing a tungsten filament. Unlike the discharge lamps,

this could be run continuously, permitting adjustments in focussing and masking to be made.

This lamp was now set up (Fig.20) with the condensers in turn, and the image projected on a cylinder covered in white drawing paper, the axis of the cylinder being at right angles to the axis of the cylindrical lens. A plate camera mounted above the lamp was used to photograph from a constant distance of 20" the pattern projected on the screen by the lens under test.

The purpose of using a cylindrical screen, was to obtain a first approximation to a polar diagram of the lens without the use of a photometer. The light incident at any point on the screen produced an intensity dependent on its original intensity and the Cosine law.

This was photographed, using a plate of moderately high contrast such as Ilford Special Rapid. If an intensity I_o falling in the centre of the screen produced a certain opacity in the plate, then the intensity I_1 required to produce the same opacity at some distance x from the line joining the centre of the cylinder (radius r) to the camera, would be given by:

$$I_1 = I_o / \sqrt{(I - x^2/r^2)}$$

Thus if $I_1 = 1.5\ I_o$, $x = 0.7\ r$, or if $I_1 = 2\ I_o$, then

$x = 0.9\ r.$

A set of photographs, taken with the lamp at 10", then 20" (Fig.20: a,b), showed that the spread was considerable. The double line of the source is due to the double tungsten wire; the equivalent discharge tube would have a uniform source the same width.

After some experiments with adjustable masks, an opaque screen with a slit $\frac{1}{8}$" wide was mounted in front of the lenses, and the exposure increased to detect any remaining scattered light.(Fig. 20 c)

These photographs show a marked improvement in every case.At 20", the perspex and optical glass lenses gave a beam $\frac{3}{4}$" wide, while that of the soda glass lens was $1\frac{1}{4}$" wide; in the latter case, the intensity appeared only slightly less, despite the wider field.

It seemed to the author that the narrower field of the first two lenses was desirable, and therefore two further photographs (Fig. 20 d) were taken comparing their field on a flat screen 20" wide, illuminated from a distance of 20". This showed the perspex much the less satisfactory of the two.

Later discussion suggested that the wider field of the soda glass lenses would not necessarily be a disadvantage, especially as they would

not normally be used at so great a distance as 20". In addition they were naturally much cheaper than their optically ground counterparts, a not inconsiderable factor as three would be required in each of some six or eight lamps.

The author designed a simple housing, suitable for construction in Tufnol or similar insulating material. In the front (Fig.11) the edges of a slot $\frac{3}{4}$" by $10\frac{1}{2}$" were recessed to take the three lenses, which were held in position by an aluminium plate having a $10\frac{1}{2}$" by $\frac{3}{4}$" slot. This aluminium facing extended $\frac{1}{2}$" above and below the front, being bent back over the top and bottom. Tufnol and similar materials appear translucent under the very high intensity of discharge lamps, and this, combined with the necessity for preventing any stray light from cracks, was the reason for providing a complete aluminium facing towards the chamber.

Bearing in mind the strong secondary lobes that had been observed (Fig. 20 b) a mask with a slit $\frac{1}{2}$" wide and of length equal to about two thirds the diameter of the chamber was mounted 1" in front of the lamps, and secured to the supporting pillars.

The lamps themselves, held in small Terry

spring clips, were mounted on short ebonite pillars which were fixed to the bottom by screws tapped into the pillars, and passing through slots in the bottom. These slots were obscured to light by oversize washers under the screw-heads. Thus focussing could be carried out safely, and without opening the case; while the clips and their mounting pillars could easily be altered to accommodate varying diameters of lamp.

The lamp housing was mounted on pillars extending horizontally, and supported by the short vertical pillars clamping the top and bottom of the chamber. Over these horizontal pillars fixed to the chamber were fitted hollow pillars, secured to the lamp house. As these latter would normally be in line with the centre of the chamber, and thus with the centre line of the lamp and lens, and as the separation of the two pillars would be much less than 10½" with the smaller size of chamber, a bridge joined the hollow pillars to the studs projecting from the front of the lamp house above and below the lens. The lamp could be tilted slightly for alignment by altering the relative length of top and bottom studs. Several pairs of holes were therefore tapped into the front of the lamp house corresponding with the pillar separation found on

various chambers. To avoid blind tapping in the rather thin (¼") material, these holes were tapped right through, and strips of thin aluminium secured along the back, to mask the holes not in use. To these strips were attached narraw vertical strips to mask any gaps between the lenses.

In use these lamps were connected to a bank of capacitors, each lamp having its own bank, which was charged to a potential of 2 kV. An electrode external to the lamp was wired to the high voltage side of a car ignition coil. At the appropriate interval after an expansion had occurred, a small charged capacitor was connected with the primary of the coil, and the resultant high voltage pulse applied to the lamp, causing sufficient ionisation to initiate the discharge.

In the past, this external electrode had taken the form of a semi-circular reflector, fixed to the lamp along its working length. This appeared to have the effect of increasing the apparent source diameter, so instead a few turns of wire round the tube were tried, but as this did not give regular firing, the reflector system was returned to. With the Mullard lamps, however, the effective length extends to within about a centimetre of the terminal wires, fused into the ends of the tube. It is thus difficult to prevent the trigger pulse tracking to these terminals, and

failing to discharge the lamp. A compromise was found in two bands of fine wire some five inches apart near the centre of the tube, with a wire between them, passed several times round the tube (Fig. 11). This method was free of tracking, and fired the lamp regularly, without in any way increasing the effective size of the source.

vii) Alterations to cameras and photographic procedure.

The small quantity of mercury di-methyl available, coupled with the decision to run the chamber continuously, made it doubly necessary to ensure that on the photographic side particularly, there would be no delays or complications. It was for this reason that one major alteration in the previous camera design was made. The cameras, which had been specially made in this department (Fig. 18) were broadly based on the design of certain Leica 35 mm. models, the main differences being in that they used 60 mm. perforated film, were not fitted with light tight casettes, and had a small built in motor for advancing the film. In addition, the removal of a light tight plate on the back permitted the insertion of an optical condenser for reprojection purposes. As in the Leica the film passed over a sprocket, one revolution of which corresponded with an advance by one frame by the film. A cam on the sprocket shaft operated a switch, wired in parallel

with the wind-on button, so that once the film started moving, the motor remained on until the sprocket had completed one revolution.

Unfortunately, the spacing of the perforations was not always uniform, and in one film the apparent exposure of every alternate frame was traced to the film moving over the sprocket in a curious manner: the holes in the film would fit over one tooth, then jump the next, and so on, with the result that, for every tooth in the sprocket, two perforations were allowed to pass. In addition, it appeared that tears in the film, in the cameras or during processing, usually started with a torn hole in the perforation. It therefore seemed worth looking at the possibilities of using non-perforated film, and modifying the cameras accordingly.

Although the casettes had been designed to accommodate 100' of film, more than 25' had never been used, as this was the limit of the spiral tank used in processing. The size of the core in the take-up casette, to which the film was attached was therefore increased to the diameter of a 75' roll of film, the added 25' now just filling the casette. One complete turn of this core now advanced the film by three frames at the beginning of the film, and towards the end about three and a quarter frames, owing

to the slight increase in diameter. The sprocket was now replaced by guide rollers, and the switch operated by a negative cam having three depressions, and mounted on the casette drive shaft.

One factor remained; with the sprocket, if the film broke or ran out, the sprocket did not turn, and the wind-on motor ran continuously until switched off. With, however, the cam operated switch, the motor rotated the casette core by one third of a revolution, whether any film was passing or not, thus giving no indication of a film that had broken, or was finished. A small insulated, spring-loaded ball bearing was therefore made to bear on the film at the very edge, pressing it against a smooth conducting surface. This in turn operated a warning light, as in the absence, for any reason, of film the ball made contact with the film guide underneath.

An earlier attempt at making light-tight casettes had been unsuccessful, but it was clearly undesirable to have to remove the cameras to the dark room in order to unwind the film from the take-up casette for processing; some compromise was therefore sought.

An unperforated film, tightly rolled, can safely be exposed to dim lighting; the outside layer will it is true be fogged, but the end six inches or so

are normally required for threading up in any case, so their loss is not serious. Some tubes were therefore cut, 2" diameter by 2½" long, to fit over the core of the take-up casette (Fig.19). They could be slipped easily over the ebonite core, a screw in the latter engaging in a slot in the tube, so that they turned as a unit. A small piece of adhesive tape attached the end of the film to the tube.

The procedure for reloading cameras was therefore now as follows:-

The new film and wrapping was removed from its tin.

With lights dimmed, the camera was opened, the casette removed, and the tube and film placed in the vacant tin to await processing.

With normal lighting, a new tube was fitted to the take-up casette, which was replaced in the camera, and the driving dog engaged.

With lights dimmed, the new film, on its cardboard core, was mounted in the run-off casette, the end led through the gate, and attached to the adhesive tape.

The back being replaced, the camera was ready for use, and the exposed film, in its tin, could be removed for processing.

The whole process, for both cameras, took normally about three minutes, so that only one expansion need have passed unphotographed.

One 25' roll of film would take about 120 exposures; so, if the chamber was cycling at the rate of one expansion every two minutes, a film would last some four hours. If therefore the original intention were carried out and the chamber operated continuously, from as soon as possible after the injection of mercury di-methyl until sufficient photographs had been obtained, or tntil track quality deteriorated, then it would be desirable to process and later identify films at the rate of two every four hours, or twelve every day.

It had long been the practice of the author to photograph at the beginning of each film, a slate bearing in chalk the date, gas in use, source, exposure and film. This slate was laid accross the top of the chamber; although out of the focal plane, it was clearly recorded on the film in such a size as to be readily legible. The exposure, with normal room lighting, was usually in the region of a second. This was again used, a serial number being substituted for the date.

The identification of individual frames for

analysis had been done by numbering each fifth frame with a chinagraph pencil, or alternatively, a sharp scriber. This, however, apart from taking a considerable time, had been found liable to errors, with consequent delay when correlating films, or identifying effects observed during a run. An automatic system of numeration was clearly necessary.

At an earlier date the author had constructed a device to count the actual number of flashes of a discharge lamp. This consisted of a coil that could be laid on top of the chokes wired in series with these lamps to lengthen the flash. The output from this lossely coupled secondary fired a gas triode and thus recorded the number of flashes on a Post Office type counter.

As it was intended to continue giving every film a serial number, it seemed unnecessary and undesirable to record more than the actual frame number; again the digits on a P.O. counter are so small as to make their identification difficult after photographic reduction by a factor of five. With these considerations in mind, it was decided to base the new device on a uniselector. This would not operate directly off the lamp flash counter just described, but in this case it appeared an

asset rather than otherwise that the number of frames wound on should be counted rather than the flash of either or both lamps. As the camera wind-on motors operated from a 24v. supply, this made a convenient source of pulses for the uni-selectors.

The previous practice of numbering every fifth frame had proved convenient in principle, so was retained. One uniselector was used as a divide by five device, and fed pulses to a second uniselector, at every fifth frame. The shaft of this rotated a six-inch perspex disc (Fig.13) to which was affixed a disc of Kodaline paper, bearing round its circumference the numbers 5, 10, 15, 20, - - - 150, in white on a black ground. A small lamp behind this paper was switched on for every fifth cycle of the chamber.

The second uniselector was of an obsolete type with eleven ways and triple arms. Thus one complete revolution was performed in 33 steps. As this corresponded to a count of 163, and more than 130 frames were unlikely, the last four positions were wired to the homing contacts on the first uniselector, so that if the film ran out at, say 125, after changing film it was only necessary to rotate the disc by hand through the remaining places to reset, and in the process the first uniselector

would also reset itself, while winding off the first four frames advanced it to "0", at which point the slate bearing the serial number of the film was inserted.

Pending modification of the cameras to enlarge the field and permit the numbers to appear between frames, the numerator was used in conjunction with the chamber log book, both on photographing and on reprojection, the decades being read off the perspex disc, and the integers from a small scale attached to the first uniselector.

viii) Alterations to make chamber fully automatic

Earlier work by F.C. Champion (1938) had suggested the possibility that mercury di-methyl might decompose or be absorbed. While he himself did not believe this, it was clearly a contingency which could not be ignored. It therefore seemed desirable that the whole run be carried out as rapidly as possible after the injection of the mercury di-methyl. Also it had been found that much could be gained towards uniform results by complete standardisation of procedure.

It was therefore decided to make the whole operation of the apparatus completely automatic. Thus, once the minimum cycling time for good tracks had been ascertained, the period between expansions

need never exceed this time, even if other adjustments were being carried out.

The expansion chamber was ready for a fast expansion when the following conditions were fulfilled;-

i) The pressure in the lower half of the chamber was atmospheric, and the moving plate was therefore resting against its upper stops.
ii) The solenoid valve connecting the lower half of the chamber to the vacuum reservoir was closed.
iii) The pressure in the vacuum reservoir was about one centimetre of mercury.
iv) The discharge lamp condensers were fully charged.

The sequence would then be as follows;-

a) The camera shutters opened.
b) The solenoid valve opened, and the plate, with now a partial vacuum underneath, moved rapidly down to its lower stop, causing an expansion to take place.
c) The lamps were discharged by the application of a trigger pulse.
d) The camera shutter was closed.
e) The solenoid valve was reset.
f) A rotary two way valve was started, connecting

the lower part of the chamber alternately with the vacuum system and the atmosphere, producing a succession of slow expansions automatically. This device was known as "George".

g) When a fog was no longer obtained on slow expansions, usually after two or three, "George" was stopped while the plate was in the upper position.

h) The chamber was left undisturbed for about half a minute to allow the drops formed by slow expansions to settle, and meanwhile the film in the cameras was wound on to the next frame.

The chamber was now ready for the next expansion.

It was thus necessary to design a rotary switch to perform these operations, and in such a way that each function could be adjusted in sequence and duration.

Already several of these operations were grouped under a master switch. When this was closed:

a) The solenoid valve was short-circuited, causing the lower part of the chamber to be connected with the vacuum system, and an expansion to occur.

b) If required, the electrostatic field was removed.

c) After a delay, variable between 0 and 1 second, a triggering pulse was applied to the discharge lamps, causing them to fire.

d) "George" was switched on, producing a succession of clearing expansions.

When the master switch was (manually) opened:

a) "George" switched itself off when the lower chamber was next connected with the atmosphere, i.e. when the plate was up.

b) The electro-static field, if switched off, was restored.

The prospective rotary switch was therefore required to:

i) Switch on the master switch and, after 1/3 to 2/3 of the complete cycling time, switch it off again.

ii) Reset the solenoid-operated chamber release valve before any clearing expansions occurred.

iii) Wind on the film in the cameras.

iv) Open the camera shutters for about one second during the expansion, the actual timing being done by the flash lamps.

Special cameras had already been designed in this department for expansion chamber work (Fig.18)

and they were already provided with wind-on motors and solenoid operated shutters; so, apart from some modifications described elsewhere to permit the use of non-perforated film, they required no alteration. Thus the fitting of a solenoid to the reset arm of the chamber release valve was the only change needed to make all the operations purely electrical.

As a cycling time of approximately two minutes was envisaged, and it was desired to avoid having the camera shutters open for more than a second, some doubt was felt about the reliability of a cam operated switch closing for only 3° of arc, with a tolerance of $\pm 1^{\circ}$ with reference to a second switch. A further problem was that it was desired to keep shutters open for about the same time irrespective of changes in the overall cycling time between say one minute and three minutes.

With these requirements in mind, the following design appeared satisfactory. A motor (Fig.), driven through a variable resistance as fine speed control, drove the switch through a train of interchangeable Meccano gears, giving ratios of 1 to 1, 2, 3, 4, 6 or 9. On the rotating shaft were secured five brass-bushed discs of ebonite, $2\frac{1}{2}$" in diameter, and $\frac{1}{2}$" long. On the periphery of two of these were inset sectors of copper 120° long, and

electrically connected with the shaft. Two standard P.O. relay contacts, connected together, and bearing on the periphery of the discs were wired to the master switch, the shaft providing the oommon return. When the two discs were set so that the two copper sectors made contact simultaneously, the master switch was made for one third of the total time, while if one was set to make contact at the point when the other sector was on the point of breaking, the master switch would be made for two thirds of the total time. (It may be mentioned that if the sectors were disconnected from the shaft, one relay contact being wired to the switch, and the other to the common return, a range of 0 - 1/3, instead of 1/3 - 2/3 could be obtained).

In each of the remaining three discs axial saw-drifts were cut in the edge, and small strips of 1/16", 1/8" and 1/4" copper sheet inserted. With the surface turned smooth, the protruding ends of the strips were tinned, and in due course the appropriate one connected by a short pigtail with a tag on the central bush. These thicknesses were chosen to give contact times of about one second with cycling times of 4, 2, and 1 minutes respectively. Although unnecessary for the chamber release valve reset contact, this was essential for the shutter

and for the camera wind on circuit. In the latter case a pulse longer than two seconds would result in two frames being wound on. Here two separate relay contacts, one to each motor, were staggered so that the motors were wound on independently; a provision that was found necessary, as otherwise one motor running slower than the other, would cause the second faster motor to wind on twice. (Fig.15). The winding on of the cameras could take place at any part of the cycle, but it was arbitrarily chosen that the second motor should wind on about five seconds before an expansion occurred, and across this motor was wired a relay connected as a buzzer; as an indication that an expansion was about to take place, this was found preferable to a warning light.

It has already been mentioned that with the expesure kept at one second, the setting of the shutter contact would be rather critical, so the author made a fine adjustment on this disc (Fig.14). The disc was left free on its bush, to which latter was affixed a short tangential arm, with a slightly elongated hole at its end. Through this a 1", 4 B.A. screw was passed, and screwed into a transverse thread on a self aligning boss mounted in the ebonite at the same radial distance. A compression spring on the screw kept the assembly firm.

Once the requisite number of clearing cycles, and the necessary "rest" period had been determined, the motor and gears were set for the appropriate cycling time, and discs 1 and 2 adjusted to give the appropriate number of clearing expansions. The one-second sectors on the other discs were wired, and numbers 3 and 4 set to make contact just before, and just after the expansion, for camera wind-on and chamber valve reset respectively. The shutter disc was now set to open the shutter at approximately the moment of expansion, the fine control being later used to synchronise the actual opening with the earliest probable time of firing of the discharge lamps.

This then provided for all the basic operations: in addition, separate switches and buttons made it possible to isolate any circuit, or operate it, or the whole chamber, manually.

In order to measure the energy of the particles photographed, this chamber was mounted between a pair of Helmholtz coils and these, dissipating some 50 watts, disturbed the thermal equilibrium of the chamber if left on continuously. They were therefore controlled by a heavy duty relay, which in turn, operating from the shutter circuit of the rotary switch, was closed only for one second covering the period of an expansion.

Having thus developed apparatus and techniques for assembling and vacuum-testing a mercury di-methyl resistant expansion chamber, for saturating it with mercury di-methyl vapour and subsequently taking photographs as rapidly as possible, it was now felt justifiable to proceed to the final assembly and filling of the chamber.

Fig. 21.

Fig. 22.

Fig. 21. General view of chamber. The upper Helmholz coil and one lamp have been removed to show the windows and injection port connected to a liquid-air trap to recover mercury di-methyl.

Fig. 22. Erosion of gel caused by liquid mercury di-methyl injected at A. The trajectory of the jet from the syringe is seen at B.

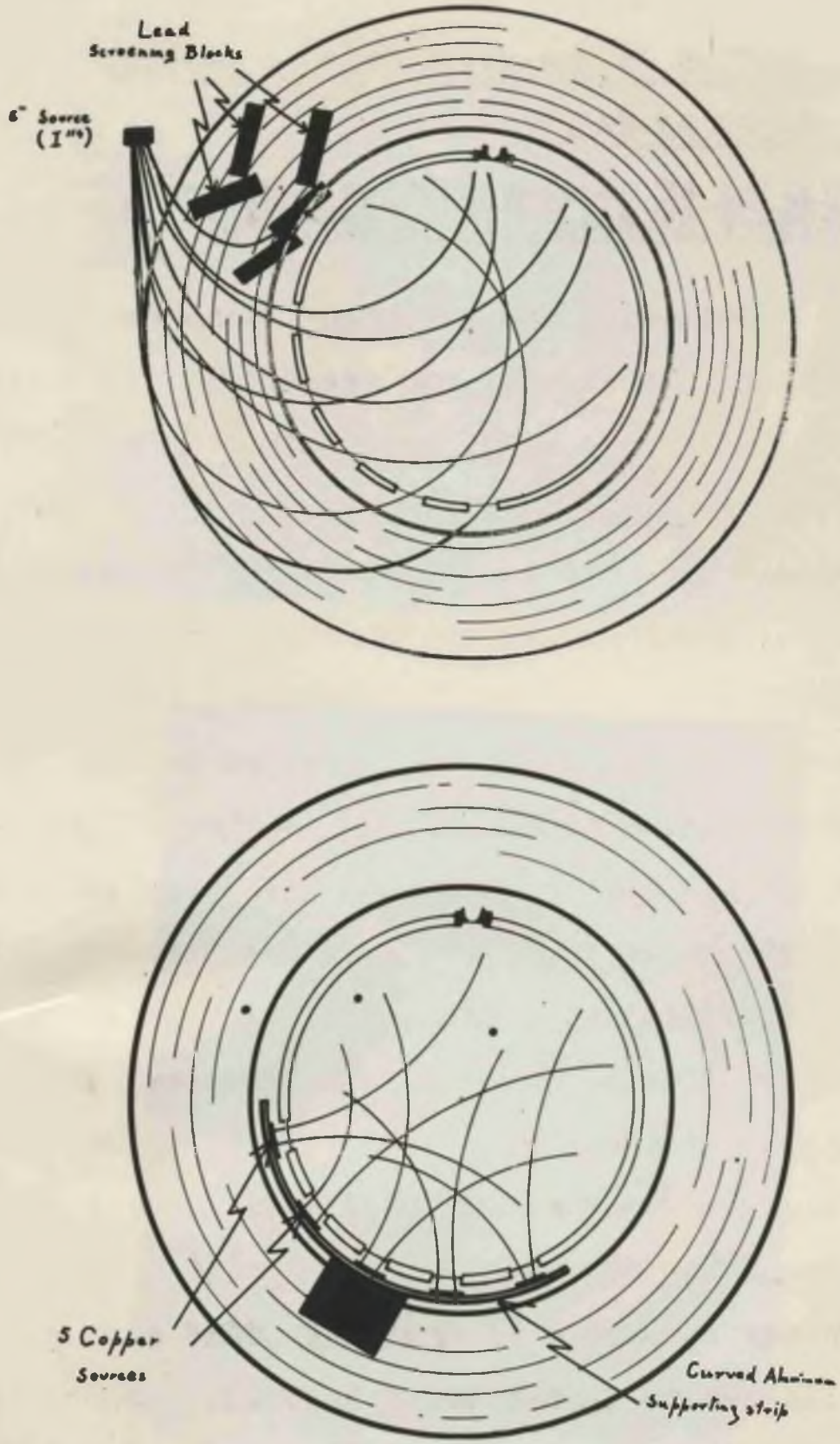


Fig. 23. (Top) Lead blocks used to eliminate γ-radiation and slow electrons from I^{131}. (Bottom) The position of copper sources used with Cu^{62} (positron emitter) and later with Cu^{64} (electrons and positrons).

III. OPERATION OF EXPANSION CHAMBER CONTAINING MERCURY DI-METHYL

i) Filling of chamber and its behaviour with Mercury di-Methyl and Argon alone

Following the techniques already described, the chamber was assembled, its active volume being bounded by a half inch plate glass top, a glass cylinder of quarter inch wall ten inches in diameter and two inches high, and a moving bottom consisting of an eight inch diameter brass plate flexibly joined at its edges by a disc of one mm. sheet rubber to a solid brass ring (Figs. 9, 21). Lead wire sealed the glass cylinder to the brass ring, and also the glass cylinder to the glass top, in addition providing an upper electrode to maintain the usual electrostatic field. Six holes of seven eights inch diameter accommodated five windows and, further round, the injection port. The former consisted of discs of .002" copper, soft soldered to turned brass inserts; these, together with a similar insert carrying an internal thread, were cemented with "cold"-setting Araldite to the glass cylinder. A rubber cap from a penicillin bottle was placed

in the brass mounting in the injection port, and held in place by a threaded retaining ring, after the manner of lens assemblies. The bottom of the chamber was covered with a disc of velvet. This was stitched to a light metal ring, the latter being screwed to the bottom brass plate.

Previous work in this department has shown that the scattering of electrons and positrons in argon at energies in the region of 1 Mev did not differ significantly from that predicted by Mott; moreover the use of a monatomic gas of large gamma would help to reduce the large expansion ratio that would be required if mercury di-methyl were used as condensible vapour. It was therefore decided to add argon to make, with the vapour pressure of mercury di-methyl, a total of about 50 cms. when the chamber was expanded.

Both halves of the chamber, above and below the diaphragm, were therefore evacuated to 1 cm. pressure, and the upper or expanding part filled with argon to atmospheric pressure. This was then evacuated and refilled, the process being repeated several times, and the upper part finally filled with argon to a pressure of 47 cms. The repeated flushing procedure avoided the sustained strain to windows and rubber

diaphragm that would result from continuing evacuation until a hard vacuum had been obtained. The rather low final pressure of 47 cms. was necessary to ensure a pressure gradient of at least 5 cms. across the moving plate holding it firm against the upper stops, even when these were raised to allow the expansion ratio to be increased to 1.5, this being the ratio anticipated when using mercury di-methyl alone with argon.

It had been found difficult to control the injection of a liquid into a vessel whose pressure was substantially below atmospheric, so the bottom plate was allowed to rise to its highest position (corresponding to an expansion ratio of 1.5) thus increasing the internal pressure to about 70 cms. of mercury.

The room in which the chamber was beingoperated opened directly on to an open courtyard, so a raised platform was built. The chamber, which was mounted on wheels, could thus be moved into the open air during the process of injection, and on subsequent occasions when it was necessary to unseal it to measure pressure.

Only on one occasion did the writer himself inject mercury di-methyl into the chamber; this process was normally carried out by Mr. J.T. Lloyd,

who first filled the syringe with the requisite quantity in one of the fume cupboards in the adjacent radio-active laboratory. With the needle inside a test tube, the syringe was then carried over to the chamber. In the absence of wind, a fan was used to blow any vapour clear of the operators, while, the injection completed, the outside of the seal, the syringe and the rubber gloves worn, were cleaned with sodium sulphite solution, to break down the mercury di-methyl into non-volatile and less toxic compounds.

A light nose and mouth mask fed with a copious supply of oxygen from a cylinder was used by Mr. Lloyd, but the writer felt that any inconvenience, unless essential, increased rather than reduced the hazard.

With the expansion ratio reduced to 1.2 several slow expansions were followed by the normal cycle of fast and slow expansions, at gradually increasing expansion ratios. When a ratio of 1.4 had been reached, a moderately dense cloud still showed no sign of tracks. The expansion ratio was increased to 1.45, at this point there were a number of blobby patches in the cloud which may have been due to the tracks of slow electrons. The background, however, rendered them completely useless, and continued cycling at this

ratio resulted in a steady increase in density of the fog.

Reducing the ratio to 1.2 and again increasing it slowly showed that the cloud limit was now down to 1.26, Continued cycling resulted in the nature of the cloud changing, its onset (in the region of 1.2) being marked by the appearance of very fine drops which became more numerous as the ratio was increased. There was thus now no clearly defined cloud limit, and all the appearances strongly suggested the continuous production of condensation nuclei.

One of the objects of the experiment had been to find out if it was possible to use mercury di-methyl alone as condensible vapour, and the chamber had been deliberately assembled free of water or other vapours. This had been confirmed by the absence of any cloud after a fast expansion of ratio 1.3. It has thus been impossible to test the chamber, except for leaks, before injecting mercury di-methyl. As it had not been possible to inject sufficient of this to saturate the velvet, and as dry velvet had previously been found to result in a high background, five ccs. of water were injected, spread out fanwise over the velvet. The immediate result of this was to reduce the cloud limit to 1.16. The drops becam larger, but the cloud did not clear sufficiently to render tracks visible.

There seemed little more to be gained by further attempts to operate the chamber with mercury di-methyl alone, so, as it had been found that there were no rapid reactions between the latter and a water gelatine gel, it seemed wise to dismantle and clean the chamber, and reassemble with a gelatine bottom.

Partly on the ground of safety, and partly because of the scarcity of mercury di-methyl, several attemps were made to recover it with a liquid air trap before dismantling. The procedure adopted (Fig.21) was to raise the moving plate thus bringing the pressure inside almost to atmospheric. The rubber cap was now removed from the injection port, and rapidly exchanged for a flange carrying a short length of half inch brass tubing which was secured in its place. This in turn was connected, through a U - tube of similar bore, with a one litre flask. The U-tube was immersed in liquid air and the chamber set to carry out very slow expansions at the rate of about four a minute, with the maximum expansion ratio of 1.5. As the displacement volume was thus about 50 cubic inches, and greatly in excess of the volume of the U-tube it was hoped that in due course all the vapour in the chamber would pass through the U-tube and, condensing on its walls, run down into a short tube attached at the lowest part of the bend. About three cubic

centimetres of liquid were recovered, the bulk of it water (identified by its frezzing point). This was recovered after the first twelve hours and, as after a further twelve hours the amount had not increased significantly, the U-tube was sealed and removed to a fume cupboard.

With the chamber in the open air, a tube connected with a nitrogen cylinder was passed through the now open injection port, and, from a discreet distance, the nitrogen turned on in order to evaporate and partially flush out any remaining mercury di-methyl. From the "up-wind" side, the top clamping nuts and ring were removed, and the glass to glass seal broken. As a further precaution, after the top plate and glass cylinder had been removed, the lower half of the chamber was left in a steady draught for some hours before any attempt was made to dismantle the moving plate assembly. As each part was dismantled, it was first placed in a 'decontaminating' bath of sodium sulphite, before washing and cleaning in the normal manner.

ii) Partial clearance of fog, and run with Argon, Mercury and Water

With the glass thoroughly cleaned, and the brass polished to remove discolouration, the chamber was assembled as before, with fresh rubber and (dry) velvet.

After filling with argon, even a large expansion ratio did not produce a cloud, thus confirming the absence of condensible vapours. For purposes of comparison, five cm^3 of water were now sprayed over the velvet, and allowed to disperse. On a fast expansion the background was found to be much heavier than on preliminary runs under apparently similar coditions, and bore a strong resemblence to the description by Milojevic (1952). "After the chamber had been quiescent for several hours, the first expansion was satisfactory; background clear, with crisp, sharply defined tracks. Subsequent expansions were marred by a thin fog, increasing in intensity, and persisting even with a reduced expansion ratio. Finally tracks disappeared completely". However, while Milojevic attributes much chamber fog to the use of unsuitable rubber for diaphragms, this seemed unlikely in the present case as various specimens taken from the same roll had proved clean in use. Two factors remained; the velvet bottom and the

glass cylinder. In all the preliminary runs an old stock of prewar velvet had been used, but in the final assembly a fresh supply had been obtained, and it was possible that chemicals used in processing might be causing trouble. It was also possible that undried adhesive or cleaning materials trapped in crevices round the window inserts were giving rise to condensation nuclei. After filling these gaps with "Q" compound and restoring the older velvet, fog was much improved, but as it seemed likely that a wet gel on the velvet would reduce the background further, the injection port was opened and a solution of gelatine in water applied to the velvet with a pipette. In the absence of warm tap water to circulate in the normal cooling system of the bottom plate, this was warmed by radiant heat to facilitate even flowing of the gel. The top plate also was warmed to prevent condensation, and for this reason also the bottom plate was cooled as rapidly as possible once the gel had run evenly.

As the chamber had now been exposed to the air, it was refilled with argon by evacuating it until the pressure was reduced to the point where the gel began to show a tendency to boil, then admitting argon rapidly, until atmospheric pressure was

reached. This was repeated several times, and no damage was done to the gel.

After the usual preliminary clearing expansions, tracks were very much improved, and it was decided to proceed at once with the injection of one cc. of mercury di-methyl. This was carried out in exactly the same manner as before, and was followed by a rise in pressure of 3.3 cms. On this occasion, however, the cloud began to clear in about half an hour, and an hour later electron tracks were clearly discernible. Cameras were loaded, and three hours after the mercury di-methyl had been injected, thermal equilibrium had been established, and the track quality justified starting the cameras.

During the first film, electron tracks were photographed, using Indium 114 as source. During this film the behaviour of the chamber was watched closely, and adjustments carried out to the expansion ratio and the cycling time of the master control unit. For the latter, a period of 1 minute 30 seconds, which included a 30 second quiescent interval, was found the minimum compatible with track quality, while it seemed that an expansion ratio somewhat greater than would be chosen with a steady light was desirable in the light of the discharge lamps, especially if the delay of the latter was made rather short, and the electrostatic clearing field kept on continuously.

When the first film was finished, the cameras were reloaded at once, and a second film commenced, also with electrons. In the meantime the first film was developed, and carefully studied. A record slate had been photographed to mark the point from which the clearing field had been kept on all the time, and from this point the tracks were markedly sharper. The side film was rather dense, so the aperture on the side camera was reduced by one stop. In other respects the results supported visual observations.

A copper source had been prepared, and this was now irradiated in the Glasgow 30 Mev Synchrotron, to obtain Cu^{62}, a positron emitter of 2.6 Mev. This synchrotron has a beam cross-section of about 1 sq. cm., and it was known that the geometry would require to be as efficient as possible. Five half inch squares of thin copper sheet had therefore been stitched at the corners to a length of empire tape in such a way that one square could be mounted outside each window by clipping the tape to a curved strip of aluminium, as had been done in previous experiments in this Department on positron scattering in xenon and argon. The strip of tape, with the copper squares, could then be folded up in such a way that all the copper was irradiated in the beam of the synchrotron.

When it had been irradiated, the source was mounted outside the windows of the chamber, a record slate photographed, the magnetic field reversed, and photography continued.

With the large window area, it was estimated that six to eight tracks could be readily separated and measured, and this was accepted as the optimum number when adjusting the sources; it was at once evident, however, that the number of positron tracks obtained was very much below this, even when the source was new-it has a half-life of 10 minutes - and placed close to the windows. Thus, while during the earlier xenon work the same source was used for half an hour, being brought gradually closer to the windows, on this occasion it had to be discarded after 10 minutes, and the electron source replaced.

The opportunity was taken here of improving the layout of the screening lead blocks and source (Fig.23). The latter, collimated, was mounted with its direction almost tangential to the chamber, the fringing field of the resolving magnet deflecting the electrons into the chamber, while the gamma rays and soft electrons were stopped by a lead block, and deflected clear, respectively.

At the end of this second film, the pressure in the chamber, which had risen from 52.53 cms. to 55.83

cms. on injection of the mercury di-methyl initially, was checked and found to be 54.66 cms.

The Indium source was again used for the third film, and the second at once developed. This confirmed the visual impression that the positron tracks were much fewer than in the earlier xenon run. Several causes were considered. The possibility that the output of the synchrotron was lower could not be ignored, but in any case this was a factor outwith our control. Of more immediate importance was the possibility that the sensitive time of the chamber was less than usual; it was therefore decided to examine closely the effect of variation of expansion ratio, delay time and clearing field. There seemed, however, little doubt that unless a very considerable improvement could be achieved, the Cu^{62} would have to be discarded ten minutes after irradiation had been completed.

To afford some immediate improvement, two further source strips were made up, thus permitting a continuous cycle of twenty minutes irradiation and ten minutes service. Drilling and stitching each square would have taken too long, but cementing the copper to empire cloth had previously proved unsatisfactory. The broad, self-adhesive fabric tape used in sealing film tins was therefore used, the copper square being

pressed firmly on to it in the correct positions, and the whole covered with thin paper which was then cut away over the copper. This worked well for the duration of the run, the copper being held firmly by the adhesive, and the paper preventing the tape sticking to itself when folded up. Latterly, however, the repeated warmth from the synchrotron magnet caused the latex adhesive to soften and permeate the fabric. In this respect a plastic-based tape might have been more durable.

In the experiments that followed to obtain the best results from the positron sources, one point became very clear, and that was that with an average of about two tracks per frame, it was important not to alter the expansion ratio unless several successive frames suggested that this was necessary; otherwise it was difficult to distinguish between tracks that were thin because late, and those whose thinness was genuinely due to a low expansion ratio. Mr. Atkinson, who since the beginning of the run had helped materially in obtaining good track quality despite difficult conditions, pointed out that much of the background fog came up after the tracks were already well defined, and could therefore be excluded from the photographs by using a very short delay on the discharge lamps.

Thus, by photographing the tracks very early, and by cautious adjustment of the expansion ratio to

develop the tracks as far as possible without increasing early fog, the quality of the positron tracks was very much improved. Examination of the photographs taken showed that this was a better solution than endeavouring to obtain a greater number of tracks by increasing the sensitive time, with the resultant increase in fog.

The use of a local water tank to stabilise rapid changes in the temperature of the cooling water has already been referred to, and throughout the run it was necessary also to maintain the closest control possible over room temperature. A draughtscreen between the chamber and the door, together with a deflector plate across the hot air supply louvres, helped to prevent temperature gradients developing across the chamber, with resultant non-uniform supersaturation, and to this end also the steady lamp was used with great reserve.

Following these principles further films were proceeded with, the general policy being to use the positron sources during the day when the synchrotron was available for irradiation, and the electron source at night.

The pressure had been measured at the end of the third film and found to be 54.34 cms. by the

end of the fifth it had fallen to 54.11 cms., and it was decided to inject a further 0.5 cm^3 of mercury di-methyl. Following this the pressure rose 3.35 cms. to 57.46 cms. At the end of a further five films the pressure was 55.38 cms., and after the twelfth film the run was terminated.

Throughout the run the adjustment of the expansion ratio had been very critical. The average ratio was 1.164, and it had drifted between the limits 1.160 and 1.168, the tolerance for good tracks being less than $\pm$ .0005 at any one time. The first film had been commenced at 9.30 p.m. on 21/7/52, and the last completed and developed by 8 p.m. on 23/7/52. During this time twelve pairs of films had recorded 1350 expansions, and this had occupied three-quarters of the total time. In view of the unstable nature of mercury di-methyl, the aim had been to record its scattering as rapidly as possible after it had been injected; and this, it was felt, had been achieved.

iii) <u>Chamber modified to reduce fog; run with Nitrogen, Mercury di-Methyl and Water</u>.

A preliminary analysis of the photographs taken of the scattering in mercury di-methyl and argon had shown that while the scattering of

electrons appeared to be in agreement with Mott theory, sufficient positron tracks had not been photographed to obtain a satisfactory ratio between the positron and electron cross-sections at large angles.

There had been two principle objects in studying scattering in mercury; to compare the ratio of scattering between positrons and electrons with the Mott theory for heavy nuclei, and to investigate the anomalous results reported by Champion in 1938, from his studies of the scattering of electrons by mercury di-methyl vapour in a chamber filled with nitrogen.

As the mercury-argon run just described had shown no signs of anomalous electron scattering, there remained the possibility that the nitrogen was in some way capable of affecting the results. The chamber was therefore filled with nitrogen; for, since it was no longer hoped to use mercury di-methyl alone, the necessity for a higher expansion ratio resulting from the use of a diatomic gas was no longer a serious disadvantage, whereas the lower scattering cross-section of the lighter gas would be a distinct asset.

It was known that R.R. Allen and M. Lipsicas of Metropolitan Vickers Research Department had

obtained a supply of mercury di-methyl with the intention of carrying out the same work, and that the experiment had now been abandoned. As the amount remaining out of our original order from Messrs. Lunevale Products was insufficient to carry through a further run, and as they were unable to supply any more, Messrs. Allen and Lipsicas generously agreed to give us 20 ccs. from the amount they still retained.

In view of the difficulty that had been experienced in obtaining sufficient positron tracks using Cu^{62}, alternative sources that would be available in greater strength were considered. None of equal energy could be found that was available, but a good compromise appeared to lie in Cu^{64}, emitting both positrons and electrons of approximately equal intensity and energy, i.e. 0.65 Mev. As the source has a half-life of 12 hours, pieces of copper foil of varying size and thickness were prepared, and sent to Harwell for irradiation. The maximum strength available is 5 mC, whereas the strength required at each window was estimated at 0.02 mC; it was hoped therefore that by using pieces of different thickness and area (up to 1 cm. square) this optimum strength could be maintained over several days.

Considerable importance had been attached by Champion to his attempts to demonstrate the continued presence of mercury di-methyl vapour in the chamber, and so this could not be allowed to escape our attention. As soon therefore as the total number of scattered tracks had been measured by direct viewing, a count was made of the mean number of deflections recorded per metre of electron track in each of the twelve films, and again in the first six films as a group as against the last six as a group. The results are appended.

Film No.	Events/Metre.	Mean.	
			0.5 cc. mercury di-methyl injected
I	1.04		
II	1.23		
III	0.82		
		0.94	
IV	0.75		
V	0.8		
VI	1.03		
			0.5 cc mercury di-methyl injected.
VII	e^+ only		
VIII	1.38		
IX	1.17		
		1.08	
X	0.87		
XI	1.12		
XII	e^+ only		

Whether the rise in probability from 0.8 to 1.0) following the injection of the further half cc. of mercury di-methyl between films V and VI is significant is difficult to say, but it will be noted that there is a somewhat larger rise (from 0.87 to 1.12) between films X and XI, where no such association is possible. It may perhaps be mentioned that here, as in all similar analysis carried out, the films were analysed in a non-chronological sequence (in this case I, XII, II, XI, III, X, . . .) to prevent human factors simulating or concealing a genuine drift in results.

As the large amount of scattering, together with its uniformity throughout the run, left no doubt that sufficient mercury di-methyl had been injected to maintain a uniform vapour pressure throughout the experiment, it was decided to proceed with preparations for a further run, with the change in gas and source already referred to. The chamber remained substantially the same, but the opportunity was taken of making minor alterations.

Of primary concern was the reduction of background fog. Examination of the chamber after the previous run showed markings on the gelatine (fig.22) where the liquid mercury di-methyl had

landed, the path of the jet from the syringe being clearly marked by local "erosion". There was no direct evidence that this reaction was causing fog, but the rest of the gelatine, where it had been in contact only with the vapour, had remained intact, so a small shallow cup was incorporated in the bottom, so that the liquid could be injected directly into it (Fig. 16); this had also - at least in theory - the further advantage of showing how long the liquid remained in the reservoir before evaporating entirely. The difficulty in practice was that water tended to condense on the metal cup, and it was not easy to distinguish between the two colourless liquids.

It had been suggested to the author that the accelerator used with 'cold' setting araldite cement would, containing as it does by its very nature a large number of free radicals, be a very fruitful source of fog. This was amply confirmed by injecting 0.1 cc. of water into the chamber when it was running normally, and observing the time it took for the resultant fog to clear, a matter of minutes; this was followed by a like quantity of the liquid accelerator, which resulted in a much denser and more persistent fog.

As more trouble was anticipated with window leaks with the original cylinder, apart from the

possibility that the remaining accelerator might be causing fog, a new cylinder was bored and brass windows prepared as before. This time, however, the hot setting solid araldite would be used, the temperature of the whole cylinder and fittings being slowly raised and lowered in an oven.

This was carried out, but unfortunately in the night following its return to room temperature a large number of cracks appeared round the windows, due of course to differential contraction. Since then Mr. Gubbins of A.E.R.E. has drawn attention to the suitability of glass solder for mounting the copper foil directly on the glass cylinder, but at the time there did not appear to be any practical alternative to the two forms of araldite, so the original cylinder was cleaned and overhauled. The inside of the windows was given a sealing coat of Glyptol vacuum sealing paint to seal off any vapour that might still come from the cement, while the outside joins were also given a coat for more conventional reasons.

In the interval developing procedure had also been improved, mainly by attention to details. For some time a spiral developing reel had been used; this was a commercial product designed to take 25

feet of 35 mm. film, which had been modified in this department to accept 60 mm. film. This could be loaded with film only when dry, and thus the complete cycle of developing, fixing and washing of the film, followed by drying the reel took over an hour. As a pair of films were exposed every three hours, this left little margin when other jobs, such as preparation of sources, arose.

The modification of two further reels, coupled with the use of a dark room fitted with a double door "light lock" and a drying cupboard removed this bottle-neck completely. Three films could now be developed virtually simultaneously, separated only by the actual time of development, the second and third being loaded on spirals while the first was developing. The light-lock permitted such operations as the checking of temperature and setting of time clocks, as well as inspection of previous films, to be carried out in normal light while development was proceeding in total darkness. The loading of the reels was itself facilitated by the more uniform width of the unperforated film now used exclusively in this department, stocks of the earlier perforated film, used in part in the previous run, being now finished.

Some attention had also been given to choice of developer, and of exposure and developing time.

It is clear that, for any given subject, various combinations of exposure and development will give the same density of image, though not the same contrast, a fact made much use of in the era of plate camera photography. What is less obvious is which combination will be best under any given conditions. It was accepted as axiomatic that a high degree of contrast was desirable, so 5G91 film was used, with two developers, Kodak D19b, and Ilford ID 33 ultra high contrast developer. Using a beta source and a moderate expansion ratio, two lengths of film were similarly exposed, at a range of apertures above and below normal. A small developing tank was partially filled with D19b and one film loaded in the spiral and placed in the tank, agitation being carried out gently to avoid splashing. When development had proceeded for about a quarter of the normal time, the film was removed, the level of developer raised by about one centimetre, and development proceeded. This process continued until the first part of the film immersed had received one and a half times the normal duration of development. When this had been repeated for the other developer, all the possible changes had been rung on time-exposure-developer combinations, and the films were studied.

It was at once evident that there was no single combination giving maximum contrast under all conditions. If contrast between two shades of gray in the subject was chosen as the criterion, then the classical conditions of under-exposure, followed by very full development in maximum contrast developer gave, not unnaturally, the maximum contrast. This was accompanied, however, by a marked degree of chemical fog, and would be quite unsuitable for the photography of rather thin beta tracks. In this latter case, the better technique would be to use a larger aperture, and develop only to the onset of chemical fog, in practice less than the normal developing time. This would give the maximum contrast between the tracks and background; moreover local variations in intensity of illumunation would be less marked.

The difference between the two developers, despite the disparity in developing time, was very slight. Ilford ID 33, however, had appeared to give rather better contrast without fog, and was therefore chosen, the exposure being adjusted to make the chamber background just visible with development times slightly less than the recommended values.

When the chamber, assembled and leak tested

with the modifications referred to, had been filled with nitrogen, a short trial run was carried out, and the optimum expansion ratio found to be 1.23 .

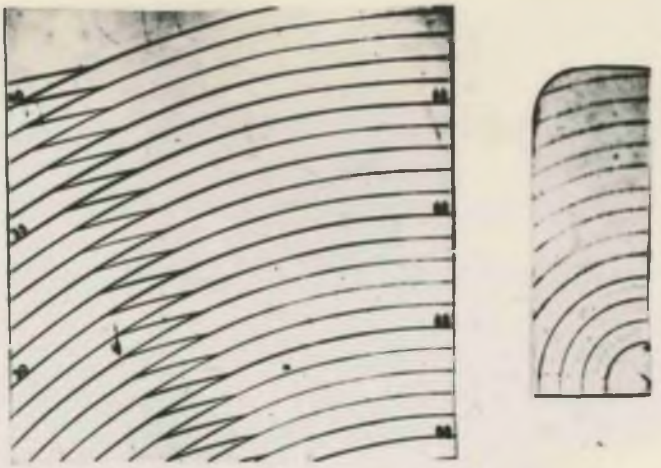
One cm^3 of the new supply of mercury dimethyl was then injected, using a five inch aspirating needle that permitted the liquid to be placed directly in the cup now fitted in the centre of the bottom plate.

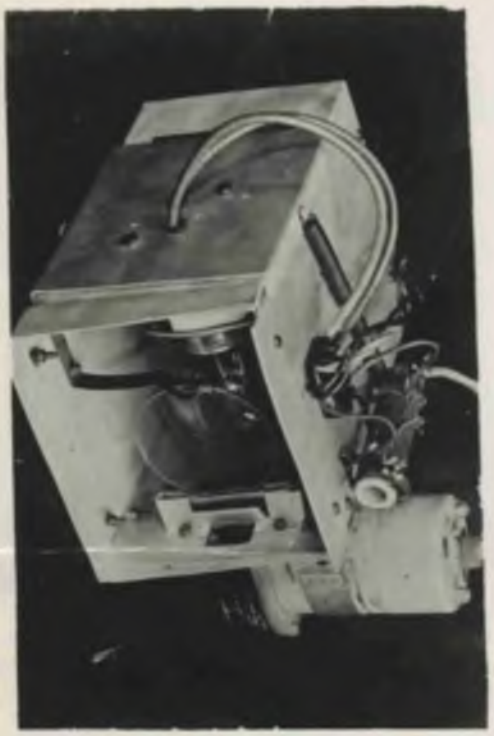
When expansions were commenced there was at first some sign of drop turbulence over the cup, but this disappeared when part of the liquid had evaporated. While machining this cup the author had endeavoured to copy the design of unspillable inkwells, the bottom being slightly conical to limit the liquid to the perimeter, while the top edge of the walls had an overhang to prevent liquid being splashed up and out of the cup at the moment of expansion. Unfortunately this narrow inverted conical ring at the top of the walls caught the light from the lamps, even with the plate in the down position, and had to be removed. Nevertheless the behaviour of the liquid when the level was reduced by evaporation showed that much of the initial splashing had been due to the liquid swilling across the centre of the cup and hitting the opposite side of the wall, a problem that did not arise once the level had

been reduced below the raised central part.

Tracks appeared after about half an hour at an expansion ratio of 1.23, the same ratio as had been used in a trial run with nitrogen and water alone, but during the first film this ratio was increased steadily until it had reached 1.26 for best tracks. Throughout the remainder of the run, the ratio varied between 1.23 and 1.26. This variation was certainly due in part to the difficulty of keeping a constant temperature day and night in a small detached building, but a rather different cause was a tendency shown by the chamber to develop a heavier background fog after it had been running for several hours; this necessitated a lower expansion ratio even at the expense of thinner tracks. It is significant that after a break of two hours, enforced by a defective mechanical valve, the ratio, which had been steadily lowered almost to 1.23, could be raised to 1.25.

This incident had occurred during the fifth film; a further three were exposed with little change in the expansion ratio, but during the ninth film, fog became very heavy. After a short break it appeared to have improved, for the first expansion was almost clear, but fog rapidly built up again. The chamber was left for some hours, but no permanent improvement resulted, and the run was terminated.





Reprojection and Analysis.

Fig. 24. (above) Anormal radius plate with standard 15° deflections, and a miniature used for film measurement.

Fig. 25. A fan-cooled reprojection lamp housing

Fig. 26. Complete re-projection assembly showing swinging mask obscuring the side camera.

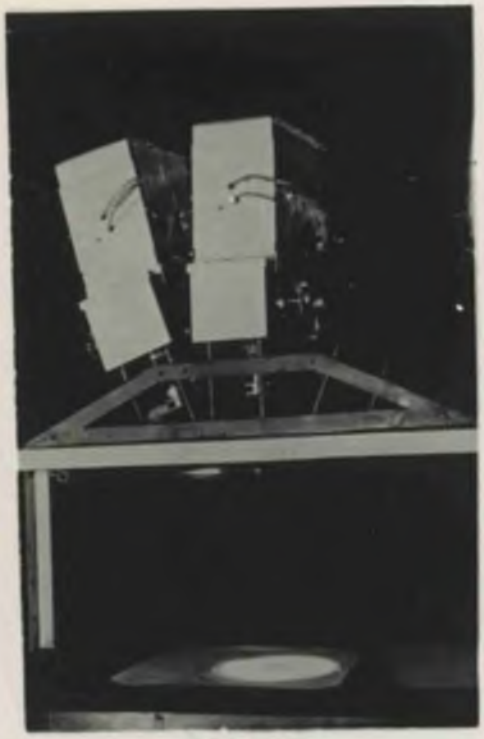
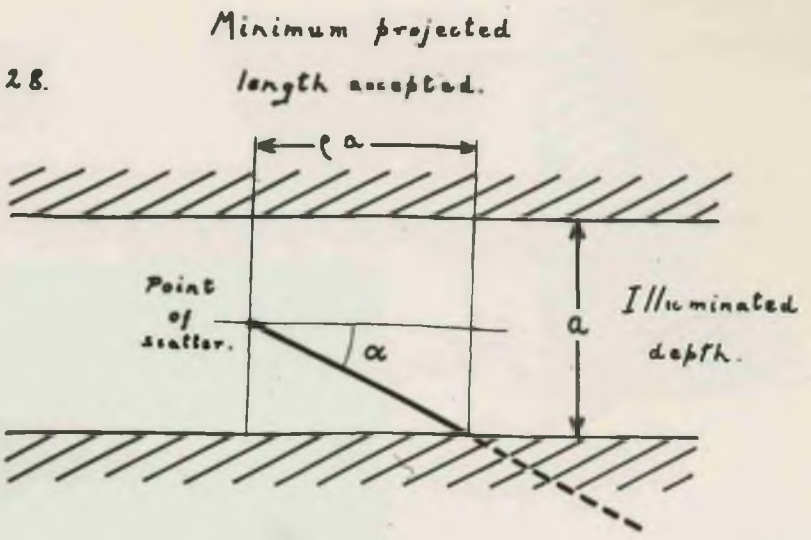


Fig. 27. An electron track being compared with a radius plate during re-projection. (The track is at the tip of the pencil)

Fig. 28.

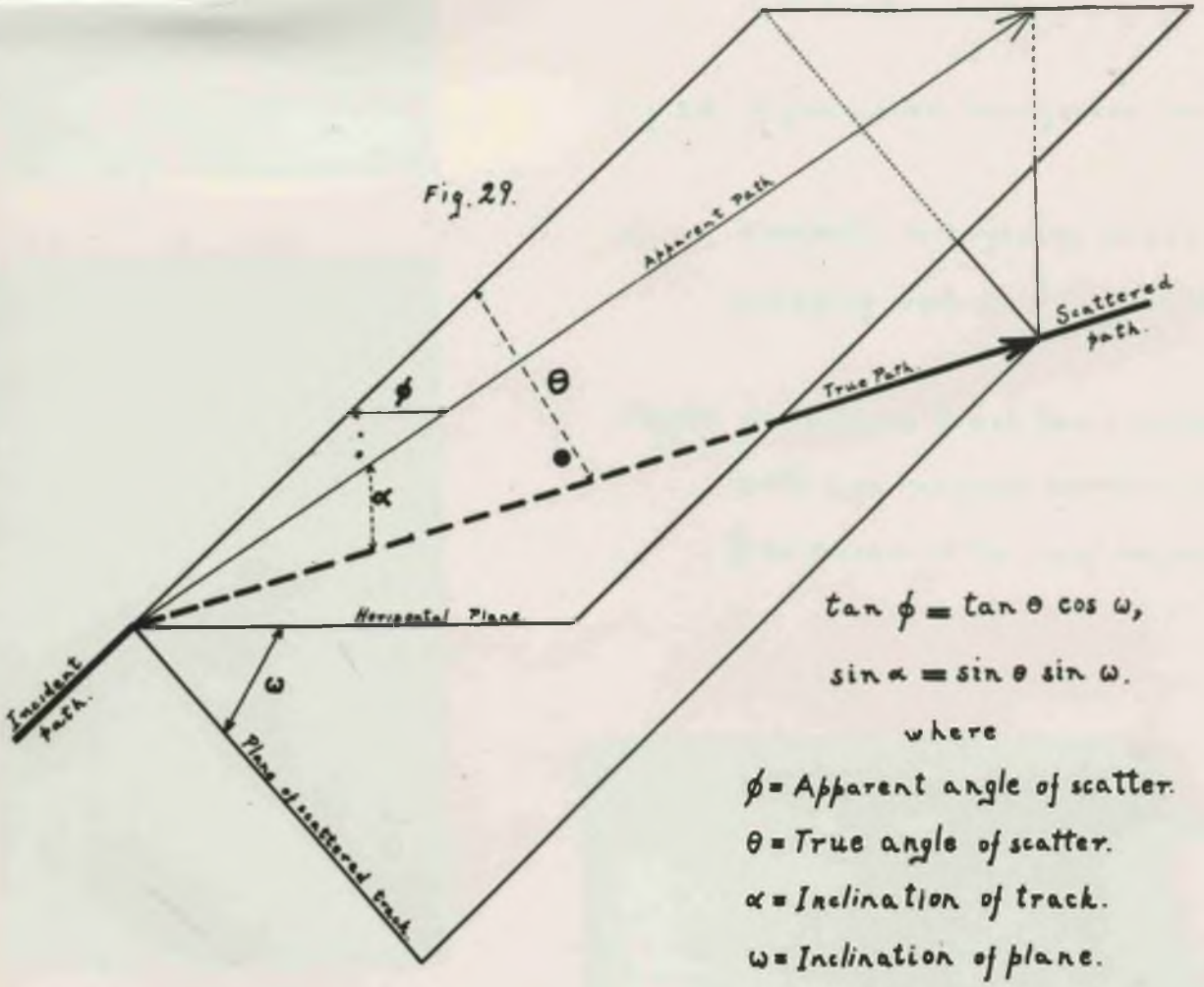


Here, $\tan\alpha \leq \frac{1}{2}a/\rho a$. If $\rho = 1$, $\alpha \leq 27°$

(for a scatter in the centre of the illuminated depth 'a')

Figs. 28 & 29. Apparent length and deflection of non-horizontal fragments of scattered tracks is determined for statistical corrections.

Fig. 29.



$\tan\phi = \tan\theta \cos\omega$,

$\sin\alpha = \sin\theta \sin\omega$.

where

ϕ = Apparent angle of scatter.

θ = True angle of scatter.

α = Inclination of track.

ω = Inclination of plane.

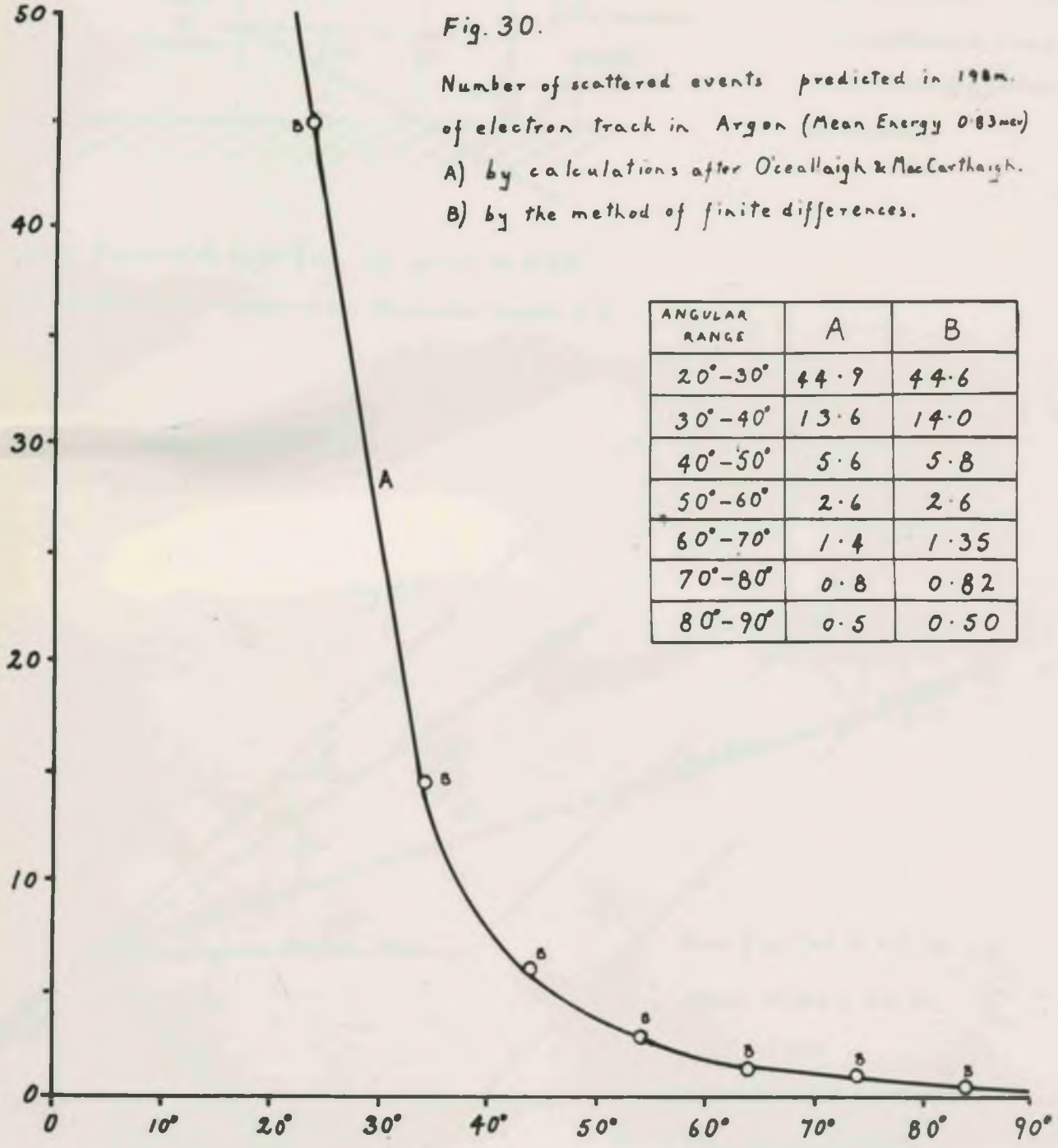
Fig. 30.

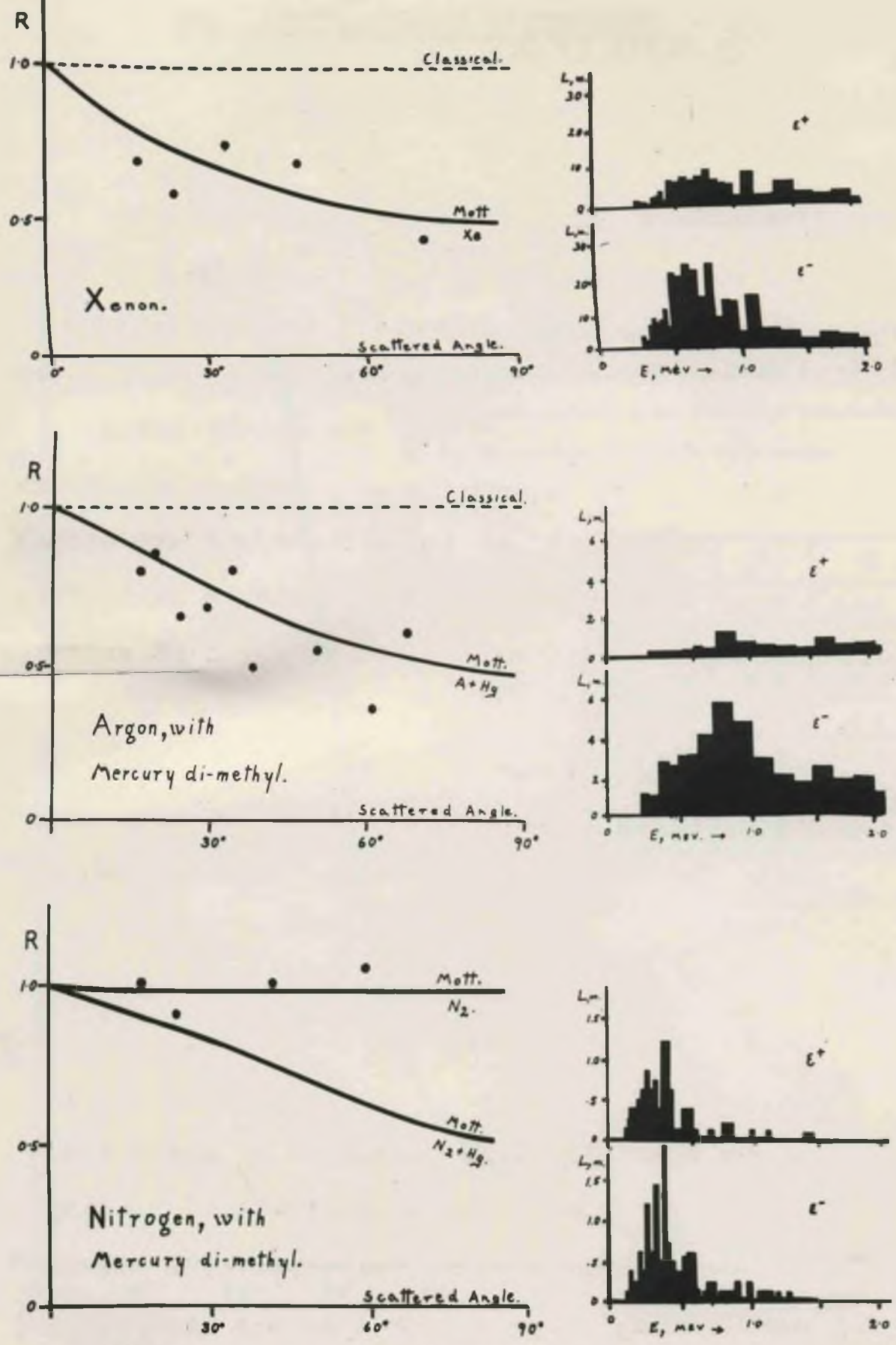
Number of scattered events predicted in 198m. of electron track in Argon (Mean Energy 0·83mev)

A) by calculations after O'ceallaigh & MacCarthaigh.

B) by the method of finite differences.

ANGULAR RANGE	A	B
20°–30°	44·9	44·6
30°–40°	13·6	14·0
40°–50°	5·6	5·8
50°–60°	2·6	2·6
60°–70°	1·4	1·35
70°–80°	0·8	0·82
80°–90°	0·5	0·50





$R = \frac{\sigma_{\varepsilon^+}}{\sigma_{\varepsilon^-}}$ (expl.), after normalisation for track length and mean energy.

L = track length in each energy range.

Fig. 31. Ratio of positron/electron scattering, and corresponding spectra.

IV. PLANE PROJECTION CALCULATIONS, AND ANALYSIS OF RESULTS

i) Survey of Methods of Analysis

It has been shown that, although various techniques are employed for computing scattering cross-sections from the Mott formula, the important comparison lies between the classical Rutherford formula, even if this is corrected for the relativistic rise in mass of the particle, and calculations such as those by Massey or Bartlett and Watson which treat electrons and positrons as different Dirac particles. The validity of these hypotheses may be tested in either of two ways. The angular distribution of scattered electrons, or positrons, may be compared with the predicted distributions; alternatively, the number of electrons scattered through a given angular range may be compared with the number of positrons of the same energy similarly scattered. In the latter case it has been shown that the ratio predicted by classical theory is always unity, whereas that arising from the Dirac concept increases with atomic number, rising to over 2.1 in the case of mercury. In order to make the best use of the second procedure, which seemed the more

likely to give positive results, it was essential to use a scattering element of atomic number as high as possible.

J.R. Atkinson and A.F. Howatson (1951) studied the scattering of electrons and positrons in argon, photographing and analysing 360 metres of track, in part of which the author assisted.

A total of 370 metres of electron and positron track was also photographed in xenon, and this had been measured and analysed by the author, using the same apparatus and technique, while making preparations for studying scattering in mercury di-methyl. Two difficulties were, however, encountered;

i) The plane projection calculations of O'Ceallaigh and MacCarthaigh are based on the Mott Light Element Fomula which is not applicable to elements heavier than argon.

ii) The tracks were thinner and less well defined in xenon than they had been in argon. This rendered measurement difficult with existing reprojection apparatus.

As these difficulties apply with even greater force to the analysis of mercury scattering, a general technique was developed for calculating the number of deflections to be expected in a chamber containing any heavy element, and

this will be discussed in the next section. While, however reprojection was proceeding the opportunity was taken of studying critically the techniques of analysis used in this department and elsewhere with the twofold object of:

a) ensuring an unambiguous interpretation of tracks under difficult conditions.

b) speeding up routine measurements with a view to increasing the material that could be analysed in a given time.

The information to be obtained from photographs of scattering falls under three headings: total length of track examined, number of scattering events and their distribution, and the mean energy of particles involved in scattering events. This latter is normally obtained from their radius of curvature in a magnetic field.

In the analysis of photographs, erroneous results are very much more likely to be caused by systematic errors, or by inconsistency of interpretation, than by random inaccuracies in individual cases. This is in marked contrast with such processes as photo-disintegration, where results depend on the greatest possible accuracy in measuring a relatively small number of events.

This fact was therefore borne in mind when

considering techniques that had been previously used in similar work. These may be broadly divided in two ways; direct measurement or re-projection, and stereoscopic or plane projection.

STEREOSCOPIC MICROSCOPY.

In 1929 P.M.S. Blackett described a form of stereoscopic direct measurement, examining under a microscope the plates from two cameras, each at 45° above the chamber. By resolving the components measured in the two plates he determined the position of the tracks in space. A recent paper by Campbell and Welch (1952) describes a graphical method of performing this, but unless a monochromatic source is used this method would be unsuitable for scattering analysis owing to the difficulty of measuring the length and radius of curvature of the tracks.

STEREOSCOPIC REPROJECTION.

Although Champion had used a method in which only deflections were measured by microscope (1936) the spectrum of the source having been previously determined by other methods, this cannot have been entirely successful, for in later work on mercury with Barber (1938) he used stereoscopic reprojection, replacing the films in their cameras, and mounting a lamp and condenser behind each. The photographs were then projected on to an adjustable

plane which could be tilted in any direction until the two images of any required track coincided, measurements of angle being then carried out in this plane.

PLANE REPROJECTION

Randels Chao and Crane (1945) describe a method where the tracks were projected on a plane corresponding with the centre of the chamber, and all angular measurements carried out in the horizontal plane. Angles occurring in non-horizontal planes would in general appear smaller than in fact they were, and allowance was made for this in calculating the theoretical figures with which the results were compared. Two camera stereoscopy was still used, but here the measurements were all carried out on the image projected by the top camera, and the side camera was only referred to in any doubtful case where it was necessary to distinguish between two separate tracks superposed, and a genuine deflection.

ADVANTAGES OF PLANE PROJECTION

If stereoscopic measurements in the original plane are to include, as they must, scattered tracks which are inclined at large angles to the horizontal, the projectors must be carefully set

up for each frame, using fiducial marks or a reference grid. Even with this precaution it is difficult to be certain that none will be ignored, or, in certain positions, wrongly interpreted. This will be seen if we consider a chamber illuminated to a depth "a", and if we assume that the incident electrons, are in a narrow layer in the middle of the illuminated region. Any track dipping at 45° (Fig.28) will have an apparent length of only a/2, irrespective of its original length, and a slightly greater "true" length if measured in its original plane.

Half of all scattered fragments will on average be in a plane inclined at more than 45° to the horizontal and thus, where the scattered angle lies between, say, 60° and 120°, the average fragment length will be less than 2/3 a (perhaps 1 cm.) even in the original plane. This would make it very difficult to measure accurately the angle of scatter and change of curvature, if any.

In the method of projected angles, as the authors call it, this difficulty is overcome by deliberately neglecting any scattered fragments whose horizontal projection is less than a certain

length (this may be chosen to be equal to the illuminated depth). This means that in practice about one half of the "observed " scattering events will be neglected; on the other hand, this may be allowed for when comparing the results with predicted values. The advantages of this system are obvious when it is appreciated that these "rejected" tracks, in many of which it would be nearly impossible to detect changes in curvature, would form a large portion of the statistics of results analysed stereoscopically.

This, in principle, was the technique that was being used in analysing the xenon tracks. The films were replaced in the original cameras, and a lamp mounted behind a special aperture to permit of the tracks being projected full size on a sheet of white paper, on which had been drawn a circle one centimetre less than the radius of the chamber. All tracks of acceptable quality, including any scattered tracks occurring within the circle, were traced in pencil on the paper. Scattered fragments outside the circle could be used to assist in the measurement of radius or scattered angle, but events outside were ignored, as it would not be

possible to tell if the shortness of a fragment was due to a large angle of dip, or simply to proximity to the chamber wall. Subsequently, the tracks traced on the paper were measured, the length inside the circle with a map measurer, and the radius of curvature by comparison with a set of curves, of radius from 15 - 70 cms, engraved on perspex (Fig.24). Where a track had been scattered, the angle was measured by drawing the normal to each section, and measuring the angle between the normals. For this purpose the radius plates were drawn having one edge along the common radii of all the curves.

This procedure, though laborious, is satisfactory when the number of tracks in each frame is relatively small, and the background is low. The author however, found some difficulty in applying it to the photographs of xenon scattering, where in the presence of other tracks it was frequently difficult to distinguish between one continuous track and two tracks of similar curvature but not lying on quite the same arc. Several times a track, which on sketching appeared continuous, was seen on examination with the radius plate to bonsist of two tracks of similar radius, but with a discontinuity which could only be explained otherwise as two equal and opposite small angle

scatters. This suggested to the author that it would be very desirable to examine the tracks with a radius plate at the moment of selection. (Fig. 27).

IMPROVEMENTS IN ILLUMINATION

The existing illumination, while adequate for tracing tracks was insufficient for comparing them critically with drawn curves, and was therefore improved.

There was, fitted to the back of the cameras, an "inspection plate" which could be removed to allow an optical condenser to be inserted, and behind this a lamp was mounted.

This condenser was of greater diameter than the circular image of the chamber formed on the film, but owing to the method of mounting was some distance behind it. In this position a condenser of considerably greater size would have been required than could be accommodated on the back plate. In order to provide illumination over the whole image, therefore, opel enlarging type lamps were used, as were "photofloods" for short periods.

The author felt that contrast oould be considerably improved by modifying the optical system to use direct rather than diffused light, and using bunched filament projector bulbs.

The film in the cameras is held in position by a glass pressure plate mounted on a hinged gate, so a single condenser lens with a focal length similar to the camera lens was permanently mounted in contact with this glass plate, and a second condenser mounted in place of the inspection plate when the camera was being used for reprojection. This provided a uniform field, using a point source some four inches above the camera. The ideal lamp would have been a type "A" projector bulb, but these can only be run within 20° of the vertical, cap down, and were therefore quite unsuitable. Type "B 1" bulbs, with a larger envelope and less concentrated filament seemed suitable as they may be run in any position except cap up, but a better solution lay in the use of aircraft landing lights which have a small spiral filament of 360 watts at 24 volts rating, and a glass envelope rather smaller than a type "B 1" lamp of 250 watts at 230 volts; also their efficiency, in lumens/watt, was almost 50% greater. It was decided to use forced draught cooling and Chance ON 18 glass heat filters, so the author constructed two prototype lamp houses (Fig.25) with generous cooling vents and a simple focussing device. These proved a considerable improvement, there being no appreciable heating of

the lower condenser even after the lamp had been on for several hours, while the illumination and contrast were greatly improved. If still further intensity were required locally, for other types of work, a third condenser could be inserted, and the assembly adjusted to illumine the required area. It was more often found, however, that for scattering work less intensity was required and the transformers supplying the 24 volts to the lamps were controlled by Variacs. If, as frequently happened, the side film was more fully exposed than the top film, the use of Variacs also enabled the two projected images to be adjusted to the same intensity.

EXAMINATION OF APPARENTLY INTERSECTING TRACKS

As the reprojection apparatus was now satisfactory, attention was devoted to details of technique.

Even when using plane projection, the stereoscopic properties of the cameras must sometimes be invoked to discover if two portions of an apparently scattered track are in fact coplanar.

This had hitherto been done by determining the planes of the two sections of track, but as this requires careful alignment of the films in both directions, some experiments were carried out with a two-colour system of stereoscopic viewing. With

a little practice it was found possible to get a very clear impression of the position of tracks in space, and to see the separation (or otherwise) of apparently touching tracks without the use of a moving screen to determine their individual planes. Unfortunately it became rather a strain on the operator after a period. During a visit of the author to Copenhagen, Professor Bøggild suggested that the use of polarised filters and suitable spectacles, or preferably a direct viewing image integrator, had been found to cause less eye-strain under similar conditions, but neither was found entirely satisfactory.

After some time it was found that, with increasing practice, it became possible to distinguish between co-planar and non co-planar tracks by viewing the two films alternately; if necessary, one image was sketched, and this sketch compared with the second image. To this end a pedal operated swinging mask was constructed (Fig. 26); this enabled the operator to view the two films alternately in rapid succession, while leaving the hands free to make sketches or adjust the radius plates. The use of these plates in measuring radii of curvature is discussed elsewhere. From these radii, together with the measured track length, the sum $\Sigma \{ l/(H\rho)^2 \}$ was

formed. By equating this with $\Sigma \ell/(H\rho_{av})^2$ the effective mean energy was determined, and this was used in calculating theoretical distribution.

PLANE DIRECT VIEWING

The possibility of carrying out a preliminary survey of films by direct measurement was also considered, using a conventional condenser type viewer that had been previously designed by the author. The gate of this was removed to allow miniature radius plates to be laid against the film, which was held flat by rubber bands.

The image on the 6 cm film was one fifth full size, so the radius plates were scaled down accordingly, and track lengths measured by stepping off the arcs on the plates in half centimetre sections. (Fig.24).

Scattered angles could be measured by the same method as in reprojection; the normal to one fragment being drawn with the edge of the plate which was then reversed, a protractor laid against its edge, and the angle read off. Clearly parallax could not affect results, provided the arc on the plate was set to coincide with the scattered track at the point of deflection. Here again it was found possible in the majority of cases, to identify non co-planar tracks by separate examination of the top and side films.

This procedure, periodically assisted with a watch-maker's eyeglass, proved satisfactory. The contrast was excellent, and radii could be measured to better than 10%, lengths to 5%, and angles to about 2°.

The position may now be summarised thus:

Direct viewing seemed the most rapid method.

The accuracy, on length and radius of curvature measurements, is unsatisfactory on individual tracks, but being a random error, would not affect total track length or mean radius of curvature.

The accuracy of angular measurement is adequate if it is only necessary to allocate the events to a certain angular range, borderline cases being noted and reprojected.

If statistics justified displaying the results in 5° or 10° groups; or if individual results were of interest, for example owing to apparent loss of energy, it might be desirable to reproject all events, carrying out only a) search b) total length or c) mean radius measurements by direct viewing.

Whether the tracks were being measured by direct viewing, by reprojection, or by tracings made during reprojection, it was essential to use a radius plate to verify the continuity of

tracks before selecting them. (Fig.27)

It was therefore decided to use the method of projected angles, and make suitable allowance in the predictions; the precise combination of tracing, reprojection and direct viewing used would depend on individual circumstances.

ii) Calculation of Plane Projection Corrections

The experimental advantages of measuring the horizontal projection of track length and scattered angles have already been discussed. If an electron is scattered through an angle θ, the scattered track will lie on the surface of a right circular cone whose axis is along the incident path and whose apex is at the point of scattering. If we define the scattered plane, in which lie both the incident and scattered paths, to make an angle ω with the horizontal plane, then for most values of ω the horizontal projection of θ, which we may call ϕ, and term the apparent angle of scatter will be considerably smaller than θ. In general $\tan \phi = \tan \theta \cos \omega$ (Fig.29).

If the depth of the illuminated area is small, as is normally the case, the horizontal projection of the scattered fragment may also be very small (if θ is in the region 90°) and approaches zero as ω approaches $\pm 90^{\circ}$. It is therefore

necessary to choose a minimum length of track, and ignore fragments shorter than this. O'Ceallaigh and MacCarthaigh (1944) define the minimum length as equal to the illuminated depth multiplied by a constant ρ ; this is normally chosen to be unity, and in the treatment that follows, this will be assumed in the interests of clarity.

If we consider the simplest case, that of a particle scattered in the centre of an illuminated zone of depth a, then the maximum accepted angle of dip, α, will be given (Fig. 28) by $\tan\alpha = \frac{1}{2} a/\rho a$. Hence if ρ be taken as unity, the maximum angle of dip is 27°.

Clearly this limitation will only apply to tracks which are themselves scattered through a greater angle than 27°. For values of Θ above 27°, the maximum value of ω that is accepted will be given by;

$\sin\omega_{max} = \sin\alpha \operatorname{cosec}\Theta = 0.454 \operatorname{cosec}\Theta$, if $\alpha = 27^{\circ}$.

It should be mentioned that in the actual calculations this simple hypothesis of all events occurring in the centre of the illuminated depth was not used. It was instead assumed that the majority of electrons, and hence deflections,

would be found in the centre of the illuminated depth, and that the number would fall off linearly towards the top and bottom. In this case the best approximation is obtained by assuming that if α is less than 20°, 90% of the fragments will be greater than the minimum; if α is between 20° and 35° only 50% will be above minimum; and if α is greater than 35°, none will be acceptable.

It is at this stage, having found the general limiting conditions that the problem of applying them to the theory arises. If a number of particles are in fact scattered through an angle Θ, what will be observed is a distribution which may be continuous between zero and Θ. Thus the number of particles observed in any range of angles, $\Theta_1 - \Theta_2$, will be a function, not only of the number actually scattered between Θ_1 and Θ_2, but also of those scattered in the higher range $\Theta_2 - \Theta_3$, and possibly $\Theta_3 - \Theta_4$.

O'Ceallaigh and MacCarthaigh (1944) have applied relations, similar to the foregoing, to the appropriate formula for the differential cross section for scattering, and have then integrated with respect to ϕ and thus obtained the number of events which it is expected will be observable in any required angular range. This, however, is

only possible because they have made use of the Mott Light Element Formula,

$$\sigma = \frac{Z^2 e^4}{4m^2 v^4} \operatorname{cosec}^4 \theta/2 \; (1-\beta^2 \sin^2 \theta/2)(1-\beta^2)$$

an approximation which is only valid for elements with atomic numbers below forty.

The general Mott formula is in the form of a conditionally convergent series, as has been referred to earlier, for which a number of solutions have been obtained numberically by several methods for particular cases; these solutions are normally expressed as the ratio of the cross section for any angle to the cross section at the same angle predicted by the "Relativistic Rutherford" formula,

$$\sigma = \frac{Z^2 e^4}{4m_o^2 c^4} \frac{1-\beta^2}{\beta^4} \operatorname{cosec}^4 \theta/2$$

It was clear that the Mott Light Element Formula would be quite inapplicable to mercury, with an atomic number of 80, and it was equally clear that the operations performed by O'Ceallaigh and MacCarthaigh could not conceivably be carried out with the general Mott formula. The author decided therefore to use a graphical method of approach, evaluating the "Relativistic Rutherford" cross section and applying the appropriate corrections published by Massey (1942), by McKinlay and

Feshbach (1948) and by Bartlett and Watson (1940) for positrons and electrons in mercury in the region of 1 Mev. Finally the actual distribution to be expected in plane projection would be obtained.

The form of the "Relativistic Rutherford" formula giving the cross section for a scattering event between the angles Θ_1 and Θ_2 is

$$\sigma_{\theta_1\theta_2} = \frac{Z^2 e^4}{4m^2 c^4} \frac{1-\beta^2}{\beta^4} \frac{\pi \cos \theta/2}{180 \sin^3 \theta/2} d\theta$$ if Θ is expressed in degrees.

The Θ dependent term was integrated over 10° ranges, each integrated cross section being multiplied by the appropriate Mott/Rutherford ratio, R.

The plane projection corrections were now considered. From the minimum track length criterion, the general maximum angle of dip was found and thus the maximum permitted value of for any given value of Θ.

The total number of events in any angular range were regarded as occurring at one point in that range, thus those occurring between say 20° and 30°, were treated as if they all occurred at 24°, since the number expected between 20° and 24° is equal to that between 24° and 30°. With each range in turn, then,

the value of ω was calculated which would just make an event appear small enough to belong to the next lower range - and also that which would place it in a still lower range, having regard to the maximum value of ω already referred to. In the example quoted, (using the relation $\tan \phi = \tan \theta \cos \omega$) a track scattered through 25° would still appear in the $20^\circ - 30^\circ$ range if the inclination ω is less than 38°; it would appear in the $10^\circ - 20^\circ$ range if ω is between 38° and 68°; while if ω is greater than 68°, it would have an apparent angle of less than 10°. On the other hand, while a value of ω in excess of 36° would cause a 65° scatter to appear in the range $50^\circ - 60^\circ$, the maximum permitted value of ω for large angle scatters is 30°.

If we can now assume that particles are equally likely to be scattered in any plane, we may take the possible values of ω as a measure of the probability of any event appearing in any given angular range. Thus in the first case quoted, 38/90 of 25° events will appear in the $20^\circ - 30^\circ$ range, while 30/90 and 22/90 would appear in the $0^\circ - 10^\circ$ and $10^\circ - 20^\circ$ range respectively, were these both being used. In

the second case, the lower value 30/90 will be observed in the range 50° - 60°, and none will be transferred.

This procedure, using the rather fuller correction referred to, was therefore applied to each of the 10° ranges in turn, and thus the total number of events to be observed in each range found, by adding to the numbers remaining, the components transferred from other ranges.

As several approximations had been made in the foregoing, it was very desirable that the results should be checked with those obtained by an analytical method. By the nature of the problem, this could not be done for the element under review, so the calculations were repeated for argon, as A.F. Howatson (1951) had already calculated the probability of scattering for this material using O'Ceallaigh and MacCarthaigh's equations. The author followed the same procedure as for mercury, obtaining the appropriate values of 'R' from a general table for electrons published by McKinlay and Feshbach (1948).

The comparative results (Fig.30) being the probable number of events in 198 metres of electron track at a mean energy of 0.83 Mev, show an agreement that may be regarded as entirely satisfactory,

especially as the two approaches are built on different formulae.

All the data required for the formulae used in calculating the final plane projection distribution were now regrouped so that they could be evaluated as constants for any set of conditions; the angle dependent terms, which did not depend on energy or atomic number, were also evaluated and tabulated, as were the sets of factors used in calculating the plane projection corrections. (Appendix)

iii) Xenon - Analysis and Results

The tracing, measurement, and analysis of the photographs taken with a xenon-filled chamber had been proceeding simultaneously with the preparations for using a chamber with mercury di-methyl. The methods used, which followed conventional practice in this department, have already been described (IV i), the only departure being in the design of a radius plate to assist in the immediate rejection of events where the track was scattered through less than 15°.

Superimposed on the normal set of curves were short arcs (fig. 24), each making an angle of 15° with the full curve of the same radius, and, at its other end, making approximately the same angle with the neighbouring curve. These arcs

would normally be about 5 cms long.

Owing to the operation of the $\text{cosec}^4\,\theta$ law, the number of tracks to be expected with scattered angles between 14° and 15° is of the same order as the total number in the range 30° to 40°. The precise definition of this boundary is thus of some importance, and the use of specimen curves, of all radii and bent through 15°, provides a sensitive as well as a rapid test which is probably less liable to error through multiple scattering than is the conventional drawing of normals.

Despite this precaution, it will be seen that the number of tracks with scattered angles between 15° and 20° is markedly less than that predicted by theory. Owing to the unavoidable errors introduced by small angle scattering occurring close to deflections, many writers have omitted the lower angular ranges entirely, and Randels, Chao and Crane (1945) have quoted correction factors ranging from 1.13 to 1.73 for the range 15° - 25°. The departure from theory is not therefore regarded as significant, especially since the ratio of scattered positrons to electrons is in agreement with Mott.

The table shows also the total track length

in metres, and the mean energy for electrons and positrons respectively.

ELECTRONS

Track Length 260 m. Mean Energy 0,83 Mev.

	15°-20°	20°-30°	30°-40°	40°-60°	60°-90°	90°-180°
Exp.	60	41	22	13	5	4
Th.	87	60	20	13	5	-

POSITRONS

Track Length 111 m. Mean Energy 0.7 Mev.

	15°-20°	20°-30°	30°-40°	40°-60°	60°-90°	90°-180°
Exp.	23	13	9	5	1	1
Th.	38	24	7	4	1	-

Before considering the ratios, the positron results are normalised to allow for their differing track length and mean energy.

	15°-20°	20°-30°	30°-40°	40°-60°	60°-90°	90°-180°
R.Expl.	0.68	0.56	0.73	0.69	0.4	0.5
R.Mott	0.78	0.74	0.67	0.60	0.51	0.49
R Classical	1.0	1.0	1.0	1.0	1.0	1.0

Classical theory, corrected for relativistic rise in mass but taking no account of spin, does not distinguish between electrons and positrons, and thus predicts the same scattering cross section for both. This is clearly at variance with the experimental results which show good agreement with the ratio of cross sections predicted by Mott, treating the electron and positron as Dirac particles. (Fig 31)

iv) Mercury + Argon - Analysis and Results

For some time following the completion of the run carried out with mercury di-methyl in an argon filled chamber it was not possible to set up reprojection apparatus, so, as direct measurement was already considered to have some advantages, it was decided to carry out a preliminary survey by this method. It had been clear during the run that the positron source used was unsatisfactory when the background in the chamber was heavy, and it was hoped that the preliminary survey would throw some light on the desirability or otherwise of endeavouring at once to recover some of the mercury di-methyl that had been used, or of obtaining or making some more, should either be possible.

The films were examined directly in a viewer, and individual frames marked with wax pencil to show tracks, scattered and otherwise, whose length, curvature and, where applicable, scattered angle, had been recorded. The radii and scattered angle were found in the usual way with radius plates, and the arcs on these were divided in 0.5 cm steps so that the track lengths also could be measured. In any dubious cases

the corresponding tracks in the side film were referred to.

As has already been discussed, the application of plane projection corrections to theoretical predictions for heavy elements cannot be carried out by the normal algebraic processes, and so it was not immediately possible to assess the precise significance of the results. It was at once clear, however, that the final cross section would not have the abnormally low value reported by Champion; moreover further positron data were felt desirable.

For these reasons it was decided to endeavour to carry out a further run with mercury di-methyl, this time using the same gas as Champion, in case this had any bearing on his results; and a source which, although of lower energy, would ensure approximately equal numbers of positron and electron tracks.

While making preparations for this second run, a more detailed analysis of the first results was carried out. The films were replaced in their cameras, and tracks reprojected full size; each frame was then scanned to ensure that no tracks had been wrongly omitted or

included, and angles checked, especially if they fell on a boundary between two angular ranges. The number of events actually on a boundary was divided between the two angular ranges: this gives rise to the non-integral numbers. A number of tracks with deflections in the range 15° - 20° were found to have been classified as uniform tracks of a smaller radius of curvature, but there were otherwise few additions or deletions. In view, however, of this uncertainty, events in the 15° - 20° angular range have not been included.

The development of a means of calculating plane projection corrections by a graphical technique has been described elsewhere, and this could now be applied to the calculations of predicted angular distribution for comparison with experimental results.

Below is shown the observed angular distribution, together with that predicted for mercury, and for argon. The cross section of the CH_3 radical is, by comparison, negligible.

ELECTRONS

Track Length 64.0 m. Mean Energy 0.614 Mev.

	20°-30°	30°-40°	40°-60°	60°-90°
Expl.	31	12.5	12	6
Th. A	22	7	4	1
Th. Hg.	32	11	8	4
Th. A+Hg	54	18	12	5

POSITRONS

Track Length 12.1 m. Mean Energy 0.475 Mev.

	20°-30°	30°-40°	40°-90°
Expl.	6	3	2
Th. A.	4.8	1.5	1.1
Th. Hg.	5.6	1.7	1.3
Th. A+Hg	10.4	3.2	2.4

These two tables exhibit a marked similarity in that in each case the agreement with theory is poor for deflections of less than 30°, both the values for the range 20° - 30° being about two thirds that predicted. Nevertheless, in view of the correction factors of up to 1.7 referred to by Randels, Chao and Crane for scattering measurements in this region, the ratio of positron to electron scattering was calculated, the number of positron deflections being normalised for the different track length and mean energy. This is shown compared with the ratio to be expected from a mixture of argon and mercury nuclei, in the

appropriate proportions. The additional points were obtained by considering intermediate angular ranges, such as $25^{\circ} - 35^{\circ}$ (whose effective mean angle is 29°)

Mean Angle	19°	24°	29°	34°	38°	50°	60°	67°
R. Expl.	.83	.65	.68	.80	.48	.54	.35	.61
R Th.	.83	.79	.75	.81	.68	.61	.55	.52

It will be seen (Fig.31) that these points represent a distribution about the theoretical curve that is well within the limits of statistical error; and this, rather than the absolute cross section, is regarded as confirming the different behaviour of electrons and positrons predicted by Mott.

v) Mercury + Nitrogen - Analysis and Results

In the light of previous experience in analysing tracks, it was decided to trace only scattered tracks, and to select and in some cases measure these while being reprojected, the side camera being used as before in cases of doubt. At the same time a separate list was kept of tracks of similar quality without deflections, and their length was allowed for when calculating absolute cross section.

Tracks whose radius was uncertain owing to multiple scattering were rejected from both

categories, and it was found much easier to carry out this selection during reprojection than later, for the slightest inaccuracy in tracing can easily lead to wrong interpretation, especially in a short scattered track.

As before, the angular distribution, total track length, and effective mean energy were found for the electron and positron tracks, and then compared with the predicted number of deflections, allowance being made for plane projection corrections. Half integers appear where scattered angles fell on a boundary between two angular ranges.

ELECTRONS

Track Length 34.5 m. Mean Energy 0.195 Mev.

	20°-30°	30°-60°	60°-90°
Expl.	33.5	14	1
Th. N_2	26	13	1.6
Th. Hg	107	63	12
Th N_2+Hg	133	76	13.6

POSITRONS

Track Length 26.3 m. Mean Energy 0.185 Mev.

	20°-30°	30°-60°	60°-90°
Expl.	24.5	12	1.5
Th. N_2	21	10.5	1.4
Th. Hg	72	35	4.6
Th. N_2 + Hg	93	45.5	6.0

It is at once evident that in both tables the number of deflections is about a quarter of the total predicted for the mixture of mercury and nitrogen nuclei; it will also be seen that the number of deflections observed is only slightly in excess of the number to be expected from the scattering of nitrogen alone. Moreover, not only the absolute cross section, but also the angular distribution clearly agrees with that to be expected for nitrogen. This is demonstrated by the ratio of deflections between positrons and electrons which, normalised for energy and track length, is compared, in the table below and in Fig. 31 , with the ratios predicted for mercury and nitrogen.

Mean Angle	17°	24°	42°	72°
R Expl.	1.0	0.9	1.0	(1.8)
R Th. N_2	.98	0.99	0.98	0.98
R Th. Hg	0.90	0.82	0.65	0.47

These results leave little room for doubt that the scattering observed was due solely to nitrogen nuclei; where then was the mercury di-methyl? A count was therefore made of what may be termed the mean cross section, that is the total track length, for the first four as against

the last four films.

	First four	Last four
Track length, metres	32.2	30.0
Number of deflections	96	84
Deflections/Metre	2.9	2.8

Had mercury di-methyl vapour been present during part or all of the first films, the number of deflections per metre would have been greater by a factor of up to four; so the absence of any significant difference suggests, as before, that the mercury di-methyl was not absorbed during the run.

This appeared to leave three possibilities:

i) It was not mercury di-methyl that had been injected.

ii) The mercury di-methyl had been rapidly absorbed, or decomposed into some non-volatile compound.

iii) The mercury di-methyl had remained in the chamber, but, owing to some surface interaction, had not evaporated sufficiently to saturate the chamber with its vapour.

As it seemed that in the investigation of the second and third of these hypothesis there might also lie an answer to the anomalous results obtained by Champion, a series of experiments was carried out on the behaviour of mercury di-methyl under various conditions.

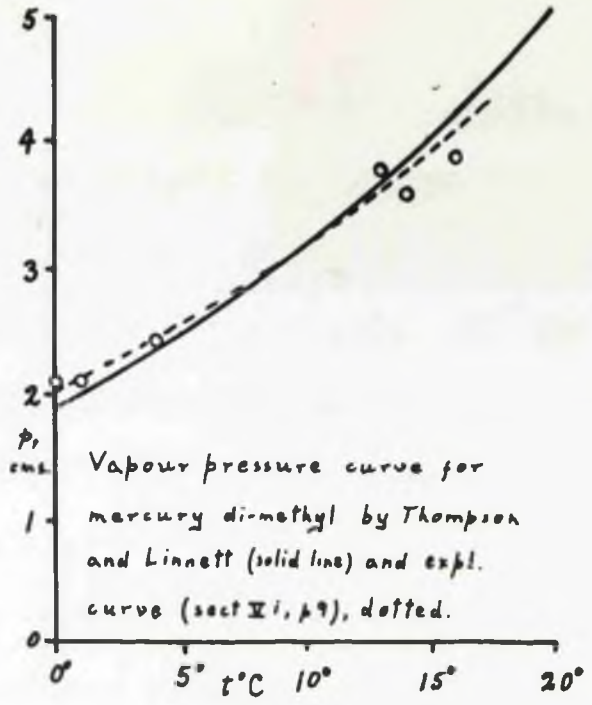


Fig. 32. In the presence of water, low vapour pressures had been observed for mercury di-methyl, so the vapour pressure was measured in vacuo over a short range of temperatures, and found to be in agreement with the pressures observed by Thompson and Linnett.

Fig. 33. In order to study the effect of different methods of injection on equilibrium vapour pressure, a dummy chamber was assembled containing velvet, rubber, and some water. Carbon tetrachloride has many physical properties similar to mercury di-methyl, and was here used in its stead.

V. DISCUSSION OF ANOMALOUS SCATTERING AND GENERAL CONCLUSIONS

1) Investigation of behaviour of Mercury di-Methyl in an expansion chamber, and the Champion Anomaly

When the analysis of the photographs of scattering in mercury and nitrogen was complete, it was found that, for both positrons and electrons, the number of deflections was in agreement with that predicted for nitrogen alone. As a comparison of the probability of scattering in the first and second halves of the run showed no evidence of a changing cross section, three hypotheses were suggested, and these, with the experiments arising out of them, will now be considered in detail.

VERIFICATION OF LIQUID INJECTED

That the liquid injected was not mercury dimethyl seemed improbable under the circumstances, but the latter's unusually high density suggested a rapid check. The small bottles in which penicillin is supplied have airtight rubber caps which can be readily pierced with a hypodermic needle. Using a 'tuberculin' syringe of 1 cc. capacity graduated in .01 cc. divisions, 0.305 cc. of the sample of liquid used on the run was injected, an increase in weight of 0.928 gms.

gave a density of 3.04 gm./cc., with an estimated error of ± .05. The author was unable to trace any colourless, mobile liquid of this or similar density other than mercury di-methyl, and therefore felt confident about accepting it as such.

EXPERIMENTAL DIFFERENCES BETWEEN NORMAL AND ANOMALOUS RUNS

Once it was accepted that the liquid was the same in each of the two runs, it seemed profitable to consider what differences there had been between the first, or normal, run and the second, which is under review.

Apart from the lower energy source, the gas, which was argon in the first run, was changed for nitrogen, the gas used by Cahmpion; again, in the first run the liquid mercury di-methyl was sprayed over the chamber bottom from a short needle, while in the second a long needle reaching into the central brass cup allowed the liquid to be almost poured in. These facts suggested various hypothesis.

DECOMPOSITION OF MERCURY DI-METHYL IN AN EXPANSION CHAMBER

Mercury di-methyl is a very unstable compound; it is, moreover, the only compound of mercury with a vapour pressure that is, from a scattering point of view, significant.

Thus it follows that a breakdown into almost any other compound would produce the same effect as its total disappearance from the chamber.

Dr. Beck, in a private communication, suggested that if even a small number of nitrogen molecules were broken down by radiation into monatomic nitrogen, the following chain reaction would follow rapidly, with an end product of ethane.

$$CH_3 HgCH_3 + N = HCN + H_2 + Hg + CH_3'$$
$$CH_3 HgCH_3 + CH_3' = C_2H_6 + Hg + CH_3'$$

He also pointed out that even if argon atoms were excited by radiation, each excited atom would break down only one molecule of mercury di-methyl as the mechanism does not involve a chain reaction.

$$CH_3 Hg CH_3 + A^* \rightarrow C_2H_6 + Hg + A$$

Clearly it was necessary to test this hypothesis, so two penicillin bottles, of the type already referred to, were filled with argon and nitrogen respectively. The pressure in the bottles was measured by water filled open manometers, hypodermic needles secured to the ends of their connecting tubes (also filled with argon and nitrogen) being inserted in the rubber caps of the bottles. Into each bottle was then injected 0.5 cc. of mercury

di-methyl, and the change in pressure observed. The pressure rose slowly until after about five minutes it had risen by an amount corresponding to two centimetres on a mercury manometer. In each case it remained steady for some hours, and then fell slowly to slightly above its original value. A second injection of mercury di-methyl showed a similar rise, and this time a 30 mc. Cobalt source was placed between them. Over several hours there were slight thermal changes in pressure common to both, but no differential effect.

At a rather later stage, using two all glass 'barometers', partially filled with nitrogen and argon, and containing also 0.2 cc. mercury di-methyl, some further tests were carried out to confirm beyond doubt the stability of mercury di-methyl under chamber conditions. There was no reaction at all to the Cobalt gamma source previously referred to, so the source was removed and the electrode of a Tesla coil wired to clips on the tubes. Even when these clips were lowered to within five centimetres of the surface of the mercury column and a direct, visible discharge was formed, no pressure change appeared during over an hour. It therefore seemed that no amount of ionisation

that might occur in the chamber would be capable of decomposing the mercury di-methyl.

Radiation from a photoflood lamp caused a rise in pressure in both tubes during an hour, but this gradually returned to normal, and was probably thermal. A discharge lamp, similar to that used for illuminating the chamber, was wired with a Tesla coil permanently connected to its triggering electrode, thus causing a discharge to occur whenever the electrode potential rose to about 500 v. and producing a flash every second. This resulted in a slight common rise in pressure, but no differential change. Attempts to make the lamp self-triggering at its normal working voltage of 2 Kv. by an artificial surface track were unsuccessful, but a suitable discarded lamp was found, and thus a full discharge was obtained approximately three times every minute. This was allowed to continue for two and a half hours, thus simulating ten hours of normal running. Over this period the pressure in both columns increased by one millimetre.

Had the decomposition in nitrogen been occurring in the manner that had been suggested, a steady rise in pressure would have been expected as the production of gaseous ethane from liquid mercury

di-methyl proceeded, while a much lower rise might have been observable as the result of the argon reaction. There was, however, no evidence that either reaction was taking place, even under irradiation, illumination, and direct ionisation greatly in excess of anything that would be encountered in the normal operation of an expansion chamber.

VAPOUR PRESSURE OF MERCURY DI-METHYL IN THE ABSENCE OF WATER

It had been noted, in the first of the experiments described, that under certain conditions the vapour pressure measured on the manometer was much lower than had been expected. As it had also been noted that the liquid mercury di-methyl could be rapidly absorbed by, for example, a rubber bung, it seemed possible that the low pressure observed was the result of absorption in the rubber tubes, coupled either with slow diffusion through the hypodermic needles, or with a rate of evaporation that had been slowed down by a film of water on the surface of the mercury di-methyl.

In order to eliminate the first, a glass vessel was made from a short length of 20 mm tube. To one end was sealed a 5 mm. tube, and at the other a brass injection port was cemented,

similar to that used on the chamber, and like it carrying a rubber 'penicillin' seal. The same procedure of injection and pressure observation, with and without irradiation, was carried out for nitrogen only, with exactly the same result as before. It therefore seemed that the low vapour pressure was the result of some interaction, physical or chemical, occurring only at the evaporating surface, an interaction that inhibited evaporation, but did not occur in such a way (if of a chemical nature) as to produce a measurable gaseous product.

It should be mentioned at this stage that no attempt had been made initially to exclude water from the experiments, since it was invariably present in the chamber, and thus any reaction that could only occur in its absence was of no direct interest. (The all-glass 'barometer' experiments on decomposition already described were chronologically later). For this reason a small quantity of water had always been introduced into the test bottles in advance; this was also part of the reason for choosing water manometers, though their larger displacement for small changes in pressure proved an asset in making readings from a distance, all these experiments being carried

out in a well ventilated fume cupboard. Nevertheless it now seemed desirable to consider separately the effects of water and of the two gases, and also to verify that the pressure in vacuo was in agreement with published data (Thompson and Linnett 1936 and Ratman 1936).

A mercury barometer was therefore made in the normal manner, the lower end of the tube being opened out to form a bell. The tube was then filled and inverted over a beaker partially filled with mercury, and mounted with a gap of about a centimetre between the end of the tube and the bottom of the beaker. After the height of the barometer had been checked, a syringe containing mercury di-methyl was fitted with a hooked needle. When the end of this had been plunged below the surface of the mercury in the beaker, a layer of sodium sulphite solution was poured over the mercury, to render safe any mercury di-methyl rising to the surface. The plunger of the syringe was now depressed to expel air, until drops of mercury di-methyl rose to the surface of the mercury, under the sodium sulphite. The hook of the needle was now inserted under

the bell end of the barometer tube, and about 0.3 ccs. of mercury di-methyl injected. This rose at once to the top of the column in bubbles, and the pressure rapidly fell by 3.7 cms. A limited temperature/vapour pressure curve was drawn by first warming the fume cupboard to 20° C., then chilling it to 0° C. by drawing the air intake over chips of solid carbon dioxide. The resulting curve (Fig. 32) was found to lie closely over that published by Thompson and Linnett. The pressures published by Ratman are not included as they are almost identical with the others. This was also regarded as a final check on the identity of the mercury di-methyl.

Two further, similar, 'barometers' were now prepared, but after inversion over beakers they were filled with argon and nitrogen respectively to pressures of about 50 cms. The use of these 'barometers' in the later tests for decomposition has already been referred to. In order to produce a slow and controlled flow of gas into the 'barometer' tubes, the following technique was evolved. A one inch glass tube several inches long was sealed at one end, and the other drawn out into a very fine jet. This was connected

with a pumping system and evacuated until a Tesla discharge was almost invisible. It was then filled to slightly over atmospheric pressure with the required gas, removed from the pumping system, and the end plunged under the bell end of the tube. Gentle heating, with the hand or with a bunsen burner caused the gas to bubble slowly into the tube, until the required pressure of 50 cms. was reached. As in the previous case, 0.2 ccs. of mercury di-methyl was introduced into each with a hooked needle, and the change in pressure carefully observed.

In each case the pressure rose steadily, until after an hour it had risen to three quarters of that observed in vacuo, allowance being made for the changing volume of gas as the mercury column was displaced. After a further hour it had settled down at a pressure corresponding to that in vacuo. The pressure had changed at precisely the same rate in the two gases, and during several days, the changes in pressure caused by alterations of atmospheric pressure and temperature, as well as by the illumination and irradiation already referred to, were again identical.

It seemed clear from the foregoing that the vapour pressure of mercury di-methyl was normal in the absence of rubber and water, so, in order to observe directly the fall in vapour pressure resulting from absorption by rubber, some diaphragm rubber was finely shredded, and several pieces held in forceps were released under each tube. Unfortunately the rubber adhered much more strongly to the glass than did the mercury, and despite considerable agitation, none could be persuaded to float up to the vapour at the top of the column.

Although this last check had been unsuccessful, there was already ample evidence that mercury di-methyl was readily absorbed by rubber; for example, a rubber sealing cap in contact with the liquid had absorbed a third of its own weight of mercury di-methyl in four hours.

It had already been postulated that the presence of water might affect the rate of evaporation and hence, in the presence of an absorber, the pressure of vapour developed in the steady state. The effect of water was therefore considered next, and, rather than carry artificial experiments further, this was done in a dummy chamber in which the actual methods of injection used were

repeated. As it was felt unwise to carry out this test with mercury di-methyl itself, carbon tetrachloride was used as a substitute. This liquid was chosen because, like mercury di-methyl, it is very volatile, is denser than water and insoluble in it, and is readily absorbed by rubber.

EFFECT OF METHODS OF INJECTION ON STEADY STATE VAPOUR PRESSURE

The dummy 'chamber' consisted of two ten inch diameter glass plates separated by a glass cylinder nine inches in diameter and two inches high. It was thus identical in size with the expansion chamber that had been used. In the glass cylinder there were two holes, to one of which was secured a tube connected with a manometer and also a pump (Fig. 33.). In the second hole there was fixed a brass injection port fitted with a rubber seal. The bottom of the 'chamber' was covered with black velvet; in the centre was a shallow cup whose inner surface was wetted with water, to simulate the effect of condensation; and to one side was a folded sheet of thin rubber, similar to that surrounding the moving plate, in a working chamber.

With a pressure inside the 'chamber' ten cms. below atmospheric, 0.5 cc. of carbon tetrachloride

was injected with a long needle into the cup on the bottom. The pressure rose slowly (six minutes) to a maximum of 0.75 cms. A similar quantity was now sprayed over the velvet using a short, fine, needle. Within one minute the pressure had risen to 2.8 cms., and two minutes later to its maximum of 3.6 cms. After this it began to fall slowly, and two hours later the pressure was 2.0 cms, having thus ranged between three and five times the pressure produced by liquid injected directly into the cup. At 18° C., the published value for the vapour pressure of carbon tetrachloride is 8 cms.

GENERAL CONCLUSIONS

While it is impossible to apply these results quantitatively to the evaporation of mercury di-methyl, it will be clear that under certain conditions the steady state vapour pressure may be very much less than the value it would have in vacuo, and this despite the continued presence of free liquid.

In the first of the two experiments described in this paper, the mercury di-methyl was injected in a fine spray over a bottom consisting of a thin layer of gelatine on velvet. A rapid rise to a pressure of 3.3 cms. was recorded. In this

case the scattering was normal when compared with a predicted distribution based on a vapour pressure of 3.3 cms.

In the second experiment the chamber was completely sealed off before the mercury di-methyl was injected so - most unfortunately in the light of later information - no pressure readings were taken. On this occasion the mercury di-methyl was 'poured' with a long needle into a small brass cup, in direct contact with the cooled (brass) moving plate. A rim had been fixed to the perimeter of the plate thus permitting the gel to be at once deeper and more nearly fluid. This alteration had been carried out with the object of reducing fog, but would undoubtedly result in water condensing on the central cup, while any mercury di-methyl condensing on the gel might well sink to the bottom and be effectively lost. Under these conditions the steady state vapour pressure would be very low, as now appears in the light of later work, and it does not therefore seem surprising that the amount of scattering observed was not different from what would have been expected from the filling gas, nitrogen, alone.

THE CHAMPION ANOMALY

It is the opinion of the author that it is

this effect of inhibited evaporation, coupled with absorption by rubber, that explains the apparently anomalous scattering of electrons in the vapour of mercury di-methyl reported by F.C. Champion (1938)

In the first experiment described by Champion, the mercury di-methyl was contained in a U-tube, and the vapour drawn into the chamber at intervals. It would seem equally probable that water vapour from the chamber would in turn pass into the U-tube, condense on its walls, and run down to form a layer on the surface of the mercury di-methyl, thus restricting the rate of evaporation from an already small area. In the second experiment, carried out to provide confirmation, it appears from the description that the mercury di-methyl was mixed with water on the floor of the chamber, and the same effect would apply; the precise steady state vapour pressure reached depending entirely on the geometry of the chamber, and on the amount of water and rubber present.

At first sight, the fact that the scattering in both experiments was about one sixth of that predicted appears significant, but the possible consequences of a relatively small

error in the estimated mean energy, for which no details are given, should perhaps be pointed out. If this were lowered by about 10%, the increased number of deflections predicted for nitrogen alone would approximately equal the total observed, even in the total absence of mercury di-methyl vapour.

SURVEY OF FURTHER EXPERIMENTS USING MERCURY DI-METHYL

As volatile non-radioactive compounds of heavy elements are relatively rare, it seemed profitable to consider briefly possible techniques for further work, while the material was on hand. It was already clear that it is not well suited to expansion chamber work, as, used alone, the gamma of the vapour/gas mixture is very much lower than when, say, water is used, and an expansion ratio of the order of 1.5 is required. While it is not impossible to design an expansion chamber to operate at a ratio as large as this - one is described in this paper - it becomes very difficult to prevent turbulence causing serious track distortion. In any case there was no definite evidence that electron tracks could be detected. If a separate condensible vapour is used, such as water, there

must always be some doubt about the steady state pressure of the mercury di-methyl vapour, and even with a separate vapour, the track quality is still far from satisfactory for electrons owing to the persistent background fog. Whether a diffusion chamber could be operated with mercury di-methyl as condensible vapour is a possibility that might perhaps be worthy of consideration.

As there were not already any known scintillators in the organometallic range, this possibility was considered.

Three ccs. of mercury di-methyl in a flat bottomed weighing bottle were placed on the window of an E.M.I. type 5311 photomultiplier and a 20 mC. thorium (gamma) source mounted in lead six inches away. The phototube, operating at 950 v., was connected with a 50 dB. amplifier and a discriminator set at 5 v. The counting rate with xylene (terphenyl activated), with mercury di-methyl, and with no phosphor was measured, as also was the true background with no source.

SOURCE	PHOSPHOR	TIME (mins)	COUNTS	RATE (COUNTS/MINUTE)
Thorium	Xylene (act.)	5	237,622	47.524
"	None	30	1,439	47.6
"	$Hg\ Me_2$	30	1,298	43
"	"	30	1,106	36.3
"	None	30	1,055	35
"	Xylene (act.)	5	234,066	46,813
None	None	60	46	0.8

Mean rate with mercury di-methyl as phosphor ---------- 39.8 counts/minute

Mean rate with no phosphor ----- 41.3 counts/minute

Approximate rate with terphenyl activated xylene ---- 47,000 counts/mimute.

Although the counting rate of around 40/minute disappears when the source is removed, there is no significant difference between the mean rate with no phosphor (41.3) and that with mercury di-methyl as phosphor (39.8). It must therefore be assumed that this rate represents gamma conversion at the photocathode of the photomultiplier. In any case it seems clear that, if mercury di-methyl does act as a phosphor with an output in the visible or soft U.V. regions, its output is down by at least a factor of 10^5 when compared with terphenyl activated xylene.

ii) Summary of experiments and results

When the Dirac prediction of an anti-particle to the electron was followed by the observation of the positron, Dirac's concept of particles differing in spin as well as in charge was developed by Mott to give a rigorous quantum-mechanical theory of relativistic scattering. thus the most sensitive test of Mott theory is to compare the relative number of electrons and positrons scattered under the same conditions.

To study in a cloud chamber the single dispersed scattering by an element, it must be present in the form of either a vapour or a gas. Some photographs of scattering in the gas xenon (Z=54) had already been taken by J.R. Atkinson and A.F. Howatson, and these were analysed by the author. When, however, heavier elements were considered, the most suitable compound was the volatile di-methyl of mercury. A further reason for choosing this was that when F.C. Champion (1938) had studied the scattering of electrons in mercury di-methyl, he had found a scattering cross-section much lower than either Mott or Rutherford theory allowed, and this experiment had never been repeated.

The difficulty and delay in obtaining even a small quantity of mercury di-methyl ruled out pilot

experiments, but it was hoped to use its vapour alone as condensible medium. Calculations suggested that an expansion ratio of about 1.5 would be required; so among other alterations described is the modification of the expansion chamber to permit the use of large ratios.

No definite tracks could be obtained with mercury di-methyl alone, but with added water a total of 2,500 pairs of photographs were taken during two separate runs.

Although O'Ceallaigh and MacCarthaigh (1944) have carried out plane projection calculations using the concise Mott light-element fomula, it would be impossible to repeat the algebraic method used by them with any form valid for mercury.

Starting therefore from the published ratios between the Mott and the "Relativistic Rutherford" cross sections, the author carried out calculations on the basis of finite steps, and, for certain standard conditions, the results have been tabulated for subsequent use .(IV ii, and Appendix.)

Using this technique, the 2,500 pairs of photographs of scattering by mercury were analysed, together with 1,000 pairs that had been previously taken using xenon. Electron scattering was greatly in excess of positron scattering, showing good

agreement with Mott theory for xenon, and also for mercury di-methyl on the first run, but in the second run there was no evidence of any scattering by mercury nuclei at all.

A series of experiments carried out to study the relevant properties of mercury di-methyl showed that the explanation lay in the dependence, under certain conditions, of the steady state vapour pressure on the area of the evaporating surface. In the second run this had been greatly restricted as a result of some chamber alterations designed to reduce fog.

A study of the apparatus used by Champion, in the light of this work, shows that the steady state vapour pressure of mercury di-methyl in his chamber would be a small fraction of that in vacuo, and it therefore seems probable that here, rather than in any variation of nuclear forces, lies the explanation of the subnormal scattering that he observed.

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APPENDIX

In order to facilitate the calculation of plane projection angular distributions, for this and other experiments, a standard procedure was adopted and, where possible, results tabulated. For such calculations the attached sheet has been found useful, and in this appendix its derivation and use are outlined.

CROSS-SECTION CALCULATIONS

If in the Rutherford Formula (I iii) the term $(m_o c^2)^2(\beta^4/1-\beta^2)$ is substituted for $(m_o v^2)^2$, the cross-section will equal the Mott cross-section for $\theta = 0$ and for other values of θ will differ by a factor r, for which values have been published (I iii).

If this cross-section is multiplied by $2\pi \sin\theta\, d\theta$ and integrated between θ_1 and θ_2 the probability is obtained of a particle being scattered by a single nucleus, and the deflection lying in the range $\theta_1 - \theta_2$ further constants are introduced to express this in terms of the number of deflections to be expected in 10 metres of track.

$$n = 4\pi \cdot \frac{Z^2 e^4}{4m_o^2 c^4} \frac{1-\beta^2}{\beta^4} \int_{\theta_1}^{\theta_2} \frac{\cos\theta/2}{\sin^3\theta/2}\, d\theta \cdot r \cdot \frac{N}{2.24 \times 10^4} \cdot 10^3 \cdot \frac{p}{76}$$

Evaluating constants:

$$n = (6.68 \times 10^{-3} \times Z^2 \times p/76)(1-\beta^2/\beta^4) \times r \times \operatorname{cosec}^2 \theta/2 \Big/_{\theta_1}^{\theta_2}$$

$$= K \times B \times r \times f(\theta)$$

It is convenient to evaluate K and B separately,

as sources of differing energy may be used during one run.

PLANE PROJECTION CALCULATIONS

It is clear that the apparent length of a scattered fragment of track will depend (Fig.28) not only on its angle of dip, but also on the position of the point of scatter in the illuminated zone. On this basis we may show that 80% of tracks having an angle of dip not exceeding 20° will have an apparent length exceeding the minimum, but only 35% of those with an angle of dip exceeding 20° will, on average, be acceptable.

For the reasons discussed in section IV, a track scattered through 34° will appear to be deflected through 30° or less if ω, the inclination of the scattered plane (Fig. 29), is greater than 31°.

Since an equal number of events occur in the ranges $30^{\circ} - 34^{\circ}$ and $34^{\circ} - 40^{\circ}$, we may say that, in general, $\frac{31}{40} \times 80\%$, i.e. 28% of events occurring in the range $30^{\circ} - 40^{\circ}$ will be seen as such.

In the same case, if $\omega \geqslant 57^{\circ}$ the same deflections would appear as less than 20°. For an angle of dip, α, equal to 20°, $\omega = 38^{\circ}$, so the proportion of these deflections appearing in the range $20^{\circ} - 30^{\circ}$ will thus be $\frac{38 - 31}{90} \times 80\% + \frac{57 - 38}{90} \times 35\%$ i.e. 13%.

Thus of the total number of events occurring

between 30° and 40°, 28% will have apparent deflections of $30^{\circ} - 40^{\circ}$, and 13% will have apparent deflections of $20^{\circ} - 30^{\circ}$.

Since the limitations on possible values of α (arising out of the minimum track length criterion) invariably rule out apparent changes of angle in excess of 10°, a simple tabular form is again possible. The procedure is therefore to determine r and evaluate $K B$, thereby obtaining the number of events in space per 10 metres of track ($= f(\theta).r.K.B$). The percentages retained and transferred are now calculated and the totals to be expected in each range thus found, still for 10 metres. From this the number is obtained for the appropriate track length.