THICK MAGNETIC ELECTRON LENS βETA-RAY SPECTROMETER, ITS THEORY, CONSTRUCTION AND ITS APPLICATION FOR THE MEASUREMENT OF ENERGY SPECTRA.

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PREFACE

In this work, a new βeta ray spectrometer is used for the measurement of Energy Spectra. This apparatus, like the rest of this type, is based on the selective focusing action of a magnetic lens on βeta rays of heterogeneous velocity. It differs, however, from them in size, shape and constructional details.

The spectrometer is designed on the geometrical model of electron trajectories in a standard field, obtained from the determinants of their parameters and radial displacements. The design admits about 5% of 4π in solid angle of βeta rays into the field of selective focusing action. It is because of these essential considerations in its construction that the apparatus is expected to have high efficiency and consistently adequate resolving power. The usefulness and advantage, the expected efficiency and resolving power are proved and verified by the results of experiments.

PREFACE

(Contd.)

In concluding the preface, I take the privilege of offering my best thanks to Professor James Chadwick, F.R.S., for the encouragement and guidance he has given me. Also my thanks are due to Dr. M. H. L. Pryce for the suggestions he gave at the beginning of this work. I owe much to all the colleagues with whom I have had useful discussions.

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CHAPTER I

Thick Magnetic Electron Lens Beta Ray Spectrometer

1. Introduction.

Magnetic Electron Lenses are usually used for concentrating electron beams in electron diffraction apparatus and in cathode ray oscillographs and for the production of enlarged images of objects emitting electrons in electron microscopes.

Kapitza[1] appeared to have suggested that a large solenoid could be used as an electron lens to focus βeta rays of determinate energy on some kind of recording device. An instrument involving this principle was built by Tricker[2]. Afterwards Klemperer[3] has constructed an electron lens type spectrometer making use of the selective focusing action of a flat coil on βeta particles of heterogeneous velocity.

Davies and Oceallaigh[4] , Cosslett[5] and M. Deutsch[6] have subsequently improved the flat coil type mainly modifying lens apertures and stops which arrest unresolved rays along the axis. The resolving power of an electron lens βeta ray spectrometer is determined by the aberrations of the electron lens as well as by the form, sise and position of the βeta ray source, recording device and focusing system. In these subsequent spectrometers, improvements were mainly affected either by lens aperture or by the aperture of the recording device. In these models, the magnetic electron lenses being thin, deviations from homogenity should be exceptionally great due to the end effect, and therefore the influence of aberrations should be considerable.

In thick magnetic electron lenses, the field is axially symmetrical and very nearly homogeneous, and the influence of aberrations in such fields is expected to be reduced to a satisfactory degree[7]. C. M. Witcher[8] made use of a thick magnetic electron lens as a βeta ray spectrometer. In this model, as in all other former types, the distance between the point of departure and the focal point of βeta particles was long and this great length with the relatively small diameter of the body of the spectrometer could be detrimental to the intensity or to the efficiency. Owing to the long focal distance, only a comparatively small percentage of 4π in solid angle could be employed in the thick magnetic electron lens spectrometer designed and constructed by Witcher[8]. With this model, therefore, only 1.5% efficiency could be obtained.

2. Motion of electrons in axially symmetrical magnetic fields.

In the study of the energy spectra of artificial radio-active elements, it is often difficult to obtain sufficiently strong sources. With weak sources, it is desirable to have a spectrometer of comparatively high efficiency with adequate resolving power. It is with this object in view that a thick magnetic electron lens βeta ray spectrometer has been designed, constructed and made use of for the energy spectrometrical study with great advantage. The design of the construction is based upon the considerations of the motion of electrons in magnetic fields and of the geometrical shape of electron trajectories in axially symmetrical magnetic fields.

To summarize these considerations of an analysis of the magnetic electron lens phenomenon on which the principle of the design of the spectrometer is based, let it be supposed that a narrow beam of electrons leaves a point source lying on the z-axis of a cylindrical co-ordinate system z, r, φ, that the field H whose deviation from homogeneity is negligible, lies along the axis of an image forming system and is devoid of φ component and that the magnetic field H is equal to the curl of another vector A such that

$$H = \text{curl } A.$$

As A_z is assumed to be lying along the axis of an image forming system, the axis is encircled by A. A_φ is the tangential component of A and the vector itself is along the tangent. Hence $A_\varphi = A$. Then, there being no other components, $A_z = A_r = 0$. Let it also be assumed that the electrostatic potential is axially symmetrical. If this potential be denoted by V and the ratio e/m of the electrostatic charge to the mass of the individual electrons by λ, the electron motion may be expressed by

$$r = -\frac{\partial}{\partial r}\left(\frac{1}{2}\lambda^2 A^2 + V\right) \qquad \text{I}$$

$$z = -\frac{\partial}{\partial z}\left(\frac{1}{2}\lambda^2 A^2 + V\right) \qquad \text{II}$$

$$V_\varphi = \lambda A. \qquad \text{III}$$

Let the field along the z-axis which is homogeneous and vortex free be H_0 (z,r=0). Suppose the beam of electrons is quite narrow and therefore with small r. Then from the expression of the field distribution, we have

$$A = \frac{1}{2} r H_0(z) - \frac{r^3}{2^2 \cdot 4} H_0''(z) + \frac{r^5}{2^2 \cdot 4^2 \cdot 6} H_0^{IV}(z) - \cdots \qquad \text{IV}$$

and the electrostatic potential V at any point (z r) within the electron optical system,

$$V = \gamma(z) - \frac{r^2}{2^2} \gamma_2(z) + \frac{r^4}{4^2} \gamma_4(z) - \cdots \qquad \text{V}$$

with

$$\left.\begin{aligned} \gamma_2(z) &= \gamma''(z) + a_0(z), \\ \gamma_4(z) &= \frac{1}{2^2}\gamma^{IV}(z) + \frac{1}{2^2}a''(z) - a_2(z), \\ &\ldots\ldots\ldots\ldots \end{aligned}\right\} \quad \ldots \quad \text{VI}$$

where $\gamma(z)$ is the electrostatic field along the axis, the differentiations being with respect to z, $a_0(z)$, $a_2(z)$ etc. are the coefficients of powers of r of space charge S_c,

$$4\pi S_c = a_0(z) + r^2 a_2(z) + \qquad \text{VII}$$

If the values of A and V given by the expansions IV and V be substituted for A and V in the expressions I and II, we have equations of motion of the form,

$$\ddot{r} = -r\left[\frac{\lambda^2}{4}H_0^2(z) - \frac{\lambda}{2}\gamma^2(z)\right] + r^3\left[\frac{\lambda^2}{8}H_0(z)H_0''(z) - \frac{\lambda}{4}\gamma_4(z)\right] + \cdots \qquad \text{VIII}$$

$$\ddot{z} = -\lambda\gamma'(z) - r^2\left[\frac{\lambda^2}{4}H_0(z)H_0' - \frac{\lambda}{4}\gamma_2'(z)\right] + \quad \cdots \quad \cdots \qquad \text{IX}$$

In the case of a narrow beam of electrons, since the terms involving all powers of r above the first may be neglected, the equations of motion VIII and IX may be written as

$$\ddot{r} = \frac{d^2r}{dz^2}\dot{z}^2 + \frac{dr}{dz}\ddot{z} = -r\left[\frac{\lambda^2}{4}H_0^2(z) - \frac{\lambda}{2}\gamma_2(z)\right] \qquad \text{X}$$

and

$$\ddot{z} = \lambda\gamma'(z), \text{ or on integration } \dot{z}^2 = \omega^2 - 2\lambda\gamma(z), \qquad \text{XI}$$

where ω, the constant of integration is identical to the longitudinal component of electron velocity, ($\omega = v\cos\alpha$, being the direction of the particle with respect to the lines of force and v the velocity of electrons.)

Now if the values given by the expression XI be substituted for $\dot{z}$ and $\ddot{z}$ in the equation X, we obtain

$$\frac{d^2r}{dz^2}\left[\omega^2 - 2\lambda\gamma(z)\right] - \frac{dr}{dz}\lambda\gamma'(z) = -r\left[\frac{\lambda^2}{H}H_0^2(z) - \frac{\lambda}{2}\gamma_2(z)\right] \qquad \text{XII}$$

In the case of an air cored straight solenoid, used as a magnetic electron lens, since the electrostatic field may be taken to be vanishingly small and negligible, the expressions given by XI may be written in the forms

$$\ddot{z} = 0, \qquad \dot{z} = \omega \quad --- \qquad \text{XIII}$$

and therefore the equation XII may be reduced to

$$\frac{d^2r}{dz^2} = -r\left(\frac{\lambda H_0(z)}{2\omega}\right)^2 \qquad \text{XIV}$$

The magnetic field being axially symmetrical,

$$\left.\begin{aligned} H_z(r_0) &= H_0(z) = H_0 \cdot h(z), \\ h(z) &= 1 - a_1\left(\frac{z}{z_0}\right)^2 - a_2\left(\frac{z}{z_0}\right)^4 - a_3\left(\frac{z}{z_0}\right)^6 - a_4\left(\frac{z}{z_0}\right)^8 \end{aligned}\right\}$$

and therefore the equation XIV may be written as

$$\frac{d^2r}{dz^2} = -r\left(\frac{\lambda H_0(z)}{2\omega}\right)^2 = -r\left(\frac{\lambda H_0 \cdot h(x)}{2\omega}\right)^2 = -r\chi^2(z) \qquad \text{XV}$$

an homogeneous differential equation of the second order which relates the two variables r and z and as a first approximation, it determines r(z) of electron trajectories.

An electron trajectory from the maximum r_m to the focal point may be viewed as a steady differentiable curve whose ordinate difference between a maximum $r_m z_m$ and the curve point $r_1 z_1$, lying right therefrom is expressed by

$$r_m - r_1 = -\int_{z_m}^{z_1} (z_1 - z) \frac{d^2 r}{dz^2} dz.$$

To find a solution, we consider

$$\frac{d}{dz}\left[(z_1 - z)\frac{dr}{dz}\right] = (z_1 - z)\frac{d^2 r}{dz^2} - \frac{dr}{dz}$$

Then

$$\int_{z_m}^{z_1} (z_1 - z)\frac{d^2 r}{dz^2} dz = \int_{z_m}^{z_1} \frac{d}{dz}\left[(z_1 - z)\frac{dr}{dz}\right] + \frac{dr}{dz} = \left[(z_1 - z)\frac{dr}{dz} + r\right]_{z_m}^{z_1} = r_1 - r_m$$

so that

$$r_m - r_1 = -(z_1 - z)\frac{d^2 r}{dz^2} dz$$

In the case of an electron trajectory, if its maximum $r = \hat{r}$ lies at $z = 0$ ($r_{max} = \hat{r}$ at $z = 0$) and if the focal point $z = z_1$ at $r = 0$ be chosen as the point of reference $r_1 z_1$, then

$$\hat{r} = -\int_0^{z_1} (z_1 - z)\frac{d^2 r}{dz^2} dz$$

which, oh substituting the value for $\frac{d^2 r}{dz^2}$ given by the expression XV, becomes

$$\hat{r} = \int_0^{z_1} (z_1 - z)\left[\frac{\lambda H_0 \cdot h(z)}{2\omega}\right]^2 \cdot r \, dz.$$

$$= \int_0^{z_1} (z_1 - z) \frac{\lambda^2}{4\omega^2} H^2(z) \, r \, dz \qquad \text{XVI}$$

or after dividing all through by $\hat{r} z_1$

$$\frac{1}{z_1} = \frac{\lambda^2}{4\omega^2}\int_0^{z_1} \left(1 - \frac{z}{z_1}\right)\frac{r}{\hat{r}} H^2(z) \, dz \qquad \text{XVII}$$

If the point on the z-axis corresponding to the maximum r ($r = \hat{r}$) of the electron trajectory be taken as zero point, the point of departure of the electron rays ($z = z_2$) may, analogous to the equation XVII, be written as

$$\frac{1}{z_2} = \frac{\lambda^2}{4\omega^2}\int_{-z_2}^{0}\left(1+\frac{z}{z_2}\right)\frac{r}{\hat{r}}H^2(z)\,dz \qquad \text{XVIII}$$

The sum of the values of the reciprocals of z_1 and z_2 given by XVII and XVIII, being the reciprocal value of the focal length, we have an expression for the reciprocal focal length $\frac{1}{f}$ of the magnetic electron lens given by

$$\frac{1}{f} = \frac{1}{z_1}+\frac{1}{z_2} = \frac{\lambda^2}{4\omega^2}\int_{-z_2}^{z_1}\phi(z)\frac{r}{\hat{r}}H^2(z) \qquad \text{XIX}$$

where, as shown in the Fig.1,

if $z \geq 0$, $\phi(z) = 1 - \frac{z}{z_1}$

and $z \leq 0$, $\phi(z) = 1 + \frac{z}{z_2}$

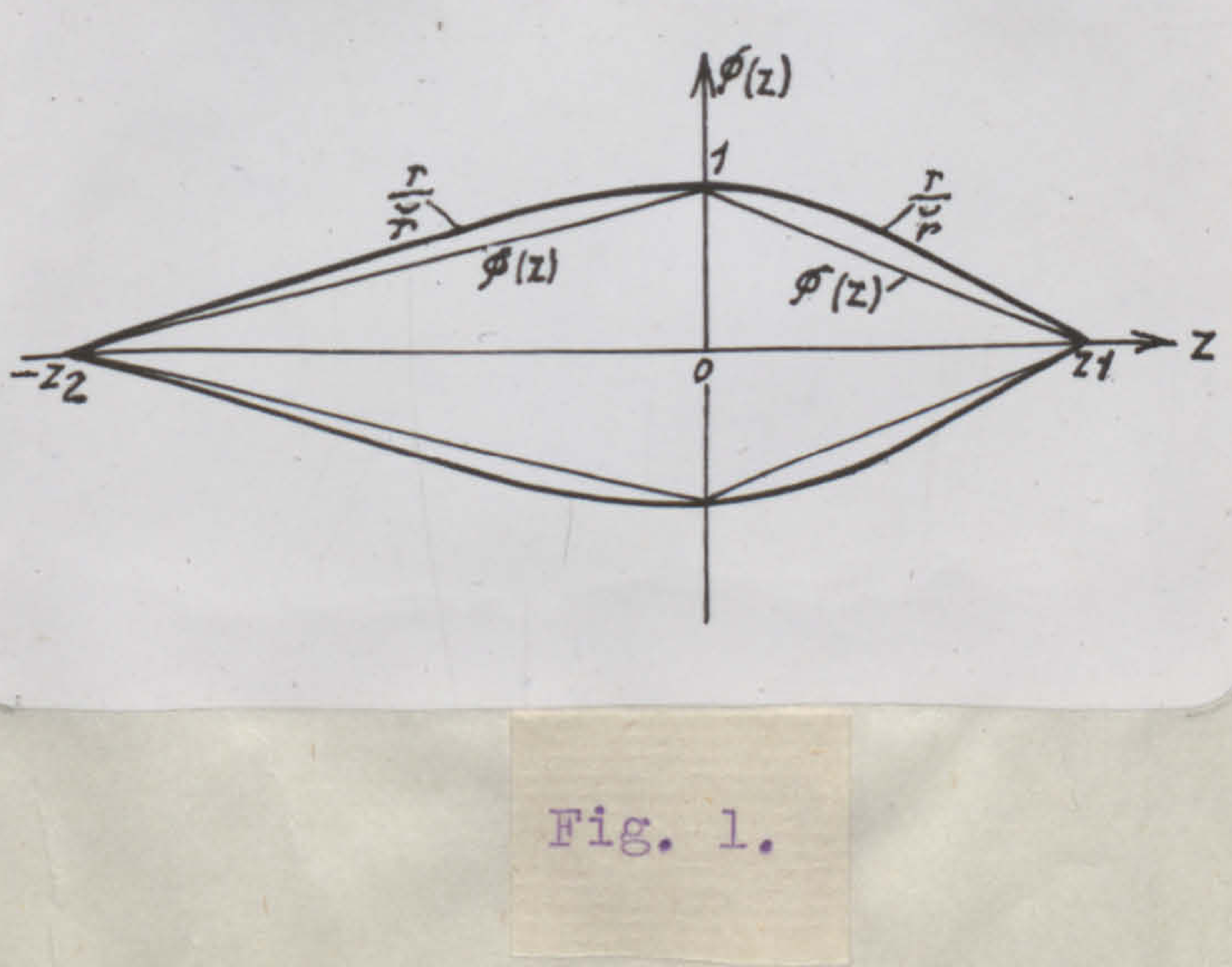


Fig. 1.

Then from the reciprocal value given by the expression XIX, we obtain the Busch Law of focal length[9] of magnetic electron lenses, given by

$$f = \frac{4m^2\omega^2}{e^2\int_{-z_2}^{z_1} H^2(z)\phi(z)\frac{r}{\varphi}} \qquad \text{XX}$$

3. Focal length of magnetic electron lenses and the determinants of electron trajectories.

Let a βeta particle be moving from a point source at $-z_2$ with an initial velocity v in a direction making an angle α with the direction of the lines of force of an axially symmetrical field. In the motion of the particle in such a field, the velocity remains constant. Therefore its dynamic mas $\upsilon = m\Big/\sqrt{1 - \frac{v^2}{c^2}}$, and its momentum υv are constant. Then its trajectory of the form of circular helix will be of radius

$$\rho = \sin\alpha .\, v\upsilon/e.H_{(z)} \quad --- \quad --- \qquad \text{XXI}$$

with a range R or a parameter at an auxiliary variable $\theta = 180^\circ$ given by

$$R_{(z,r=0)} = P(\theta=180^\circ,\ r=0) = \cos\alpha .\, v\upsilon 2\pi/e.H_{(z)}. \qquad \text{XXII.}$$

We consider a paraxial or very nearly co-axial βeta-rays traversing a magnetic electron lens system. Then the focal length $F(\alpha \cong 0^\circ,\ r = 0)$ of this lens system when traversed by rays with $\alpha \cong 0^\circ$, may be considered to be identical to the parameter of the electron trajectory $P(\alpha \cong 0,\ \theta = 180^\circ)$, so that

$$F(\alpha \cong 0^\circ,\ r = 0) = P(\alpha \cong 0,\ \theta = 180^\circ) = v\upsilon 2\pi/e.H_{(z)}, \qquad \text{XXIII}$$

since $\alpha = 0^{\circ}$ and $\cos\alpha$ is unity. Therefore, the paramete $P(\alpha \gg 0^{\circ}, \theta = 180^{\circ})$ of an electron trajectory with $\alpha \gg 0^{\circ}$ at the auxiliary variable $\theta = 180^{\circ}$ and the focal length $F(\alpha = 0^{\circ}, r = 0)$ bears the same relation as the one between the longitudinal component of velocity ω and the electron velocity v on condition that the velocity in either case be of the same value. Hence we have,

$$P(\alpha \gg 0^{\circ}, \theta) = F(\alpha = 0, r = 0) . \cos\alpha . \frac{\theta}{180}, \quad \text{———} \quad \text{XXIV}$$

$\alpha \gg 0$ being the angle which the trajectory subtends with the lines of force, and θ the auxiliary variable of the trajectory, $(\theta(-z_2) = 0^{\circ})$.

From the relation between ρ and p and p and F given by the expression XXI, XXII and XXIII and the geometrical characteristics involved in these relations, we derive an expression for the displacement of the electron from the z-axis, or, in other words, for the radial extension of an electron trajectory from the z-axis at an auxiliary variable θ, given by

$$r(\alpha \gg 0, \theta) = \frac{\operatorname{Sin}\alpha}{\pi} . \sin\theta , \quad \text{----} \quad \text{XXV}$$

where r is the radial extension of an electron trajectory when the angle α is appreciably greater than zero.

Thus the expressions XXIV and XXV respectively give the parameter along and the radial extension from the axis of the magnetic field. They therefore determine the magnitude and the geometrical shape in a (z,r) plane of a trajectory of an electron traversing a given axially symmetrical magnetic field.

4. Tracing of electron trajectories in (z,r) plane and the basic design of a magnetic electron lens spectrometer.

In tracing electron trajectories in (z,r) plane to determine our design of a magnetic electron lens βeta ray spectrometer, the choice of the range of α-values of the trajectories essentially depends upon the dimensions of the tube which forms the body of the spectrometer and the effective central stop which arrests unresolved rays from reaching the focal position and upon the percentage of 4π in solid angle to be employed for the required efficiency. The diameter of the tube which we had in hand for using as the body of the spectrometer is 9.5cm. In a cylindrical tube of this diameter in conjunction with a central stop of effective magnitude, about 5% of 4π in solid angle permits those trajectories having such directions which subtend angles with the lines of force, ranging from $\alpha = 15^{0}$ to $\alpha = 32^{0}$.

Let F of the magnetic electron lens be unity, then from equations XXIV and XXV the parameter at $\theta = 180^{0}$ and the maximum radial extension at $\theta = 90^{0}$ of an electron trajectory with $\alpha = 32^{0}$ are

$$P(\alpha=32^{0},\theta=180^{0}) = 0.84804 \quad \text{and} \quad r(\alpha=32^{0},\theta=90^{0}) = 0.168677$$

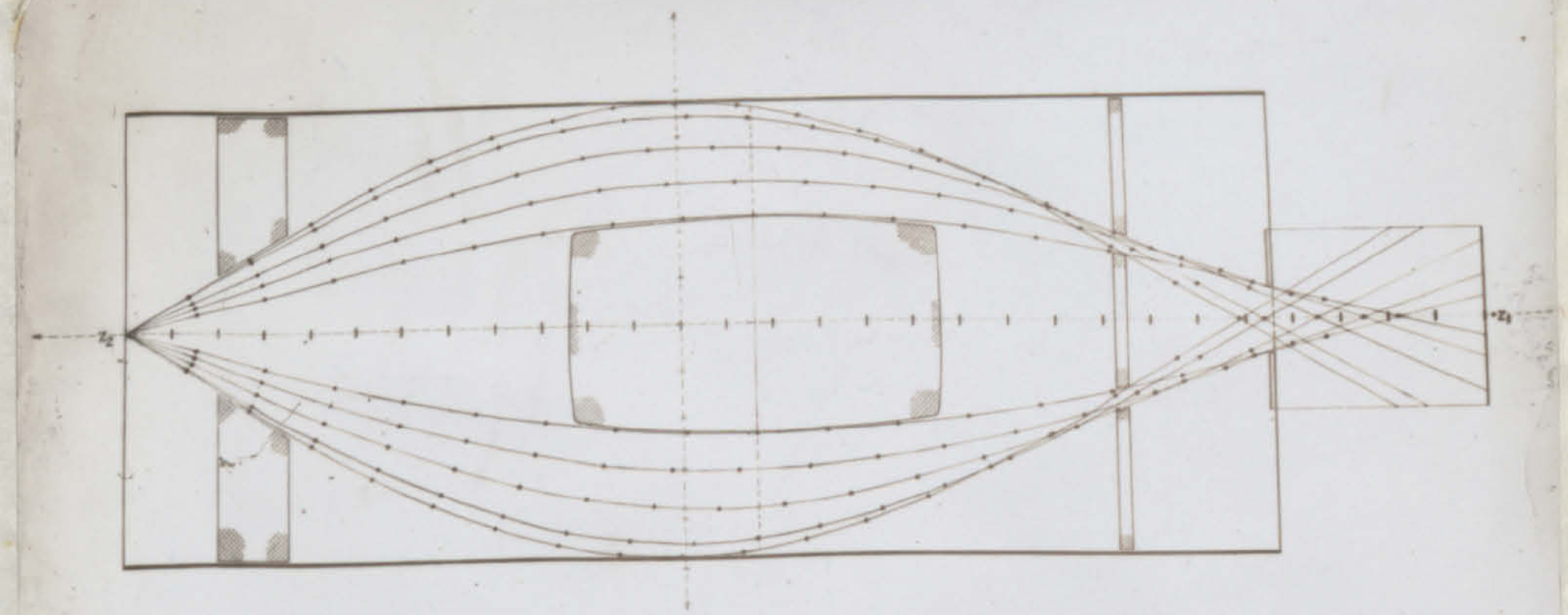
This maximum radial extension of the electron trajectory with $\alpha = 32^\circ$ at $\theta = 90^\circ$ is taken to be limited to the radius of the spectrometer tube. Therefore,

$$r(\alpha=32^\circ, \theta=90^\circ) = 0.168677 = 4.75 \text{ cm.}$$

and hence

$$F = 28.16\text{cm.}$$

Again from expressions XXIV and XXV and with $F = 28.16$cm, p and r values for the range of the auxiliary variable (from $\theta = 0^\circ$ to $\theta = 180^\circ$) of five different electron trajectories with $\alpha = 15^\circ, 20^\circ, 25^\circ, 30^\circ$ and 32° respectively are obtained. With these values the trajectories have been traced in the (z,r)-plane as shown in the Fig.2, in order to determine the shape and dimensions and thus also the design of the magnetic lens spectrometer with 5% efficiency. From the trajectory tracings in the (z,r)-plane, shown in the Fig.2, the position, shape and size of the stop which arrests the unresolved rays and the front ring, annular and window apertures which improve the resolving power are fixed as indicated in the Fig.2.



ELECTRON TRAJECTORIES IN A STANDARD AXIALLY SYMMETRICAL MAGNETIC FIELD
AND
THE BASIC DESIGN OF A MAGNETIC ELECTRON LENS BETA-RAY SPECTROMETER.

Fig. 2.

5. Magnetic Electron Lens and its field distribution

(a) Magnetic Electron Lens. Seven air cored multilayered straight solenoids, each 5 cm. long, connected together in series and mounted on a cylindrical brass tubing, form a thick magnetic electron lens.

The total number of coil-turns in the magnetic electron lens of 35cm. long being 7 x 22 x 29 = 4466, the average number of turns per centimeter is $\frac{4466}{35}$ = 127.6. The magnetic field of this electron focusing system, calculated from the relation given by

$$H = \frac{4\pi ni}{10} \text{ gauss,}$$

where n is the number of turns per cm., i the current in amperes and H the magnetic field in gauss, has the following values (Table 1.) for different values of magnetizing current.

TABLE I.

i in Amperes	H in gauss	i in Amperes	H in gauss
0.1	16	2.0	321
0.25	40	2.25	361
0.5	80	2.5	401
0.75	120	2.75	441
1.0	160	3.0	481
1.25	200	3.25	521
1.5	240	3.5	561
1.75	281	3.75	601
2.0	321	4.0	641

These values given in the Table I may be valid in the very centre of electron lens on the axis. The field along the axis at other parts, especially towards the ends of the electron focusing system may vary from that of the centre along the axis. These variations in the field distribution and the resultant small deviations of the field from homogenity are to be taken into account in the actual construction of the βeta ray spectrometer from the basic design given in the Figure 2. Hence the field of the magnetic electron lens is measured at the centre of each one of the seven solenoids along the axis in order to determine the field distribution and the field-current characteristics of the magnetic electron lens.

(b) Magnetic field measurements and the determination of the field distribution of the magnetic electron lens.- The magnetic field is determined or calibrated in terms of the magnetizing current by observing the deflection of a ballistic galvanometer produced by the charge induced in an exploring coil when it is rotated through 180° in the field at the centre of each solenoid along the axis of the magnetic electron lens. The galvanometric deflection is calibrated by breaking as well as reversing the current through a mutual inductance. The experimental arrangement for the determination of the magnetic field is shown in the Figure 3. (Fig.3).

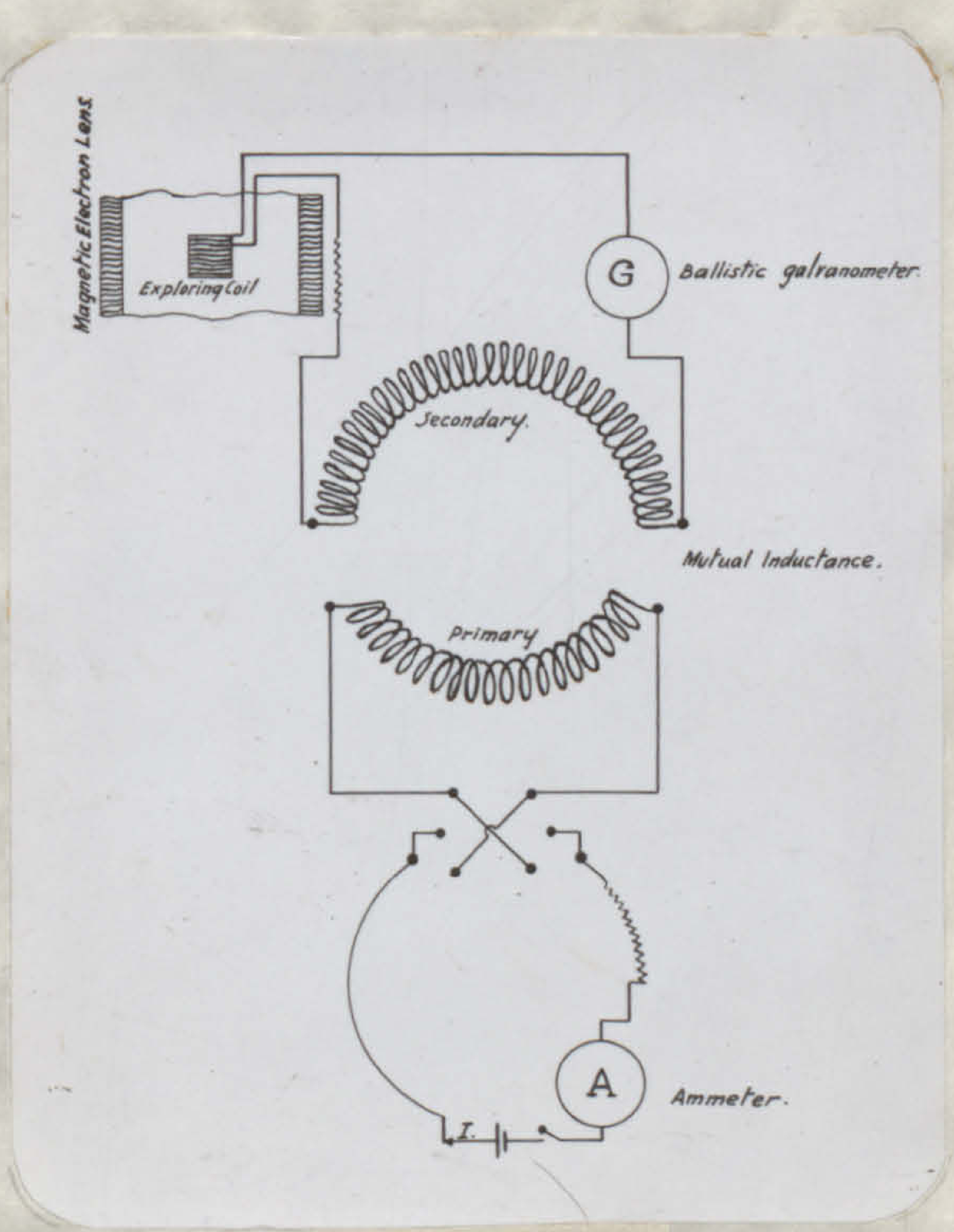

Magnetic Electron Lens
Exploring Coil
G
Ballistic galvanometer.
Secondary.
Mutual Inductance.
Primary
A
Ammeter.
I.

Fig. 3.

If m be in henries, i_o the current through the primary of the mutual inductance measured in amperes and the effective area nA in square centimeters, the magnetic field H is given by

$$H = \frac{10^8 m}{2nA} \frac{\theta}{\theta_o} \; i_o \text{ gauss} = \frac{10^8 m}{2nA} k \, \theta \text{ gauss}, \qquad (V.I)$$

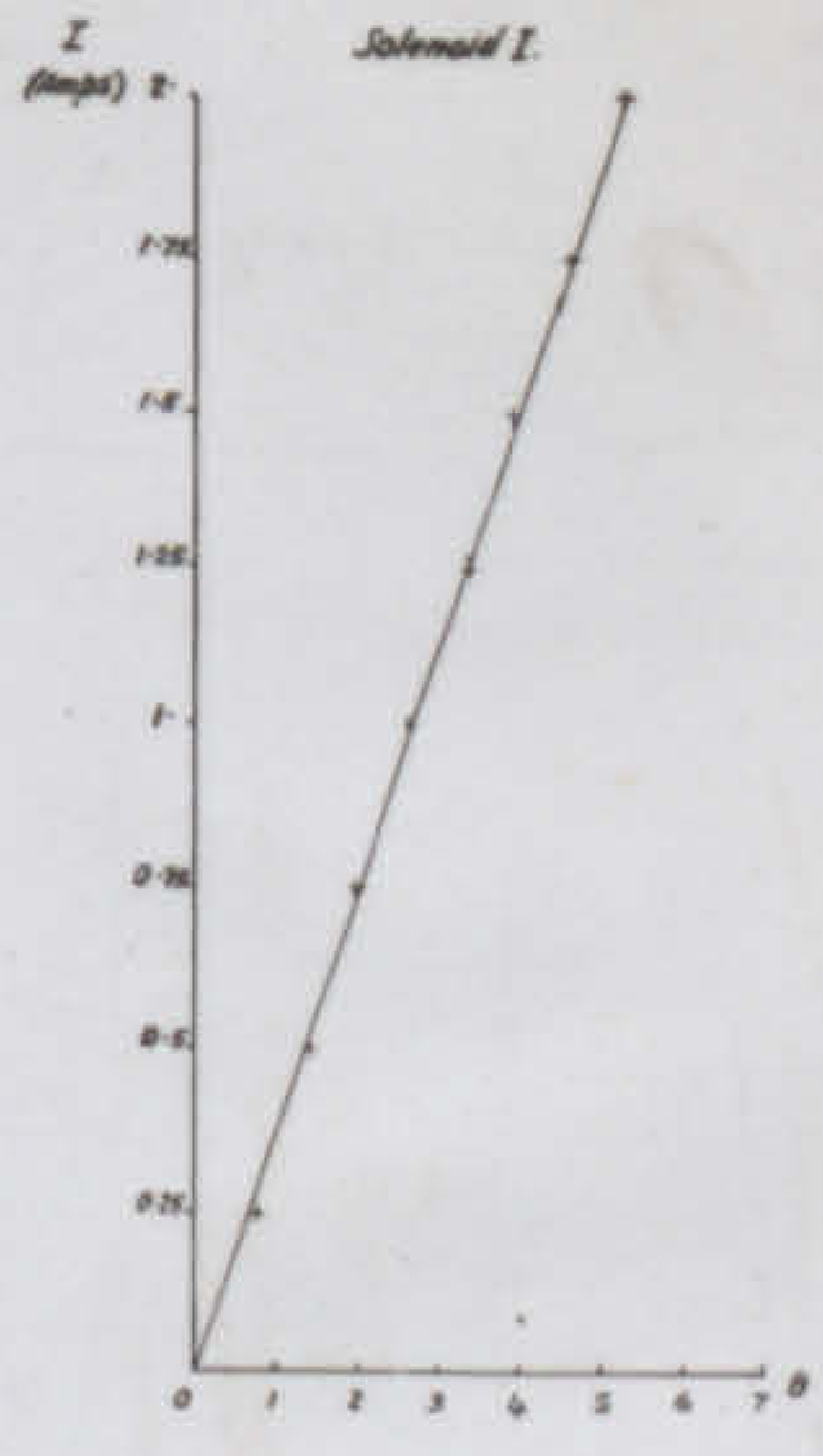
where θ is the galvanometric deflection produced by the charge induced in the exploring coil when rotated through 180^o, θ_o the galvanometric deflection due to current i_o through the primary of the mutual inductance and $k = \frac{i_o}{\theta_o}$. With the experimental arrangement, shown in Fig.3, since the coefficient of mutual inductance m = 0.02 henries, the effective area nA = 645 cm^2, and k = 0.03077 as determined from the measurements plotted in the graph I (Fig.4), the expression (V.1) for H the magnetic field becomes

$$H = \frac{10^6}{645} \times 0.03077 \times \theta \text{ gauss} \quad \text{----} \quad \text{----} \quad (V.II)$$

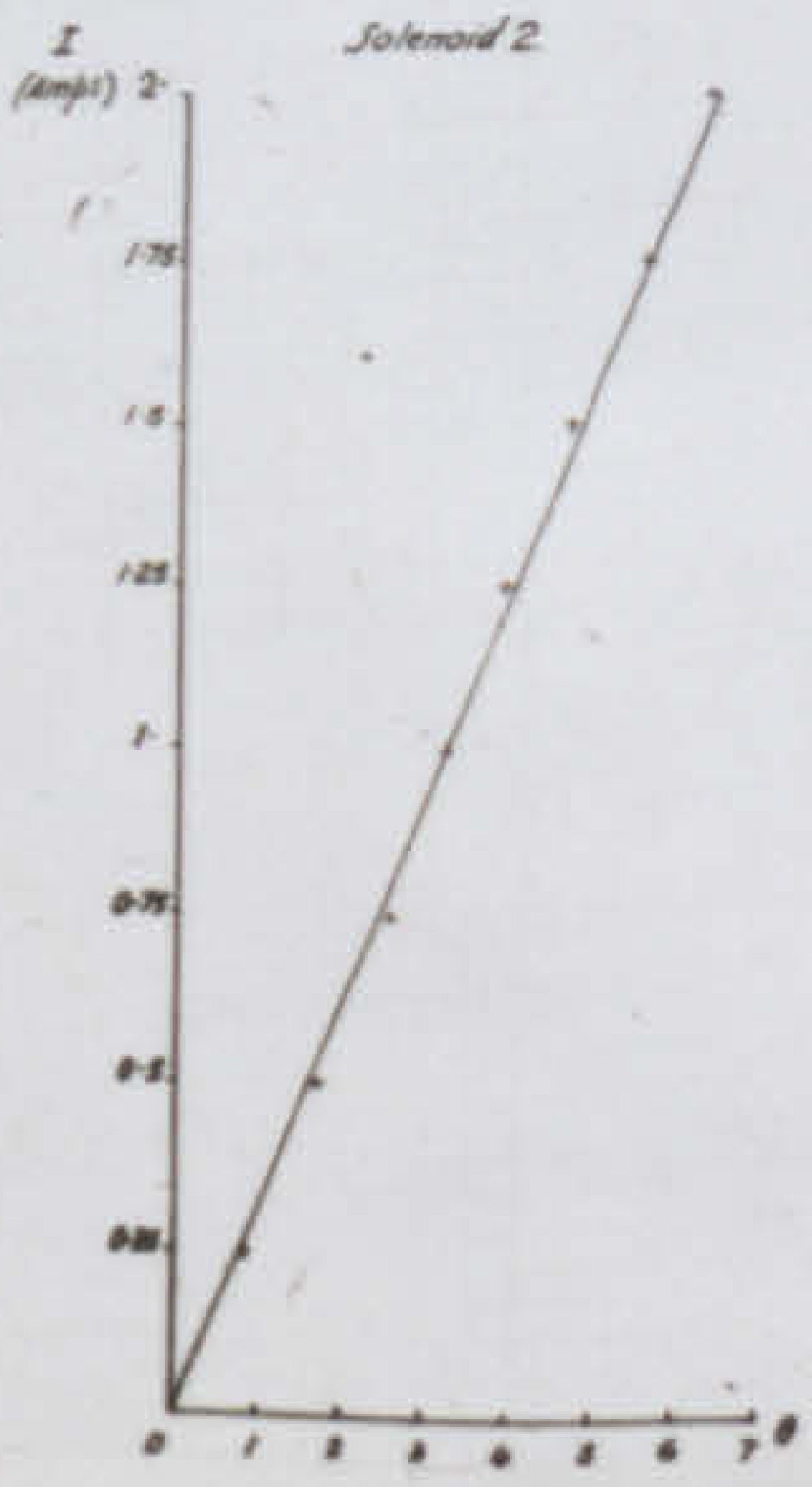
The exploring coil is mounted at the centre of each solenoid along the axis of the magnetic electron lens. For each value of the magnetizing current with each one of the solenoids, its corresponding galvanometric deflection is recorded when the exploring coil is rotated through 180^o. The current deflection relations are plotted separately for each one of the seven solenoids as shown in the Figs. 5, 6, 7, 8, 9, 10 and 11 (graphs 2, 3, 4, 5, 6, 7 and 8.) Then for a ready estimation

Graph 1.

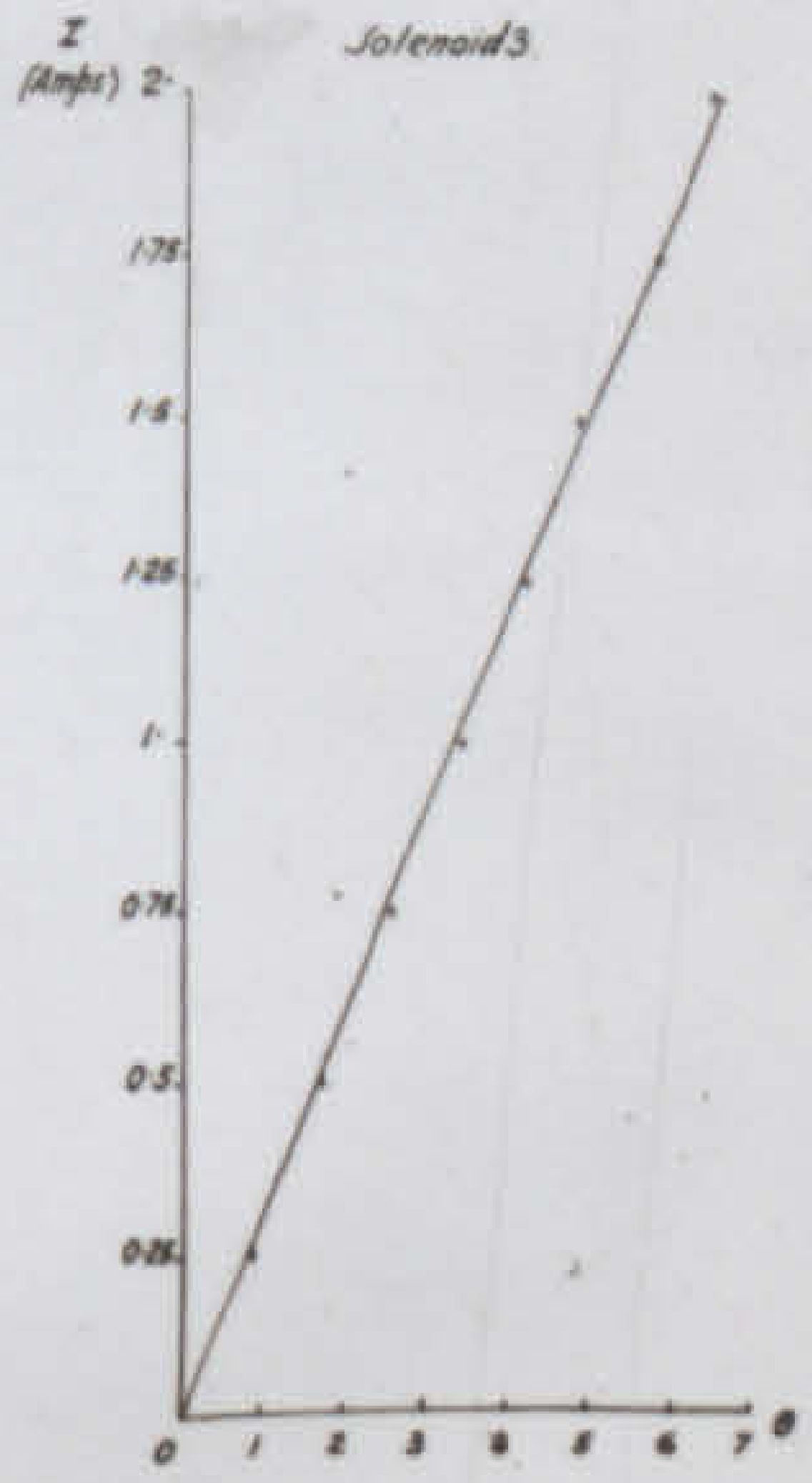
$K = \frac{I_0}{\theta_0} = 0{\cdot}03077$.



Graph 2.



Graph 3

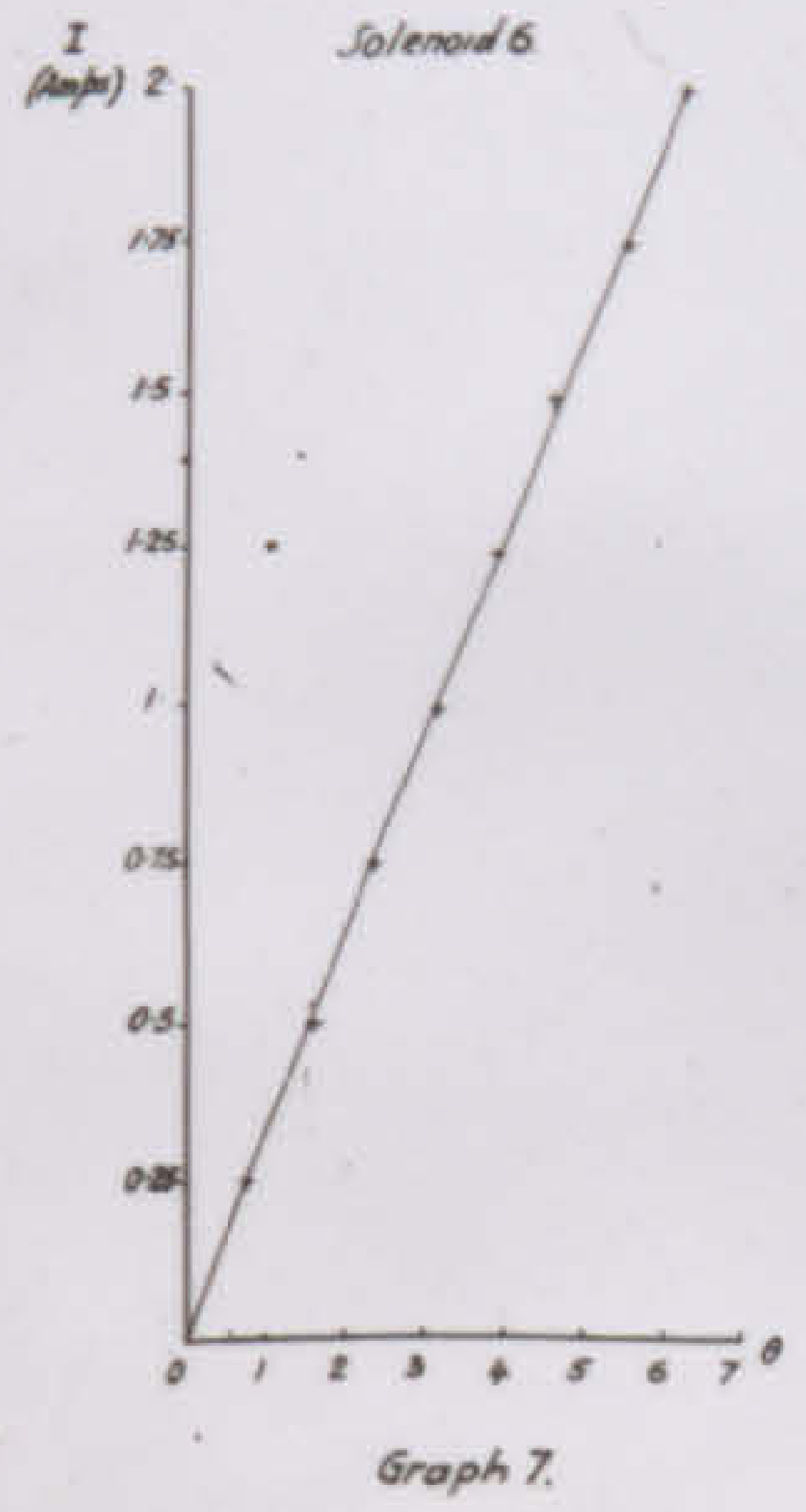


Graph 4.

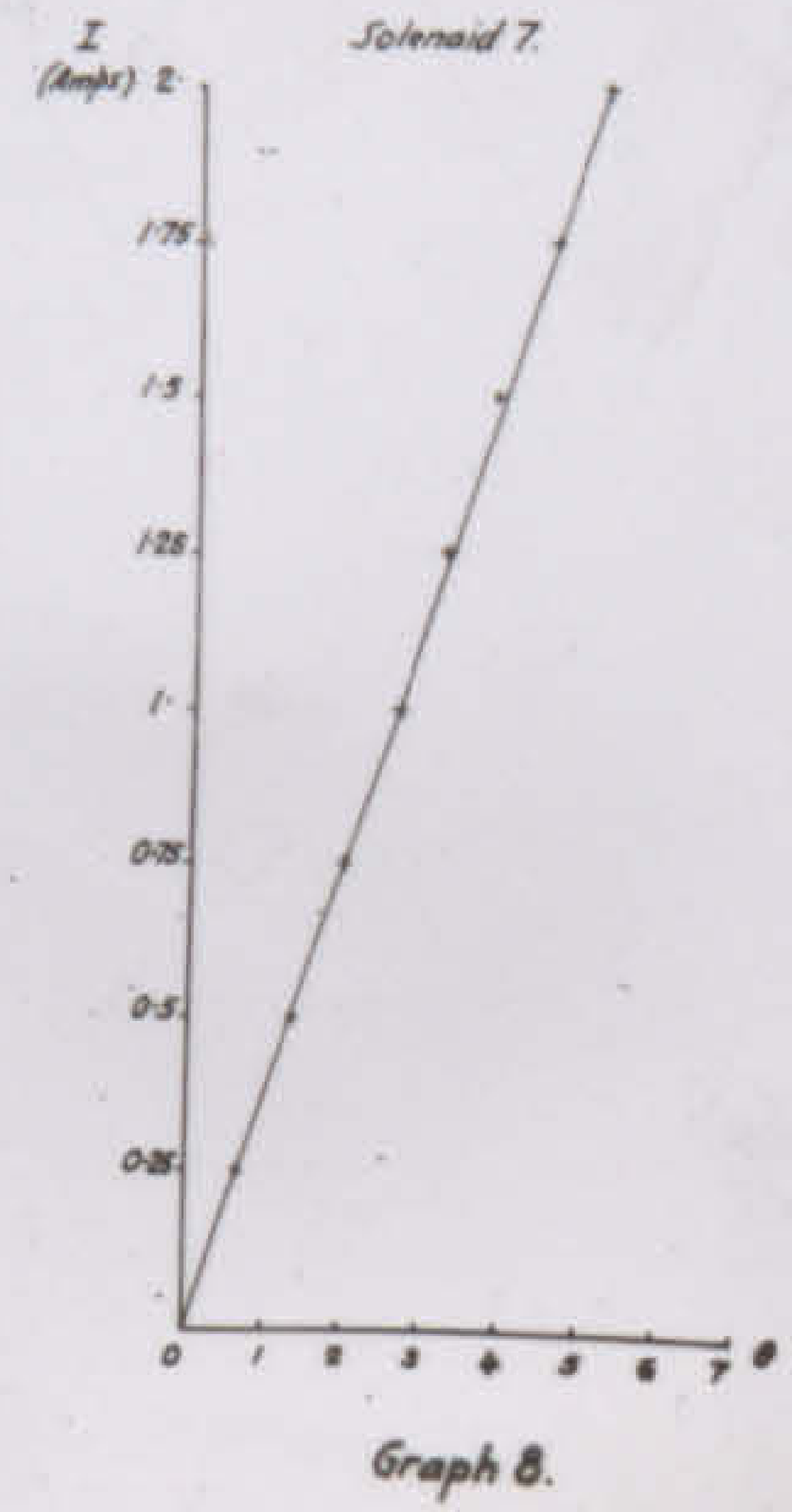
Figs. 4, 5, 6, and 7.

Graph 5.

Graph 6.



Graph 7.



Graph 8.

Figs. 8, 9, 10, and 11.

of the variations of the field distribution in the different solenoids for each magnetizing current, the current-deflection relations are plotted in the magnetic field survey map shown in Fig.12.

The value of the magnetizing current i, the corresponding galvanometric deflection θ for the different solenoids given in the survey map (Fig.12) and the value of the constant k given in the graph (Fig.4) are experimentally determined according to the outlined deflection method in order to compute therefrom the magnetic field H for different values of magnetizing current, plotted in the graph 9 (Fig.13) by the relation given in the equation (V.II).

(c) Magnetic field distribution and the orientation of the βeta ray spectrometer in the magnetic electron lens.

The mean magnetic field for the magnetizing currents of 1 Amp., 2 Amp. and 2.4 Amps, obtained from the measured values are graphically represented as shown in Fig.14, and the curves indicate the field distribution at these values of the magnetizing current. The field-current characteristics given in Fig.13 and the field distribution curves from Fig.14, indicate that, for any magnetizing current, the field is a maximum in the middle of the focusing system and gradually decreases on either side towards the ends, that the magnetic field at the centres of the first and the seventh solenoids

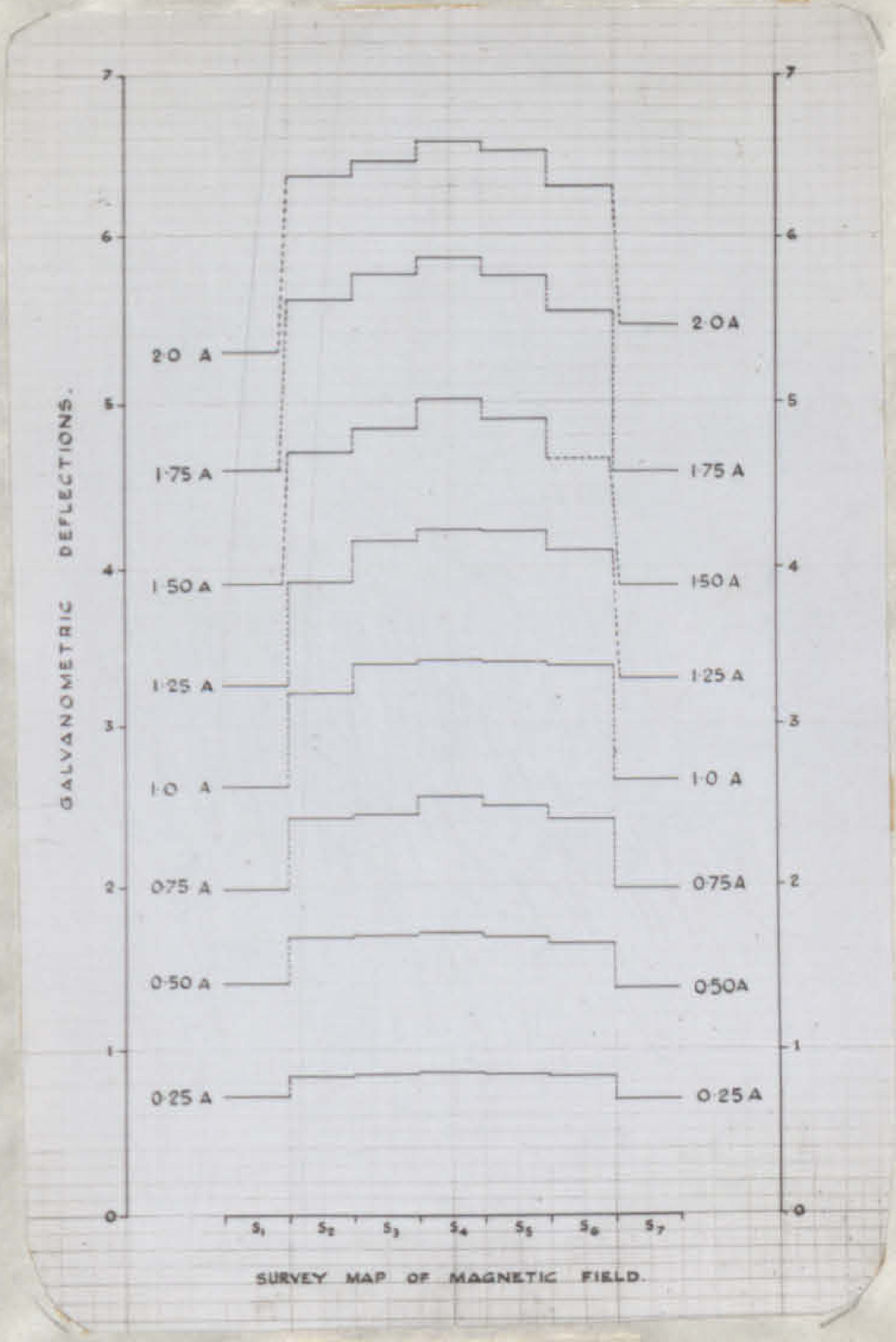


Fig. 12.

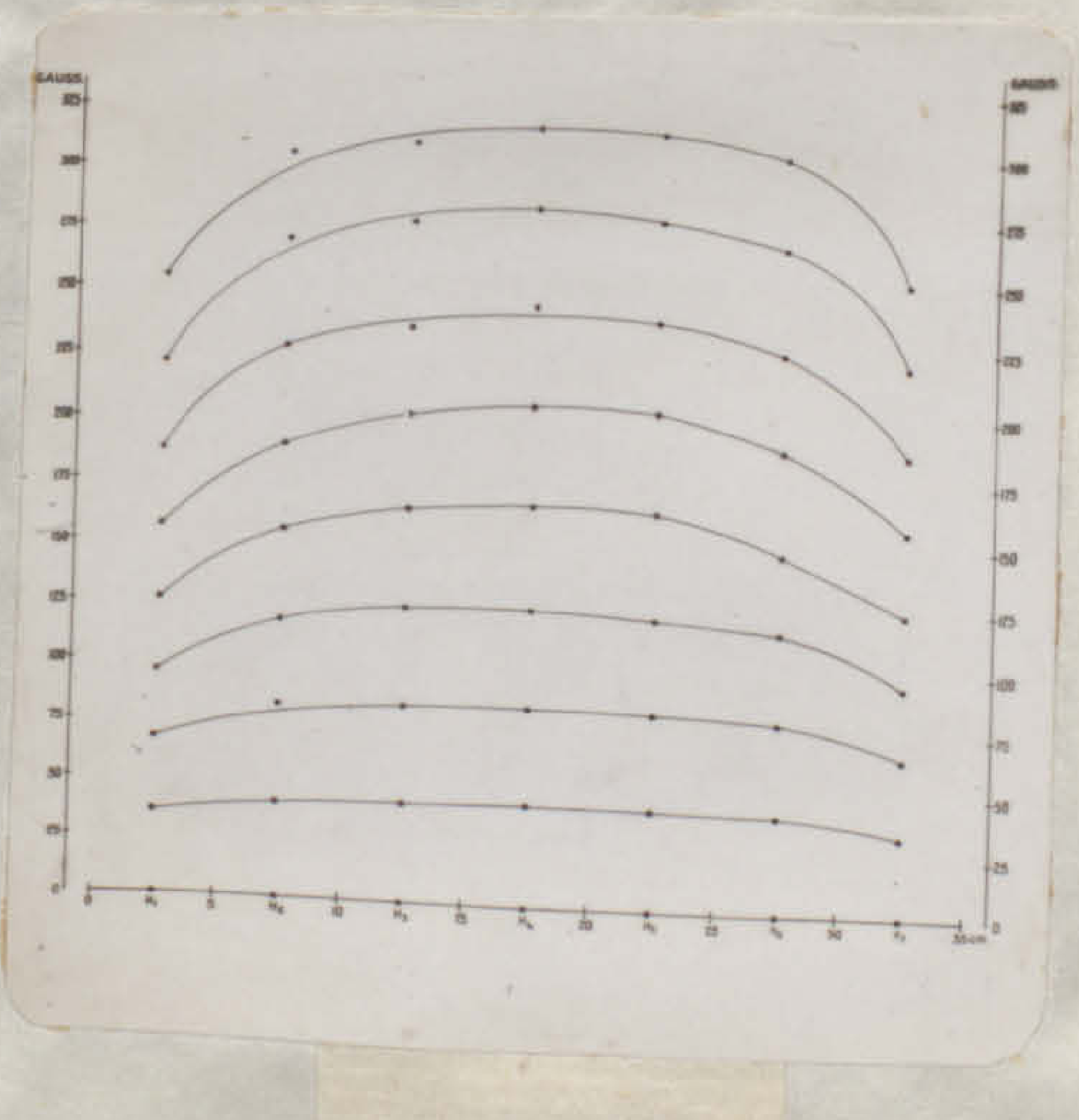


Fig. 13.

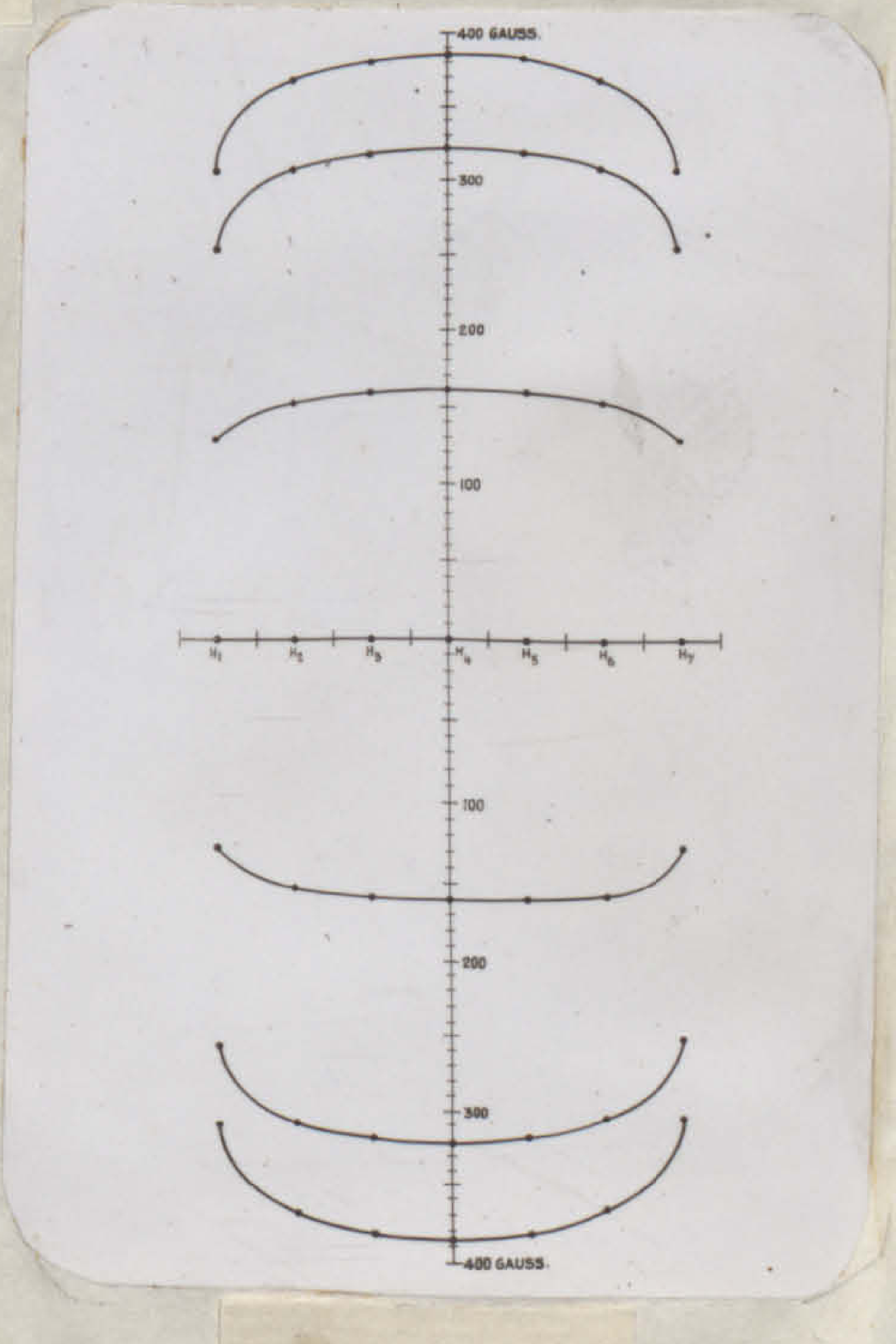
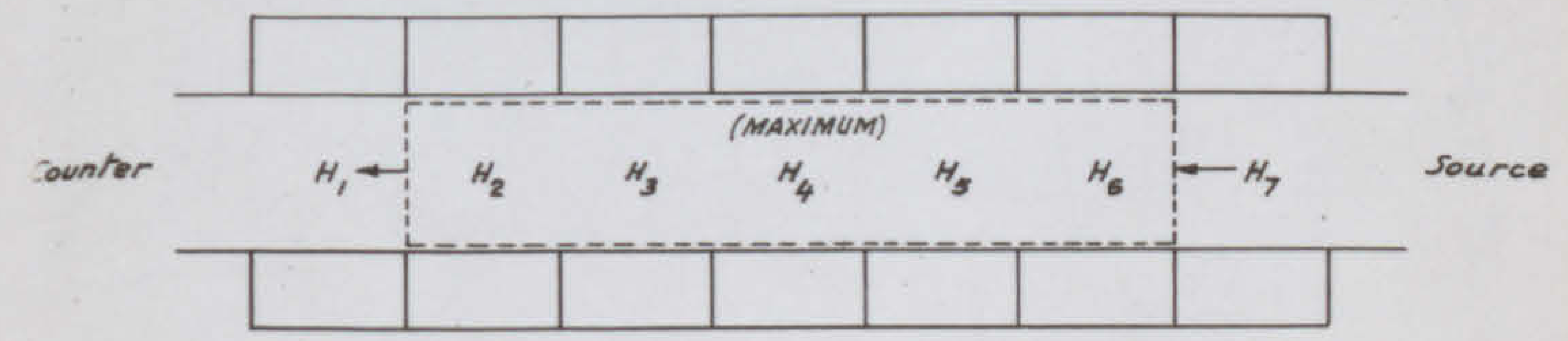


Fig. 14.

Differs as much as over 20% from the maximum, and that the field at the centre of any one of the rest along the axis does not differ more than 3 or 4% from the maximum, so that the slight deviation from homogenity of the field along the axis of the rest of the solenoids (excepting the first and the seventh) may be considered to be negligible. Therefore a spectrometer constructed according to the basic design given in Fig.2, when mounted in the body of the focusing system, beginning from the second up to the end of the sixth solenoid, as shown in Fig.15, where the magnetic field may be taken to be nearly axially symmetrical, should be quite satisfactory for the energy spectrometrical study of even weak artificial radioactive elements.

Plan of the Magnetic Electron Lens – βeta ray Spectrometer.



In the boundary of the dotted lines, where
the magnetic field is nearly axially homogeneous
the β-ray spectrometer is mounted.

Fig. 15.

6. The construction of the spectrometer.

(a) The body of the spectrometer with its accessories.

A brass tube 9.5 cm. in diameter, with walls about 3 mm. thick, is used for the construction of the βeta ray spectrometer, based upon the design shown in Fig.2. The tube is provided at either end with a brass lid about 1.5 cm. thick. Each end of the tube, covered with a greased rubber washer, is inserted into the recess of the lid. These two lids at either end of the tube are firmly clamped together over the tube so that the joints between the tube and the lids are vacuum tight. This brass tube with lids at either end clamped together forms the body of the spectrometer, as shown in Fig.16.

One of the lids (Fig.17a) has an outlet port, fitted with a conducting tube leading to a high vacuum pumping system. Through this port the spectrometer, together with a source holder chamber, is exhausted to a pressure of nearly 10^{-4} mm Hg by means of a single stage Apiezon oil diffusion pump backed by a rotary pump. The free path of the residual molecules at this pressure being larger than the length of the spectrometer and the collision frequency being comparatively very low, the scattering of the traversing βeta particles, which is detrimental to a satisfactory energy spectrometrical analysis, is practically eliminated.

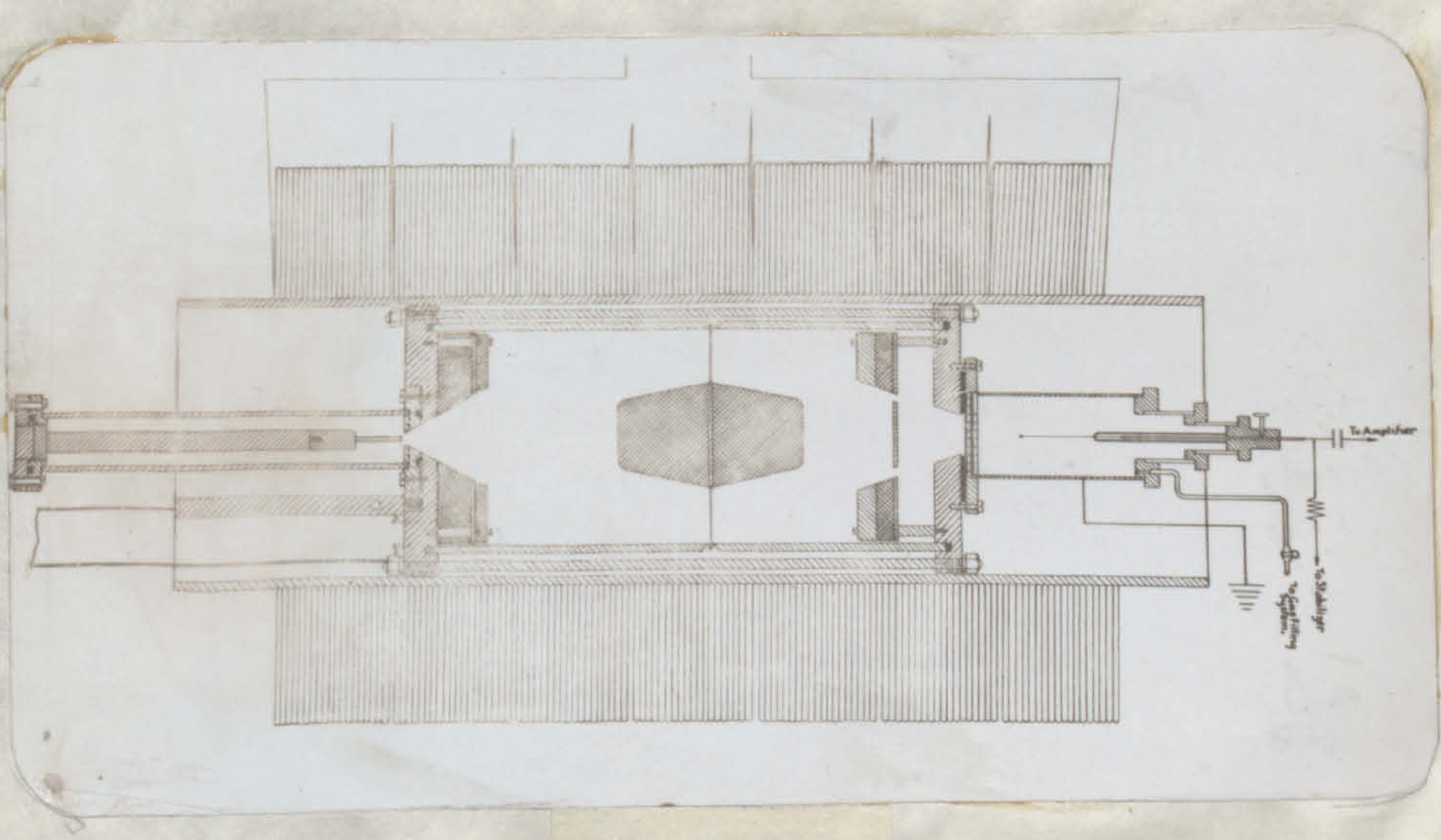
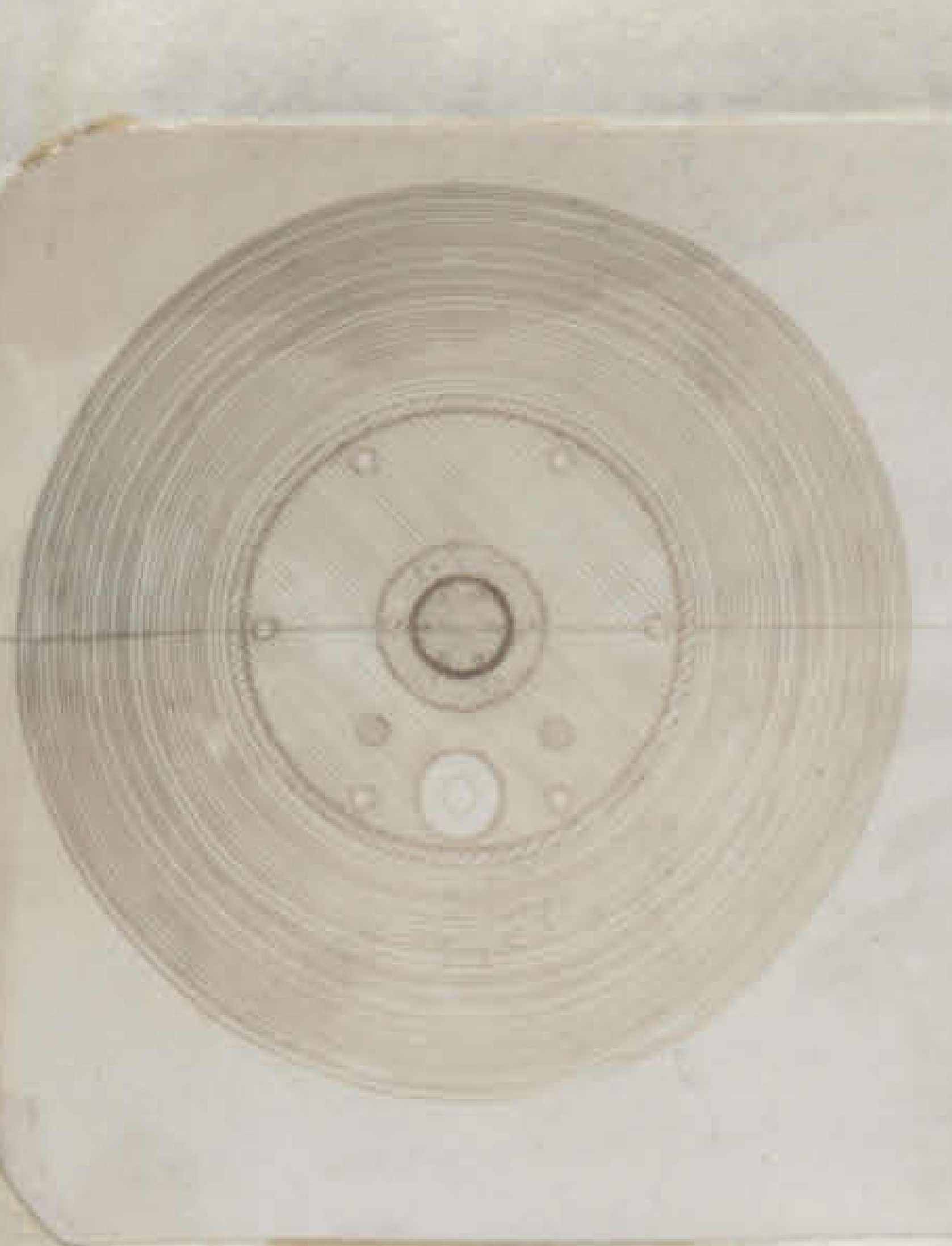
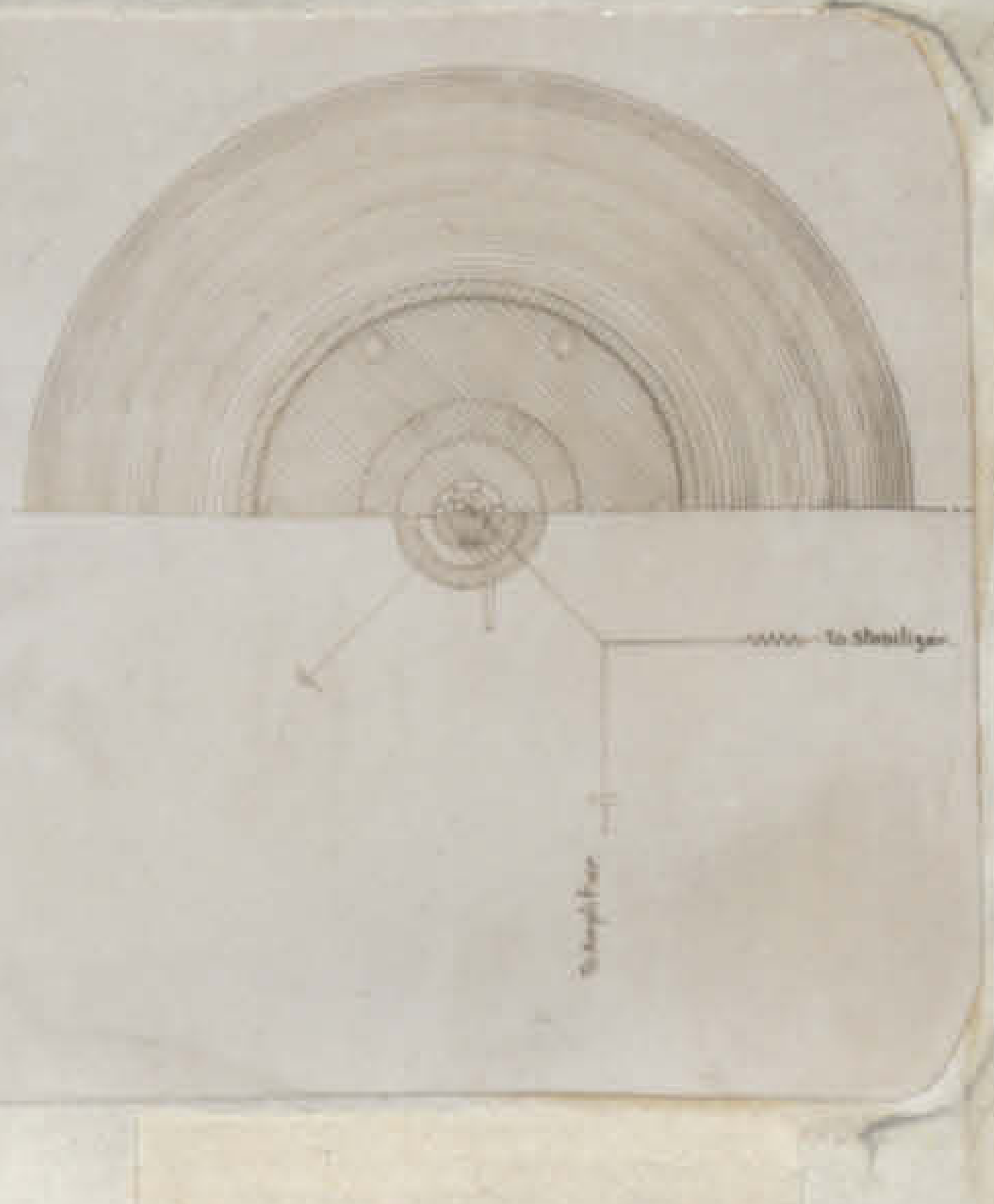


Fig. 16.



A
Fig. 17



B
Fig. 17.

The lid with the outlet port for exhaustion is provided with a βeta ray entrance aperture 5 mm. in diameter, exactly at its very centre. This aperture, starting from the outer plane of the lid, extends through its wall to its inner surface into the body of the spectrometer, forming a taper with an angle of 32° with the axis of the spectrometer. On the outer surface of this lid, surrounding the entrance aperture, a tubular brass chamber with a diameter of about 2.5 cm., which contains a radioactive source holder, is firmly fixed by means of screws. The joint between the lid of the spectrometer and the flange of the source holder chamber is rendered vacuum tight by means of a suitable greased rubber washer.

The second lid (Fig.17b) at the other end of the spectrometer has a circular aperture, 1.4 cm. in diameter at the outer end. The βeta ray outlet aperture passes from the outer end down through the wall of the lid into the spectrometer in the form of a taper with an angle of 32°. An electrical counter, shown in Fig.18, with its window facing directly the βeta ray outlet aperture, is mounted with a suitable greased rubber washer on the outer surface of this lid and is firmly fixed by means of screws, so that the axis of the electrical counter remains in perfect alignment with those of the spectrometer and the radio active source holder chamber. The clamping screws between the lid of the spectrometer and the flange of the electrical counter are so tightened as to let the rubber washer seal the intervening dead space of the joint and thus make the joint vacuum tight.

Thus the radio active source holder chamber is fitted on one end and the electrical counter on the other end of the brass tube which forms the main body of the spectrometer. The position of the source holder is so adjusted that the centre of the source lies on the axis of the spectrometer just in front of the entrance aperture. The dimensions and the geometrical form of the trajectories of βeta particles determine the distance between the radio active source and the window of the counter, as indicated in the basic design shown in the Fig.2. Accordingly, this distance between the source and the counter-window is fixed in the actual construction, illustrated in Fig.16.

The inlet and the outlet apertures, located at the centres of the lids of the spectrometer tube, form the essential requisites of the outer structure. In addition to these apertures, there are three component parts within the body of the spectrometer. The form, size and position of these internal parts, the preliminary aperture, the central stop and the annular slit are, as can be seen in the basic design, determined by the geometry of the helices within the chosen solid angle.

(b) Preliminary aperture.

Two blocks of circular discs, one of lead and the other of brass, each about 9.45 cm. in diameter, are fastened together to form a compound cylindrical disc. This disc, with a circular hole at its very centre tapered at an angle of 32° is clamped to the inner wall of the lid of the spectrometer immediately adjoining the inlet, so that the edge of the narrow end of the taper in this compound disc nearly overlaps that of the broad end of the aperture in the lid of the spectrometer. This tapered hole in the compound disc at its broad end forms the actual preliminary aperture. It is about 4.4cm. in diameter at a distance of about 3.5cm. from the source measured along the axis. It filters down more effectively than the entrance aperture in the lid, those radiations whose angles of departure from the source are within the external limit of the chosen 5% of 4π in solid angle into the converging medium. The rest whose angles with respect to the lines of force at the point of departure excel this limit, are prevented from entering it. If this preliminary aperture with adequate lead shielding be not used, scattered radiations cause unduly large background and the βeta particles beyond the limit of the chosen solid angle, striking against the walls of the spectrometer, may scatter and render the resolution of the spectral lines vague and indistinct.

(c) Central stop.

The central stop is a brass disc whose diameter corresponds to $2 \times r_{(\alpha=15^{\circ},\ \theta = 90^{\circ})}$ It is mounted at a distance from the source equal to $p(\alpha=15^{\circ},\theta=90^{\circ})$ in such a way that the axis of the spectrometer passes through its centre. Two tapered blocks of lead, each 4cm. thick, are fastened on either side of this brass disc, as shown in Fig.16. This central stop is quite essential, for it prevents access to the focal region of all unresolved radiations. The stop in conjunction with the walls of the tube restricts the influence of spherical aberrations of the magnetic electron lens to such an extent that almost the entire line focus of the βeta particles of the chosen solid angle falls into the effective region of the detecting device.

(d) Annular slit.

From the plot (Fig.2) it can be seen that the trajectories of βeta rays of the chosen solid angle have a common overlapping track before they reach their respective positions in the line focus on the z-axis, r = o. The position of the part of the trajectory overlapping track with minimum width and the magnitude of this minimum width define the actual position and the dimensions of the annular slit. It admits the βeta rays of a specific velocity corresponding to the determinate field of force into the focal region. It prevents, however, stray and scattered βeta particles whose velocity does not correspond to the selected field of force from reaching the sensitive detecting device. This slit in conjunction with the outlet aperture in the lid of the spectrometer and the window aperture of the electrical counter, improve the resolving power and thus enhance the clearness of the spectral lines without any loss of efficiency. The outer disc of the annular slit is provided with lead and brass linings of about 1.5cm. thick for an effective prevention of the scattered γ-rays from reaching the counter.

7. Orientation of the magnetic electron lens and the adjustment of the beta ray spectrometer.

The seven solenoids, connected together in series, are mounted on a heavy brass cylindrical tubing, about 12cm. in diameter and about 50cm. in length. This tube forms the body of the magnetic electron lens. The current for the solenoids is supplied from 102 volt accumulators. Magnetising currents are measured by a calibrated shunt connected to an ammeter.

The magnetic electron lens is so orientated as to let its axis be in alignment with the earth's magnetic lines of force. Then the spectrometer, with the source holder on one end and the electrical counter on the other end, and with the different component parts carefully assembled together, is mounted in the body of the magnetic electron lens in such a way that both of them are perfectly co-axial, and is fixed in the part of the lens body where the magnetic field is nearly homogeneous and axially symmetrical.

8. Relation between the parameter linear difference and the resolving power.

The design and construction of the magnetic electron lens spectrometer, as elaborated in the preceding sections and shown in the Figs.2, 16 and 17, are based upon the size of the part of 4π in solid angle employed and the geometrical form of the electron trajectories in a standard axially symmetrical magnetic field. The dimensions and forms of the apertures, central stop and annular slit are chosen according to the conditions which determine the size and shape of the electron trajectories. The momentum spread of an energy line obtained by this instrument should be a definite function of the parameter linear difference. To ascertain this function, we consider a paraxial ray from a point source on the axis at $-z_2$ traversing a standard magnetic field. Then the angle α which the direction of the βeta ray at the starting point subtends with the axis of the field is so small that it can be assumed to be negligible (α = 0). Since cos 0° is unity, the focal length F of the magnetic electron lens when the traversing βeta ray is paraxial, may be written as

$$F = \frac{4m^2(1\times v)^2}{e^2\int_{-z_2}^{z_1} H^2_{(z)}\phi z \frac{r}{\hat{r}}} = \frac{4m^2v^2}{e^2\int_{-z_2}^{z_1} H^2_{(z)}\phi z \frac{r}{\hat{r}}}, \qquad \text{XX-a}$$

so that, from the relation given by XX1, we may as an approximation write as

$$F = \frac{4(H\rho)^2}{\int_{-z_2}^{z_1} H^2(z)\phi(z)\frac{r}{\hat{r}}}. \qquad \text{XX-b}$$

The spectrometer, however, is designed for the measurement of momentum of βeta particles whose trajectories have a definite α range with each individual α having an appreciable value. The range of directions of the trajectories within the limits, minimum α and maximum α, with respect to the lines of force, have a corresponding range of parameters within the limits of $P(\alpha_{max.}, r = 0)$ and $P(\alpha_{min.}, r = 0)$, giving rise to parameter linear difference,

$$\Delta p = P(\alpha_{min.}, r = 0) - P(\alpha_{max.}, r = 0), \qquad \text{XXVI}$$

so that from XXIV we have,

$$\Delta p = F.(\cos \alpha_{min.} - \cos \alpha_{max.}). \qquad \text{XXVII}$$

Then the focal spread on either side of the mean focus at $\frac{1}{2}(p_{max.} + p_{min.})$ may be written

$$df = \tfrac{1}{2}\Delta p(\alpha_{min.} \text{ and } \alpha_{max.}) \qquad \text{XXVIII}$$

From the relations expressed by XX-c and XXVIII, we obtain

$$\frac{df}{dH\rho} = \frac{4\bar{H\rho}(\cos\alpha_{max} + \cos\alpha_{min})}{\int_{-z_2}^{z_1} H^2(z)\,\phi(z)\,\frac{r}{z}} \qquad \text{XXIX}$$

where $\bar{H\rho}$ is the momentum of the βeta particles focused at $\frac{1}{2}$(p maximum + p minimum). Then the resolving power of the spectrometer which is the reciprocal of the ratio between the momenta of βeta particles focused at the mean focus and their corresponding spread $\Delta(H\rho)$ may be written

$$\frac{\Delta H\rho}{\bar{H\rho}} = \frac{\Delta p}{2F(\cos\alpha + \cos\alpha_{min})} \qquad \text{XXX}$$

From the expression XXX, it is obvious that, apart from minor factors such as aberrations in the electron lens system, the resolving power is mainly determined by the magnitude of the fraction of 4π in solid angle employed in the design of the spectrometer for attaining the required efficiency. In the case of the spectrometer, shown in the Fig.16, a further increase of the resolving power can be effected only at the expense of the required efficiency. For the study of the energy spectra of weak artificial radio active and other sources, high efficiency is very desirable. In these cases where the spectra are often simple, the resolving power associated with the attained efficiency should be quite satisfactory.

CHAPTER II

Devices of detection of β-ray energy spectrum and automatic registration of electrical counter impulse frequency

1. Introduction.

As a detecting device of βeta ray energy spectrum, a counter, which embodies the electrical effects of ions produced by the passage of charged particles of sufficient kinetic energy, is used. In conjunction with the electrical counter, the equipment is comprised of an amplifier, an adaptor, a scaling system together with a circuit of a thyraton operated mechanical recorder and the sources of power supply.

2. Electrical counter.

An electrical counter of Geiger Muller type is fitted to one end of the spectrograph for the detection of βeta-ray particles concentrated on the effective region of the counter by the selective focusing action of the magnetic lens. The counter, shown in Fig.18, is made of a brass tube 3.5 cm. in diameter and 7 cm. long, with its inner walls carefully smoothened with graded emery paper and highly polished with metal polish till its surface is free from lines and scratches. As the

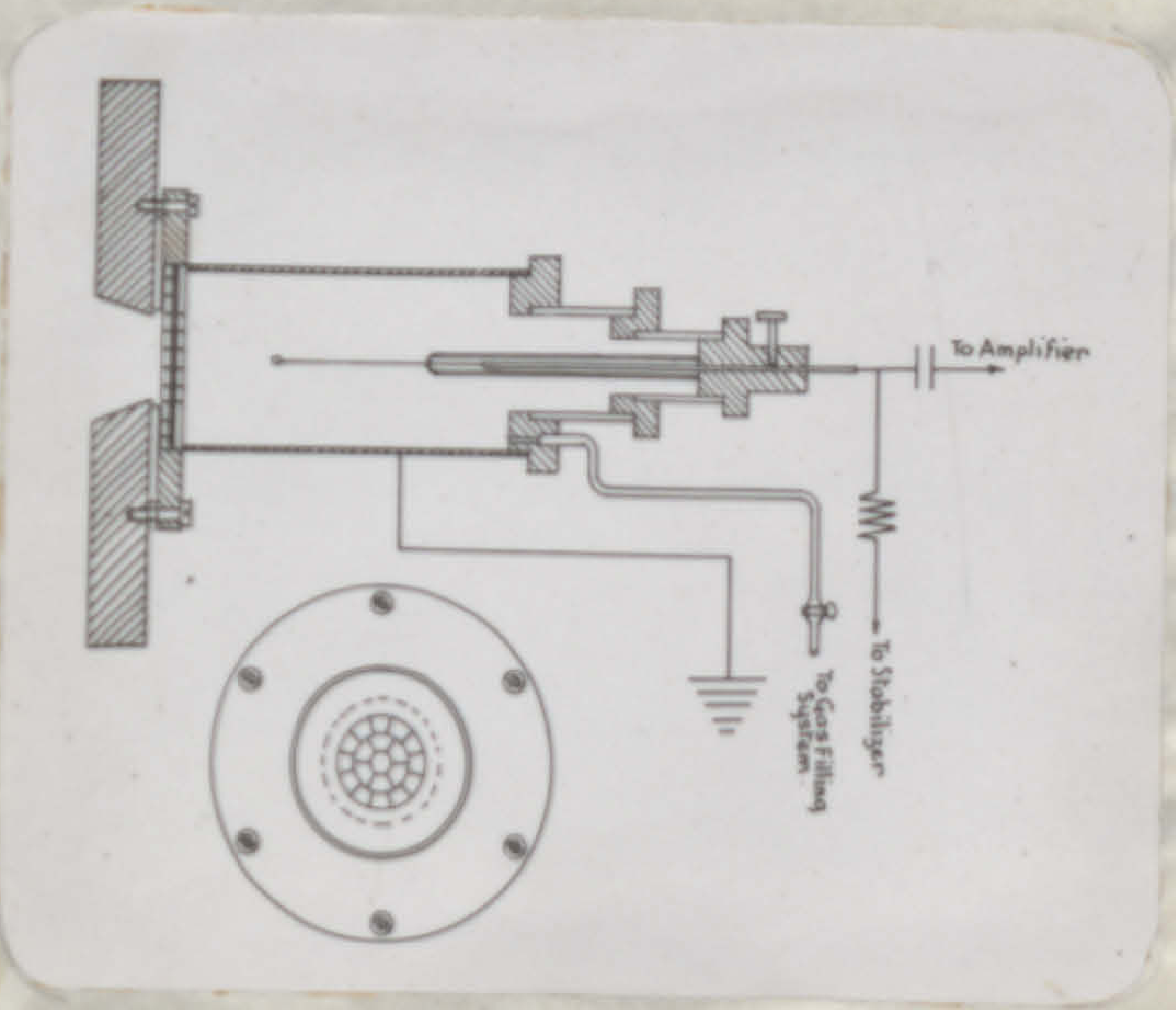


Fig. 18.

counter is connected directly to the spectrograph without any electrical insulation, it is essential to keep the walls of the tube which form its outer electrode at earth (zero) potential.

The other electrode of the counter, a tungsten wire 0.2 mm. in diameter, mounted on a brass rod and fixed along the axis of the tube, is positively charged. The counter appears to work the best when the positively charged axial electrode is ball ended. Hence a ball of pyrex glass, nearly spherical, about 1.5 mm. in diameter, is mounted on the free end of the tungsten wire by fusion. The ball is covered by a layer of Indian ink not only to render the ball conducting but also to make its spherical surface even.

The tungsten wire is held in position by inserting its other end, slightly bent into a hook shape, into a fine hole nearly 1 cm. deep axially drilled along a brass rod 1.5 mm. in diameter, and is firmly locked by means of solder. The brass rod, on which the tungsten wire electrode is mounted, passes along the axial passage of a brass cap and is fixed by means of a small clamping screw. The part of the brass rod within the body of the counter and its end on which the tungsten wire electrode is mounted together with ½ cm. of the tungsten wire near the locked joint is jacketed by means of a pyrex glass capillary, so as to eliminate spurious discharge. One end of the capillary jacket is waxed to the inner surface of the brass cap, while the other end, well rounded by fusion, extends 1.75 cm. further into the body of the brass tube from the inner wall of the primary brass mounting waxed at one end of the tube. This capillary jacket arrangement has been found to have contributed not a little towards the achievement of the flatness with abrupt endings of the counter characteristic curve.

The brass cap which supports the axial electrode is fixed to a small pyrex tube fitted in a small brass ring-mounting. This secondary brass mounting, which may be utilized, if necessary, as a guard ring, is in turn mounted on another piece of pyrex tubing of the same length but of slightly larger diameter than the former one. This latter pyrex tubing is fixed in the primary brass mounting, fitted and waxed to one end of the brass counter-tube. These two pieces of pyrex tubing, one between the end cap-mounting and the secondary ring-mounting and the other between the primary and the secondary mountings, keep the two electrodes perfectly insulated and separated from one another after assembling them together to form the electrical counter.

A baffle plate, with a circular grid 3.6 cm. in diameter, filed carefully by means of needle files, is silver soldered to the other end of the counter tube in such a way that the centre of the grid lies on the axis of the tube. The baffle-grid plate of the counter is firmly silver soldered to a ring-flange.

A mica window (from 2.7 to 2.15 mgm. per cm^2 thick equivalent to a stopping power of 1.9 to 1.5 cm. air) is mounted and sealed on the grid plate of the counter by Apiezon wax. An auxiliary brass grid, which is equally as transparent as the former, is fixed on the mica window in the body of the ring flange in such a way that the spokes of the one nearly overlap those of the other, and is then sealed all round to the inner walls of the ring flange of the counter.

The entire counter is thus kept perfectly air-tight. Any accidental variations of pressure either in the counter or in the spectrograph does not damage the mica window, as it is supported on either side by the counter and the auxiliary grids. It is essential that the mica window and the outer grid lie within the body of the ring-flange of the counter so as to avoid any mechanical strain to the sealed mica window, grid and their joints, when the counter ring flange is firmly fixed on the side lid of the spectrometer tube.

The counter flange, with a lightly greased rubber washer, is mounted on the side lid of the spectrometer in such a way that the axial electrode of the counter lies along the axis of the spectrometer tube. The counter flange and the side lid of the spectrometer tube are clamped together and tightened firmly by means of clamping screws to render the joint vacuum tight.

As an internal extinction counter with the resistance in series and a simple amplifying system has many advantages in comparison with the resistance extinction counters, the counter is fitted with a permanent arrangement to provide an internal means by which the discharge is extinguished. In this arrangement a small leak, about a mm. in diameter, drilled in the primary brass mounting of the counter is connected to a conducting capillary with a stop cock, joined permanently to alcohol vapour, argon gas filling systems and an exhaust pump.

Firstly, the counter is exhausted thoroughly almost to a pressure of about 10^{-3}mm Hg by the rotary exhaust pump, and is then filled with ethyl alcohol vapour and argon to the required partial pressures so as to provide the means of internal extinction of the discharge and of the operation of the counter. After filling the counter with alcohol vapour and argon, the taps of the alcohol and argon gas reservoirs and the stop cock of the conducting capillary are shut so as to isolate the counter from the exhaust pump and the filling system in order to maintain the necessary partial pressures of alcohol vapour and argon gas in the body of the counter.

2 (a) Counter characteristic

The counter, filled with a mixture of ethyl alcohol vapour and argon gas with partial pressures of about 1.5 cm. and 7.5 cm. respectively, has proved satisfactory for operation over periods extending several weeks. The threshold counting voltage has been in the neighbourhood of nearly 1,500 volts. With a resistance of about 10 MΩ in series, in conjunction with a three stage amplifier, the counter has given a consistently reproducible characteristic curve with a flat region of about 200 volts, as can be noted from the experimental data plotted in the graph given in Fig.19. The curve (A) refers to cosmic rays as a source of ionization, while the curve (B) γ-rays from an artificial radio active element as an ionization source. As the voltage is increased, there is first no counting whatsoever, then almost at the very threshold voltage of counting the number of counts rises quite steeply to a flat region. In this flat region, the counting rate is independent of the voltage. At a further increase of voltage, the number of counts in both of these curves again increases, and this increase appears to be independent of the source of ionization.

The counter operation has been checked from time to time by observing the cosmic ray background at a particular voltage in the flat region, and the counting rate of the F-line of ThB+C+C'+C" of a definite standard,

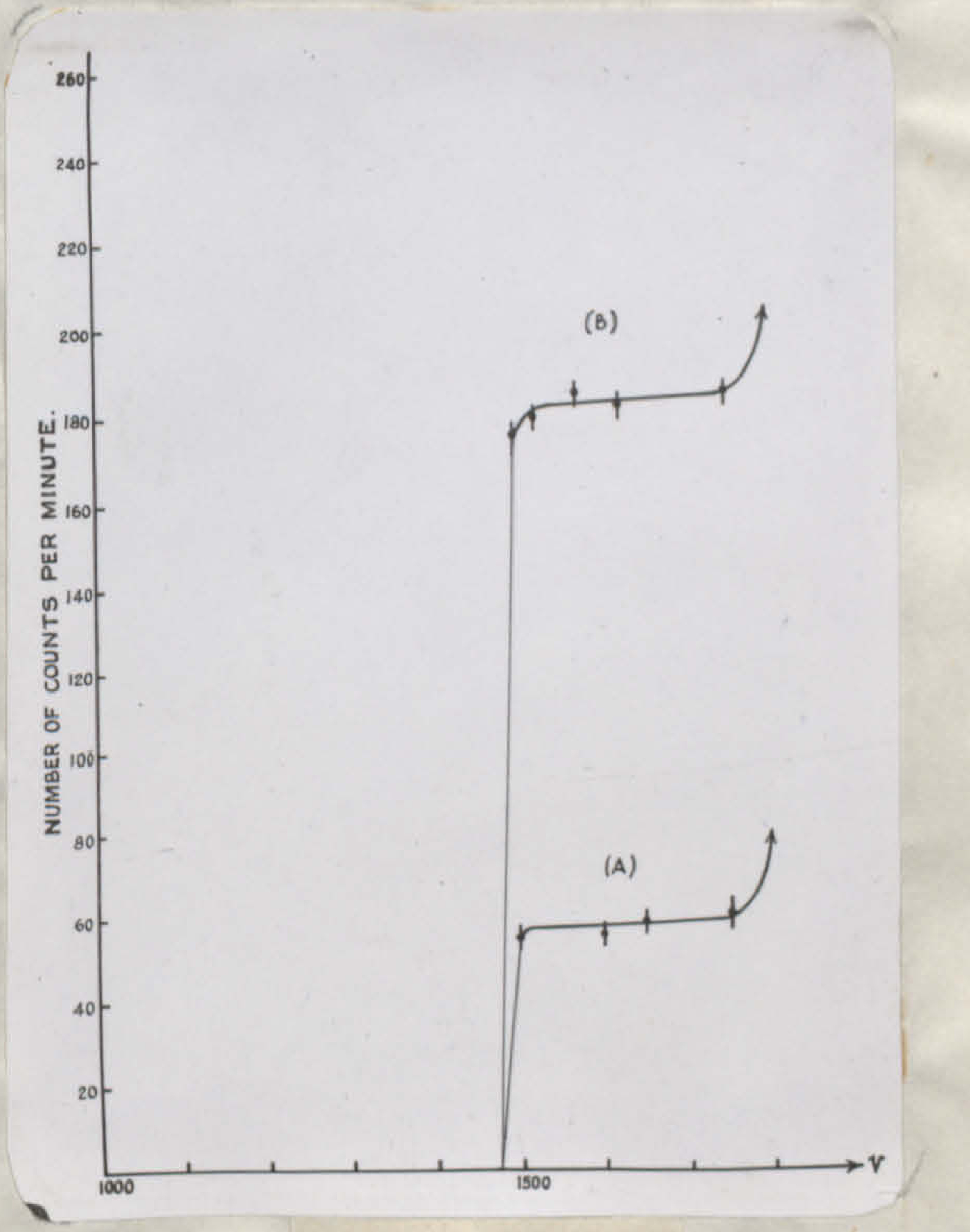

260
240
220
200
180
160
140
120
100
80
60
40
20
NUMBER OF COUNTS PER MINUTE.
(B)
(A)
1000
1500
V

Fig. 19.

defined by an arbitarily chosen number of γ-counts given by the source.

3. An amplifier and an adapter.

(a) Three stage amplifier.

The impulses of an electrical counter are usually of the order of 10^{-2} to 10^{-3} volt. With such a low amplitude, they are not adequately effective as to render the thyratron operated mechanical recorder operative and consequently are incapable of being recorded by the automatic recording device. The counter, therefore, is provided with an amplifier, shown in Fig.20, to amplify and equalize the amplitude of the impulses in order to secure the registration of the counter impulse frequency with satisfactory degree of accuracy. The operational principle of this amplifier, like that of the linear amplifier of Wynn-Williams and Ward[10], is in a way similar to that of an audio frequency amplifier.

The amplifier, as shown in Fig.20, employs three stages of resistance-capacity coupling. The greater part of the amplification is accomplished with the first two pentode tubes and the short time constant is between the second and the third tubes. The impulses, transmitted to the grid of the third tube are negative and with the positive grid bias, minor impulses, caused by the secondary electrons in the counters and by the micro-

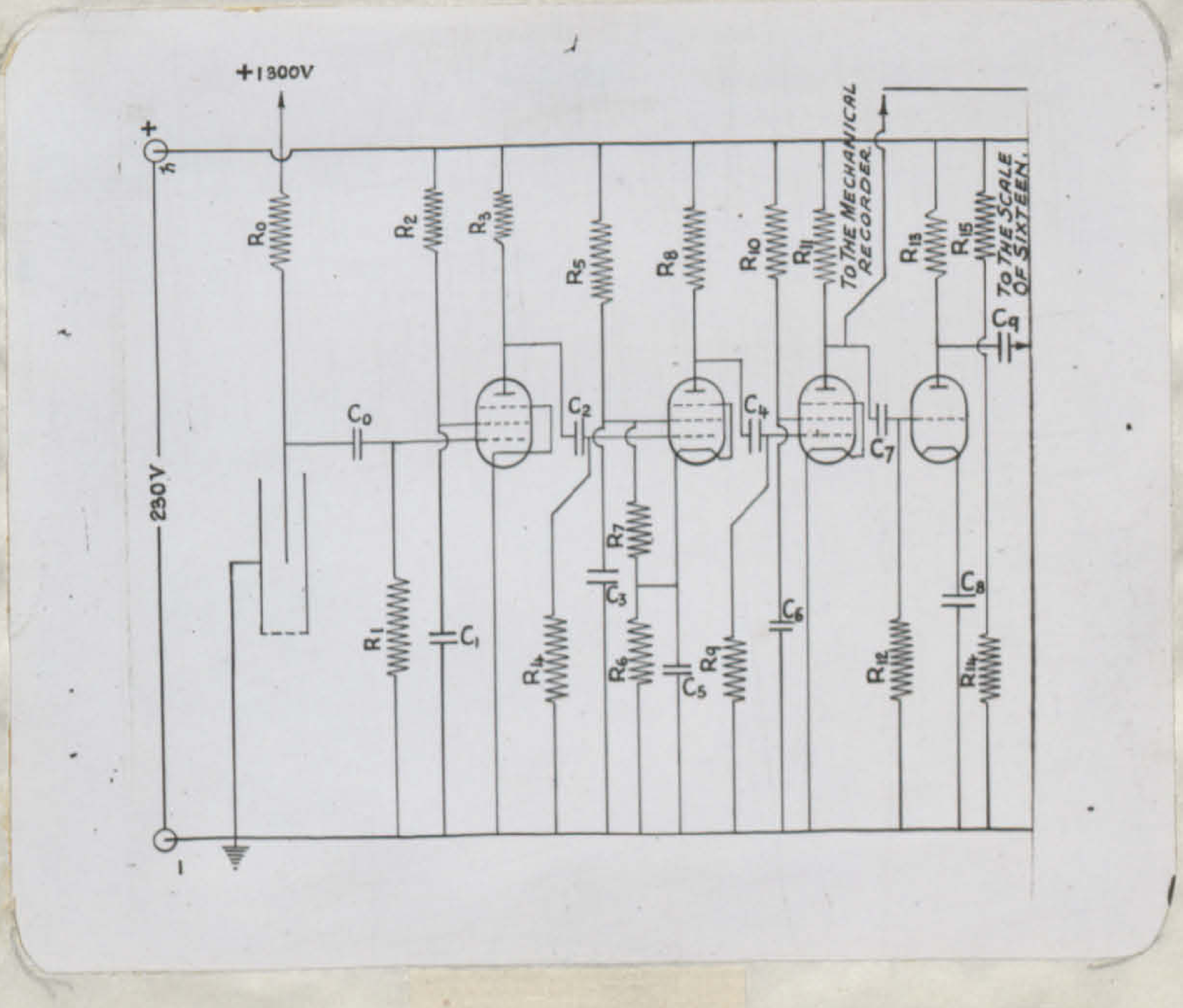

+1300V
+
h
230V
−
R0
R1
R2
R3
R4
R5
R6
R7
R8
R9
R10
R11
R12
R13
R14
R15
C0
C1
C2
C3
C4
C5
C6
C7
C8
C9
TO THE MECHANICAL RECORDER.
TO THE SCALE OF SIXTEEN.

Fig. 20.

phonics of the first tube, are suppressed.

A resistance-capacity coupling of a fairly large time constant has been employed between the first and the second tubes so as to obtain equalization of the pulses in the second stage, which is important from the view of the short time constant of the resistance-capacity coupling between the second and the third tubes. The levelling of the impulses is in fact found very advantageous for easily bringing the accompanying scaling system into a working order so as to accomplish a very reliable scaling of the impulse frequency.

The output pulses of the third stage, being of positive potential, may be directly transmitted to a thyratron operated mechanical recorder for automatic registration of the counter impulse frequency. The electro-mechanical recorder, however, is unable to cope with the high rate of impulse frequency. Hence the impulses are scaled down by means of a scaling system, shown in Fig.22, and are then transmitted to the mechanical recorder. As this scaling system, however, is ineffective to the pulses of positive potential from the third stage of the amplifier, the output negative pulses of the second stage of the amplifier may directly be applied to the suppressors of the first stage scaling valves through a condenser of a reasonably low capacitance.

(b) A triode valve adapter.

In the unit shown in Fig.20, the output pulses of positive potential from the third stage of the amplifier are applied to the scaling system through a triode valve adapter whose output pulses to the scaling system are of negative potential. With proper selection of RC-value of the coupling between the second and the third stages of the amplifier, the amplification and the time constant of the adapter stage, the amplitude, form and time constant of the input pulses applied to the scaling system can be readily moulded with greater flexibility and degree of freedom to a magnitude and form necessary for easily accomplishing scaling action, and therein lies the advantage of the adapter unit.

4. Scaling systems and a circuit of a Pentode vacuum tube scale-of-sixteen.

(a) Introduction.

The spectrograph excels in efficiency many other spectrographs, both the semi-circular type and the magnectic electron lens type. The electrical counter, which is fitted to the spectrograph as a detecting device, receives a large number of βeta particles even from comparatively weak sources. The frequency of the electrical counter impulses, on this account, being great, the mechanical recorder is quite unable to cope with the speed. Hence it is essential to construct a unit by which randomly distributed impulses of high rate of frequency can be scaled down to a rate at which a relatively slow mechanical recorder would operate satisfactorily.

(b) Types of Scaling Circuits.

There have been two types of scaling down circuits, the one using mercury Thyratron tubes based on the well-known design of the Thyratron scale-of-two of C. E. Wynn-Williams[11], or a circuit employing 885 Argon filled tubes based on the design of Shepherd and Haxby[12], and the other a form of multivibrator circuit[13] of hard vacuum tubes adopted for use in scaling circuits.

(c) Thyratron Scale-of-two.

The Thyratron type of scaling circuit of Wynn-Williams[11] is used with advantage for many purposes. Its speed, however, being limited by deionization time of Thyratrons, is not satisfactory for high counting rate. The resolution time of these circuits being long, if the pulses arrive at comparatively short intervals, which may occur sometimes even at low counting rate, the circuit may be rendered inoperative. These limitations, inherent in the mercury Thyratron tube scaling system, which forms a serious handicap to high rate impulse frequency measurements, are overcome to some extent in the counter circuit[12], employing type 885 Argon filled tubes, because the operation of these gas filled tubes, unlike that of mercury Thyratrons, is independent of the temperature and also their deionization time is shorter than that of mercury Thyratrons. This circuit, however, has one disadvantage - it involves the use of coupling tubes for arresting the large negative pulse and thus preventing the occurrence of doubling.

(d) Argon filled tube scaling circuit.

A scaling circuit employing 885 type of Argon tubes has been designed by I. Giarratana[14]. This circuit is stable and reliable, and is obviously much simpler than the former one in as much as the coupling tubes have been eliminated. With this arrangement of scale-of-eight, it is possible to obtain records up to speeds of 3,000 random counts per minute without appreciable loss. The time constant of the input pulse, however, cannot be made adequately small so as to choose the resolving time of the first and the subsequent stages sufficiently small, because of the coupling condensers of high capacitance. Therefore, either when the interval between random impulses happens to be too small or when the counting rate of random impulses is high, impulses may easily be missed, resulting in appreciable counting losses.

(e) Advantages of vacuum tube scaling circuits.

The difficulties associated with mercury Thyratron scaling circuit and Argon filled tube scaling circuit are overcome in the scaling circuits of hard vacuum tubes in as much as they have high speed and stability which render comparatively short resolving time possible. Vacuum tube scaling circuits, broadly speaking, are based on a special application of the principle of retroaction to two vacuum tubes so as to produce two conditions of stability. In one condition, one tube of the pair has low impedance and therefore is conducting, while the other has high impedance and consequently is blocked. In the other condition, on the other hand, the situation is reversed so that the former one is non-conducting and the latter is conducting. In a design involving such a principle of operation, scaling down the rate of random impulses to a half is accomplished in as much as at each incident pulse the circuit is tripped from one stable state to the other.

(f) Triode and Pentode vacuum tube scaling circuits.

Published scaling circuits employing vacuum tubes are all modifications of the outlined scheme, with slight differences in the constructional and certain operational details. The constructional details influence to a considerable extent the stability, the reliability and the efficiency of a scaling circuit. There have been two kinds of circuits employing vacuum tubes, one kind with triode valves and the other with pentode valves.

(g) Triode vacuum tube scaling circuit of Lewis.

Lewis[15] has designed a scaling system based on a symmetrical circuit of two vacuum triode valves having two states of equilibrium. When a positive impulse is applied to the line between the bias rectifiers connecting the grids of the two valves, the circuit is triggered from one stable state to the other. A continuance of the relative change of the grid potentials is maintained by the inductance of the choke included in the circuit so that the stable state which results is not the one from which the unit started. Thus successive impulses drive the unit alternately from one stable state to the other. A scale-of-eight comprises three of these scale-of-two units, followed by a Thyratron operated mechanical recorder.

A scale-of-eight circuit employing hard vacuum valves is expected to achieve a much higher counting rate than the one employing mercury thyratrons. But Lewis's scale-of-eight has a maximum counting rate of only 3,000 counts per minute, which is not greater than that obtained by the thyratron scale-of-eight. The advantage of high speeds obtainable by hard vacuum valves could not be turned into good account because of the restrictions associated with the coupling condenser and the choke. The circuit is stable, reliable and satisfactory for many purposes. It does not involve complex coupling units besides simple condensers for its operation. The employment of specially constructed grid bias rectifying units and chokes, however, makes the construction of the circuit far from simple.

(h) Lifschutz-Lawson's triode vacuum tube scaling circuit.

A scaling circuit employing triode valves, in which the high speed of such vacuum tubes is made use of for obtaining high counting rates has been designed and constructed by H. Lifschutz and J. L. Lawson[16]. A circuit employing two triode vacuum valves forms a scale-of-two unit in which pulses are applied to the valve grids in parallel through resistance-capacity coupling. The first valve of the pair is direct coupled to the other by a resistor from its plate to the grid of its mate, and similarly the second one is direct coupled to the first. Hence the system is symmetrical. The symmetrical direct coupling causes the circuit to have two stable states. Input pulses trip the circuit from one stable state to the other, causing an increase or decrease of the plate potential of each valve at alternate pulses. An electrical division by two is accomplished by the transmission of the plate-potential changes of the second valve to a thyratron operated mechanical recorder which operates only at the positive changes.

In a multiple-stage scaling circuit, the output pulses of the second valve of each stage are fed by RC coupling to an additional triode valve which is biased past cut-off so that only every other pulse is transmitted to the next scale-of-two. A scale-of-sixteen built by Lifschutz and Lawson comprises four such triode scale-of-two systems with triode coupling elements, followed by an output stage operating a mechanical recorder. This circuit has a high rate of impulse frequency counting and seems to be stable and reliable. It cannot, however, be deemed to be simple owing to the complex triode valve coupling units. In a scaling circuit of this type, if simple triode vacuum tubes are employed, the oscillations of the one may be picked up by the rest of the stages. It is also sensitive to external disturbances. These defects which cause spurious countings and render the counting records unreliable can be eliminated by covering the components of each stage by a separate grounded metal shielding or by employing triodes of the metal shell self shielding type.

(i) Alfven's triode vacuum valve scale-of-two circuit.

A circuit of a scale-of-two employing triode vacuum tubes which is simpler than that of either Lewis or Lifschutz and Lawson has been designed and constructed by H. Alfven[17]. Though the principle of its operation is similar to that of the other two, it differs from them in certain constructional details. Unlike Lewis's circuit, neither cuprous oxide rectifiers nor chokes are employed in this circuit. An addition of two or more of these scale-of-two units of this design into a single system of multiple stages does not seem to involve triode valve coupling systems between the stages, unlike the multiple stage scaling circuit of Lifschutz and Lawson.

This circuit, like the other two, has two states of equilibrium. In one state, one tube is blocked and the other is conducting while, in the other state, the situation is reversed. Positive pulses, applied to the line between the "condenser-resistance grid biases' coupling" trip the circuit from one state of equilibrium to the other, and the resulting positive pulse from the plate through an auxiliary by-pass CR coupling drives the circuit into an opposite state after the tripping pulse is over. It is these conditions that render an electrical division by two possible. Impulses are transmitted from the plate of one of the valves through a RC coupling to a thyratron circuit which operates a mechanical recorder. A further scaling may be obtained by adding two or more scale-of-two units by directly connecting the output of one stage to the input of the next without coupling units.

Alfven has mentioned neither the highest obtainable counting rate nor the efficiency of its performance in his publication[17]. With his counter circuit, he obtained records of about 200 counts per minute, and this rate obviously is too low for nuclear measurements. He points out, however, that higher counting rate may be obtained by this unit. The circuit is steady and reliable.

(j) Pentode tube scaling circuits.

Scaling circuits employing Pentode tubes have been developed by (1) Stevenson and Getting[18], (2) Reich[19] and (3) Frisch[20]. These scaling circuits, like the triod vacuum tube scaling systems, are designed so as to apply the principle of retroaction to two vacuum tubes. Their constructional and operational details, however, differ to a great extent from those of triode vacuum tube scaling circuits. With Pentode vacuum tubes, a thorough control over the operation of the scaling system, so as to obtain high efficiency and reliability, is more easily obtainable than with triode vacuum tubes. With Pentode valve scaling circuits, under certain conditions which are easy to realise, metal screening elements of the tubes and the grounded metal shielding walls between the stages may be omitted without impairing the insensitivity of the circuit to external disturbances.

(k) Pentode vacuum tube scaling circuit of Stevenson and Getting.

Stevenson and Getting [18] have devised a circuit employing Pentode tubes for scaling down counting rates. The circuit, in its essentials, consists of two Pentode vacuum tubes with a symmetrical arrangement of two sets of resistors across which a combination positive plate supply and negative grid bias is applied. The circuit has, of course, two conditions of equilibrium, in one state one tube is conducting and the other tube is non-conducting, while in the other condition the position is reversed so that the latter is conducting and the former is blocked. Two additional pentode vacuum tubes and condensers for cross coupling are employed in the circuit. The grids of the additional tubes are normally negatively biased and the plates of the pair are connected to those of the scaling pair. A positive pulse applied to the grids of the additional pair trip the circuit from one equilibrium state to the other, so that the initially conducting becomes non-conducting and the initially non-conducting becomes conducting. The next incident pulse which enters the second tube of the additional pair, connected to the present conducting tube, trips the principal scaling pair back to the original position. Thus successive incident pulses repeat the process. The resulting alternate positive potential changes of either one of the tubes of the principal pair are transmitted directly to the circuit of the mechanical recorder.

A scale-of-thirty-two, comprising five of such scale-of-two units, directly connected in series, finally followed by an output stage, operating a mechanical recorder, has been designed by Stevenson and Getting. The scaling circuit is efficient, stable and reliable.

It has a high resolving power. It is not simple and employs four pentode vacuum tubes for each stage. The circuit is not insensitive to external disturbances, and hence the sensitive parts of the circuit need adequate shielding.

(1) Reich's pentode vacuum tube scaling circuit.

A scale-of-two circuit which is a modification of a trigger circuit whose operation is based upon the principle of retroaction between two tubes, has been described by H. J. Reich[19]. It is simple in design, and, unlike the circuit of Stevenson and Getting, requires only two pentode vacuum tubes.

An operation of scaling is based upon triggering action. In this circuit the coupling is obtained by means of suppressor grids through a symmetrical arrangement of condenser-resistance by-passes. Input negative voltage pulses are applied to the control grids. The screen grids are normally at a positive potential, and the supressors at cathode potential. The circuit is very sensitive to negative voltage pulse, and is altogether insensitive to pulses of positive potential. A current transference from the tube 1 to the tube 2 presents a negative pulse, while its transference from tube 2 to tube 1 a positive pulse. It is because of these characteristics that, firstly, an electrical division into two may be accomplished, and, secondly, one stage may be coupled to the next without the use of coupling units and rectifiers.

The design of this scaling circuit is simple. It operates on a total voltage of about 45 volts. In this circuit the input pulses are applied to control grids which are by far the more sensitive than the rest. Hence it has a high degree of sensitivity which may be turned to useful account in cases where the amplitude of the incident pulses is very small. In cases where the electrical counter pulses are amplified, equalized with amplitude rightly adopted, such a high degree of sensitivity is not of any special value. This circuit is not insensitive to external disturbances. Therefore, it may easily pick up stray electrical oscillations and thus may give spurious counts. To eliminate these defects, the tubes and the sensitive components are to be adequately screened by grounded metal shields and the components of each stage are to be shielded from those of every other stage by grounded screening metal walls.

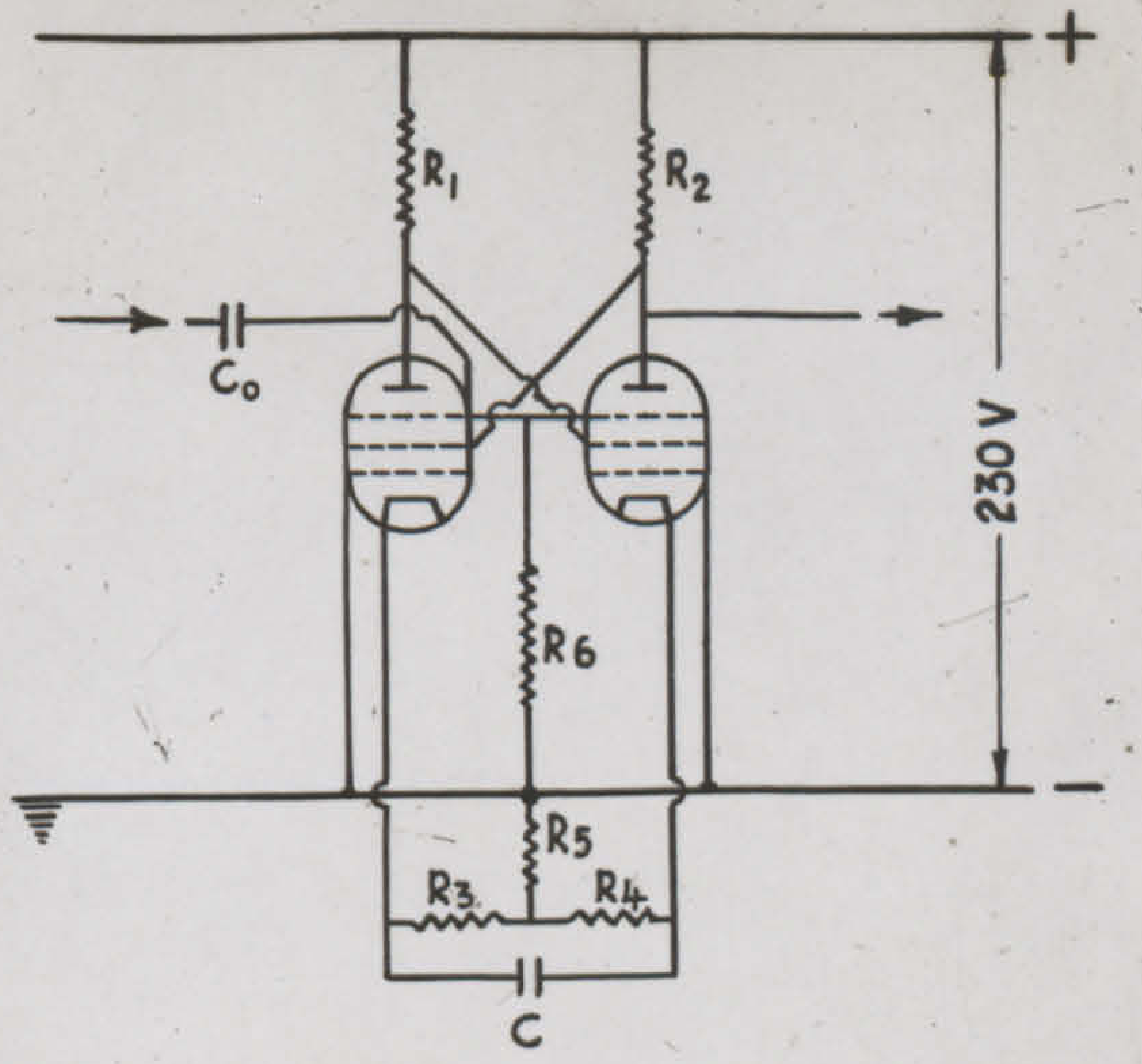
(m) Frisch's pentode vacuum tube scale-of-two.

A pentode vacuum tube scaling circuit can be rendered practically insensitive to external radio frequencies and other external disturbances by keeping the control grids at earth potential. In this case the triggering pulses which trip the circuit from one stable condition to the other are applied to the supressors. A scale-of-two with these simple modifications and with certain changes in the constructional details has been developed by O. R.

Frisch[20]. The principle of this scale-of-two circuit is not different from that of other vacuum tube scaling circuits. It differs from the rest in the constructional details which influence the operation and the efficiency of the circuit. The circuit, shown in Fig.21, consists of two pentode vacuum tubes, Sylvania 57 type, the coupling between these scaling tubes, essential for retroaction, being through screening grids and the pulses being transmitted to the suppressors in parallel.

The current through the resistor R_1 is the plate current of the tube I and the screen current of the other, while that through the resistor R_2 is the plate current of the tube II and the screen current of its mate. With a condenser C in parallel, the resistors R_3 and R_4, separately connected to the cathode of either one of the valves, the two scaling tubes are individually self-biased, while with the resistor R_5 the pair is self-biased in common. The symmetrical arrangement of the direct coupling permits the circuit to have two states of equilibrium; in one state one tube is conducting and the other is non-conducting, while in the other the condition is reversed.

A negative pulse applied to the supressor trips the circuit from one state of equilibrium to the other. Each time the circuit is triggered by an input pulse, the



FRISCH'S PENTODE TUBE SCALE-of-TWO.

Fig. 21.

current released through the individual self-biasing system with a condenser in parallel, provides for a time $(R_3 + R_4).C$ a bias to the control grid in excess to the common bias furnished by the current through the resistor R_5. The time constant of the individual self-biasing units with the condenser in parallel $(R_3 + R_4).C$ is so chosen as to let the additional bias survive the triggering pulse. The extra negative bias on the control grid, which lasts longer than the triggering pulse, drives the circuit into the reverse state after the pulse is over. The transmission of successive pulses of negative potential repeats the process, producing in each tube plate alternate positive and negative potential changes. A transmission of these potential changes of either one of the tubes into a thyratron operated mechanical recorder which is sensitive only to the positive potential pulses, accomplishes a scaling down of the counting rate to half the value.

The circuit is quite sensitive to negative pulses. Pulses of positive potential are, however, ineffective as they are absorbed by electron current. It is because of these characteristics that two or more of these systems may be joined in series without coupling units to obtain multiple stage scaling circuit. Frisch described a scale-of-eight circuit comprising three such scale-of-two units, joined together in series and followed by a thyratron operated mechanical recorder. In this system the alternate negative plate potential changes of one of the tubes of the preceding unit are directly transmitted to the one immediately succeeding it. Scale-of-eight units based upon the design of Frisch have been constructed and have been used in this laboratory with advantage in high speed counting for nuclear research.

Frisch's scaling circuit is simple in design and easy to construct. The circuit can be brought into working order within a reasonably short period. It requires fewer valves and other components than any other scaling circuit. It does not need coupling valves or other complicated coupling units. It has above all the great advantage over others of being practically insensitive to external disturbances and yet adequately sensitive to tripping pulses of comparatively low potential.

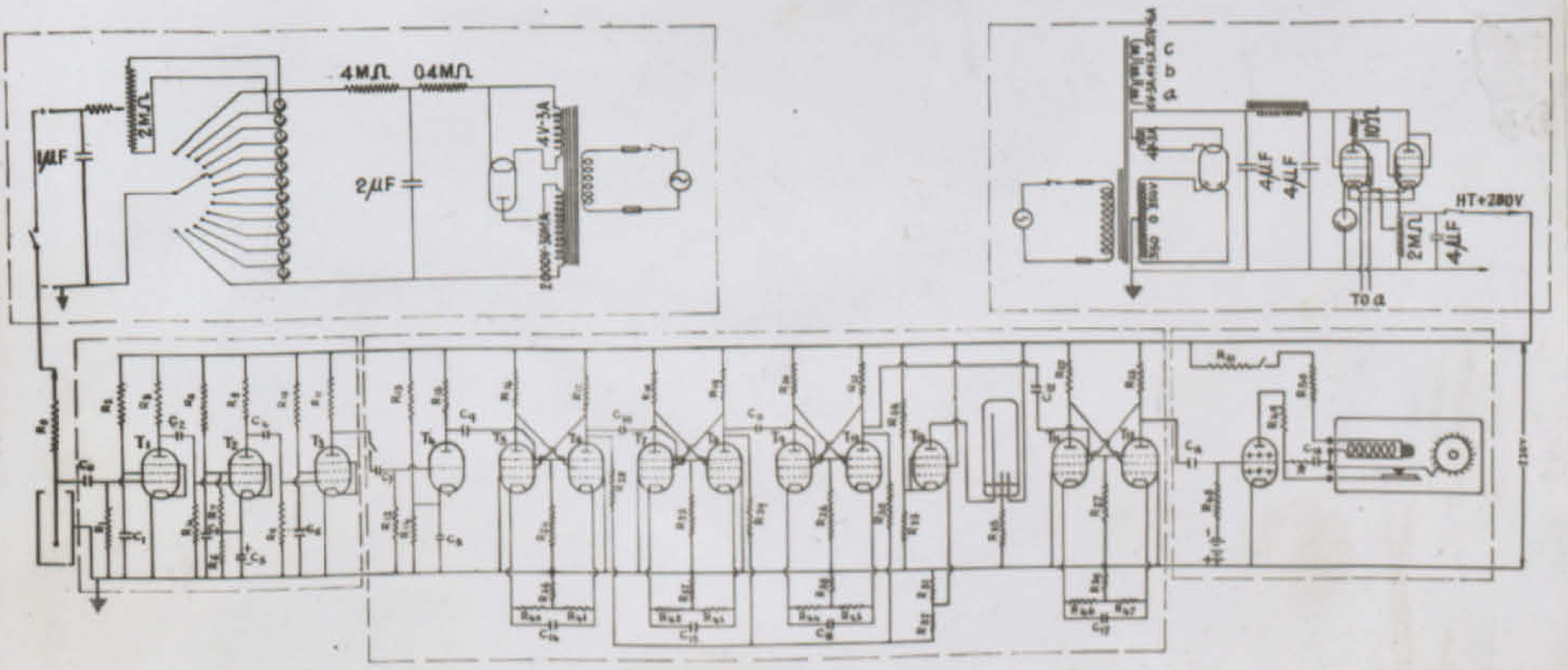
(n) Pentode vacuum tube scale-of-sixteen.

The employment of an electrical counter for the investigation into the nuclear processes of radio active elements has been one of the most sensitive methods of scientific research. Owing to high sensitivity, it is capable of indicating the presence of radio activity even from very feeble sources. Hence it may be regarded as one of the most efficient and outstanding methods.

Electrical counter circuits, owing to their sensitivity, however, are prone to be sensitive even to stray electrical oscillatory discharges and radio frequencies.

These external disturbances which may easily influence the counter circuits may render the counter records erroneous. Errors in counter records are very undesirable obstacles for the reliability and the precision of the spectrometric analysis of the energies and the intensity of the charged particles emitted by radio active elements.

To secure precision of the spectrometric analysis, it is essential to construct a high speed counter circuit which is quite sensitive to the actual counter impulses due to the charged particles from radio active sources, which copes with high impulse-frequency and which is practically insensitive to external disturbances. With this object in view, a circuit of pentode tube scale-of sixteen, involving those modifications in the constructional details so as to render it quite sensitive to electrical counter impulses but practically insensitive to external disturbances, has been constructed. The circuit is based upon Frisch's scale-of-two shown in Fig.21. The scale-of-sixteen, which is constructed for using with the detecting device of the spectrograph, comprises four of these scale-of-two units, placed side by side connecting + to +, - to - and output to input, followed by a thyratron operated mechanical recorder and with an extra pentode valve operated visual indicator for interpolation, as shown in Fig.22.



A CIRCUIT OF AN ELECTRICAL COUNTER, AMPLIFIER, SCALE OF SIXTEEN WITH VISUAL INDICATOR THYRATRON OPERATED MECHANICAL RECORDER AND THEIR SOURCES OF POWER SUPPLY.

Fig. 22.

(c) The characteristics and the basic principles of construction and assemblage.

The operation of a scaling circuit is determined by the amplitude, the resolving time and the abundance of higher harmonics of the input pulses.

Pulses of a very low amplitude are incapable of tripping the circuit from one state of equilibrium to the other. The amplitude should be adequately large, and, for the range of such amplitudes of input pulses, the circuit must be provided with a balancing self-biasing system common to the pair of scaling tubes. Pulses of much larger amplitude which exceed the limit, knock down the individual self-bias in excess to the one common to the scaling tubes with the result that the system is not forced to the reverse state of equilibrium after the pulse is over. Therefore the circuit, though it oscillates, is incapable of proper scaling action.

Since the individual self-bias in excess to the one common to both should survive the tripping pulse in order to urge the system to the reverse state of equilibrium after the pulse is over, it is essential that the resolution constant $(R_3 + R_4).C$ is larger than the time constant RC of the input pulses. But if the $(R_3 + R_4).C$ of the excess of self bias is too long as to survive not only the tripping pulse but also the arrival of the immediately succeeding pulse or pulses, the latter will not be counted separately.

The operation of a scaling circuit may be considered to be depending also upon the abundance in higher harmonics of the input pulses. A pulse is said to be abundant in higher harmonics if it has either a steep rise or a steep fall. Such a pulse with a clear cut and definite effective front has a well defined tripping function upon the scaling circuit. Consequently, even in high impulse frequencies, as the tripping actions of the successive input pulses do not overlap, pulses abundant in higher harmonics contribute a great deal to the most satisfactory operation of the scaling circuit.

If these characteristics and the basic principles are realised in the construction and assemblage of a multiple stage of scale-of-two circuit, it will be remarkably simple and easy to bring the whole system into perfect working order within a reasonably short period.

(p) Interpolation.

The number of counts in a given time may not be an exact multiple of the scaling ratio. The actual number of counts scored by the counter over and above the reading of the mechanical recorder is obtained by any one of the methods of interpolation. There are three of these, known as the meter method, the 'Electron eye' method and the neon indicator method. These methods are useful not only for determining the number of counts scored by the counter over and above the reading given by the mechanical recorder but also for observing and checking the individual performance of each stage of the multiple stage scaling system.

(p.1) The Meter Interpolation Method.

The meter method transmits a portion of the plate current from one of the tubes in each stage to a common milliameter. The contribution of the first stage is adjusted by the choice of a suitable resistor to one unit, that of the second to two units, the third to four units and so on according to the number of scale-of-two stages employed in the multiple stage system. At the commencement of a run all the tubes feeding the meter are set at a non-conducting equilibrium. Hence the meter reading is zero. After the arrival of the first pulse, the tube of the first stage feeding the milliameter becomes conducting so that the meter records one unit. Then with the second input pulse, while the tube of the first stage connected to the meter ceases to be conducting, the tube of the second stage connected to the meter becomes conducting. The meter, therefore, having drawn from the tube of the second stage twice as much as that drawn from that of the first stage, records two units indicating that two pulses have been scored. Similarly, with successive pulses the meter reading goes up in uniform steps and falls back to zero when the number scored has reached the scaling ratio.

(p.2) The 'Electron Eye' Interpolation Method.

The 'Electron Eye' method of interpolation employs electron ray tubes, one tube being direct coupled to each scale-of-two stage. In this method the number assigned to that scale-of-two stage is added to the reading of the mechanical recorder when the 'eye' of the tube belonging to that stage is opened. The additional number of counts scored over the reading of the mechanical recorder can be more easily read by the meter method than by the 'Electron eye method'. The electron ray tube has the advantages of being extremely fast and of not reacting on the scaling circuit.

(p.3) The visual indicator method of interpolation.

This method, devised by Frisch[20], has the advantages of not only precisely indicating the actual number of counts scored by the counter over the reading of the mechanical recorder but also of being fast and of not reacting on the scaling circuit. Owing to these advantages, a system involving this method has been included in the scale-of-sixteen circuit, as shown in Fig.22.

The visual indicator consists of a neon visual tuning tube ('Tuneon' - General Electric Company, England), whose long wire electrode is placed in the plate circuit of an additional pentode vacuum valve 'Sylvania 57 type', its grid bias being connected through suitable resistors to the plate of one of the tubes of each one of the four scale-of-two stages. It is essential that these coupling plate resistors from the first to the fourth scale-of-two stage are in the ratio of 8:4:2:1 in order to obtain a glow discharge of the wire electrode growing up in equally measured steps with each input pulse.

At the beginning of a run of the scaling circuit, when all the tubes feeding the grid bias of the additional valve coupled to the visual indicator are set at non-conducting equilibrium state - as there is no excess of bias added to the normal grid bias of the additional valve - the grid potential is a minimum and consequently the plate current drawn by the long wire electrode is also a minimum. In this stage, therefore, the glow discharge of the wire electrode, like a spot, is localised at the foot of the wire electrode. As the first input pulse trips the circuit, the valve of the first stage, connecting the grid bias of the additional valve, becomes conducting so that its plate current which passes through the resistor will be an additional bias in excess to the normal bias. Thus successive pulses render the tubes of the successive stages, connected to the grid bias of the valve coupled to the visual indicator, one after another conducting. Therefore, with each input pulse, the grid bias of the valve coupled to the visual indicator is increased in equal steps in excess of the normal bias, and, consequently also the grid potential in equal steps, so that with the input of each pulse the length of glow discharge of the wire electrode increases in equal measures. In this way the length of the glow discharge of the wire electrode keeps on increasing in equal measures until the number of counts scored reaches the scaling ratio, when the thyratron flashes and operates the mechanical recorder. Then the tubes of the four scale-of-two stages connected to the grid bias of the additional valve of the visual indicator are once more in the non-conducting equilibrium state, the grid bias and the grid potential run down to their initial values and consequently the glow discharge of the wire electrode falls down to the zero position. If the full length of the glow discharge of the wire electrode is calibrated into divisions, each division corresponding to the length of the glow due to each input pulse, the number of counts scored over and above the reading of the mechanical recorder can be directly read from the visual indicator tube divisions.

In the circuit of the scale-of-sixteen, shown in Fig.22, only the first three stages have been connected to the circuit of the visual indicator with the coupling resistors in the ratio of 4:2:1 to the circuit of the pentode vacuum tube operated visual indicator, the fourth stage being kept free so that for every sixteen counts which give one count on the mechanical recorder, the visual indicator makes out two turns from zero position to the full glow and back to the zero position. With this arrangement, also, the number of counts scored over and above the reading of the mechanical recorder is determined.

5. A thyratron circuit for operating a mechanical recorder.

A telephone message register with a 1,000 Ohms coil and a break contact is used as an impulse frequency recording device. It operates in less than 1/15th second, and is capable of recording about 800 to 900 counts per minute without an appreciable counting loss.

The telephone message register, as a recording counter, is rendered operative by a circuit, shown in Fig.23, involving a thyratron, T.31 type, from General Electric Company, England. The release of the counts recorder after operation is effected by an armature break contact, which interrupts the thyratron anode circuit.

Spark discharge at the armature break contact is liable to give electro magnetic pick-up in other parts of the counter circuit. A condenser of about 1uF in series, with a resistance of about 200 Ohms connected between the contacts, has been a satisfactory means of suppression of sparks, and thus of elimination of electro magnetic disturbances.

6. Sources of power supply.

(a) Eliminator.

A stabilized voltage of the order of 200 to 300 volts is required for high tension and grid bias supplies, necessary for the amplifier, the scaling system and electro-mechanical recorder. The necessary degree of voltage stabilization for the satisfactory operation of

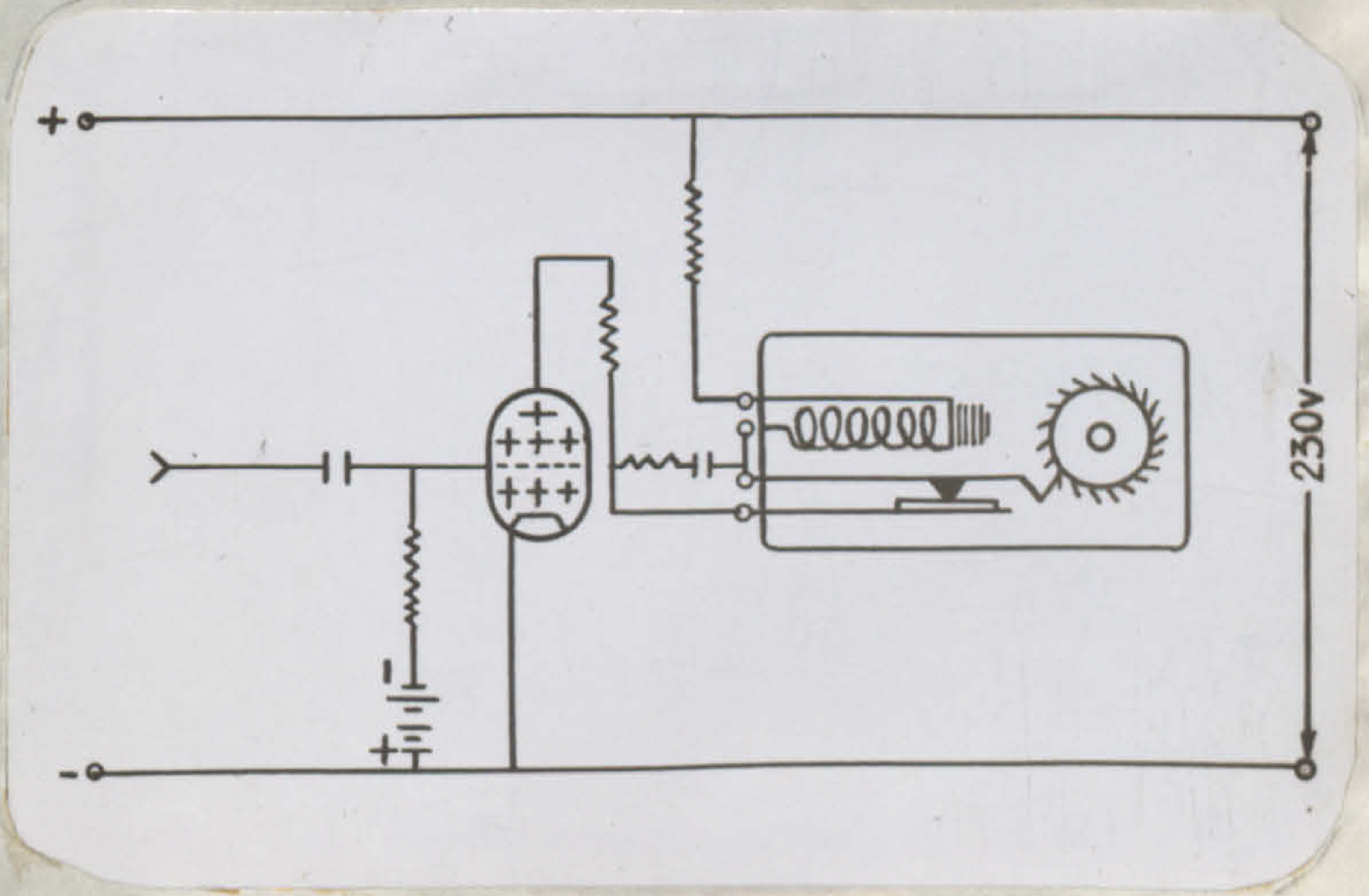


Fig. 23.

the entire circuit of the counting system is secured by a stabilizing unit, known as an eliminator.

The eliminator circuit, shown in Fig.24, employs the rectifying, the filtering, the smoothing and the suppressing elements. It is comprised of a mains transformer with low tension secondary filament windings and a high tension winding centre tapped, a double diode, U 12/14 type, for biphase half wave rectification, a 4 uF condenser input filter immediately across the rectifying valve to supply current during the period of the non-conducting state of the rectifier valve, a choke of the order of 30 to 50 henries for the improvement of smoothing, a second 4 uF condenser filter across load and a suppressing unit, employing two pentode valves, Sp. 4B and KT 4 types in conjunction with a Neon Mullard 7475 type for the suppression and final elimination of the least traces of ripple. In the suppressing unit of the system, the variations of the output voltage from the filtering unit are amplified and applied to the control valve to entirely eliminate even the least traces of minute variations in order to obtain superior stabilization.

The operation of the circuit has been found to be quite steady. It has never caused such disturbances which upset the workings of the counting, scaling and recording devices. It is never found to have given rise to spurious countings. The (current/voltage) character-

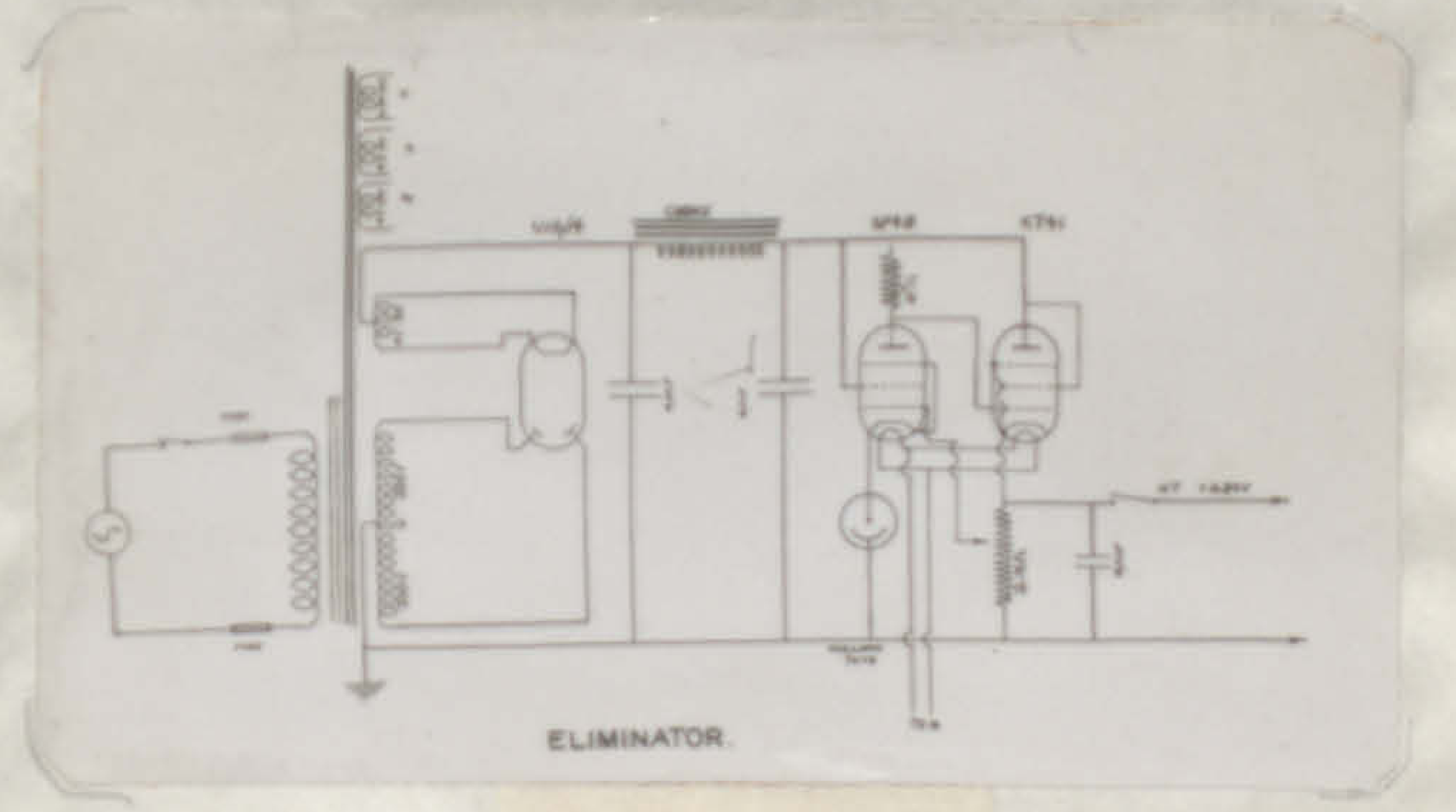

ELIMINATOR.

Fig. 24.

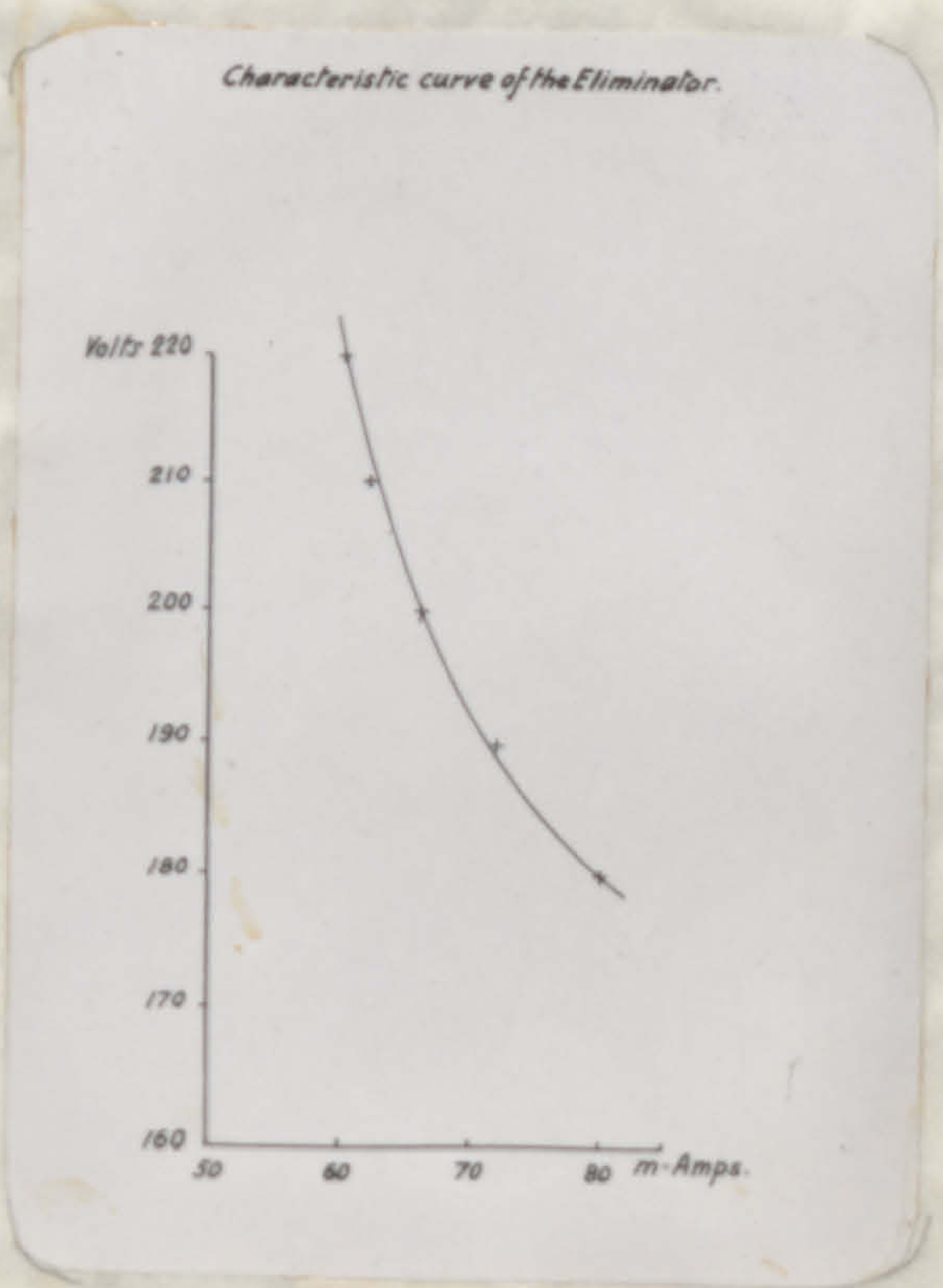

Characteristic curve of the Eliminator.
Volts 220
210
200
190
180
170
160
50
60
70
80
m-Amps.

Fig. 25.

istic of the circuit, shown in Fig.25, is found to be satisfactory for high tension and grid bias supplies.

(b) High voltage stabilizer.

1. Introduction.

A potential of the order of 1,000 - 2,000 volts, constant within a few volts, is required for the operation of an electrical counter. The problem of providing stabilized voltage supply is much simplified by the fact that the counter draws negligible current.

Street and Johnson[21] have devised two voltage source units, employing Thermionic tetrodes. One circuit has the advantage of flexibility and the other of more exact stabilization. They are simple in principle and construction. They include two high tension batteries from which a small current is drawn.

Evans[22] has evolved a circuit which appears similar in form to the Street and Johnson's second circuit, permitting more exact stabilization. In this circuit, the anode and screen grid currents are maintained constant by a balance method. The circuit includes a battery from which current is not drawn.

Medicus[23] has devised a voltage source which permits satisfactory stabilization. It is simple in design. It employs, however, a specially built stabilization tube.

Gingrich[24] has developed two voltage stabilizing units.

In one, the battery used in the Evans circuit has been eliminated through the use of a commercial neon-lamp. In the other, similar in principle to that of Medicus, a bank of neon-lamps has been used in the place of the specially built stabilization tube.

2. Description of the circuit.

The electrical counter which serves as a device for the detection of the energy spectrum is supplied by power from a high voltage stabilizing unit. The circuit of this stabilizer is similar in principle to that of Gingrich's second circuit, but differs from it in constructional details which to a certain extent influence the voltage stabilization. The circuit of this unit, shown in Fig.26, comprises a mains transformer, a diode, a first stage condenser-input-filter, a bank of neon valves and a final stage condenser-output-filter.

A diode, U 17 type, is employed for half wave rectification. A full four volt power for filament heating and a two thousand volt anode potential to the rectifier are supplied from a suitable mains transformer. It is necessary that the transformer is so constructed with adequate insulation as to permit the negative pole of the supply earthed with a maximum final output of the order of 2,000 volts.

A first stage 2 uF (2,000 volt - D.C.) condenser-input-filter across the rectifier valve circuit serves as a reservoir to supply current during the period of

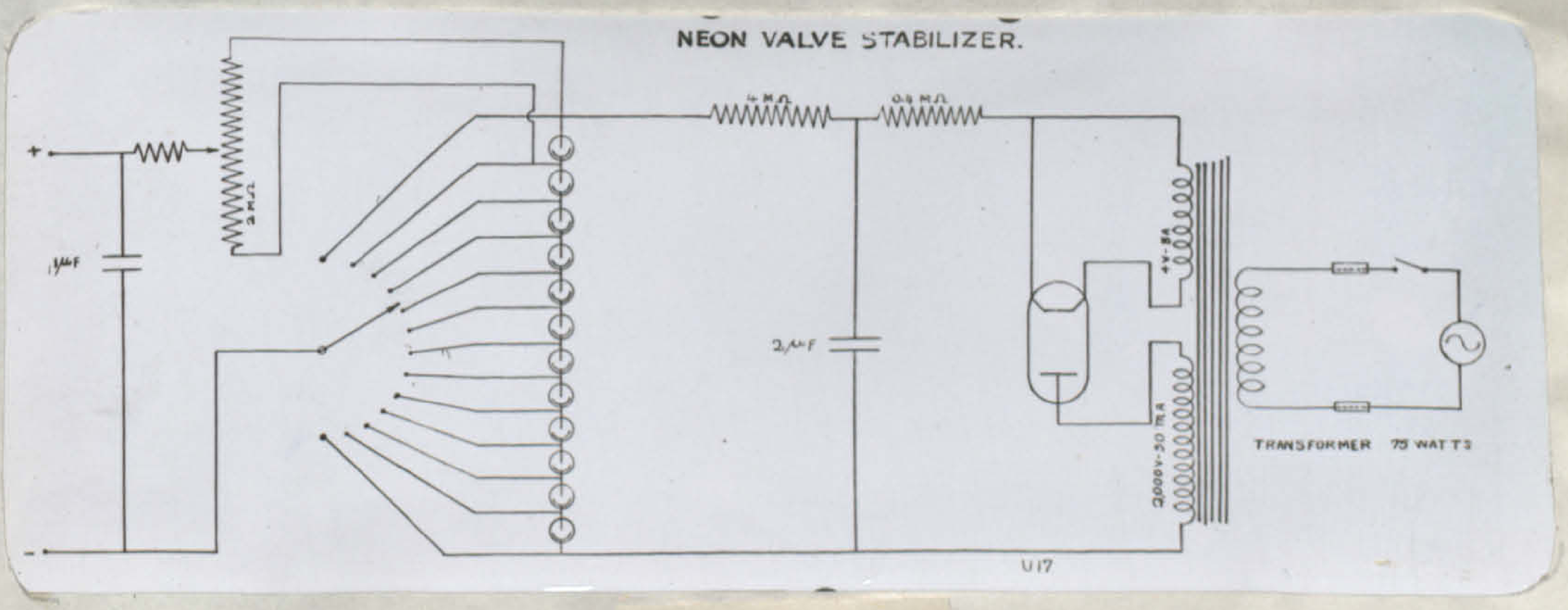

NEON VALVE STABILIZER.
+
−
1μF
2MΩ
4MΩ
0.8MΩ
2μF
4V-3A
2000V-30mA
TRANSFORMER 75 WATTS
U17

Fig. 26.

the rectifying valve's non-conducting state.

A bank of 12 neon valves (General Electric Company), wired in series across load is used to improve smoothing and to take stabilized voltages of approximately 200 volt-steps from the higher applied voltage supply. A fine regulation of the output is effected to a certain extent by a potentiometer control across the first neon valve.

A condenser of 1μF (2,000 volt - D.C.) is used as an output filter to eliminate the traces of ripple in order to supply an adequately stabilized positive voltage to the electrical counter.

The circuit is simple and its operation throughout has been found to be steady and quite satisfactory.

CHAPTER III.

Magnetic Electron Lens Spectrometer and Measurement of Energy Spectra.

1. Absolute and Relative Measurements.

In the β eta ray spectrometer, shown in the Fig.16, the positions of the source and that of the focal region where an electrical counter is placed for detection, are fixed so that every β eta ray velocity is focused at the effective region of the counter by the action of its corresponding determinate field of force of the magnetic electron lens. This specific field of force may be determined by direct measurement or by calibration of the magnetizing current in terms of the field of force which corresponds to a spectral line whose energy is predetermined.

From measurements of distance between the source and focal region, the magnitude of the factor $\frac{F}{\hat{I}}$ and the magnetic field of force $H_{(z)}$, it may be possible to estimate the absolute value of the momentum or the energy of the focused β eta rays from the relation expressed by the fundamental magnetic electron optical law expressed by equation XX. In measurements carried on by the spectrometer which employs a large percent of 4π in solid angle there is, however, a considerable difference between the maximum and the minimum angles (α maximum and α minimum) which electron trajectories at the start subtend with the lines of force. The employment of such a wide range of directions of electron trajectories gives rise to appreciable differences between $p(\alpha_{min.}, r = 0)$ and $p(\alpha_{max.}, r = 0)$ as well as between $r(\alpha_{min.}, \theta = 90^{0})$ and $r(\alpha_{max.}, \theta = 90^{0})$. The inclusion of $H^{2}_{(z)}.dz$, estimated by numerical integration and the mean of each one of the p,r-(maximum-minimum) pairs in the expression of the magnetic electron optical law for the determination of the energy of the focused βeta rays, implies a rough approximation. These energy-values thus computed, therefore, though absolute, cannot be claimed to have a precision, necessary for accurate and exact investigation into the intra and extra nuclear structures.

The magnetizing coil current may be calibrated in terms of the predetermined $H\rho$-value of a particular well defined line. This procedure, which constitutes the relative measurement of the energy spectra, however, depends upon a very accurate $H\rho$-value of a βeta line determined absolutely with semi-circular focusing method. When once the magnetizing coil current is calibrated, the spectrometer directly records the $H\rho$-values of the focused βeta lines. The relative measurements of the energy spectra, thus obtained, have the same degree of precision as the precise and accurate $H\rho$-value in terms of which the coil current is calibrated, inasmuch as the magnetizing current is constant within one in at least two thousand parts during the short interval at which each counter impulse frequency reading is recorded. Such relative measurements taken by a magnetic electron lens spectrometer can be found to be reliable and quite precise.

It is with the object of testing the spectrometer and calibrating the magnetizing current in terms of $H\rho$, active deposit of thorium is used since very many precisely measured data are available on it. A brass rod, nearly 3 mm. in diameter with its one end having an active deposit of thorium, is fixed to the holder in the source chamber in such a way that its end with the radio active deposit lies on the axis of the spectrometer just in front of the entrance aperture. The spectrometer, together with the source chamber, is exhausted to the limiting pressure attainable by the apiezon oil diffusion pump.

2. Relative intensities of the source and intensity standardization.

Then the effect in the counter without magnetizing current, consisting of natural effect of cosmic rays and the additional effect mainly due to scattered γ-rays and probably also due to a trivial number of βeta particles, has been taken as a measure of the intensity of the source. With these measures the relative intensities of the source with different amounts of deposits or of the same amount used at different times, have been estimated. Also for an arbitrarily chosen magnetizing current, the different sum total effects in the counter, the different times the deposited source is used, have been noted to verify the results obtained by the former method. There has been a fair agreement between the estimations of the intensities effected in both these ways. We have taken the mean of the results obtained by these two kinds of estimations to minimize accidental errors and also those arising out of statistical fluctuations. With the knowledge of the relative strengths of the source used, the different spectrometrical data obtained with different strengths of the source can be readily reduced to those of an intensity of the source arbitrarily taken as a standard. In other words, the knowledge of the relative strengths of the source enables us to determine the βeta ray spectrum of the source (ThB+C+C'+C") of uniform intensity even if the data obtained are those of different strengths of the source.

3. Measuring Procedure.

As a preliminary step, with an active deposit of thorium as a source, the magnetizing current has first been kept at zero position on the scale of the ammeter and has then been gradually raised in steps of 0.1 amp, each time recording the rate of the electrical counter impulse frequency until the limit 3.2 amps. is reached. From this limit the magnetizing current has been decreased gradually in steps of the same value as before, at each step once again recording the rate of the counter impulse frequency until the zero position on the scale of the ammeter is reached. These two sets of readings have given similar and approximately identical spectral records of the measured energy range. A further repetition of these measurements has confirmed the consistency of the previous results. These results have shown that the current-field characteristics of the magnetic electron lens are uniformly and accurately reproducible, that the working conditions of the spectrometer are so satisfactory as to permit high efficiency with the maximum resolving power consistent with the attained efficiency,and that the detecting and the recording devices are reliable. From these measurements it is clear that for a magnetizing current of 2.4 amps. there is a remarkable and distinctly definite maximum effect in the counter due to the βeta particles of the F-line of thoriumB. The measurements also show the rough outline of the F-line and the general shape of the continuous spectrum with an indication of a few other energy spectral lines. With this survey, it is also possible to form a rough idea of the intensity variations of the continuous spectrum at different positions and the approximate relative intensity of the F-line with respect to those of the others of the spectrum of the observed energy range.

4. F-line of Thorium B and the calibration of the Spectrometer.

In taking measurements of the energy spectrum of a given source, it is usual to use one of standard strength which is determined by the effect of a definite number of counts in the electrical counter at a fixed distance from the source due to γ-rays. A source of the same standard strength, so determined, is utilized in these investigations throughout the measured energy range. With photographic registration, this method has the advantage of readily exhibiting the relative intensities of the different energy spectral lines. If the standard source, however, be relatively strong, the most intense lines appear broad and diffused and the weak fairly distinct. If it be relatively weak, the intense lines appear clear and distinct and the weak faint and indistinct or altogether disappear.

With electrical counter registration, the use of a source of a definite standard strength has the advantage of giving directly the relative intensities of the different spectral lines and those of the different regions of the energy range of the continuous spectrum. When the standard source is very strong, the recording device is unable to cope with the rate of the impulse frequency due to βeta particles of the intense line while the weak lines appear distinctly prominent far above the limits of the errors of statistical fluctuations. With weak sources, the record of intense lines is satisfactorily distinct and that of weaker lines is vague within the tangle of statistical fluctuations.

Such being the objectionable features associated with the use of a common standard source for the measurement of all parts of the spectrum, this method has not been adopted. The strength of the source has been chosen according to the intensity of the part of the spectrum. For measurement of the parts of the spectrum with small intensities, relatively stronger source has been employed while for the measurement of the parts of spectrum with great intensities, relatively weaker source has been used. Before the commencement of the spectral measurements, the relative intensity of the source used has been determined. In every part of the spectrum, the strength of the source is so adopted as to enable the counter and the recording devices to cope with the obtained counting rate. Also the choice of the source's strength is such that the obtained counting rate in any part of the spectrum has statistical fluctuations not exceeding about 1%.

From the preliminary measurements mentioned already, it is clear that the position of the most intense region of the spectrum of Th $B+C+C'+C''$ on the scale of the magnetizing current is between 2.3 amps. and 2.5 amps. With the adequately satisfactory efficiency of the spectrometer, this region of the spectrum can be measured well even with a very weak source. As the recording device of the spectrometer has been supplied with a unit of the scale-of-sixteen, the large counting rate at this region has been recorded without appreciable counting loss.

So with a source which in this region of the spectrum emits βeta particles at a rate not exceeding the speed of the recording device in conjunction with the scaling system, the magnetizing current has at first been kept at 2.3 amps. and has gradually been increased in steps of 12.5 milli amperes, each time taking note of the rate of counting until the current has reached a value of 2.5 amps. Then from this position on the scale of the magnetizing current, it has been diminished in steps of the same value, each time again recording the rate of counting. In this way the measurements at this range on the scale of the magnetizing current have been carefully repeated a few times, each time using a comparatively weaker source. The four series of measurements, though taken with active thorium deposits of different strengths, have indicated quite precisely the same position for the F-line on the scale of the magnetizing current. The maximum number of counts recorded at this position has varied according to the strength of the source. These different series of measurements with different source strengths have recorded similar shape of the line. This F-line of Th B has been used as a standard for expressing the magnetizing current in terms of $H\rho$. The magnetizing current of 2.4 amps corresponds to the F-line at $H\rho =$ 1385.6, a value from the latest precise and absolute measurements of Ellis[25] taken by semi-circular focussing method and photographic registration.

5. Energy Spectrum of Th B+C+C'+C" and the performance of the Spectrometer.

As an additional test of the performance of the magnetic electron lens βeta ray spectrometer, the energy spectrum of Th B+C+C'+C", using this source in different relative strengths at the following energy ranges of the spectrum have been measured:-

Table 1.

Relative Strength of the Source	Energy Range of the Spectrum
17	$500 < H\rho$ $570 < H\rho$
11	$570 < H\rho$ $720 < H\rho$
6.6	$720 < H\rho$ $815 < H\rho$
3.1	$800 < H\rho$ $980 < H\rho$
2.3	$965 < H\rho$ $1125 < H\rho$
1.3	$1125 < H\rho$ $1200 < H\rho$
1.6	$1190 < H\rho$ $1230 < H\rho$
1.5	$1230 < H\rho$ $1325 < H\rho$
1.0	$1325 < H\rho$ $1440 < H\rho$
1.02	$1440 < H\rho$ $1530 < H\rho$
0.9	$1530 < H\rho$ $1600 < H\rho$
1.13	$1600 < H\rho$ $1670 < H\rho$
1.02	$1670 < H\rho$ $1715 < H\rho$
1.7	$1700 < H\rho$ $1780 < H\rho$

It may be pointed out that the measurements at the lower end of the energy spectrum have been made with relatively very large source strengths. βeta particles of the energy spectrum below $H\rho = 500$ seem to have been cut off by the counter window to such an extent that the effect in the counter due to them is trivial and practically negligible. But in the region between $H\rho = 500$ and $H\rho = 700$ there is, in spite of very strong influence of the window absorption, quite an appreciable effect due to the βeta particles of this range in addition to the natural effect. This additional effect due to βeta rays of this low energy range has been enhanced by the employment of relatively strong source in order to minimize the percentage of statistical errors.

The spectrometrical data of the source of different strengths at different energy ranges, thus obtained, show unmistakably definite and clear βeta lines, impressed, as it were, on the continuous βeta ray spectrum. These different data of the source with different strengths have been reduced to those of the source of one uniform strength throughout all the measured energy ranges. This reduction gives the energy spectrometrical data of a source of a standard strength from $H\rho = 500$ to $H\rho = 1790$, each datum being of a position in the series at an interval of $H\rho = 7.22$ approximately. A plot of the counter impulse frequency n against Hp gives the natural spectrogram shown in Fig.27, while that of $N/H\rho$ against $H\rho$, the normalized spectrogram of (Th B+C+C'+C") shown in Fig.28. From the measurements the different βeta lines observed have, as

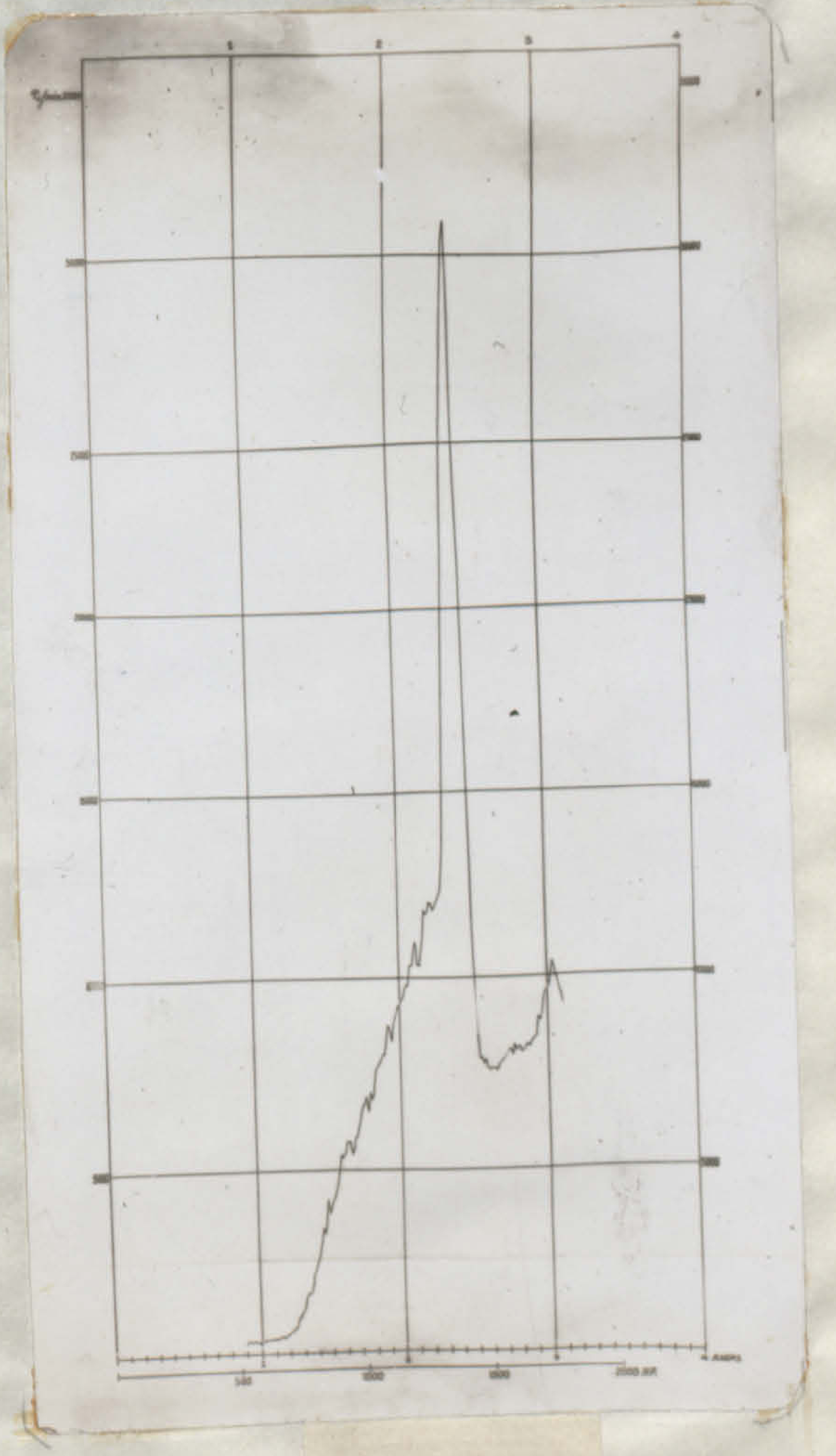
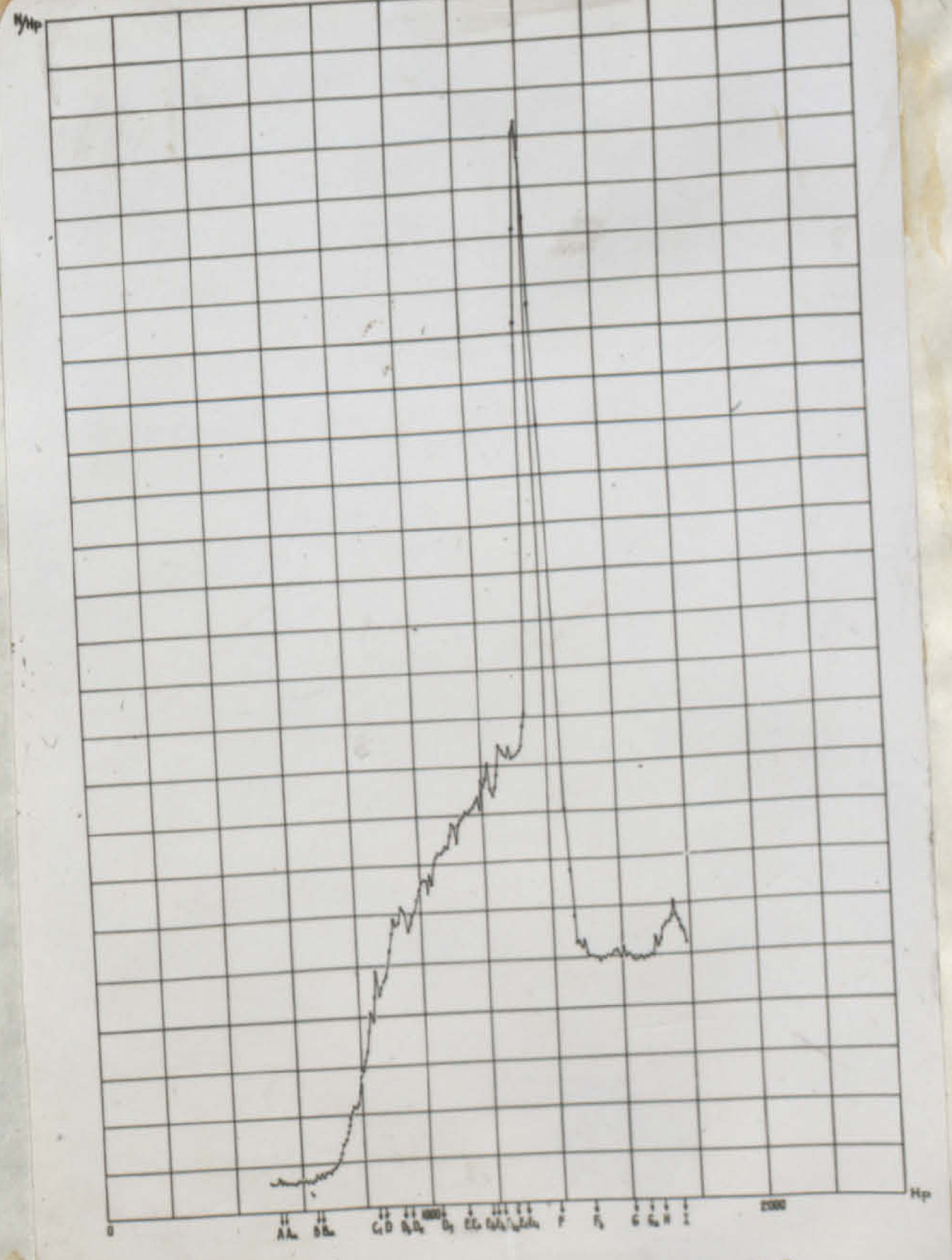


Fig. 27.



NORMALIZED BETA-RAY SPECTRUM OF THORIUM (B+C+C′+C″)

Fig. 28.

indicated in the spectrograms, been found to have the momenta and energies given in Table 2.

These results, on comparison with the available data given in Table 3, are found to agree quite well. The energy values of the βeta lines, as can be noted from the Table 3, have such precision comparable to that of very precisely measured values, obtained by semi-circular focusing method. The general shape of the spectrogram, measured within the limits of the working range of the spectrometer, resembles that of others^{25} obtained by electrical counter registration.

Thus the performance of the magnetic electron lens spectrometer has been found to be quite satisfactory for the measurement of energy spectra of the primary and secondary βeta rays. The instrument at the upper end of its working range is limited by the available source of steady magnetizing current and inadequacy of the arrangement for cooling the coil of the magnetic electron lens while at the lower end by the absorption of the counter window.

TABLE 2.

Energy Spectral Lines of Thorium B+C+C'+C"

Line's Name	Log $H\rho$	Momentum $H\rho$	Energy E.K.V.
A	2.72763	534.1	24.50
A_a	2.75921	548.5	26.20
B	2.81264	649.6	35.86
B_a	2.82219	664.0	37.41
C_1	2.92286	837.3	58.35
C_2			
D	2.93395	858.9	61.23
D_b	2.96220	916.6	69.22
D_e	2.97234	938.3	72.36
D_g	3.01347	1032.1	86.32
E	3.04446	1107.9	98.62
E_a			
E_b	3.07324	1183.7	111.18

TABLE 2.
(Contd.)

Energy Spectral Lines of Thorium B+C+C'+C"

Line's Name	Log Hρ	Momentum Hρ	Energy E.K.V.
E_{b1}	3.07851	1198.1	113.57
E_{b2}	3.08629	1219.8	117.27
E_c	3.09895	1255.9	123.82
E_{c1}	3.10882	1284.8	128.92
F	3.14170	1385.8	147.71
F_b F_{b1}	3.17227	1486.8	167.13
G G_1	3.20475	1602.3	190.52
G_a	3.21824	1652.9	201.29
H	3.22947	1696.2	209.01
I I_a	3.24401	1753.9	222.25

TABLE 8a.

Data of the Energy Spectral Lines of Thorium B+C+C'+C"

$500 < H\rho$ $1380 < H\rho$

Name of the Line	Momentum in terms of Hp measured by			
	Black	Ellis	Wang	Present
A	541	541.0	532	534
A_a		548.4		549
B	658	660.8	655	650
B_a	668	664.0		664
C		831.9	821	
C_1	835	834.9		837
C_a		849.2	845	
D	856	854.2		859
D_b		918.1		917
D_e		941.7	928	938
D_f	946	945.9		
D_g		1027.1		1032
E	1118	1106.6	1108	1108
E_a		1110.4		
E_b		1180.5	1180	1184
E_{b1}		1199.1		1198
E_{b2}		1226.2		1220
E_c		1251	1265	1256
E_{c1}		1273.8		1286
E_d	1373	1370.8	1389	1386
F	1398	1385.8		

TABLE 3a.

Data of the Energy Spectral Lines of Thorium B+C+C'+C"

$1400 < H\rho \quad 1750 < H\rho$

Name of the Line	Momentum in terms of Hp measured by			
	Black	Ellis	Wang	Present
F_b		1469.3	1470	
F_{b1}		1479.3		1487
G	1604	1593.8	1606	1602
G_a	1665	1656.8	1657	1653
H	1701	1691.0	1705	1696
I		1751.0		
I_a	1764	1754.0	1762	1754

TABLE 3b

Author & Bibliography	Method of Investigation	Registration
D. H. Black: Pro.Roy.Soc.(London) 109, 166, (1925)	Semi-circular focusing	Photographic
C. D. Ellis: Pro.Roy.Soc.(London) A,138, (1932)	Semi-circular focusing	Photographic
K. C. Wang: Zeits. Phys. 87, 633, (1934)	Semi-circular selective focusing	G.M. type of electrical counter.
Present Record. Physics Laboratory The University Liverpool.	Selective focusing action of a magnetic electron lens	G.M. type of electrical counter

CHAPTER IV.

Radioactive Isotope of Gold, $_{79}Au^{198}$, Secondary βeta Rays and Energy Measurements

1. Active Isotope of Gold.

When gold is bombarded with slow neutrons, a radioactive isotope $_{79}Au^{198}$ is produced[26] with decay period of 2.76 days[27]. It emits γ-radiation containing four components. Of those, three with energies of the order of 70, 280 and 430 e.K.v. have first been observed by Richardson[28]. Subsequently Sizoo and Eijkman[29] have, in addition to these three, found a hard component with an energy of the order of 2.5 e.M.v.

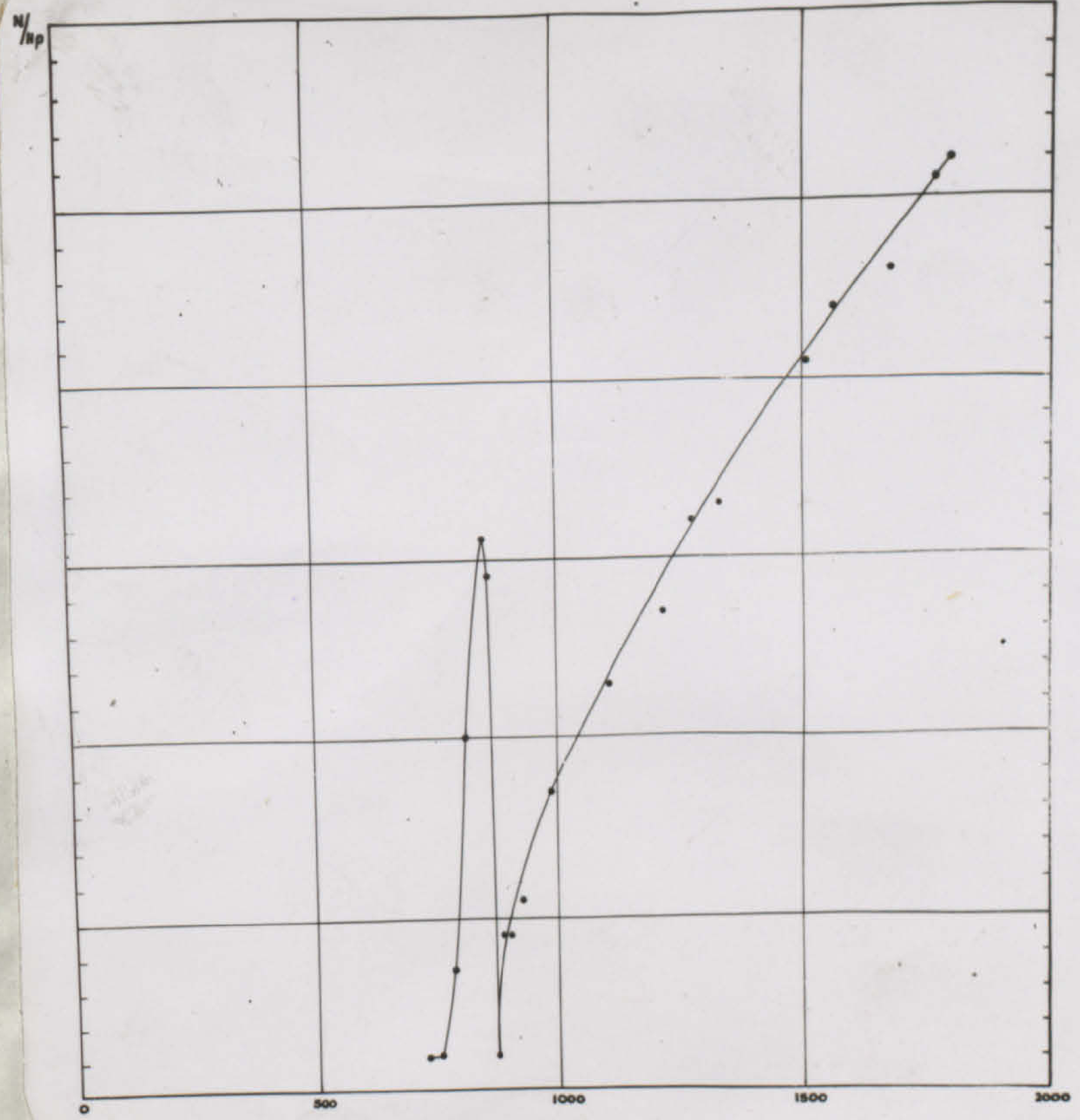
2. Energy Spectrometrical Measurements.

A multi atomic-layered foil of the radioactive gold $_{79}Au^{198}$, irradiated in the cyclotron of this laboratory, is mounted on the holder of the source chamber of the spectrometer. After exhausting the spectrometer and the source chamber, the general effect on the counter without magnetic field has been carefully observed. The result of this observation has shown that there has been an effect of four counts due to scattered radiations in addition to the natural effect.

Then magnetizing current has been applied and has gradually been raised at precisely regular intervals in fairly small steps beginning from zero position on the ammeter scale up to 3.1 amps., the upper limit of the working range of the spectrometer. At the end of each one of these intervals, the counter impulse frequency, corresponding to the magnetizing current applied during that period, has been carefully recorded. After taking these readings, the magnetizing current has been switched off and the general effect on the counter without magnetic field has been noted.

Each one of the entire series of counter readings thus taken has been individually corrected for decay. From the values of the coil currents in terms of momentum $H\rho$, obtained by the experimental determination of the magnetizing current corresponding to the F-line of Thorium B at $H\rho = 1385.6$, and these corrected series of counter frequency records, we have obtained $N/H\rho$ values for the entire measured momentum range of the βeta particles given out by the source. A graphing of $N/H\rho$ values against their corresponding momentum ($H\rho$) values gives the normalized βeta ray spectrogram of ${}_{79}Au^{198}$ up to a momentum range of $H\rho = 1800$, shown in Fig.29.

This spectrogram shows that from zero position up to a momentum range of $H\rho = 750$, an additional effect on the counter due to focused βeta particles is not apparent. The absence of the additional effect is very likely due to the absorption of the low energy βeta particles by the mica window of the counter. Above the range of $H\rho = 750$, the curve starts rising, indicating the beginning of an



ENERGY SPECTRUM OF $_{79}\mathrm{Au}^{198}$

Fig. 29.

increased effect on the counter due to focused higher energy βeta particles which penetrate the mica window and find access into the counter. Thereafter the curve rises up abruptly to a clear and distinct peak and falls down steeply to the basic position. This emergent peak on the curve with its maximum at $H\rho$ = 837.3 indicates unmistakably a spectral line of βeta particles with an energy of 58.35 e.K.v. The rest of the spectrogram shows continuous and gradual increase of counter impulse frequency with the increase of the momentum.

3. The continuous βeta ray spectrum and the line spectrum of secondary βeta rays.

The spectrogram of $_{79}Au^{198}$ within the measured range, shown in Fig.29, consists of a distinct βeta-line, impressed, as it were, on a continuous energy spectrum. In this, the βeta-line is comparatively broad, extending from $H\rho$ = 810 up to $H\rho$ = 840 nearly. From the peak the descent towards the low energy side is less steep and abrupt than that towards the high energy side. This spectral line indicates that these βeta rays are from one and the same extra nuclear group. The breadth of the line, however, suggests that the velocity of this group of βeta rays is not homogeneous but hetrogeneous, indicating thereby that these βeta rays are from different energy sub-levels of the same group ejected by a monochromatic radiation according to the law photo-electric effect.

It is very likely that the monochromatic radiation emergent from the inner atomic layers of the source $_{79}Au^{198}$ ejects electrons of L-group of $_{79}Au$ atoms from the outer atomic layers of the foil. Thus L-group photo electrons give rise to the βeta-line with βeta particles from L_I spreading towards the higher energy side and those from L_{II} and L_{III} to the lower energy side of the line. The peak of the line, however, is inclined towards the higher energy side. Hence we assume that the βeta particles corresponding to the peak of the line with a momentum $H\rho = 837.3$ are photo electrons from $_{79}Au_{L_I}$.

Now, the momentum $H\rho = 837.3$ obviously corresponds to 58.35 e.K.v. energy of the βeta particles and the ν/R for the critical absorption limit of $Au_{L_I} = 877.65$[30] corresponds to 11.883 e.K.v. Then by the law of photo electric effect, we have the energy of the monochromatic radiation:

$$58.35 \text{ e.K.v.} + 11.883 \text{ e.K.v.} = 70.233 \text{ e.K.v.}$$

Thus the energy of the monochromatic radiation from $_{79}Au^{198}$ which gives rise to the secondary βeta rays with an energy of 58.35 e.K.v., is 70.233 e.K.v. and this value agrees indeed with the value of about 70 e.K.v. obtained by Richardson[28].

From the spectrogram (Fig.29) the continuous energy spectrum indicates that the isotope of gold $_{79}Au^{198}$ is a βeta radioactive nucleus. It is very likely that, owing to the transition of $_{79}Au^{198}$, to the immediate next isobar $_{80}Hg^{198}$, the 70.233 e.K.v. monochromatic radiation could be of the K-characteristic radiation of $_{80}Hg^{180}$ emitted after internal conversion of nuclear gamma radiation.