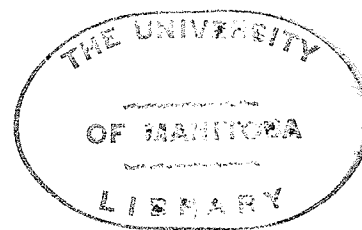


THE SIEGBAHN-SLÄTIS BETA-RAY SPECTROMETER AND
THE BETA-SPECTRUM OF IRIDIUM-192

by

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ABSTRACT

An iron-jacketed intermediate-image Siegbahn-Slatis beta-ray spectrometer manufactured commercially by LKB-Produkter Fabriksaktiebolag of Sweden is described.

Adjustments and alignment of the internal baffles were carried out prior to obtaining a calibration for the instrument using the well-known thorium active deposit conversion lines. p^{32} - p^{33} spectra were taken for the purpose of obtaining a correction for counter window absorption. An excess of low-energy electrons in the spectrum was investigated and appeared to be due to scattering. A newly devised technique of making V.Y.N.S. film source backings is described.

An iridium-192 beta spectrum was obtained with each of three different sources. End-point energies of 688, 564, and 269 kev were found and compared with the results of other investigators. K-conversion coefficients and K/L ratios were measured for the conversion lines of the 296, 308, 316, and 468 kev transitions. Comparison of α_K values with previous experimental and theoretical results for E2 transitions suggest that the theoretical coefficients are 40% too high.

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Chapter I

INTRODUCTION

Sec. I:1 Nuclear Spectroscopy and Nuclear Properties

Soon after Becquerel's discovery of radioactivity, the electronic nature of β -radiation and the electromagnetic character of γ -radiation were established by Rutherford and Ellis respectively. It was not, however, until 1910 that the first attempts at energy determination of β -particles were made by v. Baeyer and Hahn⁽¹⁾ by means of a simple magnetic spectrograph. The following year, it was noted by v. Baeyer, Hahn, and Meitner⁽²⁾ that a continuous distribution of radiation or continuum was present in β -spectra as well as discrete lines. In 1914, Rutherford and Andrade⁽³⁾ measured the wavelengths of γ -rays by crystal diffraction. Here also, discrete lines were observed.

These early experiments in nuclear spectroscopy, the study of radiation emitted by nuclei, initiated the development of nuclear physics. The presence of γ -ray lines, for instance, suggested that a given nucleus is capable of existing in only certain discrete energy states whose energy differences are those of the lines in its γ -ray

spectrum. This and other information provided a basis for the shell model of the nucleus according to which individual nucleons occupy sharply defined energy levels in much the same way as do orbital electrons in the atomic case. Transitions between nuclear levels give rise to γ -emission in a similar fashion to the way in which transitions between orbital states yield visible light.

β -spectra, however, posed a more difficult problem of interpretation. Initially, it was thought that since the discrete β -lines were grouped in series whose energy differences were precisely the differences in energy of the various electronic states, they were due to photo-electrons ejected from the K, L, etc. orbits by the monokinetic γ -rays emitted by a nucleus in the process of de-excitation after β -emission. Although the modern view has retained the gross features of this description, the interpretation of the ejection mechanism has had to be abandoned in favor of one involving a direct interaction of the nucleus with the orbital electrons. (See sec. I:3).

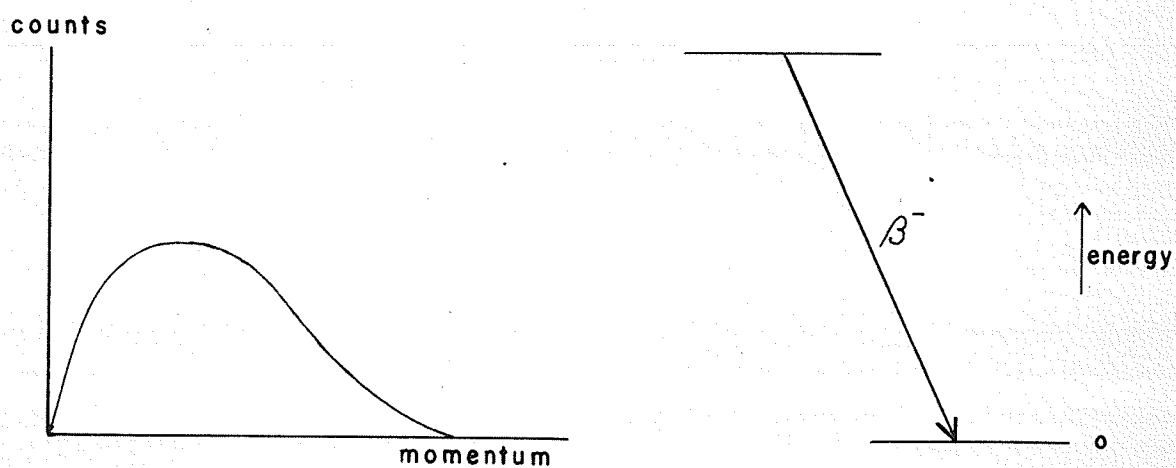
On the other hand, the β -continua were not explained until after the introduction in 1934 of Pauli's neutrino hypothesis which explained the continuous energy distribution

of β 's by asserting that β -emission was in fact a two particle process in which a neutral particle, the neutrino, having a vanishingly small rest mass, shared the available energy of a transition with the simultaneously emitted electron. (See sec I:2).

Much information can be gained from a detailed study of β -continua. For instance, the shape of a continuum can yield information about angular momentum and parity changes in a transition whose available energy can be determined by a measurement of the end-point of the same continuum. Together with data from γ -ray measurements, this information permits the construction of nuclear decay schemes which, by systematizing observed facts, shed light on nuclear properties.

Sec. I:2 Theory of β -Decay

Illustrated in fig. I.1 a is a typical β -continuum. The well-defined end-point and the continuous momentum distribution both point to a process in which the available transition energy is shared between 2 particles, a β -particle and a neutrino. The end-point energy clearly corresponds to the case where the β -particle receives all the available transition energy and the neutrino receives none. Hence a measurement of the end-point energy yields a value for the available transition energy.



A: SINGLE β - DECAY & CORRESPONDING SPECTRUM

B: DECAY WITH TWO β -FEEDS SHOWING SPECTRUM

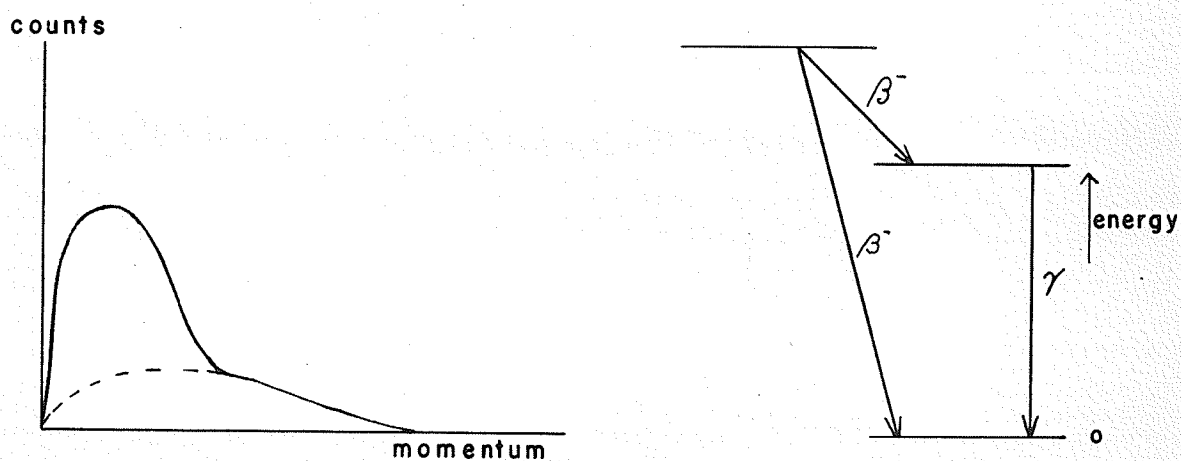


FIG. I-1

In order to obtain an equation for the β -continuum the following 2 assumptions are made:

- 1) In a single transition, the β particle and neutrino are born simultaneously.
- 2) These are treated as relativistic particles associated with a quantum-mechanical radiation field.

The momentum distribution $P(p)$ of β -particles can be written:

$$P(p)dp = T(p) \frac{dn}{dE_\beta} (4) \quad \text{---(I-1)}$$

$P(p)dp$ is actually the probability that a β -particle will be emitted with momentum in the range $p, p+dp$, and $T(p)$ is the nuclear transition probability which will be discussed later. $\frac{dn}{dE_\beta}$ is the energy density of final states and represents the possible number of oscillatory modes per unit volume of the β -particle radiation field expressed in terms of the energy and/or momentum of the β -particle.

In order to calculate $\frac{dn}{dE_\beta}$, the following procedure is adopted:

- i) First the number of possible modes of wave motion per unit volume of the de Broglie wave of either a β or neutrino is found.

ii) The number of ways in which a β and a neutrino could co-exist is calculated assuming that a β particle with a given mode can be emitted concurrently with a neutrino having any mode during a single transition.

iii) Since the only possible pairs of modes are those for which the sum of β and neutrino energies equals the total transition energy $E_{\max}$, the possibilities are adjusted accordingly.

i) In order to obtain quantum conditions for the radiation field, box normalization is used. If a , b , and c are the lengths of the sides of a box, then the conditions for stationary waves within that box are:

$$\ell_a = \frac{n_1 \lambda}{2}, \quad m_b = \frac{n_2 \lambda}{2}, \quad n_c = \frac{n_3 \lambda}{2}$$

where ℓ , m , and n , are the direction cosines of the normal to a de Broglie wave front, where n_1 , n_2 , n_3 are positive integers, and where λ is the de Broglie wavelength.

Since $\ell^2 + m^2 + n^2 = 1$, substitution of the above relations into this yields

$$\frac{n_1^2}{a^2} + \frac{n_2^2}{b^2} + \frac{n_3^2}{c^2} = \frac{4}{\lambda^2} \quad \text{---(I-2)}$$

which is the equation of an ellipsoid in $n_1 n_2 n_3$ space. If λ is specified, then the number of points on the ellipsoid for which n_1 , n_2 , and n_3 are positive integers is the number of modes for a wave of the specified λ . The number of modes in an interval $d\lambda$ is obtained by computing the volume between the positive octants of 2 ellipsoids corresponding to λ and $\lambda + d\lambda$.

The volume V of the positive octant of an ellipsoid is given by $V = \frac{1}{6} \pi ABC$ where ABC are its semi-axes. Hence for ellipsoid (I-2) we get

$$V_\lambda = \frac{4}{3} \pi \frac{abc}{\lambda^3}$$

Thus $dV_\lambda = -\frac{4\pi abc}{\lambda^4} d\lambda$ is the volume between the two ellipsoids. If λ is small, i.e., if the ellipsoids are large, then dV_λ is, to a very good approximation, equal to the number of modes in $d\lambda$ since there is but one point per unit volume to be considered in $n_1 n_2 n_3$ space.

Hence if dn is the number of modes per unit volume of real space, then

$$\text{the number of modes} = Vdn = dV_\lambda = -\frac{4\pi abc}{\lambda^4} d\lambda$$

$$\text{and } dn = -\frac{4\pi d\lambda}{\lambda^4}$$

If $k = \frac{2\pi}{\lambda}$ is the propagation constant, then

$$dn = \frac{k^2 dk}{2\pi^2}$$

Thus if dn_β is the number of possible modes for a β wave function per unit volume, then

$$dn_\beta = \frac{k^2 dk}{2\pi^2}$$

Similarly

$$dn_\gamma = \frac{q^2 dq}{2\pi^2}$$

where dn_γ is the number of modes per unit volume of a neutrino wave function whose propagation constant is denoted by q .

(ii) The number of ways, dn , in which a neutrino and β -particle could be emitted together is clearly

$$dn = dn_\beta \cdot dn_\gamma = \frac{q^2 dq}{2\pi^2} \cdot \frac{k^2 dk}{2\pi^2}$$

Since these are de Broglie waves, $p = \frac{h}{\lambda} = \hbar k$ and $x = \hbar q$ where p and x denote the momenta of the β and neutrino respectively,

$$\therefore dn = (4\pi)^2 \frac{p^2 dp x^2 dx}{h^6}$$

Using the relativistic expressions for energy

$$E_\beta^2 = m^2 c^4 + p^2 c^2$$

$$E_\gamma^2 = m_\gamma^2 c^4 + x^2 c^2$$

where m and m_γ are the rest masses of the β and neutrino respectively, we get:

$$dn = \frac{(4\pi)^2 E_\beta E_\gamma \sqrt{E_\beta^2 - m^2 c^4} \sqrt{E_\gamma^2 - m_\gamma^2 c^4} dE_\beta dE_\gamma}{h^6 c^6}$$

iii) Since only those pairs of modes are possible for which $E_\beta = E_{\max} - E_\gamma$

$$dn = \left(\frac{4\pi}{h^3 c^3}\right)^2 E_\beta (E_{\max} - E_\beta) \sqrt{E_\beta^2 - m^2 c^4} \sqrt{(E_{\max} - E_\beta)^2 - m_\gamma^2 c^4} dE_\beta dE_\beta$$

where the negative sign is ignored since only $|dn|$ is of interest.

If it is now assumed that $m_\gamma = 0$ then

$$\frac{dn}{dE_\beta} = \frac{(4\pi)^2 p^2 (E_{\max} - E_\beta)^2 dp}{c^3 h^6} \quad \text{---(I-3)}$$

since $\sqrt{E_\beta^2 - m^2 c^4} = cp$ and $E_\beta dE_\beta = c^2 p dp$.

Equation (I-3) is the energy density of final states which was sought.

The nuclear transition probability $T(p)$ may be written in the form:

$$T(p) \sim \left| \int \psi_i^\dagger H \phi_f d\vec{r} \right|^2 \quad \text{---(I-4)}$$

where ψ_i is the initial nuclear wave function, ψ_f is the final nuclear wave function, and H is a Hamiltonian operator.

Fermi⁽⁴⁾ chose H to be of the form

$$H = g \phi_\beta \phi_\gamma \quad \text{---(I-5)}$$

where g is a constant and ϕ_β and ϕ_γ are the time independent wave functions characteristic of the β and neutrino fields. Since there is but slight interaction between a neutrino and a nucleus, it is reasonable to choose $\phi_\gamma \sim \exp(i \underline{q} \cdot \underline{r})$, i.e., the free particle wave function. If, for the moment, Coulomb effects of the nucleus on β 's are neglected, then $\phi_\beta \sim \exp(i \underline{k} \cdot \underline{r})$, but this assumption is valid only if E_β is large.

$$\text{Thus } \exp[i(\underline{k} + \underline{q}) \cdot \underline{r}] = 1 + i(\underline{k} + \underline{q}) \cdot \underline{r} - \frac{[(\underline{k} + \underline{q}) \cdot \underline{r}]^2}{2} + \dots \quad \text{---(I-6)}$$

Since ϕ_i and ϕ_f vanish rapidly outside the nucleus, integration over r is taken from zero to the nuclear radius over which range $(\underline{k} + \underline{q}) \cdot \underline{r}$ and succeeding terms are small for transition energies less than 1 mev. Using this approximation, $T(p)$ becomes:

$$T(p) \sim q^2 \left| \int \psi_i^* \phi_f dJ \right|^2 \quad \text{---(I-7)}$$

or

$$T(p) = \frac{2\pi}{h} g^2 |M|^2 \quad \text{---(I-8)}$$

where $|M|^2$ is a constant,

Substituting Eqn. (I-7) and (I-3) in (I-1), the following expression for $P(p)dp$ is obtained.

$$P(p)dp = \left[\frac{g^2 |M|^2}{2\pi^3 c^3 \hbar^7} \right] (E_{\max} - E_\beta)^2 p^2 dp \quad \text{---(I-9)}$$

This expression is however invalid because of the assumption that $\phi_\beta \sim \exp(i \underline{k} \cdot \underline{r})$ which is untrue at low energies where Coulomb effects become large. These effects may be compensated by a function, the so-called Fermi Function, $f(Z,p)$, which has been calculated and tabulated.⁽⁵⁾

Then

$$P(p)dp = \left[\frac{g^2 |M|^2}{2\pi^3 c^3 \hbar^7} \right] f(Z,p) p^2 (E_{\max} - E_\beta)^2 dp$$

Hence

$$\sqrt{\frac{P(p)}{p^2 f(Z,p)}} \propto (E_{\max} - E_\beta) \quad \text{---(I-10)}$$

Usually this is used in the form:

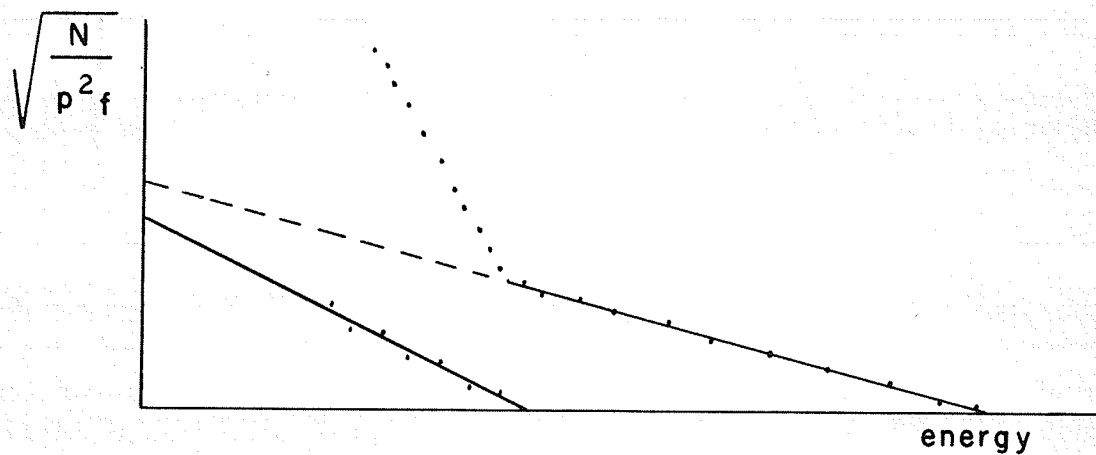
$$\frac{P(\eta)}{\eta^2 f(Z,\eta)} \propto (\epsilon_0 - \epsilon) \quad \text{where } \eta = \frac{p}{mc}, \text{ where } m \text{ is the rest mass of the electron, and } \epsilon = \frac{E}{mc^2}.$$

Equation (I-8) shows that a plot of the left hand side against E_β will yield a straight line whose E_β intercept is $E_{\max}$. Such a graph, known variously as a Fermi, Fermi-Kurie, or Kurie plot, affords a convenient method of making

an accurate determination of the β -transition energy, $E_{\max}$.

If a transition involving two or more β -feeds such as the one illustrated in fig. I-1b occurs, a complex β spectrum will result whose Fermi plot will reveal two or more distinct line segments, one for each so-called partial spectrum, i.e., one for each β -feed. The final or high energy segment of the plot may, because of its linearity, be extrapolated to lower energies as indicated by the dotted line in fig. I-2a allowing the corresponding partial spectrum to be reconstructed. Subtraction of this from the original complex spectrum leaves the sum of the remaining partial spectra for which another Fermi plot may be constructed in the usual manner. This process may be repeated until all the partial spectra have been separated.

Clearly, (I-10) holds only if the integral (I-8) does not vanish, in which case the transition is said to be allowed. If, on the other hand, the integral vanishes, the transition may still occur but the 2nd or higher terms of the expansion (I-6) must be considered and $|M|^2$ will obviously be dependent on the β -energies. Transitions of this type are said to be forbidden and result in non-linear Fermi plots. If $r+1$ terms of eqn. (I-6) are necessarily retained, the spectrum is said to be r times forbidden and r is called the degree of forbiddenness.



A: FERMI PLOT WITH TWO β -FEEDS

B: CONVERSION LINES

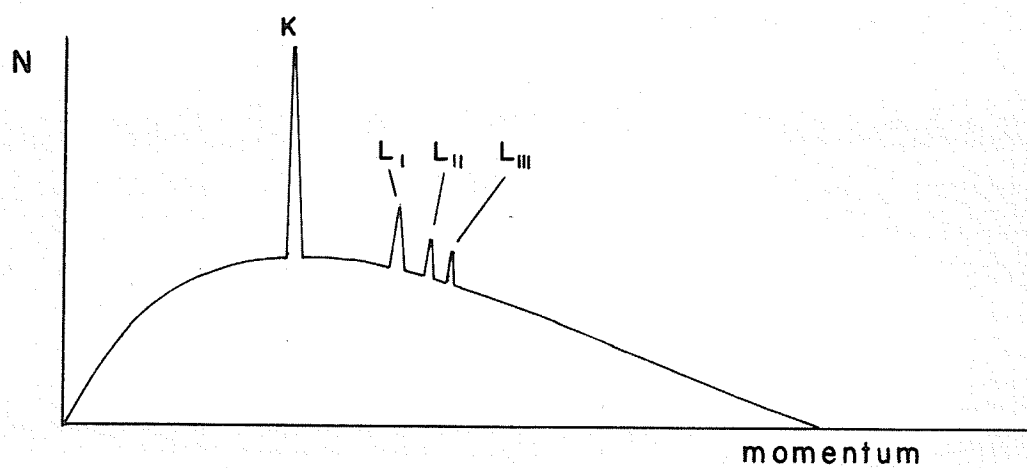


FIG. I-2

A more rigorous derivation of the transition probability, $T(p)$, taking forbidden transitions into account shows that the form of the Hamiltonian (I-5) must be changed in order that relativity requirements be satisfied, and that a slight correction due to dropping all but the first term of (I-6) must be included. The net result of these modifications is that the right hand side of (I-10) must include a factor, $S_m(E)$, known as the shape factor, where n is the degree of forbiddenness. For allowed spectra ($n=0$), $S_0(E) \equiv L_0$ which is nearly constant but which must nevertheless be taken into account in the most precise measurements.

The presence of orbital electrons screens the nuclear field in such a way that the Fermi function must be reduced. Thus one further slight correction, S , must appear as a factor on the right hand side of (I-10). The functions $L_0^{(6)}$ and $S^{(5)}$ have been extensively tabulated.

Sec. I:3 Internal Conversion

A nucleus in an excited state can revert to the ground state by either emitting a γ -ray or by ejecting an orbital electron. The latter process, termed internal conversion, was once thought to be a two-stage process consisting

of γ -emission followed by photo-electron ejection as outlined in Sec. I:1, but is now believed to result from a direct interaction of the nucleus with a K, L_I, L_{II}, etc. electron whose probability of being found within the nuclear volume is finite. Conversion electrons appear as sharp lines superposed on β -continua as in fig. I-2b.

The K-conversion coefficient, α_K , is defined as follows for a given γ -ray:

$$\alpha_K = \frac{\text{number of K electrons emitted per unit time}}{\text{number of } \gamma \text{ rays emitted per unit time}}$$

Similarly, L and M conversion coefficients, α_L and α_M , can be defined. It can be shown theoretically⁽⁷⁾ that the K conversion coefficient will depend upon, among other things, the γ -ray energy, the multipolarity, ℓ , or angular momentum of the γ -ray, and the electric or magnetic character of the transition which determines the nuclear parity change once ℓ is fixed.

Conversion coefficients have been accurately and extensively calculated on the basis of the Dirac theory of the electron, assuming a point nucleus, by Rose⁽⁸⁾, and comparison of these with observed values permits deduction of the angular momentum and parity changes of the nucleus.

The experimental determination of conversion coefficients involves measurement of the relative areas of conversion lines and the β -continuum. In general, for complex spectra,

$$\alpha_K = \frac{\text{no. of K electrons}}{\text{no. of corresponding } \gamma\text{'s}} = \frac{\frac{\text{no. of K electrons}}{\text{total no. of transitions}}}{\frac{\text{no. of corresponding } \gamma\text{'s}}{\text{total no. of transitions}}}$$

$$\text{but } \frac{\text{no. of corresponding } \gamma\text{'s}}{\text{total no. of transitions}} = \text{absolute } \gamma\text{-ray intensity}$$

and in general, this quantity is well-known from curved crystal spectrometer data.

$$\therefore \alpha_K = \frac{\frac{\text{area of K-line}}{\text{area of } \beta\text{-continuum}}}{\text{absolute intensity of corresponding } \gamma\text{-ray}}$$

In the very special case where there is a single β -feed to a level which is de-excited by one γ -ray, the total number of β -particles emitted is equal to the sum of the number of γ -rays and the number of conversion electrons since each β -transition leaves the daughter nucleus in a state which is de-excited by either γ -emission or internal conversion.

Hence

$$\begin{aligned} \frac{\text{area of continuum}}{\text{area of K-line}} &= \frac{\text{no. of } \beta\text{-particles}}{\text{no. of K-electrons}} = \frac{\text{no. of K's} + \text{no. of } \gamma\text{'s}}{\text{no. of K's}} \\ &= 1 + \frac{1}{\alpha_K} \end{aligned}$$

In actual fact, no. of β -particles = no. of K's + no. of L's + ...
 + no. of γ 's and so this method is only suitable for the
 measurement of the total conversion coefficient, $\alpha = \alpha_K + \alpha_L + \dots$

Another method applicable to the determination of
 the character of γ -radiation is by means of K/L ratios, i.e.,
 the ratio of the area of a K-line to that of the corresponding
 L-line.

It is clear from the definitions of α_K and α_L that:

$$\frac{\alpha_K}{\alpha_L} = \frac{\text{no. of K-electrons}}{\text{no. of L-electrons}} = \frac{\text{area of K-line}}{\text{area of L-line}} = \frac{K}{L}$$

This ratio is just as sensitive to angular
 momentum and parity changes as the conversion coefficients
 themselves although, in the above-mentioned case, it permits a
 determination of only the percentage mixture and type of the
 two or more γ -rays present.

Chapter II

 β -RAY SPECTROMETERSSec. II:1 Introduction: the Flat Spectrometer

A simple method of examining the momentum distribution of β -particles from a radioactive material was suggested by the fact that, owing to their electric charges, these particles are deflected by a magnetic field according to their momenta. A magnetic analyzer which accomplishes this task is known, by analogy to optical spectrometers, as a β -ray spectroscopy and the first such instrument was constructed and used by V. Baeyer and Hahn⁽²⁾. This simple instrument, which used no focussing principle, was of the type known as the flat spectrograph, so called because the electrons move approximately in a plane perpendicular to the magnetic field.

The force $\underline{F}$ on an electron of charge e in a magnetic field $\underline{B}$ is given by $\underline{F} = -e \underline{v} \times \underline{B} = \frac{d\underline{p}}{dt}$ where $\underline{v}$ is the velocity of the electron

$$\text{Hence } \left| \underline{F} \right| = \left| \frac{d\underline{p}}{dt} \right| = e B v \sin \alpha$$

where α is the angle between $\underline{v}$ and $\underline{B}$

or $\left| \frac{d\underline{p}}{dt} \right| = e B v_r$ where v_r is the component of $\underline{v}$ along some

direction in a plane perpendicular to $\underline{B}$ which shall be called the radial plane (fig. II-1a).

$$\text{Now } \underline{p} \cdot \underline{F} = p \cdot \frac{dp}{dt} = e \underline{p} \cdot \underline{v} \times \underline{B} = e(\underline{p} \times \underline{v}) \cdot \underline{B} = 0$$

since $\underline{p}$ and $\underline{v}$ are parallel.

i.e.

$$\underline{p} \cdot \frac{dp}{dt} = p \frac{dp}{dt} = \frac{1}{2} \frac{d(p^2)}{dt} = 0$$

Hence p^2 and thus p are constants of the motion.

Thus any change in $\underline{p}$ is due to a change of direction and not magnitude. Now since $\underline{F}$ is perpendicular to both $\underline{v}$ and $\underline{B}$ we see that $\underline{v}$ (and hence $\underline{p}$) must precess about the direction of $\underline{B}$ making a constant angle α with it. If the angular velocity of precession is $\omega = \frac{d\theta}{dt}$, we see from fig. II-2b that in the limit as

$$\Delta \theta \rightarrow 0, \left| \Delta \underline{p} \right| = p d\theta \text{ and } \left| \frac{d\underline{p}}{dt} \right| = p \frac{d\theta}{dt} = p\omega$$

$$\text{Hence } p\omega = e B v_r$$

$$\text{or } p = e B \frac{v_r}{\omega} = e B \rho \quad \text{---(II-1)}$$

where ρ is the radius of the circular path of the electron in the radial plane. Since equation (II-1) has been derived without introducing an explicit form for $\underline{p}$, it is valid in the relativistic as well as the non-relativistic case.

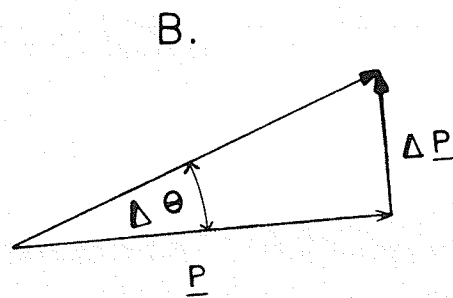
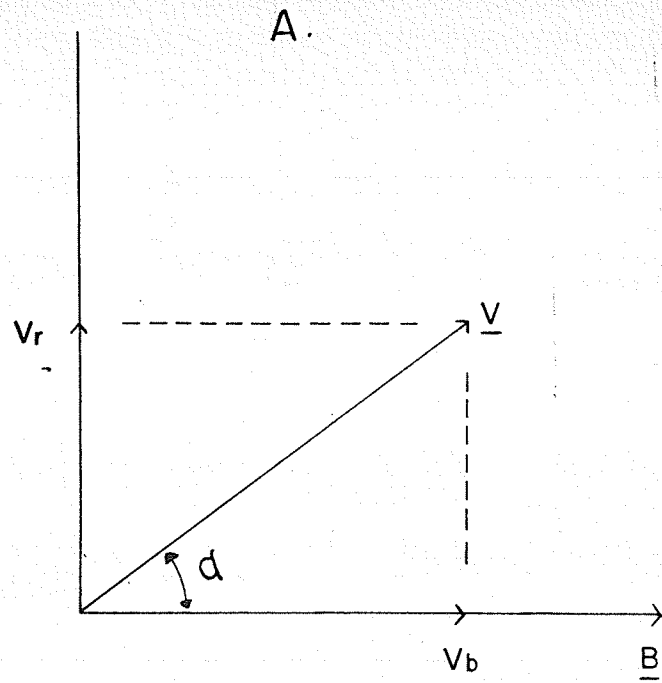
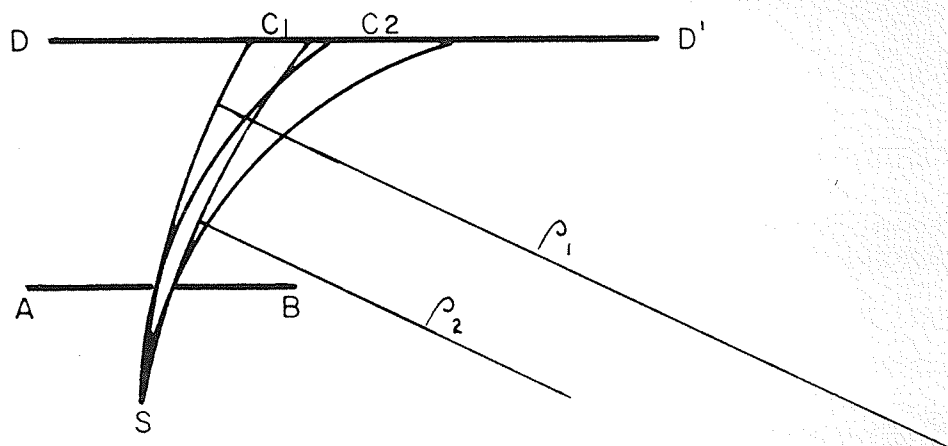


FIG. II.1



A: SIMPLE SPECTROGRAPH

B: SEMICIRCULAR FOCUSING

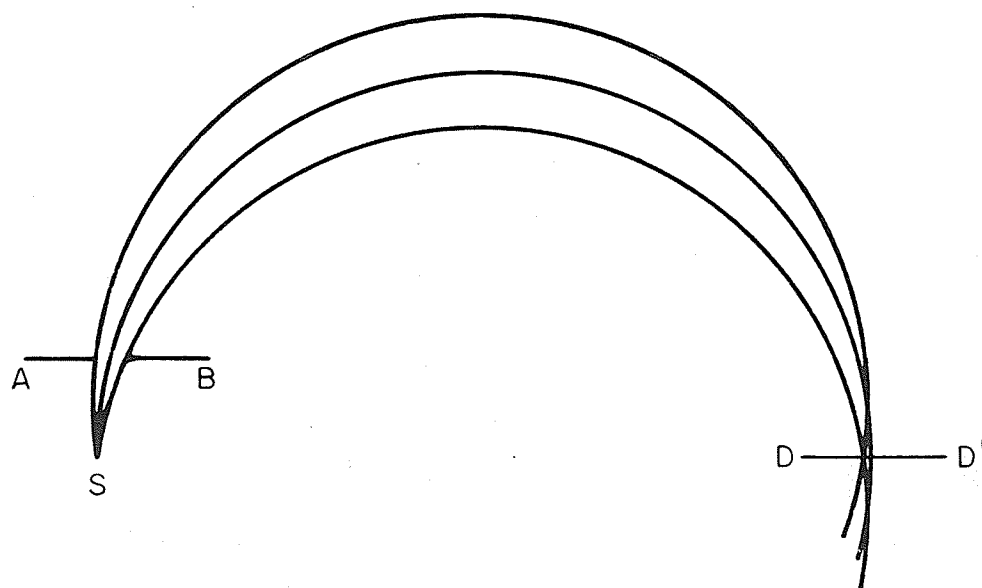


FIG. II · 2

In the case of the flat spectrometer, $\alpha = 90^\circ$ and so $v_r = v$. The orbit of a β -particle is in this case a circle having (ideally) no component of motion in the direction of the field, v_B .

Hence from equation (II-1) it can be seen that in a fixed-field spectrograph, the radii of the electron orbits vary as the corresponding momenta, and thus a determination of the orbital radius serves to fix p , i.e., a narrow beam of β -particles is dispersed linearly according to its momentum distribution. This type of instrument is illustrated in fig. II-2a where S is a source in the form of a fine wire, AB is a collimating slit allowing only a narrow bundle of β -rays to enter the spectrograph chamber, and DD' is a photographic plate. Two groups of β -particle orbits are shown, having radii of curvature ρ_1 and ρ_2 respectively. Corresponding to these 2 "lines", c_1 and c_2 , parallel to the slit AB , whose position on the plate permits a determination of ρ and hence of p . The monokinetic lines are broad since the slit width is finite and since dispersion causes each line to be broader than the slit.

A major improvement over the above mentioned direct-deflection spectrograph was the introduction by Danysz⁽⁹⁾

and the use by Rutherford and Robinson⁽¹⁰⁾ of the semi-circular focussing principle. This is based upon the simple geometrical fact that if a circle is given an infinitesimal rotation about a point on its circumference, then the diametrically opposite point is displaced tangentially. Hence in fig. II-2b, the monokinetic beam defined by the slit converges to an approximate focus approximately 180° along the circular path. In this type of instrument, focussing is still limited to the horizontal plane and a point source still gives rise to a line on a photographic plate.

At this juncture it should be mentioned that in addition to the fixed-field spectrograph already discussed, **there is a type of instrument known as the fixed geometry spectrometer** in which the photographic plate is replaced by an exit slit and a Geiger-Muller counter whose positions are fixed, i.e., ρ is fixed. Hence, in order to examine different momentum ranges, it is necessary to vary the field B . The chief advantage of such an instrument lies in the fact that it eliminates the photographic plate for which the density of blackening is seldom if ever simply related to the intensity of β -radiation.⁽¹¹⁾

Focussing in the vertical plane was achieved with the double-focussing spectrometer developed by Svartholm and Siegbahn⁽¹²⁾ in 1946 (fig. II-3). If the principal electron orbit is defined as being a circle in the symmetry plane of the magnetic field B (dotted line), it is found that electrons starting from a point S on this path and making an angle ϕ_0 in the horizontal plane with it, will return to the path after having described an angle ϕ_p along its length. Also, if an electron makes an initial angle ψ_0 with the symmetry plane, it will return to the axis after describing an angle ϕ_z along the path. ϕ_p and ψ_z are obtained from the formulae:

$$\phi_p = \pi \left[1 + \frac{\rho_0 B'(\rho_0)}{B(\rho_0)} \right]^{-\frac{1}{2}} \quad \text{---(II-2)}$$

$$\psi_z = \pi \left[1 - \frac{\rho_0 B'(\rho_0)}{B(\rho_0)} \right]^{-\frac{1}{2}} \quad \text{---(II-3)}$$

and are related by the formula: $\frac{1}{\phi_p^2} + \frac{1}{\psi_z^2} = \frac{1}{\pi^2}$ ---(II-4)

Anastigmatic focussing is clearly obtained if $\phi_p = \psi_z$ in which case the condition for double focussing is, from Eqns. (II-2), (II-3), and (II-4):

$$B'(\rho_0) = -\frac{1}{2\rho_0} B(\rho_0) \quad \text{---(II-5)}$$

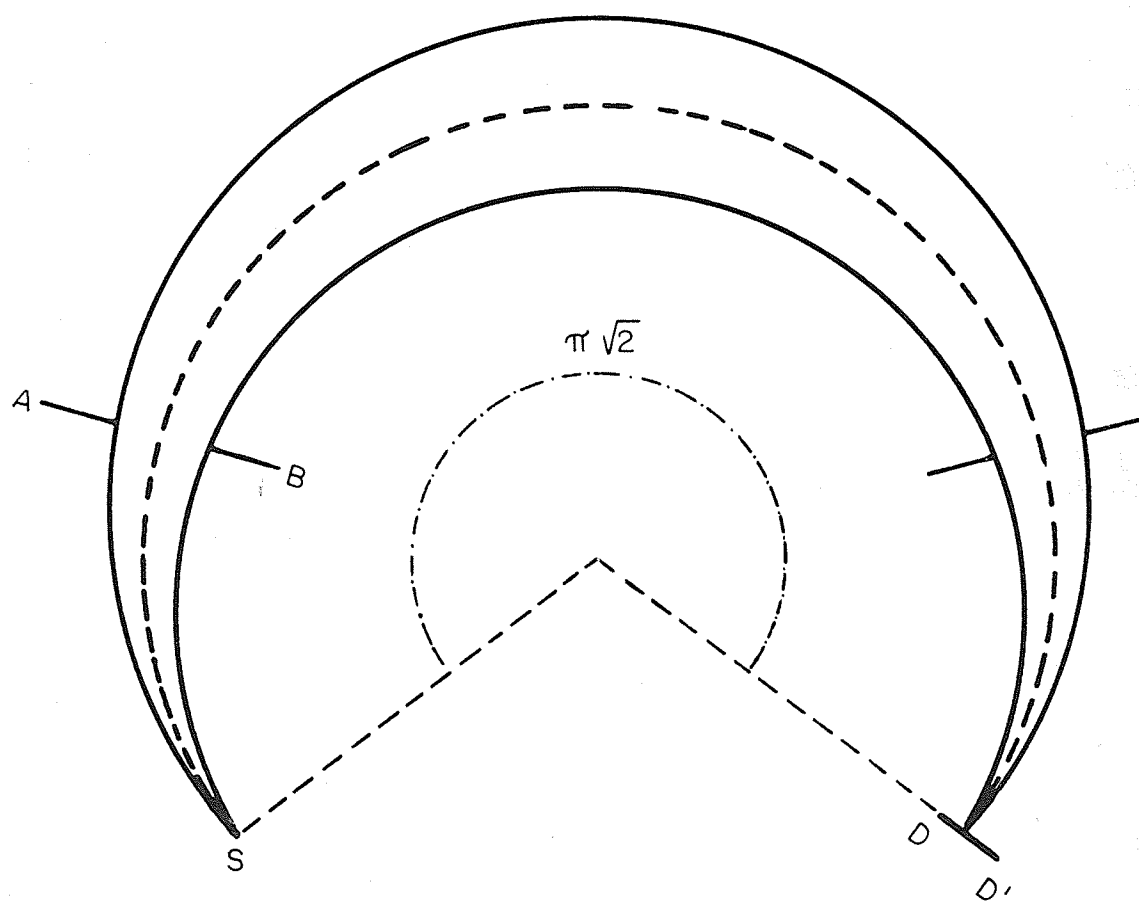


FIG. II. 3 THE $\pi\sqrt{2}$ SPECTROMETER

The solution of (II-5) requires that B should decrease as $1/\sqrt{p}$ in the vicinity of $p = p_0$ (the central path). If this condition is satisfied, it is seen from (II-4) that double focussing will occur at a point $\pi\sqrt{2}$ radians along the principal electron orbit from S .

This account of the $\pi\sqrt{2}$ double-focussing spectrometer serves to illustrate one of the many refinements which have been incorporated into β -ray spectrometer. Although many such improvements in performance have been made, the basic principle of operation expressed by equation (II-1) remains the same even for the radically different helical spectrometers to be discussed later. Hence the simple semi-circular spectrometer shall serve in the following as a prototype by means of which concepts and formulae applicable to all types of spectrometers shall be developed.

Sec. II:2 Resolution in Fixed Geometry Spectrometers

A conversion line profile⁽¹¹⁾ is the graph obtained by plotting the intensities of conversion electrons at the Geiger counter as ordinates versus the corresponding values of p (or B) as abscissae. In order that a line profile be a good reproduction of the actual intensity distribution in the line,

the detector slit width must be such that it accepts a momentum interval which is small compared to the total momentum interval occupied by the line.

Now from equation (II-1) we see that

$$dp = e B \Delta p \quad \text{---(II-6)}$$

keeping B fixed

Hence the momentum interval, dp , accepted by a slit of width Δp , is a linear function of B . Now if δp is the width of a conversion line, then it is possible to have B such that dp is not small compared to δp . Hence at moderate or large values of B the line profile will become blurred and broadened; moreover, it is easily seen that the broadening is proportional to B . Hence if $\delta p'$ is the full width at half-height of a line profile then $\delta p'$ is proportional to B . Moreover, from equation (II-1) p is proportional to B . Hence it is seen that the ratio $\delta p'/p$ is constant with respect to B and depends upon the geometry of the spectrometer. This ratio, expressed as a percentage, is known as the resolution⁽¹³⁾ of the spectrometer and is a measure of the ability of the instrument to distinguish fine detail in a spectrum. The resolution is a constant with respect to B for all fixed geometry spectrometers including the helical spectrometers to be discussed in the following section.

Another consequence of the variable momentum interval accepted by the detector is a distortion in the shape of the spectrum. This may, however, be easily compensated by a process called normalization which is discussed below.

Now $\Delta N = G(p) dp$ where $G(p)$ is the momentum distribution function, or

$$G(p) = \frac{\Delta N}{dp}$$

i.e., $G(p) \propto \Delta N$ for constant dp .

But $dp = e B d\rho$ and is a function of B .

$$\text{Hence } G(p) = \frac{\Delta N}{e B d\rho}$$

$$\text{or } G(p) \propto \frac{\Delta N}{B} \quad \text{---(II-7)}$$

Hence to obtain the true momentum distribution $G(p)$ the intensity of radiation in each interval must be divided by the field B appropriate to that interval or by something which is proportional to B . This process is called normalization.

Before proceeding to a discussion of helical spectrometers, it should be mentioned that while flat spectrometers are capable of very high resolution of the order of 0.1%, they in general suffer from poor transmission, where the transmission of a spectrometer is defined as the percentage of monokinetic electrons leaving a source that arrive at the

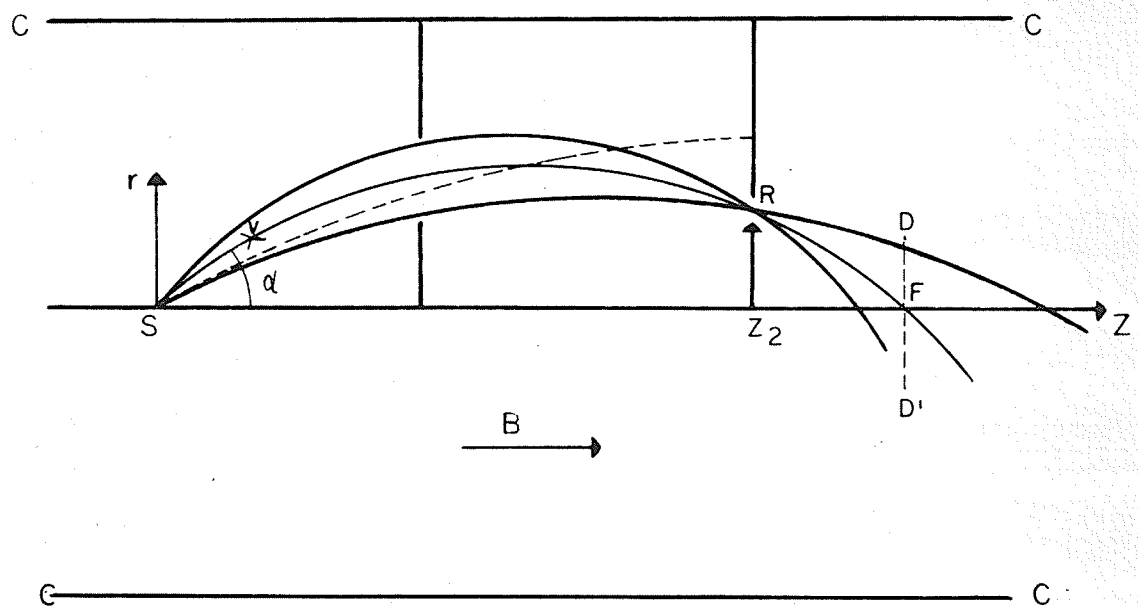
counter: In general, at high resolution, transmission is of the order of 0.5% in this type of instrument.

Sec. II:3 Helical Spectrometers

A major change in the basic design of β -ray spectrometers came with the proposal by Kapitza⁽¹⁴⁾ in 1924 to use a magnetic lens for the analysis of β -rays. This suggestion was implemented shortly thereafter by Tricker⁽¹⁵⁾ who used a long solenoidal lens which produced a uniform field, and later by Klemperer⁽¹⁶⁾ who used a short lens which produced a non-uniform field. These early helical spectrometers could not, according to Siegbahn⁽¹⁷⁾, compete in any respect with semi-circular instruments, the only type in use at that time, and it was not for some time that any serious attempts were made to improve them.

The basic operating principles of the helical spectrometer are best developed by reference to the solenoidal lens which lends itself to a simple theoretical treatment. In this instrument, β -particles emitted by a source S on the axis, SZ, of the solenoid, c, pass through an entrance slit and are then focussed on a counter window placed at another point on the axis, F. This is illustrated schematically in

A:



B:

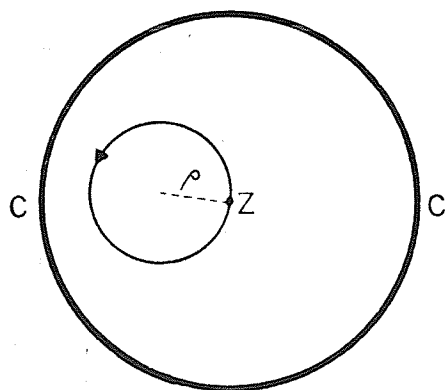


FIG. II·4: THE HELICAL SPECTROMETER

fig. II-4a which shows the trace of the electron orbit, i.e., the projection of the orbit on the meridional plane which is the plane defined by the axis of the solenoid and the instantaneous position of the electron. The trace does not completely describe the path in space of the electron since it does not take into account rotation around the axis, but, because of axial symmetry, the trace contains those elements relevant to the electron optics problem.

A co-ordinate system with origin at S is chosen so that the Z axis lies along the axis of the solenoid (parallel to B) and so that the r axis is perpendicular to this. Consider an electron of mass m and charge e emitted with velocity $\underline{v}$ from the origin making an angle α with the Z axis. Let v_Z and v_r be the components of $\underline{v}$ along the Z and r axes respectively. Thus, if p is the momentum of the electron,

$$v_r = v \sin \alpha = \frac{p}{m} \sin \alpha \qquad v_Z = v \cos \alpha = \frac{p}{m} \cos \alpha$$

Also, since only the radial part of the motion is affected by the magnetic field, we have from equation II-1 that $p \sin \alpha = e B \rho$, where ρ is the radius of curvature of the radial part of the motion (see fig. II-4b).

It is desired to locate the point F at which the electron returns to the Z axis after one revolution.

If ω is the angular velocity of the electron, then

$$\omega = \frac{v_r}{\rho} = \frac{p \sin \alpha}{m\rho} = \frac{eB}{m},$$

and if t is the time required to return to the axis, then

$$2\pi = \omega t \text{ and } t = \frac{2\pi}{\omega} = \frac{2\pi m}{eB}$$

At this time, the electron has moved a distance $\ell = SF$ along the Z axis where

$$\ell = v_z t = \frac{2\pi p \cos \alpha}{eB} \quad \text{---(II-8)}$$

$$\text{or } B = \frac{2\pi p}{e \ell} \cos \alpha \quad \text{---(II-9)}$$

Hence if B has the value determined by (II-9) electrons of momentum p leaving S at an angle α are brought to the axis at F and for different values of B , electrons of different p are brought to the axis at F along the same orbit. Hence, by the introduction of ring slits which restrict electrons to an orbit with some chosen entrance angle α , a solenoid may be used as a β -ray spectrometer.

It can be seen from fig. II-4a that two nearby traces cross over at a point R whose co-ordinates (Z_2, r_2) depend upon α . Hence, if a screen were placed at $Z = Z_2$, the electron beam would design upon it a ring of radius r_2 known as the ring focus whose position, which may be

computed⁽¹⁸⁾ locates the exit slit. The combination of entrance and exit slits shown in fig. II-4a excludes orbits such as that represented by the dotted trace and hence prevents the admission to the counter window of particles with momentum greatly different from p .

It will also be noted from equation (II-8) that for fixed p and B , λ varies as $\cos \alpha$ and hence a finite slit width allowing more than one entry angle, α , will result in the focal point, F , being blurred. This is known as spherical aberration and is illustrated in fig. II-4a.

The disadvantage of this type of instrument is a direct consequence of the large size of the disc of least confusion, represented by the line DD' which arises out of the spherical aberration of the instrument. The size of this disc determines the area of the counter window which must be used in order that a large percentage of the transmitted electrons be collected, and very large windows require a supporting grid whose presence can reduce the effective aperture of the window by as much as 30 to 50%⁽¹⁷⁾. Limiting the entry angle α by means of the entrance slit will of course reduce the spherical aberration, but the accompanying reduction in solid angle reduces the transmission appreciably thus off-setting

any advantage gained by using a smaller counter. In general, the detector problem limits the transmission of this type of instrument to 5% or less.

Attempts to decrease the spherical aberration inherent in the solenoid spectrometer have resulted in the use of non-uniform fields. Theoretical investigations⁽¹⁹⁾ have shown that spherical aberration is present only as a 3rd order effect in fields having certain singularities on the magnetic axis. Such fields cannot be produced by coils external to the electron beam, but may be approximated by a regular field which varies in such a way that the graph of its intensity plotted as a function of distance along the axis is concave upwards. Spectrometers having this type of field-form have been built by Siegbahn⁽²⁰⁾, Lauritsen and Christy⁽²¹⁾, and Agnew and Anderson⁽²²⁾, among others. Spectrometers using other strong-gradient field-forms such as the prolate spheroidal field spectrometer of Richardson⁽²³⁾ have also been constructed. The Richardson instrument has attained resolution of 2% at 6% transmission but at 1% resolution the transmission is only 1.4%.

Sec. II:4 Intermediate-Image Spectrometers

In order to explore the possibilities of concave field instruments, Slätes and Siegbahn⁽²⁴⁾ in 1949 constructed a spectrometer having a solenoid divided into five separate coils. With this arrangement, the field gradient along the axis could be varied within wide limits by simply adjusting the currents through the individual coils.

The apparatus is shown schematically in fig. II-5. A sheaf of electrons from the source S is selected by the entrance slit AB located near the source. These then pass through the exit slit EF which is situated in the median plane, i.e., that plane perpendicular to the axis located half way between the source S and the focal point F. As in previously discussed helical spectrometers a ring image is formed somewhere between source and focus.

It was found that for a certain field gradient, a pronounced increase in transmission occurred. Using the strong F-line from ThB as a monokinetic electron source, it was found by the method of photographic ray tracing that the ring image was formed in the median plane and that the electrons converged to a point F on the axis with very little spherical aberration. Hence, with this field-form, it was possible to have large transmission using a small counter window.

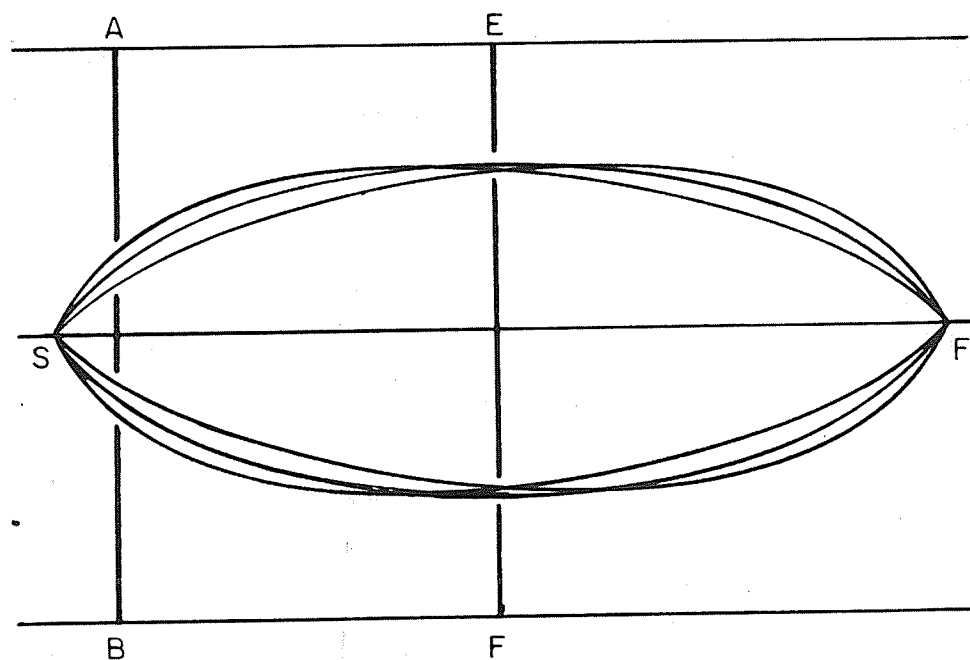


FIG. II·5: INTERMEDIATE-IMAGE FOCUSING

A value of 8% transmission at 4% resolution using a source of diameter 5 mm and a central baffle opening of 8 mm was reported, but the transmission at 1.7% resolution, the best obtained, was not given.

An improved version of the intermediate-image spectrometer of Siegbahn and Slätis is manufactured commercially by LKB-Produkter of Sweden. One of these spectrometers was used in the present work and is the subject of the following chapter.

Chapter III

THE LKB 3024 SPECTROMETERSec. III:1 Introduction

The operating principle of the β -spectrometer built by LKB-Produkter Fabriksaktiebolag of Sweden and shown in plate I is the same as that of the original Siegbahn-Slätis intermediate-image instrument discussed in chapter II. Numerous refinements have, however, been incorporated into the commercial model which greatly extend its usefulness.

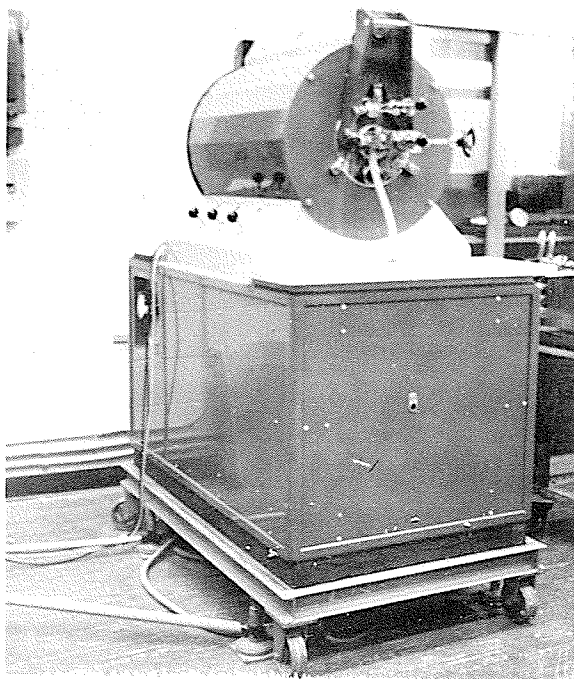
The principal components of the spectrometer system are the following:-

- 1) Spectrometer proper,
- 2) Vacuum system,
- 3) Magnet power system,
- 4) Detection system.

These will be described in detail in the sections to follow.

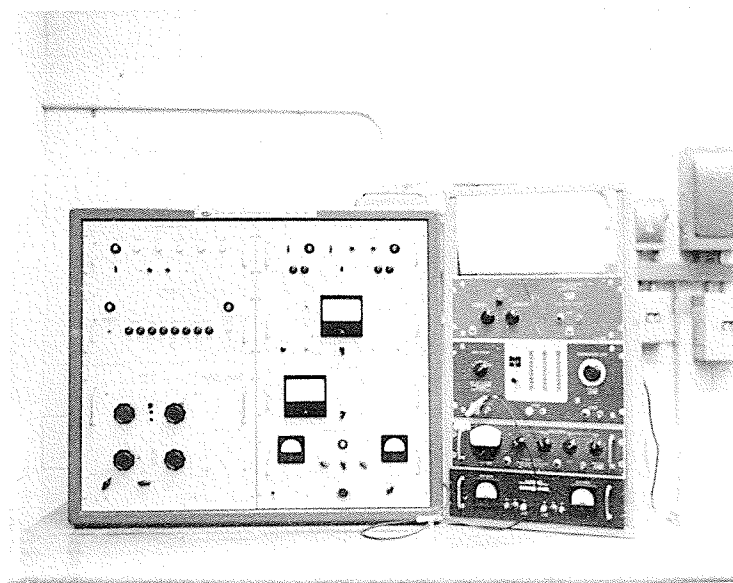
Sec. III:2 The Design of the Spectrometer

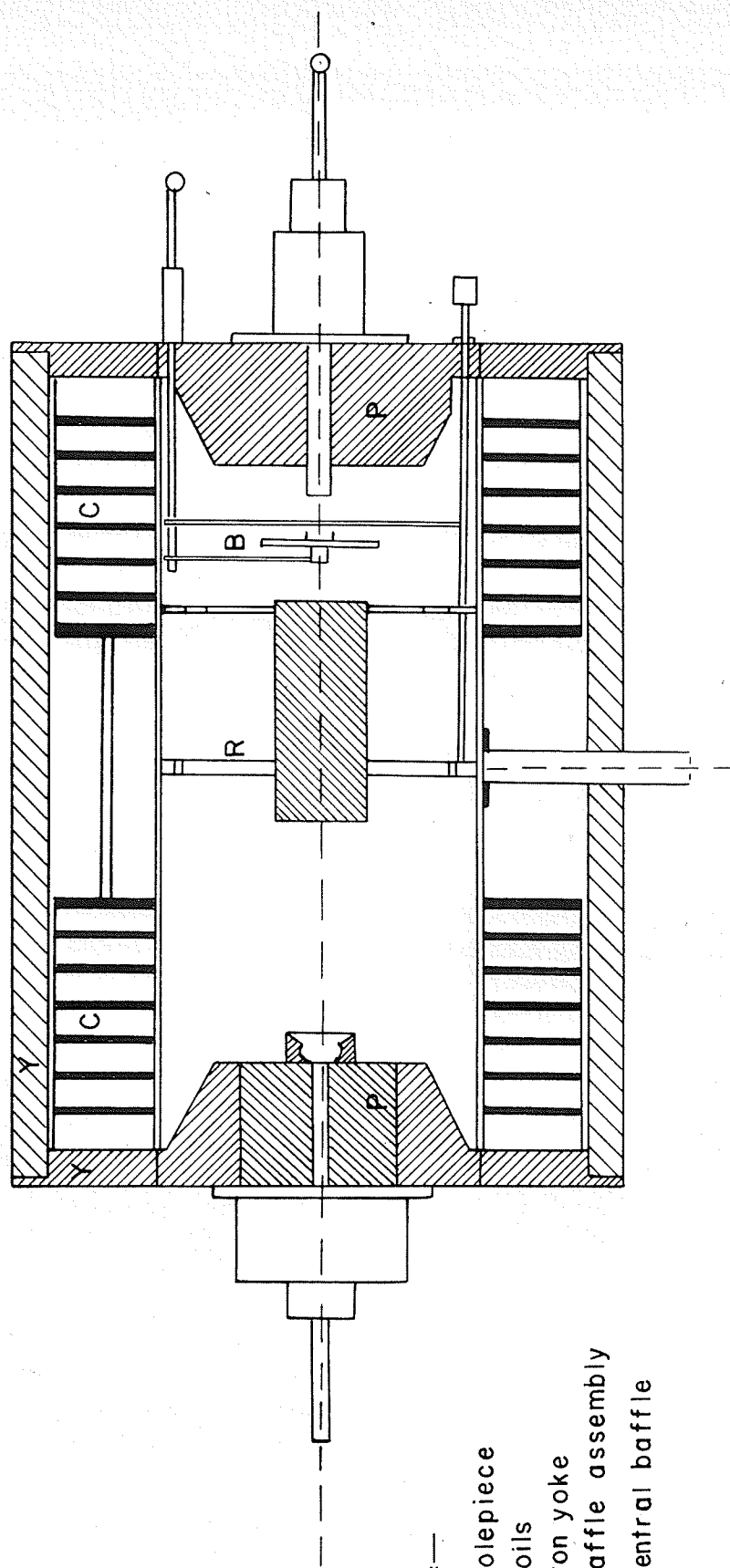
The instrument is illustrated schematically in fig. III-1. The magnet, having a source-to-detector distance of approximately 550 mm, consists of a number of disc-like



THE SPECTRO-
METER PROPER

CONTROL UNIT





LEGEND:—

- P — polepiece
- C — coils
- Y — iron yoke
- B — baffle assembly
- R — central baffle

FIG. III.1: THE LKB SPECTROMETER

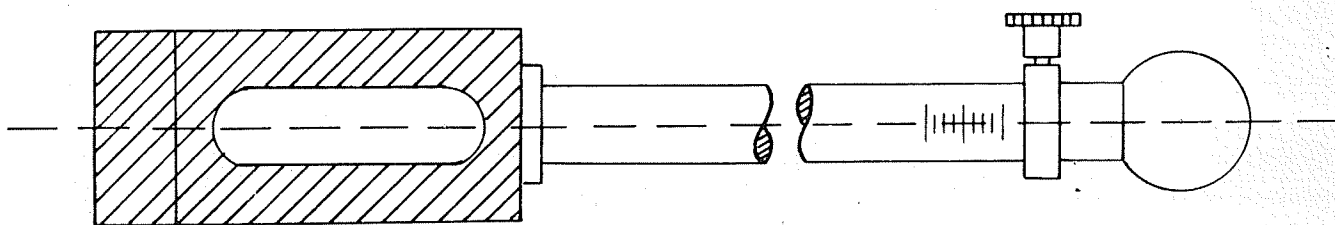
coils of hollow brass tubing arranged coaxially within a cylindrical jacket formed by 20 iron bars so that the appropriate focussing-field gradient is produced in the chamber. The individual coils are positioned relatively to each other by fiber spacers and by brass struts serving also to hold them rigidly in place with respect to the iron end-plates into which the pole-pieces are fitted. The chamber is rendered airtight by means of an 'O'-ring seal between the rims of the pole-pieces and the brass lining of the cylinder.

The entrance slit or baffle, made of 3 mm thick aluminium sheet, consists of a circular ring and a coaxial circular plate located slightly further from the source. The inner edge of the ring and the edge of the plate are bevelled to an angle of 35° . The minimum inner diameter of the ring is 94 mm and the maximum diameter of the plate is $94 + 3 \tan 35^\circ = 96.1$ mm, allowing the plate and ring to be fitted smoothly together. These are both attached to a shaft which projects outside the pole-piece. The position of the plate may be varied from 0 to 30 mm with respect to the ring by rotating the shaft which is equipped with a micrometer scale, and the axial position of the baffle unit (ring and plate), as measured by the ring-to-pole-piece distance, may be varied between 62 and 90 mm by moving the shaft parallel to

the spectrometer axis. The axial position of the ring is indicated by a millimeter scale inscribed on the shaft.

The exit slit or central baffle consists of an outer, circular aluminum ring of inner diameter 180 mm., and an inner, circular, brass plate which is coaxial and coplanar with the ring. The design of the inner plate is similar to that of the iris diaphragm of a camera and allows the slit opening to be varied from 0 to 10 mm. by means of a shaft equipped with a dial which projects through the pole-piece. The outer ring, whose outside diameter is a few mm. less than that of the spectrometer chamber, rests upon two threaded pins which project through the chamber walls. By adjusting these screws, the centre of the baffle may be aligned with the magnetic axis of the spectrometer. The central baffle is held erect by means of an aluminum and brass framework equipped with 3 adjusting screws which allow slight variation of the angle made by the plane of the baffle with the spectrometer axis. In order that paraxial radiation be prevented from reaching the detector, a lead cylinder 10 inches in length is mounted in the centre of this framework.

Sources are inserted into the spectrometer through a hole drilled along the axis of the pole-piece by means of a sample holder consisting of a stainless steel shaft



A: SOURCE HOLDER

B: GEIGER TUBE

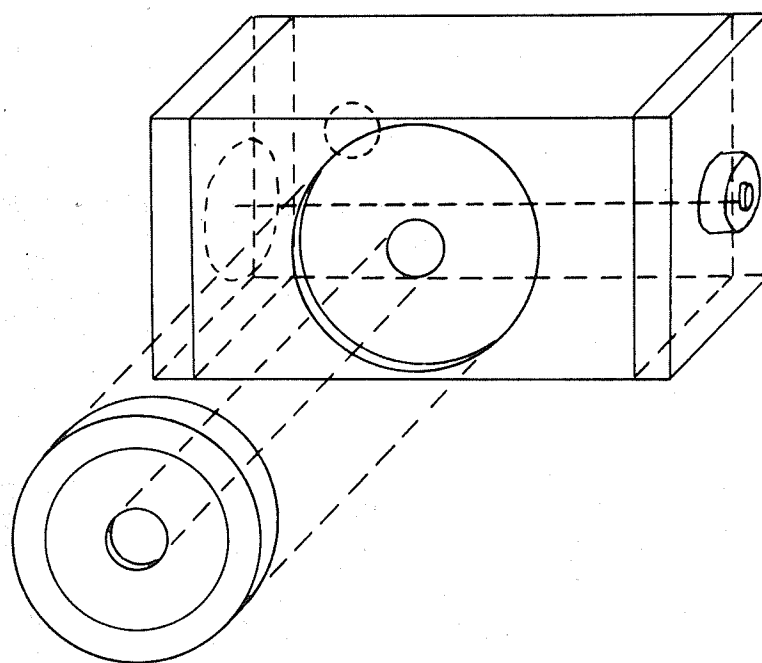


FIG. III · 2

attached to one end of a stainless steel-reinforced aluminium cylinder, the other end of which is machined to receive an aluminium source ring. This is brought into the chamber by means of a vacuum lock attached to the outside of the pole-piece. The shaft is equipped with a millimetre scale which allows the source position to be varied ± 5 mm. along the spectrometer axis about a point 37 mm. from the pole-piece. The source holder is shown in fig. III-2a.

Sec. III:2 The Vacuum System

Since the mean free path of electrons in the chamber ought to be at least several meters, the chamber pressure must be brought down to 0.1 micron Hg or less. This is accomplished by a standard arrangement consisting of an oil diffusion pump backed by a single-stage rotary pump, and shown schematically in fig. III-3.

The pressure in the system is measured by three Pirani type gauge tubes, situated as shown in the diagram, connected to a slightly modified LKB 3294B "Autovac" gauge. This device possesses an automatic range-switching relay which, together with a hydraulic flow switch in the diffusion pump cooling water line and a thermal switch mounted on the

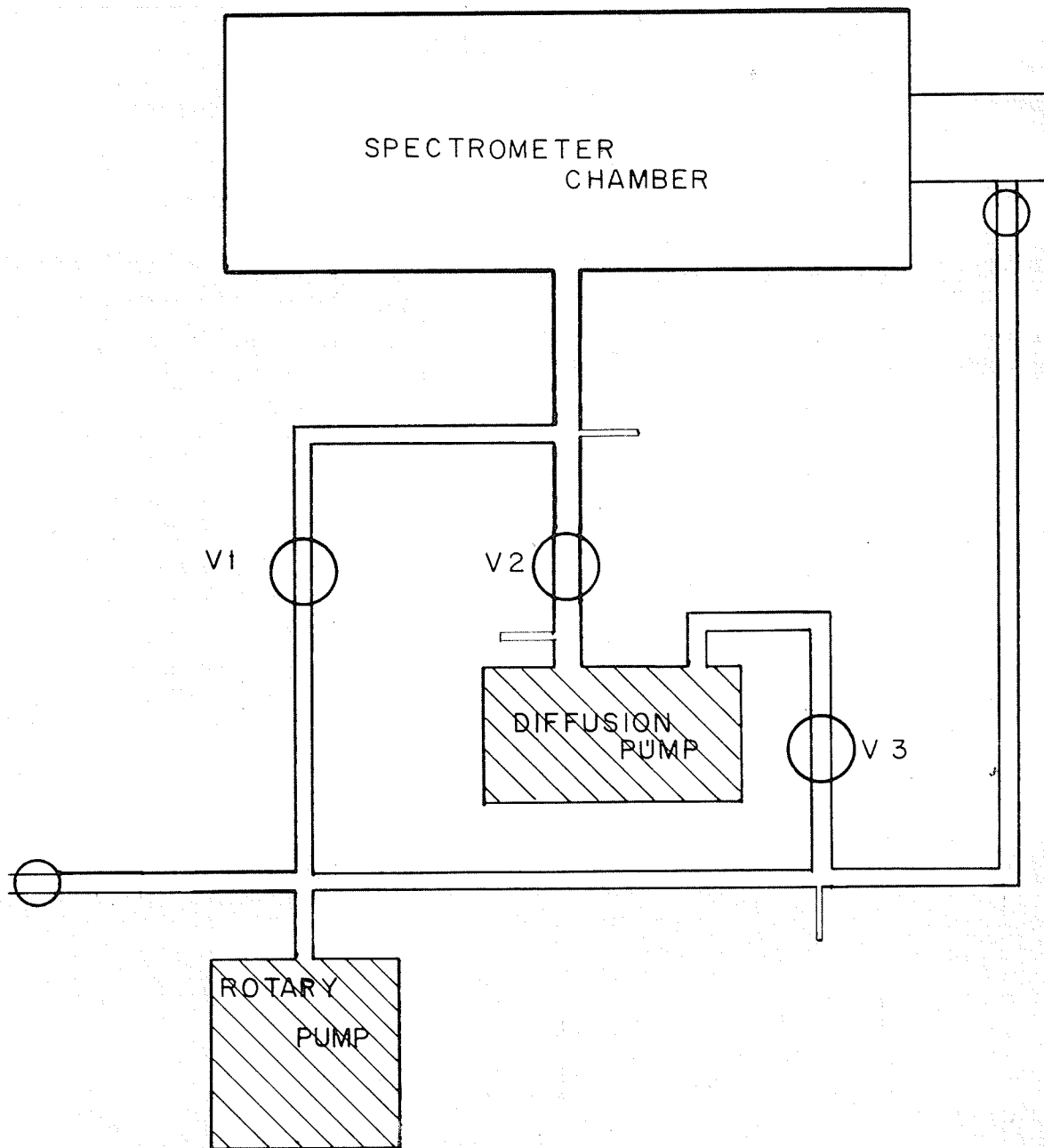


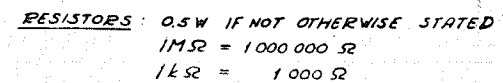
FIG. III-3: VACUUM SYSTEM

diffusion pump, forms an elaborate safety circuit for the protection of the diffusion pump oil which, when hot, oxidizes rapidly if exposed to air at pressure greater than 100 microns.

The safety system operates by means of the spring-loaded valves V1, V2, and V3 fitted with electromagnetic clutches (not shown) which, if de-energized allow the valves to slam shut instantaneously. For instance, V1 closes automatically if the forevacuum pump motor stops, V2 closes automatically if the air pressure rises to such a degree that the 'autovac' gauge switches to its high range, or if the cooling water flow is cut off, and V3 closes under any of these conditions. V3 will lock open, however, if the diffusion pump is cold, in which case there is no danger that the oil will be oxidized.

Sec. III:4 The Magnet Power System

The manufacturer's diagram of the magnet power system is included for reference as Fig. III-4. The power for the field coils is supplied by a D.C. generator rated at 60 volts, 600 amps, and driven by a 44 kw., 3-phase induction motor. The star-delta starter is equipped with a delayed thermal cut-out which switches off the power if the current in the motor



MAGNET CURRENT REGULATOR
PARTS LIST 04-6018

I-3024-E02

windings rises past a pre-selected point. This allows the current output to be maintained at 700 amps for about 15 minutes provided that the magnet cooling water supply is adequate.

The current regulator compares the voltage drop across a precision .002 ohm manganin resistor, R67, which is immersed in a water-cooled oil bath and connected in series with the magnet coils, with a continuously variable reference voltage supplied by a dry cell. After amplification, the error or difference voltage appears as an unbalanced current from 2 output valves, V8 and V9, connected in parallel through two counteracting exciter field windings, CE and CF, on the generator. Hence a difference between the reference voltage and the drop across R67 will result in an unbalanced exciter field current which will tend to change the output of the generator in such a way as to reduce the error voltage. Since the maximum imbalance current from the tubes is limited to a few milliamps, this system is suited only to stabilization of the generator output. The level of the output is controlled by a voltage-sensitive relay connected across the output tubes which fires if the imbalance current exceeds 60 microamps, starting a motor-driven potentiometer, R78, which increases

the current through a third exciter field winding, CD. As soon as the imbalance current drops below 30 microamps, the relay cuts out leaving the electronic regulator to control the output current.

In practice, an output voltage is pre-set on an accurate potentiometer connected across the manganin resistor. The generator output is then increased by increasing the regulator reference voltage until the desired current, as measured by the voltage drop across R67, is obtained. The system keeps the magnet current constant within 0.1% of any pre-set value within the normal working range 10 - 600 amps.

Sec. III:5 The Detector System

The LKB spectrometer makes use of a Geiger-Muller tube detector, although provision exists for the installation of scintillation equipment. The Geiger tube, shown in fig. III-2b and located on the front of the pole-piece opposite the source, is a small brass block having a cylindrical bore and plastic end-plates to which the central wire is attached. A hole, over which the window assembly is fitted, is drilled in the front of the block through to the bore. The window material - formvar or thin polyethylene film - is stretched

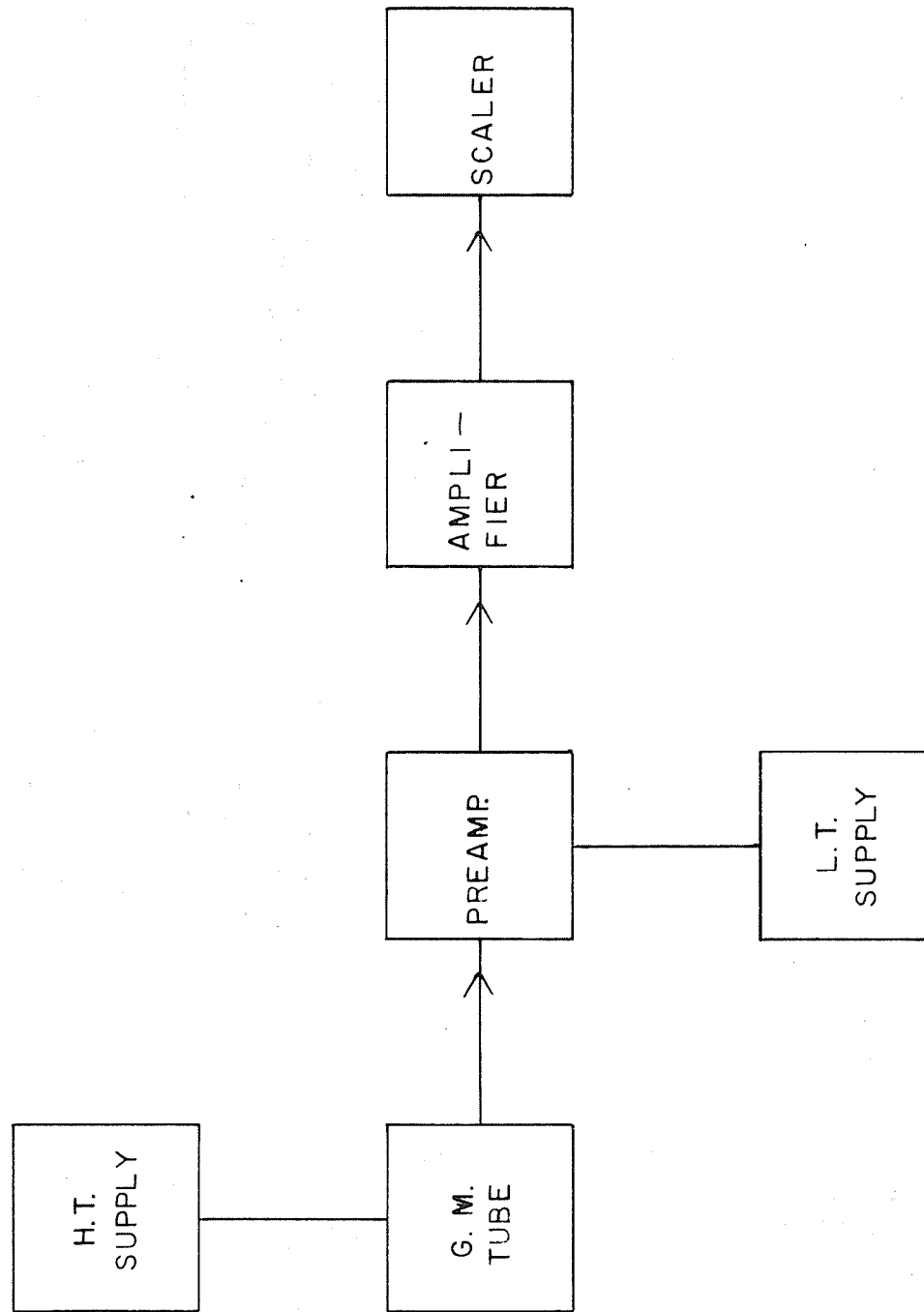


FIG. III-5: DETECTION SYSTEM

tightly over an 8 mm. diameter circular hole in a brass disc and held by means of an 'O'-ring fitted into a circular groove cut in the disc. This assembly is screwed tightly to the brass block making a gas tight seal. The brass block is itself connected by another 'O'-ring seal to a pipe, inserted through the pole-piece, by which the gas mixture, 60% argon, 40% propane at 80 mm. Hg pressure, is admitted. The pipe is equipped with a valve connecting the Geiger tube to the spectrometer chamber in order that the tube may be evacuated. The window is situated 25 mm. in front of the pole-piece at the focus of the spectrometer.

The complete detection system is illustrated in the block diagram fig. III-5. The Geiger tube is energized by the application of a positive high voltage of the order of 1000 volts to its central wire. Pulses from the counter are fed into a cathode-follower pre-amplifier supplied with the spectrometer by its manufacturer, and from there to a Technical Measurement Corp. model AL-2A linear amplifier with variable gain and pulse clipping time. Pulses from the output of the amplifier are fed to a model SG-3A scaler equipped with a bias voltage selector variable continuously from -100 to +100 volts which accepts pulses greater than the bias setting, also made

by Technical Measurement Corp. All units are powered by ordinary 110 volt 60 cycle A.C. direct from the mains with the exception of the pre-amplifier which draws both its 260 volt plate voltage and 6.5 volt filament voltage from a single regulated power supply manufactured by Lambda Electronics Corp.

All units are mounted in a small steel rack located beside the β -spectrometer control unit with the exception of the pre-amplifier which is mounted on the outside of the pole-piece on which the counter is situated.

The high voltage setting to be used is determined by plotting the counting rate versus the high voltage with a constant number of β particles per second entering the counter. The high voltage is set approximately in the centre of the "plateau" of the curve, i.e., that region of the graph in which the counting rate is constant with respect to high voltage. Because of variable gas mixture arising from residual air in the counter, the position of the plateau varies in time and must be checked periodically during operation.

Chapter IV

ADJUSTMENTS AND CALIBRATION OF THE SPECTROMETERSec. IV:1 Baffle Alignments

It was pointed out in chapter II that in helical spectrometers, the orbit followed by the electron beam from source to detector is independent of the focussing field and the corresponding electron energy. In the LKB spectrometer, electrons of all energies form intermediate ring images of different radii only one of which is transmitted past the central baffle at a given magnet current. The ring image of the Th B F-line, shown in plate II, was obtained by placing a circular sheet of x-ray film supported by an aluminium disc in the position usually occupied by the central baffle while the magnet current was adjusted to a value such that the F-line would have been focussed at the detector had the central baffle been in position and no obstructions present. Because the F-line, one of the strongest known conversion lines, is so intense with respect to the continuum and other Th B lines, its presence renders Th B an almost monokinetic source of electrons and, as such, ideally suited for photographic ray tracing. As the field is increased from zero, a ring image formed by electrons of a particular energy shrinks radially

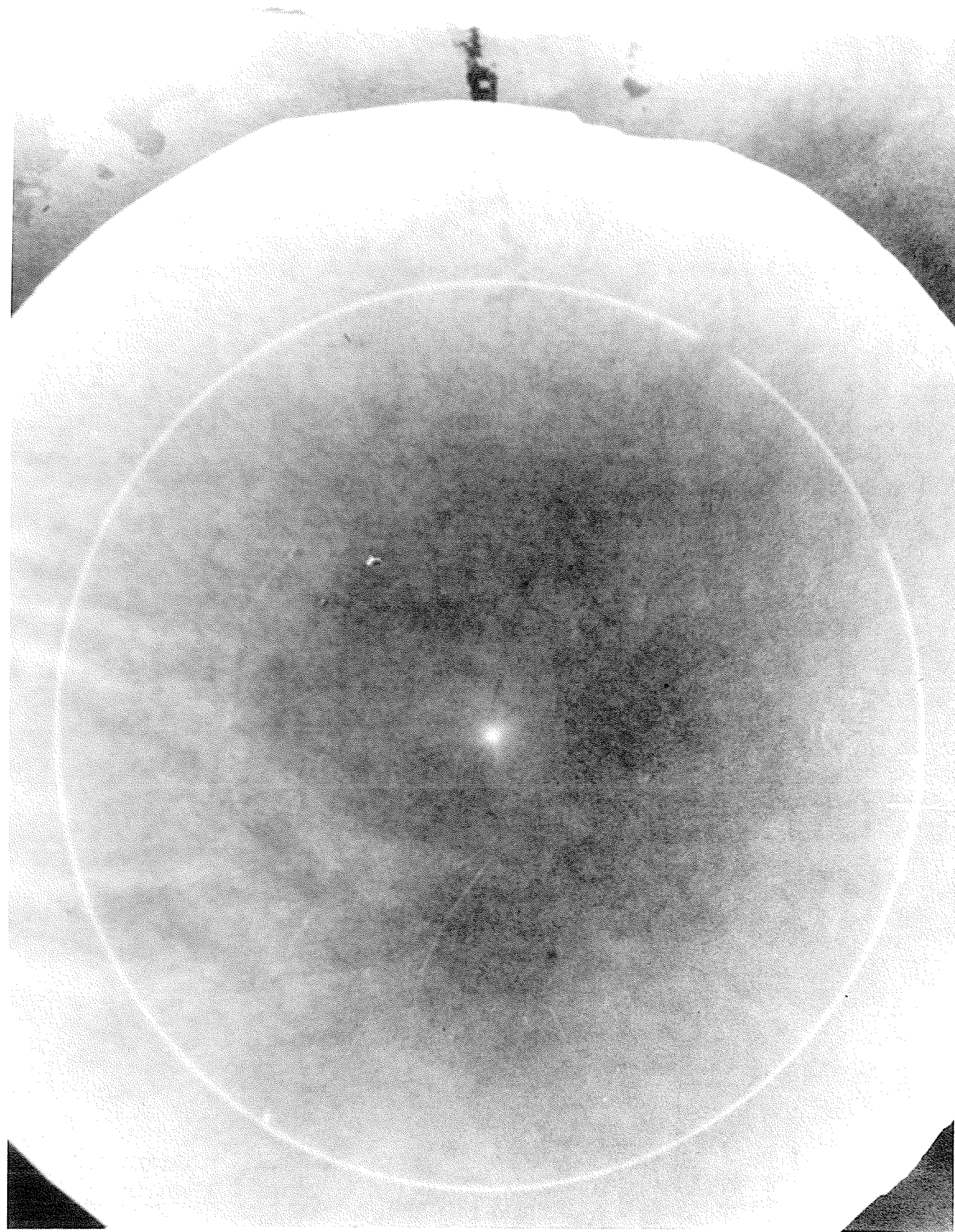


PLATE II. INTERMEDIATE IMAGE
OF THORIUM F-LINE

sweeping over the annular slit of the central baffle. In order that good resolution and transmission be attained, it is clear that the centre of the ring slit must be on the axis of the magnetic field which, because of slight irregularities in the position of the coils, does not necessarily coincide with the geometric axis of the spectrometer. One of the more extreme effects of central baffle misalignment is illustrated by the 'line' profile of fig. IV-1.

Alignment, accomplished by means of the two adjusting screws mentioned in the previous chapter, is rendered difficult by the presence of backlash in the screws and the consequent uncertainty in the baffle position. The technique of adjustment consists of taking F-line profiles at various (non-reproducible) central baffle positions until a good line profile is achieved. In the opinion of the author, the design of the spectrometer renders such adjustments unnecessarily time-consuming since the spectrometer chamber must be opened, with a consequent loss of vacuum, in order that the three adjusting screws on the supporting frame may be slackened off to allow free movement of the baffle.

The effect of nominal central baffle aperture on resolution and transmission is illustrated by the F-line



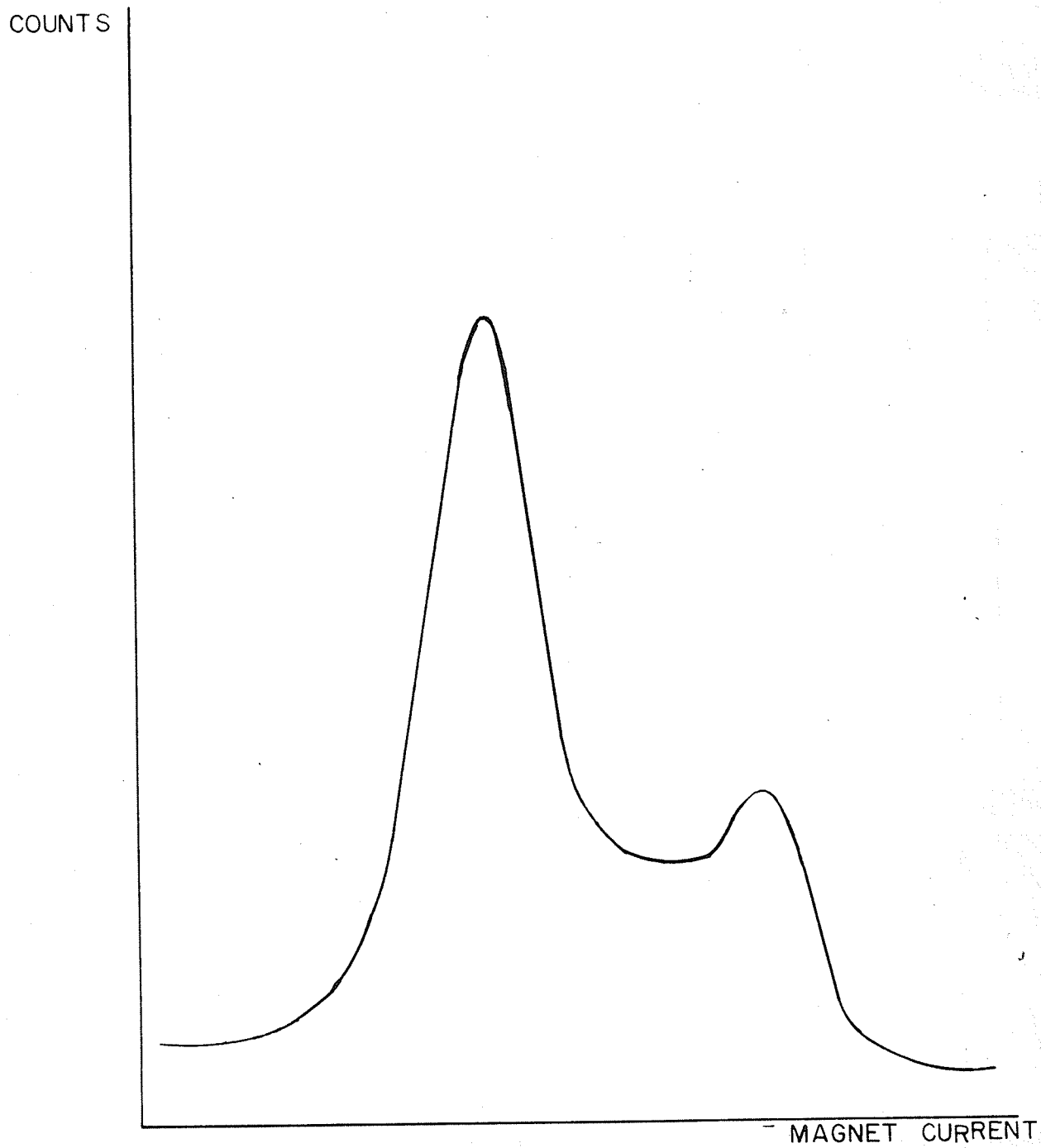


FIG. IV.1

profiles of fig. IV-2 taken with a 1/3 mm. diameter Thorium source. In general, increasing the aperture for high transmission results in a loss of resolution not necessarily undesirable if weak sources are being used. The optimum aperture opening is decided on the basis of source strength and the fineness of detail required in the spectrum.

Once the central baffle has been adjusted for good line profiles, the entrance slit baffle aperture must be adjusted for optimum resolution. This is quickly and easily done by the method of taking line profiles at different aperture openings. The results of these tests, shown in fig. IV-3, indicate that the optimum profile occurs when the circular ring is located 70 mm. from the pole-piece and the circular plate is located 8 mm. from the ring.

Since the positions of the central baffle and entrance baffle determine the geometry of the electron orbit, the source must be moved to the region where this orbit intersects the spectrometer axis. This point is determined again by the method of taking line profiles at various source positions. The results, shown graphically in fig. IV-4, indicate that the best profile is obtained for a nominal source setting of -6 corresponding to an actual source position of between 35 and 40 mm. in front of the pole-piece.

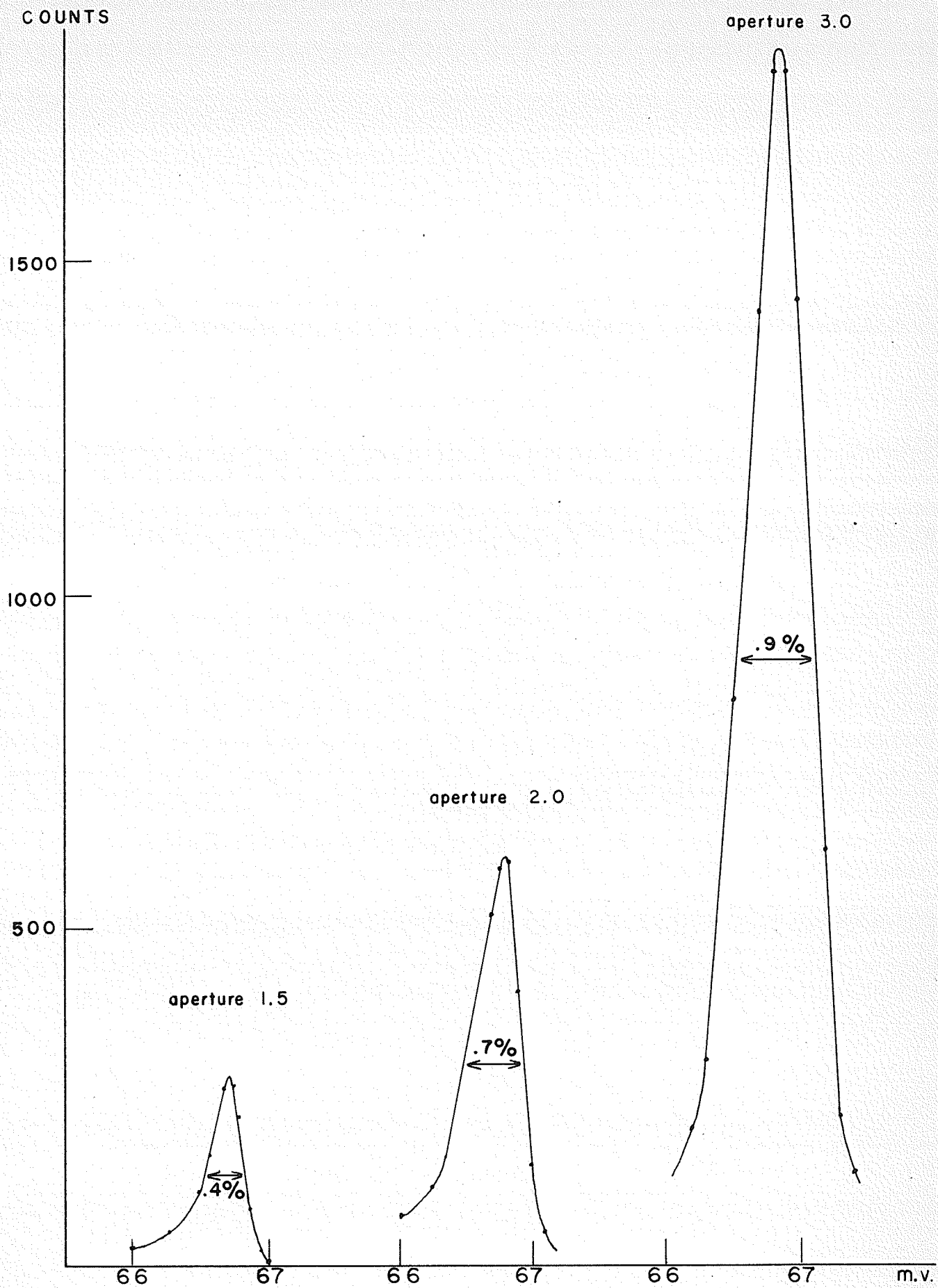


FIG. IV-2

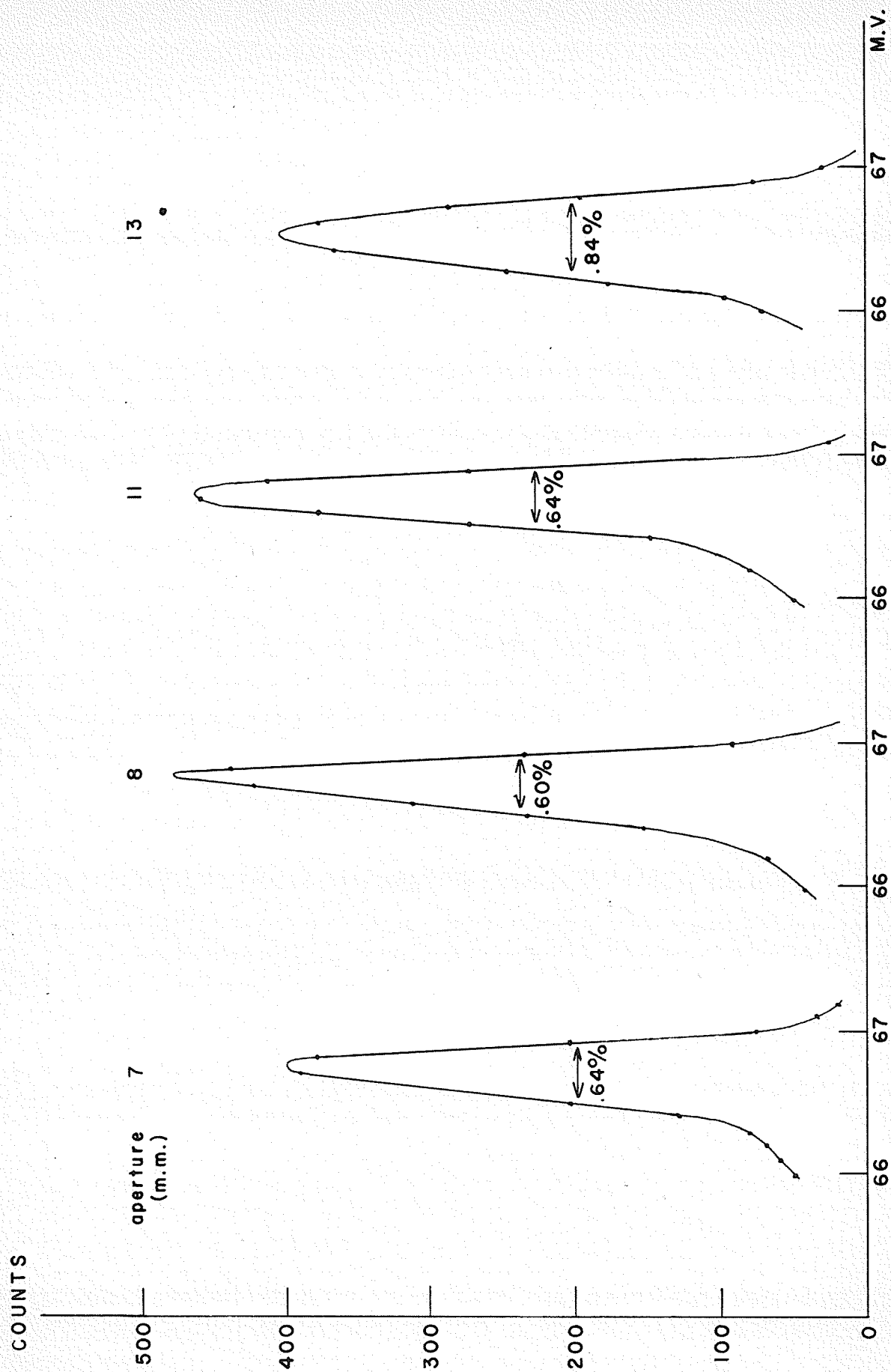


FIG. IV. 3

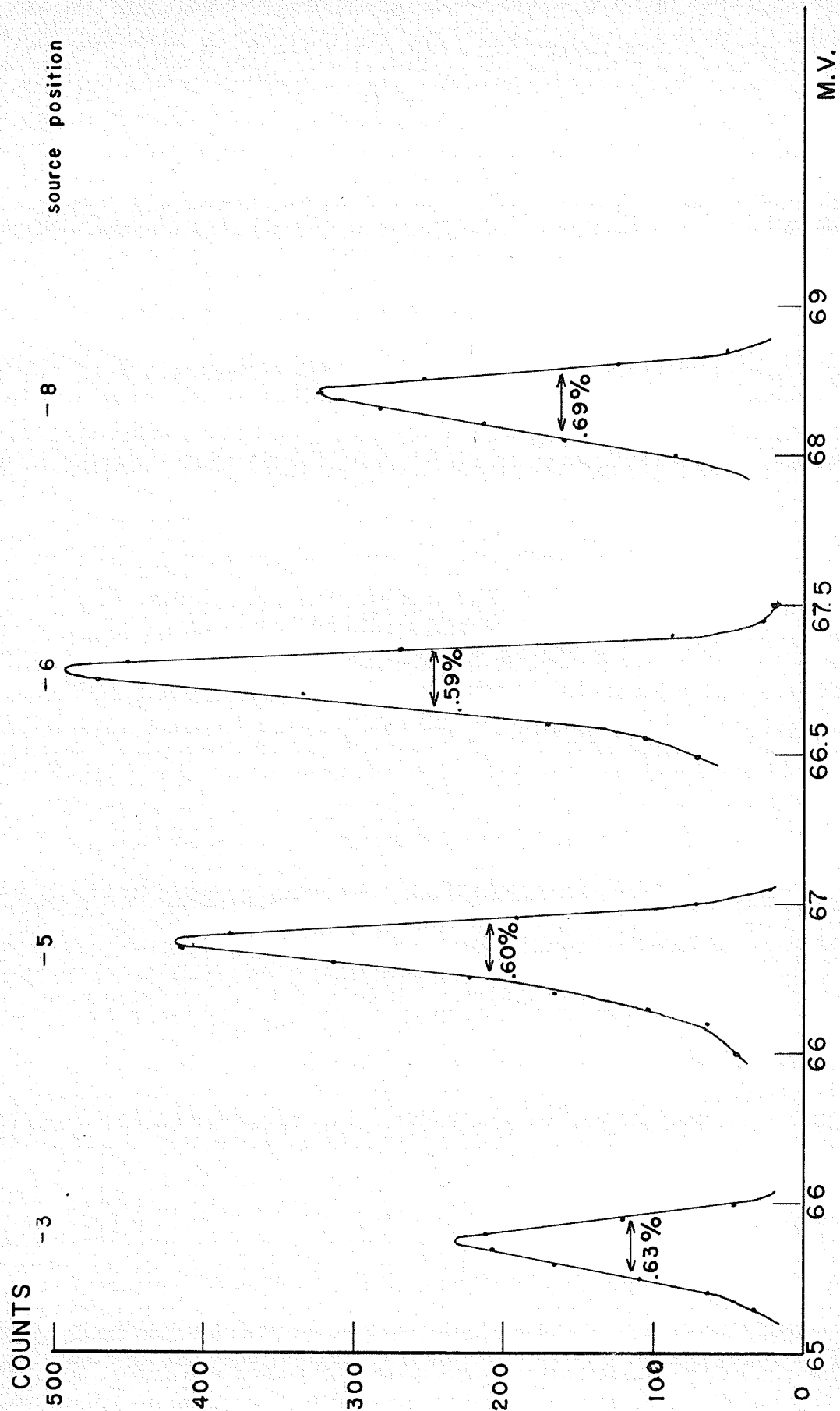


FIG. IV. 4

Sec. IV:2 Calibration of the Spectrometer

Deviations from strict linearity of the relation between magnet current and focussing field in the LKB spectrometer are stated by the manufacturer to be less than 0.1% over the region from 15 to 235 amps, i.e., from 30 to 470 millivolts as measured across the resistor R67. Since the β -particle momentum is directly proportional to the field B, as shown by equation II-1, it is possible to find a calibration factor, k, which converts millivolt readings, v, to momentum values, η , in units of $m_0 c$ where m_0 is the electronic rest mass and c is the velocity of light.

$$\text{Thus } \eta = k v.$$

But from equation II-1, $p = eB\rho$

$$\therefore \eta = \frac{eB\rho}{m_0 c} = \frac{B\rho}{1704.45} = k v$$

$$\text{and } k = \frac{B\rho}{1704.45 v}$$

$B\rho$ values for the Th A, B, F, I, Ia, and J lines have been accurately measured by Siegbahn and Edvarson⁽²⁵⁾, and for the Th L and X lines by Lindstrom⁽²⁵⁾, providing a convenient means of determining k. In the present work, the peaks of the Th B, F, I, L, and X lines were taken as calibration points.

The values of k obtained are listed in table 1.

Table 1: Calibration

line	v	B_p	$k = \frac{B_p}{1704.45 v}$
Th B	31.65	652.38	.012075
F	67.27	1388.44	.012099
I	85.04	1753.91	.012091
L	126.35	2607.17	.012097
X	483.3	9986.7	.012124
$\bar{k} = .012097 \pm .000011$			

If the spectrum of the isotope being examined possesses conversion lines due to γ -rays whose energies have been accurately determined by crystal diffraction methods, these may be used for calibration purposes in addition to or in place of Thorium lines.

In order that k be constant from one series of measurements to another, it is necessary, because of hysteresis, that the initial state of magnetization of the spectrometer be the same each time and that the magnet current always be changed in the same direction. Complete demagnetization of the spectrometer before each new series of measurements, accomplished by taking the magnet around successively smaller hysteresis loops ensures that each initial state, in which there is no residual field, is the same.

Chapter VPREPARATION AND MOUNTING OF SOURCESSec. V:1 General Considerations

Ideally, sources for use in β -ray spectroscopy should be of zero thickness and should have no backing, for if a source is of finite thickness, the energy of some of the β -particles will be reduced due to absorption in the source material⁽²⁶⁾ whereas the backing material introduces backscattering of β -particles⁽²⁷⁾. Both of these effects yield a surplus of low-energy electrons which will distort the shape of the β -ray spectrum and perhaps give false indication of low energy β -feeds. Another possible consequence of these effects is a change in curvature of the Fermi plot suggesting that a forbidden spectrum is actually allowed or vice-versa.

Since the source emits β^- -particles, it becomes positively charged and unless provision is made for grounding, a strong electric field may be set up in the neighborhood of the source which may shift the spectrum by many kilovolts⁽²⁸⁾ toward lower energies. This effect is however evenly distributed over the spectrum and will not produce distortion but merely displacement of the spectrum.

Sec. V:2 Calibration Sources of Thorium Active Deposit

For purposes of calibrating a β -ray spectrometer, it is convenient to have available a series of intense, well separated conversion lines distributed over a large energy interval. Such lines are found in the β -spectrum of Th active deposit or Th (B+C+C'') which is produced by the decay of thoron. The B_p values of these lines have been determined by Siegbahn and Edvarson, and Lindstrom⁽²⁹⁾ to within 1 part in 10^4 and hence these may be used for calibration.

The thorium active deposit is obtained from a ''pot'' containing radiothorium which decays with a 1.9 year half-life by way of ThX to gaseous thoron ($^{220}\text{Rn}^{86}$) which diffuses throughout the pot. The thoron in turn decays by α -emission with a 54 second half-life to ThA which is a solid at room temperatures. The α -emission processes disturb the extra-nuclear structure of the resulting thorium A atoms by ionization so that many are left positively charged while a few are left negatively charged and hence they may be collected by recoil from the gas on a platinum button which is maintained at a high negative potential. The thorium A then decays by α -emission with a .16 second half-life to thorium B which remains on the button, and, along with its short lived

daughter products, ThC , ThC' and ThC'' , comprises thorium active deposit which decays with an equilibrium half-life of 10.6 hours, that of thorium B.

The source thus obtained is a nearly monatomic layer and hence effects due to source absorption are negligible. Although electrons of the intense conversion lines are strongly backscattered by the platinum backing, this does not effect their shapes or positions and hence lines from such sources are suitable for calibration. The backscattering of electrons does however render such sources unsuitable for observations of the β -continua.

Sec. V:3 V.Y.N.S. Thin Source Backings

For measurements of β -continua, backscattering must be rendered negligible and hence thin films of low atomic number must be used.

In the past, use has been made of nylon, formvar, cellulose acetate and nitrate, collodion, zapon, and terylene as well as mica sheets, aluminium foils, and aluminium oxide films. In general, the organic materials mentioned yield films with thicknesses of $\sim 20\text{-}40 \mu\text{g}/\text{cm}^2$ but which suffer from either a lack of resistance to the chemical reagents

used in the commercial preparation of active materials or a lack of mechanical strength⁽³⁰⁻³⁷⁾. Mica sheets possess good mechanical and chemical properties but are too thick ($\sim 500 \mu\text{g}/\text{cm}^2$) to be useful for anything but conversion line studies. Aluminium foil on the other hand is available in thicknesses of $\sim 200 \mu\text{g}/\text{cm}^2$ but lacks both mechanical strength and chemical resistance. Oxide films show excellent chemical properties but are extremely fragile.

A new material has recently been introduced⁽³⁸⁾ viz. V.Y.N.S. resin (a polyvinylchloride acetate copolymer manufactured by the Bakelite Co.) which possesses remarkable strength both mechanically and chemically. It is soluble in cyclohexanone.

The common techniques of producing thin films such as pipetting a drop of a solution of the material onto a water surface⁽³¹⁾ or casting films on a glass slide⁽³³⁾ fail for this material. A somewhat elaborate technique described by Pate and Yaffe⁽³⁸⁾ consists in placing a small quantity of a cyclohexanone solution of V.Y.N.S. in the space between the side of a water filled tray and a half-submerged cylindrical rod. The rod is then drawn at a constant speed parallel to and slightly above the water surface leaving a thin film floating behind it. It

is frequently found that such films are wrinkled, and any flat, smooth areas are liable to show striations by reflected light, indicating non-uniformity.

The following technique⁽³⁹⁾ which has been devised in the course of this work produces strips of thin film which are invariably smooth and whose thickness slowly varies in a linear fashion with distance along the strip. Such films are nearly constant in thickness across their widths and show few, if any, striations.

A little V.Y.N.S. solution is spread evenly with a dropper along the edge of a thin plate such as that of a piece of window glass. The coated edge is then touched to the surface of water contained in a large developing tray so that all parts of the edge make simultaneous contact. This is most easily accomplished by viewing the tray from above so that the edge of the plate can be aligned with its image in the water surface by a slight rocking motion of the plate against the side of the tray. A sheet of film whose width is nearly the same as that of the edge of the plate is then drawn by surface tension across the water surface.

If a solution of one part of V.Y.N.S. resin to five parts of cyclohexanone by volume is used, films whose

thickness is of the order of $10 \mu\text{g}/\text{cm}^2$ are obtained. As is to be expected, it is found that more dilute solutions yield thinner films. It is also found that better films are produced on cold (10°C) water than on warm (45°C) water. The water must be changed frequently, for increasing concentrations of the solvent in water tend to interfere with the spreading process and wrinkling may result.

In order to remove the films a wire ring is slipped underneath the strip and raised until complete contact has been made. The excess film is then detached by running a paintbrush moistened with cyclohexanone around the perimeter of the ring. Care must be taken that the ring projects slightly above the water surface; otherwise, the detached portion of film may float free and may wrinkle if an attempt is made to retrieve it. In order that surface tension forces do not tear the film, it must be lifted from the water surface with a rolling motion so that one edge is separated first; the angle between the film and water surface is then slowly increased until the film is perpendicular to the surface. Then the film may be lifted intact from the water. This method usually prevents water droplets from adhering to the film where they would leave a residue upon evaporation.

The wire frame supporting the film is then brought down on an annular aluminium source ring so that the film makes contact with the flat, circular surface and a paintbrush moistened with cyclohexanone is used to detach the film from the wire frame. The film adheres to the aluminium ring and any wrinkles arising during the process of transfer from the wire frame may usually be removed by gently stretching the film from the edges with the fingertips. It is found that an indication of the thickness of the film can be gotten from its colour⁽³⁸⁾, bluish gray films corresponding to a thickness of 1 to 5 $\mu\text{g}/\text{cm}^2$. In the present work films of this order of thickness were used exclusively.

Sec. V:4 Evaporation of Gold onto V.Y.N.S. Films

As mentioned in the first section of this chapter, sources must be grounded in some fashion in order to prevent them from becoming charged. This was accomplished by the vacuum deposition of a very thin layer of gold onto the V.Y.N.S. films. Such films exhibit a reddish coloration by reflected light and a blue coloration by transmitted light. Pate and Yaffe⁽³⁸⁾ made spectrophotometric measurements on gold layers of various known thicknesses on V.Y.N.S. films and found that the first reddish colouration appears at a thickness of

$\sim 0.4 \mu\text{g}/\text{cm}^2$ and deepens until a rich reddish-purple is attained at $\sim 5 \mu\text{g}/\text{cm}^2$. At thicknesses in excess of $10 \mu\text{g}/\text{cm}^2$, the gold films were seen to exhibit a metallic appearance and the V.Y.N.S. films tended to sag and wrinkle.

The present writer observed that in a group of five coated films all of which exhibited approximately the same shade of blue by transmitted light, some showed only a trace of reddish color by reflected light whereas others had a more pronounced coloration. It is hence concluded that observations made by reflected light are more sensitive to the thickness of the metallic layer than those made by transmitted light. A sixth film showed a deeper shade of blue and also a very deep red coloration by reflected light but exhibited no metallic appearance in spite of the fact that sagging and wrinkling occurred. The colouration of this gold film suggests that its thickness is $< 10 \mu\text{g}/\text{cm}^2$ and the wrinkling is thought to be due to the thinness of V.Y.N.S. films used. Since the films used for actual sources exhibited fairly deep reddish coloration, it is estimated that their thicknesses are of the order of $5 \mu\text{g}/\text{cm}^2$. It is thus seen that the maximum total thickness of the source backings used is of the order of $10 \mu\text{g}/\text{cm}^2$.

It is not practical to use gold layers thicker than $5 \mu\text{g}/\text{cm}^2$, for at that thickness, the resistivity of gold is nearly as low as that of the bulk material, and any further increase in thickness would result only in an undesirably thick backing. The resistivity rises sharply for thinner layers, however, and if these are used, it is likely that source charging will occur.

The vacuum deposition of gold was accomplished with the aid of an Edwards "'Speedivac'" model 12EA/620 coating unit. This apparatus utilizes a trough-shaped piece of molybdenum ribbon clamped between 2 electrodes to hold the material to be evaporated onto the work which is supported 6 inches above the Mo trough by a ring stand. The whole assembly is enclosed in a 12" diameter glass bell jar which may be evacuated by means of an oil diffusion pump backed by a single stage rotary pump. The heater current between the electrodes may be controlled by a variac-type variable transformer.

The gold to be evaporated was in the form of a $1/8$ " length of .040 inch diameter wire. The source discs were screwed to a square aluminium plate which was placed on the ring stand. Current was passed through the trough until the gold melted and distillation was maintained until the proper

coloration was observed on the films.

Sec. V:5 Deposition of Active Material on the Films

Liquid source materials were deposited by means of a glass syringe fitted with a hypodermic needle the point of which had been ground off so that drops formed on its tip rather than its side.

Initially sources were prepared by forming a droplet on the tip of the needle, visually centering it over the source ring, and then touching it to the film. The droplet would adhere to the film and could then be evaporated to dryness.

Needless to say, sources prepared by the above dropping technique are liable to be slightly off-centre and hence a method of centering the hypodermic was needed. A device which performs the double duty of centering the active droplet with respect to the source disc and shielding the worker's eyes from the β -radiation emitted by the source was constructed. Essentially, it consists of an aluminium tube bored out to just receive the glass syringe, a threaded end-cap to facilitate raising and lowering the syringe, and a perspex tube bored out to the diameter of a source ring which allows the worker to see the drop as it touches the V.Y.N.S. film.

Sources of different strengths can be obtained by successive superposition and evaporation of droplets onto the same source disc but the usefulness of this method is circumscribed by considerations of source thickness, etc., outlined in the first section of this chapter.

Chapter VI

CORRECTION FOR WINDOW ABSORPTIONSec. VI:1 Introduction

The absorption of β particles in the region below 150 kev by the Geiger counter window will result in Fermi plots of allowed spectra showing marked deviation from linearity. It is therefore essential in low energy work to compensate for this by means of a correction to be applied to observed counting rates. Such a correction can be obtained by comparing the theoretical shape of a spectrum known to have an allowed shape with its observed shape.

It is reported by Pohm et al.⁽⁴⁰⁾ in an experiment to detect slight non-linearity of the Fermi plots of several allowed spectra, that the spectrum of P^{32} yields a Fermi plot which is very nearly linear and hence suitable for use in finding a correction factor. The small quantity of P^{33} contained in available supplies of P^{32} raises no question as to the feasibility of its use since the spectrum of P^{33} is also known⁽⁴¹⁾ to be allowed and to have a linear Fermi plot.

Sec. VI:2 The β -Spectrum of P^{32} - P^{33}

Sources were prepared on V.Y.N.S. backings using 'carrier-free' processed P^{32} - P^{33} in the form of phosphate ion in approximately 1 cc. of 0.05 N HCl solution obtained from Atomic Energy of Canada Ltd., Chalk River.

A preliminary run made on the β -spectrum revealed the presence of apparently three partial spectra instead of the two expected; in view of this, a second run was made with improved counting statistics. The Fermi analysis of this run, shown in table II(a), again revealed three partials when plotted (fig. VI-1a). An ordinary least squares determination of the end-point, ϵ_{01} , and slope, m_1 , of the first or high energy partial yielded the values $\epsilon_{01} = 4.3122 m_0c^2 = 1692$ kev and $m_1 = 3.791875$ which were used in the construction of table II(b), representing the spectrum of the second and third partials only, shown in fig. VI-1b, by the method of subtraction outlined in chapter II. A further least squares analysis of the data of table II(b) showed the end-point and slope of the second partial to be $\epsilon_{02} = 2.2727 m_0c^2 = 650$ kev and $m_2 = -3.723856$. These were in turn used to construct table II(c) and fig. VI-1c representing the third partial spectrum alone which has an end-point $\epsilon_{03} = 1.4896 m_0c^2 = 250$ kev, by the method of least squares.

Table II (a)

FERMI ANALYSIS OF 2nd P32-P33 SPECTRUM

Background = B = 10.1 counts/min.

mv	c/min	f = decay factor	N = $\frac{C-B}{mv} \times 100 f$	ϵ	1/F	N/F	$\sqrt{N/F}$
30	10.2	.	0.33	1.0638	3.049	1.01	1.005
35	18.5	.	24.00	1.0859	2.463	59.11	7.69
40	37.5	.	68.50	1.1110	2.033	139.26	11.80
45	64.1	.	120.00	1.1386	1.698	203.76	14.27
50	90.1	.	160.00	1.1686	1.441	230.56	15.18
55	111.3	.	184.00	1.2011	1.236	227.42	15.08
60	128.6	.	199.48	1.2356	1.071	213.64	14.62
65	149.7	1.01	216.92	1.2722	0.936	203.04	14.25
70	161.8	.	218.88	1.3104	.825	180.58	13.44
75	168.0	.	218.95	1.3503	.732	160.27	12.66
80	.80.8	.	221.92	1.3915	.654	145.14	12.05
85	192.2	.	222.81	1.4344	.587	130.79	11.44
90	213.6	1.04	235.15	1.4783	.530	124.63	11.16
95	238.3	.	249.82	1.5234	.480	119.91	10.95
100	264.0	.	264.06	1.5695	.437	115.39	10.74
105	285.6	.	272.88	1.6166	.400	109.15	10.45
110	316.0	.	289.21	1.6646	.367	106.14	10.30
115	338.6	.	299.93	1.7133	.338	101.38	10.07
120	368.9	.	313.95	1.7628	.313	98.27	9.913
125	390.2	.	319.28	1.8129	.290	92.59	9.622
130	416.5	.	328.25	1.8637	.269	88.30	9.397
135	446.1	.	339.11	1.9149	.252	85.46	9.244
140	475.7	1.05	349.20	1.9668	.237	82.76	9.097
145	486.4	.	344.90	2.0192	.218	75.19	8.671
150	517.9	.	355.46	2.0719	.206	73.22	8.557
155	542.6	.	360.73	2.1252	.193	69.62	8.344
160	558.5	.	359.89	2.1787	.182	65.50	8.093
170	593.7	.	360.45	2.2868	.162	58.39	7.641
180	634.1	.	364.00	2.3962	.145	52.78	7.265
190	656.5	.	357.22	2.5066	.131	46.80	6.841
200	681.8	.	356.00	2.6180	.118	42.01	6.482
210	674.9	.	335.56	2.7303	.108	36.24	6.020

this table is continued

Table II (a) continued

220	667.5	1.06	298.82	2.8433	.098	31.04	5.571
230	630.3		269.65	2.9567	.090	25.72	5.071
240	599.7		245.67	3.0709	.083	21.61	4.649
250	559.0		232.73	3.1855	.077	17.92	4.233
260	509.1		203.44	3.3007	.071	14.44	3.800
270	447.5		171.72	3.4161	.066	11.33	3.366
280	385.6		142.16	3.5319	0.61	8.67	2.944
290	310.9		109.94	3.6482	0.57	6.27	2.504
300	238.3		81.39	3.7646	.054	4.40	2.098
310	169.4	1.07	54.99	3.8814	.050	2.75	1.658
320	104.8		31.66	3.9984	.047	1.49	1.221
330	53.8		14.17	4.1156	.045	0.638	0.7987
340	23.0		4.055	4.2331	.042	0.170	0.4123

Table II (b)

FERMI ANALYSIS OF 2nd AND 3rd PARTIALS IN P³² - P³³

ϵ	$\epsilon_0 - \epsilon$	$m (\epsilon_0 - \epsilon)$ $= \sqrt{\frac{N_1}{F}}$	N_1/F	N/F	N_{23}/F $= \frac{N - N_1}{F}$	$\sqrt{\frac{N_{23}}{F}}$
1.2722	3.0400	11.527	132.87	203.04	70.17	8.377
1.3104	3.0018	11.382	129.55	180.58	51.03	7.144
1.3503	2.9619	11.231	126.14	160.27	34.13	5.842
1.3915	2.9207	11.075	122.66	145.14	22.43	4.741
1.4344	2.8778	10.912	119.07	130.79	11.72	3.423
1.4783	2.8399	10.769	115.97	124.63	8.66	2.943
1.5234	2.7888	10.575	111.83	119.91	8.08	2.843
1.5695	2.7427	10.400	108.16	115.39	7.23	2.689
1.6166	2.6956	10.121	104.47	109.15	4.68	2.163
1.6646	2.6476	10.039	100.78	106.14	5.36	2.315
1.7133	2.5939	9.855	97.12	101.38	4.26	2.064
1.7628	2.5494	9.667	93.45	98.27	4.82	2.195
1.8129	2.4993	9.477	89.81	92.59	2.78	1.667
1.8637	2.4485	9.284	86.19	88.30	2.11	1.453
1.9149	2.3973	9.090	82.63	85.46	2.83	1.294
1.9668	2.3454	8.893	79.09	82.76	3.67	1.916
1.1386	3.1736	12.034	144.82	203.76	58.94	7.677

Table II (c)

FERMI ANALYSIS OF 3rd PARTIAL IN p³² - p³³

ϵ	$\epsilon_0 - \epsilon$	$m(\epsilon_0 - \epsilon) =$ $\sqrt{\frac{N_2}{F}}$	$\frac{N_2}{F}$	$\frac{N_{23}}{F}$	$\frac{N_3}{F} =$ $\frac{N_{23}}{F} - \frac{N_2}{F}$	$\sqrt{\frac{N_3}{F}}$
1.2722	1.0005	3.7257	13.88	70.17	56.29	7.503
1.3104	0.9623	3.5835	12.84	51.03	38.19	6.180
1.3503	0.9224	3.4349	11.80	34.13	22.33	4.725
1.3915	0.8812	3.2815	10.77	22.48	11.71	3.422
1.4344	0.8383	3.1217	9.75	11.72	1.97	1.404

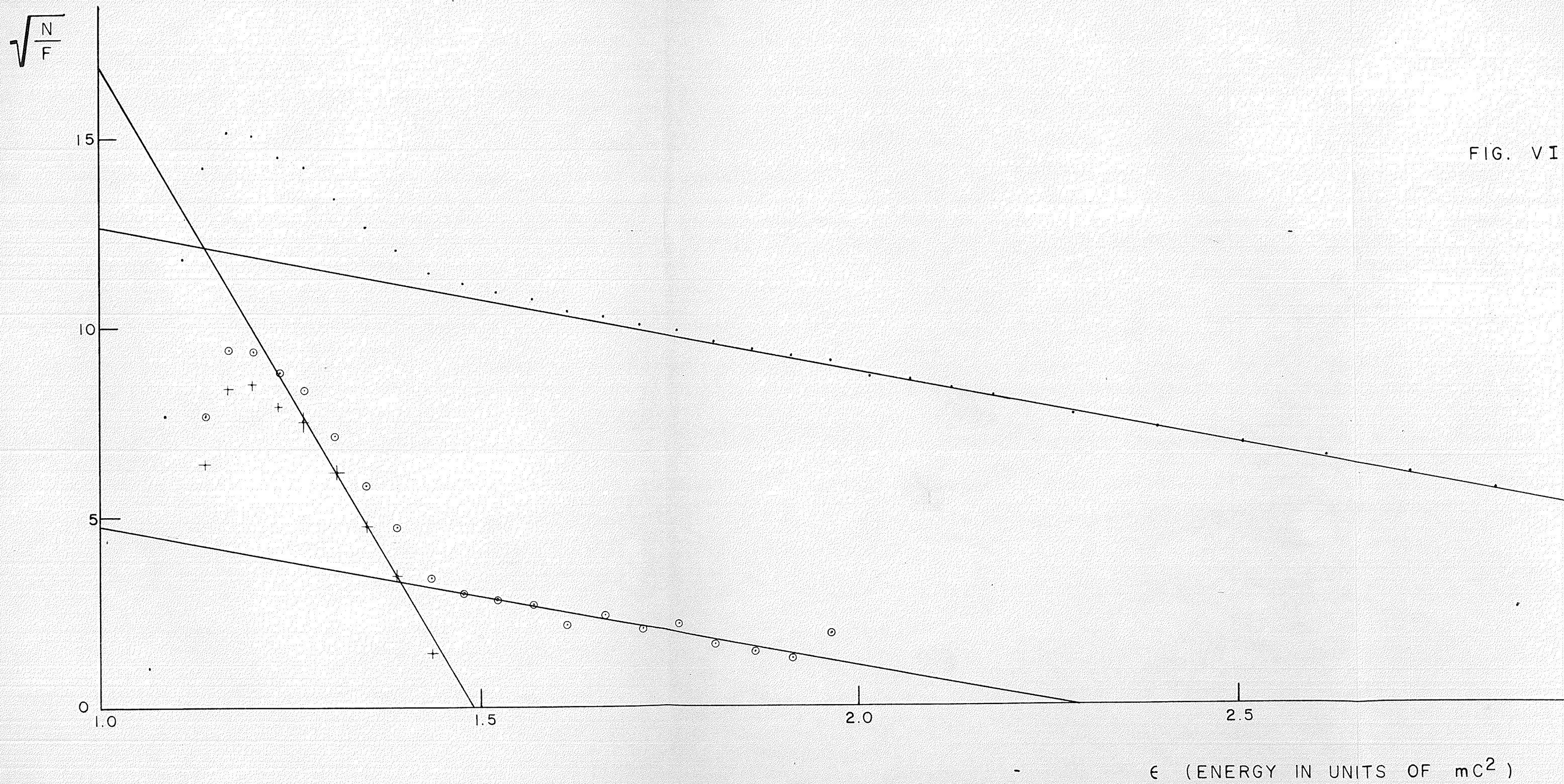
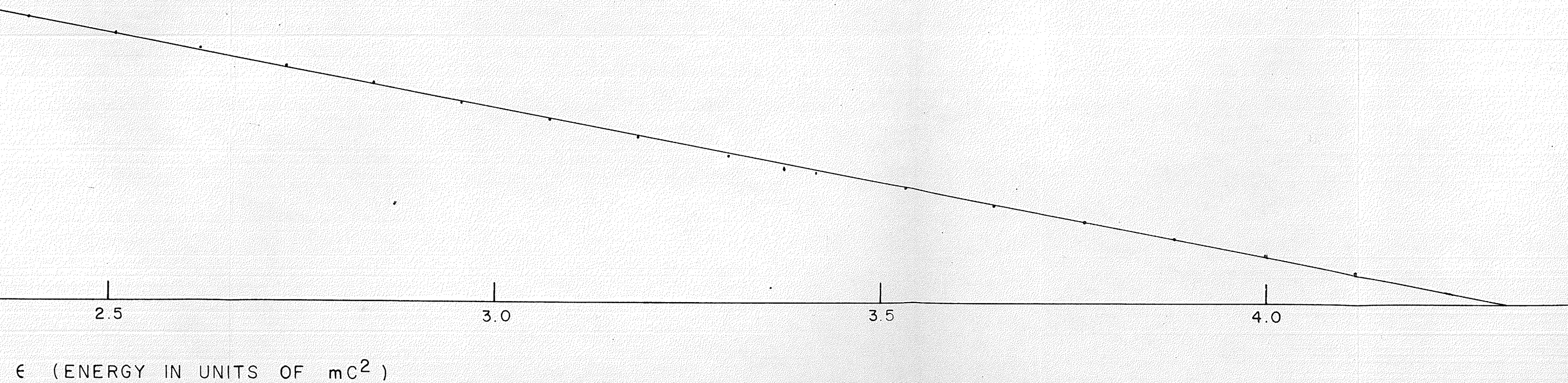


FIG. VI-1: FERMI PLOT OF $P^{32} - P^{33}$ SPECTRUM

CURVE A (·): TOTAL SPECTRUM

CURVE B (⊙): 2nd & 3rd PARTIAL SPECTRA

CURVE C (+): 3rd PARTIAL SPECTRUM



The 1692 and 250 kev end-points are both in excellent agreement with the 1707 and 246 published⁽⁴²⁾ average end-points for P³² and P³³ respectively, whereas the 650 kev end-point of the second partial spectrum does not correspond to that of any trace activity which might be present.

The possibility that the second partial might be the result of an electron excess in the low energy region due to scattered β -particles of higher energy was checked by a third run 24 days later using the same source in order to determine its half-life.

In order to determine the half-life, it is necessary to know the counting rates $(N_{23})_1$ and $(N_{23})_2$ corresponding to a certain E -value at two times, t_1 and t_2 respectively. Now the law of radioactive decay states that

$$(N_{23})_1 = N_0 e^{-\lambda t_1},$$

and

$$(N_{23})_2 = N_0 e^{-\lambda t_2},$$

where N_0 is the counting rate at some initial time and where λ is the decay constant of the activity in question.

$$\therefore \frac{(N_{23})_1}{(N_{23})_2} = e^{\lambda(t_2 - t_1)} = e^{\lambda \Delta t}$$

$$\text{and so } \lambda = \frac{1}{\Delta T} \ln \frac{(N_{23})_1}{(N_{23})_2}$$

The half-life $T_{1/2}$ is then related simply to λ by the formula

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} = \frac{0.693 \Delta T}{\ln \frac{(N_{23})_1}{(N_{23})_2}}$$

Furthermore, since $(\sqrt{\frac{N_{23}}{F}})_2$ is known⁺ from table II(b) and since $(\sqrt{\frac{N_{23}}{F}})_1$ is known from a similar table (not shown) for the third run,

$$\frac{(N_{23})_1}{(N_{23})_2} = \left[\frac{(\sqrt{\frac{N_{23}}{F}})_1}{(\sqrt{\frac{N_{23}}{F}})_2} \right]^2$$

The calculation of $T_{1/2}$ is shown in table III

⁺ Note: for the present purposes, the values of $(\frac{N_{23}}{F})_1$ listed in table II(b) are not satisfactory since they are corrected for the decay of the P³² source during the run. Hence the values shown in table III are uncorrected.

Table III

E	$\left(\sqrt{\frac{N_{23}}{F}}\right)_1$	$\left(\sqrt{\frac{N_{23}}{F}}\right)_2$	$\sqrt{\frac{(N_{23})_1}{(N_{23})_2}}$
1.5234	2.843	1.921	1.480
1.5695	2.689	1.561	1.723
1.6166	2.163	1.659	1.304
1.6646	2.315	1.745	1.327
1.7133	2.064	1.251	1.650
1.7628	2.195	1.149	1.910
1.8129	1.667	1.342	1.242
1.9149	1.294	0.771	1.678
1.9668	1.916	1.198	1.600
			1.546 av

$$\text{Hence } \frac{(N_{23})_1}{(N_{23})_2} = 2.40,$$

$$\ln \left\{ \frac{(N_{23})_1}{(N_{23})_2} \right\} = 0.876,$$

$$\Delta t = 24 \text{ days}$$

$$\text{and } T_{1/2} \approx \frac{0.693 \times 24}{.876} \approx 19 \text{ days}$$

This value is fairly close to the 14-day P^{32} half-life and it is therefore probable that the second partial is in fact due to electron scattering in the spectrometer. Its relatively low intensity is further support for this view. Assuming that deviations from linearity in the Fermi plot of the partial scattering spectrum are small, the spectrum of the second run was used to obtain a window absorption correction.

Sec. VI:3 The Window Correction

The equation of a Fermi plot of a single allowed spectrum is $\sqrt{\frac{N}{F}} = m(\epsilon_0 - \epsilon)$. Hence, knowing m and ϵ_0 it is possible to calculate $\sqrt{\frac{N}{F}}$ and hence N/F . By adding the values of N/F found for the three spectra and multiplying by F at each point, the theoretical spectrum is obtained. By dividing the theoretical value of N by the observed value for each point, a correction factor is obtained. This is done in table IV the results of which are plotted in fig. VI-2. Thus to correct for window absorption the observed counting rates in the low energy regions are multiplied by this factor.

Table IV

CORRECTION FACTOR FOR WINDOW ABSORPTION

ϵ	$\sqrt{N_1/F^+}$	$\sqrt{N_2/F}$	$\sqrt{N_3/F}$	N_1/F	N_2/F	N_3/F	$\frac{N_{total}}{F}$	$1/F$	N_{total}	$N_{observed}$	Correction factor
1.0638	12.318	4.502	14.657	151.73	20.27	214.83	376.83	3.049	123.59	0.33	374.52
1.0859	12.234	4.419	13.897	149.67	19.53	193.13	362.33	2.463	147.11	24.00	6.130
1.1110	12.139	4.326	13.033	147.36	18.71	169.86	335.93	2.033	165.24	68.50	2.412
1.1386	12.034	4.223	12.083	144.82	17.83	146.00	308.65	1.698	181.77	120.00	1.515
1.1686	11.920	4.112	11.050	142.09	16.91	122.10	281.10	1.441	195.07	160.00	1.219
1.2011	11.797	3.990	9.931	139.17	15.92	98.62	253.71	1.236	205.27	184.00	1.116
1.2356	11.666	3.862	9.744	136.10	14.92	74.46	227.48	1.071	212.40	199.48	1.065
1.2722	11.527	3.726	7.484	132.87	13.88	56.01	202.76	0.936	216.62	216.92	-
1.3104	11.382	3.583	6.169	129.55	12.84	38.06	180.45	0.825	218.73	218.88	-

$\frac{N_{\text{total}}}{N_{\text{observed}}}$

5.0

4.0

3.0

2.0

1.0

1.10

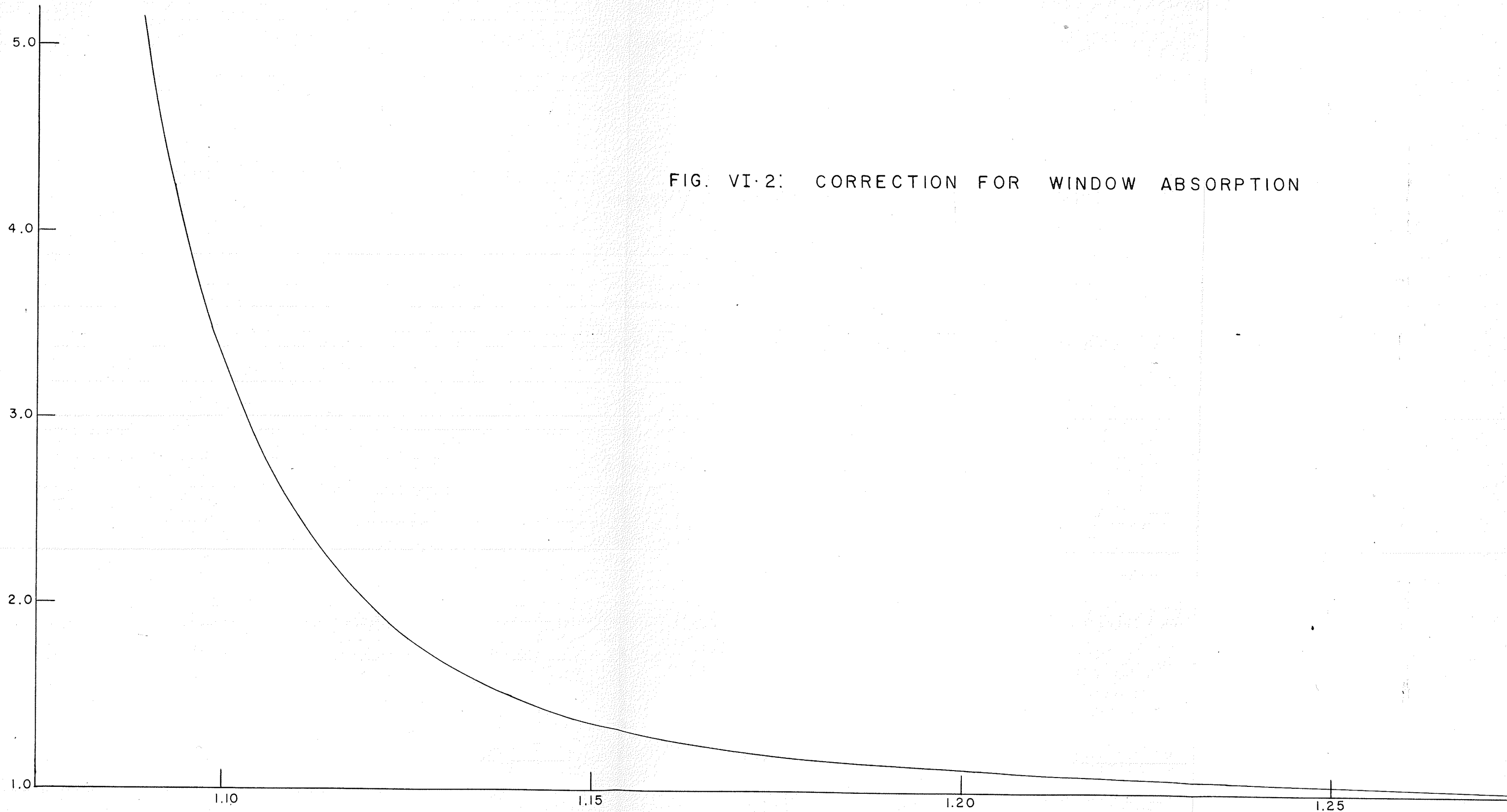
1.15

1.20

1.25

ENERGY IN UNITS OF mc^2

FIG. VI.2: CORRECTION FOR WINDOW ABSORPTION



PREVIOUS INVESTIGATIONS OF IRIDIUM-192Sec. VII:1 The β -Continua

Ir^{192} is produced by neutron capture in natural Ir^{191} . The principal mode of decay is by β -emission with a 74.5 day half-life to Pt^{192} , but there is a 4% decay by K-capture to Os^{192} .

The first investigation of the Ir^{192} β -spectrum with a magnetic spectrometer by Levy⁽⁴³⁾ gave the high-energy end-point as 670 kev. This was supported by Shpinel and Forafontov⁽⁴⁴⁾, who obtained a value of 660 kev, and by Johns and Nablo⁽⁴⁵⁾ who obtained a value of 672 kev. Using the Levy end-point and detailed γ -ray information from conversion line studies, Cork⁽⁴⁶⁾ proposed a disintegration scheme predicting an additional low-energy β -feed with a 390 kev end-point. This scheme was for the most part substantiated by the γ -ray work of Baggerly et al.⁽⁴⁷⁾ and Pringle et al.⁽⁴⁸⁾ insofar as the Pt^{192} energy levels were concerned. Unpublished data of Kyles and Campbell quoted by Fairweather⁽³⁰⁾ indicated the existence of 5 partial spectra with end-points of 1175, 849, 701, 568, and 281 kev, but subsequent work by Bashilov et al.⁽⁴⁹⁾ revealed no trace of the 1175 kev transition

although four partials with end-points of 840, 670, 540, and 240 kev were found. Both these sets of results are in fair agreement with the γ -ray data upon which Cork's scheme is based, but there is a 30 to 40 kev discrepancy in the end-points.

More recent (1958) work by Fairweather⁽³⁰⁾ showed that the two high-energy partial spectra reported by Kyles and Campbell were spurious and probably due to scattering in their instrument. In accordance with this finding, an empirical correction was applied to their data which then yielded neither an 1175 nor an 849 kev partial but which gave the remaining three partials end-points of 697, 561, and 281 kev, still in agreement with Cork's scheme. Fairweather, finding only three partial spectra with end-points of 690, 551, and 267 kev, proposed a new level scheme for Pt^{192} which sought to account for γ -rays with energies of 45, 97, and 105 kev found by Huq⁽⁵⁰⁾ by the introduction of a 1253 kev level and which included the 1156 and 1358 kev levels proposed by Pringle. This scheme is illustrated in fig. VII-1. The existence of the 1253 kev level required the presence in the γ -spectrum of two 468 kev γ -rays in cascade, but the work of Kelman et al.⁽⁵¹⁾ at 0.04% resolution found no evidence of this ray being a doublet. This was supported by the γ - γ -coincidence experiments of Connor et al.⁽⁵²⁾; hence the existence of the 1253 kev level

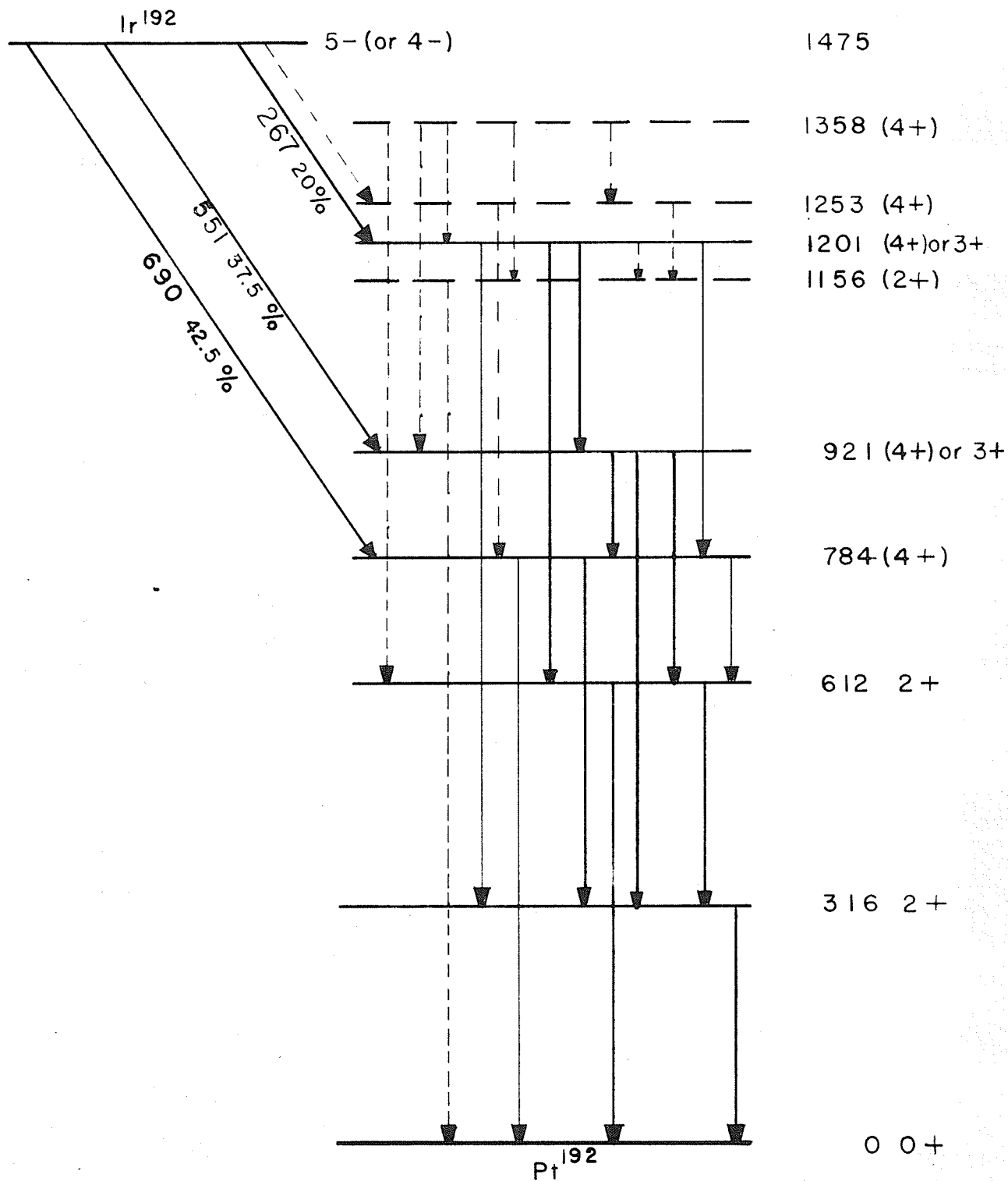


FIG. VII-1 β -DECAY OF Ir^{192}

is doubtful. The 97 and 105 kev γ -rays of Huq still remain unaccounted for as well a 167 kev γ -ray also found by Huq which could not be fitted into Fairweather's scheme. Fairweather points out that the percentage intensity contribution of the 3rd partial (20%) is greater by a factor of approximately two than can be accounted for by the intensity of 2 transitions from the 1201 kev level. This remains one of the outstanding difficulties in making a consistent decay scheme for Iridium-192.

The β -end points and corresponding percentage intensity contributions are listed in table V which, for convenience, also shows the results of the present work discussed in the next chapter.

Table V
 β -END POINT ENERGIES AND % INTENSITIES

Partial	Levy	Shpinel Forafontov	Johns Nablo	Cork	Bashilov et al.	Kyles ⁺ Campbell	Fairweather	Present Work
1	670	660	672	670	670(44%)	697(38%)	690(42.5%)	688(45%)
2	-	-	-	.390	540(40%)	561(41%)	551(37.5%)	564(40%)
3	-	-	-	pro- posed	240(16%)	281(21%)	267(20%)	269(15%)

+ revised values

Sec.VII:2 The Conversion Lines

The K/L ratios obtained by Fairweather and the workers quoted by him together with the results of the present work are listed in table VI. Included are the theoretical K/L ratios of Rose⁽⁵³⁾ for E1, M1, and M2 transitions, and those of Sliv and Band⁽⁵⁴⁾ for E2 transitions. The latter values have been obtained by the author by logarithmic interpolation from the published values and are considered to be more accurate than those of Rose since finite nuclear size is taken into account.

Values of α_K have been calculated by the author from the absolute intensities of conversion lines and γ -rays tabulated by Fairweather from the results of several workers. These results and those of the present investigation are shown in table VII. The theoretical coefficients of Sliv and Band and of Rose for E2 radiation are included also.

Table VI
K/L RATIOS

γ-ray energy kev	Experimental K/L Ratios					Theoretical K/L Ratios				Transition Assign't
	Kyles Campbell	Bashilov et al.	Baggerly et al.	Kelman et al.	Fairweather	Present Work	E2	M2	E1	M1
296	2.6	2.2	2.1	2.35	2.1	1.9	2.0	4.3	6.2	6.2
308	2.4	2.2	1.9	2.38	2.1	1.9	2.2	4.3	6.2	6.2
316	2.4	1.9	2.2	2.22	2.1	1.9	2.2	4.4	6.2	6.2
468	4.2	3.5	3.6	3.0	4.0	3.2	3.5	4.8	6.5	6.2
										E2(4%ML) E2 E2 E2(35%ML)

* Transition Assignment is due to Fairweather who used Rose's

α_K and Sliv's α_L to obtain K/L in the case of E2 radiation

Table VII

K-CONVERSION COEFFICIENTS

energy of γ -ray	Experimental α_K				Theoretical α_K		
	Kyles Campbell	Bashilov et al.	Baggerly et al.	Fairweather	Present Work	Sliv Band	Rose
296	.058	.053	.049	.051	.071	.063	.064
308	.049	.049	.050	.048	.048	.058	.058
316	.039	.039	.039	.038	.042	.054	.054
468	.018	.013	.015	.015	.013	.022	.021

Chapter VIII

THE β -SPECTRUM OF IRIDIUM-192Sec. VIII:1 Introduction

As mentioned in the last chapter, the high (20%) intensity of the third partial β -spectrum of Ir¹⁹² is one of the major stumbling-blocks in the way of finding a self-consistent decay scheme. It is thought that the large values obtained by previous investigators might be due to (a) energy degradation of electrons by absorption in thick sources, and (b) an excess of low-energy electrons scattered by the source backing. In addition, there is disagreement between the Edinburgh group (Kyles, Campbell, Fairweather) and the others regarding the end-points of the partial spectra, especially the first.

The main purposes of the present investigation are to re-determine the percentage intensity of the third partial spectrum using thin V.Y.N.S. source backings in order to eliminate effect (b) above, and to re-determine the end-points.

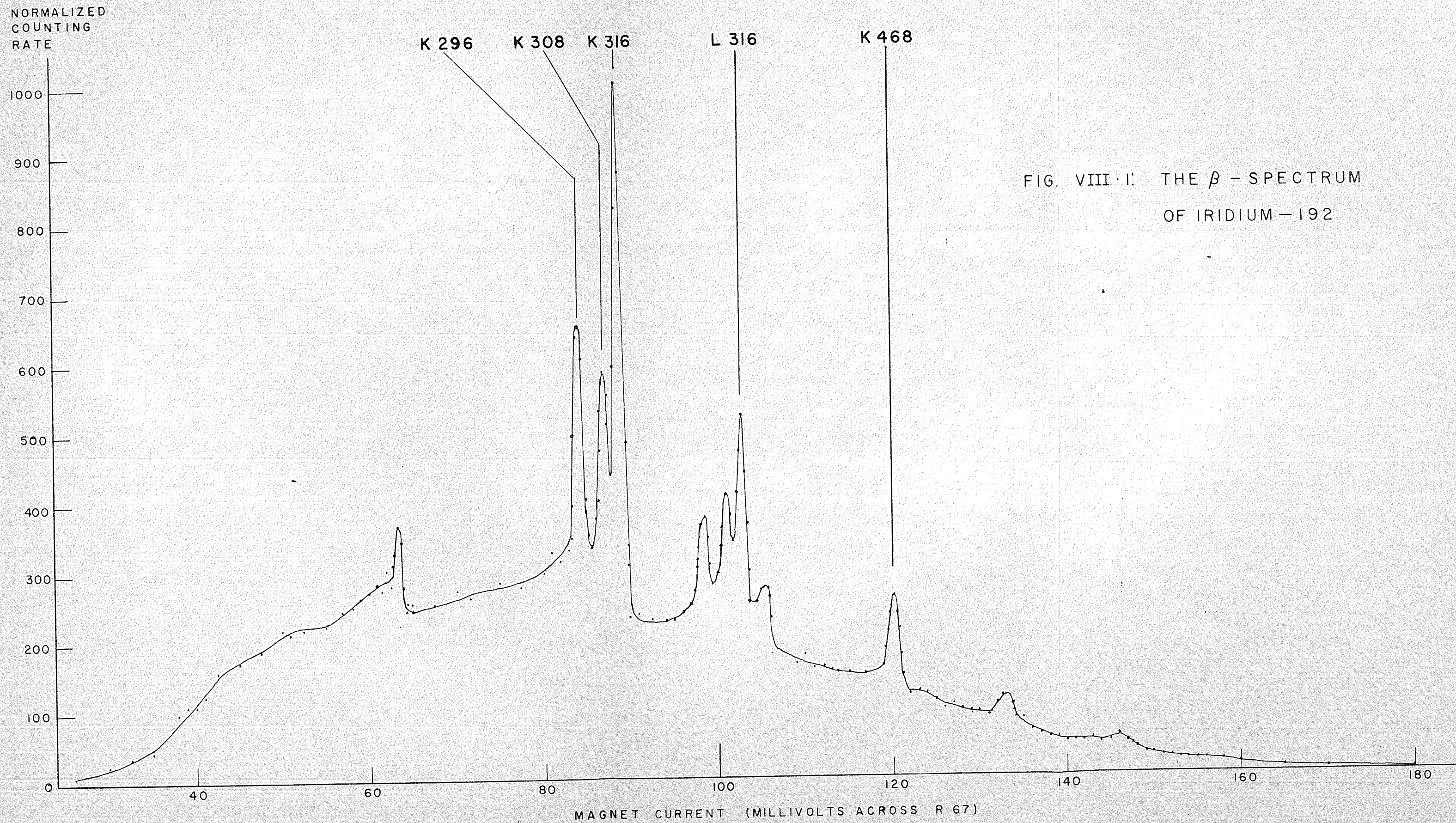
The previous work has indicated (see chapter VII) that experimental K-conversion coefficients are much lower than theory predicts, at least for E2 (electric quadrupole)

radiation. Unpublished data⁽⁵⁵⁾ of those engaged in conversion-line studies seem to support this result. A determination of α_K values and K/L ratios for several lines was thus undertaken as part of the present investigation.

Sec. VIII:2 Experimental Procedure

2 millicuries of Ir^{192} processed isotope were obtained from Oak Ridge National Laboratory in the form of $\text{Na}_2 \text{Ir Cl}_6$ in one ml. of 0.1 N HCl. Two sources were then prepared by successively pipetting drops onto V.Y.N.S. backings. The smaller (2 mm. diameter) source was used to obtain a spectrum (shown in fig. VIII-1) at 0.9% resolution for purposes of examining the conversion lines whereas the larger (3 mm. diameter) source was used to obtain a spectrum at 1.8% resolution with better statistics in order to examine the continuum. These sources were of necessity very thick in order that a countable activity be present.

After evaluation of the data from the first two runs (sec. VIII:3), it was found that results calculated for the third partial spectrum were of a very questionable nature



$$\sqrt{\frac{N}{FLoS}}$$

8

6

4

2

0

1.15

1.35

1.55

1.75

 ϵ (ENERGY IN UNITS OF mc^2)

FIG. VIII.2

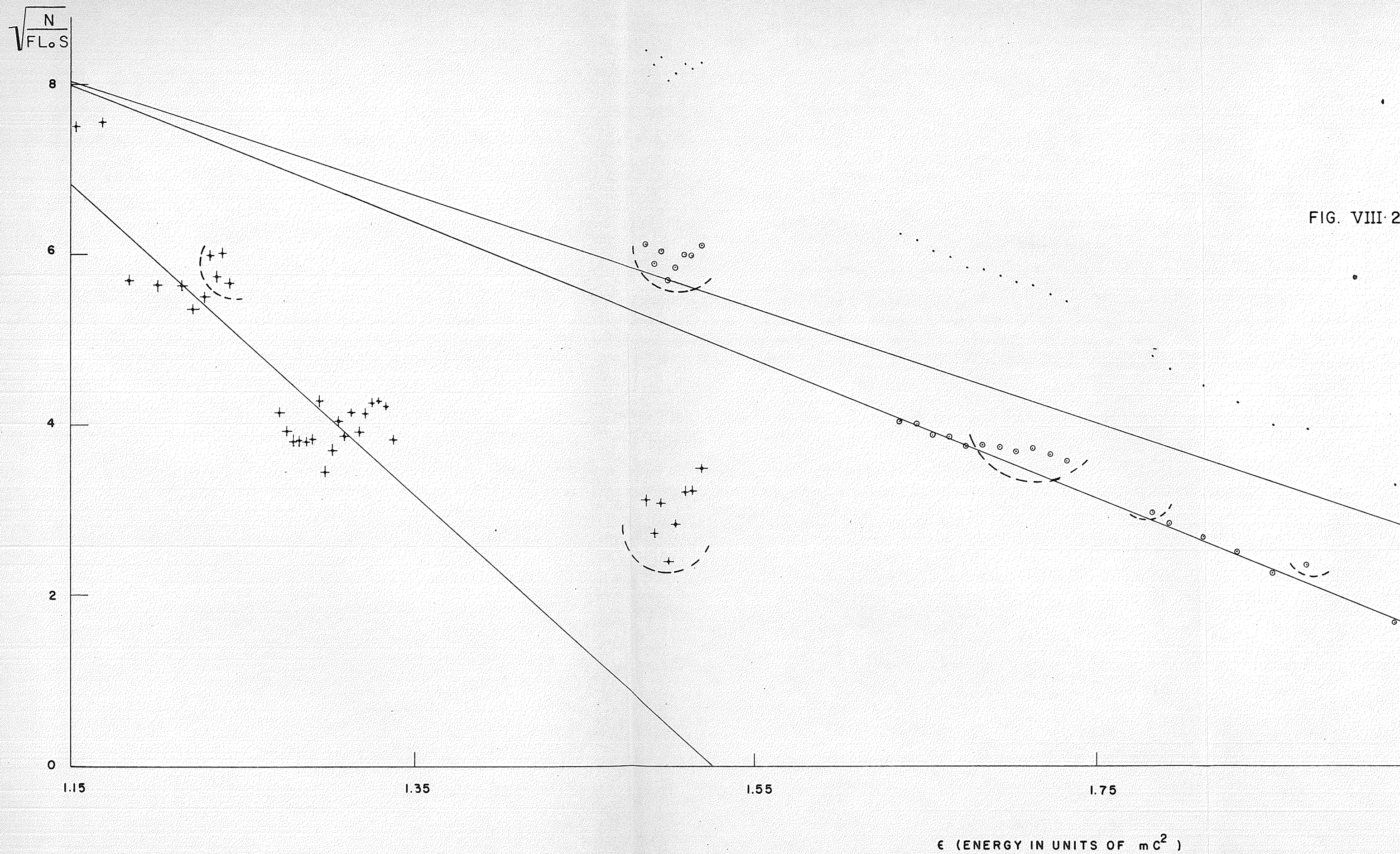


FIG. VIII.2: FERMI PLOT OF ^{192}Ir SPECTRUM: RUN NO.3

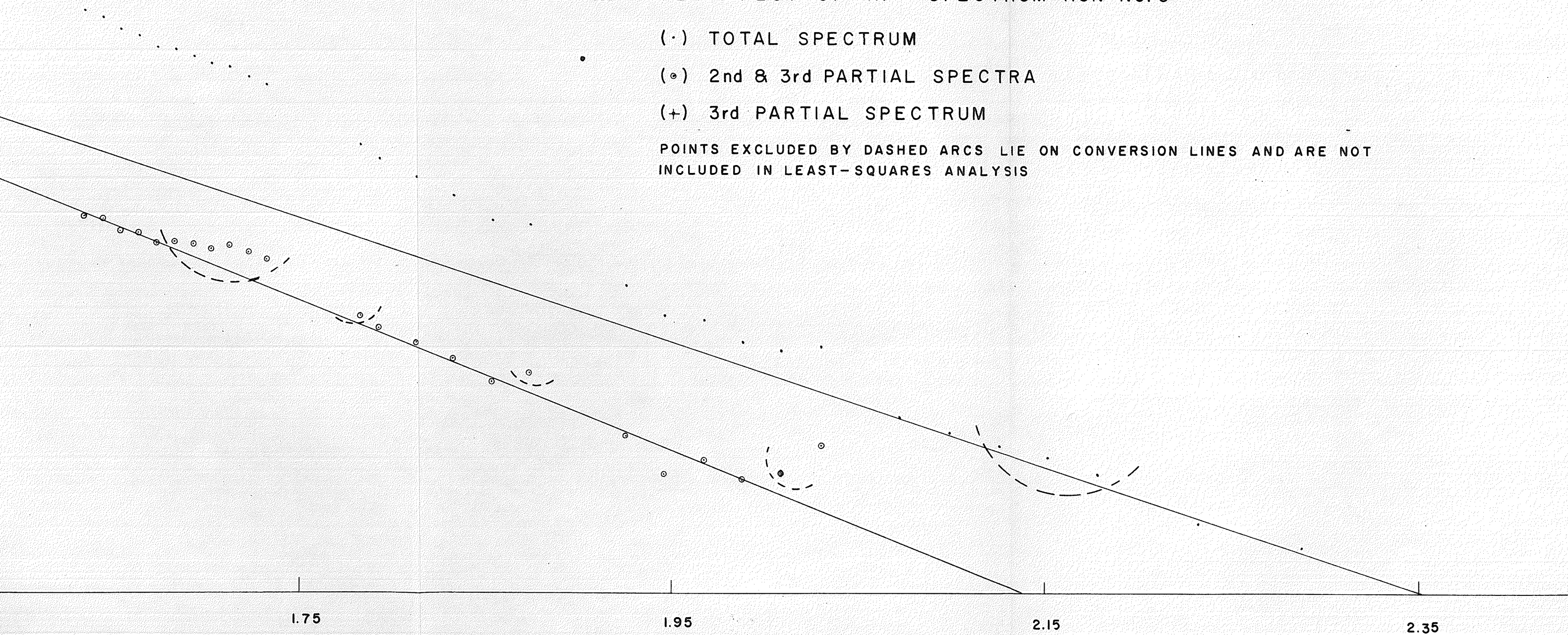
(·) TOTAL SPECTRUM

(◉) 2nd & 3rd PARTIAL SPECTRA

(+) 3rd PARTIAL SPECTRUM

POINTS EXCLUDED BY DASHED ARCS LIE ON CONVERSION LINES AND ARE NOT INCLUDED IN LEAST-SQUARES ANALYSIS

ϵ (ENERGY IN UNITS OF $m c^2$)



probably because of source absorption effects. Hence a fresh 10 millicurie sample of Ir^{192} from the same supplier was used, after an interval of two weeks during which the 19 hour Ir^{194} activity present as an impurity had completely died out, to make a new source of much higher specific activity. The spectrum obtained in the third run, with the new source, was used for measurements of the third partial.

Sec. VIII:3 The β -Continuum of Ir^{192}

Fermi plots (fig. VIII-2) of all three runs were obtained in the same way as the P^{32} - P^{33} plot of chapter VI. The end-points so obtained are listed in table VIII with the percentage intensities of the partial spectra. An attempt to calculate the end-point of the third partial using points with pronounced statistical scatter from run 2 yielded a value of 219 kev. The poor agreement of this value with the results of previous investigations can be attributed to an excess of electrons with degraded energies due to source absorption effects. In view of this, it was decided to disregard the third partial data from this run. The percentage intensities were however obtained from the measured relative intensities of the first and second partials by assuming that the percentage intensity of the third partial was the same as that

obtained in run 3. It should be mentioned that the relative intensities are calculated by the method of reconstructing the three separate partial spectra using the values of the slope and end-points of the Fermi plots and finding the area, which is proportional to the total counting rate or intensity, under each by numerical integration.

Table VIII

 β - END-POINTS AND INTENSITIES

run no.	1st partial	2nd partial	3rd partial
1	694 $\pm$ 4 kev	557 $\pm$ 43 kev	
2	688 $\pm$ 1 kev(43.0%)	561 $\pm$ 2 kev(41.6%)	219 kev
3	686 $\pm$ 4 kev(46.1%)	574 $\pm$ 4 kev(38.5%)	269 $\pm$ 13 kev (15.4%)
accepted results	688 $\pm$ 1 kev(45%)	564 $\pm$ 2 kev(40%)	269 $\pm$ 13 kev (15%)

Sec. VIII:4 The Conversion Lines

The 296, 308, 316, and 468 kev K and L lines for run 1 were isolated by subtraction of the continuum. Points of which lying beneath lines were found by the method of reconstruction from the known Fermi-plot. Since the lines were not completely resolved, it was necessary to separate them in order to measure their areas. Since the resolution is

constant, the full width at a specified fractional height divided by the abscissa of the peak is a constant for all lines. Using the full widths of the isolated K₄₆₈ line at various fractional heights as a guide, the full widths of the K and L ₃₁₆ lines at these same fractional heights were found, i.e., the shapes of these lines were determined, allowing them to be subtracted from their respective line groups. This process when repeated resulted in a complete separation of the two line groups into three distinct lines each. It is necessary to point out that the error involved in determining the full widths of the K₄₆₈ reference line is cumulative, resulting in a much larger error in the K and L ₂₉₆ lines. The areas of the lines were measured by counting squares of the graph paper on which they were plotted.

Since the third partial spectrum was not obtained for run 1, it was impossible to extrapolate the continuum back to rest energy ($\mathcal{E}=1$), but the continuum was however approximated in the low energy region by applying the window absorption connection to a few points therein. The area of the continuum was then found by the method of counting squares.

The absolute intensities of the K conversion lines, i.e., the ratios of their area to that of the continuum, were

calculated and are shown in table VIII together with the mean absolute intensities of the corresponding γ -rays computed from the values obtained by Johns and Nablo⁽⁴⁵⁾ and by Baggerly et al.⁽⁴⁷⁾

Table IX

K-CONVERSION COEFFICIENTS

γ -ray energy kev	absolute K-electron intensity, N_{ek}	absolute γ -ray intensity, N_q	$\alpha_K = \frac{N_{ek}}{N_q}$
296	.021	.303	.071
308	.015	.307	.048
316	.036	.866	.042
468	.008	.598	.013

The value of α_K obtained for the 296 kev transition is much higher than those of the previous investigations listed in table VII; this is probably not significant but due to the cumulative error mentioned before. The values of α_K obtained for the 308, 316, and 468 lines are, however, in excellent agreement with previous results and tend to indicate that the theoretical coefficients of Sliv and Band, as well as those of Rose, are approximately 40% too high.

The K/L ratios for the 296, 308, 316, and 468 kev transitions, calculated directly from the measured area of the lines, are listed in table VI. In the case of the 296 kev transition most work seems to indicate the presence of some M1 admixture whereas the present result would point to a pure E2 assignment. It is seen again from the present results that the 468 kev transition would appear to be E2 rather than E2 with strong M1 admixture. It is tempting to conclude that the present K/L ratios are consistently and significantly lower than the theoretical values. Such a conclusion, based on the results of a single run, is unjustified, however, in view of the absence of any clear-cut trend to low values in the investigations of K/L ratios to date as there was in the case of α_K .

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