PREFACE

The research work described in this thesis was done at the University of Glasgow between January 1954 and December 1956 as part of the requirements for a Ph.D. degree.

There are two parts to this thesis. The first and major part is a description of the development and use of apparatus to measure the lifetimes of excited states of atoms. The second part which forms an appendix deals with the design and construction of equipment to measure the cross-section for the photoproduction of neutral pi-mesons at the helium nucleus.

The work on atomic lifetimes was done under the guidance of Dr. E.H. Rhoderick and was started by Mr. S. Heron. Before he was killed in a climbing accident in December 1953 Mr. Heron had built most of the apparatus required for the experiment. He had also shown that in the form in which it then existed it was not capable of yielding accurate values. I was responsible for making the changes which his work had shown to be desirable as well as a number of others dictated by subsequent experiments. All the lifetime measurements were carried out by myself. This work was completed by March 1955.

I joined Dr. E.H. Bellamy in August 1955 to design and construct apparatus for the determination of the cross-section for the reaction.

$$\gamma + He^4 \rightarrow He^4 + \pi^\circ$$

In October 1955 Mr. P. Palit started work on the same apparatus and together we built it. By December 1956 it had been shown to work and before I left measurements had been made. Subsequently Mr. Palit completed the series of measurements.

In the appendix in which this work is described I have concentrated on the design and construction of the apparatus.

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Contents

List of Symbols

(Only those used frequently are listed)

Subscripts are used to denote levels, terms etc. (0 is ground, 1 is lower and 2 is upper.) They are also used to specify a transition usually by the wavelengths in Å.

Symbol	Meaning	Value	Units
A	Transition Probability	-	sec^{-1}
c	Velocity of light	3×10^{10}	$cm. \times sec^{-1}$
e	Electronic charge	$4{\cdot}80 \times 10^{-10}$	e.s.u.
f	Oscillator strength	-	number
g	Escape factor (Resonance Radiation)	-	number
h	Planck's constant	$6{\cdot}62 \times 10^{-27}$	erg x secs.
I	Intensity of radiation	-	$ergs \times sec^{-1} \times cms^{-3}$
k	Boltzmann's constant	$1{\cdot}38 \times 10^{-16}$	$ergs \times deg^{-1}$
m	Mass of electron	$9{\cdot}11 \times 10^{-28}$	gms.
N	Density of atoms	-	cms^{-3}
n	Refractive index	-	number
Q	Atomic cross-section	-	cms^{2}
T	Temperature	-	^{o}K
t	Time	-	secs.
v	Velocity	-	$cm \times sec^{-1}$
ϵ	Energy	-	ergs.
λ	Wavelength	-	Å
ν	Frequency	-	sec^{-1}
τ	Mean lifetime of a state or level	-	secs.
ω	Statistical weight of a level $(2J + 1)$ / a term $(2S + 1)(2L + 1)$		

A NEW METHOD OF MEASURING THE LIFETIMES OF EXCITED STATES OF ATOMS

1. INTRODUCTION

The importance of spectra in the development of Bohr's theory of the atom is well known. The measurement of the wavelengths of the lines leads directly to the evaluation of the energy levels. The interpretation of the intensities of spectral lines is a very much more complex problem depending often on a detailed analysis of atomic collision processes and the re-absorption of radiation by neighbouring atoms. If the atoms are present in very low concentrations so that re-absorption is not important then the intensity I_{21} of a line is given by the relation

$$I_{21} = N_2 . A_{21} . h\nu_{21}$$

The commonly used symbols are listed at the beginning of the thesis. The transition probability ~~quantity~~ A_{21} is a constant of the excited atom and the value of N_2 depends on the types of collisions taking place between the atoms and electrons.

In the literature the term "oscillator strength" or "f-value" is sometimes used (represented by the symbol f). This is related to the transition probability by

$$\omega_2 A_{21} = \frac{8\pi^2 e^2 \nu_{21}^2}{mc^3} . \omega_1 f_{12}$$

where ω_1 and ω_2 are the statistical weights of the lower and upper states respectively.

The conception of oscillator strength arose as part of the classical electrodynamical theory of dispersion. The oscillator strength is the number of electrons per atom associated with the dispersion of light of the wavelength concerned.

The lifetime of an excited state of an atom which is not perturbed by external influences is the reciprocal of the sum of the transition probabilities to all states with which this particular state will combine.

$$\frac{1}{\tau_2} = \sum_n A_{2n}$$

The measurement of this quantity is the particular problem discussed in this thesis.

Dirac derived an expression for the transition probability A_{21} on the basis of quantum theory. He showed that an electric dipole of energy $\epsilon_2 - \epsilon_1$ will radiate according to classical electrodynamics while dipoles having the energies of the bound states ϵ_1 and ϵ_2 will not give rise to radiation. He showed that the transition probability is related to the probability that an electron will find itself alternately in states 1 and 2. The expression for A_{21} is

$$A_{21} = \frac{64\, e^2 \pi^4}{3h} \cdot \nu_{12}^3 \cdot R_{21} \cdot R_{12}$$

where R_{21} and R_{12} are the space parts of the transition moments between the states and the other symbols have their usual meanings.

$$R_{21} = \int \psi_2 \, \psi_1^* \, r \cdot d\tau \qquad \text{(for dipole radiation)}$$

ψ_1 and ψ_2 are the space parts of the wave functions describing the states 1 and 2. The integration is taken over the whole volume of the atom.

Thus the evaluation of the transition probability requires

knowledge of the wave functions of the initial and final states. Since the integration extends over the whole atom the contribution to the integral from regions remote from the maxima of the wave functions may be significant. This makes the theoretical calculation uncertain for complex atoms. The exact calculation is possible for hydrogen-like atoms and has been carried out by Bethe[1]. Approximate wave functions have been used to calculate values for more complex atoms (see especially [2]), considerable progress having been made recently by the use of computing machines[3]. In such calculations it is common to find that answers based on different wave functions differ by a factor of two or more, although for the simpler atoms greater consistency is found.

In this situation comparison with experimentally measured values is especially important. Most of the measurements that have been made are on atoms of the metals, mainly because of their astrophysical interest. One finds values for the same transition measured using different techniques differing by factors of two and three[4]. Very little experimental data is available on the simpler atoms.

A set of careful measurements of the transition probabilities for a hydrogen-like atom would be a useful fundamental check of the underlying quantum theory. It will be shown later that the technique described in this thesis could be used for such a measurement. As a compromise between the additional experimental difficulties of using hydrogen, and the desire to use a simple atom, helium was chosen for the experiments to be described.

A new technique of measurement may also be of value in clearing up the discrepancies among the recent experimental results. Accurate knowledge of transition probabilities is required for the analysis of stellar spectra as well as for the recent work on high temperature gas discharges. In both cases the intensities of spectral lines are measured and from these

the populations of the various excited states calculated. The relative populations of the atomic states in the atmosphere of a star (assumed in thermal equilibrium) is a measure of the electron temperature. At the temperature of a stellar atmosphere (10^4-10^5 degrees), most atoms are ionised so that laboratory measurements of the transition probabilities of ions are required. In some of the recent high energy gas discharges the measurement of line intensities is used as a guide to the types of atomic collision processes taking place. The very high temperatures existing in some of the discharges mean that highly ionised atoms are produced, in fact, spectra of $O\overline{V}$ have been reported[66]. In each case the step from line intensities to populations of the excited states requires knowledge of the transition probability. The exponential factor in Boltzman's equation means that one can get good estimates of the temperatures of stars despite inaccurate transition probabilities. In the analysis of gas discharge spectra there is a need for more accurate values.

In the work to be described, a technique developed in nuclear physics has been applied to this field for the first time. It appears to have a number of advantages over some other methods and may be capable of being developed to cover a wider range of measurements. Some of these are discussed later.

2. REVIEW OF PREVIOUS WORK

There are in existence a number of reviews of both theoretical and experimental work[4] [5] [6] [65]. The material of this review falls naturally into two categories. The first includes work done mainly in the decade spanning 1930 and the second is a description of more recent experiments. It was during the first period that the fundamentals of the subject were being established and experiments were done in support. The measurements which will be described in this thesis represent an extension using recent techniques of these earlier experiments. Most recent work has been inspired by the need to know atomic transition probabilities for the interpretation of the intensities of lines of stellar spectra in terms of the temperature of the outer layers of the stars. Even more recently the work on high current gas discharges has created a demand for accurate values of transition probabilities of ions. Thus recent work has been concentrated on the fairly complex atoms of the iron group of metals, since these are present in stellar spectra. Special methods have been developed for these materials and there are few connecting links between the large number of measurements made on these complex atoms and the many calculations for the simpler structures, where few measurements have been made.

(a) Oscillator strengths by the intensities of spectral lines.

The best known of the recent experiments have been done using electric arcs. Before discussing the three different types of arc which are representative of those in use, some general considerations will be given.

The intensity I_{21} of a spectral line is

$$I_{21} = N_2 A_{21} h\nu_{21}$$

(provided there is no re-absorption of the emitted radiation).

Thus, if the intensity of a line is measured and the population density N_2 of the upper state is known, then the transition probability can be found. In most discharges (which are the usual laboratory sources of spectra) the value of N_2 is not known. However, in a spectroscopic arc it has been established that the levels of atoms present are populated according to Boltzman's law; that is to say that thermal equilibrium exists in the plasma of the arc or that inelastic collisions (mainly between electrons and the atoms) are much more likely than the spontaneous decay of excited states.

Boltzman's equation is

$$N_2 = N \frac{\omega_2 e^{-\frac{\epsilon_2}{kT}}}{\sum_n \omega_n e^{-\frac{\epsilon_n}{kT}}}$$

where N is the total number of atoms/c.c. The summation over n includes all states of the atom.

The important question of thermal equilibrium in an arc has been investigated by Mannkopff[7]. He was able to show that departures from the Boltzman distribution would give rise to errors small in comparison with those due to other causes. His measurements were based on the observation of the scattering of ions passed through the arc and on the rate of cooling of the arc.

Ornstein and Brinkmann[8] have set out the conditions necessary for the existence of thermal equilibrium. These are:-

1. That an electron in the arc must exchange with the electric field less energy than its thermal energy in travelling a mean free path.

2. That the "temperature" should not change appreciably in a distance of the order of the mean free path of an electron.

To meet these conditions in an arc of normal size the gas pressure

requires to be about an atmosphere or more so that in order to avoid self-reversal (i.e. re-absorption of the spectral line in the vapour of the arc), the atoms being observed must be present at low concentration and form only a small proportion of all those present in the arc. For this reason it has not been possible to estimate accurately the number of atoms of a particular species present in the plasma of an arc. Thus measurements of relative f-values are possible, while absolute estimates are liable to much larger errors.

A group working at Utrecht have used a low current carbon arc to measure a large number of f-values. This work has been summarised recently by Maecker[9]. The steady and gradual introduction of atoms of the species of interest is achieved by boring out the core of one of the electrodes and filling it with a "wick" containing the material. The temperature of such an arc has been determined by measuring the relative intensities of the rotation bands of CN molecules (especially at λ3883Å) and by measuring the intensities of very strong spectral lines. These suffer so much re-absorption that the intensities are those for a black body at the temperature of the discharge (see Maecker[9]). It is not possible to use the Doppler broadening of a spectral line as an estimate of temperature due to the strong Holtsmark and Stark broadening usually present.

Maecker has developed the water- or air-vortex stabilised arc at Kiel for spectroscopic purposes. By causing a vortex of air or water to flow round the arc the current channel is constricted and the current density raised so that higher temperatures have been achieved (10,000 - 50,000°K have been reported[4]). With these arcs which are reported to be accurately controllable, f-values for transitions in some of the ions should be measurable. Jurgens[10] has written a general review of methods of determining the temperature of the vortex stabilised arc. He finds that all the methods

lead to the same value within experimental error so that we may have confidence in the measurements (quoted with an error of ± 1%) Motschmann[11] has recently measured oscillator strengths of transitions in N I using such an arc.

Allen[12] has used copper electrodes alloyed with very small quantities of other metals for an arc from the spectrum of which he was able to estimate the f-values for many transitions of the materials present. His measurements are quoted as absolute values, this having been done by comparison with those values measured by other means. The essential advance which this series of measurements makes over others is that, since the alloy metals are present in accurately controlled proportions, it is possible to determine relative f values between different elements. The authors of this work, on the basis of their measurements of about 400 oscillator strengths, suggest an approximate empirical relationship between the (modified) line strength and the excitation potential. Once established, such a relationship would be of great value in astrophysics where approximate values are often adequate. Confirmation must be sought through measurements by different methods.

Oscillator strengths have been determined by Carter by the somewhat related method where the material being studied is heated in a very high temperature furnace (~ 2,500°K)[13]. The atoms of the vapour are in thermal equilibrium so that the oscillator stengths are obtained from the intensities of the spectral lines as with an arc. Because of poor light intensity, photomultipliers were used instead of the more usual photographic plate. By this means, lines requiring up to 3·5 e.V. to excite them were detected. One must rely on the vapour pressure curve of the material being studied in order to estimate the atomic density and hence evaluate oscillator strengths. Carter's values are relative.

The furnace method has some advantages over the arc, viz.

i) Accurate measurement of temperature is possible by established methods.

ii) Temperature gradients across the vapour can be avoided

iii) Density variations are less likely.

On the other hand, the lower temperature means that it is not possible to excite the higher states in a furnace.

The main sources of error in measurements of oscillator strengths from emission spectra of the type described above are

i) Difficulties are involved in measuring accurately the temperature of the vapour. Since temperature appears in the exponent of Boltzman's equation, it strongly influences the value of the result. Under the conditions of Carter's experiment mentioned above, an error of 1% in estimating the temperature leads to an error of about 10% in the final answer.

ii) There are difficulties in calibrating the detector in the ultra-violet region of the spectrum. A tungsten filament lamp has been used down to about 4000 Å but the intensity at shorter wavelengths is insufficient to be readily detected. Tomboulian and Hartman[14] have suggested that the radiation emitted by the centripetally accelerated electrons in a synchrotron be used as a standard for the calibration of detectors in the ultra-violet and soft X-ray regions of the spectrum.

iii) Where photographic plates are employed, the Eberhard effect may require corrections of as much as 25% to be applied to the intensity as measured from the photographic blackening.

iv) In an arc it is not possible to avoid a temperature gradient so that, to this extent, the temperature of the source cannot be determined accurately.

v) It is difficult to introduce material smoothly into an arc discharge.

vi) It is impossible to avoid completely self-reversal of the lines observed.

It has been suggested that the spectrum of the flash from a shock tube be used for the estimation of oscillator strengths[65]. A number of authors[15][16][17] have shown that the region immediately following a shock front is in thermodynamic equilibrium under certain conditions of pressure etc. Temperatures up to 10^5 degrees K have been measured in strong shocks so that measurements of oscillator strengths of fairly highly ionised atoms should be possible. The short duration of the shock requires that photomultipliers be used as detectors and, in general, the resolving time of the apparatus must be 1 μ. sec. or less. To avoid self-reversal and at the same time meet the requirements of thermodynamic equilibrium the material being investigated requires to be present as a trace impurity in another gas (probably argon). Accurate estimates of shock temperature are probably possible as the kinetics of the process are well understood. Finally, since one can introduce known quantities of materials absolute estimates of f-values should be possible.

(b) Oscillator strengths by absorption.

The optical absorption coefficient k_ν cms.$^{-1}$ is defined as follows. Suppose a parallel beam of light of frequency ν and intensity $I_{\nu,0}$ ergs/sec./sq.cm. falls upon a column of length ℓ cms. of absorbing atoms so that the intensity of the emergent beam is I_ν then

$$I_\nu = I_{\nu,0} \cdot e^{-k_\nu \ell}.$$

It may be shown that

$$\int k_\nu \, d\nu = \frac{\pi e^2}{mc} \cdot N_1 f_{12}$$

where the symbols have their usual meanings and the integral is taken over the absorption line ν_{12}. The integral is simply the area under the

profile of the absorption line

$$\int k_\nu \, d\nu = \frac{1}{\ell} \int \ln \frac{I_{\nu,0}}{I_\nu} \, d\nu$$

It is evident that a measurement of this area yields a value for $N_1 f_{12}$.

R.B. and A.S. King[18][19] developed a furnace in which specimens were heated to temperatures up to 3000°K in an absorption cell having quartz windows. The absorption spectrum was observed and from measurements of the equivalent widths of the lines the oscillator strengths were estimated. The proper relative value of N_1 was estimated from the Boltzman distribution law and the absolute value from vapour pressure estimates for the material studied. This latter estimate was the main source of error in the measurements.

Bell, Davis, King and Routly[20] have developed the "atomic beam" method of Kopfermann and Wessel[21]. In this they have overcome the difficulty of measuring N by forming a broad beam of atoms from a furnace to act as the absorber while at the same time measuring the rate of deposition of material on a collector plate. As it stands this method is only applicable to resonance transitions of atoms but, with the development of powerful ion beams, it may be possible to use the method for ions.

When compared with methods depending on the emitted spectrum, the absorption method has the advantage that an intensity ratio has to be measured. Thus the spectral calibration of the detector is avoided.

(c) Oscillator strengths by measurement of the dispersion in the neighbourhood of an absorption line.

The theory of anomalous dispersion has been developed in terms of the oscillator strength of the neighbouring absorption line. This leads to the following expression for the refractive index n (see Ladenburg[22]).

$$n - 1 = \frac{e^2 N_1 f_{12}}{4\pi m c^2} \cdot \frac{\lambda_{12}^3}{\lambda - \lambda_{12}}$$

where λ_{12} is the wavelength of the absorption line and the other symbols have their usual meaning.

The most accurate experimental arrangement devised to make use of this relation to determine f-values is that due to Rozhdestvenskii and still used by him and his co-workers in Leningrad. A modified Jamin interferometer is used in conjunction with a spectrograph to produce "hook" images of the fringes near the absorption line. These occur when the gas or vapour to be studied is present in one of the arms of the interferometer.

In order to measure oscillator strengths for the astrophysically important metallic atoms these workers have built elaborate vacuum furnaces capable of heating specimens to 3000 degrees K.

Ostrovsky and Penkin[23] have used the method to measure the absolute oscillator strengths for lines of Chromium, Manganese and Copper. They use the relation

$$N_1 f_{12} = \frac{4\pi m c^2}{e^2 \ell} \cdot \frac{K_{12}}{\lambda_{12}^3} \beta_{12}$$

where K_{12} depends on the separation of the fringes and on λ_{12}

$\sqrt{\beta_{12}}$ is the wavelength separation of the peaks of the hooks, and

ℓ is the path length in the vapour. The other symbols have their usual meanings.

Like other absorption methods this is liable to give rise to erroneous values due to uncertainty in the vapour pressure of the material studied. However, this error is not present when relative f-values are measured. Experimental errors of only ± 1% have been quoted by Parchevskii and Penkin[24] (Aluminium and Copper) and by

Nikonova and Prokofev[25]. (Al I, Tl I, Cr I, Mn I, Mo I, Ba II, Ca II, Sr II).

This method is limited to only a fairly small class of transitions, viz. those which combine with the ground state or other very low-lying levels. (A translation of the paper by Nikonova and Prokofev is not available and it is not known how they obtained values for ions).

The above is a fairly representative survey of the most recent f-value measurements. There have been, however, a few isolated measurements using other methods. Stephenson[27] used Weingeroff's method, which depends on the magneto-rotation of polarised light. Brossel and Bitter[28] developed a method in which they excited a particular magnetic state of an atom by illuminating it with the proper component of the resonance line. They then measured the amount of R.F. power absorbed by the atoms in equalising the populations of the states.

Despite the refined methods used and comparatively small experimental uncertainties quoted (in general 10-20%) values determined by different techniques differ by factors of two or three (See comparisons by Unsold[4], Garstang[26] Allen[12] and Minnaert[6]).

Until such differences are resolved, none of the measured values can be treated with any confidence. In this situation, measurements by a new and fundamentally different technique would be of great value, and it is possible that the method which is the subject of this thesis could be developed for this purpose.

(d) Review of previous measurements of oscillator strengths of hydrogen and helium

This part of the review covers measurements on the simpler atomic systems where the calculations are more reliable. The measurements are intended to provide a check on the fundamental theory of atomic transition

probabilities. Many of the papers are dated in the late 1920's when the theory was being developed.

Slack[29] has measured the duration of radiation from hydrogen excited by 10·2 volt electrons. The tube in which the hydrogen was excited had four electrodes. Electrons emitted by a thermionic cathode were modulated by an alternating potential on a near-by grid. This was the source of excitation. The ultra-violet radiation (mainly from the transition 1S - 2P) fell upon a zinc plate which thereupon emitted photo-electrons. These either escaped or were returned to the photo-electric electrode according to the instantaneous potential of a second grid which was also fed with an alternating voltage of the same frequency. The current to the photo-sensitive electrode was observed as a function of the phase difference between the voltages on the grids. The phase difference for maximum current is related directly to the lifetime of the excited atoms. From his measurements, Slack obtained the value $1{\cdot}2 \times 10^{-8}$ secs. for the lifetime of the 2P state of hydrogen. This should be compared with the quantum mechanical value of $1{\cdot}6 \times 10^{-9}$ secs. (Bethe[1]).

Slack did not take account of the imprisonment of resonance radiation which is probably the main factor contributing to any error in his value. Its quantitative importance is difficult to assess in the data provided.

Using the apparatus developed by Kopferman and Ladenburg[30] (after that of Rozhdestvenskii[31]) Carst and Ladenburg[32] measured the anomalous dispersion near the H_α and H_β lines of hydrogen and found the ratio of f-values to be

$$f_{H\alpha}/f_{H\beta} = 5{\cdot}28 \pm 0{\cdot}62.$$

The theoretical ratio is 5·37. The value depends on the weights given to the S and P states (range of values:- 4·16 - 5·68).

As a check on the theory, Snoek[33] measured the absorption intensities of the fine structure components of the Balmer lines. He found the relative intensities to be

(Initial level $j = 1\frac{1}{2}$) $H_\alpha : H_\beta : H_\gamma = 100 : 18{\cdot}8 : 7{\cdot}4$

Theoretical ratios (Bethe[1]) $= 100 : 17{\cdot}6 : 6{\cdot}3$

(Initial level $j = \frac{1}{2}$) $= 100 : 20 : 8{\cdot}5$

Theoretical ratios (Bethe[1]) $= 100 : 20{\cdot}8 : 8{\cdot}1$

The analysis is based on the assumption that the $2s_{\frac{1}{2}}$ and $2p_{\frac{1}{2}}$ levels are equally populated.

Ornstein and Burger[34] used a vacuum thermo-pile and a monochromator to measure the relative intensities of hydrogen lines having the same upper total quantum number. Their results are

H_β/P_α	2·6	(3·6)	n = 4
H_γ/P_β	2·5	(3·4)	n = 5
H_δ/P_γ	2·0	(3·2)	n = 6

The values in parenthesis are the quantum theoretical values calculated on the assumption that the upper levels are equally populated.

Griffiths[35] measured the lifetimes of excited states of hydrogen employing a Kerr cell operated by a high frequency oscillator which was also used to run a Geissler tube containing water vapour. By varying

the distance the light had to travel from the tube through a monochromator and cell to the photographic plate, the lifetimes of the excited states were measured in terms of the velocity of light. Griffiths results were

τ (Hα) = 1·75 ($\pm$ 0·3) x 10^{-8} secs. Theoretical 1·52 x 10^{-8} secs.

τ (Hβ) = 3·1 ($\pm$ 0·5) x 10^{-8} secs. Theoretical 3·13 x 10^{-8} secs.

The agreement with theory is good but the analysis depends on the assumption that the various levels (different angular momentum quantum numbers) are populated according to their statistical weights.

A paper by Ardenne[36] on the measurement of hydrogen lifetimes has been published recently. He used a modification of the method originally developed by Wien where a beam of atoms is excited over a short region and the consequent luminous trail measured to give an estimate of the lifetimes. While Ardenne took great care to free the atomic beam of interfering ions, his method of observation of the luminosity appears to have been rather crude. He obtained a value of 1·1 x 10^{-8} secs. for measurements on the Hβ line. The quantum mechanical value is 3·35 x 10^{-8} secs. It is difficult to assess the experimental error associated with this measurement (the author does not attempt to do so) but the factor contributing most is undoubtedly the method of estimating the length of the luminous trail. This was done without the use of a spectrograph.

Maxwell[38] has used a somewhat similar method to measure the lifetime of excited helium ions; a system which can be treated exactly by quantum theory. The ions were drawn out from a beam of excited atoms by a transverse electric field. The broadening of the luminous region is a measure of the lifetimes of the excited states of the ions. Measurements were made on the λ 2733Å line corresponding to the transition $n = 6 \rightarrow n = 3$ and a value of 1·1 x 10^{-8} secs. obtained. Supposing the

levels are populated according to their statistical weights, the quantum theoretical lifetime comes out to be $1{\cdot}17 \times 10^{-8}$ secs. in good agreement with the measurement.

All the measurements of hydrogen (and He^+) atomic transition probabilities which have been made depend upon assumptions about the relative populations of the levels. There remains to be done an accurate measurement of the transition probabilities between levels of one of the atomic systems for which the quantum theoretical calculation can be done exactly.

For reasons already mentioned, helium gas was chosen for the measurements described in this thesis. Previous measurements on helium will now be reviewed.

Levy[39] adopted Ladenburg's method and made use of a Janin refractometer to measure the anomalous dispersion of electrically excited helium. He obtained the following ratios for transitions having a common ground level. The values in parenthesis are those obtained theoretically by Bates and Damgaard[2] and Hylleraas[40].

$$\frac{A_{5876}\ (2^3P - 3^3P)}{A_{7065}\ (2^3P - 3^3S)} = 3{\cdot}0 \pm 0{\cdot}3 \quad \text{(B and D: 2·6)} \quad \text{(H.: 2·5)}$$

$$\frac{A_{6678}\ (2^1P - 3^1D)}{A_{7281}\ (2^1P - 3^1S)} = 3{\cdot}1 \pm 1{\cdot}5 \quad \text{(B and D: 3·5)} \quad \text{(H.: 3·6)}$$

$$\frac{A_{5876}\ (2^3P - 3^3D)}{A_{4471}\ (2^3P - 4^3D)} = 8{\cdot}7 \pm 0{\cdot}7 \quad \text{(B and D: 2·9)} \quad \text{(H.: 4·8)}$$

Burger, van Milaan and Ornstein[41] measured the relative intensities of lines having a common upper level and got directly the ratio of the transition probabilities. The major uncertainty lies in

the calibration of the detector at various wavelengths. The results are compared with the theoretical values as before

$$\frac{A_{4471}\ (2^3P - 4^3D)}{A_{17010}\ (3^3P - 4^3D)} = 2{\cdot}3 \pm 0{\cdot}1 \quad \text{(B and D: 3·7)} \quad \text{(H: 2·3)}$$

$$\frac{A_{3965}\ (2^1S - 4^1P)}{A_{15090}\ (3^1S - 4^1P)} = 3{\cdot}15 \pm 0{\cdot}25 \quad \text{(B and D: 4·6)} \quad \text{(H: 4·7)}$$

A more accurate and more extensive set of experimental results is required before one would have complete confidence in the theoretical values. It is desirable also that the ~~results be~~ absolute values, be measured. Better measurements would enable one to choose between the various theoretical calculations.

3. DESCRIPTION OF THE EXPERIMENTAL METHOD

The method used in the experiments to be described consisted in principle of measuring the time between the excitation of an atom and its subsequent decay. The mean lifetime τ_2 of the excited state2 of the atom is related to the transition probability by $1/\tau_2 = \sum_n A_{2n}$ where the summation is taken over all the lower states with which this particular excited state will combine. Thus if $N_{2,0}$ is the number of atoms initially excited in state 2 then after a time t there will remain excited a number

$$N_{2,t} = N_{2,0}\, e^{-t/\tau_2}$$

Webb[42] was the first to use a method based on the principle of lifetime measurement. His apparatus was similar to that used later by Slack[29] to measure the lifetime of excited hydrogen and already described. Together with Messenger[43] he measured the lifetime of the resonance radiation of mercury $\lambda 2537$Å. Some years later Garrett[44] made a much more careful measurement of the same transition. His apparatus consisted of two quartz tubes each containing electrodes. In the first, which was the source of radiation, there was a thermionic cathode and a grid system to which was applied a rapidly alternating potential. In this way the mercury vapour in the tube was periodically excited. The radiation, varying in a later phase due to its lifetime, fell upon the other tube. This second quartz tube contained a photo-sensitive plate from which photo-electrons either escaped or were returned according to the potential on the neighbouring grids, these being fed by the same alternating potential as the first. By varying the frequency of the alternating potential a

frequency was found for which the photo-electric current was a maximum. This frequency is related to the lifetime of the excited state. Garrett claimed an accuracy of ± 1% for his measurements. Later Sinclair and Webb[45] reported a similar measurement for the potassium resonance doublet.

In other similar experiments atoms have been excited by a source emitting the resonance radiation. The intensity of the incident radiation is varied usually by a Kerr cell operated by a radio frequency oscillator. Gaviola[46] was the first to use this type of apparatus to measure the duration of radiation. Recently, Ziock[47] has used a pulsed photomultiplier as detector in a similar piece of apparatus to measure the lifetime of the resonance radiation λ 3720Å of iron. He reported that the shortest resolving time of his apparatus was 10^{-7} secs. and that this was set by the Kerr cell. The experimental error quoted in this paper is ± 30%.

Our method which has already been reported upon in the literature[48] is essentially the application of a technique used in nuclear physics[49] to the problem. A volume of helium gas was excited by a short burst (10^{-8} secs. duration) of mono-energetic electrons. The photons which were emitted in the subsequent decay were detected by a photomultiplier, the particular transition being selected by an optical filter. The time between the exciting pulse and the emission of photons, which were detected as single quanta, was determined by delaying pulses synchronous with the exciting pulses and counting coincidences between these delayed pulses and the pulses from the photomultiplier. In this way, by varying the length of the delay we obtained a curve of the probability of emission of a photon as a function of the time following the excitation of the state under investigation. Typical delayed coincidence curves are reproduced in Figure 1. This method has a number of advantages over previous methods depending on the

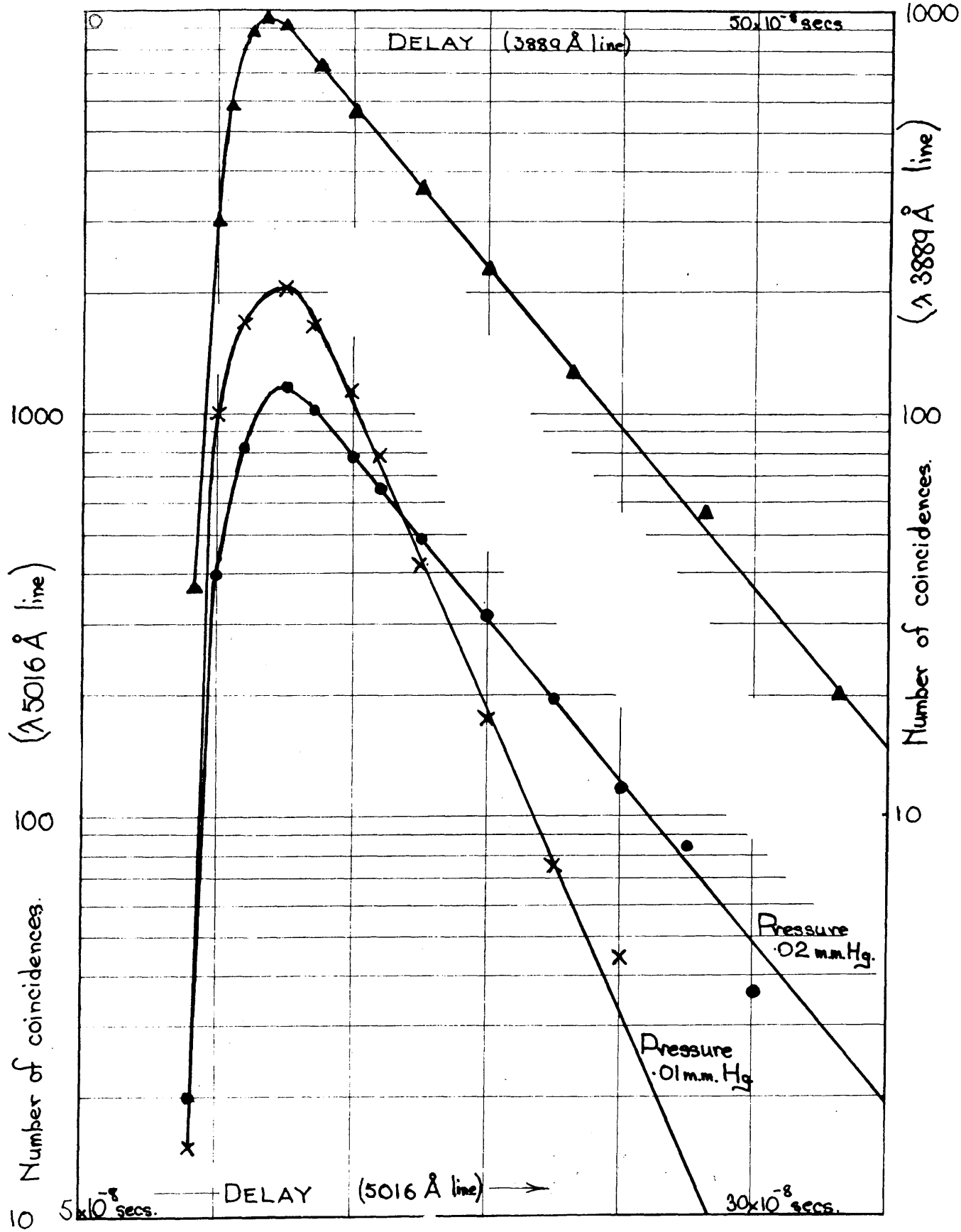


FIG. 1. Delayed coincidence curves obtained with our apparatus.

same principle. These are:-

(i) Shorter resolving time - the present apparatus is capable of resolving down to 10^{-8} secs.

(ii) Since the actual decay curve of the particular transition is plotted it is possible to separate out components having different decay rates, as would result, for example, from repopulation due to cascading from higher levels or from excitation induced by collisions of the second kind.

(iii) Since the electrons are mono-energetic, and of independently selected energy, a particular level can be preferentially excited.

(iv) The photomultiplier detector is sensitive to very low intensity lines. It is limited in wavelength at the red end only to less than $\lambda\lambda 7000\text{-}8000$ Å because of its poor red response.

Unfortunately the measurement which is made is not the transition probability, but the sum of all transition probabilities from that level. Sometimes one particular transition probability either dominates or can be separated out by varying the conditions (see the measurement on the $2^1S - 3^1P$ transition of helium described later). This disadvantage would be removed if we knew the photon detection efficiency of the apparatus as a function of wavelength.

Brannen, Hunt, Adlington and Nicholls[50] have used a modified version of our method to measure the lifetime of the 7^3S_1 level of mercury. In their experiment two photomultipliers were used to observe a steady discharge. By using filters, one photomultiplier was made sensitive to radiation arising from a transition to the particular excited level and the other to radiation produced on the decay of that level. Delayed coincidences were observed between the photomultiplier pulses. This method has the

great advantage over ours that it avoids uncertainty due to the repopulation by cascades from higher levels. On the other hand, when one examines the term schemes of the elements one finds very few which have consecutive transitions which produce radiation in the spectral region where normally available photomultipliers are sensitive.

Some of the points raised by Brannen et al. in their paper are worth considering. They claim that an advantage of their method is "that it is a means of absolute calibration of the strength of a source". The analysis leading to this conclusion is based on consideration of three states of an atom which combine upper with intermediate and intermediate with lower. The following assumptions are made:-

(i) The only mechanism of excitation of the intermediate state is by a radiative transition from the upper state.

(ii) The only mode of decay of the intermediate state is by a radiative transition to the lower state.

Such a situation is seldom, if ever, met with in practice. However, an analysis applied to a realistic situation results in the conclusion that it is possible to determine the total number of atoms in the intermediate state in the region being viewed by the photomultipliers, provided

(i) The ~~number~~ rate of noise counts in the individual channels is less than the signal count rates.

(ii) The coincidence resolving time is accurately determined.

(iii) There is no angular co-relation between photons of the two transitions.

In any case one could only hope to get an order of magnitude from such a measurement, mainly because with the coincidence circuit used it is not possible to measure the pulse rates in the individual channels in a unique

manner. This point will be made clearer later when the circuit is considered in detail.

The system with two photomultipliers would be of general applicability if the spectral range was extended by using a vacuum ultra-violet monochromator in one channel. However, our method of a pulsed electron beam has the advantage of simplicity, especially when used for helium.

The method depends upon using a photomultiplier to detect single quanta of radiation produced in the transition. The use of a photomultiplier for single photons has been studied recently by Colli, Facchini and Rossi[51]. They showed that the frequency of noise pulses due to the thermo-electric emission of electrons from the photo-cathode was about 10^4 per second for a carefully treated tube at room temperature. In our apparatus such pulses are indistinguishable from pulses arising from a photo-produced electron from the cathode. By making use of a coincidence unit having a short resolving time ($\sim 10^{-8}$secs.) we were able to follow Colli et al. and discriminate between signal pulses and the random noise pulses. It is worth noting at this point that, while it is desirable to increase the number of signal pulses, this is limited in the present case to the point where there is an appreciable chance of two photon pulses coming in a single interval between electron bursts.

Osherovich and Savich[67] have repeated some of the measurements reported in this thesis using the same method and obtaining the same result.

4. DESCRIPTION OF APPARATUS - THE EXCITATION TUBE

The essential features of the apparatus are shown in Figures 2 and 3. The tube in which the gas atoms are excited is of glass with a quartz window. The electrode system which it contains consists of an indirectly heated oxide-coated cathode (a) followed by control grid (b), the anode (c) and the collector electrode (d). The electron beam is modulated by positive pulses which are fed to the grid via the isolating pulse transformer. The negative steady bias on the grid is supplied by a dry battery. This also supplies a positive voltage for the anode and collector electrodes and thus determines the energy of the electrons when they enter the field free region which is the only part exposed to the photomultiplier through the quartz window and optical filter. Care was taken in the construction to prevent reflected light from the hot cathode from entering the photomultiplier. This was done by using light shields and attempting to enclose the cathode completely in the electrode structure. To prevent the scattering of electrons from its surface back into the sensitive region, the collector electrode had a hole in it entering into a cavity to form an electron trap. The entrance was covered by an open grid.

Nickel was used for the construction of the electrodes because of the ease with which it can be spot welded. The accompanying photograph (Figure 4) shows the nature of the construction.

The emission of the cathode was tested both with steady D.C. voltages applied to the electrodes and with pulses being fed to the grid in the same way as when making measurements. The D.C. tests showed that a useful current of 1 m.A. could be drawn to the collector electrode when

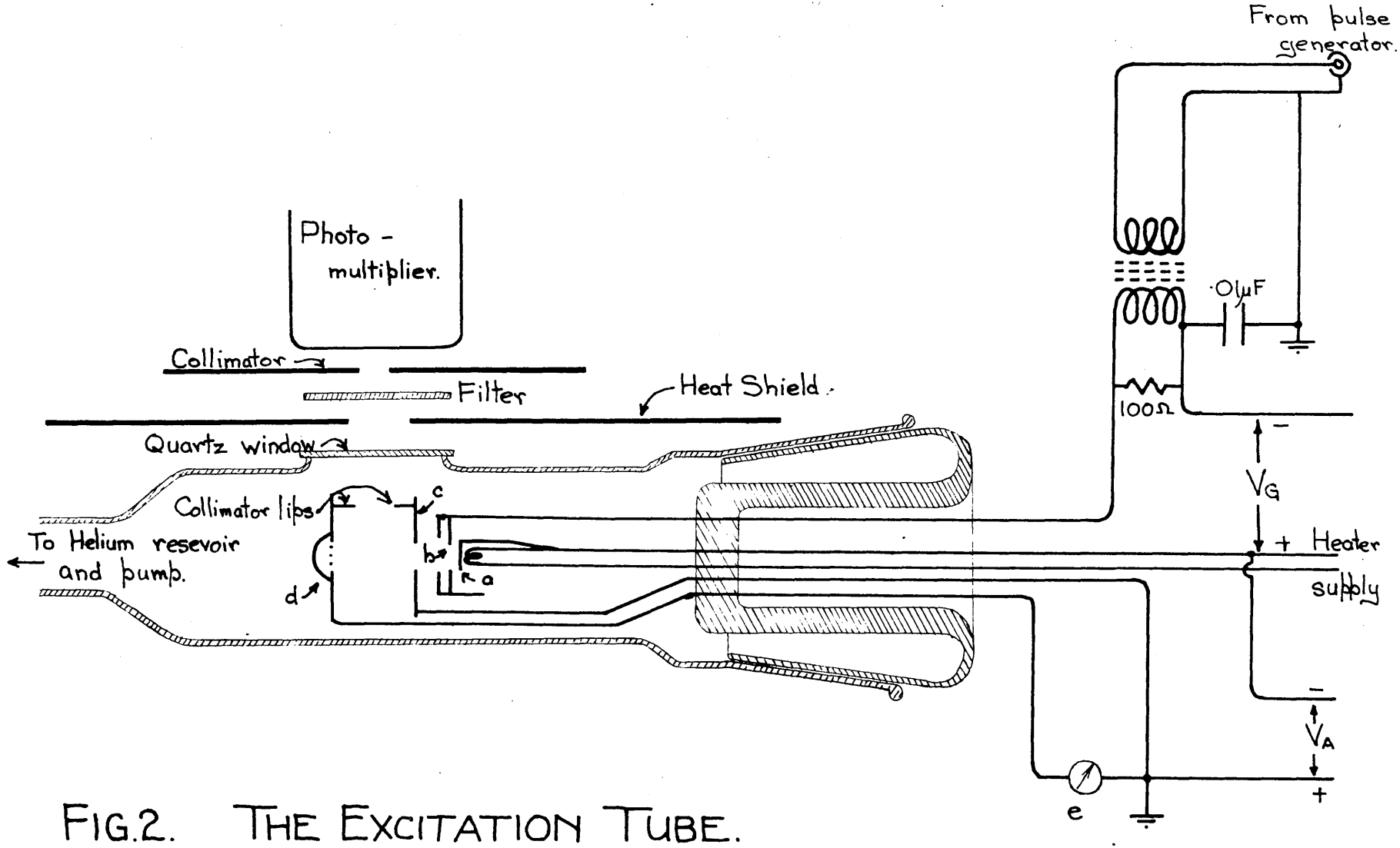


FIG.2. THE EXCITATION TUBE.

The parts marked are 'a': the cathode, 'b': the grid, 'c': the anode, 'd': the electron trap, and 'e': a meter measuring the electron current.

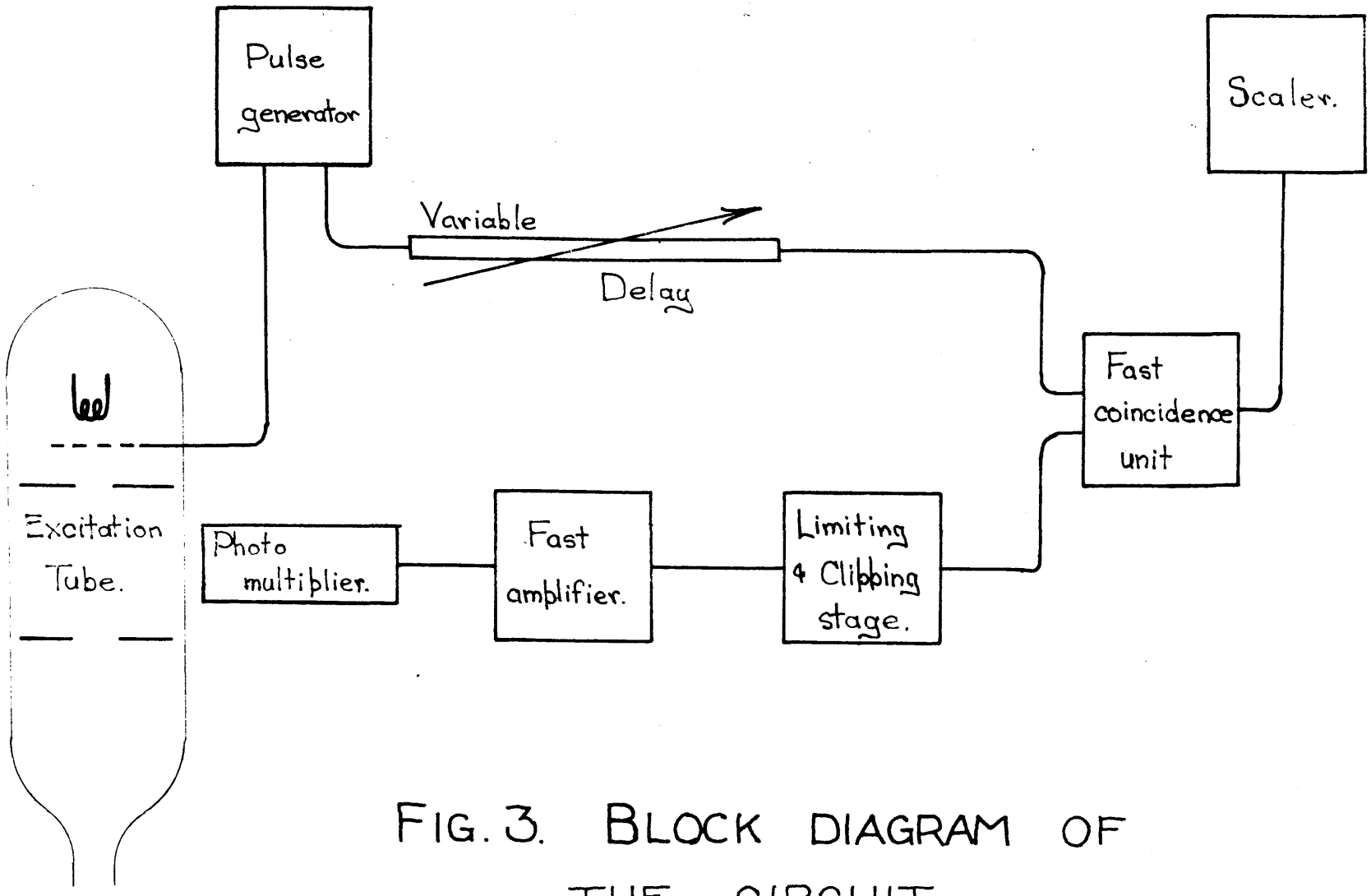


FIG. 3. BLOCK DIAGRAM OF THE CIRCUIT.

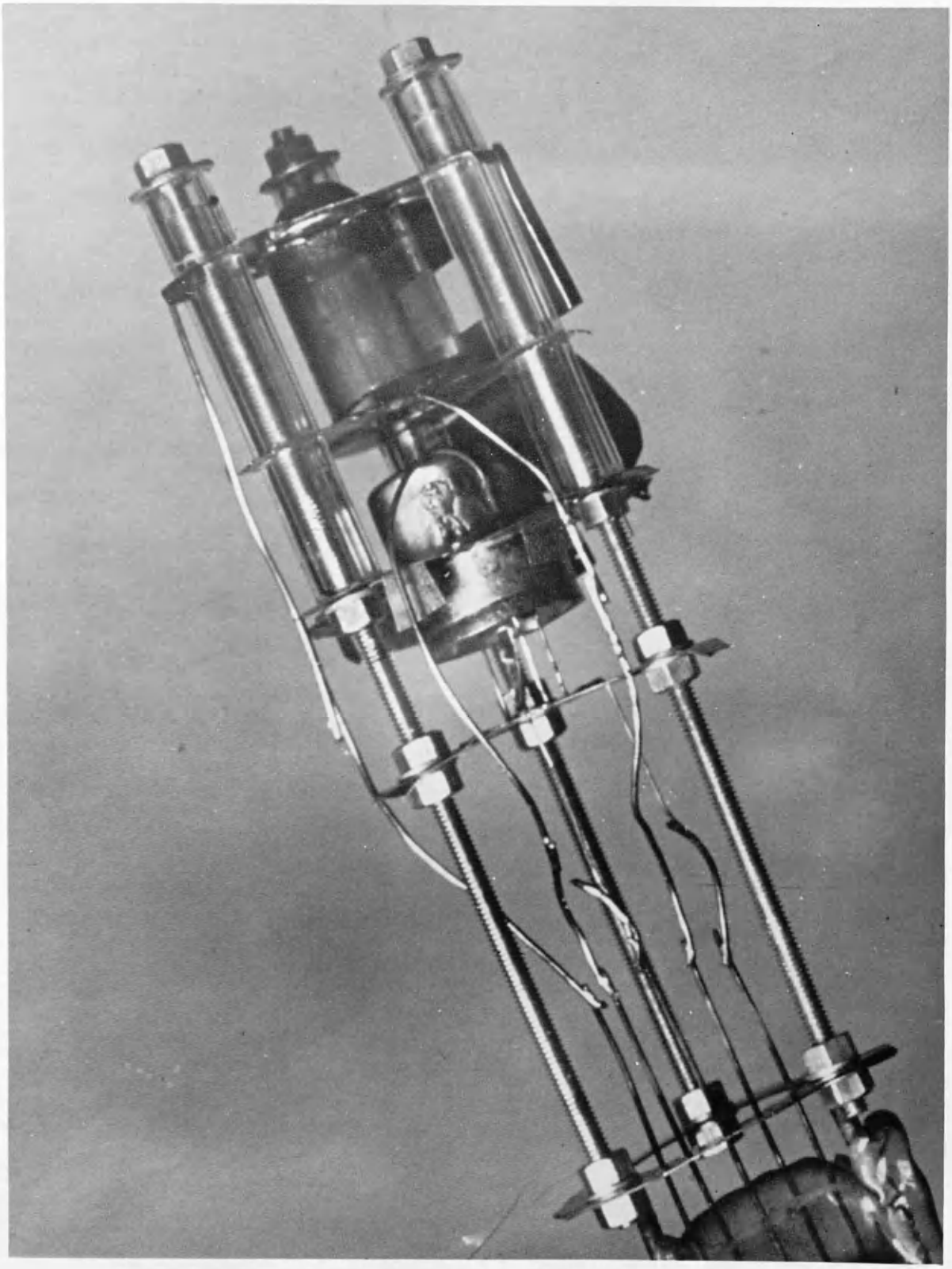


FIG. 4. Photograph of the electrodes showing the inner quartz tube and, on the far side, the collimator lips.

50 V. were applied to the anode and + 10 V. to the grid. The electron beam was completely interrupted when the potential of the grid fell below about -5 V. Under pulsed conditions the current was reduced as expected by the on-off ratio of the pulse ($\sim 10^{-4}$) and a grid bias of about -30 V. was necessary to cut off the electron beam completely ($\sim$ 25 V. pulses were applied to the grid). These figures, of course, are only approximate as they are dependent on minor changes in the inter-electrode spacing and on the cathode temperature. When gas was let into the tube the emission fell due to the fall in cathode temperature as the gas improved the thermal conductivity to the walls. There was also a steady slow depreciation of the thermo-electric efficiency due to positive ion bombardment. Despite these troubles, useful currents (over the period of the pulse) of 0·2 m.A. to the collector electrode were achieved regularly.

Using values of the atomic excitation cross-sections (Q) for helium measured by Lees[52] (these are in fair agreement with calculated cross-sections due to Massey and Burhop[53][54]) and the measured values for the electron beam current, the numbers of photons coming from the various transitions were calculated to be:-

λ	Transition	Q	Electron Energy	Yield
3188 Å	$4^3P - 2^3S$	-	-	-
3889 Å	$2^3S - 3^3P$	$6{\cdot}7 \times 10^{-19} cm^2$	35 V.	$6{\cdot}7 \times 10^3$ photons/pulse
4713 Å	$2^3P - 4^3S$	$2{\cdot}0 \times 10^{-19} cm^2$	30 V.	2×10^3 photons/pulse
5016 Å	$2^1S - 3^1P$	$9{\cdot}3 \times 10^{-19} cm^2$	90 V.	$9{\cdot}3 \times 10^3$ photons/pulse
5875 Å	$3^3D - 2^3P$	-	-	-

A helium gas pressure of 10 μHg. was assumed for the calculation.

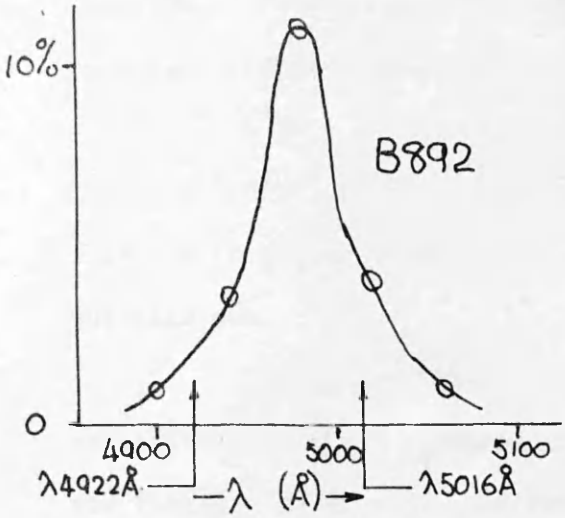
The Optical System

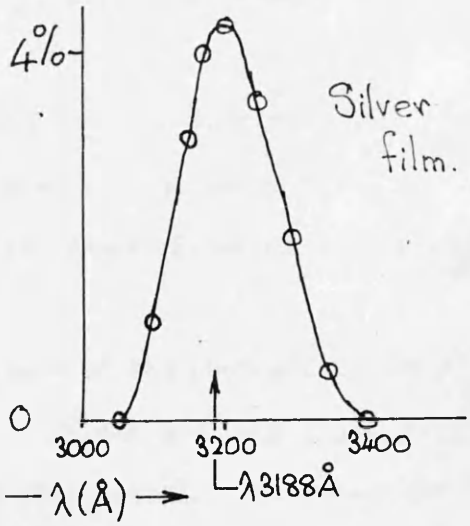
Filters were used to select the particular line corresponding to the transition being studied. This was a much simpler and cheaper system than a spectroscope, which would have given the apparatus a greater adaptability. Also, there was very much less restriction on the width of entrance slit that could be used with filters. In general, combinations of filters were used for each line.

λ 3188 Å - A film of silver deposited on a quartz plate was found to be the best filter for this ultra-violet line. A transmission curve for the actual filter used shows that it has a maximum trnasmission of 4% at λ 3200 Å and that it has a band-width of 180 Å. The lines λ 3203 Å and λ 3355 Å fall within the band of this filter. The former is a fairly strong He II (n = 5 - n = 3) line and the latter a weak He I line. A long photographic exposure showed that, under the conditions of excitation used here, neither of these two lines was transmitted.

λ 3889 Å - An interference filter B 223 specially made by Messrs. Barr and Stroud Ltd., was used for this line. These filters have a peak transmissivity of about 10% and a band width of 60 Å. It was found that the transmission band of these filters varied slightly in wavelength over the filter. This feature proved to be quite useful, as it made it possible, by selecting the region used, to "tune in" to the desired wavelength. A photograph through a spectrograph indicated that the weak neighbouring lines λ 3867 Å and λ 3965 Å were not transmitted.

λ 4713 Å - was best isolated by the Ilford gelatine filters 501 and 303 in combination with the Chance glass filter OY8. The nearest line liable to interfere is the λ 4686 Å He II line which is not excited in the





Filter transmission curves.

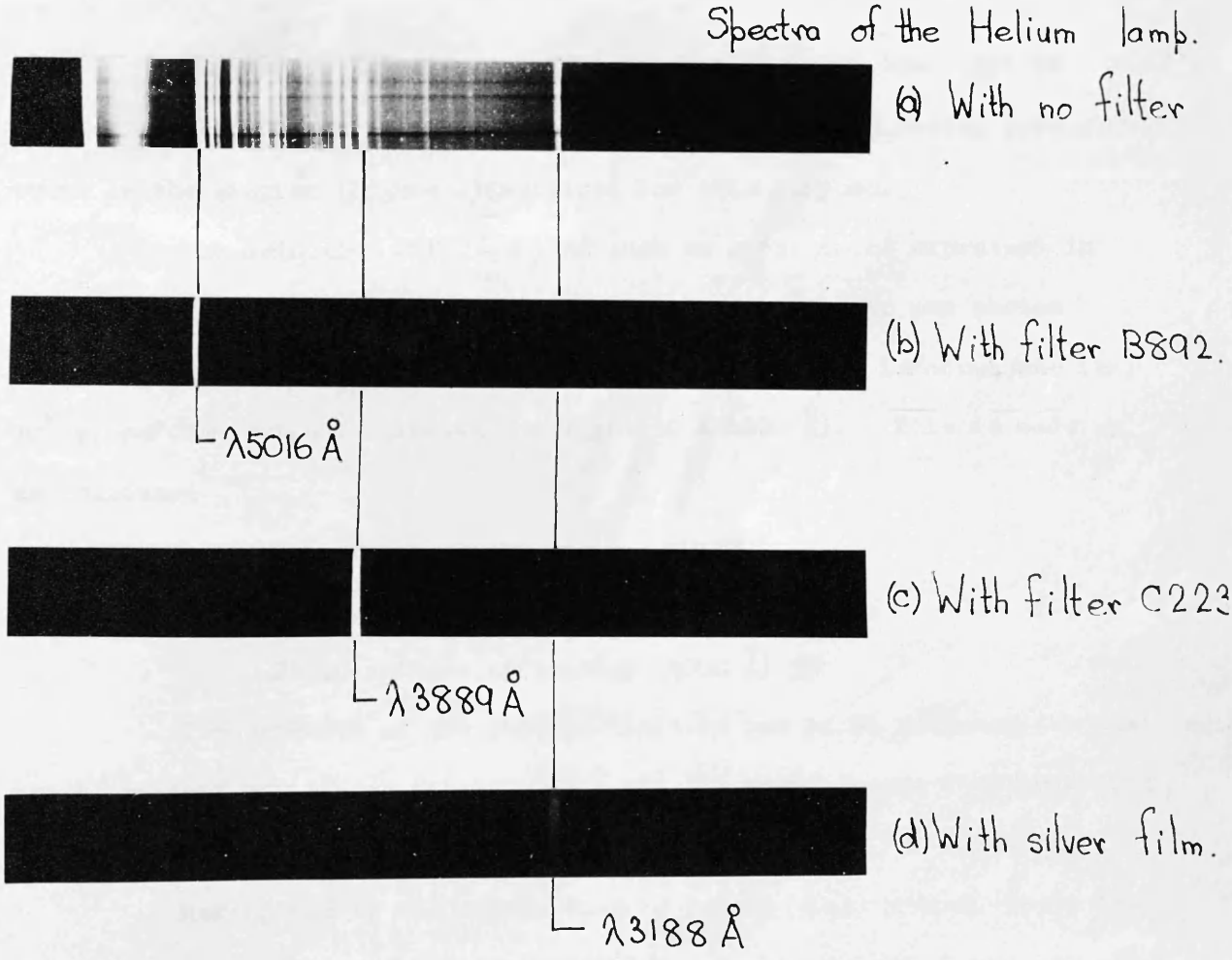


FIG. 6. Filter transmission characteristics.

conditions of the present experiment. Otherwise, this line is well separated from its neighbours.

λ 5016 Å - A specially made interference filter B092 was used for this line. It was found that this filter also transmitted a blue line due to higher order interference. A yellow Chance filter OY 4 or 6 cut this out.

λ 5875 Å - This line is at the red limit of the photomultiplier sensitivity so that, by using Ilford red gelatine filter 808, all lines in the violet side were cut out and only red light transmitted. Measurements at this wavelength were most affected by reflected cathode light, which was predominantly red.

The use of interference filters demanded that the light be incident on the filter at right angles. The simple collimating arrangement shown in the diagram (Figure 2) sufficed for this purpose.

The detection efficiency of such an arrangement expressed in electrons released from the cathode of the photomultiplier per photon emitted from the sensitive region of the excitation tube is about one in 10^6 electrons/photon (estimated for light of λ 4000 Å). This is made up as follows:-

Geometrical solid angle	0·2%
Typical filter transmission	5%
Photo-cathode efficiency (4000 Å)	1%

The cathodes of the photomultipliers had an S4 response, so that their greatest efficiency was at 4000 Å and the above figure represents the maximum efficiency.

Making use of the calculation of photon yield already done, the counting rate for a given set of conditions (results depend on the lifetime

of the state as well as resolving time of coincidence unit) can be estimated. These come out to be of the same order of magnitude as the observed rates. A source of error in the calculation is the efficiency of the photo-cathode - the value taken here is that supplied by the manufacturer.

Electronics

The grid controlling the intensity of the electron beam in the excitation tube is modulated by short (2×10^{-8} secs.) positive pulses from a pulse generator having a repetition frequency of 10^4 sec.$^{-1}$.

The choice of these values is important as they have a direct influence on the experimental accuracy which can be achieved. In the discussion which follows, three sources of error will be considered. These are:-

(i) The statistical uncertainty of the number of signal counts recorded.

(ii) The random coincidence rate arising from noise in the photomultiplier.

(iii) The possibility that two photons be detected within a single period following an exciting pulse in the grid, and be registered as one.

The following symbols are introduced in this connection:-

n_1 :	p.r.f. of the pulse generator.	sec^{-1}
t :	resolving time of the coincidence unit.	secs.
n_2 :	maximum rate at which photons are detected (i.e. zero delay)	sec.$^{-1}$
N_s :	rate of counting signal coincidences = $n_1 n_2 t$	sec.$^{-1}$
N_r :	rate of counting random coincidences = $n_1 10^4 t$	sec.$^{-1}$

It is supposed that the noise pulses from the photomultiplier are at a rate 10^4 sec.$^{-1}$ as measured by Colli et al.[51]. In fact, this is in agreement with our own estimate. When observing a red line, the random counting rate increased, due to cathode light but no account is taken of this here.

$N = N_s + N_r$: total coincidence rate. sec^{-1}

$\bar{\tau}$: lifetime of the state observed. sec.

So that an experimental run did not take too long, counting periods of one or two minutes were generally adopted. For this analysis, periods of 100 secs. are taken. Since the random coincidence rate was measured only once during a run, a larger counting time was used for this and the statistical uncertainty kept under ± 1% .

(i) and (ii) Statistical uncertainty of signal and random coincidences

$$= \sqrt{100\ (N_s + N_r)} \qquad = \qquad 10\sqrt{n_1 t\,(n_2 + 10^4)}$$

Expressed in terms of percentage of signal coincidence counts the probable error

$$= \frac{10}{n_2}\sqrt{\frac{n_2 + 10^4}{n_1 t}} \quad \%$$

(iii) The probability of detecting two photons (or noise pulses) in one single period, following an exciting pulse

$$= \left(n_2 + 10^4\right)^2 \bar{\tau}^2$$

The probability that this should fall within one resolving period t

$$= \left(n_2 + 10^4\right)^2 \bar{\tau}^2 \frac{t}{\bar{\tau}}$$

Percentage error from this cause

$$= \frac{\left(n_2 + 10^4\right)^2 \bar{\tau}^4}{n_2}\ 100$$

It should be noted that it is possible to correct for this error provided that n_2, $\bar{\tau}$ and t are known (the noise rate has little

influence in the important cases).

The expressions obtained above have been used to prepare the following table with t put equal to $\bar{\tau}$.

$t = \bar{\tau}$	n_1 \ n_2	10^4	10^5	10^6	10^7
		secs.$^{-1}$			
10^{-7} secs.	10^5	1·8%	1·5%	10%	100%
"	10^4	4·9%	2·2%	10%	100%
"	10^3	14%	4·4%	11%	100%
10^{-8}	10^5	4·5%	1·1%	1·3%	10%
"	10^4	14%	3·4%	2%	10%
"	10^3	45%	11%	4·2%	11%
10^{-9}	10^5	14%	3·3%	1·1%	1·3%
"	10^4	45%	11%	3·3%	2%
"	10^3	140%	33%	10%	4·2%

In setting the resolving time of the coincidence unit, the magnitude of the lifetime to be measured must be considered as well as what can be achieved with normally available components. In our apparatus the resolving time was about 3×10^{-8} secs. For obvious reasons this must not be much longer than the lifetimes to be measured. If it is very much shorter, then the values calculated in the Table require to be modified. For example, in approximately the conditions of our experiment and $\bar{\tau} = 10^{-7}$ secs.

t	n_1 \ n_2	10^4	10^5	10^6	10^7
		secs.$^{-1}$			
10^{-8} secs.	10^4	14·4%	4·5%	11%	100%
10^{-7} secs.	10^4	4·9%	2·2%	10·3%	100%

It should be noted that these errors refer to individual counting periods. In one run there were generally over a dozen counting periods and each measurement quoted is the mean of a number of runs. Thus the ultimate accuracy of the method is about 1%.

The pulse generator also provides smaller negative pulses which are fed into the delayed channel to the coincidence unit. The circuit adopted for this unit resembles one developed by Hutchinson[55]. It consists of a free running blocking oscillator (see diagram Figure 5) whose out-put provides a trigger for a monitoring oscilloscope as well as a delayed pulse to a triggered blocking oscillator. The positive going pulses on the cathode of the second valve are clipped to 2×10^{-8} secs. by a shorted length of 100 ohm cable and fed to both the excitation tube grid and to a pulse shaping valve. This last valve provides cleanly-shaped negative pulses for the coincidences unit.

The other channel of the coincidence unit derives its pulses from the photomultiplier. A single photo-electron from the cathode of the 14 stage tube that was used in the present apparatus (gain of $\sim 10^8$ under typical conditions) gave rise to a pulse of about $\frac{1}{2}$ V. at the collector. To provide a suitable pulse for the coincidence unit this was amplified by a factor of about 10 in a fairly conventional fast amplifier (Bandwidth 30 Mc/s, differentiating time constant $\sim 1\,\mu$s.). The last valve of this unit acted as a limiter so that pulses with a height not greater than -5 V. were produced. These fast rising pulses ($\sim 10^{-8}$ secs.) decayed with the amplifier time constant of 10^{-6}secs. so that when they were passed into a clipping circuit, short pulses were produced (duration 2×10^{-8} secs.) of similar form to those being fed to the other side of the coincidence unit by the pulse generator.

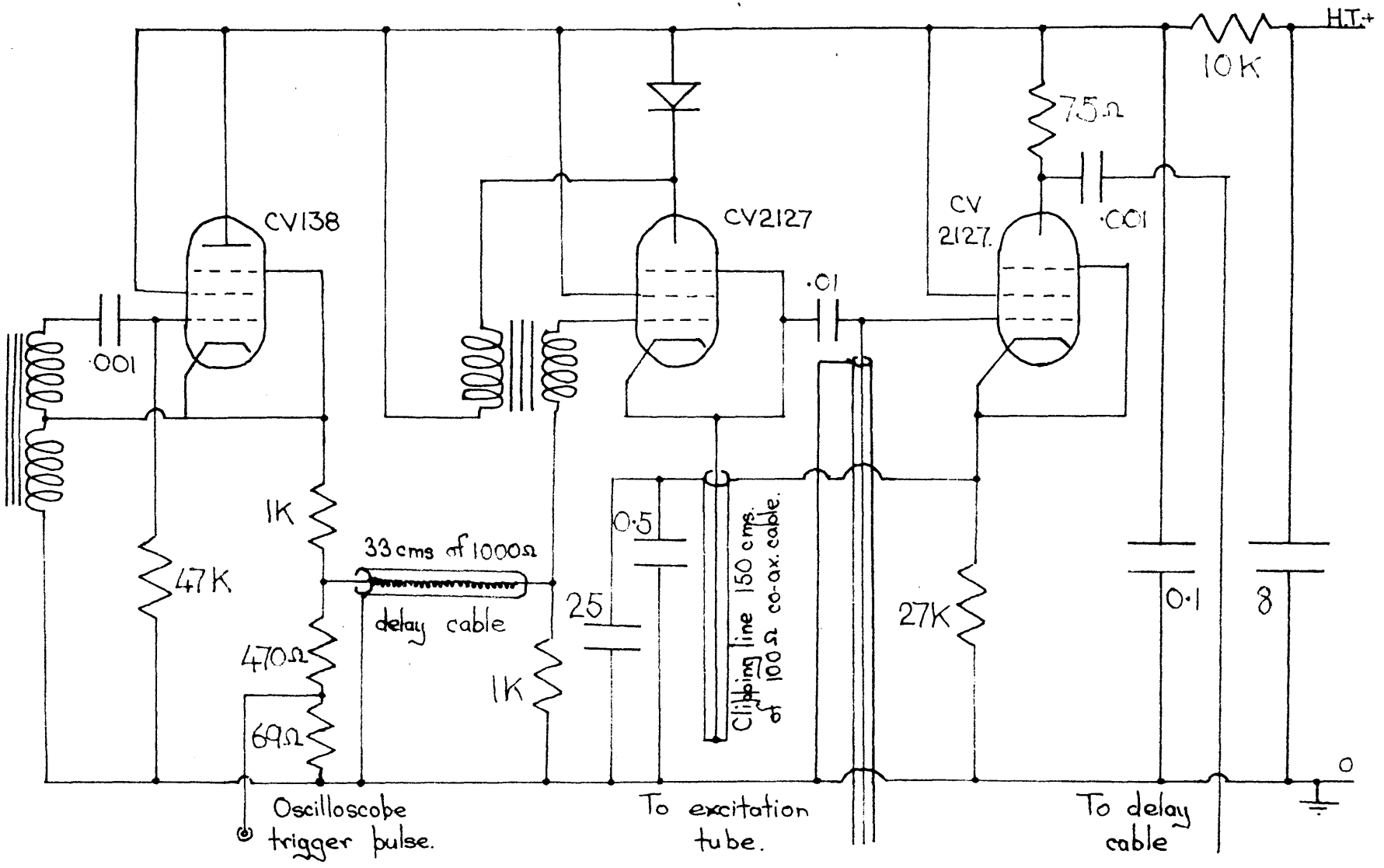


FIG. 5. PULSE GENERATOR CIRCUIT.

The coincidence unit was a simple adding circuit consisting of two CV2127 valves in parallel and having a small load resistor to preserve a fast resolving time. This was followed by a unit which lengthened the pulses (to $\sim 1\,\mu$sec.) before they were fed to a type 200 scaler. The pulse height discriminator on this was used to block small pulses produced when pulses in the individual channels are not in coincidence. Since the pulses have a finite rise time ($\sim 10^{-8}$ secs.) and therefore are not rectangular the resolving time of the coincidence unit depends on the level of the discriminator setting.

It was desirable to check that the pulses in the two channels of the coincidence circuit were of equal height. This was done by connecting the channels separately to the coincidence unit and adjusting the limiting level till the pulses in each channel were cut off at the same discriminator setting.

The attenuation characteristic of the delay cable was also checked in a similar manner. Due to the dependence of the coincidence unit on the measurement of pulse height (in the discriminator) it is very important that the pulses should not be attenuated appreciably in passing down the longest lengths of cable used. Pulses from the blocking oscillator were passed down various lengths of cable and their height measured using the discriminator. No variation could be detected in the cut off setting between pulses having passed along 1 metre and those having passed along 200 metres of cable. The cable used was Uniradio 57 and it was so cut that any length in integrals of 1 metre up to 195 metres could be inserted in the appropriate channel.

The time by which a particular length of cable delayed the pulses was measured by measuring the frequency of the radio frequency alternating current at which the cable resonated. The R.F. signal generator was

calibrated against a standard crystal oscillator. For the cable used a delay of $5{\cdot}17 \times 10^{-9}$ secs./metre was measured. Thirty different cable lengths were measured and over these there was a random fluctuation of $\pm$ 0·6% in the product of resonant frequency with length of cable. Thus any error in the results arising from this cause will be less than 1%.

Perhaps the most stringent test that can be applied to a circuit of this kind is the observation of a prompt transition. Attempts to do this are described elsewhere in this thesis.

Some of the difficulties encountered with this part of the apparatus can be usefully considered at this stage.

It was found that the greatest yield of photons was obtained at an electron energy somewhat greater than the value found by Lees (52). With a steady electron beam the effect was even more pronounced. From its variation from one cathode to another, it was concluded that the effect was due to the development of a potential difference across the thickness of the oxide cathode. This explanation also accounts for the "smoothed out" nature of excitation curves measured on this apparatus as compared with those found by Lees.

The variation of transit time for the electrons in the photomultiplier with the voltage applied is important when comparing the results of different experiments. An investigation of this was the subject of a short paper (56) published during the course of the experiments. The electron transit time was found to be in agreement with the time calculated from the electrostatic field in the multiplier. The measured time of transit was proportional to the field applied.

Some trouble was experienced due to satellite pulses from the photomultiplier. These pulses appeared above a certain voltage applied

to the multiplier and were always almost exactly 0.5×10^{-6} secs. after the main pulses. The period between the main pulses and the satellite pulses did not vary with the voltage applied to the tube. Also, there was no sign of a second satellite pulse at a period of 1m. sec. after the main one. Both these observations were out of sympathy with the usual explanation for satellite pulses. This is that they are due to the release of positive ions on the arrival of an avalanche of electrons at the collector. The ions are supposed to travel up to the photo-cathode and release a second burst of electrons. It was noted also that the number of main pulses was reduced when the satellites began to appear.

No satisfactory explanation was found for these pulses but as they occurred at applied voltages greater than were normally used their presence could be avoided.

Vacuum system

Gas was admitted to the excitation tube through a needle valve from a resevoir containing helium at about atmospheric pressure. The tube was pumped continuously by an oil diffusion pump so that the helium pressure was such as to maintain equilibrium between the pumping speed and the rate of flow from the resevoir. The pressure was monitored constantly by a Pirani gauge and was measured periodically using a McLeod gauge. A photograph of this part of the apparatus clearly shows the parts mentioned (Figure 7).

Since impurities in the gas could cause false results, care was taken to ensure that only pure helium was allowed into the excitation tube. The makers claimed an impurity content of less than two parts in a thousand for the gas used. However, we did find that it contained some condensible vapour (probably water) which, fortunately, was easily removed by passing the gas through a liquid air trap. When the helium flow was stopped, the

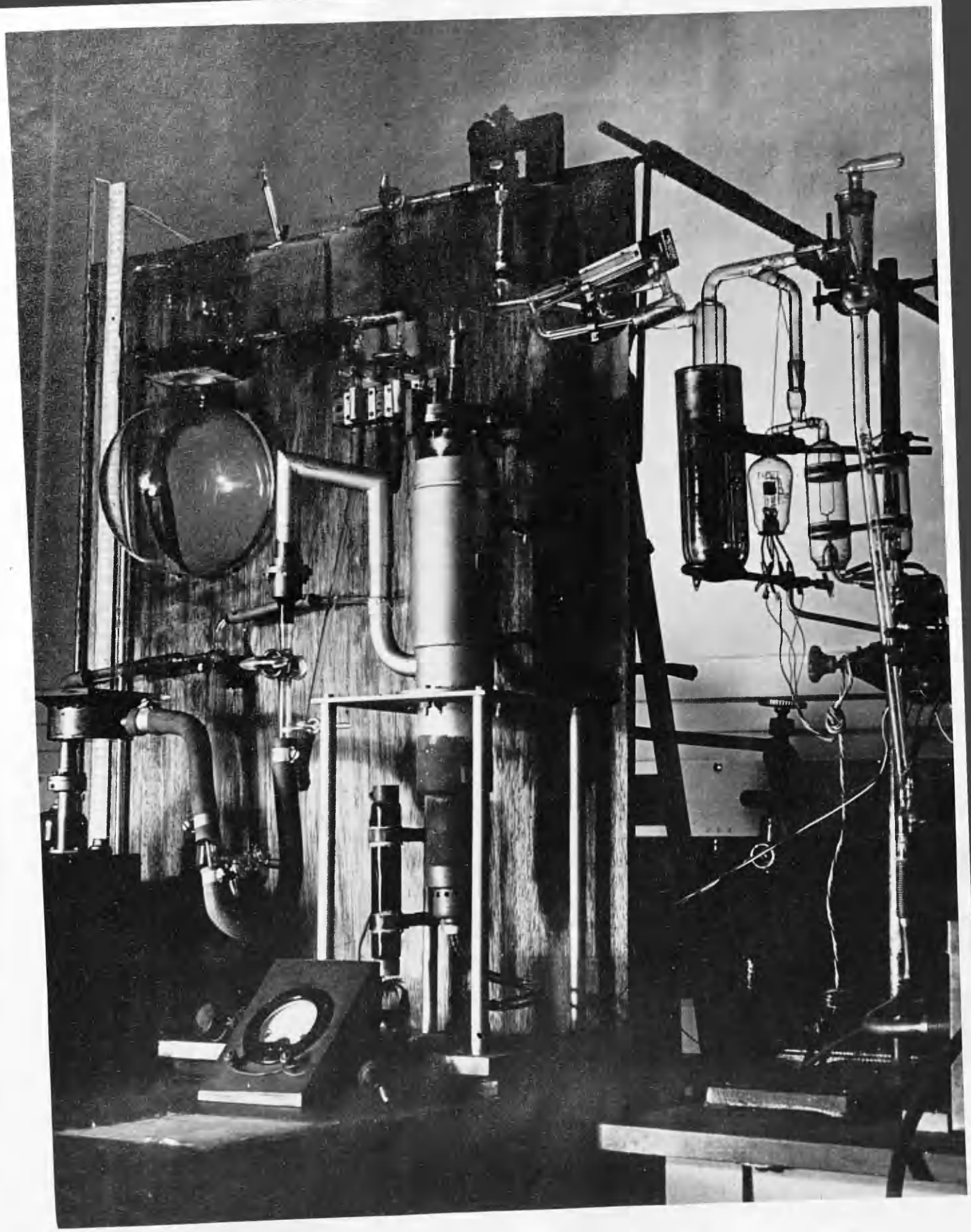


FIG. 7. The vacuum system.

pressure in the excitation tube fell to less than 10^{-5} m.m. of mercury, so that no trouble was experienced due to residual gas or a leak of air into the system. As a check on the purity of the gas, a long exposure photograph of the spectrum produced by a continuous electron beam was taken and found to contain no lines that could not be identified as helium lines.

5. EXPERIMENTAL RESULTS

(a) Method of making measurements

Each day before any measurements were made, the base pressure of the vacuum system was checked to guard against the appearance of leaks. The apparatus was switched on some time before it was used to ensure that conditions had stabilised. Gas was then admitted to the excitation tube and its pressure adjusted to the required value. The electron current was set to a level which gave a suitable yield of photons by raising the heater current. During the runs the pressure and beam current were monitored and kept constant to within a few per cent of their nominal values.

The numbers of coincidences for various lengths of delay cable were now recorded. The delay was always increased and then decreased during a run to guard against any minor fluctuations in the conditions. Counting periods of about 2 minutes were used and, where the counting rate was poor, repeat measurements were made to reduce the statistical uncertainty.

The effect of varying the pressure and the potential accelerating the electron beam was observed for each line measured. Any variation in the lifetimes with these conditions is noted and explanations suggested.

(b) Attempts to observe a prompt coincidence

The best test that can be applied to a coincidence circuit of the type described above is to measure with it a transition whose lifetime is very short compared with the resolving time of the circuit. With this in mind, a search was made for a fast transition in helium. Those states with transition probabilities predicted to be greater than 10^{+8} secs.$^{-1}$ are singlets which combined with the ground state and whose lifetimes are therefore modified by the phenomenon of imprisonment of resonance radiation.

This has the effect of increasing the lifetime by a large factor. Bates's and Damgaards[2] figures lead to a value for the lifetime of the 3^3D state of $1{\cdot}4 \times 10^{-8}$ secs. but the wavelength λ 5875 Å corresponding to the transition $2^3P - 3^3D$ is so near the red sensitivity limit of the photomultiplier that it was difficult to resolve. Measurements on this line are discussed later.

The shortest lifetime that was measured was that of the 3^1P state which decays by $2^1S - 3^1P$ and $3^1S - 3^1P$ as well as $1^1S - 3^1P$. Steps were taken to reduce to a minimum the effects of imprisonment. The decay curve obtained during this experiment is reproduced in Figure 8. It will be seen that this curve has a width at half height of $3{\cdot}25 \times 10^{-8}$secs. so that the resolving time of the apparatus is less than this amount. The asymmetry of the curve is due to the finite lifetime of the state. The resolving time thus estimated is in agreement with the value expected from the magnitudes of the circuit parameters.

(b) A study of the phenomenon of imprisonment of resonance radiation - (measurements on the λ 5016 Å line)

There are a number of theoretical papers on the imprisonment of resonance radiation[57][58][59]. Of these the most extensive is a paper due to T. Holstein[59]. The earlier work treated the subject by analogy with the diffusion of gases. While clearly there is a similarity, two major differences exist. The first (considered by Kenty[58] as well as Holstein) is that the probability of a photon exciting an atom is a very sharp function of the frequency of the radiation. The second, which was pointed out by Holstein, is that, since resonance radiation energy spends so much more time as an excited atom than travelling between atoms, an evaluation for the mean free path of a photon by analogy with the kinetic theory of gases has no meaning. He found an expression for the "mean free

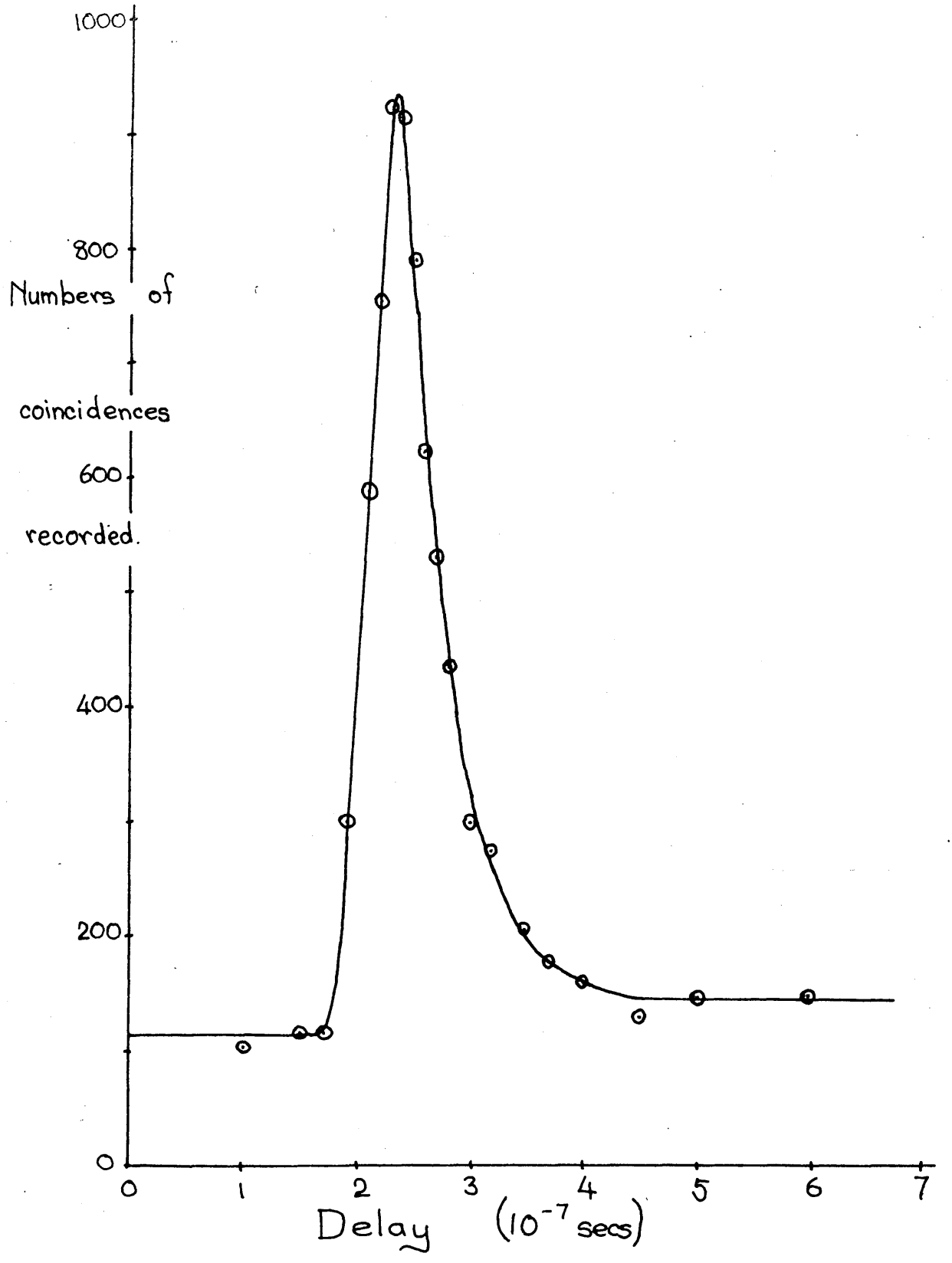


FIG 8 : The "fastest" coincidence curve obtained (λ5016 Å at 0·005mm.Hg)

path" which is divergent.

As an alternative and more meaningful conception, Holstein introduces the probability $T(\rho,\nu)$ that a photon ν will traverse a distance ρ before losing its energy to an atom. Because of its "resonance" nature, this probability varies sharply with ν so that it is desirable to find the mean over the spectrum of the line. If $k(\nu)$ is the absorption coefficient of the atoms for this particular line then

$$T(\rho,\nu) = e^{-k(\nu)\rho}$$

and the probability $T(\rho)$ for a photon anywhere in the emitted spectrum $P(\nu)$ of the line going a distance ρ is given by

$$T(\rho) = \int_0^\infty P(\nu)\, e^{-k(\nu)\rho}\, d\nu$$

It is now necessary to find expressions for $P(\nu)$ and $k(\nu)$. The nature of the absorption $k(\nu)$ depends on the conditions of the gas and in the present case is influenced mainly by Doppler broadening.

For Holstein's results to apply, it is necessary that emission and absorption spectra of the line have the same form i.e. $k(\nu) \propto P(\nu)$. Holstein goes to some lengths to show that even if the radiation and atoms are not in thermo-dynamic equilibrium, then in the case of a Doppler broadened line this relation applies. However, for this to be so the dimensions of the reaction vessel must be much greater than the radiation length ($\sim 1/k(\nu)$). At some of the low pressures used in the present experiment the radiation length approached the tube dimensions (~ 1 cm.). Holstein makes use of an approximation in integrating the expression for

$T(\rho)$ thus:-

$$T(\rho) = \frac{1}{k_{21}\rho(\pi \log k_{21}\rho)^{1/2}} \qquad [k_{21}\rho \gg 1]$$

where $$k_{21} = \frac{\lambda_{21}^2 N_1}{8\pi} \cdot \frac{\omega_2}{\omega_1} \cdot \frac{1}{\pi^{1/2} v_0 \tau_{21}}$$

$\lambda_{21} = c/\nu_{21}$ wavelength of radiation at line centre (cms.)

N_1 = Density of normal atoms ($cm.^{-3}$)

ω_1, ω_2 = Statistical weights ($2J+1$) of normal and excited levels respectively.

$v_0 = (2RT/M)^{\frac{1}{2}}$ (cms./sec.)

τ_{21} = Lifetime of state of an isolated atom (sec.)

A consideration of the transport of resonance radiation in a cylindrical space involves $T(\rho)$ as evaluated above and leads to an expression for an "escape factor" for the radiation g given by:-

$$g = \frac{1 \cdot 60}{k_{21}R(\pi \log k_{21}R)^{\frac{1}{2}}}$$

where R is the radius of the tube and g is the factor by which the spontaneous transition probability has to be multiplied to give the apparent transition probability taking imprisonment into account.

The lifetime $\tau(3^1P)$ of the 3^1P level is determined by

$$\frac{1}{\tau(3^1P)} = gA(1^1S - 3^1P) + A(2^1S - 3^1P) + A(3^1S - 3^1P)$$

where g is Holstein's escape factor for resonance radiation.

We measured $\tau(3^1P)_{obs.}$ for a series of gas pressures (g is a function of pressure) and plotted $1/\tau(3^1P)_{obs}$ against $gA(1^1S - 3^1P)$. In order to extend the measurements to slightly different conditions a 1 cm. bore

quartz tube was placed inside the excitation tube co-axially with the electron beam. Since the λ 537 Å resonance radiation was not transmitted by this inner tube the imprisonment was confined to the interior. In both cases the graphs of $1/\tau$ v. gA are straight lines and the intercepts on the $1/\tau$ axis are very nearly equal, the intercepts being $1{\cdot}37 \times 10^7$ secs.$^{-1}$ and $1{\cdot}33 \times 10^7$ secs.$^{-1}$ respectively (see Figure 9).

These values correspond to the situation where the imprisonment of the λ 537 Å radiation is complete and the only mode of decay is by the other two possible transitions. The mean value found for $A(2^1S - 3^1P)+A(3^1S-3^1P)$ was therefore $1{\cdot}35(\pm 0{\cdot}02) \times 10^7$ secs.$^{-1}$.

It is concluded that the results are in qualitative agreement with Holstein's theory. More extensive measurements would have been required to find an explanation for the lack of exact quantitative agreement (the slopes of the curves are not unity as they should be). Possible explanations are the following:-

i) The evaluation of g depends on the estimates made of the temperature and the transition probability in the absence of imprisonment (taken as 60°C and 10^9 secs.$^{-1}$ respectively) as well as on the calibration of the pressure gauges. Poor estimates could cause an error of up to about $\pm$ 50% in g.

(ii) Holstein's theory was developed for the idealised geometry of an infinite cylinder with no reflection at its surfaces. He also supposed that the radiation was isotropic. In our apparatus there will be some polarisation due to directed electron beam so that it may be necessary to use modified statistical weights of the levels in his formula.

(iii) It is a requirement of the proof that $k_0 R \gg 1$. In

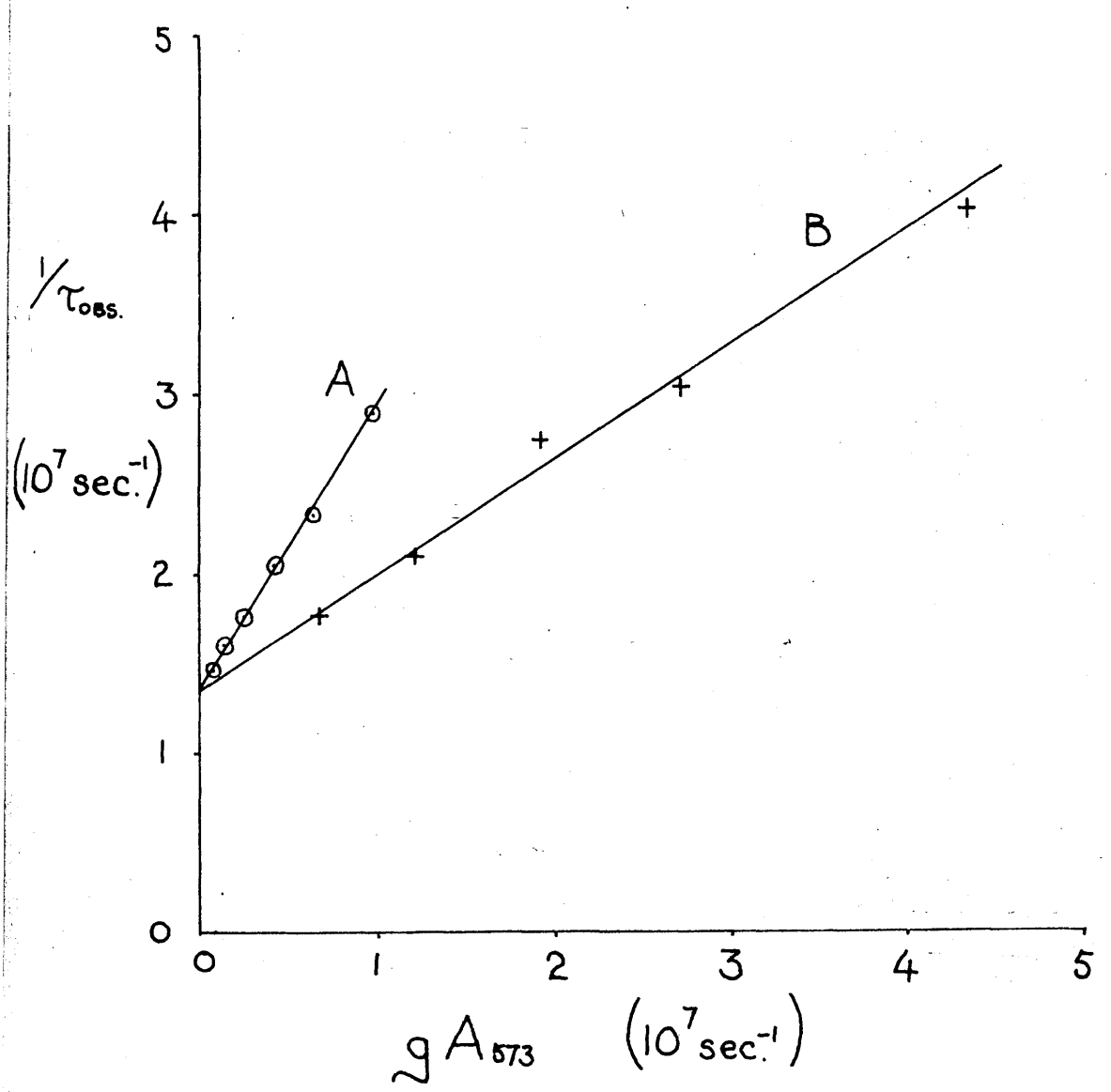


FIG. 9. The effect of imprisonment on the observed lifetime of λ5016 Å radiation. Holstein's theory gives 'g' as a function of the pressure which was varied to obtain the above curves.
Curve A : without the inner tube. R = 1·5 cms.
Curve B : with the inner tube R = 0·5 cms.

the conditions of our experiment this is not met very well. It was found that values at pressures less than 10 μ of mercury (where k_oR is bout 10) fell some distance from the straight line graph. These have been omitted but, even so, the criterion that k_oR be greater than 10 is somewhat arbitrary.

(iv) The method of analysis of the results was not altogether satisfactory. For low pressures and hence small values of τ it was difficult to measure the slope of the exponential part of the coincidence curve. An analysis based on Newton's method of displaced centroids[62] (discussed later) gave a curve having a different slope but the same intercept. Because a prompt coincidence curve could not be obtained, the first method of analysis was regarded as the more reliable.

(d) The λ 5875 Å ($2^3P - 3^3D$) transition

This was the fastest triplet line that could easily be resolved and it was used to confirm the test made above on the λ 5016 Å line to check the resolving time of the apparatus. As mentioned above, this wavelength is near the upper limit of sensitivity of the photomultiplier and for this reason the background counting rate was high (the cathode light being predominantly red) and number of signal counts was low (low photo-cathode sensitivity). Better spectral resolution would have improved matters a little. The results of a measurement on this line are illustrated in Figure 10. The complex curve may be divided into two components each having a simple exponential shape. The faster component has a lifetime of the same order of magnitude as the resolving time of the apparatus (10^{-8}secs.) and so cannot reliably be measured from the slope of the exponential. The slower component is associated with a transition having a mean life of about

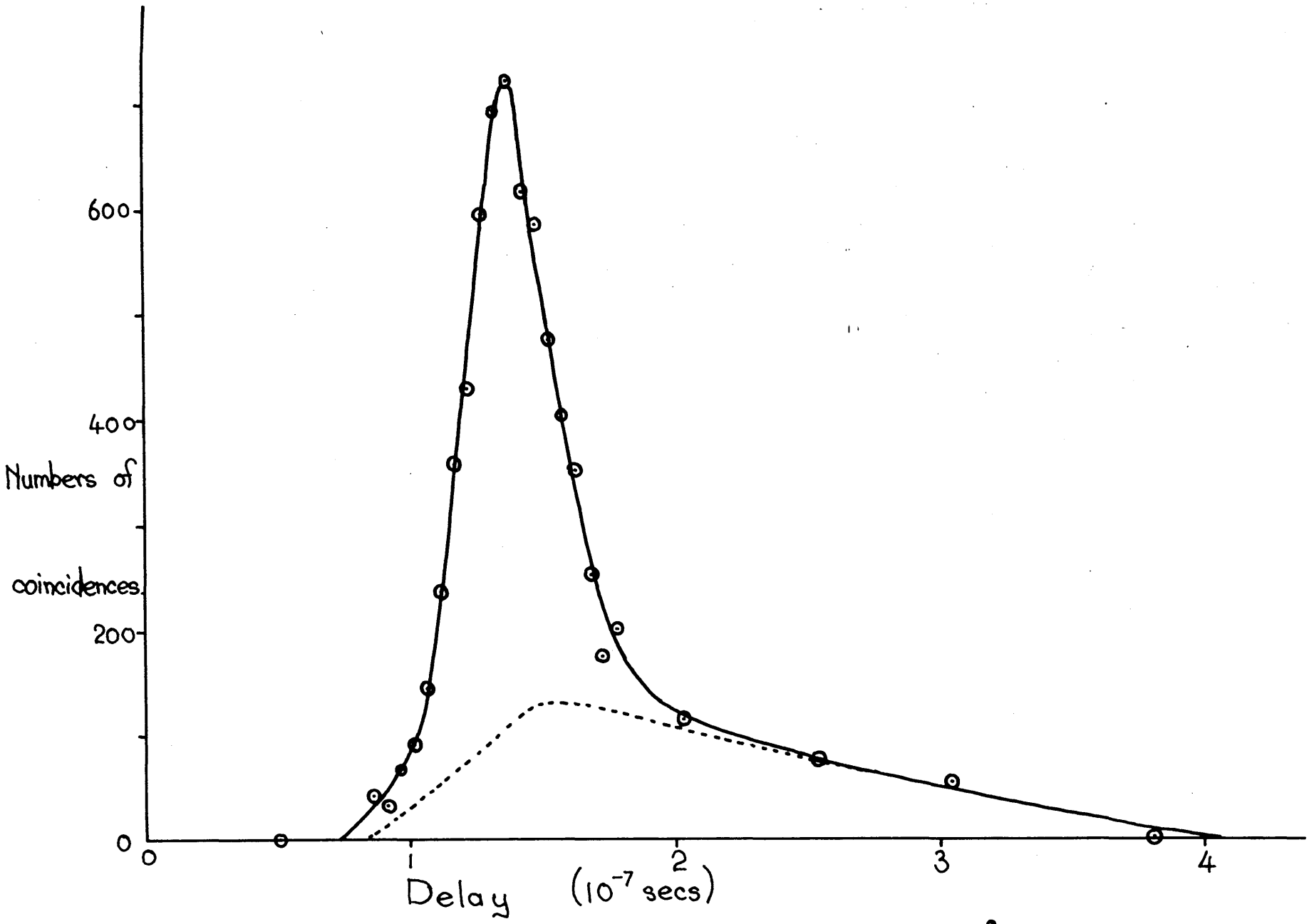


FIG. 10. The delayed coincidence curve for the λ 5876 Å line.

5×10^{-7} secs. From the curve it is possible to estimate the relative yields associated with the two components. It comes out that they are in the ratio of 1 : 10 approximately (fast to slow). It is tempting to ascribe this complex shape to the same source as that which gives rise to the complex shape of the excitation curve for this line. This was observed by Lees and Skinner[52] and others who have suggested that the triplet states can be populated by collisions of the second kind of the type

$$3^1P + 1^1S \rightarrow 3^3D + 1^1S$$ - the energy discrepancy being $\frac{1}{100}$ e.V. It will be noted that this reaction does not conserve electron spin so that theoretically it is expected to have a small cross-section. Thus one would expect there to be only a small number of triplet states produced by this mechanism and that the lifetime associated with them would be equal to that of the 3^1P state (including modifications due to imprisonment). For the particular conditions at which the measurements were made, the lifetime of the 3^1P state is about 5×10^{-8}secs. (c.f. 5×10^{-7} secs. for slow component). Also taking the value of the cross-section for this process as measured by Maurer and Wolf[60] it comes out that 1/10th of the atoms in the 3^1P state are affected by it. These would give rise to a negligible yield in comparison with those excited directly to the triplet state. Thus, for two reasons, it appears that this process is not responsible for the complex shape of the λ 5876 Å curves.

The possibility that the slow component arises from cascades from the $L \geqslant 3$ levels (it is the preferred route for such decays) is considered later and rejected on the grounds that the observed yield is much too large. However, the explanation may be outside the λ 5876 Å line due to the poor spectral resolution already mentioned. Fluorescence in the glass or the

presence of metastable states may be the cause. A more extensive investigation of this point must await a photomultiplier sensitive in this region and the use of a spectroscope to isolate the desired lines.

(e) The other measurements of the lifetimes of states

Before going on to consider these individually, it is important to consider the processes which may influence the results. These will be considered under the following headings:-

(i) Modification of the population densities of the states by collisions of the second kind.

(ii) The repopulation of levels by cascade from higher levels and from the continuum of ionised states.

The probability of processes of type (i) occurring is given by

$$A_{col.} = Q \cdot N_o \cdot \upsilon \text{ secs.}^{-1}$$

where Q is the cross-section for the process (cm.^{2}). N_o is the density of atoms in the state concerned (the ground state gives the greatest contribution and need only be considered) and υ is the mean velocity of the atoms.

$$A_{col.} = Q \times 10^{20} \quad \text{at } 30\,\mu \text{ Hg. pressure.}$$

Some values of the cross-sections for possible processes are:-

$1^1S + 3^1P \rightarrow 1^1S + 3^3D$ 10^{-14} cms.^{2} (Maurer and Wolf[60])

$1^1S + 3^1P \rightarrow 1^1S + 3^3P$ 10^{-15} cms.^{2} (Maurer and Wolf[60])

Gas kinetic Q for He atoms 10^{-16} cms.^{2} (Loeb[61]).

The effect of the most important of these (that leading to the formation of 3^3D states) has already been mentioned and was shown for the λ 5016 Å line to be negligible. The value $A_{col.}$ (at 30 μ.Hg.) for this process is 10^6 secs.$^{-1}$ and is therefore important only in those cases where the spontaneous transition probability is of this order. This situation

occurs for only one case in the present series of experiments viz. where the λ 5016 Å line ($2^1S - 3^1P$) was observed at a helium pressure of 100 μ Hg. In this case, the measured value of $1/\tau_{5016}$ was $1{\cdot}4 \times 10^{-7}$ secs.$^{-1}$ and the value of $A_{col.}$ comes out to be 6×10^6 secs.$^{-1}$. Thus about 1 in 3 of the atoms in the 3^1P state would be expected to be removed from this state by a collision process. The fact that a linear dependence of $1/\tau_{5016}$ on pressure was observed suggests that the value taken for the cross-section may be too high.

The effect of recombination of ions will now be considered. Because of the greater probability of ionisation, the number of ions produced under typical conditions was about 20 times the number of atoms raised to the 3^1P state and decaying by emission of λ 5016 Å radiation (the 3^1P state is more densely populated than any other in the present conditions). However, the recombination cross-sections for positive ions and electrons is very small ($\sim 10^{-19}$ cms.^{2} Massey and Burhop(54)) and this, coupled with the small density of free electrons ($\sim 10^{13}$cms.$^{-3}$), makes the rate of this recombination process very small. The probability that an ion will recombine with an electron is, for the condition of the experiment, ~ 1 sec.$^{-1}$. Despite 20 times as many ions as excited atoms, this process is entirely negligible beside a process having a transition probability of $\sim 10^8$secs.$^{-1}$.

We may now consider effects due to cascades from higher levels. By way of example, we consider the 4^3P state and determine the number of transitions from, say, the 5^3S state as compared with the total number of transitions from this state. Using Bates's and Damgaard's values for the transition probabilities, it comes out that only one in two hundred of the transitions goes to the 4^3P level. This, coupled with the smaller cross-section for excitation to the 5^3S state (4×10^{-20}cms.^{2}) as compared with

excitation to the 4^3P state, makes the cascade process entirely negligible for this case.

In general, triplet S and triplet P levels with main quantum numbers $\geqslant 4$ will not be significantly influenced by cascades, due to the very small branching ratio from upper states to that level, with respect to transitions to the metastable state. The same remarks apply to higher singlet S and singlet P states than the 2^1P and 3^1S.

Some effect from cascades from higher states was observed when investigating the 3^3P level. The decay of the 4^3S state can re-populate the 3^3P state. The probability of this happening depends upon the initial population of the 4^3S state and upon the probability that the decay will take place to the 3^3P state. This latter may be calculated from the tables given by Bates and Damgaard[2] and is found to be 2/5ths of all decay transitions from the 4^3S level. The initial population of the states depends on the energy of the exciting electrons. Using the values of the cross-sections measured by Lees, it comes out that the ratios of the initial populations of the $\frac{4^3S}{3^3P}$ states are for the following electron energies

30 e.V.	50%	20%
40 e.V.	18%	7%
60 e.V.	16%	6·5%
80 e.V.	15%	6%

The third column is the increase in the population of the 3^3P state due to cascades from 4^3P. The effect of this on the result depends on how the measurement is made from the decay curve which will not now be strictly exponential. Since the lifetime of the 4^3P state is about half of that of the 3^3P state, it is estimated that this effect will cause an error of less than 1% to measurements taken above 40 e.V. excitation potential.

The following table shows how the measured values varied with excitation potential.

Excitation energy e.V.	32·5	40	60	80
Lifetime units of 10^{-7} secs.	1·27 ± ·05	1·15 ± ·02	1·15 ± ·04	1·14± ·02

The lifetime appears to be longer at lower excitation energies as predicted.

An important case arises for the 3^3D state. Inspection of the helium energy level diagram shows that all states having angular momentum quantum number L equal to or greater than 3 will tend to decay via this level. A calculation of the transition probability of 3^3D - 4^3F based on the Coulomb approximation of Bates and Damgaard[2] yields a value of 1·3 x 10^{-7} secs.$^{-1}$. This in itself is too great to account for the slow component observed in the λ 5876 Å measurement but it may be that even higher levels will lead to a re-population at the observed rate of decay. However, this explanation seems unlikely on the grounds that the yield from this source must be very small - certainly less than the observed 10 times direct 3^3D yield.

It may be shown similarly that the effect of cascades to the upper of the other levels under observation leads to effects less than 1% in magnitude.

(f) The method of analysis of the results

For each run a curve was plotted of the coincidence rate as a function of the delay inserted. The random rate was measured for a delay long compared with the lifetime of the state and this subtracted from the other readings. After an initial rise the corrected coincidence curve decreased exponentially. The slope of the exponential was measured to give the lifetime of the atomic state.

Newton[62] has considered the problem of the analysis of such

delayed coincidence curves and has shown that to measure the slope of the exponential decay is a reliable method when the lifetime observed is longer than the resolving time of the coincidence unit. He has also developed a method of analysis of delayed coincidence measurements for cases where the lifetime of the state being observed is equal to or slightly less than the resolving time of the coincidence unit. The method depends on plotting a prompt decay curve i.e. one where the lifetime of the state being observed is very much shorter than the resolving time of the coincidence unit. Newton has shown that if the curves are normalised to enclose equal areas then

(i) The maximum point of the delayed curve falls on the prompt curve.

(ii) The displacement of the centroid of the delayed curve from that of the prompt curve is equal to the mean life $\bar{\tau}$ of the state.

Since it was not possible to obtain a truly prompt coincidence curve, the method of displaced centroid could not be used to analyse results. However, the method was used to check the differences between values measured by the slope of the curve.

(g) The results.

3^1P state

As already described the measurements on the λ 5016 Å line were modified by the imprisonment of resonance radiation. They were also insensitive to the spontaneous transition probability to the ground state but an estimate of that to the 2^1S and 3^1S states was made and found to be $(1{\cdot}35 \pm 0{\cdot}02) \times 10^{-7}$ secs.$^{-1}$. The error quoted is the random experimental error.

3^3D state (λ 5875 Å)

This is a short lived state so that it was not possible to measure its lifetime from the slope of the decay curve. The direct application of Newton's method of displaced centroid was not possible as a prompt curve could not be obtained. However, by comparing the present curve with the fastest λ 5016 Å curve, an estimate of the lifetime was possible, the difference in the positions of the centroids being taken as equal to the difference in mean lifetimes. A value of $(1{\cdot}0 \pm 0{\cdot}5) \times 10^{-8}$ secs. was obtained for the mean lifetime. The large error quoted is a result of the low counting rate due to poor photomultiplier sensitivity as well as the method of analysis.

3^3P state (λ 3889 Å)

When care was taken to avoid re-population by cascades from higher levels as described above, a value of $(1{\cdot}15 \pm 0{\cdot}05) \times 10^{-7}$ secs. was obtained for the lifetime of this level. The value was estimated from the slope of the exponential.

4^3S state (λ 4713 Å)

None of the complicating effects appear to influence this line. A value of $(6{\cdot}75 \pm 0{\cdot}10) \times 10^{-8}$ secs. was measured (slope of the exponential) for its lifetime.

4^3P state (λ 3188 Å)

This line was measured because it extends the technique into the ultra-violet region of the spectrum. There was no other difficulty about the measurement which yielded a value of $(1{\cdot}53 \pm 0{\cdot}02) \times 10^{-7}$ secs. for the lifetime of the state.

6. COMPARISON OF THE MEASURED VALUES WITH THEORETICAL CALCULATIONS

The basic principles for the quantum mechanical calculation of atomic transition probabilities were first laid down by Dirac. He showed that the significant electron density associated with dipole radiation from the atom was given by the product of the wave-functions of the electron in the initial and final states of the relevant transition. The resulting wave-function contains a time dependent component varying with a frequency ν_{21} such that $h\nu_{21}$ is the energy difference between the two states and in this respect leads to the same conclusion as the Bohr model. The amplitude of this wave-function depends upon the spacial parts of the individual state wave-functions so that it can only be calculated exactly where the former are known, i.e. for systems consisting of two particles. The transition probability for the transition 2 - 1 i.e. the probability that a photon resulting from this transition should be emitted by a particular atom during a particular interval of time is given by the product of the squares of the amplitudes of the wave-functions

$$A_{21} = \frac{64e^2\pi^4\nu_{21}^3}{3h} \underline{R}_{21}\,\underline{R}_{12}$$

where $\underline{R}_{21}$ is a vector with components given by $R_{21,x} = \int \psi_2 \psi_1^* x \, d\tau$ etc. Similarly for $\underline{R}_{12}$.

ψ_2 and ψ_1 are the spacial parts of the wave functions of the electron in the initial and final states respectively and the integration is taken over the whole volume of the atom. It may be shown that A_{21} is independent of the magnetic quantum number; that is, all states of a level have the same lifetime.

Detailed calculations for particular atoms have been done by a number of authors. In general they assume Russell Saunders coupling between electrons. The calculations lead to some universally applicable conclusions, summed up in the selection rules for atomic transitions.

Besides electric dipole radiation, it is possible for atoms to lose energy by electric quadruple radiations and by magnetic dipole radiation as well as further insignificant multipole radiation. Calculations show that the ratio of the transition probabilities by electric dipole to electric quadruple is generally of the order of $1 : 10^{-8}$ while that for electric dipole to magnetic dipole is about $1 : 10^{-5}$. Magnetic dipole transitions may therefore be of importance sometimes in the de-excitation of metastable states.

The calculations now to be discussed are for electric dipole radiation. The central problem in such calculations is the choice of wave-functions for the two stationary states of the atom. In the case of hydrogen atoms and ions having only one planetary electron, these can be evaluated exactly. For helium, their evaluation is inexact.

Hylleraas[40] and Goldberg[63] each made use of the successive approximation method of the self-consistent field to arrive at appropriate wave-functions. The values found by Hylleraas are probably more accurate as Goldberg deliberately sacrificed accuracy for ease of computation, by using simpler wave-functions. On the other hand, it has been suggested by Bates and Damgaard[2] that Hylleraas' work suffers from a number of numerical mistakes. Bates and Damgaard have carried out a computation based on a simple Coulomb potential field for the electron in excited states (the calculations should not be extended to the lowest state, since the Coulomb

approximation could not be expected to be valid in the vicinity of the second un-excited electron). The agreement between Hylleraas' results and those of Bates and Damgaard is very good. Differences between individual results occur in a completely erratic manner and it was this that led Bates and Damgaard to suspect numerical error as the cause of the small discrepancies. The agreement with the values due to Hylleraas adds confidence to the adoption of Bates's and Damgaard's figures, which are quoted below in comparison with the values measured in the present experiment.

$\lambda_{obs.}$	Transitions (determining the lifetime of the upper state)	Transition probability (sec^{-1}) Bates and Damgaard		Experimental
5016 Å	$2^1S - 3^1P$	$1{\cdot}34 \times 10^7$	$1{\cdot}37 \times 10^7$	$(1{\cdot}35 \pm {\cdot}02) \times 10^7$
	$3^1S - 3^1P$	$3{\cdot}06 \times 10^5$		
4713 Å	$2^3P - 4^3S$	$6{\cdot}43 \times 10^6$	$1{\cdot}57 \times 10^7$	$(1{\cdot}48 \pm {\cdot}02) \times 10^7$
	$3^3P - 4^3S$	$9{\cdot}25 \times 10^6$		
3889 Å	$2^3S - 3^3P$	$9{\cdot}26 \times 10^6$	$1{\cdot}03 \times 10^7$	$(0{\cdot}87 \pm {\cdot}04) \times 10^7$
	$3^3S - 3^3P$	$1{\cdot}07 \times 10^6$		
3188 Å	$2^3S - 4^3P$	$5{\cdot}65 \times 10^6$	$7{\cdot}25 \times 10^6$	$(6{\cdot}54 \pm {\cdot}09) \times 10^6$
	$3^3S - 4^3P$	$0{\cdot}73 \times 10^6$		
	$4^3S - 4^3P$	$0{\cdot}22 \times 10^6$		
	$3^3D - 4^3P$	$0{\cdot}65 \times 10^6$		
5875 Å	$2^3P - 3^3D$		$7{\cdot}17 \times 10^7$	$(10 \pm 5) \times 10^7$

The agreement between theory and experiment is good (being never greater than ± 15%). As there are only ~~three~~ five measurements, it would be unwise to attempt to find an explanation for the ~~consistently~~ smaller values obtained experimentally.

7. SOME SUGGESTIONS FOR EXPERIMENTS WHERE THE METHOD DESCRIBED IN THE THESIS HAS AN ADVANTAGE.

There have been suggested during the course of this thesis a number of measurements which could be done with advantage using the delayed coincidence technique. These, and other experiments, will be considered in a systematic manner but, beforehand, it is worth pointing out a few changes that would increase the range of application of the apparatus.

(i) Greater electron beam currents (x 100) could be obtained with a specially designed cathode and the spread in energy of the electrons could be reduced by using a metallic cathode (rather than the oxide-coated one in use at the moment). Light from this could be prevented from entering the photomultiplier by careful design of the collimator system.

(ii) A monochromator would increase greatly the usefullness of the apparatus. In the visible and quartz ultra violet regions, an f 4 grating monochromator would increase the counting efficiency by a factor 50 over the present arrangement. Coupled with the greater beam current, an improvement of 10^4 in sensitivity could be achieved. Knowledge of the spectral characteristic of the detector would allow the absolute determination of transition probabilities. Since pulses are counted the wavelength calibration of the detection system would not be dependent on the gain of the electron multiplier and this is the most important cause of uncertainty in the usual measurements of intensity using a photomultiplier. A vacuum spectrograph and Allen-type photomultiplier could be used to extend the range of sensitivity down to a few hundred Angstroms.

(iii) By varying the path length between the excitation tube

and the detector a direct calibration of the delay constant against the velocity of light could be made.

The following are some suggestions for experiments:-

(i) An extensive range of measurements is required on a simple system such as helium in order to compare and establish the various theoretical calculations on these systems. However, it is even more important to obtain reliable and accurate data for a hydrogen like system. Such data would provide one of the surprisingly few fundamental checks on quantum theory. Provided a high coincidence rate was obtained one could measure the lifetimes of the various unseparated levels of the hydrogen-like terms by separating out the various components of the delayed coincidence curve. Hydrogen atoms or hydrogen like ions could be produced by running a continuous discharge in a near-by tube connected to the excitation tube. The atoms or ions would have a lifetime long enough to let them diffuse in sufficient numbers into the sensitive region.

(ii) In reviewing recent measurements of astrophysically important oscillator strengths, it was noted that differences of factors of two and three existed between measurements by different methods. Our method could be used to provide further data. By placing the excitation tube inside a furnace, sufficient vapour pressure would be obtained for measurements of lifetimes of the atoms of interest. In comparison with the other methods, this one has the following advantages:-

(a) The measurement made (lifetime) is closely related to the desired quantity (oscillator strength) and

(b) One has independent control over the mode of excitation.

With greater sensitivity than the present apparatus is capable of, it should be possible to make measurements on complex ions and molecules, the former being produced in a neighbouring discharge.

(iii) In the past, measurements of excitation functions have been bedevilled by uncertain effects due to cascades from upper levels, collisions of the second kind and imprisonment of resonance radiation (see an article written recently by Massey[64]). Provided care was taken to make the electrons mono-energetic and the detector was calibrated against wavelength, then the coincidence method has much to commend it for measurements of excitation cross-sections. From measurements of the lifetimes of the atoms account could be taken of all the effects mentioned above. It may be necessary to use two photomultipliers like Brannen et al[50] in order to account completely for the effect of cascading.

At the same time, it should be possible to estimate cross-sections for the collision processes and study the imprisonment of resonance radiation.

By using the method of Brannen et al[50] and since the transition probabilities are known, one could possibly make an absolute measurement of the excitation cross-sections for hydrogen even if the concentration of hydrogen atoms was not known independently.

(iv) Since, with this apparatus, individual decay processes are observed one could, carrying over another nuclear physics method, measure any angular co-relation that there may be between photons emitted in consecutive transitions of a cascade.

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APPENDIX

An apparatus to measure the energy of alpha-particles in the presence of energetic He^3 nuclei and other ionising radiations.

Contents

AN APPARATUS TO MEASURE THE ENERGY OF ALPHA PARTICLES IN THE PRESENCE OF ENERGETIC He^3 NUCLEI AND OTHER IONISING RADIATIONS

1. INTRODUCTION

The apparatus described in this part of the thesis was built with the primary purpose of studying the photoproduction of neutral pi mesons at the helium nucleus. Some preliminary results of this investigation will be reported in the concluding paragraphs but, in the main, the scope of this note is confined to a description of the apparatus and of its development. However, in order to justify the experiment, there is a brief review of the meson physics aspect.

The photoproduction of π° mesons at hydrogen nuclei has been extensively studied by a number of workers.(1)(2) Their results have been satisfactorily described in terms of a theory of resonance production. The relative contributions of the various angular momentum states has been determined from measurements of the angular distribution of the scattered pions about the target nuclei. Experiments where high energy γ rays are incident on other light nuclei (and in particular deuterons) indicate that neutrons are as effective as protons in producing π° mesons. The theory of pion photoproduction at single nucleons has been discussed in a recent paper by Ross(3). A study of the π° yield from deuterium as target gave information about phase relationships between meson waves from the two types of nucleon and led the way to the development by Chew(4) of the impulse approximation method of estimating the yield from complex nuclei whose wave-functions are known. In this, the nucleons of the nucleus are regarded as scattering centres which give rise to a particular angular distribution of scattered mesons in much the same way as

two near-by slits give rise to an interference pattern when ordinary light is incident upon them.

A refinement of the impulse approximation takes account of the effect of multiple scattering where, once a meson has been produced at one nucleon, it may be scattered by direct interaction with other nucleons present in the nucleus.

In the case of deuterium, this calculation has been done by Brueckner and Chappelear[5] and their results have been confirmed experimentally most recently by Rosengren and Baron[6]. This work established the usefulness of the impulse approximation method for such calculations and encourages its application in cases of more complex nuclei whose wave-functions are not known accurately. The closely bound helium nucleus or alpha-particle is the obvious first choice for such an investigation which may be expected to yield information about the structure of this fundamental particle.

Till now, there has been only one detailed experimental study of the π° photoproduction in helium. On the other hand, by making observations on the γ rays which are the decay products of π° mesons, Goldwasser and Koester[15] were able to estimate the cross-section for the reaction but it was not possible to make angular and energy co-relation measurements using this method. The more detailed investigation was done by de Saussure and Osborne[7] who used a gas target (atmospheric pressure) and detected the recoil He^4 nuclei in nuclear emulsion plates. The incident γ rays were produced by the 350 M.e.v. synchrotron of the Massachusetts Institute of Technology. Unfortunately, this method of detection is not sufficiently sensitive to distinguish between He^4 particles and the He^3 particles which we also produced. De Saussure and Osborne did other runs at lower γ ray

energy where mesons could not be produced (threshold for π^o materialisation is about 150 M.e.v.) but where the He^3 reaction which was supposed responsible for most of the He^3 particles (viz. $\gamma + He^4 \rightarrow He^3 + n$) was possible. By taking account of the relative intensities of the γ ray beams during the two runs, it was possible to subtract the He^3 yield and hence estimate the yield of π^o mesons. The method is very sensitive to the form of the synchrotron beam calibration curve and their results are liable to fairly large errors.

Stoodley[8] has recently treated the photoproduction of π^o mesons from helium on the basis of Chew's impulse approximation method. By choosing six forms of the wave-function to describe the He nucleus, he was able to investigate the general effect of such a choice on the π^o yield curve. He considers also the effects of multiple scattering, using a simplified and symmetrical model for the He nucleus. His predictions indicate that the cross-section (at a π^o angle of 90^o in the laboratory) is reduced due to multiple-scattering by a factor of $\frac{1}{2}$ near threshold and by about 1/5 at 260 M.e.v. γ ray energy - resulting in a maximum for this curve at 220 M.e.v. instead of 250 M.e.v. (γ ray energy) predicted on the basis of simple impulse approximation. Our preliminary measurements are in fair agreement with Stoodley's predictions and our values for the cross-section are about 1/6 of those reported by de Saussure and Osborne (see Fig. (1)).

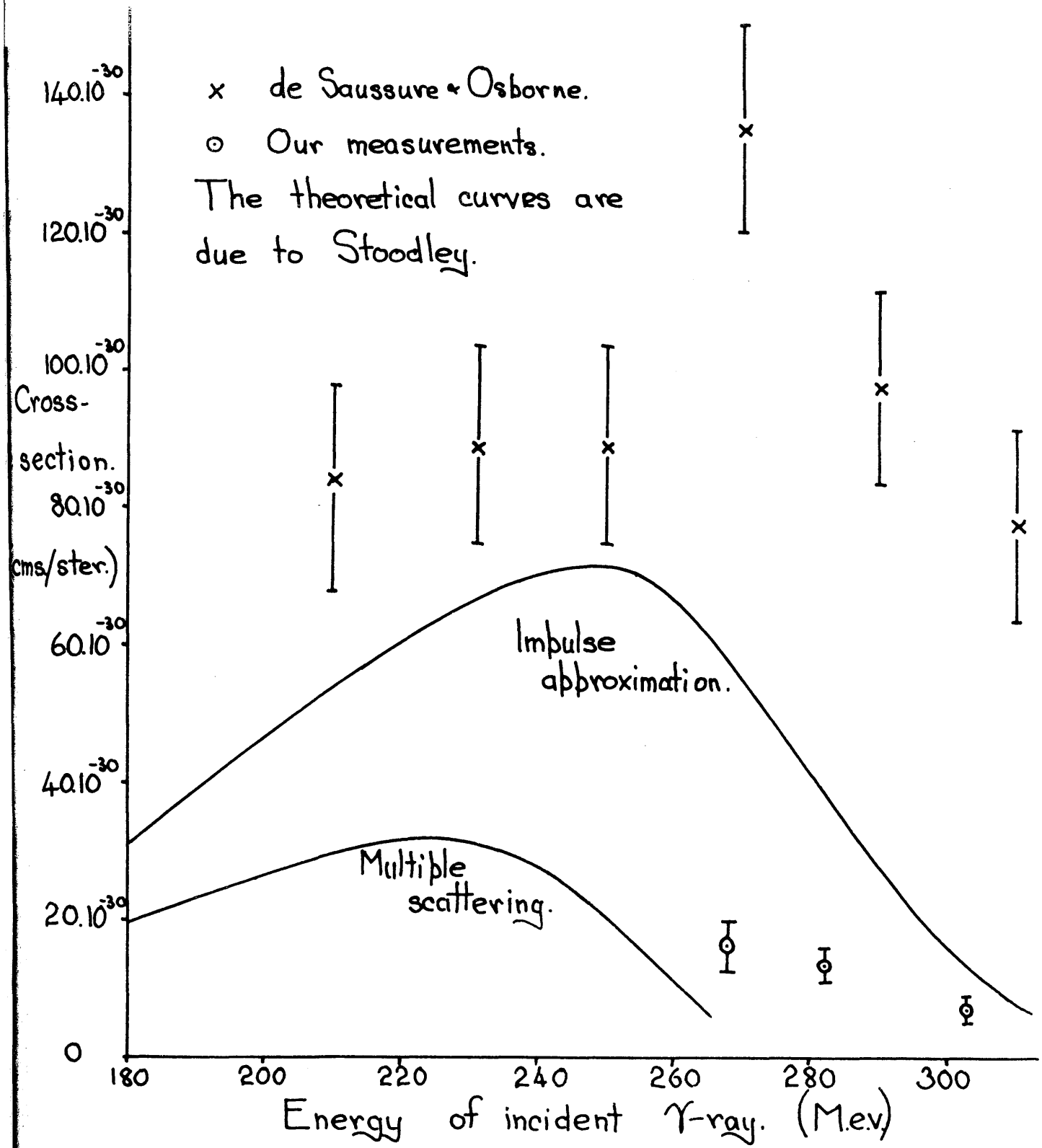


Fig. 1. Comparison of our preliminary results with theoretical predictions and previous measurements. (Photo-production of π^0's at 90° in the centre of mass frame.)

2. EXPERIMENTAL METHOD

(a) The Basic Requirements

The object is to measure the differential cross-section for the reaction

$$\gamma + He^4 \rightarrow He^4 + \pi^o$$

To do this one or both of the final particles must be detected and measured. The π^o particle may be detected only by virtue of the two γ rays to which it gives rise on decaying. Since these γ rays do not share the momentum of the meson in a unique way, it is possible only to set up detectors which are sensitive to a very small proportion of the π^o's produced. As the reaction cross-section is small ($\sim 10^{-28}$ cms^2) such an inefficient method of detection must be rejected. The same arguments apply to a method requiring the detection of an alpha-particle in coincidence with one of the decay γ rays.

Thus the method chosen was to measure the energy and angle of recoil of the alpha- particles. Since only two particles are involved in each collision; this measurement is sufficient to calculate all the parameters of each event recorded (See Feg. (2) for the inter-relation of some of these parameters). Despite the greater efficiency of this method of detection, a yield of only about 10 recorded events in an hour can be expected - hence the rejection of less efficient methods.

A consideration of the effect of bombarding helium with high energy γ rays shows that besides the reaction

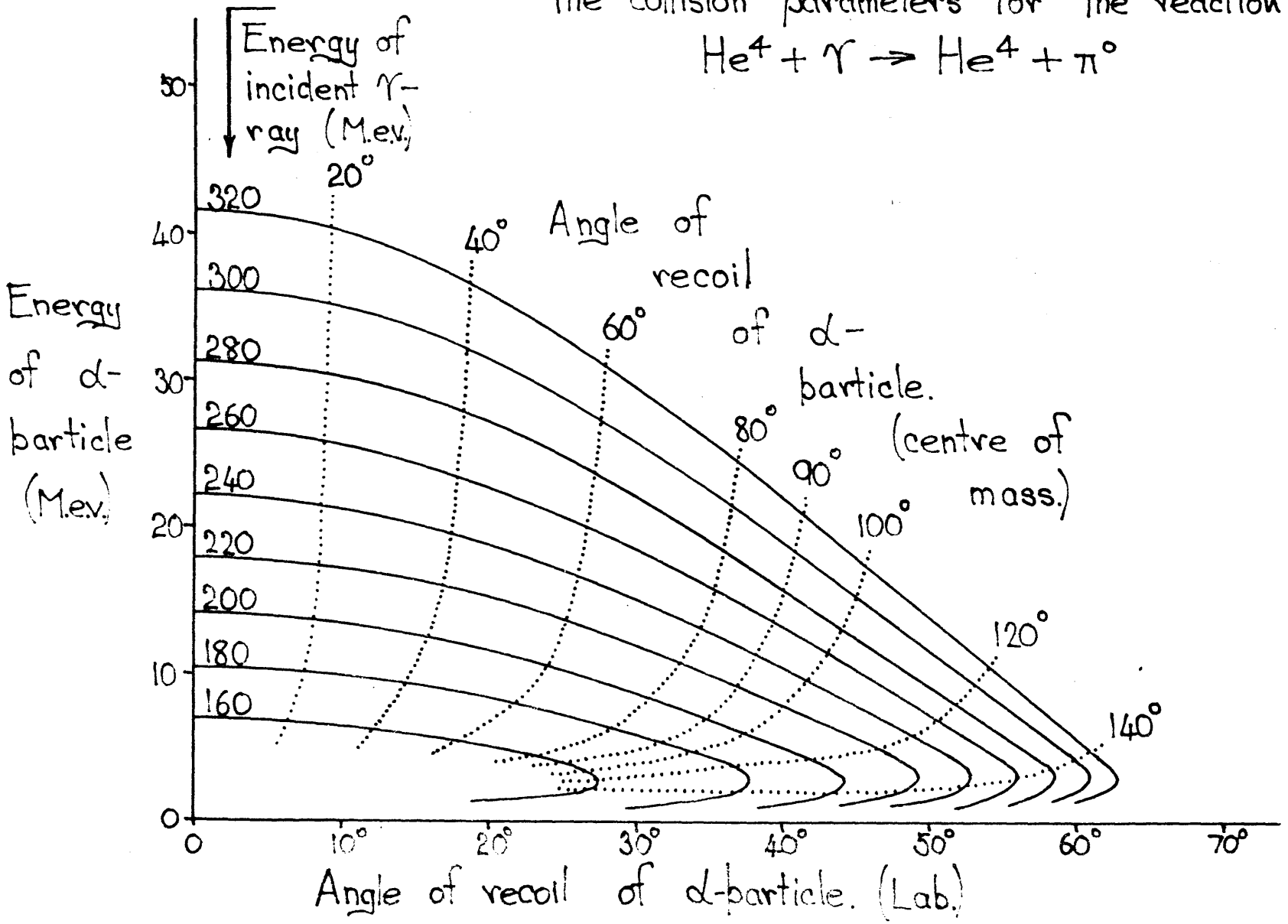
$$\gamma + He^4 \rightarrow He^4 + \pi^o \qquad (1)$$

the following are also possible:-

$$\gamma + He^4 \rightarrow He^4 + \gamma \qquad (2)$$

Fig 2. Illustrating the inter-relationship between some of the collision parameters for the reaction

$$He^4 + \gamma \rightarrow He^4 + \pi^0$$



$$\gamma + He^4 \longrightarrow He^3 + n \qquad (3)$$

$$\gamma + He^4 \longrightarrow He^3 + n + \pi^\circ \qquad (4)$$

$$\gamma + He^4 \longrightarrow He^3 + p + \pi^- \qquad (5)$$

as well as others where lighter nuclei result. Any effect due to Compton scattering (reaction 2) will be negligible due to the small cross-section for this process[9]. However, the other reactions (3)-(5) may not be negligible - see measurements due to de Saussure and Osborne[7] - so that it becomes necessary to build a detector which will distinguish between He^3 and He^4 particles or to resort to the subtraction method used by de Saussure and Osborne, to allow for the He^3 particles produced in reaction (3). They used a plausible, but not altogether satisfactory, argument to show that the number of particles from reactions (4) and (5) are negligible at the energies and angles at which their apparatus was sensitive.

In order to distinguish the particles, two parameters of their motion must be measured for each particle - these will also give the particle energy.

The low yield from the reaction requires that the detector have a large acceptance cone so that to keep the apparatus of reasonable dimensions a long flight path for the alpha-particles had to be avoided. Thus, methods depending on magnetic resolution or time of flight measurements (in each case a flight path of $\sim$ 100 cms. would be required) were not acceptable.

A further limitation on the choice of detector is set by the high rate of loss of energy suffered by alpha-particles in passing through an absorbing medium. Thus, windows of solid material were to be avoided and the first measurement must absorb the least possible proportion of the particle's energy.

These considerations lead fairly logically to the adoption of the measurements of

(a) the rate of loss of energy $\frac{dE}{dx}$ in a gaseous absorber (which depends on the velocity of the particle) and of

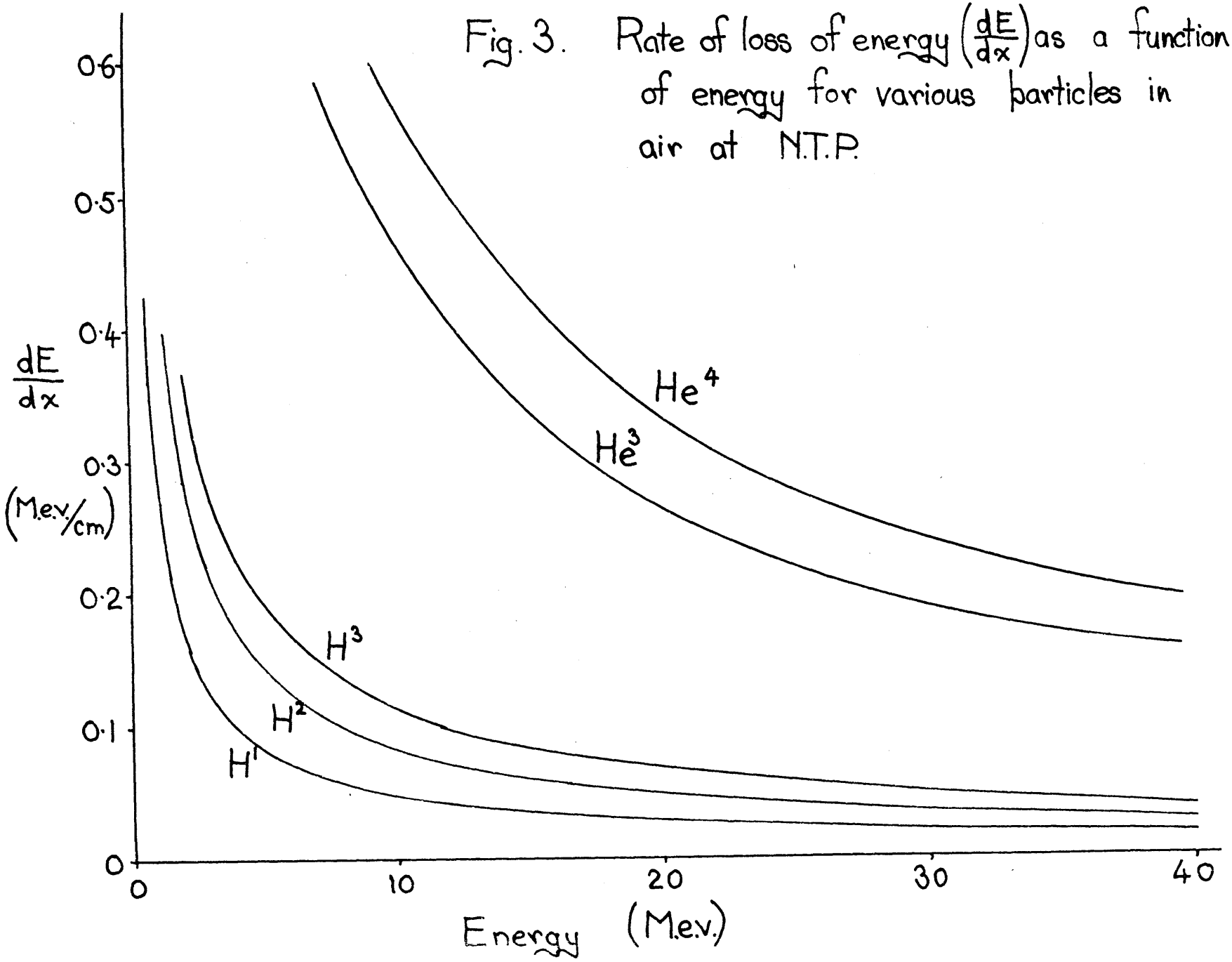
(b) the total energy E, in order to distinguish the two species. The degree of separation between He^3 and He^4 particles which in principle can be achieved is illustrated in Fig. (3) where are plotted rates of loss of energy as a function of particle energy for all the heavier particles liable to be produced in the target. From these curves it is apparent that uncertainty in either measurement must be less than about ± 15%. The first attempt to achieve this will now be briefly described.

(b) The scintillator and helium filled ionisation chamber

In this apparatus the $\frac{dE}{dx}$ measurement was made in an ionisation chamber while the residual energy of the particles was absorbed in a thin scintallator mounted on a photomultiplier. In order to avoid completely the need for windows, the same helium gas was used in the chamber as in the target tube. There is a sketch of this apparatus in Fig. (4). Its design will not be described further, as the considerations were similar to those to be described for the more successful instrument built later.

The resolution required of the detector was estimated from Fig. (5) where the calculated pulse heights from the two detectors are plotted against each other for the two species of particle. It was found impossible to maintain the purity of the helium gas sufficiently so as to avoid a deterioration in resolving power of the ionisation chamber. A furnace tube containing calcium chips was fitted in communication with the chamber in an attempt to remove any impurity. Also, helium gas was flowed continuously through the

Fig. 3. Rate of loss of energy $\left(\frac{dE}{dx}\right)$ as a function of energy for various particles in air at N.T.P.



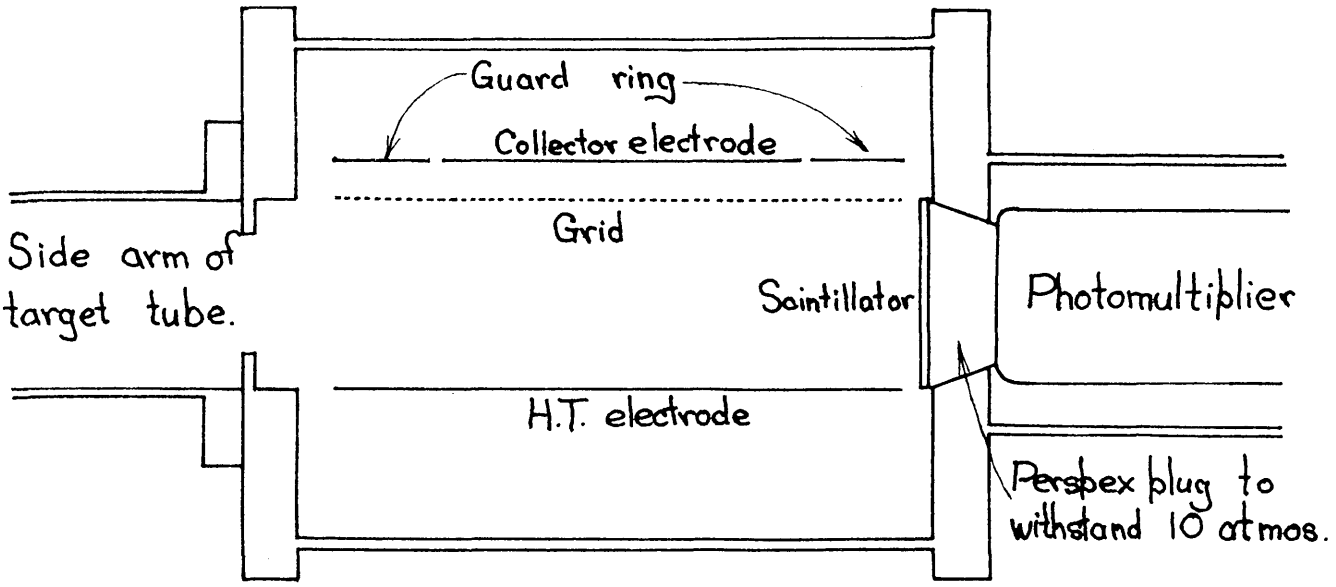


FIG. 4. Original arrangement with scintillator and helium-filled ionisation chamber.

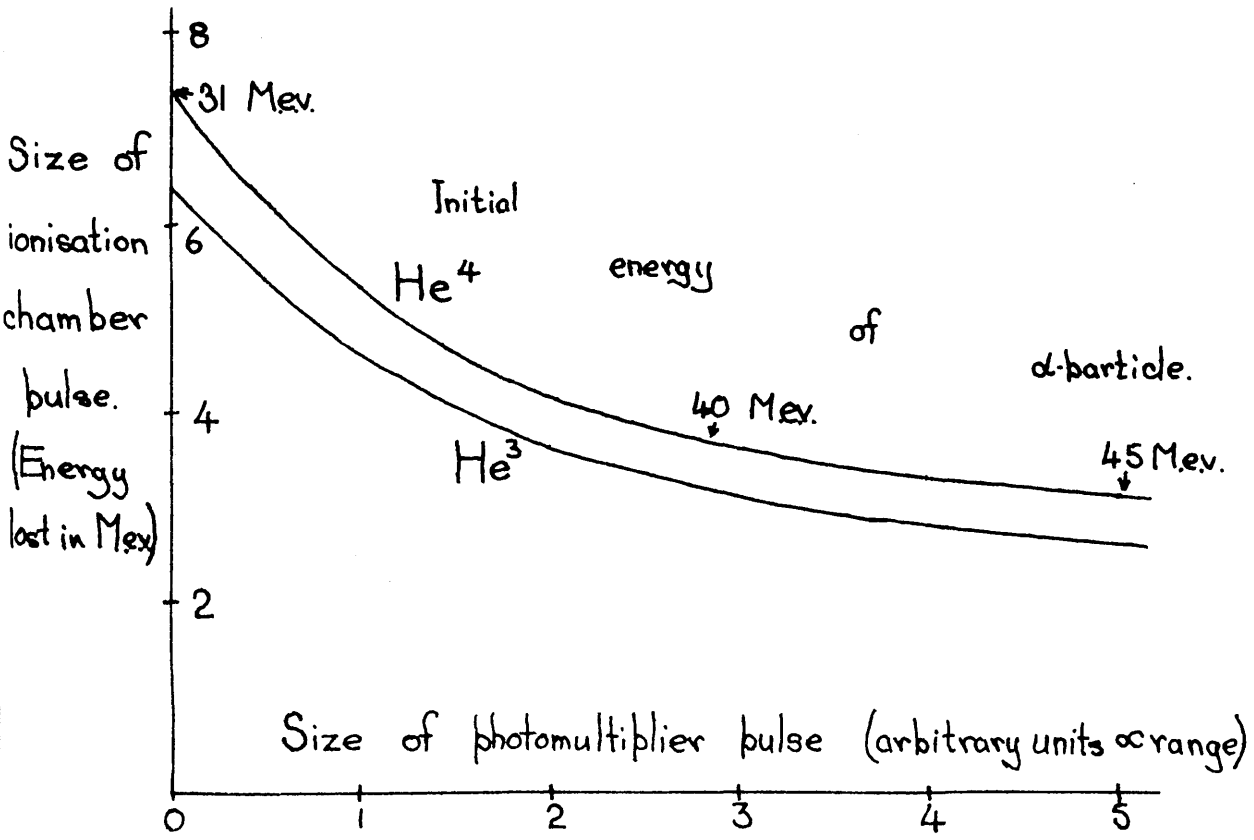


FIG. 5. The resolution expected from the original apparatus.

apparatus during an experiment. In neither case was the resolving power good enough. The possibility of adding methane to the helium in order to raise the electron temperature and avoid their capture by impurity molecules was considered but rejected because this gas in the target region would give rise to confusing alpha-particles.

Most of the tests of resolving power mentioned above were done using alpha-particles from polonium. The best measurements gave ± 7% as the resolving power over a short period but the pulse height varied by over 10% in an hour.

At this stage, before the apparatus was re-designed, a window of mylar was fitted between the chamber and the target tube and the chamber filled with a mixture of argon and methane - a "good" ionisation chamber gas. With this apparatus and despite the low pressures used (because of the greater stopping power of argon - 6 : 1 compared to helium) the resolving power appeared to be just ~~almost~~ good enough to make the experiment possible. However, with the introduction of a window, the fundamental principles on which the choice of detectors was based were modified so that a new design became desirable

(c) The Double Ionisation Chamber

The introduction of a window and a mixture of argon and methane makes the detector insensitive to a greater range of low energy particles as compared with the previous design. This arises from two causes:-

(a) Energy loss in the mylar window - a particle of energy 15 M.e.v. loses about 2 M.e.v. in the thinnest suitable window.

(b) Because argon has about six times the stopping power of helium, the particles lose a much greater proportion of their energy in the

insensitive regions of the chamber (viz. the space between the window and the electrodes, and including the guard ring region). A low energy alpha-particle may lose up to about 1 M.e.v./cm. in argon at atmospheric pressure.

The importance of making measurements on low energy particles may be seen from the reaction kinetics diagram (Fig. 2). For a proper study of the reaction it is very desirable that measurements be made up to a recoil angle of 90° in the centre of mass frame. For this the detector requires to be at a laboratory angle of about 50° to the γ ray beam and to be sensitive to alpha-particles having an energy of less than 20 M.e.v. Also, if our results are to be meaningfully compared with the theoretical curves by Stoodley (Fig. 1) then it is desirable to make measurements of reactions induced by γ rays of energy down to about 220 M.e.v. This again requires that the detector be sensitive to alpha-particles having only about 15 M.e.v. energy.

For these reasons, very great care was taken in designing the chamber so that the least loss in range of sensitivity would arise.

Because of the greater stopping power of argon it was possible to build a detector consisting of two ionisation chambers in series (these will be distinguished in future by designating them the "$\frac{dE}{dx}$ chamber" and the "E chamber" for obvious reasons). With this arrangement there is no need for a guard-ring between the chambers so that there was a reduction in the size of the insensitive region. There followed two further advantages over the scintillator used in the previous arrangement:-

(a) An ionisation chamber has greater inherent resolving power

(b) The back-ground of γ rays will have less effect because of the less dense absorbing medium.

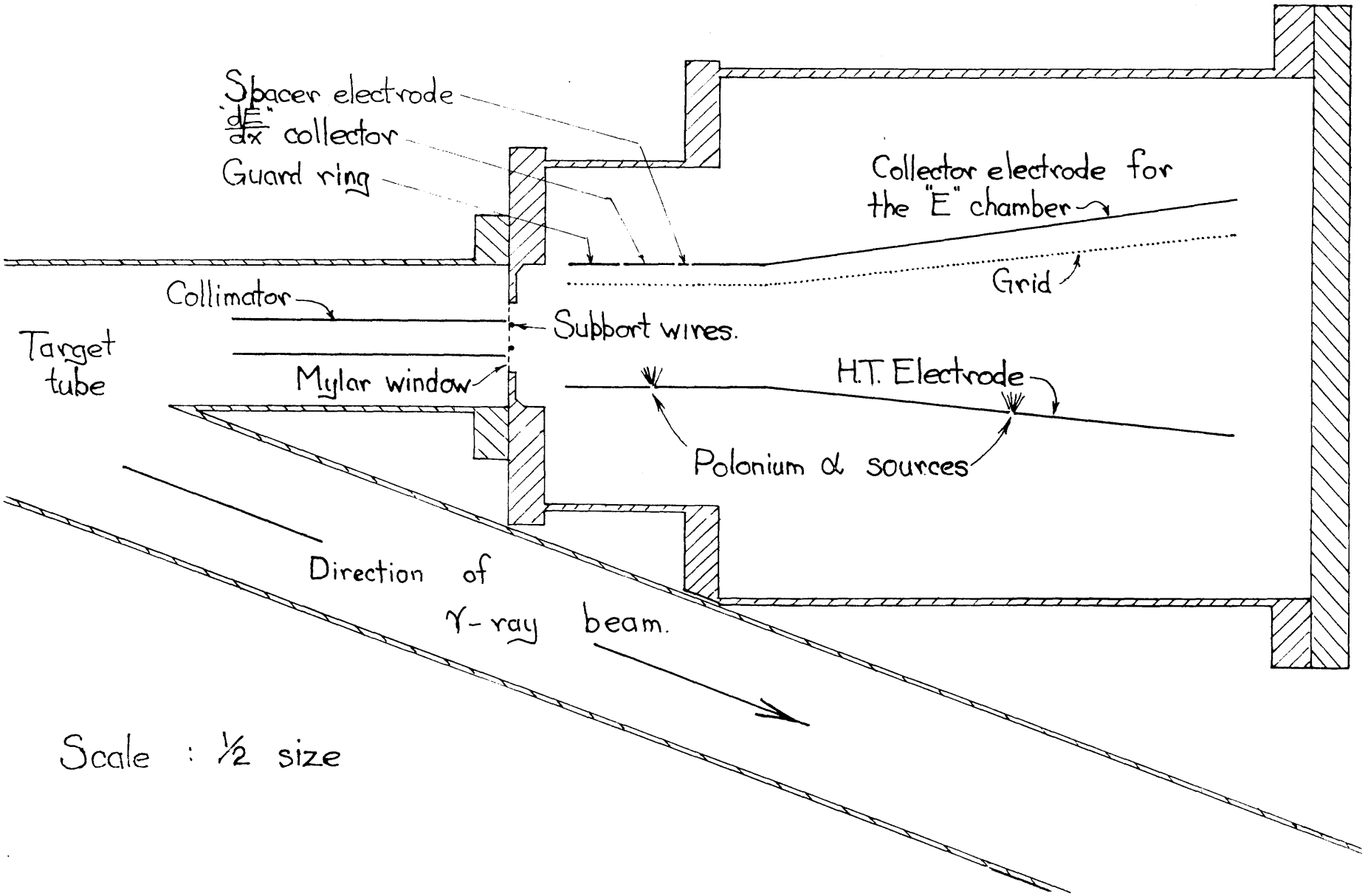
The considerations leading to the detailed design of the apparatus will now be reported.

The entire detector was made about 30 cms. long so that at 5 atmospheres pressure of argon it would absorb completely the energy of a 50 M.e.v. alpha-particle.

Because of the physical size of the apparatus, it is not possible to make measurements at angles less than 20° to the beam. To accomodate the chamber at this angle and still to maintain the required acceptance cone, it was necessary to incline the electrodes of the second half of the instrument as shown in the diagram (Fig. 6).

It was desirable to make the "$\frac{dE}{dx}$" chamber as thin as possible to increase the number of particles which would pass right through and be recorded in the "E" chamber. The limit was set by the smallest pulse which could be measured accurately above the amplifier noise. The size of the noise from our amplifier (type 1008 with H.F. head) was measured through the associated circuit, which limited the band width, and found to be 40 μ.v. (equivalent R.M.S. voltage on input grid of the head amplifier). Setting 5% as the greatest error that can be accepted for this cause, then the smallest pulse must not be less than 800 μ.v. Since the input capacity including the electrode is about 10 $\mu.\mu$.F. and does not vary much with electrode size, it comes out that a particle must lose 2 M.e.v. or more in the $\frac{dE}{dx}$ region. Thus the width of the first chamber is set by the path length over which a high energy (50 M.e.v.) alpha-particle loses 2 M.e.v. in 5 atmospheres of argon. On these grounds, the $\frac{dE}{dx}$ chamber must be 2 cm. wide, but there are other points to be considered before this can be settled finally.

Fig. (6) Sketch of the double ionisation-chamber showing it set up at 20° to the γ-ray beam.



Scale : ½ size

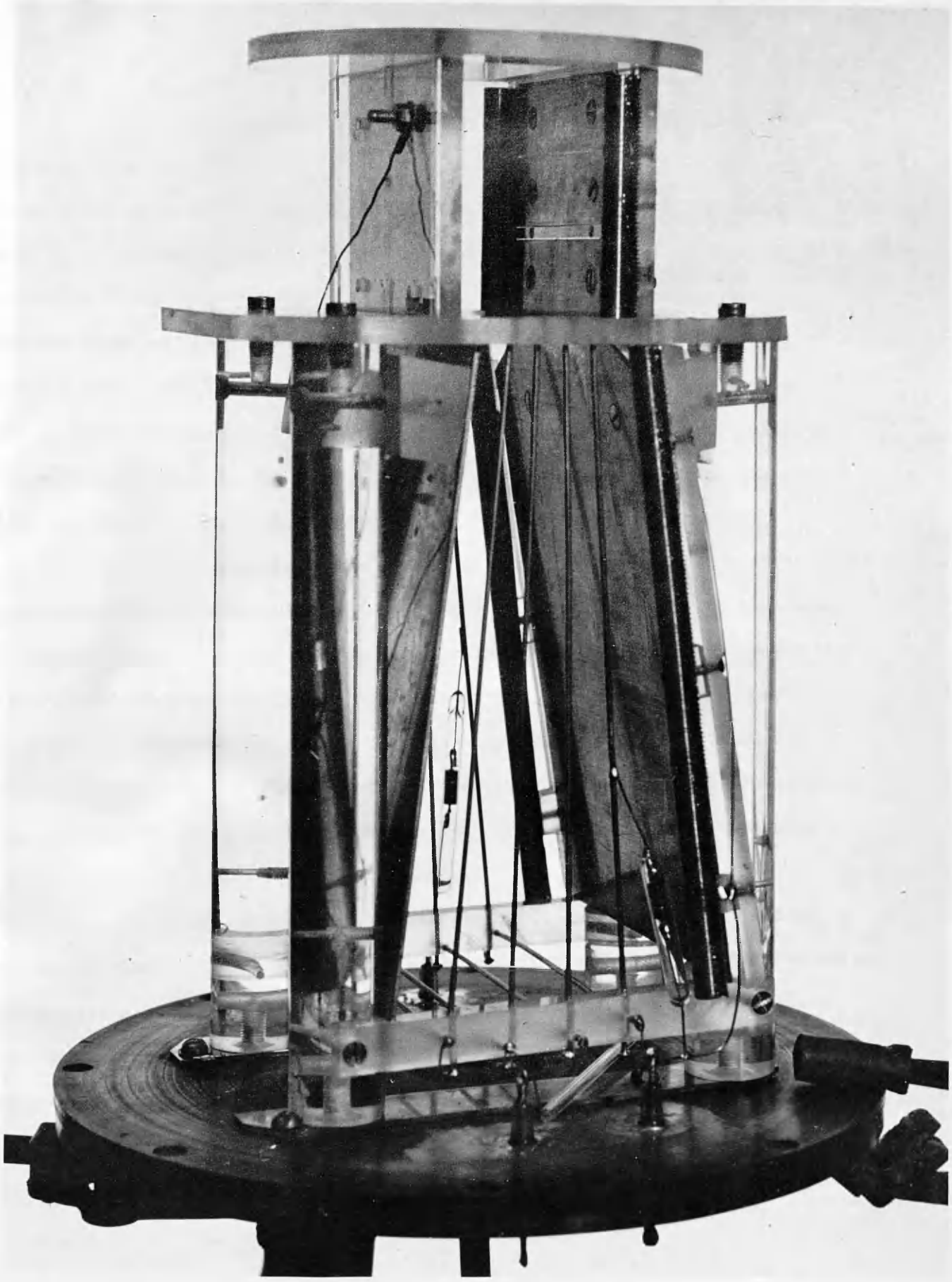


Fig. 7. The electrode structure of the double chamber.

For maximum range of sensitivity to low energy particles, the distance from the entrance window to the beginning of the "E" chamber must be as small as possible i.e. the width of the guard-ring plus "$\frac{dE}{dx}$" chamber must be a minimum. Setting ± 1% as the greatest loss in resolution due to curvative of the electric field between the plates, it was calculated that the optimum sizes of the two parts, viz. guard-ring and $\frac{dE}{dx}$ chamber, are each about 2 cms. The analysis of the curvative of the field was based on a method described by Jeans[10] for the edge effect between two semi infinite condenser plates. In the present case a factor 2 was allowed for the fact that the width of the plates is comparable with their distance apart.

Further uncertainty in the $\frac{dE}{dx}$ measurement is due to the statistical fluctuation in the energy lost by the particles by collisions with the atoms of argon. Rossi[11] has treated this problem theoretically. He uses Rutherford's formula for the collision cross-section of an ionising particle in a gas and computes the probability of the particle being scattered out of a given energy range. The statistical distribution of this quantity gives the uncertainty of our energy measurements. Putting in figures appropriate to the present case yields the following:-

An alpha-particle of initial energy 20 M.e.v. will lose energy in the $\frac{dE}{dx}$ chamber liable to a 1.0% statistical fluctuation. The corresponding figure for a 50 M.e.v. particle is 2·3%. These values have been calculated for typical conditions of the apparatus (5 atmospheres pressure of argon). Because of the finite acceptance aperture of the collimator and detector, the particles do not all travel parallel to the chamber axis. This introduces an uncertainty of about ± 1% in the $\frac{dE}{dx}$ measurement.

The above analysis of uncertainty in energy measurement is summarised in the following table (alpha-particles only have been considered but the values will be similar for He^3 particles)

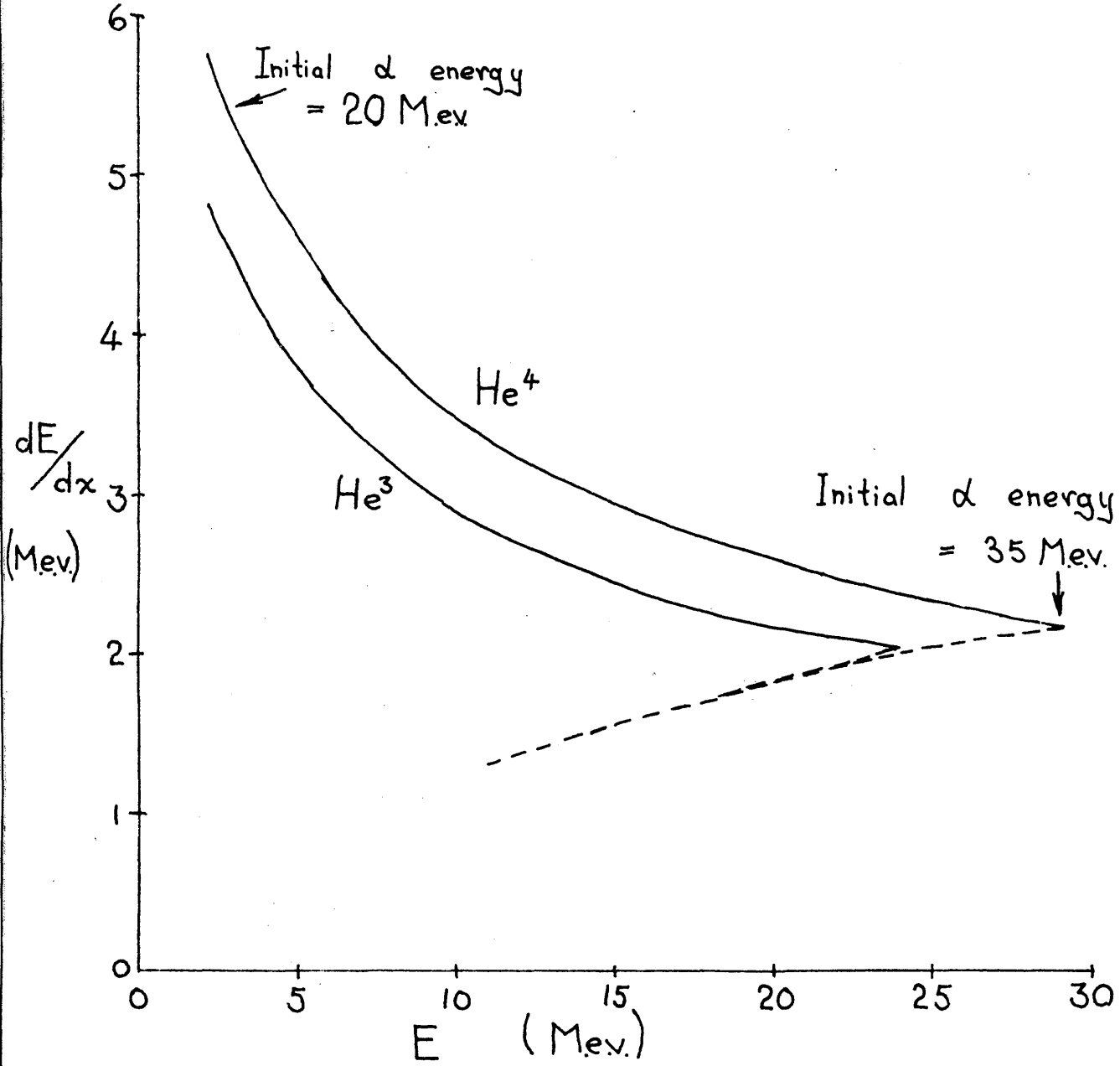
Initial α-particle energy	Collimation error	Curvature of field loss	Statistical Uncertainty	Amplifier noise	Total $\frac{dE}{dx}$
20 M.e.v.	1%	1%	1%	2%	5%
50 M.e.v.	1%	1%	2·3%	5%	9·3%

A similar analysis on the E region of the ionisation chamber shows that this favours high energy particles since they stand well above amplifier noise. There is no loss of resolution here due to curvature of the field nor to collimation error and the statistical uncertainty is the same as before. Nothing has been allowed for any effect that may result from the divergence of the electrodes in the second part of the "E" chamber.

Thus, in conclusion, this analysis indicates that over the range of initial partical energies 20 - 50 M.e.v. the resolving power of the double chamber will be better than ± 10%. This (see Fig. 8) is adequate to distinguish between mass 3 and mass 4 particles.

The diagram (Figs. 6 and 7) shows in detail the construction of the double ionisation chamber. The grid has the effect of shielding the collector electrodes from the electrostatic field of the positive ions. Wilkinson[12] discusses the design of gridded ionisation chambers and the present design is based on his treatment. The grid is made from wire 0·002" diameter spaced 50 to the inch. According to Wilkinson, such a grid should collect only 1·5% of the electrons incident on it and, with the field between the grid and collector about twice the main field, there should be negligible induction of charge from the positive ions. Some uncertainty arises from the divergence of the plates

FIG. 8



Theoretical plots of the $^{dE}/_{dx}$ pulse height as a function of the height of the E pulse for He^3 & He^4 particles under the conditions of the experimental runs. (Inter-capacity effect included)

but on the grounds that the first part is the more important the design here was made optimum.

To improve the uniformity of the field at the edge of the 'E' chamber, wires at intermediate potentials were mounted at positions clearly visible in Fig. 7.

If the 'E' chamber had been made to follow the first one immediately an intercapacity of about 15 $\mu\mu$F. would have resulted. When a high energy ($\sim$ 50 M.e.v.) particle passed through such an arrangement the pulse induced on the $\frac{dE}{dx}$ electrode from the E electrode due to the intercapacity would have been about twice the size of the proper $\frac{dE}{dx}$ pulse. While account could fairly easily have been taken of this effect, the resolving power of the device would have been reduced. Thus a narrow 3 m.m. spacer electrode was placed between the collectors (see Figs. 6 and 7). With this the intercapacity was only 2 $\mu\mu$F. and the induced pulse about 25% of the proper one.

(d) The electronics

The pulses from the ionisation chambers were passed through two identical channels of electronic units, which will now be described, and finally fed to a cathode ray tube on which recorded particles gave rise to bright-up spots. These were photographed.

The collector electrode was connected directly to the input grid of 1008 H.F. head amplifier (Voltage gain : 100 Band width : 3Mc/s). The circuit was modified so that the pulses decayed with 10 μ sec. time constant. This amplifier fed via a long cable from the synchrotron beam room to the apparatus room, into a pulse shaping unit. This consisted of a shorted lumped constant delay line which clipped the pulses

to 2 μ.s. The 16 elements of this line were very carefully matched so that there was less than 1% distortion of a square shaped pulse. A cathode follower circuit simplified the termination of the line in a matched 1000 Ω load.

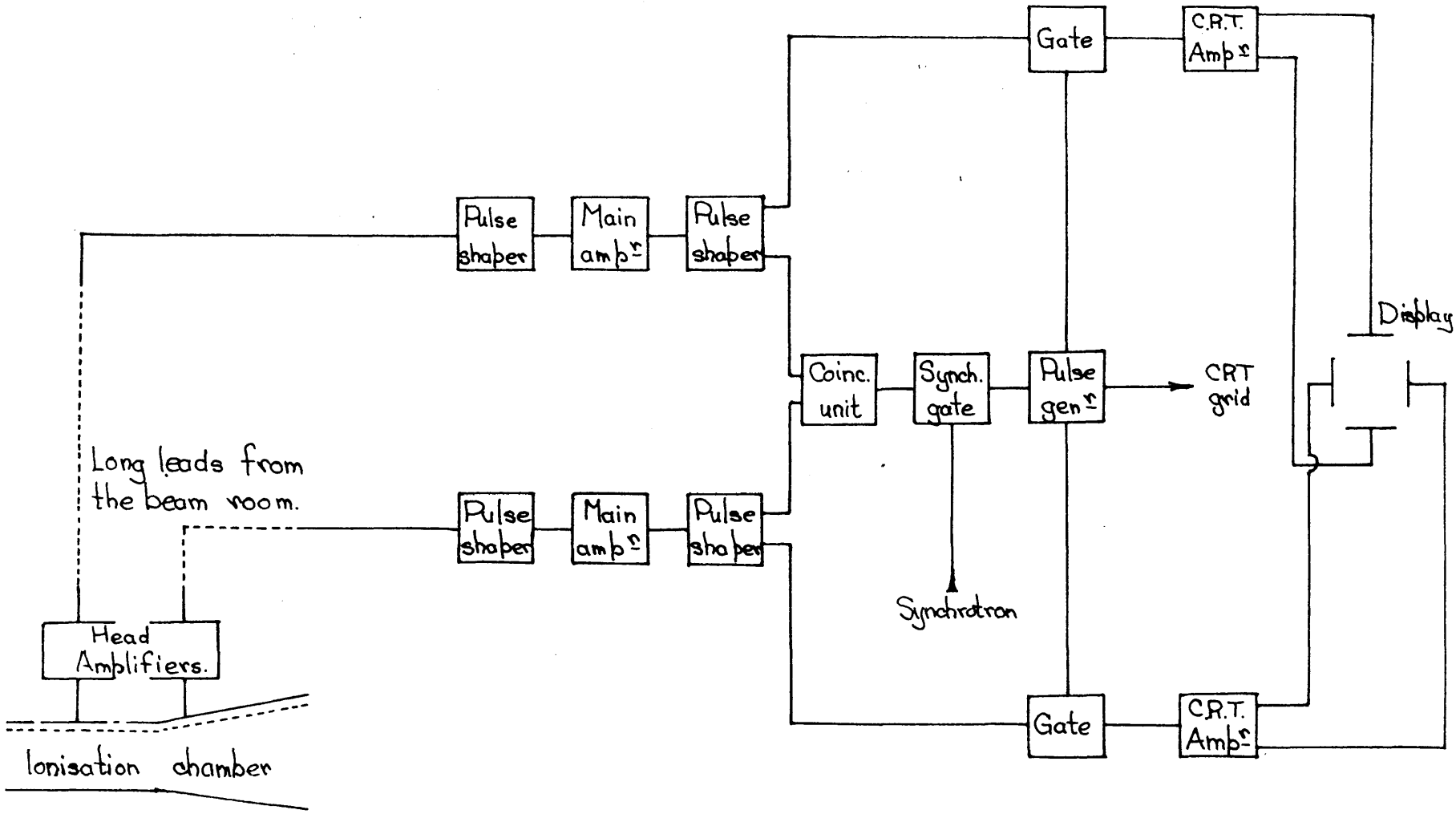
The shaped pulses were passed to the main 1008 amplifier from which they went to a second similar pulse shaper. This second clipping circuit was found useful in reducing the pile-up effect due to the electron back-ground in the detector.

The shaped pulses from the two channels now fed a coincidence unit of 4 μ.sec. resolving time which, if the two pulses were in coincidence, opened gates and passed the same shaped pulses into pulse amplifiers connected directly to the X and Y deflection plates of the cathode ray tube. At the same time a positive pulse was passed to the grid of the tube so that a bright-up spot was caused. A block diagram of the circuit is reproduced (Fig.9).

(e) Resolving power measurements

Before the apparatus was moved into the synchrotron beam, a series of experiments were done to check that the resolving power was within the limits predicted. 5·6 M.e.v. alpha-particles from the decay of polonium were used for this purpose. The same sources were used to calibrate the apparatus by a method to be described later. They were mounted on the negative electrodes of the ionisation chambers and were only weakly collimated so that the alpha-particles travelled approximately parallel to the chamber field. With this arrangement, the tests were sensitive only to effects due to amplifier noise and tended to give pessimistic results due to absorption in the sources.

FIG. 9. Block diagram of the electronic circuit.



The resolving powers measured in this way were for the

$\frac{dE}{dx}$ chamber $\pm$ 3%

and for the E chamber $\pm$ 6%

(Measured as the mean spread in pulse height as recorded on a multi channel kick-sorter). To meet the design requirements, the resolving power of the $\frac{dE}{dx}$ chamber for 5·6 M.e.v. particles would have to be $\pm$ 2%. The factor of about 2 between the chambers is due to the capacity of the E collector being about twice that of the $\frac{dE}{dx}$ collector (the measured values being about 70 and 32 $\mu\mu$F. respectively).

The measurements just described were made with the gas pressure such as to stop the particles completely in crossing the chamber (pressure $\sim 1\frac{1}{2}$ atoms of argon with 10% of methane). No detectable change in pulse height could be found after a period of 20 hours since filling the chamber with gas.

A measurement of the collection time of electrons in the chambers was done as a further check on the operation of the chamber. Extensive measurements of electron mobilities in various gas mixtures have been done by English and Hannah[13]. They took very great care to purify the gases used and found for a field to pressure ratio of 0·11 volts/ cm./m.m. of Hg. that the electron mobility was $\sim$ 6 cms/μ sec. in a 10% methane to argon mixture. The mobility decreased slightly for higher fields.

Using a high speed "Tektronix" oscilloscope with a delay we were able to observe the rise time of the pulses from the chambers. With the same field to pressure ratio and with the pressure adjusted so that the alpha particles passed right across the chamber before coming to rest,

a pulse rise time corresponding to a mobility of 3 cm./μ.sec. was measured. There was no improvement at larger fields. In view of the greater care taken in purifying the gas by English and Hannah and the comparative crudeness of our measurement, this agreement is probably as good as can be expected. To reduce any effects due to the build-up of impurities, the chambers were normally run with a field to pressure ratio of about 0·2 volts/cm./m.m. Hg. (as measured at the parallel part of the chamber).

3. EXPERIMENTS IN THE SYNCHROTRON BEAM

(a) Setting up and the experiments

It was found necessary, in order to avoid spurious pulses originating in the synchrotron circuit, to include a gating circuit which allowed pulses to be recorded only while the beam was present and, by earthing the apparatus at only one point, to eliminate "earth loops". Even with these precautions, a few large sharply rising pulses broke through the coincidence unit and caused spurious bright-up spots to be recorded (see Fig. 10 which is reproduced from a typical photograph and took $3\frac{1}{2}$ hours to expose). The large number of spots near the origin are probably mostly due to singly charged particles (see Fig. 4.).

Also on this photograph the calibration spots are clearly visible. These were due to the polonium alpha sources already mentioned. The spots were produced on the photograph by shortening the in-puts to the coincidence unit so that single pulses in either channel caused bright-up spots. To guard against the possibility of spots appearing in the centre of the screen during calibration, each deflector plate was earthed in turn. For the calibration of the E channel, the gain of the amplifier in the channel was increased by a known amount so that the 5·6 M.e.v. particles gave a reasonable deflection. There was no change necessary in the $\frac{dE}{dx}$ channel.

In this way, each photograph included a permanent record of the gain of the electronic circuits. The calibration spots also provided a means of inter-relating the photographs. Unfortunately, since the Po α 's were completely stopped in the ionisation chambers, the calibration did not in any way give an indication of the gas pressure. This was

measured independently using a mercury manometer.

(b) Analysis and Results

Once a series of about a dozen photographs had been exposed in the way described, they were analysed. The method of analysis took into account the slight curvature of the axes as photographed (see Figs. 10 and 11). The particle energy was computed by comparison with the calibration points and from the formula due to Livingston and Bethe[14] for the energy lost by charged particles in an ionising medium. The effect of the intercapacity between the collector electrodes was allowed for after this had been carefully measured.

In the first place, the spots had to be identified as due to He^3 or He^4 particles. This was done by dividing the region into zones separated by lines corresponding to sub-integral mass numbers (see Fig. 11). The spots in each zone were counted and on this basis the histograms of Fig. 12 plotted. From these, it is clear that a relatively successful separate identification of He^3 and He^4 particles has been achieved. The experimental uncertainty as measured from the width of the He^3 peak at 90° (lab.) is about $\pm \frac{1}{4}$ mass units.

While the above is the main result to be reported in this thesis, it is tempting to record also a preliminary estimate of the reaction cross-sections. These are (for an alpha-particle centre of mass angle = 90°).

Mean γ energy	268 M.e.v.	$= (16{\cdot}3 \pm 3{\cdot}7) \times 10^{-30}$
	282	$(13{\cdot}7 \pm 1{\cdot}8)$
	303	$(6{\cdot}8 \pm 1{\cdot}4)$
	315	negligible

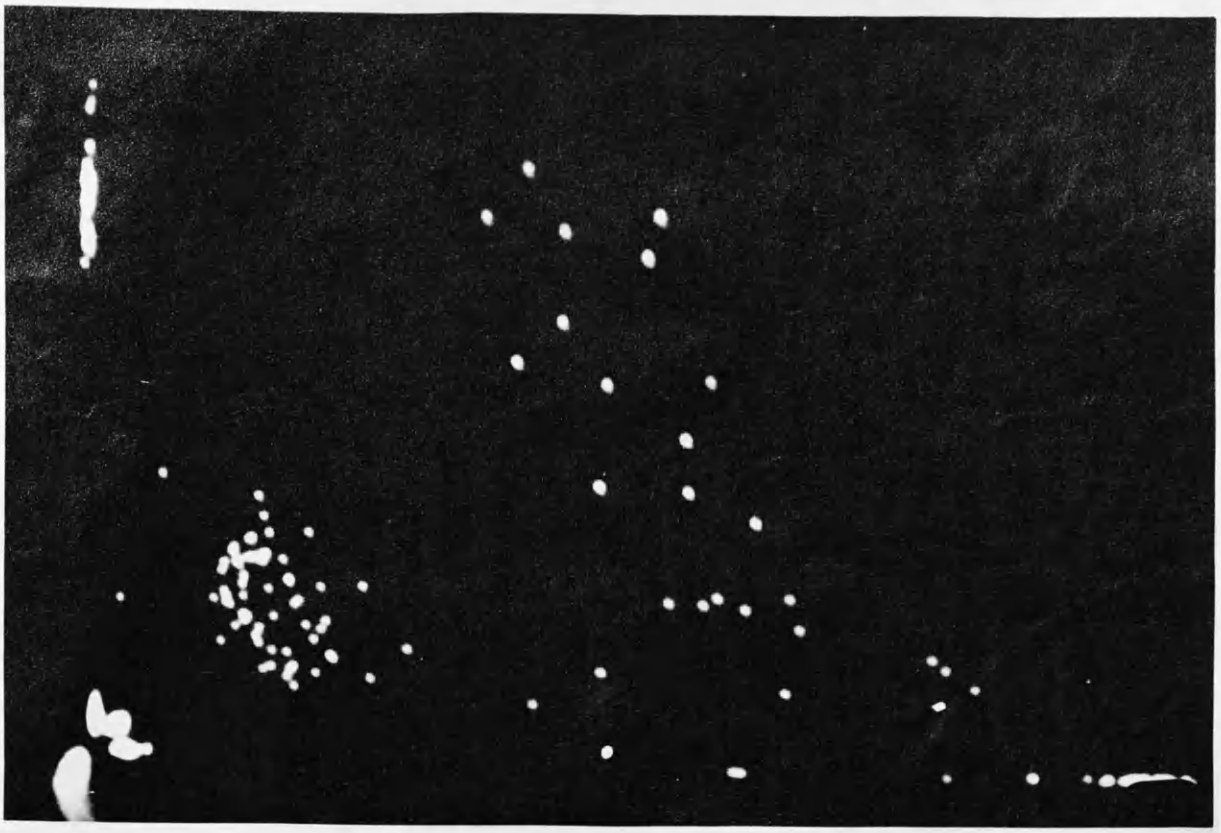


Fig. 10 A typical cathode-ray tube photograph.

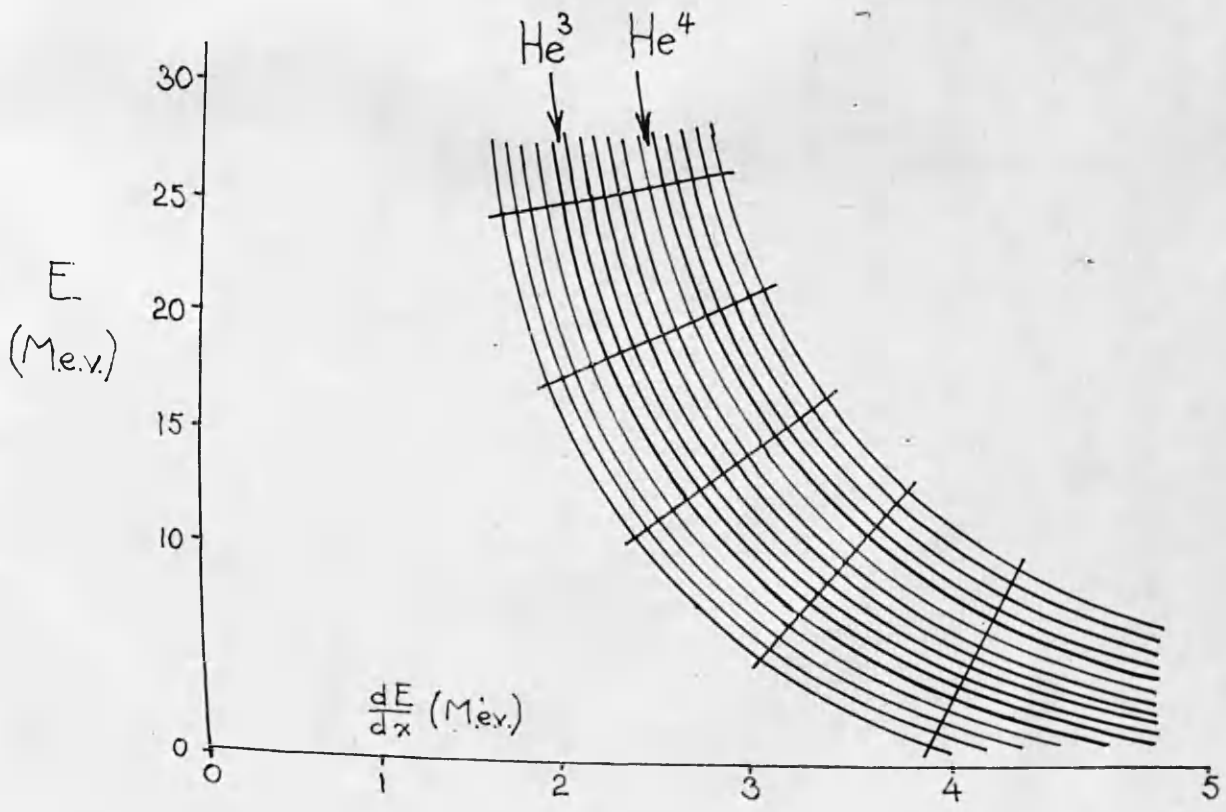
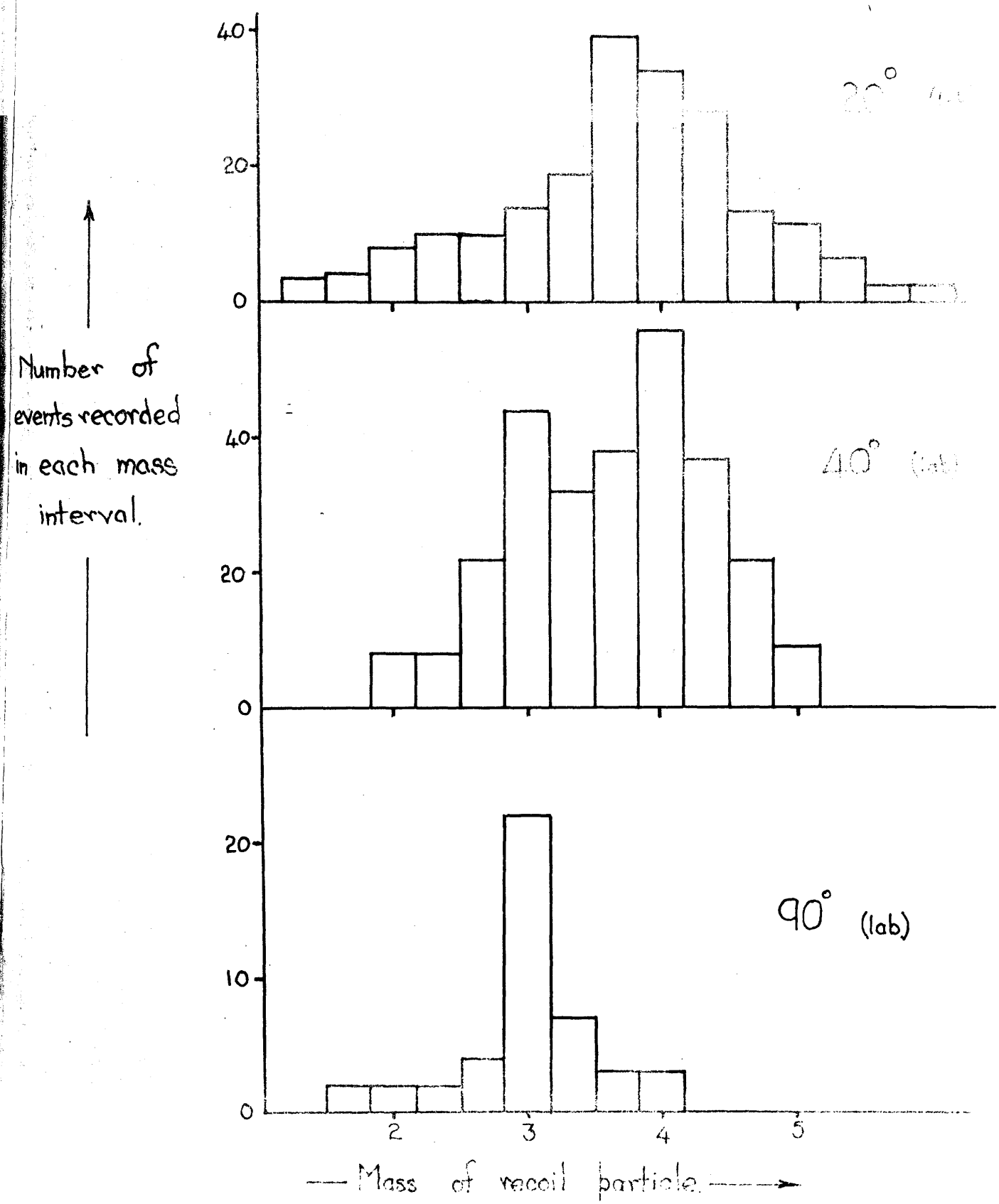


Fig. 11. Calculated curves used in analysing the photographs.

Fig. 12. Histograms showing result of analysis for three angles of dete



These have been plotted in Fig. 1 for comparison with de Saussure and Osborne's results as well as those predicted by Stoodley.

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