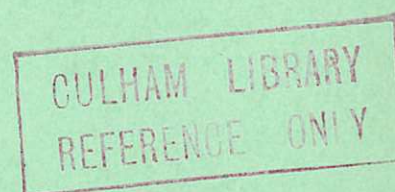


United Kingdom Atomic Energy Authority

RESEARCH GROUP

Report



AN APPARATUS FOR THE DETECTION AND ENERGY ANALYSIS OF FAST NEUTRAL ATOMS

D. W. MASON
J. M. S. SCHOFIELD

Culham Laboratory,
Culham, Abingdon, Berkshire

1966

Available from H. M. Stationery Office

THREE SHILLINGS NET

© - UNITED KINGDOM ATOMIC ENERGY AUTHORITY - 1966
Enquiries about copyright and reproduction should be addressed to the
Librarian, Culham Laboratory, Culham, Abingdon, Berkshire, England.

U.D.C.
621.039.624
621.384.83

AN APPARATUS FOR THE DETECTION AND ENERGY
ANALYSIS OF FAST NEUTRAL ATOMS

by

D.W. MASON
J.M.S. SCHOFIELD

A B S T R A C T

The apparatus was constructed to measure the energy and time dependence of the flux of neutral atoms emitted, due to the process of charge exchange, from plasma contained in a magnetic mirror machine. As the momentum change of the ions in this process is negligible the energy measurements, which are made outside the trap are simply related to the distribution function of the plasma ions within it.

The atoms pass through a water vapour cell where approximately 6% are re-ionized. This fraction is electrostatically analysed and counted using a scintillation technique. Measurements of the ionization efficiency and the scattering losses in the water vapour cell are described.

C O N T E N T S

Page

PART I

PRINCIPLES OF THE APPARATUS

INTRODUCTION	1
APPARATUS	1

PART II

MEASUREMENTS OF IONIZATION EFFICIENCY IN THE WATER VAPOUR CELL

INTRODUCTION	7
PRINCIPLES OF MEASUREMENT	7
ACKNOWLEDGEMENTS	10
REFERENCES	10
APPENDIX	11

PART I

PRINCIPLES OF THE APPARATUS

INTRODUCTION

In magnetically confined laboratory plasmas that are not fully ionized plasma ions are lost from the containment region by the process of charge exchange. In this process the ions acquire electrons from the background gas and on becoming neutral are no longer affected by the magnetic field and so escape. Because of the small ratio of the electron mass to ion mass the momentum change of an ion in this process is negligible and the resultant flux of neutrals $F_0(\epsilon)$ per unit volume of plasma with an energy ϵ is simply related to the corresponding density distribution of ions $n_i(\epsilon)$ in the plasma by:

$$F_0(\epsilon) = - \frac{dn_i(\epsilon)}{dt} = n_i(\epsilon) \cdot n_0 \cdot \sqrt{\frac{2\epsilon}{M}} \cdot \sigma_{i0}(\epsilon) \quad \dots (1)$$

where M is the ion mass, n_0 the density of the background neutral gas and $\sigma_{i0}(\epsilon)$ the charge exchange cross section. When n_0 is constant the neutral flux is proportional to the ion density so that a measurement of $F_0(\epsilon)$ as a function of time gives a value of the containment time of the plasma.

The device to be described was constructed to measure the flux of neutral atoms emitted from plasma contained in a magnetic mirror machine, and to determine their energy.

APPARATUS

1. MODE OF OPERATION

The principal features of the apparatus are shown in Fig.1. Neutral atoms enter the apparatus via the connecting tube and are ionized by passing them through a cell containing water vapour. The ions leaving the water vapour cell are first deflected by curved electrostatic deflector plates and then energy analysed by retarding potential grids⁽¹⁾. The deflector plates provide crude energy resolution (no collimating slits are used) and deflect the ions clear of photons which are also emitted by the plasma and which would otherwise give rise to photo emission in the secondary electron scintillator used to detect the ions⁽²⁾. It is essential that the background pressure in the containment region is not appreciably increased by influx from the ionizing cell, otherwise the charge exchange losses would be enhanced by the presence of the instrument. This influx is

greatly reduced by the use of a condensable vapour* rather than a permanent gas in the ionizing cell; as a result an instrument of much greater aperture and sensitivity can be built. The water vapour in the cell is condensed on liquid nitrogen cooled surfaces: a cylindrical cold trap between the cell and the vacuum chamber ensures that water molecules lying only in the line of sight solid angle can flow back into the containment region.

2. DIMENSIONS

In order to minimise statistical fluctuations the device was designed to yield a high particle counting rate. The dependence of the counting rate R_C on the dimensions of the device is (see Section 4)

$$R_C \propto \frac{r^4}{(\ell_1 + \ell_2 + \ell_3 + \ell_4)^2} \quad \dots (2)$$

where $r, \ell_1, \ell_2, \ell_3, \ell_4$, are as indicated in Fig.1.

There are two restraints on the choice of dimensions. Thus the flux of water vapour streaming into the containment region must not exceed some limit W_{crit} if the background gas pressure is not to be significantly increased, and the water vapour pressure P in the electrostatic analyser must not exceed some critical pressure P_{crit} if electrical breakdown is not to occur. The value of W_{crit} depends on the pumping speed and base pressure in the plasma containment region. Thus if the base pressure is P_0 and the pumping speed S then

$$W_{crit} \ll P_0 S. \quad \dots (3)$$

The value of P_{crit} is independent of the apparatus on which the device is used. In the design calculations a figure of P_{crit} equal to 10^{-4} Torr was adopted. Since the mean free path of water molecules in the regions ℓ_1 , and ℓ_3 is large compared with the dimension of the device

$$\begin{aligned} W &\approx \frac{\bar{n}\bar{c}}{4} \frac{\pi r^4}{\ell_1^2} \quad \text{molecules/sec} & \text{where } n &= \text{water vapour density in cell} \\ & & \bar{c} &= \text{mean thermal speed} \quad \dots (4) \\ &\approx \frac{44.0p}{\ell_1^2} \frac{r^4}{\ell_1^2} \quad \text{Torr litres/sec} & p &= \text{water vapour pressure in cell in Torr.} \end{aligned}$$

Also

$$P \approx \frac{p r^2}{\ell_3^2} \text{ torr} \quad \dots (5)$$

(In calculating P it is assumed that after randomising in the detector the water vapour diffuses back to the cold trap where it condenses out).

* An apparatus very similar in principle to the one described here has been developed⁽³⁾ using a non-condensable gas to re-ionize the atoms. In order to limit the backflow of gas into the plasma the aperture of the apparatus must, as a result be small.

There is an optimum value h of the product* $p\ell_2$ of about 10^{-1} Torr cms for maximum ionization (see Part II).

Thus R_C may be maximised subject to the conditions

$$W_{\text{crit}} = \frac{44h}{\ell_2} \cdot \frac{r^4}{\ell_1^2} \ll P_0 S \quad \dots (6)$$

and

$$P = \frac{h}{\ell_2} \cdot \frac{r^2}{\ell_3^2} \leq P_{\text{crit}} \quad \dots (7)$$

In Appendix I it is shown that as a consequence of conditions (6) and (7) above, the counting rate R_C increases with the radius r and that an optimum value is obtained when the length ℓ_2 of the water vapour cell equals half the sum of the lengths ℓ_1 and ℓ_3 . The length ℓ_4 which comprises the deflector plate system, the electrostatic energy analyser and the distance between the plasma and the first cold trap should, as relation (2) indicates, be as small as possible.

Two fast neutral atom detectors have been constructed. The principal dimensions are given below.

Detector I		Detector II	
r	= 1.9 cms	r	= 0.64 cms
ℓ_1	= 101.5 cms	ℓ_1	= 19.0 cms
ℓ_2	= 10.2 cms	ℓ_2	= 9.2 cms
ℓ_3	= 40.7 cms	ℓ_3	= 9.2 cms
ℓ_4	= 114 cms	ℓ_4	= 90 cms

3. ION ENERGY ANALYSIS AND DETECTION

In order to use as large an aperture as possible electrostatic energy analysis is carried out by a system of grids rather than by a method employing particle optics which necessitates a well collimated beam and hence a small acceptance aperture. The analyser is shown in Fig.2 and operates as follows. Ions pass through the earthed grid g_0 and are decelerated by the positive potential V_1 applied to grid g_1 . Only those with sufficient energy to overcome this potential barrier pass through g_1 . The grid g_2 which is 50% transmitting and maintained at - 8 kV allows about half of these ions to pass into the region between g_2 and g_3 where they are decelerated by the potential V_3

* Since the water vapour from the cell penetrates a short distance into the cold traps the effective length ℓ_2^* of the cell is greater than its geometrical one. It may be shown that $\ell_2^* \approx (\ell_2 + \pi r)$. Since the value of h is not critical (see part II) this correction has been ignored.

applied to grid g_3 (the remaining half strike the front surface of g_2). Those ions with insufficient energy to pass through g_3 are reflected and strike the reverse side of g_2 giving rise to secondary electron emission. These electrons are accelerated by the -8 kV on g_2 and produce scintillations in the phosphor which is in optical contact with a photomultiplier. Thus the analyser detects ions in the energy range $Z_e V_1$ to $Z_e V_3$, where Z_e is the ionic charge.

4. COUNTING RATE

The particle counting rate R_C may be estimated from simple geometrical considerations together with a knowledge of the ionization efficiency δ in the water vapour cell and the detection efficiency k of the electrostatic energy analyser. Thus if z is the length of plasma in the line of sight of the device then from equation (1) the rate of neutral atom emission R_O from the volume $\pi r^2 z$ is

$$R_O = \pi r^2 z \cdot n_i \cdot n_o \langle \sigma_{io} V_i \rangle = \frac{\pi r^2 z \cdot n_i}{\tau} \quad \dots (8)$$

Where V_i is the ion speed, $\langle \sigma_{io} V_i \rangle$ is averaged over the particle distribution and τ is the charge exchange decay time.

The solid angle ω subtended at the plasma by the detector is

$$\omega = \frac{\pi r^2}{(\ell_1 + \ell_2 + \ell_3 + \ell_4)^2} \quad \dots (9)$$

So neutral atoms enter the detector at a rate F (assuming an isotropic source) given by

$$F = \frac{\omega}{4\pi} R_O = \frac{\pi r^4}{4(\ell_1 + \ell_2 + \ell_3 + \ell_4)^2} \cdot \frac{n_i z}{\tau} \quad \dots (10)$$

A fraction δ of these are ionized in the water vapour cell and if f is the fraction of these ions lying in the energy range of the electrostatic analyser then the counting rate R_C is given by

$$R_C = \delta f k F \quad \dots (11)$$

If t_r is the resolving time of the detection circuit then the percentage statistical fluctuations S.F. in the signal is

$$S.F. = \frac{100}{(R_C t_r)^{1/2}} \quad \dots (12)$$

For a plasma with $z = 10$ cms $n_i = 10^{11}/\text{cc}$ and $\tau = 1$ msec then since δ is approximately 0.06 (see Part II) and k approximately 0.25, detector I gives $R_C = 5.8 \times 10^7$ counts per second and S.F. = $\pm 13\%$ for $t_r = 1$ μsec and $f = 0.05$.

5. SIGNAL AMPLITUDE

Each ion that strikes the reverse side of g_2 produces about three secondary electrons⁽²⁾. These enter the phosphor with some 4 keV (since ≈ 4 keV is lost in the light tight aluminium coating on the phosphor). Approximately one photo electron is produced at the cathode of the photomultiplier for each keV of energy deposited in the phosphor⁽⁴⁾. Thus for a current gain in the photomultiplier of 10^7 each ion results in a final charge of about 1.9×10^{-11} coulombs at the output of the photomultiplier. For the example discussed in Section 4 above the mean output current I_{pm} is therefore

$$I_{pm} = 1.9 \times 10^{-11} \times 5.8 \times 10^7 = 1.1 \times 10^{-3} \text{ amps}$$

which develops about a volt across the 1 K Ω output resistance of the photomultiplier.

6. PROBING OF THE CONTAINMENT REGION BY THE WATER VAPOUR

Under certain conditions the stream of water vapour entering the containment region from the water vapour cell will produce a significant local enhancement of the background pressure P_0 although the overall flux of water vapour satisfies condition (6) of section 2. In this case the water vapour acts as a probe producing a locally high rate of charge exchange. This effect may be useful in cases where the background pressure is very low and is not known with certainty. Probing will occur if the water vapour pressure P_W on the line of sight of the device is comparable with the base pressure P_0 .

From kinetic theory (assuming the distance between plasma and the first cold trap to be small) it may be shown that

$$P_W = \frac{pr^2}{4\ell_1^2} \quad \dots (13)$$

also

$$W_{crit} = \frac{44 pr^4}{\ell_1^2} = \alpha P_0 S \quad \dots (14)$$

cf equation (6)

where $\alpha \ll 1$ (α is defined by equation (14))

hence

$$\frac{P_W}{P_0} = \frac{\alpha S}{176r^2} \quad \dots (15)$$

Thus the water vapour acts as a probe if

$$\frac{\alpha S}{176r^2} \gtrsim 1 \quad \dots (16)$$

When probing becomes significant the counting rate R_c is increased by a factor $(1 + \frac{\alpha S}{176r^2})$ over that given by equation (11). Thus if for example $\alpha = 0.1$ at a pressure P_0 equal to some specific value P_b and S equal to 10^3 litres/sec and $r = 1$ cm then

$$\frac{\alpha S}{176r^2} = 0.57$$

so that for base pressures $\gg P_b$ probing is not significant whilst for base pressures $\ll P_b$ probing is dominant in producing the fast neutral atom signal in the detectors.

PART II

MEASUREMENTS OF IONIZATION EFFICIENCY IN THE WATER VAPOUR CELL

INTRODUCTION

In the water vapour cell three atomic processes take place. Neutral atoms entering the cell are ionized by collisions with molecules of water vapour, the resulting fast ions are neutralised by charge exchange with water vapour: in addition scattering of both neutral atoms and ions occurs. If the water vapour constitutes a thick target, equilibrium is established between the first two processes and the particle beam suffers scattering losses only. Thus there is an optimum value h Torr. cm for the product of water vapour pressure and cell length at which the output from the cell will contain a maximum number of ions for a given incident neutral particle flux. The experiments to be described were carried out to determine h , and find the fraction δ of neutrals ionized. The scattering loss from the beam was also determined. Measurements of these quantities were made using both proton and atomic hydrogen beams incident on the water vapour cell.

PRINCIPLES OF MEASUREMENT

1. PROTON BEAM METHOD

A mono-energetic beam of protons was injected into the water vapour cell of detector I (see Part I) and the attenuation of the beam as a function of the water vapour pressure measured. It may be shown that in passing through the cell the ion beam is reduced in intensity by a factor $(\alpha\beta)_i$ where

$$(\alpha\beta)_i = \left[\frac{\sigma_{oi} + (\sigma_{io})e^{-\Sigma\sigma n\ell}}{\Sigma\sigma} \right] e^{-n\sigma_s\ell} \quad \dots (17)$$

σ_{io} = cross section for neutralisation of protons by water molecules

σ_{oi} = cross section for ionization of atomic hydrogen by water molecules

σ_s = cross section for scattering of protons and atomic hydrogen out of the beam

$\Sigma\sigma$ = the sum of the first two sections above

n = water vapour density

ℓ = thickness of water vapour target.

Thus by measuring $(\alpha\beta)_i$ as a function of n the relevant cross sections may be obtained.

In Fig.3 the experimental data obtained with a 3 keV proton beam is shown together with the theoretical curve predicted by equation (17). In view of the reasonable agreement it appears justified to assume for the purposes of calculating h and δ that the scattering cross sections for protons and atomic hydrogen are the same.

2. ATOMIC HYDROGEN BEAM METHOD

The proton beam was replaced by an atomic hydrogen beam of the same energy. The water vapour pressure in the cell was then varied and the amplitude of the ionized component of the emergent beam was measured. The fraction $(\alpha\beta)_0$ of the incident beam of neutrals emerging from the cell as ions is given by

$$(\alpha\beta)_0 = \left[1 - e^{-\Sigma \sigma n \ell} \right] \frac{\sigma_{oi}}{\Sigma \sigma} \cdot e^{-n \sigma_s \ell} \quad \dots (18)$$

A set of experimental and theoretical results is shown in Fig.4 where the same cross sections as those used for the incident proton beam experiment have been taken to obtain the theoretical curve from equation (18). Since however the magnitude of the incident neutral beam is not known the results have been normalised at the point indicated.

3. APPARATUS

An R.F. ion source⁽⁵⁾ supplied with hydrogen from a nickel leak was used to provide the ion beam. The energy of the ions was determined by the extraction voltage, no post acceleration being applied. The ions passed through a velocity filter* and then entered the fast atom detector via a differential pumping system (Fig.5). By using the velocity filter in conjunction with the energy analyser of the detector ions of a chosen energy and charge to mass ratio could be selected.

In order to produce an atomic beam the diffusion pump nearest the R.F. source was shut off, thereby increasing the background hydrogen pressure in that region sufficiently for a significant fraction of the ions transmitted by the velocity filter to be neutralised. In order to distinguish neutrals produced in this way from those originating in the region between the source and the velocity filter a small sinusoidal voltage was

* The velocity filter⁽¹⁾ consisted of an electric field crossed with a magnetic field, both fields being orientated normal to the trajectory of the ions from the source. The filter transmitted ions whose velocity v satisfied the condition.

$$v = \frac{\int E \times d \ell}{\int H \times d \ell} \quad (\text{The integrals are those of the electric and magnetic field taken over an ion trajectory.})$$

superimposed on the D.C. voltage applied to the velocity filter to produce a modulated output. The unneutralised component of the beam was removed by means of a permanent magnet placed between the velocity filter and the water vapour cell.

4. RESULTS

Measurements were made at beam energies of 1.8, 2.2 and 3 kV. Within the experimental error h and δ did not vary significantly over this energy range. It will be noted from Fig.4 that the water vapour pressure in the cell for optimum ionization of incident neutrals is not critical in the range 13 mTorr to ~ 20 mTorr. The ionization efficiency δ is $5.4 \pm 1\%$ and a value of 6% has been adopted in calculating the sensitivity of the detectors (see Part I).

ACKNOWLEDGEMENTS

The authors' thanks are due to D.R. Sweetman for much helpful information obtained by him in the course of constructing and operating a similar device to the one described here. Thanks are also due to G.M. McCracken for the loan of an R.F. ion source and to P. Avivi who did some of the initial calculations. Finally it is a pleasure to thank G. Francis for his encouragement and suggestions in the preparation of the manuscript.

REFERENCES

1. MASON, D.W. An electrostatic ion-energy analyser. J. Nucl. Energy, Pt C, vol.6, no.6, 1964. pp.553-558.
2. RIDLEY, B.W. A large aperture detector for slow positive ions. Nucl. Instr. and Methods, vol.14, no.2, December, 1961. pp.231-236.
3. AFROSIMOV, V.V. and others. Method of investigation of the flux of atoms emitted by a plasma. Sov. Phys.-Tech. Phys., vol.5, no.12, June, 1961. pp.1378-1388.
4. OWEN, R.B. Private communication.
5. THONEMANN, P.C. and others. Performance of a new radio-frequency ion source (Letter). Proc. Phys. Soc., vol.61, pt.5, 1 November, 1948. pp.483-485.

APPENDIX I

In order to find the optimum lengths ℓ_1 , ℓ_2 and ℓ_3 for any given radius r equations (10), (6) and (7) are differentiated with respect to ℓ_2 ; the dimension ℓ_4 being taken as fixed.

Then

$$\frac{1}{F} \left(\frac{\partial F}{\partial \ell_2} \right)_r = \frac{-2 \left(\frac{\partial \ell_1}{\partial \ell_2} + 1 + \frac{\partial \ell_3}{\partial \ell_2} \right)}{\ell_1 + \ell_2 + \ell_3 + \ell_4} \quad \dots (1a)$$

$$0 = \frac{2}{\ell_1} \left(\frac{\partial \ell_1}{\partial \ell_2} \right) + \frac{1}{\ell_2} \quad \dots (2a)$$

$$0 = \frac{1}{\ell_2} + \frac{2}{\ell_3} \left(\frac{\partial \ell_3}{\partial \ell_2} \right) \quad \dots (3a)$$

From equations (1a), (2a) and (3a) $\left(\frac{\partial F}{\partial \ell_2} \right) = 0$ if $\ell_2 = \frac{\ell_1 + \ell_3}{2}$

Also $\left(\frac{\partial F}{\partial \ell_2} \right)_r$ changes sign from + ve to - ve as ℓ_2 increases through this value hence it gives a maximum for F .

Using this result together with equations (6) and (7) ℓ_1 , ℓ_2 and ℓ_3 may be calculated as functions of r for any selected values of W_{crit} and P_{crit} .

Thus

$$\ell_1 = \left(\frac{44 P_{crit}}{W_{crit}} \right)^{\frac{1}{2}} \cdot r \cdot \ell_3$$

and if

$$\ell_2 = \frac{\ell_1 + \ell_3}{2}$$

$$\ell_1 = \left(\frac{88 h r^4}{\left(1 + \frac{1}{\gamma r} \right) W_{crit}} \right)^{\frac{1}{3}} \quad \dots (4a)$$

where

$$\gamma = \left(44 \frac{P_{crit}}{W_{crit}} \right)^{\frac{1}{2}} \cdot r$$

$$\ell_3 = \left(\frac{2 h r^2}{(1 + \gamma r) P_{crit}} \right)^{\frac{1}{3}} \quad \dots (5a)$$

Thus for example if

$$\begin{aligned} h &= 0.1 \text{ Torr cms} \\ r &= 1.0 \text{ cms} \\ \alpha &= 0.1 \\ P_o &= 10^{-6} \text{ Torr} \\ S &= 10^3 \text{ litres/sec} \\ P_{\text{crit}} &= 10^{-4} \text{ Torr} \end{aligned}$$

Then

$$\begin{aligned} W_{\text{crit}} &= 10^{-4} \text{ Torr litres/sec} \\ \gamma &= 6.64 \end{aligned}$$

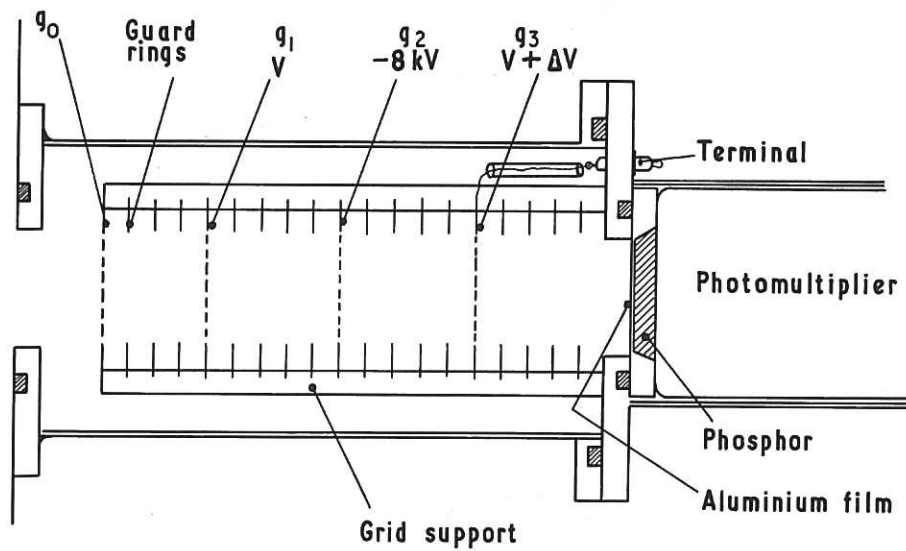
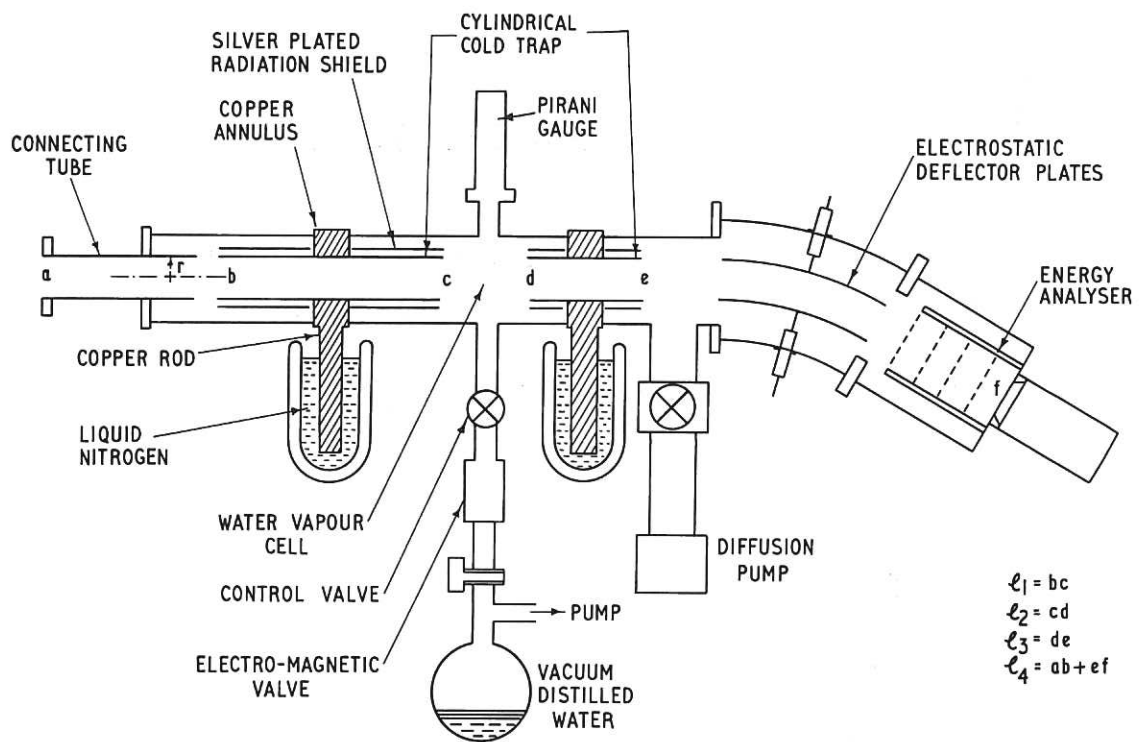
Hence

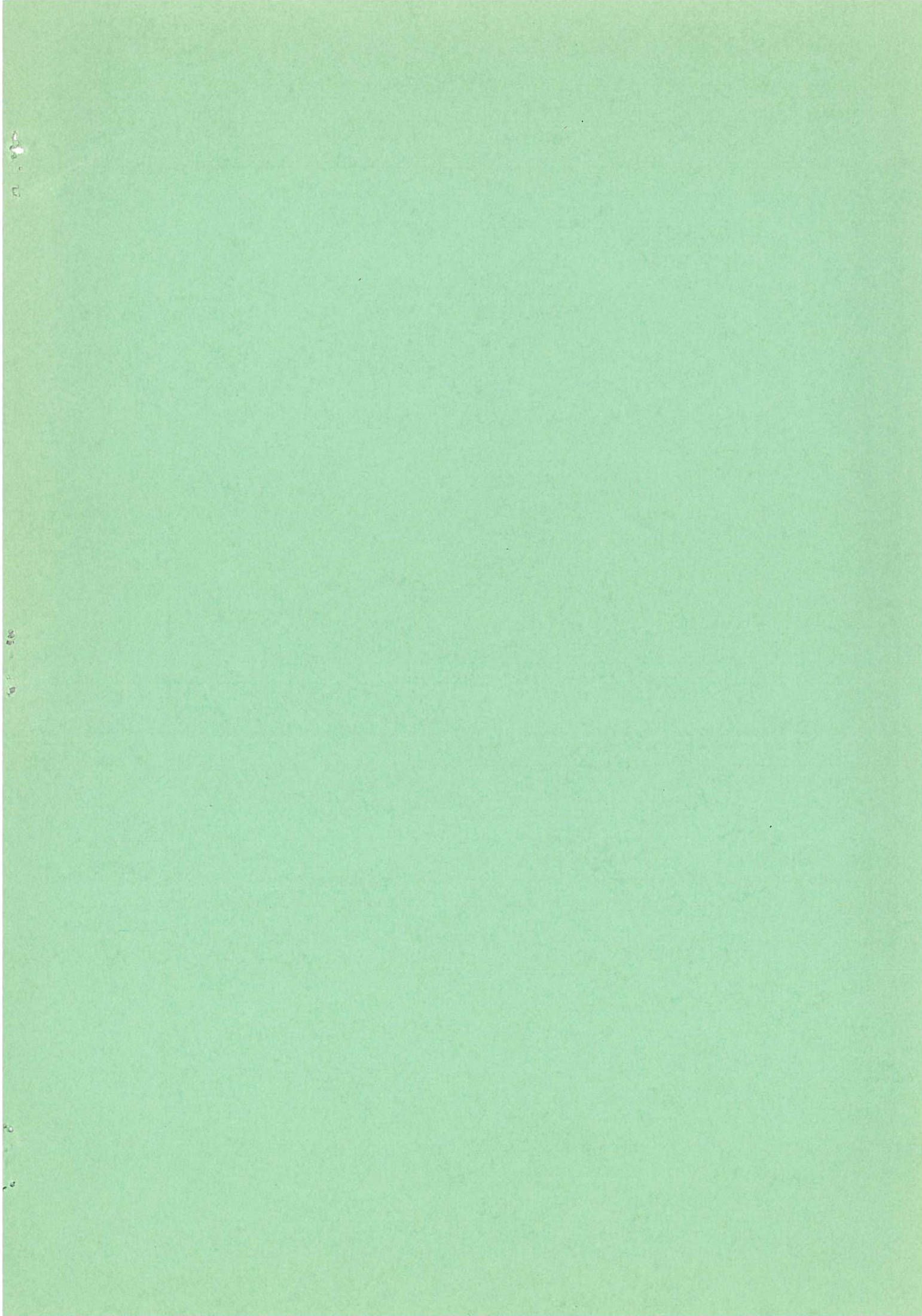
$$\begin{aligned} \ell_1 &= 42 \text{ cms} \\ \ell_2 &= 24.2 \text{ cms} \\ \ell_3 &= 6.4 \text{ cms} \end{aligned}$$

To find the optimum value for r equation (10), (4a) and (5a) are differentiated with respect to r . Then using the relation that $\ell_2 = \frac{\ell_1 + \ell_3}{2}$ the following result is obtained

$$\frac{1}{F} \left(\frac{\partial F}{\partial r} \right)_{\ell_4} = \frac{4}{r} - \left[\frac{\ell_1}{r} \left(4 + \frac{1}{1 + \gamma r} \right) + \frac{\ell_3}{r} \left(2 - \frac{\gamma r}{1 + \gamma r} \right) \right] \frac{1}{\ell_1 + \ell_2 + \ell_3 + \ell_4}$$

The R.H.S. is + ve for all γr hence F increases with r .





Available from
HER MAJESTY'S STATIONERY OFFICE

49 High Holborn, London, W.C.1
423 Oxford Street, London W.1
13a Castle Street, Edinburgh 2
109 St. Mary Street, Cardiff
Brazennose Street, Manchester 2
50 Fairfax Street, Bristol 1
35 Smallbrook, Ringway, Birmingham 5
80 Chichester Street, Belfast

or through any bookseller.

Printed in England