THE OPERATION OF A LOW ENERGY BETA RAY SPECTROMETER AND THE MEASUREMENT OF THE SPECTRUM OF RADIUM D

by

Harry Brown

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ABSTRACT

A semi circular focussing spectrometer has been built to examine beta spectra in the energy range below 100 Kev. The detection of the beta particles is accomplished by means of Geiger counters filled with the saturated vapor of liquid heptane (C_7H_{16}) kept in a bath of melting ice. The windows of the counters are made from thin films of zapon about 5 to 8 micrograms/cm^2 in thickness. The sources are mounted on similar films approximately 10 micrograms/cm^2 and have an average total thickness of the order of 30 micrograms/cm^2. The combination of thin source and thin windows enables measurements of spectra to be made down to an energy of 2 Kev.

An examination of the beta spectrum of RaD ($_{82}Pb^{210}$) with the spectrometer has been carried out. It consists of L, M and N conversion lines of a 47 Kev gamma ray, a peak at about 3 Kev assigned to conversion of a 7.7 Kev gamma in the M shell of the atom, and a primary beta spectrum. A Kurie plot of the primary beta spectrum yields an end point of 21.7 Kev. In addition there are two weak conversion lines at 18 and 21 Kev which are tentatively assigned to the L conversion of gamma rays of 34 and 37 Kev.

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THESIS

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INTRODUCTION

As soon as it was realized that radio-active substances emitted charged particles with a wide range of velocity, attempts were made to analyze the velocity distribution using a magnetic field. The simplest method, that of collimating a beam of particles by slits and observing the small deflection caused by a transverse field with photographic methods, proved quite successful with alpha particles. It was first used with a source which emitted beta particles by Baeyer and Hahn.[1] Here the angles of deflection were larger than with alpha particles, but were not greater than 60°. The photographic plate showed a number of lines indicating that the electrons did not leave the source with a unique velocity but rather were emitted in groups, each with a different velocity. Such an analysis of the velocity distribution of the electrons was called a beta-ray spectrum.

This method of determining the beta-ray spectrum of a substance was obviously limited in its resolving power since only by improving the collimation could the lines be made narrower. The collimation could only be improved at the expense of intensity, necessitating stronger sources or longer exposures to get usable results. The way out of the difficulty was to devise some method of focussing the electrons so that

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1. G. Baeyer and O. Hahn: Phys. Zeit. 11, 488, 1910.

the image on the plate would be smaller than the exit slit of the collimating system.

This was done by Danysz[2] who pointed out that if two equal circles were drawn about two points separated by a small fraction of a radius the circles would intersect at points diametrically opposite. Then, since electron paths in a uniform magnetic field are circles whose radii depend on the momentum of the particle and the strength of the field, focussing could be obtained by allowing electrons to travel through a semicircle before striking the photographic plate. In Fig.1, electrons starting from the source S at an angle A with each other are selected by the baffle and brought together to strike near the same point of the plate. Electrons of greater or less momentum are brought to a focus at further or nearer parts of the plate. It is obvious that the focussing is not perfect for a finite baffle slit. The central ray in Fig.1 will not hit the photographic plate at exactly the same spot as the two outer rays.

This semicircular focussing spectrograph was used by many workers, notably Rutherford and Robinson[3] to determine the momenta of a number of lines in the beta-ray spectra of most of the naturally radio-active elements. Ordinarily the lines are referred to by the quantity Hr (in gauss-cms) from which the energy can be obtained by use of the relativistic formula

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2. J. Danysz: Comptes Rendus 153, 339, 1066, 1911.

3. E. Rutherford and H. Robinson: Phil.Mag. (6) 26, 717, 1913.

$$Hr = 10^4/3\sqrt{T(T+1.02)}$$

where T is the energy of the particles in Mev and r is the radius in cm. of their orbit in a uniform field of H gauss. A non-relativistic approximation good to a few percent below 50 Kev is

$$Hr = 3.37\sqrt{E}$$

where E is the energy of the electrons in volts.

The first modification of the method was the substitution of an electrical method of detection for the photographic plate. A Faraday cage,[4] an ionization chamber,[5] or later a Geiger counter was placed behind an exit slit and the magnetic field was varied to change the energy region being investigated. This spectrometer was an improvement since with photographic detection the resolution, dispersion and focussing changed from one end of the plate to the other.

With such a spectrometer Chadwick[5] proved that in addition to the groups of electrons of discrete energies there was a continuous distribution so that a normal spectrum appeared as in Fig.2. Rutherford et.al.[6] proved that the discrete groups were of secondary origin by wrapping foils of various metals around the cylindrical source in a beta ray spectrograph. When the foils were thick enough to stop all electrons from the source

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4. E. Gurney: Proc. Roy. Soc., A109, 540, 1925.

5. J. Chadwick: Verh.d.D.Phys.Ges., 16, 383, 1914.

6. E. Rutherford, H. Robinson and Rawlinson: Phil.Mag., 28, 281, 1914.

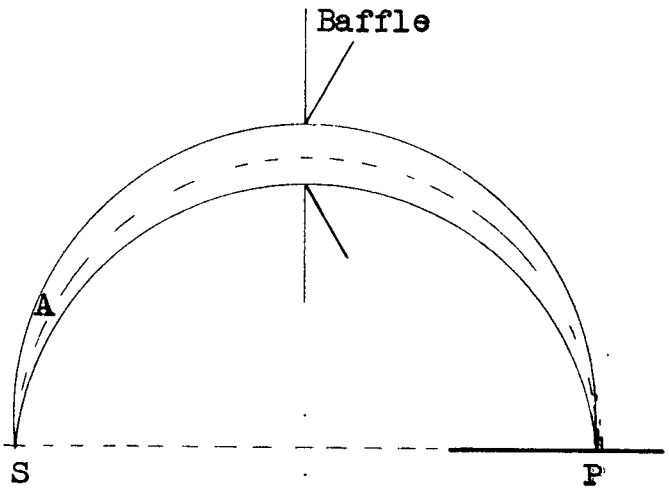

FIGURE 1.

ILLUSTRATION OF SEMICIRCULAR FOCUSSING

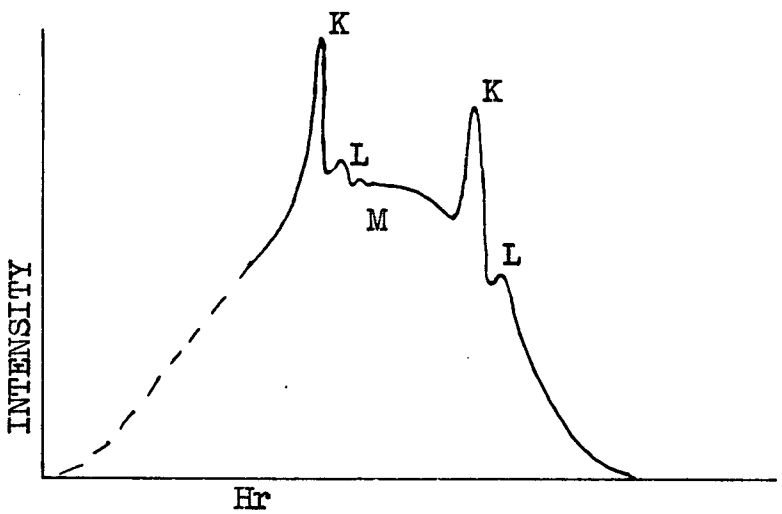

FIGURE 2.

A NORMAL BETA SPECTRUM

a line spectrum was still observed.

From these and other experiments a comprehensive theory of beta-ray spectra was built up. The electrons emitted during the disintegration of radio-active nuclei had a continuous distribution of energy. The daughter nucleii were usually left in an excited state and gave up more energy by emitting gamma rays or by ejecting electrons from the K, L, etc, shells of the newly formed atom. In Fig.2 it is indicated that a strong line in a beta-spectrum is often accompanied by a weaker satellite line or lines. If the binding energy of a K electron of the daughter atom is added to the energy of the most intense line, an L to the next, and so forth, a constant energy value is obtained which usually corresponds to the energy of a known gamma ray. The gamma ray is said to be partially internally converted and the peaks in the beta-ray spectra are known as conversion lines.

The continuous distribution of the disintegration electrons presented great difficulties in regard to the conservation of energy, particularly when it was shown that the energy available corresponded to the maximum energy of the beta particles. A detailed theory of beta disintegration was given by Fermi[7] in which he assumed that a disintegration was a three body process with another particle, called a neutrino, being emitted with the electron. The properties of the neutrino were assumed to be such that its detection was difficult, if not impossible. The charge was zero. The mass was presumed to be very small. Indeed, on

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7. E. Fermi: Zeits für Phys. 88, 161, 1934.

the basis of experiments[8] on the beta momentum distribution of H^3, an upper limit to the mass of the neutrino has been placed at 0.002 electron mass.

In the simplest form of the theory plane wave functions are assumed for the electron and neutrino which are created at the moment of emission. The transition probability is calculated by combining the value of these functions at the nucleus with a matrix element relating the initial and final states of the nucleus. In addition there is a new universal constant called a coupling factor. The shape of the momemtum distribution of the emitted beta-particles depends to a considerable extent on the type of interaction used in the matrix element. Also the total probability of decay is a function of the spin change and parity change between the initial and final states and this function is also included in the matrix element. The most probable type of transition involving a spin vector change of 1 and parity change is called an allowed transition. A simple re-arrangement of the Fermi probability function enables one to plot a complicated function (which includes N, the number in a small momentum interval) against the beta energy E to give a straight line with an intercept on the energy axis corresponding to the disintegration energy. This is called a "Kurie plot".[9]

In a beta disintegration the mass of the nucleus

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8. S.C. Curran, A.L. Cockcroft and C.Insch: Phil.Mag., 41, 517, 1950.

9. F.N.D. Kurie, J.R. Richardson and H.C. Paxton: Phys.Rev., 49, 368, 1936.

changes by a small fraction of the mass of a neutron or proton but the atomic number is changed by one unit. If a negatron is emitted the nucleus increases its atomic number by one as illustrated in Fig.3. Positron emission as in Fig.4 reduces the atomic number. Fig.5 shows the case where the atomic number is reduced by the absorption of an external electron into the nucleus. As the electron absorbed is usually from the K shell of the atom this process is known as K capture. After any of these transitions the nucleus may be left in an excited state from which it reverts to the ground state by emitting a gamma ray or a conversion electron. Whenever an atomic electron is removed, either by K capture or conversion of a gamma ray, there are also characteristic X rays of the daughter atom emitted and in some cases Auger electrons. Sometimes a transition by beta emission is possible to two different excited states of the daughter nucleus, as in Fig.6. This is most readily detected by the Kurie plot which is no longer a single straight line but rather two intersecting lines. (Fig.7).

The methods of beta-ray spectroscopy have been successful in determining the energies of particles and photons emitted by radio-active nucleii and thus have provided a knowledge of nuclear energy levels. While these energies have been measured over a large range with a considerable degree of accuracy there are limitations. In very few instruments has a resolution of one part in a thousand been attained and a more usual value is one in thirty to one in one hundred. A standard spectrometer may cover the range from 0.1 to 3 Mev, the lower

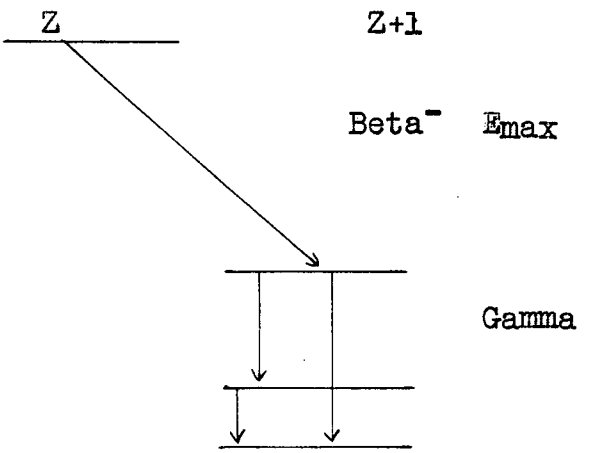

FIGURE 3.

ENERGY LEVEL DIAGRAM FOR NEGATRON DECAY

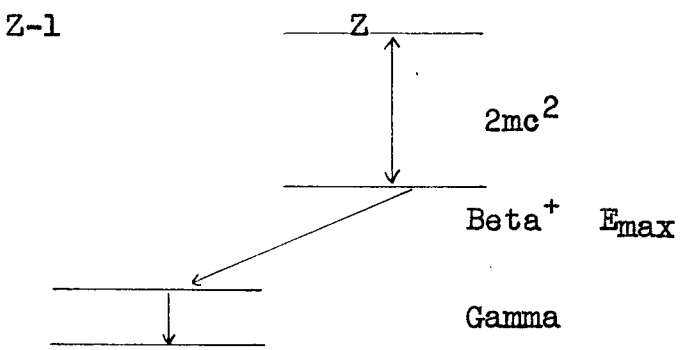

FIGURE 4.

ENERGY LEVEL DIAGRAM FOR POSITRON DECAY

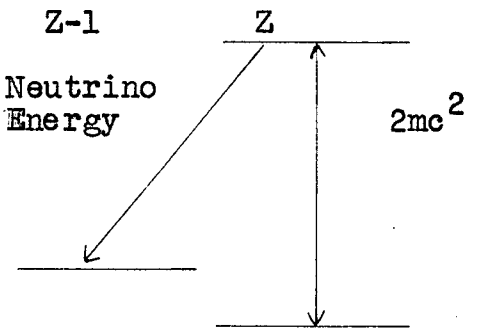

FIGURE 5.

ENERGY LEVEL DIAGRAM FOR ORBITAL ELECTRON CAPTURE

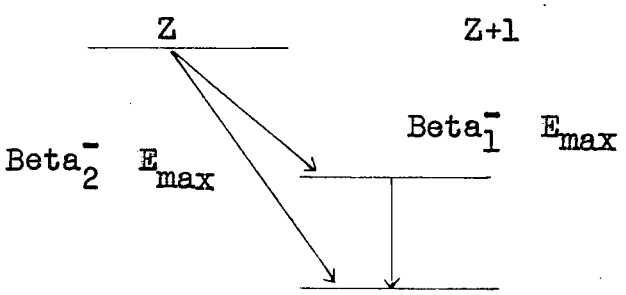

FIGURE 6.

ENERGY LEVEL DIAGRAM FOR NEGATRON DECAY TO TWO DIFFERENT STATES

limit being an instrumental limit, caused by excessive scattering of low energy electrons from baffles and residual gas, by the increasingly serious defocussing by uncompensated earth's field components over the long path length as the energy decreases and by absorption of the low energy beta particles in both the source and the counter window. The upper limit is set by the power demands of the focussing magnet. A few spectrometers have been built to measure energies greater than 10 Mev and some to extend the lower limit to 10 Kev or less.

While this low energy region has been neglected because of experimental difficulties a number of reasons for its investigation exist. In the simple derivation of the shape of the continuous spectrum it is assumed that the electron has a plane wave function at the nucleus. A correction must be made to account for the perturbation of the wave by the coulomb field. The amount of the correction increases at low energies and is in different direction for positrons and negatrons. Thus there is considerable difference between the shapes of positron and negatron spectra. (Fig.8) If this factor is incorporated into the theory a value of the ratio N^+/N^- can be obtained for nucleii which disintegrate by either negatron or positron emission. Cu^{64} is an isotope for which this can be calculated and considerable work has been done on the question. Backus[10] working in the region 5 to 50 Kev found N^+/N^- to be ten times greater than expected at the lowest energy. The entire spectrum was investigated by Cook and Langer[11] from 10 to 700 Kev.

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10. J. Backus: Phys.Rev., 68, 59, 1945.

11. C.S. Cook and L.M. Langer: Phys.Rev., 73, 601, 1948.

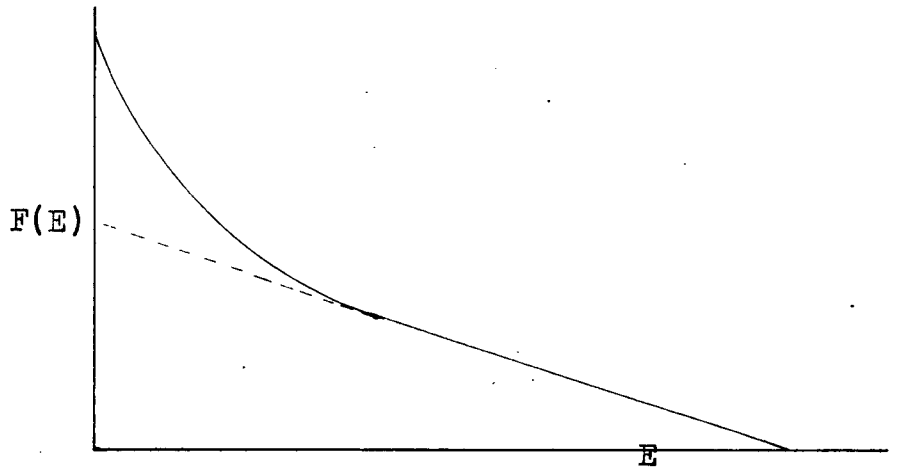

FIGURE 7.

KURIE PLOT FOR NEGATRON DECAY TO TWO DIFFERENT STATES

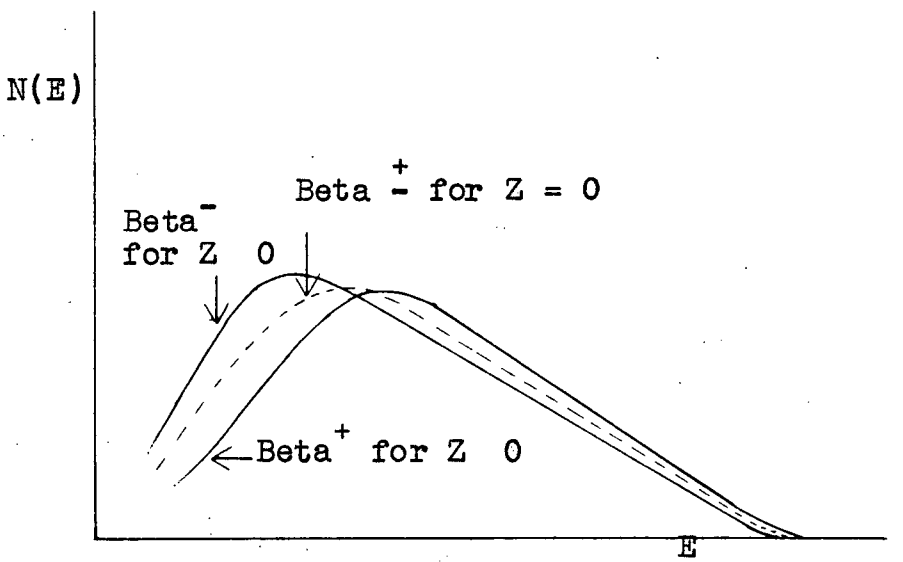

FIGURE 8.

THE EFFECT OF THE COULOMB FIELD ON THE SHAPE OF THE BETA SPECTRUM

Their measurements are in agreement with Backus and show that N^+/N^- deviates from theory below 150 Kev. Lewis and Bohm[12] have attempted to explain the discrepancy by using linear combinations of the five relativistically invariant interactions which are possible in the matrix element of the transition probability. However Wu and Albert[13] report deviations from theory much less than the above and conclude that any remaining are entirely instrumental in origin. As the techniques used by these three groups seem to be similar the question warrants further investigation.

Cook and Langer[11] and other experimenters[14,15,16] report that in a number of cases the Kurie plot deviates from a straight line at low energies. More recent work[17,18,19] indicates that these results were entirely due to the thickness of the source. However there is always the possibility that the curvature of the Kurie plot at the low energy end is caused by the presence of a low energy beta group. (Fig.7). Only the most refined techniques can distinguish between these possibilities.

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12. H. Lewis and D. Bohm: Phys.Rev., 69, 129, 1946.

13. C.S. Wu and R.D. Albert: Phys.Rev., 75, 315, 1949.

14. A.W. Tyler: Phys.Rev., 56, 125, 1939.

15. J.L. Lawson: Phys.Rev., 56, 131, 1939.

16. A.A. Townsend: Proc.Roy.Soc., A177, 357, 1941.

17. R.D. Albert and G.S. Wu: Phys.Rev., 74, 847, 1948.
Phys.Rev., 75, 1107, 1949.

18. L. Feldman and C.S. Wu: Phys.Rev., 76, 697, 1949.

19. L.M. Langer, J.W. Motz and H.C. Price Jr.: Phys.Rev., 77, 798, 1950.

Besides the low energy beta groups there may be low energy conversion lines. Even a 0.1 Mev gamma from a nucleus of high Z may yield a conversion line of a few Kev when converted in the K shell. Lines at less than 50 Kev have been found in the beta spectra of almost all naturally radio-active substances[20] and in some artifically prepared isotopes.[21] There is also a possibility of detecting the Auger electrons ejected from the electronic shells of an atom after K capture has taken place.[22] If a nucleus is in the ground state on capturing a K electron the soft X rays and the Auger electrons offer the only means of detecting the change.

Many suggested decay schemes for various nuclei based on the measurements of high-energy gamma-rays and conversion electrons have energy levels within 50 Kev or less of each other. Most current spectrometers could not detect transitions between such states if they did exist. An instrument which could do so would be a valuable tool in checking the proposed spin and parity values assigned to these states on the evidence of the high energy transitions alone.

Thus the extension of the energy range measured by beta ray spectrometers to as low a value as possible is important in checking the agreement of experiment with theory and

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20. Radiations from Radio-active Substances. Rutherford, Chadwick and Ellis: pp.360-380.

21. R.D. Hill: Phys.Rev., 74, 78, 1948.

22. F. Miller Jr.; Phys.Rev., 67, 309, 1945.

in increasing our knowledge of the energy levels of nucleii. This increased knowledge is essential to the development of a theory of nuclear processes. This research describes the design, construction and use of a spectrometer for this purpose.

II

THE SPECTROMETER

A. Primary Considerations in Design.

The design of a spectrometer to be used primarily in the energy region below 100 Kev requires careful consideration of a number of fundamentally important points.

(a) The scattering of electrons from all parts of the instrument increases greatly at lower energies. It has been shown[23] that at low energies the scattering varies inversely as the first power, at least, of the electron energy and directly as the atomic number of the scattering material.

(b) The detection of low energy beta particles presents a great deal of difficulty. Photographic detection could be possible, despite the objections to a spectrograph. However, the sensitivity of even the best plates falls off very rapidly as the energy of the impinging electrons is decreased.[24] The sensitivity of the crystal and electron multiplier combination also decreases tremendously at low energies, and the operation of the multiplier is seriously affected by a magnetic field. A Geiger counter seems to be the best method of detection since it is well known that electrons of almost zero energy can be detected in this way providing they penetrate into the

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23. Appendix I.

24. L. Cranberg and J. Halpern: R.S.I., 20, 641, 1949.

sensitive volume of the counter. The problem is reduced to one of making the window of the counter sufficiently thin to avoid absorption at low energies yet strong enough to withstand the pressure of the counter gas.

Windows of nylon, zapon, formvar and collodion as thin as a few micrograms/cm^2 can be made quite readily with the method described by Backus.[10] Windowless counters have been used with success by Langer, Motz and Price[19] with an equivalent window thickness due to diffusing gas of about one microgram/cm^2.

The problem of the counter windows has been solved satisfactorily for our problem. Zapon films of 3 to 5 micrograms /cm^2 are cemented over a counter entrance slit 0.025 cm. wide. The combination of the narrow window and the low gas pressure used in the counter (1.1 cm.Hg.) makes the use of such films entirely practicable.

(c) The method by which the radio-active source is prepared and mounted is important at energies up to at least 0.5 Mev but particularly so at low energies.[17,25,26,27] The thickness of the support and of the layer of radio-active material deposited on it can have a great influence on the shape of the low energy spectrum even when only a few micrograms/cm^2.[19] This necessitates extreme care to ensure that

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25. Curran, Angus & Cockroft: Phil.Mag., 40, 53, 1949.
26. Langer, Moffat, & Price: Phys.Rev., 76, 1725, 1949.
27. G.E. Owen & C.S. Cook: Phys.Rev., 76, 1726, 1949.

the source is spread uniformly over the active region.

The extremely thin source mounts required by these considerations leads to a new difficulty. Because of the low conductivity of the backing and the small capacity to ground the source can acquire a potential of several thousand volts, seriously distorting the low energy spectrum.[28]

To overcome these difficulties, the source was prepared by depositing an approximately uniform strip of radioactive material on a zapon or LC600 film of about 10 micrograms/cm^2. The film was supported by a lucite holder which was cut away directly behind the source. The accumulation of charge was prevented either by evaporating aluminum onto the holder until a finite electrical resistance appeared or by painting thin lines of aquadag to connect the ends of the source to the metal of the spectrometer. See APPENDIX III for further details.

(d) The difficulties of handling large amounts of activity require that maximum use be made of the source. A reduction in the size of the spectrometer and therefore of the source ensures that the amount of activity/cm^2 is reasonably large while the absolute amount of activity is kept small. This last is essential in a low energy spectrometer since the source cannot be covered because of absorption of electrons in the covering material. In addition the fragility of the backing provides a constant danger of contamination. With

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28. C.H. Braden, G.E. Owen, J. Townsend, C.S. Cook & F.B. Skull: Phys.Rev., 74, 1539, 1948.

materials of low specific activity the source strength will be limited by considerations of source thickness.

Evidently then, a low energy spectrometer should be as efficient as possible, that is, the fraction detected of all electrons leaving the source in a given momentum range should be as large as is consistent with the resolution required. It will be shown later that this fraction is a function of the same variables as is the resolution. However, since the line width at low energies is greatly increased by scattering and self absorption, the resolution need not be too good.

(e) An electron with 10 Kev of energy has an Hr value of 340 gauss cms. If its radius of curvature in the spectrometer is to be, say, 10 cms. the field required is 34 gauss. The influence of the earth's field is considerably greater than one percent of this and electric motors, regulating transformers and other electrical equipment, can radiate fluctuating fields of this order for several feet. The measurement of a small magnetic field with an accuracy of a few percent is difficult. It is an advantage to keep the size of the spectrometer down in order that fairly large fields can be used. If the field can be obtained without the use of an iron core the instrument can be calibrated quite readily without the measurement of small fields.

B. <u>The Inner Spectrometer</u>.

The semi-circular focussing type of instrument best fulfils the above conditions. The radius of curvature of

detected electrons can be reduced to a small value, the path length is short and the inner surface can be kept small, reducing scattering to a minimum. In order to have a large transmission the spectrometer was designed to accept electrons from the source in four different directions. Detection is accomplished by means of Geiger counters with zapon windows, the pressure being kept constant by a dynamic filling system.

Construction views of the inner spectrometer are shown in Fig.9. The dimensions are in inches because of the sizes of materials available.

The source is in the form of a line about 0.1 cm. wide and 1.5 cm. high. It is mounted on a backing of 10 microgram/cm^2 zapon which is supported by a lucite holder. The holder is arranged in the spectrometer so that the middle line of the source passes through the center of the apparatus. The counters are symmetrically spaced about the source on the circumference of a circle of 2.4 inches radius (3.05 cm.). The four sets of baffles are arranged so that electrons leaving the source at angles of $45° \pm 5.7°$ to the plane of the backing travel a circular path of $3.05 \pm .03$ cm. radius (in the corresponding magnetic field) to strike the counter windows. The baffles were cut on a lathe to the required radius and grooves cut in the surface to reduce the reflection of electrons from the baffle surfaces into the counters.

Each counter (see Fig.9) was made by drilling a 0.625 inch diameter hole through a block of brass 1.5 inches long. The brass was then trimmed down with a shaper, with

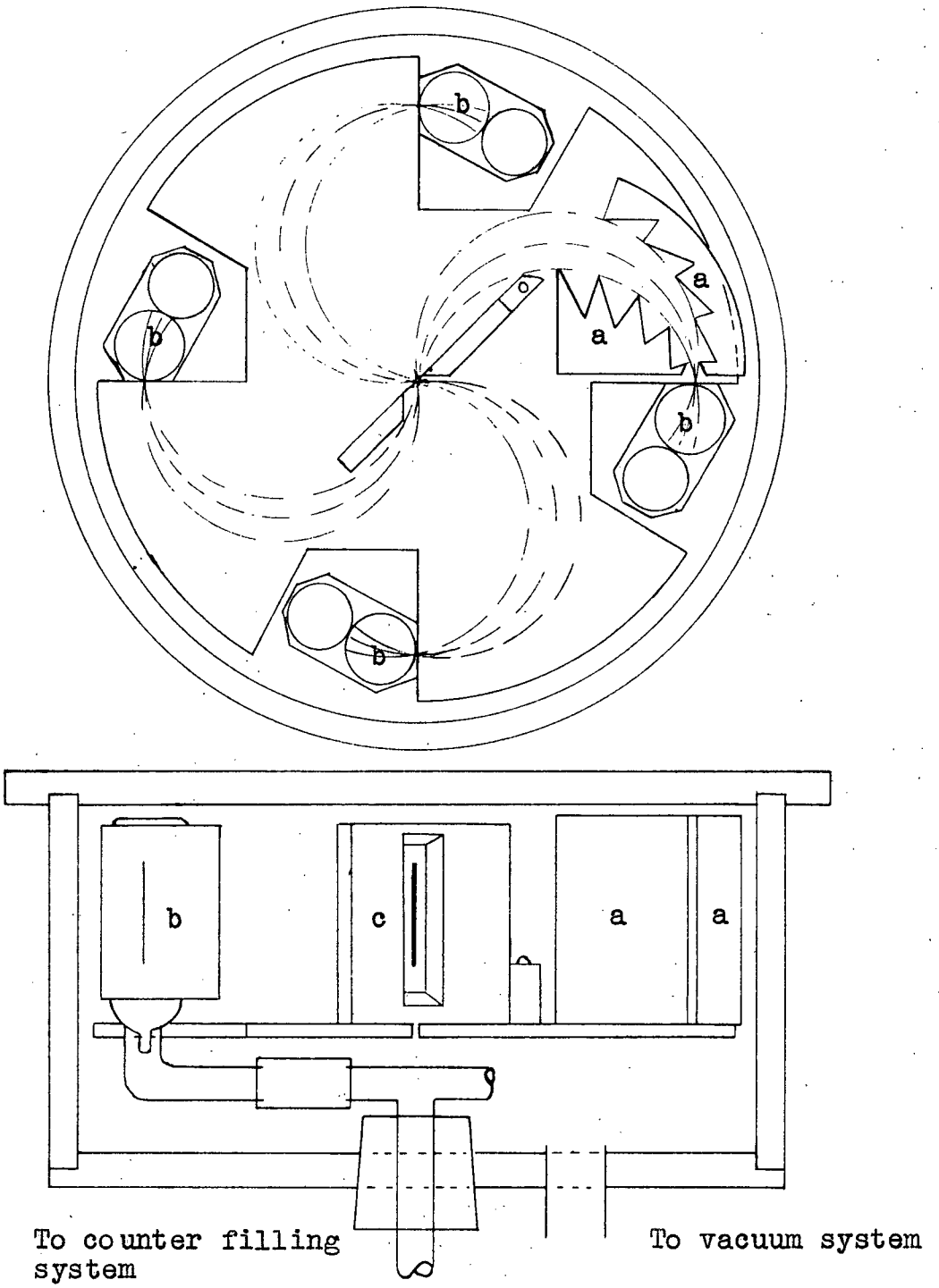


FIGURE 9.

INTERNAL CONSTRUCTION OF THE SPECTROMETER

a Baffles
b Counters
c Source holder

particular care taken with the face containing the window. This face was cut as smooth as possible, to leave a thickness of .030 inches in the center. Through the narrowest part a longitudinal slot about 5/8 inches long and 0.010 inches wide was cut. The inside of the counter was then polished thoroughly with emery paper and crocus cloth.

Another hole of about the same size was drilled through the brass, parallel to the first, for the purpose of filling the counter, so that about 0.050 inches of metal separated the two. Small holes (No.48 drill) were drilled through this separating wall to allow the filling gas to enter the counter proper. The auxiliary hole was then plugged at one end with a brass plate and at the other with a copper tube to allow connection to the filling system.

The entire counter was then immersed in boiling nitric acid (0.1 Normal) for a few minutes until the surfaces appeared clean. It was then washed, first in distilled water, and then in absolute alcohol and dried. One end was closed with a Kovar seal and the other with a pyrex cap sealed with deKhotinsky wax. A .005 inch tungsten wire was used for the anode.

The apparatus is contained in a brass cylinder of 6.5 inches inside diameter. The end plates are of 5/16 inch brass. Soft rubber rings are used as vacuum seals. In the bottom plate a number of holes are drilled for the admission of the counter filling gas, the high voltage lead and for connection to the vacuum system.

One inch above the lower end plate is mounted a 1/8 inch brass plate (hereafter called the base plate). The base plate was highly polished and the position of the source, the position of the baffles and the locations of the entrance slits of the counters were marked on it. The counters were aligned with the baffle system by observing that the counter window, its reflected image, and the mark on the base plate, were in one straight line. The error introduced was certainly no more than the width of the slit (.025 cms.) and was probably less. The counters were connected to a four arm glass tee by lengths of Tygon tubing to allow movement during alignment.

All exposed metal surfaces were coated with a material of low atomic number in order to reduce scattering as much as possible. This was done by dissolving vacuum wax (Apiezon W) in carbon tetrachloride and applying several coats of this paint.

C. Production of the Magnetic Field.

In order to eliminate the necessity of measuring small magnetic fields it was decided to produce it without the use of iron. The field would then be proportional to the current used and calibration at one point on a well known line would give Hr values for the entire spectrum.

From the description of the inner spectrometer it is seen that a uniform magnetic field is required over a disc-shaped region, 12 cms. in diameter and about 2 cms. thick with

the magnetic vector perpendicular to the surface. The usual method of providing a uniform field over a considerable volume of space is to use Helmholz coils. However, considerations of space, mechanical stability, the power available and the amount of wire required led to an attempt to provide the field required with a combination of flat coils.

If a current I travels in a circular path of radius a the field at any point P inside the loop and in the plane of the circle is given by

$$\frac{H_x}{H_o} = \frac{2a^2}{\pi(x^2-a^2)} \int_0^{\pi/2} \sqrt{1-k^2 \sin^2\phi} \; d\phi$$

where x = the distance of P from the center

$k = x/a$

H_o = the field at the center = $\frac{2\pi I}{10a}$

This is an elliptic integral and must be obtained from tables. A curve plotting H_x/H_o against x/a is shown in Fig.10.

Using empirical methods and this curve it was determined that three coplanar coils, one of +14000 ampere turns of radius 17.5 cms., a second of -2700 ampere turns of radius 11 cms. and a third of +120 ampere turns of radius 8.5 cms. would give a field of approximately 360 gauss at their common center, with a maximum inhomogeneity of 0.28% over an area of radius 6 cms. (The minus sign on the second coil indicates that the current in this coil is in the opposite sense to the current in the other two coils).

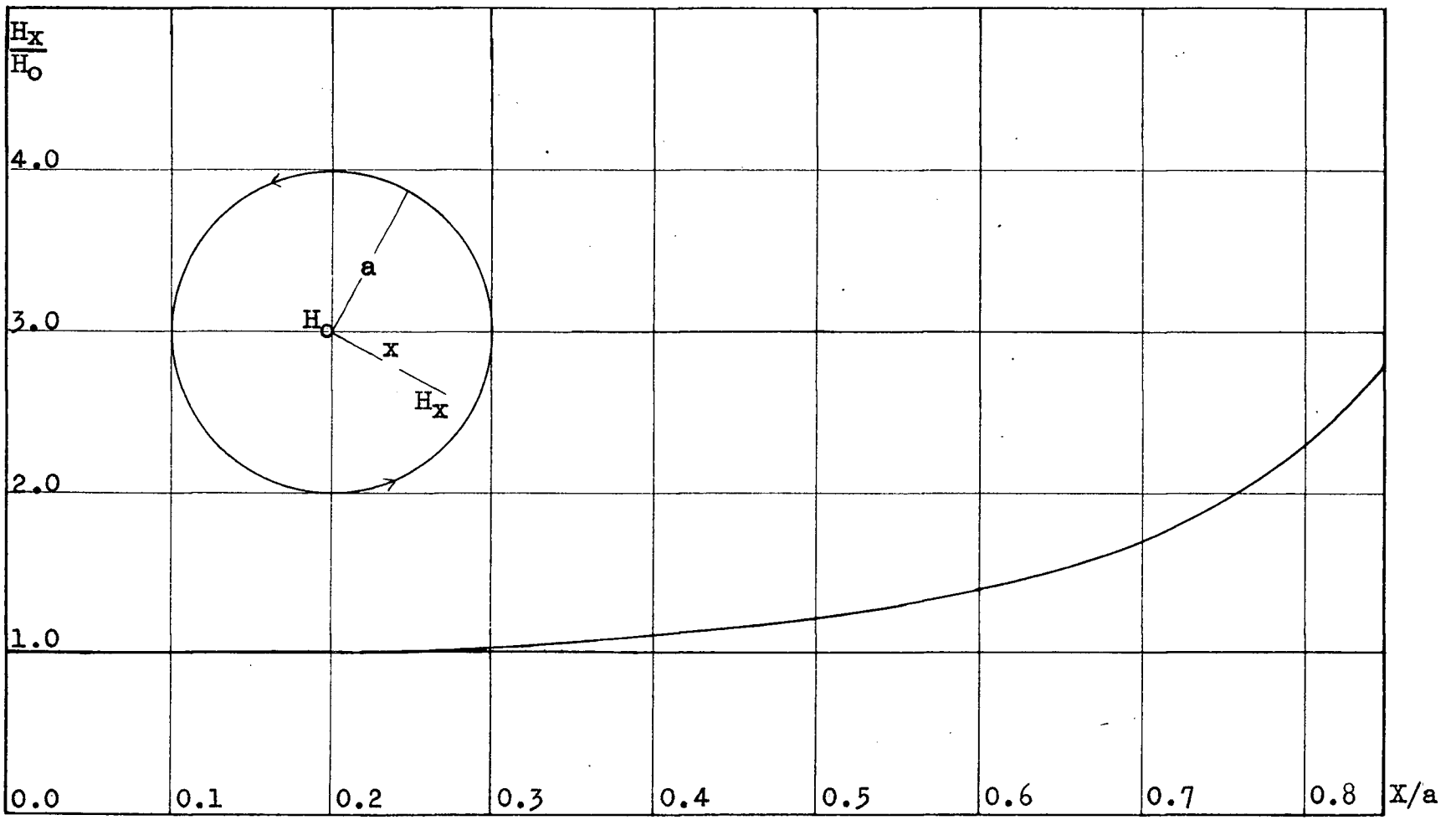


FIGURE 10.

THE FIELD OF A PLANE CIRCULAR COIL
AS A FUNCTION OF THE DISTANCE FROM THE CENTER

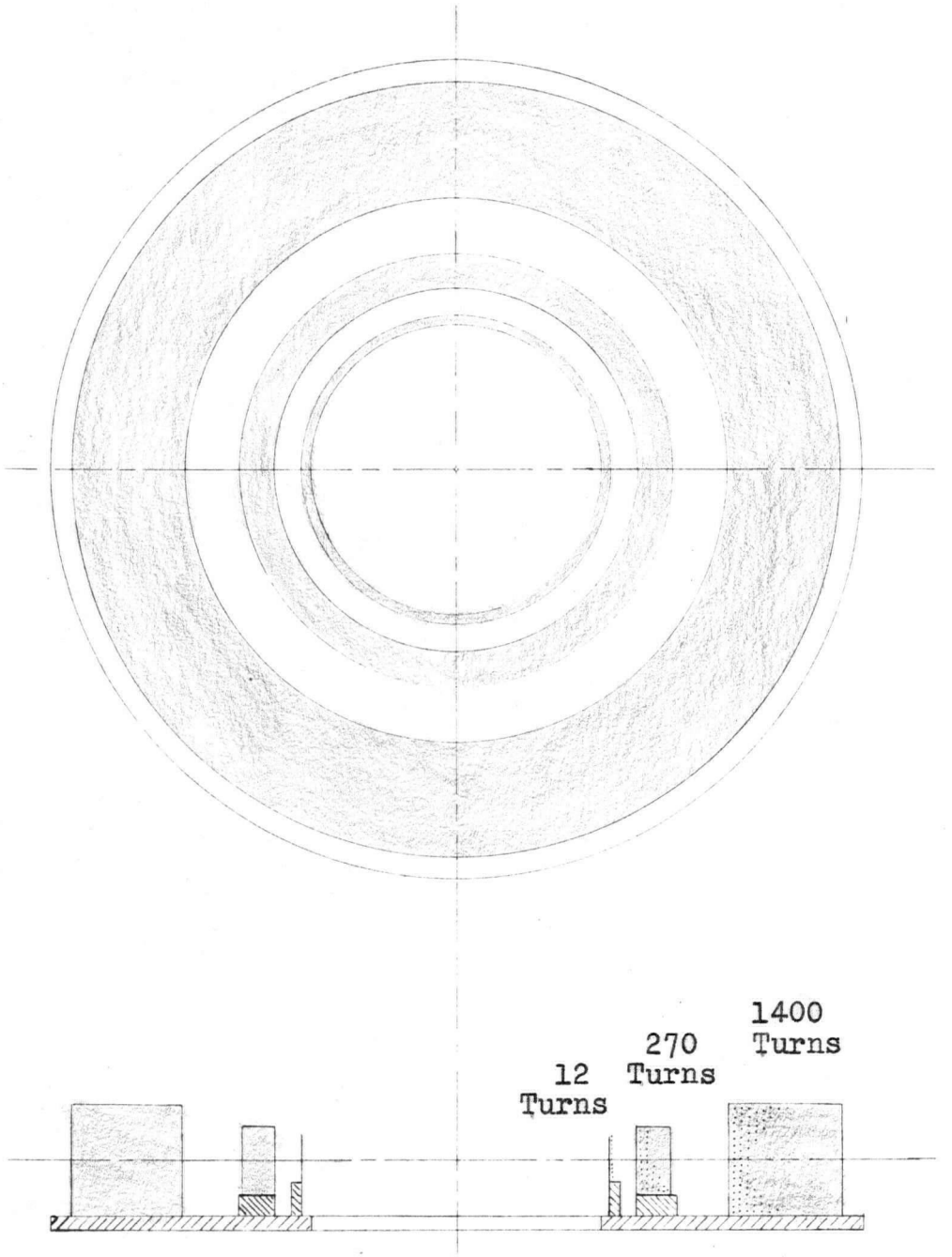
These calculations, however, were for ideal coils and would not necessarily hold for coils of a finite cross section such as is necessary to carry the current required. The design for the actual coil windings with finite cross-sections was carried out by approximate solutions, whereby each coil was replaced by a series of thin coil sections. The fields due to the individual coils were added graphically.

The construction of the magnet is shown in Fig.11. The coils were wound from No.14 wire and can carry a current of up to 10 amps for 10 minutes without external cooling. An approximate calculation of the effect of the finite size of the coils showed that there should be no change in the distribution of the field but that a small decrease in strength could be expected. The calculated value of H_o for 10 amps through the coil was 347 gauss.

The current through the coil is set to a known value with an accuracy of one part in ten thousand and is controlled by an electronic circuit to somewhat better than one part in a thousand. A setting of 1.0 volts on the control potentiometer corresponded to a current of $9.7 \pm .05$ amps and thus to a field of 336 ± 1.6 gauss.

D. Testing the Uniformity of the Magnetic Field.

The uniformity of the field was checked experimentally by the following method. Two identical coils of No.28 copper wire were wound on bakelite forms so that the inside diameter was 1 cm. and the coil winding cross-section was a square of 0.5 cm. side. The two coils were connected in series with a



1/4 Scale

FIGURE 11.

CONSTRUCTION OF THE MAGNET

ballistic galvanometer. With a measured current of 4 amperes through the magnet one coil was placed in the center of the magnet and the other at "infinity". The magnet circuit was broken and the deflection of the galvanometer observed. When the coils were interchanged and the process repeated the observed deflection differed by less than 0.5%.

Then one coil was fixed at the center of the magent and the other, in opposite sense to the first, was placed at a point in the region to be occupied by the spectrometer. When the current was interrupted the observed deflection of the galvanometer was proportional to the difference of the e.m.f.'s induced in the coils and thus proportional to the difference in the field at the two points. By comparing the deflection to that due to one coil alone the percentage variation of the field could be found. The results are shown in Fig. 12A.

It can be seen that the maximum variation over the region was about 2% and that the field increased steadily with the distance from the center.

As the inner coil of 12 turns is very close to the spectrometer and thus has a fairly large effect on the field for the larger values of r a trial was made with this coil disconnected. The results are shown by the curves of Fig. 12B. The maximum variation over a cylindrical region 6 cms. in radius and 2 cms. thick is seen to be 1%. It was decided that this amount of inhomogeneity would not be serious and that future measurements would be made with the inner coil disconnected.

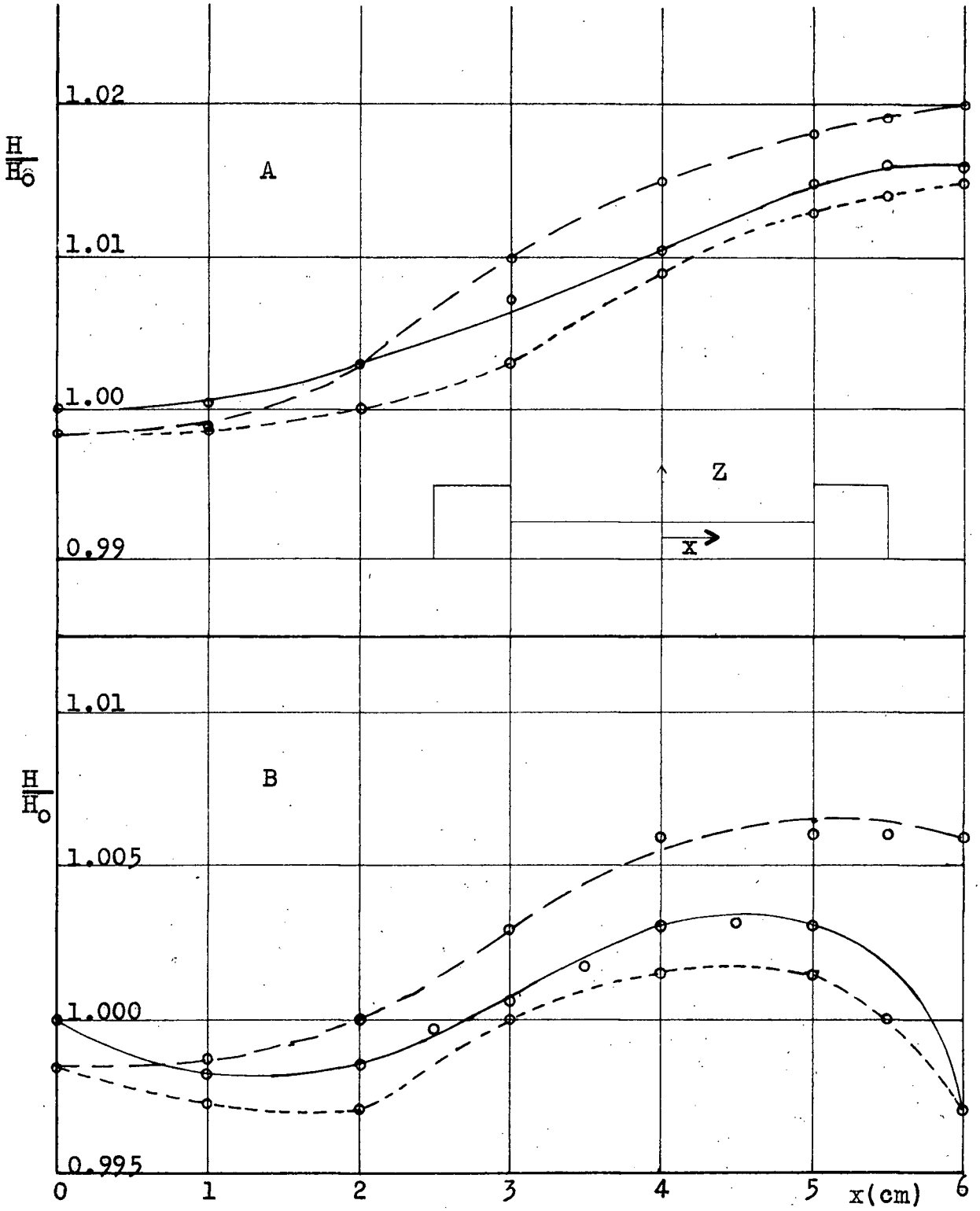


FIGURE 12.

OBSERVED VARIATION OF MAGNETIC FIELD IN SPECTROMETER REGION

A. Inner coil connected

B. Inner coil disconnected

E. Mathematical Treatment of a Spectrometer.[29]

Erect a right handed system of coordinates OX, OY, OZ in a uniform magnetic field so that the negative direction of the Z axis is in the direction of H. Consider a two dimensional radio-active source occupying a rectangular area in the ZOX plane, from x = -Q/2 to +Q/2 and Z = -h/2 to +h/2. (Fig.13). An electron leaving the source from a point $P(X_o, 0, Z_o)$ will meet the ZOX plane again at a point $P^1(x,y,z)$ whose coordinates are given by the equations:

$$x = x_o + 2r \cos A \cos B$$

$$y = 0$$

$$z = z_o + r (\pi + 2A) \sin B$$

where:

r is the radius of curvature of the electric path in the magnetic field. It is equal to the momentum of the electron divided by the field H and by the electronic charge expressed in electromagnetic units. Since in beta ray spectroscopy the momentum always appears divided by the electronic charge it is usual to redefine the units of the momentum so that

$$p = Hr$$

expressed in gauss-cms.

A is the angle between the initial direction of p and the plane YOZ and B is the angle between the initial direction

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29. This development is essentially that given by C. Geoffrion: R.S.I., 20, 638, 1949.

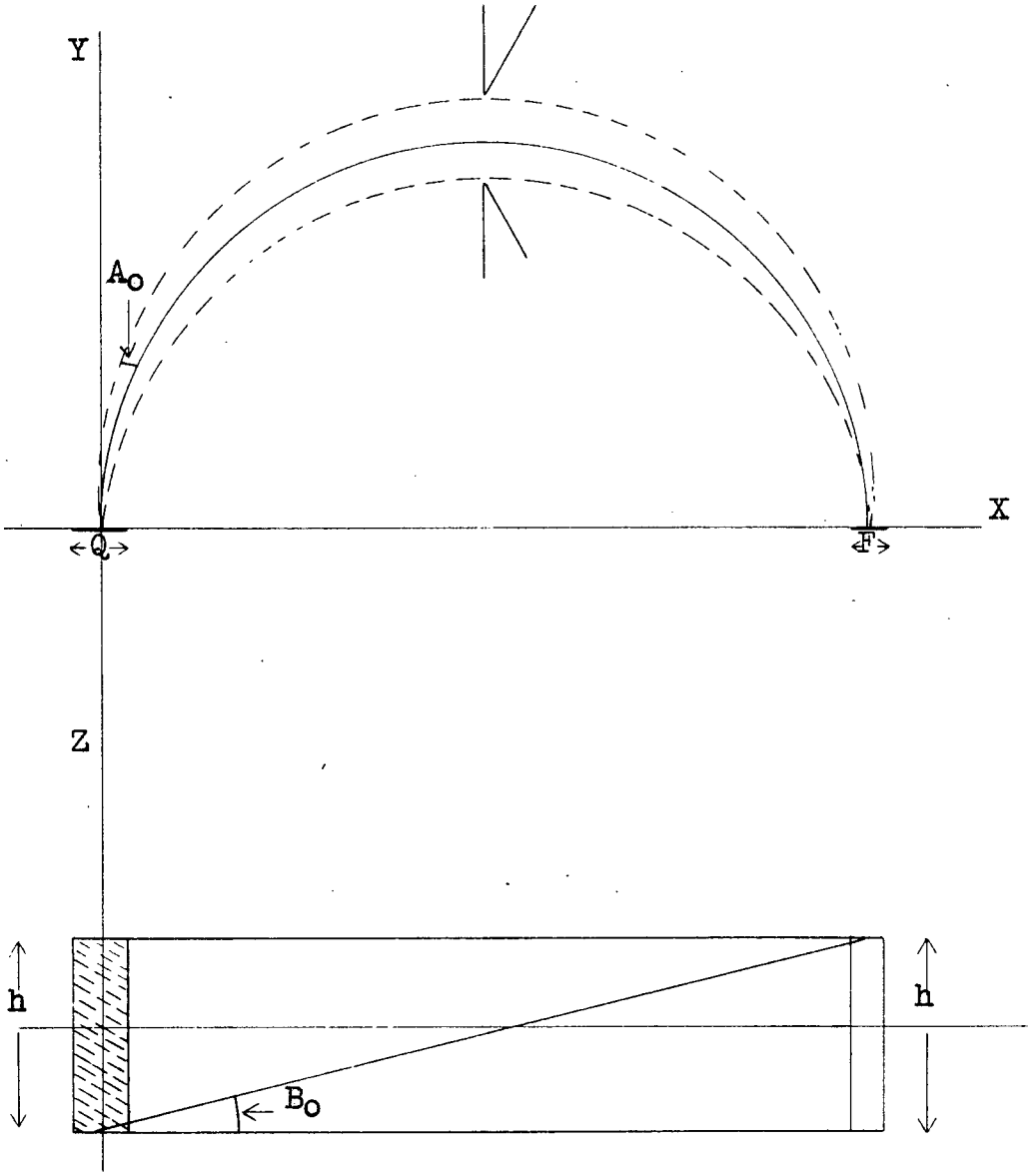

FIGURE 13.

DIAGRAM OF ELECTRON PATHS IN THE SPECTROMETER

of p and the YOX plane. Note that the angles A and B are measured positively from the initial direction of p to the respective planes.

Normally A is limited to $-A_o < A < +A_o$ by at least one baffle opening of width 2b perpendicular to the electron path at a point 90° from the source. Then

$$A_o = b/r \quad \text{- 1.}$$

It is also usual for the exit slit and source to have the same height h, B is then restricted so that $-B_o < B < B_o$ with

$$B_o = h/(\pi r) \quad \text{- - - - - - - - - - - - - - - - - - - 2.}$$

Under these conditions electrons of a given momentum will form an image of the source on the ZOX plane with certain aberrations caused by the finite values of A and B. The size of the image will be given by:

$$\text{Width} = Q^1 = Q + 2r(1 - \cos A_o \cos B_o)$$

$$\text{Height} = h^1 = h + 2r(\pi + 2A_o)\sin B_o)$$

The right hand edge of this image is located a distance 2r from the right hand edge of the source. Since r depends on the momentum of the electrons a number of images will be formed with different values of r for different values of the momenta.

If a detector is placed behind an exit slit in the ZOX plane of height h and width F (normally less than or equal to Q) it will receive electrons with only a certain range of values

of momenta. The width of the exit slit adds to the effective width of the image of the source so that it now becomes equal to

$$F + Q + 2r(1-\cos A_o \cos B_o)$$

If H is constant there is an uncertainty in the diameter of the electron trajectory of exactly this amount or one half of this in the radius of the trajectory.

The limit of resolution of a spectrometer is defined as the ratio $\Delta p/p$ where Δp is the range of the momenta of those electrons passing through the exit slit. Now since

$$p = Hr$$
$$\Delta p = H\Delta r + r\Delta H$$

and if H is constant

$$\Delta p = H\Delta r$$
$$= H\left\{F + Q + 2r(1-\cos A_o \cos B_o)\right\}/2$$

Now since $p = Hr$ we have

$$\frac{\Delta p}{p} = \frac{F + Q + 2r(1-\cos A_o \cos B_o)}{2r}$$

and since A_o and B_o are small this can be simplified to

$$\frac{\Delta p}{p} = \frac{F + Q}{2r} + \frac{A_o^2 + B_o^2}{2} \quad \text{- - - - - - - - - - - 3.}$$

Now if T is the kinetic energy of the particle in Mev

$$p = Hr = \frac{10^4}{3}\sqrt{T(T + 1.02)}$$

and it can easily be derived that

$$\frac{\Delta p}{p} = \frac{T + .51}{T + 1.02} \frac{\Delta T}{T}$$

The luminosity of a spectrometer is a measure of the number of electrons of a given momentum range which form an image of the source. It is a function of the source area and the solid angle w of the baffle system where

$$w = 2A_oB_o$$

The luminosity L can be defined as follows

$$L = KQhw/4\pi$$

where Qh is the area of the source and K is the number of electrons in the given momentum range emitted by the source in all directions per unit area per unit time. From previous equations it can be shown that

$$L = KQrA_oB_o^2/2$$

Thus the luminosity is a function of the same variables as the resolution $\Delta p/p$ i.e. Q, r, A_o, B_o. Geoffrion[29] has applied the method of undetermined coefficients to establish the optimum relationships between these variables making L a maximum. They are:

$$Q = 2A_o^2 r \quad \text{- 4.}$$

$$B_o = A_o(2)^{1/2} \quad \text{- 5.}$$

Under optimum conditions then the luminosity becomes

$$L = 2Kr^2A_o^5$$

It can also be shown that if F is the width of the exit slit its optimum value is F = Q. The value chosen for F has an effect on both the resolution and on the luminosity which now become under optimum conditions

$$\triangle p/p = 7A_o^2/2$$

and

$$L = 0.725\ Kr^2(\triangle p/p)^{5/2} \text{ - - - - - - - - - - - - 6.}$$

The limit of resolution given above is defined for complete separation of two lines,

$$\triangle p/p = 3A_o^2/2 \text{ - - - - - - - - - - - - - - - - - - 7.}$$

gives the width of a line at half maximum intensity as is more usual.

The spectrometer described in this report has a radius of 3.05 cms. and A_o was chosen as 0.1. The optimum values of Q, F, and B_o are then

$$Q = 2 \times 3.05 \times .01$$
$$= .06 \text{ cms.}$$
$$F = Q = .06 \text{ cms.}$$
$$B_o = 1.4A_o = .14$$

The width of the source could not be made much less than 1 mm. because of the difficulties in handling small drops of radio-active solutions. However this is multiplied by the factor .707 since the source is at an angle of 45° to the plane of the source and exit slit. (See Fig.9). The actual value of Q is probably within 10% of the optimum value given above.

The height of the source and exit slit are about 1.5 cms. This gives

$$B_o = h/\pi r = .156$$

about 10% higher than the optimum value.

The width of the exit slit (width of counter window) is about .025 cms. because it was feared that a wider window would not stand the pressure. This was not checked, however, and it might be interesting to construct a counter with optimum window width. This should improve the performance of the spectrometer.

The resolution of the spectrometer should be about 1.7% at half maximum intensity using equation (7). From equation (3) using the actual values of Q, F, A_o and B_o the resolution comes out to be about 1.5%. The difference is due almost entirely to the small value of F. This small value of F should reduce the luminosity of the spectrometer by F/Q. Assuming K to be unity this gives

$$L = .146 \times 10^{-3} \text{ cms}^2$$

and adding the luminosity for the four sections of the spectrometer

gives

$$L = .58 \times 10^{-3} \text{ cm}^2$$

Geoffrion (ibid) shows a curve of the intensity to be expected under optimum conditions using an exit slit of infinitesimal width (this is the case in photographic detection). The theoretical line profile for an exit slit of a given width F can be obtained from this curve by integration. Fig.14 shows the profiles obtained from the dimensions of our spectrometer for F = .025 cms. and F = .06 cms. Note that the profile is not symmetrical, the lower energy side extends further than the high energy side. This tendency is exaggerated by the effect of a thick source as can be seen from the 30 Kev line in the spectrum of RaD (Fig.16). Other experimenters have reported entirely similar results.[30]

Persico and Geoffrion[31] have made an analysis of the various beta ray spectrographs and spectrometers mentioned in the literature and compiled their results in the form of a table. This is reproduced in part in Table I for comparison with the results for the spectrometer described by this report. They also give a scatter diagram of the various instruments, plotting resolution against what they call the efficiency.

$$\text{eff.} = 10^7 L/r^2$$

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30. G.E. Owen and H. Primakoff: Phys.Rev., 74, 1406, 1948.

31. E. Persico and C. Geoffrion: R.S.I., 21, 945, 1950.

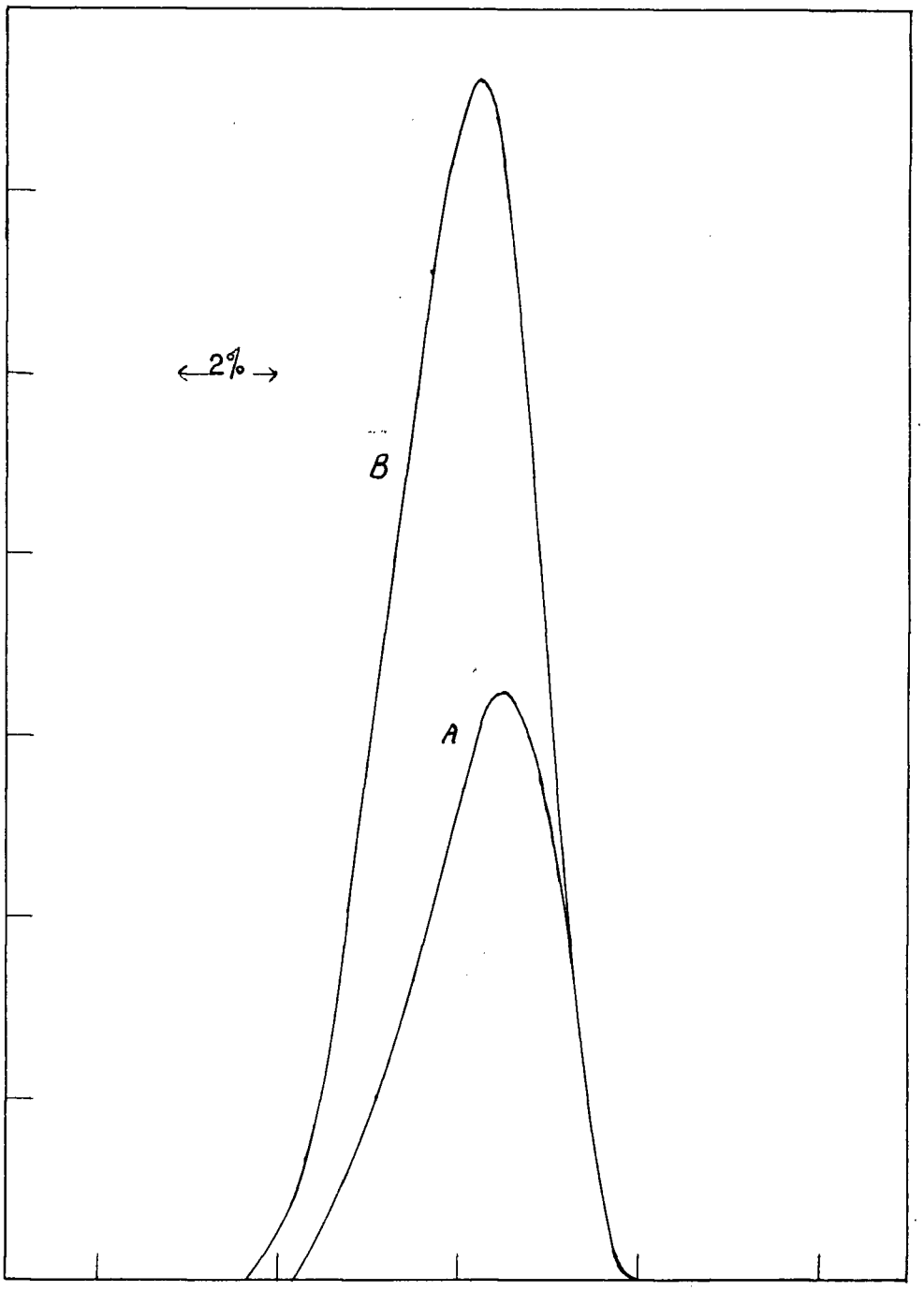

FIGURE 14.

THEORETICAL LINE PROFILES

A Counter slit 0.025 cm wide

B Counter slit 0.06 wide

This is proportional to the luminosity divided by the cross-sectional area of the magnetic field. The diagram is reproduced in part in Fig.15.

The quantities compared in Table I are self-explanatory with the exception of W, C and D which are defined as follows

$$W = w/4\pi$$

$$C = \left(\frac{\Delta p}{p}\right)^{5/2} \frac{L}{r^2}$$

$$D = \left(\frac{\Delta p}{p}\right)^{1} W$$

The luminosity and solid angle of these spectrometers cannot be compared directly since they are influenced by the resolutions of the instruments. However, the quantities C and D provide a means of comparison which eliminate the different resolutions. The value of C calculated for this instrument (0.34) is considerably higher than any of the others and, in fact, is almost one-half of the optimum value (0.725). It could be increased by making the counter entrance slit the same width as the source. D representing the ratio of the solid angle to the resolution has different values depending on whether one or four counters are used. With one counter D = 0.15 and with four D = 0.60. No 9 in the table is the spectrometer described in this report, (a) is the data for one counter only and (b) is the data for four counters. The values of the resolution and luminosity in 9(b) are calculated on the basis that the exit slits are all lined up exactly with the electron trajectories. This

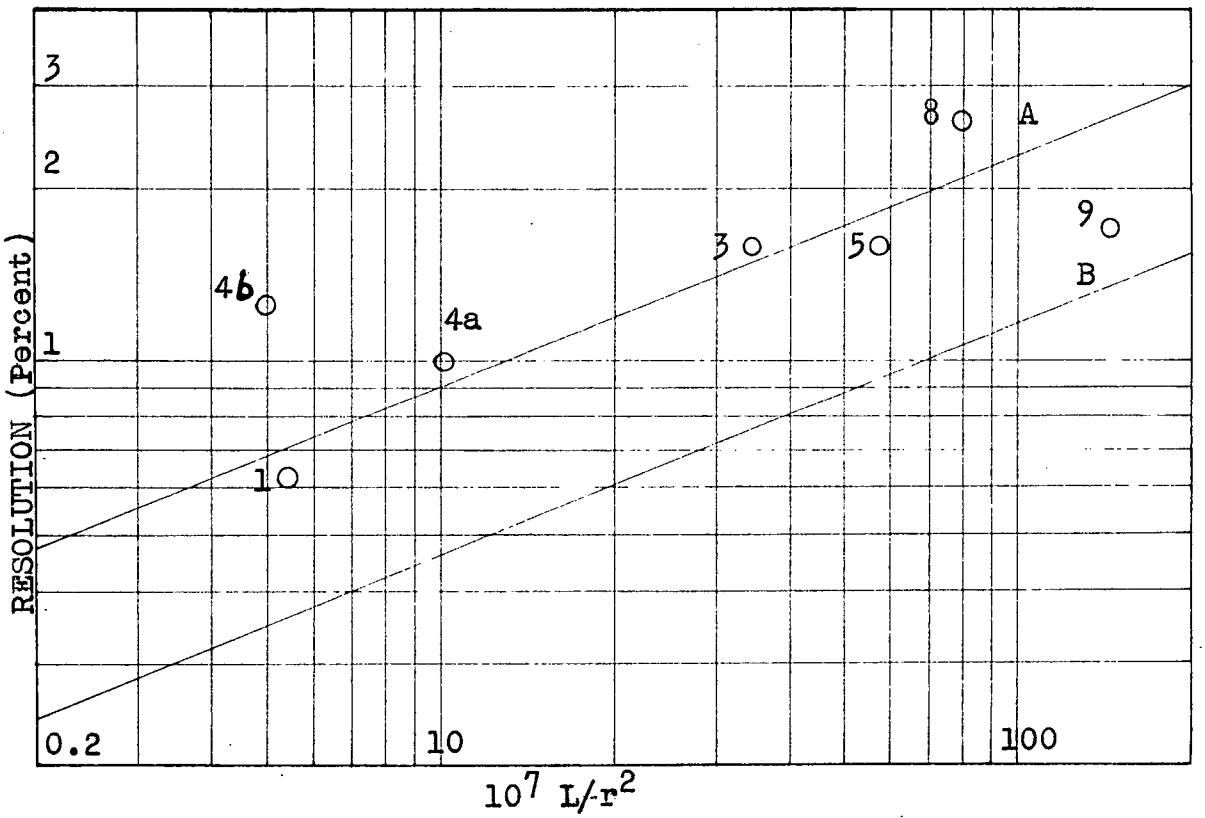

FIGURE 15.

COMPARISON OF VARIOUS BETA RAY SPECTROMETERS

(The numbers on the points refer to the corresponding instruments in TABLE I)

A Optimum values for the usual semi circular focussing spectrometer

B Optimum values for high source type of semi circular focussing spectrometer

is almost true as will be shown later. 4(a) and 4(b) are two conditions of operation of the same instrument.

TABLE I

No	Authors	Year	Ref.	Type	Iron	Emax Mev	r cm.	$\frac{\Delta p}{p}$%	W%	Lx10^3 cm^2	Cx10^2	Dx10^2
1	Li	1937	32	Spg.	y	--	6	0.63	0.0067	0.020	18	1.1
2	Arnould	1939	33	Spg.	n	0.26	13.5	0.2	0.011	0.00022	0.74	5.5
3	Lawson and Tyler	1939	34	Spm.	y	3.1	12	1.6	0.10	0.50	11	6.3
4	Neary a	1940	35	Spm.	y	--	7	1.0	0.041	0.052	11	4.1
	b					--	10	1.26	0.041	0.052	2.8	3.3
5	Townsend	1941	36	Spm.	y	--	8	1.6	0.10	0.38	19	6.3
6	Plesset, Harnwell and Seidl	1942	37	Spg.	y	10	11.4	0.2	--	--	--	--
7	Seigbahn	1944	38	Spm.	y	--	12	0.17	0.029	0.00073	4.2	17
8	Langer, Motz and Price	1950	19	Spm.	n	0.23	5	2.6	0.10	0.20	7.3	3.9
9	Brown a	1951		Spm.	n	0.10	3.05	1.7	.25	0.146	34	15
	b					0.10	3.05	1.7	1.0	0.58	34	60

32. K.T. Ki: Proc.Camb.Phil.Soc., 33, 164, 1937.

33. R.Arnould: Ann.de Phys: Serie 11,to 12, 241, 1939.

34. J.L. Lawson & A.W.Tyler: R.S.I.,11,6,1940.

35. G.J. Neary: Proc.Roy.Soc., 175,71,1940.

36. A.A. Townsend: Proc.Roy.Soc.177,358,1940.

37. Plesset, Harmwell & Seidl: R.S.I., 13, 351, 1942.

38. K. Siegbahn: Arkiv.Mat.Astrom.Fys.Bd., 30A, (No20) 1944.

III

RESULTS

Radium D ($_{82}Pb^{210}$)

The primary beta spectrum has long been known to consist of continuous distributions of electrons, conversion electrons and Auger electrons all in the energy region below 50 Kev. The very real experimental troubles attendant upon a detailed analysis of these radiations have led to large discrepancies among and uncertainties in the reported findings. The bulk of the work has been done with cloud chambers and absorption techniques which have grave limitations in resolution and statistical accuracy. Because of the low energy of any gamma-rays, there are many conversion electrons from theL, M and N shells superimposed upon the primary beta distribution which makes it difficult to locate the end-point accurately. The Auger electron lines further obscure the beta spectrum.

In spite of these obvious problems, it was felt that this nucleus would provide a good test of the performance of the spectrometer under very unfavorable conditions. Also, if successful, the experiment would provide useful information that might help in eliminating some of the reported inconsistencies in the decay of RaD.

The beta spectrum was studied extensively by early experimenters with photographic methods. It appeared to be

very simple, consisting of a group of conversion lines all attributable to the action of one gamma ray. Rutherford, Chadwick and Ellis report the following values.

TABLE II

Number of line	Intensity	Hr	Energy in Kev
1	50	600	30.9
2	2	606	31.5
3	0.5	628	33.8
4	20	714	43.3
5	10	738	46.1

which are analyzed as follows

TABLE III

Number of line	Origin	Energy + absorption energy in Kev	Energy of Gamma in Kev
1	L_I	30.9+16.3	47.2
2	L_{II}	31.5+15.7	47.2
3	L_{III}	33.8+13.4	47.2
4	M_I	43.3+ 4.0	47.3
5	N_I	46.1+ 1.0	47.1

G. von Droste[39] using a Wilson cloud chamber and magnetic analysis obtained most of the above conversion lines and agrees roughly on the energy of the primary gamma. He also

39. G. von Droste: Zeits. fur Phys., 84, 17, 1933.

observed a large number of tracks corresponding to the x-ray spectrum of the inner shell electrons of atoms of atomic number 83. Richardson and Leigh-Smith[40] distributed Radium D as a gas in the form of tetra-methyl lead throughout a cloud chamber. The beta spectrum was calculated from electron path lengths and range-energy measurements. In addition to the usual conversion lines they report a large number of electrons of very low energy. Their results were based on a small number of observations and thus have poor statistics. A Kurie plot of the results gives an end point of 16 Kev. Lee and Libby[41] used absorption techniques to study the gammas from RaD and a screen wall counter with magnetic deflection to observe the primary beta distribution. They report an end point of 25.5 ± .1 Kev. The continuous distribution has also been observed by Saha[42] who gives the end point as 29 Kev.

A great deal of work has been done on the analysis of the gamma rays of RaD by Tsien San-Tsiang, Frilley et al.[43] By a number of methods such as a bent crystal spectrometer,

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40. H.O.W. Richardson and A.Leigh-Smith: Proc.Roy.Soc. 160, 454, 1937.

41. D.D. Lee and W.F. Libby: Phys.Rev. 55, 252, 1939.

42. A.K. Saha: Proc.Nat.Inst.Sci.India, 12, No.3, 1946.

43. Tsien San-Tsiang: Comples Rendus, 216, 765, 1943.
Ouang TeTchao: J. Surugue, Tsien San-Tsiang: Comptes Rendus, 217, 535, 1943.
Tsien San-Tsiang: Comptes Rendus, 218, 503, 1944.
M. Frilley: Comptes Rendus 218, 505, 1944.
Tsien San-Tsiang and C.Marty: Comptes Rendus,220,688,1945.
Tsien San-Tsiang and C.Marty: Comptes Rendus,221,177,1945.
Tsien San-Tsiang: Phys.Rev., 69, 38, 1946.

measurement of path lengths in a cloud chamber, magnetic deflection in a cloud chamber, absorption measurements they show the existence of the following nuclear gamma rays.

TABLE IV

Number of line	Energy in Kev	Quanta/100 disintegrations
1	65 ± 5	< 0.2
2	46.7 ± 0.1	2.8
3	43 ± 1	0.2
4	37 ± 1	0.2
5	32 ± 1	0.4
6	23.2 ± 0.6	1.0
7	7.3 ± 0.7	~ 10

More recently Curran et al.[44] have investigated the gamma rays of RaD by means of a proportional counter. The beta particles from their source were deflected magnetically and the gammas entered the counter through a thin mica window. They report the following gamma rays

TABLE V

Intensity	Energy
7.3	7.7 Kev
0.4	25.8 Kev
3.0	46.6 Kev

44. S.C. Curran, J. Angus and A.L. Cockcroft: Phil.Mag., 40, 36, 1949.

and in addition strong L x-ray lines in the 10-15 Kev region Their results appear to be the most reliable to date.

Another investigation of RaD has been done by Cranberg[45] using thin sources (average thickness about 43 micrograms/cm^2) and a semicircular focussing spectrograph. His plates show the L_I, L_{III}, M and N conversion lines from the 47 Kev gamma ray. There is also some evidence of a line at 19 Kev (470 gauss cm.). The sensitivity of the emulsion is evidently very poor below 15 Kev.

Fig.16 shows the results obtained here with a source of about 30 micrograms/cm^2. The readings have been repeated a number of times with different source strengths without any appreciable change in the spectrum. The L_I, L_{III}, M, and N conversion lines of the 47 Kev gamma line are indicated. The broad peak at about 300 gauss-cms is probably due to the continuous spectrum of nuclear beta particles. The low energy peak at about 150 gauss-cms is hard to identify because of its width. The most probable loss of energy of an electron of 3 Kev energy is about 50 electron volts per microgram/cm^2. Since the source weighs 30 micrograms/cm^2 the width of the line can readily be explained in terms of absorption in source.

If this is the cause of the line width then the actual energy of the electrons must be at the high energy end of the line, about 200 gauss-cms, corresponding to 3.7 Kev. Thus the line may be due to an M shell conversion of the 7.7 Kev gamma reported above.

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45. L. Cranberg: Phys.Rev., 77, 155, 1950.

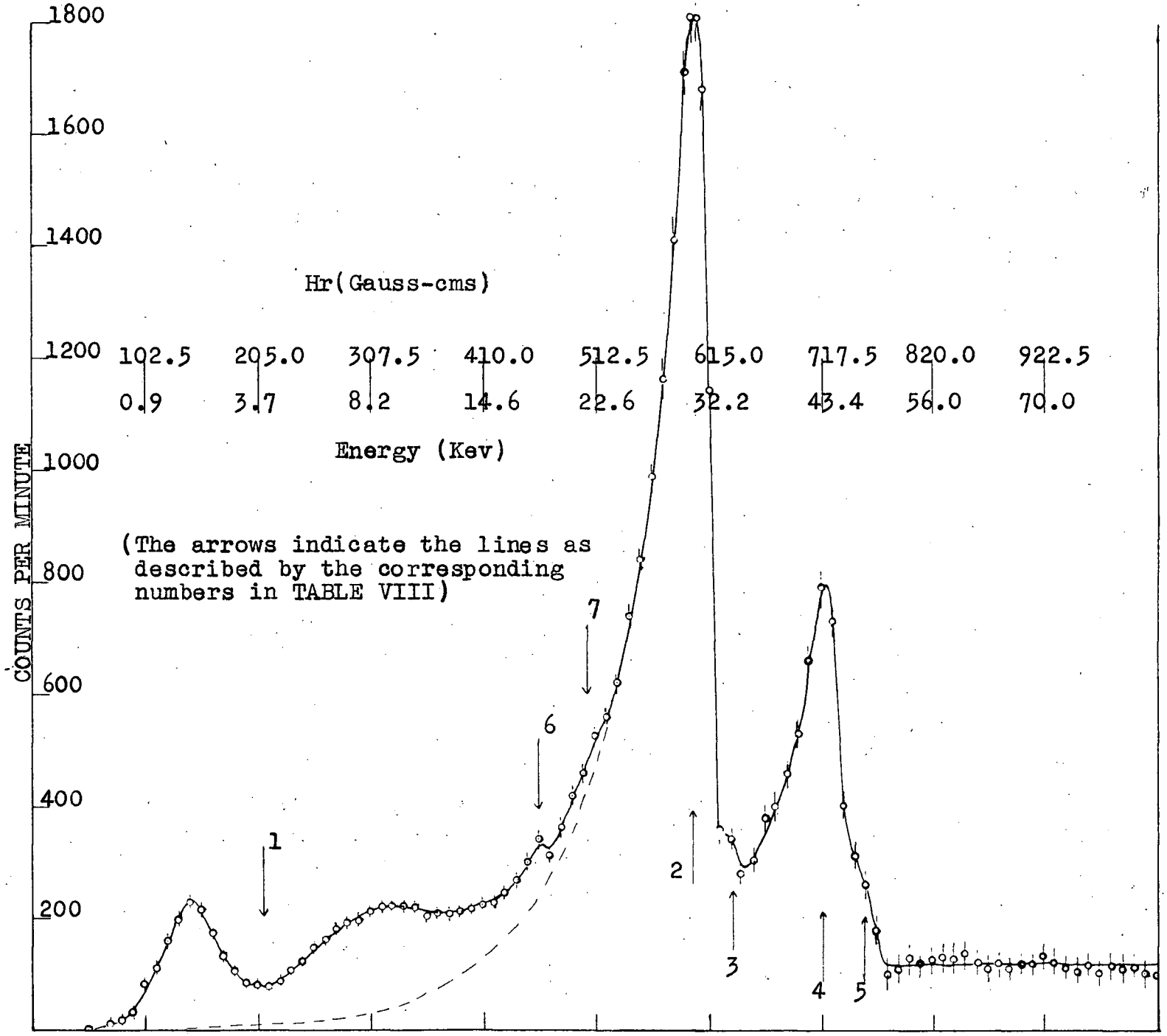

FIGURE 16

BETA SPECTRUM OF RADIUM D

On the other hand the line may be due wholly or in part to Auger transitions in the electronic shells of the daughter Bi atoms. Since the 46 Kev gamma is most highly converted in the L_I level it is to be expected that most Auger transitions would start from here. The process can be pictured as follows. The atom is singly ionized, having lost an L_I electron. This vacancy can be filled by an electron from any higher energy state L_{II}, L_{III}, M_I, --- N_I --- and simultaneously another electron is ejected from the atom. For an energy balance, the kinetic energy of the ejected electron plus its binding energy must be equal to the energy given up by the reversionto the L_I state. Note that since there is a vacancy in the L shell the binding energies of the M and N electrons are increased, and must be calculated on the basis of an increase of unity in the nuclear charge.

As an example, consider transition from an atom singly ionized by lack of an L_I electron to doubly ionized by lack of L_{III} and M_{IV} electrons.

$$L_I \longrightarrow L_{III}\, M_{IV}$$

The kinetic energy of the ejected electron is given by:

$$E(Kin) = E(L_I)_Z - E(L_{III})_Z - E(M_{IV})_{Z+1}$$

Table VI[46] lists the binding energies of the L

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46. These values were obtained from Compton and Allison: X rays in Theory and Experiment, and from the International Critical Tables.

electron in bismuth and some of the M and N electrons in polonium and Table VII gives some of the possible transitions together with the kinetic energy of the ejected electrons.

Richtmeyer and Kennard[47] state that the transitions

$$L_I \longrightarrow L_{III}\ M_{IV,\ V}$$

are often observed in X ray work for Z>75. However, the excess energy in this case is too small for detection.

TABLE VI

	L	M	N
I	16,400	4,000	900
II	15,700	3,700	800
III	13,400	3,200	700
IV		2,700	500
V		2,600	400

Thus there are a number of transitions that could yield electrons in the energy range occupied by this line. They have different energies and different degrees of probability of occurring. It is likely that the line is actually composed of electrons resulting from several Auger transitions and the M conversion of the 7 Kev gamma with its structure totally obscured by absorption in the source, with further confusion due to the variation of transmission of the counter windows in this region.

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47. Richtmeyer & Kennard: Introduction to Modern Phys., 3rd Edition, p.548.

TABLE VII

No	Transition	Energy in e.v.
1	$L_I \rightarrow L_{III}M_{IV}$	300
2	$L_I \rightarrow L_{III}M_V$	400
3	$L_I \rightarrow L_{III}N_I$	2100
4	$L_I \rightarrow L_{III}N_{II}$	2200
5	$L_I \rightarrow L_{III}N_{III}$	2300
6	$L_I \rightarrow L_{III}N_{IV}$	2500
7	$L_I \rightarrow L_{III}N_V$	2700
8	$M_I \rightarrow N_IN_{II}$	2200
9	$M_I \rightarrow N_IN_{III}$	2400
10	$M_I \rightarrow N_IN_{IV}$	2600
11	$M_I \rightarrow N_IN_V$	2800

With one source which was made thinner than usual (of the order of 10 micrograms/cm^2) some structure was noticed but before reliable statistics could be obtained an accident occurred in which the source became damaged. If a source could be made less than 5 micrograms/cm^2 more information could be obtained about this line.

There is some evidence of a very weak peak at 450 gauss-cm (18 Kev). If this corresponds to M-shell conversion then the energy of the transition is about 22 Kev and an L-shell peak should occur near 5.5 Kev. There is no evidence of this. Therefore should this transition actually exist, the transition energy is about 34 Kev and the conversion takes place

in this L shell. There is a similarly doubtful peak at 500 gauss-cm (21 Kev) which by the same arguments would be an L-shell conversion of a 37.5 Kev transition.

Table VIII lists the results of this experiment to determine the conversion transitions of the RaE daughter product. The energies were determined by use of the theoretical value of the field. (See page 19).

TABLE VIII

No. of line	Origin	Conv.line + Shell Binding	Transition Energy
1*	M	3.7±1.0+4.0	7.7 Kev
2	LI	31.0±1.0+16.4	47.4
3	LIII	34.3±1.0+13.4	47.7
4	M	43.4±1.0+4.0	47.4
5	N	48.0±1.5+1.0	49.0
6**	LI	18.3±1+16.4	34.7**
7**	LI	21.5±1+16.4	37.9**

* Corrected for source absorption.
** Doubtful.

The Primary Beta Spectrum

The low-energy tail on the LI conversion line of the 47 Kev gamma is unfortunate in that it tends to obscure the distribution of the disintegration electrons and any weak conversion lines in this region. The leading edge of the line corresponds well with the expected half maximum intensity resolution of 1.7%. The low energy tail appears to be caused by the

spectrometer rather than by source absorption since different thicknesses of sources did not make much difference. Owen and Primakoff[48] have reported almost identical line profiles from their small semicircularly focussing spectrometer. They describe the fitting of the trailing edge of the line by means of an exponential curve

$$N(H) = \text{Constant X } \exp\left\{ - \frac{p_o - p}{a} \right\}$$

where p_o is the Hr value of the leading edge of the line and a is the average width of the line in gauss-cms.

This has been done with the L_I conversion peak (the solid line in Fig.16) and the calculated values subtracted from the observed distribution, resulting in the plot shown in Fig.17. Inspection of this curve gives a beta ray end point of 22.4 Kev, a value which is strongly influenced by the fitting of an exponential curve to the 46 Kev L_I conversion line.

The Kurie plot of the beta spectrum is shown in Fig.18. In the calculation of the curve the following procedure was used. The Fermi relation is given by

$$\left[\frac{N}{\eta^2 f} \right]^{1/2} = E_{max} - E$$

where η = the momentum of the electrons in units of $M_o C$.

N = the number of electrons in the momentum interval η to $\eta + d\eta$

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48. See reference No.30.

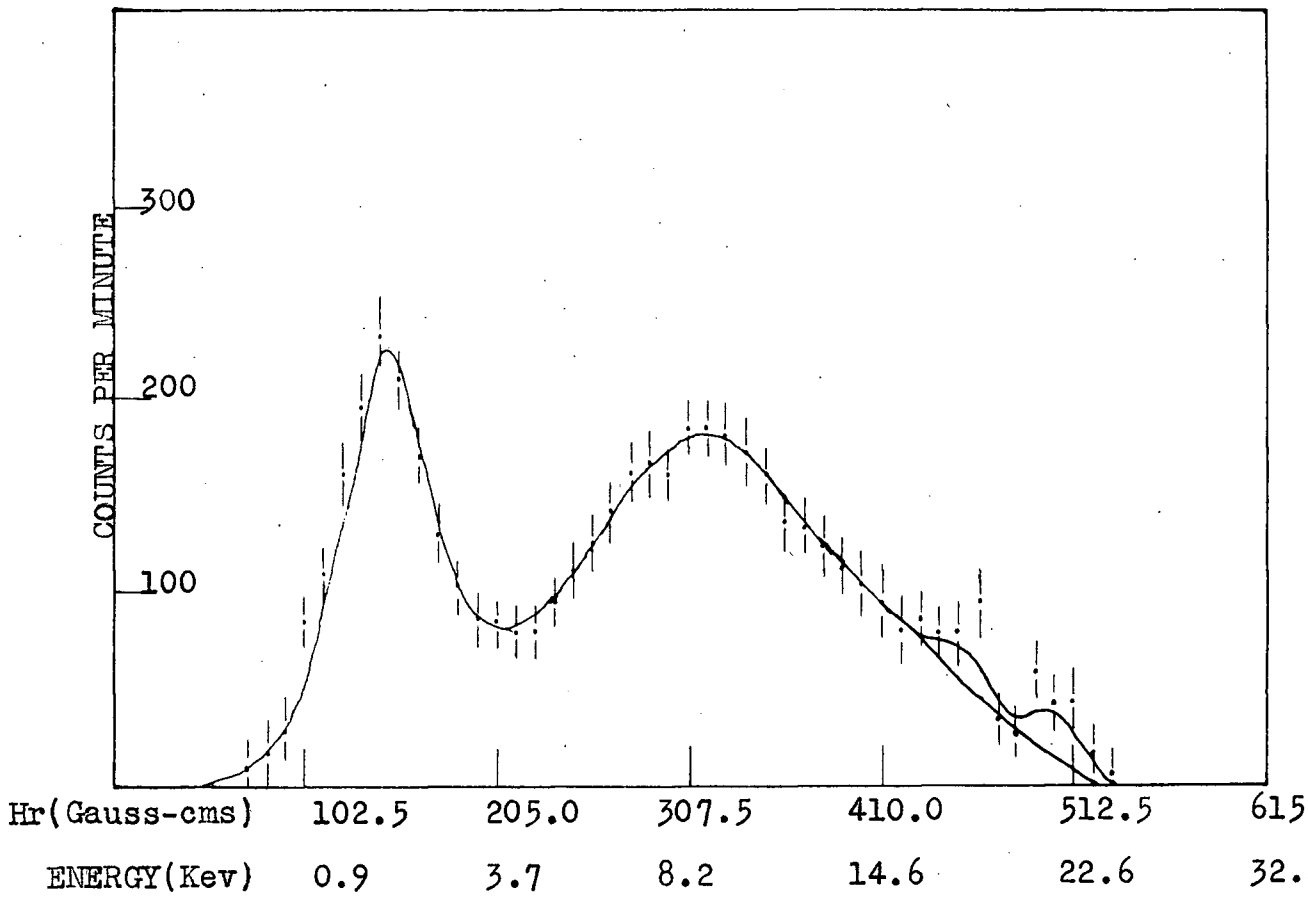

FIGURE 17.

BETA SPECTRUM OF RADIUM D WITH
30 KEV CONVERSION LINE SUBTRACTED

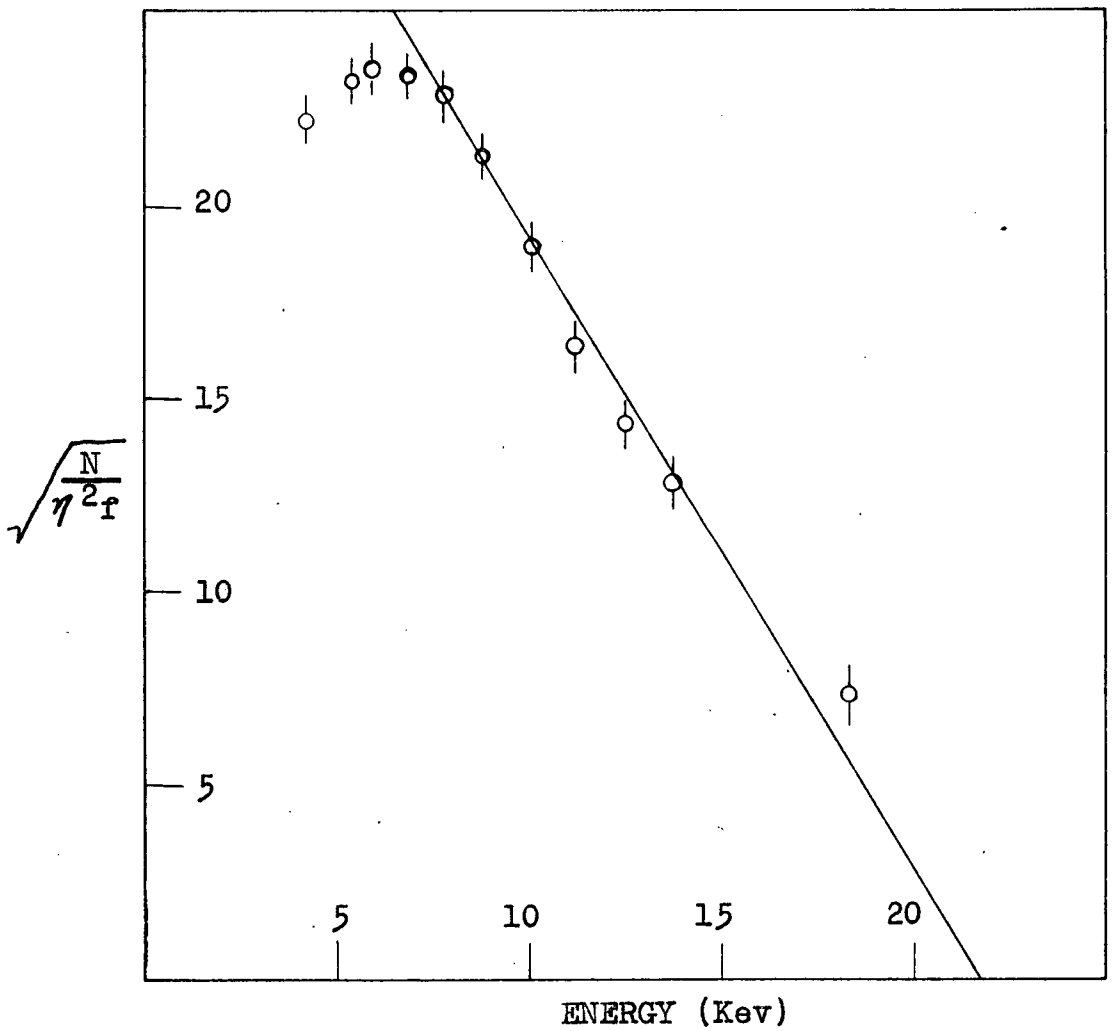

FIGURE 18.

KURIE PLOT OF BETA SPECTRUM OF RADIUM D

and $f(Z,\eta) = \eta^{2S} e^{\pi y} \left|\Gamma(1 + S + iy)\right|^2$

$$S = \sqrt{1-(Z/137)^2} - 1$$

$$y = \frac{Z\sqrt{1+\eta^2}}{137\eta}$$

Since there are no complete tables of the complex gamma function available it was approximated by means of a Taylor expansion to the first power only of S. Neglecting higher terms we get

$$\left|\Gamma(1+S+iy)\right|^2 \simeq \frac{\pi y}{\sinh \pi y}\left[1+S\left\{\frac{\Gamma'(1+iy)}{\Gamma(1+iy)} + \frac{\Gamma'(1-iy)}{\Gamma(1-iy)}\right\}\right]$$

The expression in $\{\ \}$ was further expanded in a series using a well known expansion for $\Gamma'(Z)/\Gamma(Z)$. The series involved of the form

$$\sum_{n=1}^{\infty} \frac{1}{n(n^2+y^2)}$$

was approximated by

$$\int_1^{\infty} \frac{dn}{n(n^2+y^2)}$$

whence

$$\left|\Gamma(1+S+iy)\right|^2$$

$$\approx \frac{\pi y}{\sinh \pi y}\left\{1+2S\gamma+S \ln (1+y^2)\right\}$$

with γ = Euler constant = 0.5772

The final result is that

$$f(Z,\eta) = \eta^{2S}\pi y \frac{e^{\pi y}}{\sinh \pi y}\left\{1+2S\gamma+S \ln (1+y^2)\right\}$$

A straight line was fitted to the points from 7 Kev to 15 Kev by means of the least squares procedure yielding an end point of 21.7 $\pm$ 1 Kev

Below 7 Kev the curve deviates from a straight line due to absorption in the source. The point at 18.3 Kev was neglected in the determination of the line since it is so strongly influenced by the two small peaks in that region and by the tail of the L_I conversion line.

Most of the readings on RaD were taken with only three of the four counters operating as one counter was found to be unreliable and could not be made to operate properly. A run was taken on the 600 gauss-cm line using only one counter, as a check on the alignment of the spectrometer. The comparison is shown in Fig.19, the difference in resolution is very small and of the order of magnitude to be expected from the alignment procedure.

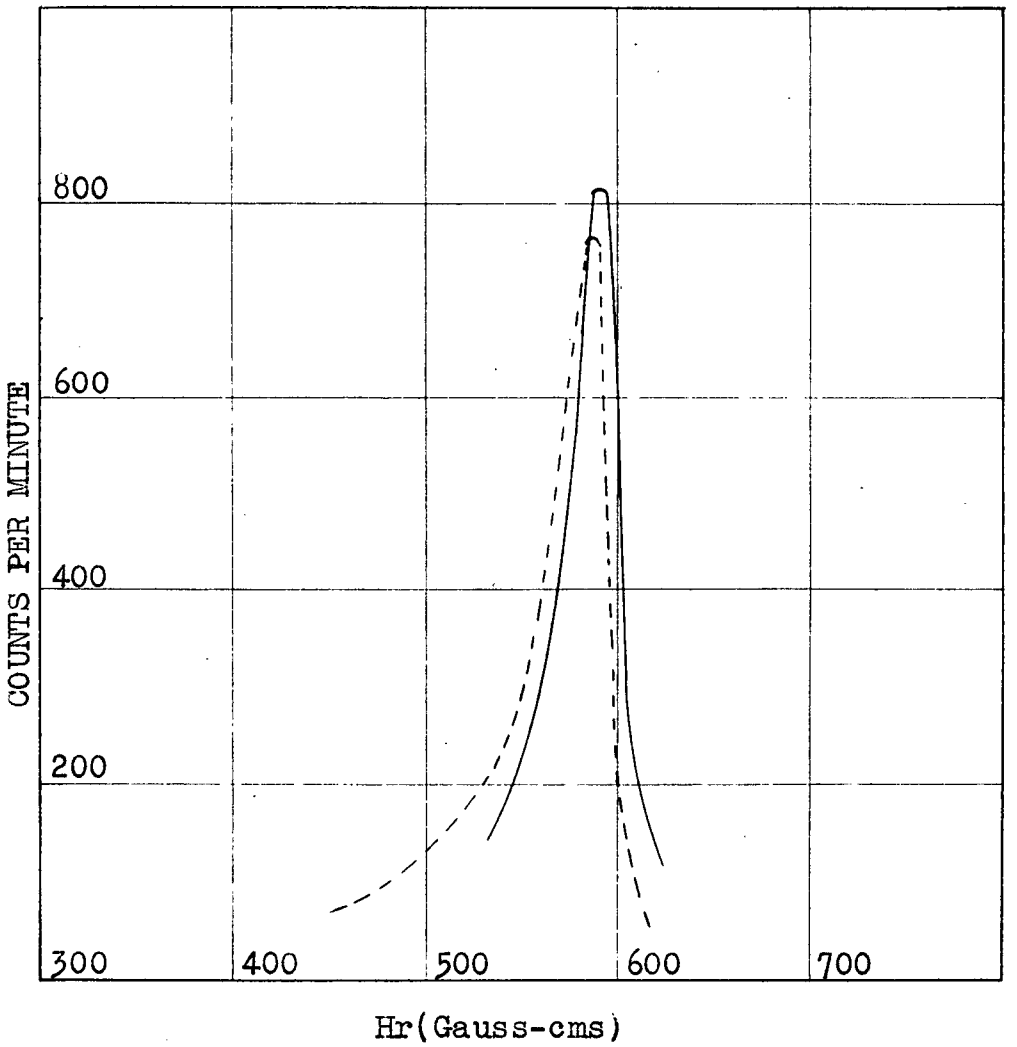

FIGURE 19.

LINE WIDTHS FROM ONE COUNTER AND FROM THREE COUNTERS

Solid line ..... One counter

Dashed line..... Three counters

Discussion of the Results on RaD

There seems to be no doubt but that the decay RaD⟶RaE takes place with a negatron decay to an excited state of RaE. The predominant gamma-ray and the conversion electrons correspond to a transition energy of 47 Kev and one of 7.7 Kev. The maximum energy of the beta-spectrum as taken from the Kurie plot is 21.7 Kev.

In addition to these two major transitions there is conflicting evidence of other very weak transitions with very little correlation between the different reported figures. Examination of the experimental evidence in each case leads one to conclude that the evidence is not very strong in most cases. All quantitative experiments quote the 47 Kev and the 7.7 Kev transitions, and it appears that these are the only transitions upon which much reliance can be placed.

Now it is impossible to postulate a decay scheme for a nucleus when the radiations consist of one beta-group and two major gamma-rays, unless one assumes the gamma-rays are in cascade. We can make this postulate and try to fit the known data to such a scheme to see if such data are consistent or not. If a cascade gamma scheme is correct then there should be equal numbers of transitions corresponding to the 47 Kev and the 7.7 Kev lines. That is, the sum of the conversion electrons plus the gamma-rays should be the same in both cases.

The relative numbers of conversion electrons for the two transitions may be roughly estimated for the first time from the results of the present investigation if we make the some-

what drastic assumption that the true height of the 7.7 Kev peak is that of a peak whose area is equal to the measured peak and whose half-width is about 1.5% in momentum. This corresponds to a corrected peak height of 1200 counts/minute. This estimate will probably err on the low side because at the energies involved, we may expect scattered and absorbed conversion electrons that would not reach the counter. The total number of 47 Kev conversion electrons will of course be proportional to the sum of all the conversion peak heights corresponding to this transition--i.e. 1800 + 800 + 300 --- or $\backsim$ 3000 counts per minute. Hence

$$\frac{(N_e)_{7.7}}{(N_e)_{46}} \rangle \frac{1200}{3000} = 0.4 \quad \text{- - - - - - - - - - - 1.}$$

The work of Curran and collaborators on the gamma-rays of RaD gives the ratio of 7.7 Kev gammas to 47 Kev gammas as about 2.4. San-Tsiang and co-workers put the value of the ratio at 3.6. Taking the mean value, we accept

$$\frac{(N_\gamma)_{7.7}}{(N_\gamma)_{46}} \backsim 3.0 \quad \text{- - - - - - - - - - - - - - - - - 2.}$$

Finally on the basis of his measurements, San-Tsiang concludes that there are approximately 10 quanta of 7.7 Kev energy emitted for each 100 disintegrations.

To summarize then, for each 100 disintegrations, there will be 10 - 7.7 Kev quanta and 90 conversion electrons

for this energy. On the cascade picture, using equation (2) there are approximately 3 - 47 Kev quanta and 97 corresponding conversion electrons. This would predict

$$\frac{(N_e)_{7.7}}{(N_e)_{46}} = \frac{90}{97} \text{ or} \backsim 0.9$$

whereas our rough estimates put the value as greater than 0.4 from (1). Considering the data available, then there is nothing inconsistent in the assumption of a cascade gamma system. This would then lead to a decay scheme as illustrated in Figure 20.

This scheme could be tested by the use of coincidence techniques except for the presence of Auger electrons and X-rays in the 7.7 Kev energy region which are coincident with the 47 Kev transition. It is likely that the experimental difficulties would preclude this check.

From our previous figures, we can estimate the order of magnitude of the conversion coefficients since by definition

$$\alpha = \frac{N_e}{N_\gamma}$$

Hence α_M for the 7.7 Kev transition has the value 9 while $\alpha = \alpha_L + \alpha_M + \alpha_N$ for the 47 Kev transition is approximately 30 or α_L alone has the value 18. Unfortunately there is no available calculation of values of M-conversion coefficients, the literature at present being limited to K- and L-conversion. Hebb and Nelson[49] list values of L-conversion coefficients from which we

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49. M.H. Hebb and E. Nelson, Phys. Rev., 58, 488, 1940.

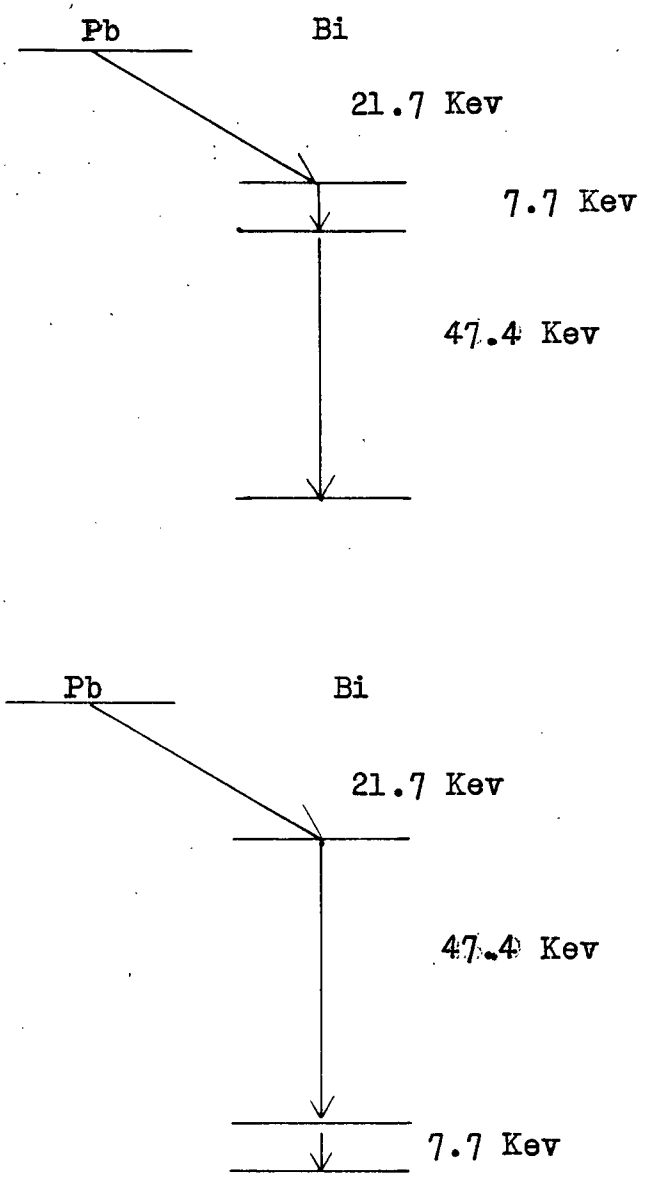

FIGURE 20.

SUGGESTED DECAY SCHEME FOR RADIUM D

would expect a value of $\alpha_L = 0.5$ for the 47 Kev transition if the spin change is 1 (Electric Dipole) and $\alpha_L = 38$ if the spin change is 2 (Electric quadrupole). Our cascade-gamma hypothesis then would identify the 47 Kev radiation as electric quadrupole if a choice has to be made. Now an estimate of the mean life-time of this state may be had (to one or two orders of magnitude) by using the relation of Segrè and Helmholz[50] where

$$\lambda_\gamma = \frac{e^2}{h}\left(\frac{w}{c}\right)^{2\ell+1}\frac{R^{2\ell}}{[(2\ell-1)!!]^2} = \frac{1}{\tau_\gamma}$$

R being the nuclear radius which we can take as $1.5 \times 10^{-3}\ A^{1/3}$. From this, $\tau_\gamma = 3 \times 10^{-10}$ seconds for $\ell = 1$ and $\tau_\gamma = 6 \times 10^{-3}$ seconds for $\ell = 2$. These of course are lifetimes by gamma emission only and hence the total lifetimes are probably much less than this since conversion is the predominant decay method on our basic assumption. It is improbable that ℓ is greater than 2 since this would mean a long lifetime, i.e. an isomeric state and would have been observed. Therefore, quadrupole radiation is not an unreasonable assignment for the 47 Kev transition. Unfortunately, for the reasons given above, no such guess may be made for the 7.7 Kev transition other than to suggest that because of its low energy even an assignment of $\ell = 2$ would probably produce a metastable state that is observable. This

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50. E. Segrè and A.C. Helmholz; Rev.Mod.Phys., 21, 280, 1949.

is of course possible and perhaps should it exist, its low energy might make its observation difficult.

In all the above, which must be classed as speculation based upon what evidence there is, we have been discussing the major transitions. Of other weak or doubtful transitions. little can be said. If they exist, they may be due to alternate branch transitions from the high energy excited state through intermediate levels to the ground state. Further discussion must await more precise and reproducible experimental results.

IV

CONCLUSIONS AND RECOMMENDATIONS

The experiment has shown that it is feasible to build a spectrometer to study beta and gamma spectra in the low energy region down to 2 Kev or less. The resolution as taken from high energy side of the 30 Kev peak in RaD is very close to the value calculated from the design of the spectrometer. It is unprofitable to try to increase the resolution of the instrument because of the line width produced by absorption in the source. In addition the resolution is limited under present conditions, mainly by the width of the source, and it would be difficult if not impossible to make sources much narrower than 1 mm.

A number of improvements to increase the reliability and ease of operation of the instrument can be suggested. First the baffles in the spectrometer should be redesigned so that new windows can be attached without removing the baffles and source from the instrument. Secondly the counters should be connected together outside of the apparatus so that they could be checked individually at any time and any faulty one or ones disconnected. Finally the 6AS7 regulator tubes should be monitored with a wattmeter in order to prevent overloading them.

With the method of attaching the counter windows now used it might be possible to make the entrance slits wider, say to 0.05 cms. This would increase the luminosity without changing the resolution appreciably. The problem of evaporating line sources on the backing should be investigated. This might be done

from a crucible of some sort as well as from a filament. Finally the problem of external quenching of the counters should be investigated more fully. Possibly with greater quench voltage and longer pulses an improvement in performance might be obtained.

APPENDIX I

THE SCATTERING AND ABSORPTION OF BETA-RAYS

The beta spectrum of radio-active substances as measured with the spectrometer, can be distorted in many ways by the scattering and absorption of electrons. If the spectrometer is set to observe a certain energy range the number of electrons counted may be reduced by some of them losing energy in passing through the material of the source and source backing, by scattering from molecules of the residual gas, by reflection (scattering through more than 90°) from the window of the counter and by absorption in the window. If the counter is of the end window type an electron may be absorbed in the counter gas between the window and the sensitive volume of the counter without being recorded. However, it has been shown[51] that with a side window counter the sensitive volume extends as far as the window. An increase in the number of electrons counted can be caused by electrons of higher energy losing energy in the source and backing and by reflection from the source supports, baffles and all other surfaces in the spectrometer.

A knowledge of the theoretical estimates of the magnitude of scattering and absorption effects and of the experimental work on the subject is useful in designing a low energy spectrometer since it is in the low energy region that the distortion becomes most troublesome.

An electron may be scattered by an atom in either of two ways: it may be deflected through a large angle by the nucleus

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51. S.C. Brown: Phys.Rev., 59, 954, 1941.

without loss of energy (elastic scattering) or it may be deflected through a small angle by an electron. For energies greater than 1000 e.v. and for low Z the second is always accompanied by a loss of energy and is called inelastic scattering. It can be shown that for elastic scattering the probability varies as

$$\left\{\frac{Ze^2}{M_o v^2}\right\}^2 \quad (1 - v^2/c^2)$$

Thus the probability of an electron being scattered is 10^8 times the probability of an alpha particle of the same velocity.

The thickness of counter windows used is such that a 'single scattering' theory can be applied, at least for energies greater than 50 Kev. The reflection of electrons from the windows is due almost entirely to elastic scattering and increases as the energy decreases. While this theory cannot be extrapolated to lower energies the 'plural scattering' theory yields similar results.

The reflection of high energy electrons from the walls of the spectrometer can take place through a large number of small angle deflection. Thus a 'multiple scattering' theory can be applied. Fermi[52] states that the root mean square angle of deflection of an electron after passing through a given thickness of matter of atomic number Z is approximately equal to Z divided by the kinetic energy of the electron.

Thus in any circumstance the scattering increases as the energy of the electrons decreases and as the atomic number

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52. E. Fermi, Nuclear Physics, p.37.

of the scattering material increases.

An electron loses energy by inelastic scattering, that is, by ionization of the atoms it encounters. Mott and Massey[53] give the following non-relativistic formula for the rate of loss of energy.

$$-\frac{dT}{dx} = \frac{4\pi e^4 N}{mv^2} \quad Z \ln\left(\frac{mv^2}{E}\right)$$

Where T is the kinetic energy of the electron.
x is the distance.
e is the electronic charge.
m is the electronic mass.
v is the velocity of the electron.
N is the number of atoms per cc. of absorber.
Z is the atomic number of the absorber.
E is the mean ionization potential of the absorber.

This formula is good for electron energies from 1 Kev to 50 Kev.

Integration of this should yield a value for the range of electrons of a given energy, but because of the tortuous paths followed by electrons it would be slightly greater than the maximum experimental range.

The most extensive experimental work on the absorption and scattering of electrons is that of Schonland[54]. With his apparatus he could measure the number of electrons reflected, absorbed, or transmitted by foils of a number of metals and of different thicknesses. He found the amount reflected to be 13% for Al, 29% for Cu, 39% for Ag and 50% for Au.

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53. N.F. Mott and H.S.W. Massey, The Theory of Atomic Collisions

54. B.F.J. Schonland; Proc.Roy.Soc. A104, 235, 1923.
A108, 187, 1925.

For a given energy of electrons, a value of the thickness of foil necessary to stop all but a few percent of the electrons, could be obtained from his curves. This value he called the range and found that it varied only slightly with the atomic number of the material of the foil. At twice the energy corresponding to a given range approximately 50% of the electrons were transmitted. A curve of range versus energy plotted from his results is shown in Fig. 21.

In the region below 10 Kev there are very few experimental values of the range of electrons. A paper by Tsien San-Tsiang[55] et al, gives the range of photo electrons ejected by weak X-rays in a low pressure cloud chamber from 1 Kev to 40 Kev. They define "le parcours" as the path length--the total distance an electron travels in its meanderings and "la portée" as the range--the distance in a straight line between the beginning and end of the track. There appeared to be a constant ratio of 0.67 between the r.m.s. values of the range and the path lengths.

The average path lengths were found to be very close to the values obtained by integration of the formula for energy loss mentioned above. The curve obtained by integration of this formula is plotted in Fig.21. It will be noticed that between 10 and 100 Kev the range as given by Schonland falls between this curve and another obtained by multiplying the ordinates by 0.67. Hence it seems reasonable to take the worst of the values as the range of electrons of a given energy. On this basis the range

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55. Tsien San-Tsiang, C. Marty and B. Dreyfus: Jour.de Phys. et Rad., 8, (Ser.8), 269, 1947.

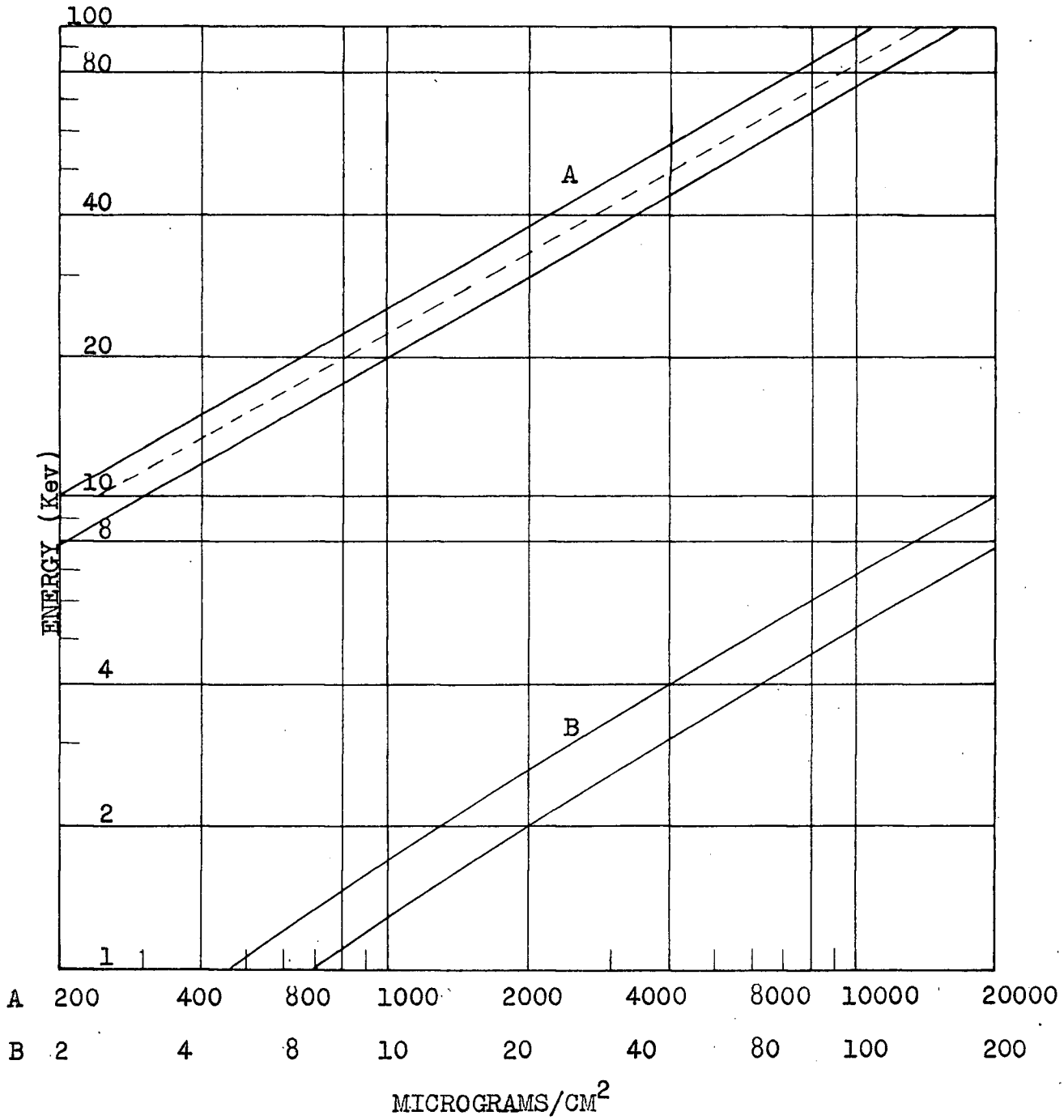

FIGURE 21.

RANGE OF ELECTRONS IN ALUMINUM AND IN AIR

Dashed line ..... Schonland values

Solid lines ..... San-Tsiang values

of a 1 Kev electron is about 5 micrograms/cm^2 and a window of this thickness should transmit 50% of electrons of 2 Kev energy, with some absorption to 5 Kev.

The loss of energy by electrons in an absorber is a statistical process. Some will lose more energy than the average amount, others less. Fig.22, taken from the work of White and Millington[56] shows the spread in energy of an originally monochromatic beam of electrons after passing through various thicknesses of absorbing material. This spread in energy is of no great importance in the determination of the thickness of counter window required but must be taken into account in the manufacture of the source and source backing.

Both theoretical and experimental studies of absorption and scattering indicate that there is no easy way over the difficulty. All possible scattering surfaces must be of as low an atomic number as is possible and care must be taken in the design of the baffles and supports to ensure that an electron must be scattered at least twice before entering the counter. The source backing and the counter window must be of low atomic number and as thin as possible.

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56. P. White and G. Millington: Proc.Roy.Soc., A120,701,1928.

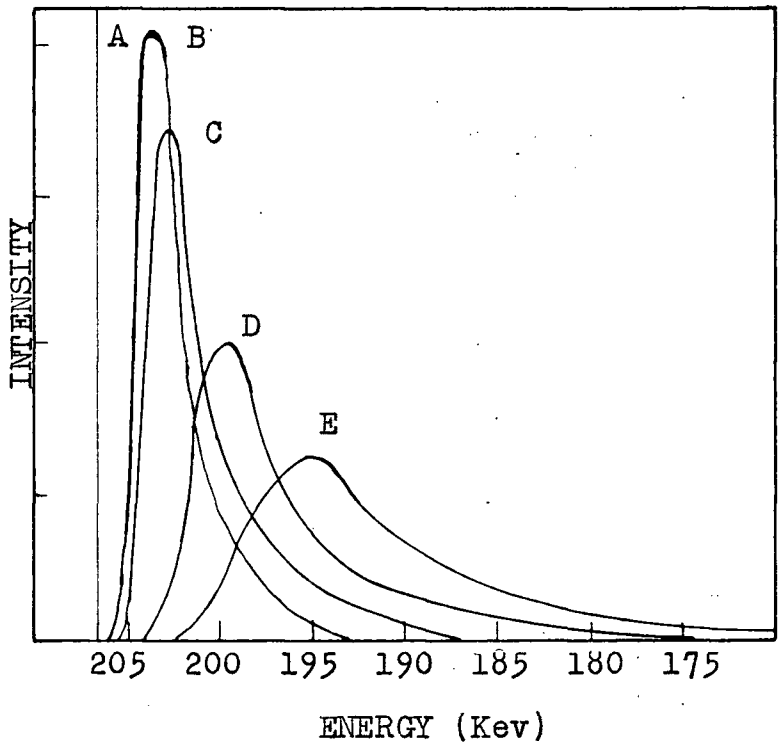

FIGURE 22.

LOSS OV ENERGY OF MONOENERGETIC ELECTRONS IN AN ABSORBER

A Energy of incident electrons

B Line profile after electrons pass through 2.25 milligrams/cm^2 of mica absorber

C Line profile after 2.65 milligrams/cm^2

D Line profile after 3.95 milligrams/cm^2

E Line profile after 5.72 milligrams/cm^2

APPENDIX II

COUNTER WINDOWS

A. Production of Counter Windows

The windows are produced by the method first published by Backus[57]. A few drops of a solution of zapon lacquer in amyl acetate are dropped on the clean surface of distilled water. The solution spreads out over the surface of the water and the amyl acetate evaporates leaving a thin film of zapon on the surface. This is picked up by means of a rectangular wire frame so that the film falls on both sides of it making a double layer. There appears to be a certain amount of art to picking up very thin films--a slight sidewise motion while lifting seems to help. Attempts were made to remove the human element from this process by lifting the films very slowly with mechanical device or by holding the wire frame underneath the film and allowing the water to run out very slowly. These attempts were not successful since films about 1/4 as thick could be lifted by hand.

The solution used is one part of zapon to two parts of amyl acetate. When 20 microliters of this solution is dropped on the water from a height of about 1 cm. it spreads over a circle about 30 cms. in diameter. The film can be cut in sections by moving a thin wire rapidly through it with an up and down motion. The sections are then picked up on the frames and hung on a rack to dry.

It was noted that some of the films produced had small

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57. See reference No.10.

streaks in them; these were evidently due to breaks or creases in one layer of the film and appear to be due to strains set up by the film collapsing around the end of the frame. The number of these streaks could be reduced by extending the top of the frame in both directions in order to provide a support. The quality of the films produced is also increased by not using solutions more than a week old and by using fresh distilled water. The zapon takes at least half an hour to dissolve in the amyl acetate and the process should be assisted by a certain amount of agitation.

The weight of the windows was obtained by weighing a microscope slide then placing several thicknesses of film on it and weighing again. From the area of the slide, the number of films, and the difference in weight, the number of gms/cm^2 of a single film could be calculated. This was checked by depositing 20 drops, each of the usual size, on a previously weighed glass plate. After the amyl acetate had evaporated another weighing determined the amount of solid material in the drops. From the area of the circle which one drop formed on the surface of the water, the average thickness of the film could be determined. The maximum difference in weights determined by these two methods was 50%. The thinnest films that could be produced were about 3 micrograms/cm^2 but it was found easier to work with those of 5 to 8 micrograms/cm^2.

B. Attaching of the Windows to the Counters

About a dozen films of approximately the same thickness are made and are hung on the rack to dry for an hour or so.

A solution of one part vinylite resin to one part of acetone has been previously made and to one part of this solution is now added two parts of amyl acetate. The old windows are stripped off the counters with scotch tape and the surfaces cleaned with amyl acetate if necessary. About 10 microliters of the vinylite solution is dropped on a surface of water and picked up with a wire frame in a similar manner to the zapon windows. The film formed is very elastic and the frame has to be manoeuvered so that the loose ends wrap around the handle of the frame. Immediately this vinylite film is picked up it is taken to the spectrometer and placed on the face of the counter. The entrance slit to the counter is cleaned out with a sharp corner of a piece of paper. As soon as possible a zapon film with no creases is selected from the rack and placed over the vinylite. When all the windows are on, the pressure inside the counters is reduced by about 1 cm. for a minute or two to help cement the windows in place. They are left to dry for half an hour and then checked by blowing in to the counters while a small gas flame about 1/4 of an inch long is passed in front of the windows. Most pinholes in the film can be readily detected by the deflection of the gas flame.

APPENDIX III

PREPARATION OF SOURCES

The source holder is made from a piece of 3/16 inch lucite 2 inches square. A rectangular slot 2 cms. long by .05 cms. wide is milled through the lucite with the back cut away at an angle of 45°, leaving a narrow edge around the slot. A hole is drilled in the lucite for mounting on the base plate of the spectrometer and a line scribed abross the middle of the slot to indicate the position of the source.

The source backings are made of LC600 resin[58] in a similar manner to the zapon windows. At first the resin was dissolved in LC600 thinner but it was found out that thinner and more uniform films could be made if it was dissolved in amyl acetate. The film is picked up on a frame made of 1/16 inch lucite and laid on the source holder while still wet.

A solution of one part of zinc insulin[58] to eight parts of distilled water is made and about 1/4 of a micro liter deposited with a pipette at each end of the film in line with the mark on the holder. The pipette is made from a .25 mm capillary tubing with the end pulled down to about 1 mm outside diameter and the hole to about 0.1 mms. The solution is brought up into the pipette and the end wiped clean with a paper towel. Careful blowing into the pipette makes the liquid bulge out of the end of the capillary without forming a drop. This is touched to the film and leaves a spot somewhat less than 1 mm. in diameter.

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58. L.M. Langer, R.S.I., 20, 216, 1949.

The source holder is now placed on a flat surface with one edge along a ruler. A refill from a ball point pen (ink removed) is lowered very slowly by means of a jig until the point just touched one of the drops of insulin solution. The holder is moved back and forth along the ruler until a line of insulin is formed. If a line does not form the pen is lowered a small amount and the process repeated until a line forms or the film breaks. If the insulin solution is sufficiently concentrated a line can be drawn every time without breaking the film.

When the source backing is completed the radio-active material is dropped on it in the form of a water or weak acid solution (concentrated hydrochloric acid does not appear to harm the LC600 films but concentrated nitric acid will burn holes in them in about 10 minutes time). The radio-active solution is deposited with a similar pipette to the one used for insulin.

This pipette is connected by rubber tubing to a balloon in a bottle in order to isolate the active solution. Another piece of rubber tubing connects the bottle to a mouthpiece which is fastened to a wire frame and hung on a hook so that it is never laid on the bench or touched with the hands. The active solution is deposited on the source backing in the same fashion as the insulin. When very small drops of about 1/4 microliter are placed on the backing the solution covers the area coated with insulin but does not spread onto the remainder of the film. The sources made were about 1.5 cms long by 0.1 cms wide. The source is slowly dried under an infra red lamp. The application of too much heat causes the backing to wrinkle and the holder to warp.

Two methods of grounding the source were used. The first was to put drops of aquadag on the holder and lead it along with a fine pointed brush until it touched the end of the insulin line on the backing. The aquadag then ran along the line of insulin until it touched the source. It is not certain that this method is reliable, some sources checked gave a resistance of about 1000 megohms between ends while others gave no detectable conduction.

The second method of grounding the source is to evaporate a thin layer of aluminum onto it. Aluminum layers were made which were about 90% transparent and had a resistance of 10,000 ohms over a distance of one inch provided a large area of contact was used. Attempts were made to weigh these aluminum films but all that could be determined was that they were less than 5 micrograms/cm^2. This thickness checks with the values given in Strong.[59]

The aluminum is evaporated from a filament made of three .015 inch tungsten wires. Two of the wires are twisted together with about 1 turn per centimeter and the third twisted around the other two with about five turns per centimeter. About 10 milligrams of aluminum is hung on the filament in the form of strips and preheated in a vacuum to insure contact. An attempt was made to do this preheating in illuminating gas but this proved unsuccessful.

Two small areas about 1/2 inch apart on a lucite plate were painted with aquadag and these areas connected to an ohmmeter

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59. J. Strong, Procedures in Experimental Physics, p.186.

outside the vacuum system. The lucite plate is placed near the source holder and as evaporation proceeds the resistance of the aluminum layer can be checked. By use of this method, evaporated layers have been made to any desired thickness with quite reproduceable results.

A great deal of trouble was encountered while evaporating aluminum onto very thin films. This was minimized by protecting the film with a baffle until the filament heated up and evaporation started. The baffle was then moved, by means of a magnet held outside the vacuum system. It was also very necessary to let the air in very slowly and to handle the holder with the utmost care.

APPENDIX IV

THE COUNTER FILLING SYSTEM

The counters at first were filled with alcohol vapor and argon in the usual mixture. However, the characteristics of the counters changed rapidly and this was found to be the result of the pressure changing due to gas slowly diffusing through the zapon windows. An attempt was made to keep the pressure reasonably constant by means of ballast flask but this was unsuccessful besides being uneconomical.

An obvious method of keeping the pressure in the counters constant is to use the saturated vapor of a liquid held at a constant temperature for a filling. Using this method the temperature of the liquid has to be lower than room temperature since otherwise the liquid would be distilled to other parts of the apparatus. The constant temperature that can be attained most conveniently is that of melting ice. A search was made for liquids whose vapor pressure at 0°C was 1 to 5 cms of mercury.

The first vapor tried as a counter fillinggas was that of pure ethyl alcohol at 1.2 cms pressure. This did not give any plateau and the counting rates were very unreliable. A number of other vapors such as methyl alcohol, benzene, and acetone were tried without success. In view of Farmer and Brown's[60] experiments with methane it was decided that hydro carbon compounds offered the best chance of success. Heptane (C_7H_{16}) has a vapor pressure of 1.15 cms at 0°C and a counter filled with its vapor gave a short but useful plateau shown in Fig.23. Its efficiency for gammas and

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60. E.C. Farmer and S.C. Brown: Phys.Rev., 74,902,1948.

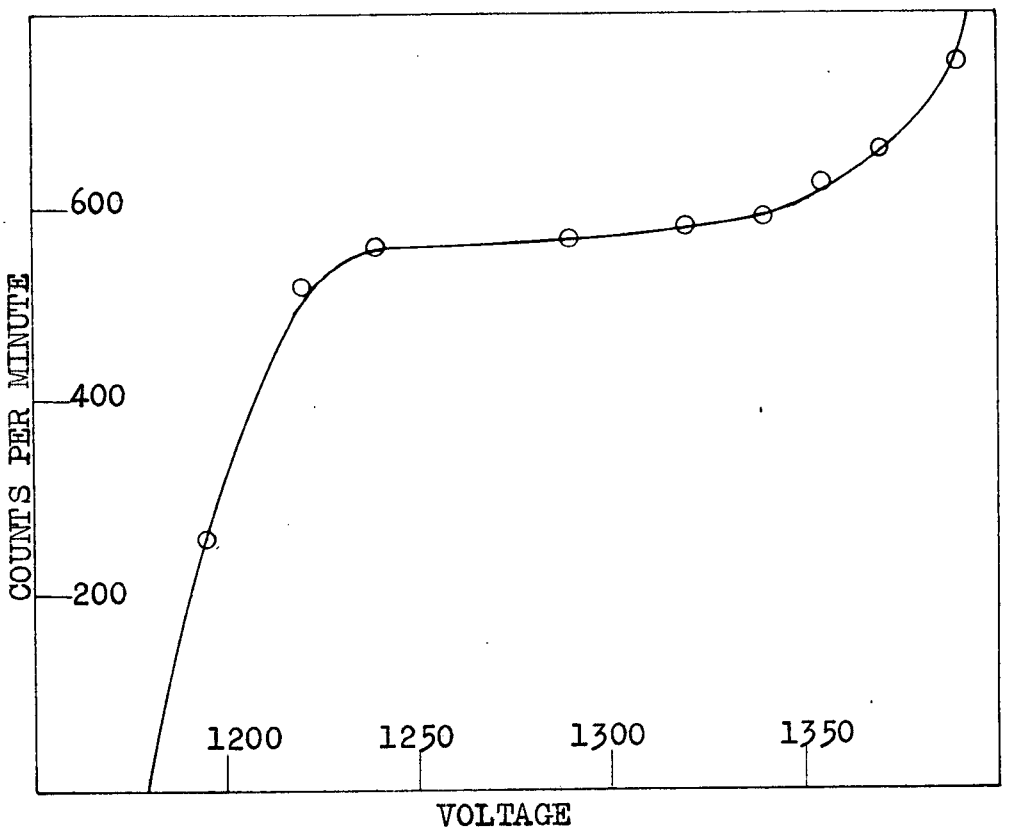

FIGURE 23.

PLATEAU EXHIBITED BY ONE COUNTER
FILLED WITH 1.15 CMS OF HEPTANE VAPOR

for high energy betas was the same as with an alcohol and argon filling.

The counter exhibited a rather long proportional region. It started counting with about 800V on the anode giving very small pulses, less than .01V. As the voltage on the counters was increased the maximum pulses increased in size but were accompanied by large numbers of smaller pulses. At a counter voltage of about 1250 volts the pulses were of a uniform size, about three or four volts peak amplitude with a rise time less than one microsecond and a length of about 50 microseconds. The Geiger region started here and extends to almost 1350 volts. The best plateaus obtained were with .005 inch tungsten wire as anode.

The counters in the spectrometer were then filled from a flask of heptane purified as follows: flask A in Fig.24 was almost filled with heptane and then connected to the vacuum system. About 1/10 of the liquid in A was carefully pumped away. It was then cooled to dry ice temperatures by means of an external bath and evacuation continued for about half an hour. At this point the stopcock was closed, isolating flasks A and B from the vacuum system and the cold bath moved to flask B. The heptane vapor evolving from the liquid in A passed through a drying agent and condensed in flask B. When about 1/10 of the heptane remained in A the process was stopped.

Flask B was then surrounded by a bath of melting ice and connected to the counters. The counters were checked individually and as one of them was unreliable, the other three were used in parallel; a plateau is shown in Figure 25.

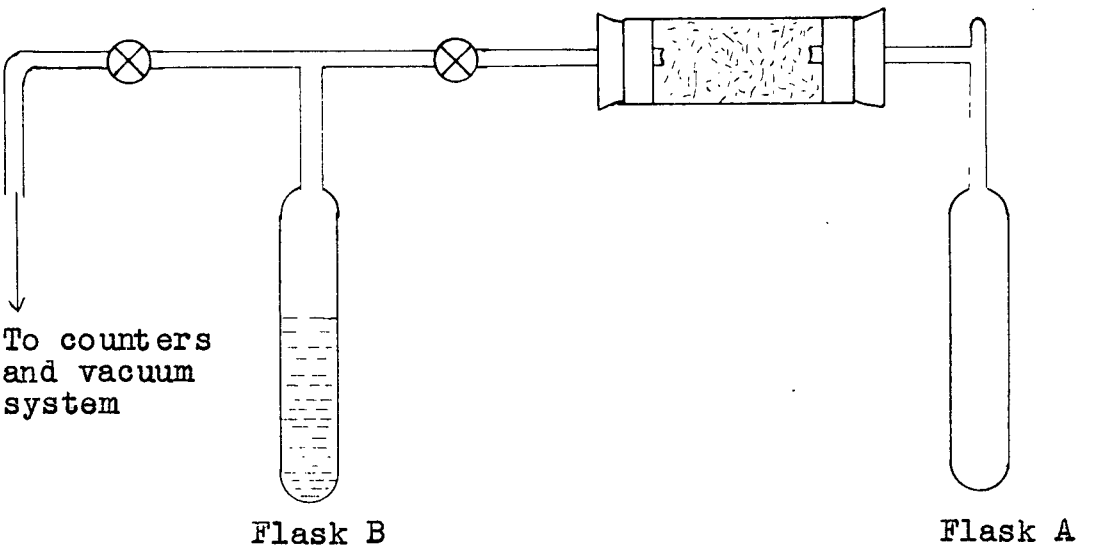

FIGURE 24.

HEPTANE PURIFICATION SYSTEM

(The heptane remains in Flask B and in operation is surrounded by a bath of melting ice.)

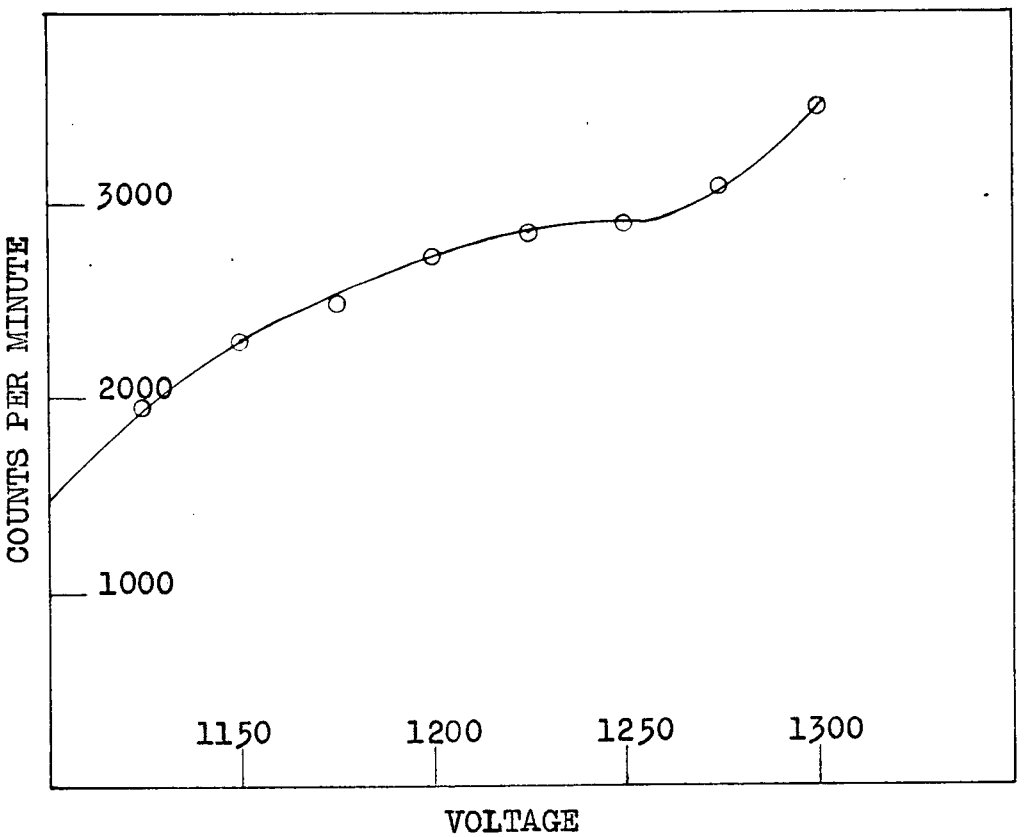

FIGURE 25.

PLATEAU EXHIBITED BY THREE COUNTERS IN PARALLEL

The counters worked very well at first but the plateau grew worse after a few months of use. Intermittent discharges gave occasional bursts of 50 to 100 counts in a second or two before the counters recovered. This appeared to happen most often in the last 30 seconds of a ten minute count.

An attempt was made to improve the performance of the counters by the use of external quenching circuits. A number of these circuits were tried, some with quenching pulses of 200 V amplitude and 400 microseconds duration, without the least success. The use of external quenching was abandoned and it was found that replacing the anode of the counters and thoroughly cleaning the cathodes with benzene and absolute alcohol restored them to their original condition.

APPENDIX V

AUXILIARY ELECTRONIC APPARATUS

A. Current Regulating System.

In order to observe a beta or gamma spectrum with the spectrometer it is essential that the magnetic field should not change of itself during the course of a single reading, and to realize the advantages of building the instrument without iron, means must be provided to set the current, and therefore the magnetic field, at any desired value. Since the resolution of the instrument is of the order of 1%, the magnetic field should be regulated to at least one part in a thousand and the calibration should be better than this.

The control system is quite straight forward, the current through the magnet also passes through a 'standard resistor' of about 0.1 ohms, made of 10 feet of 1 in. manganin strip. This resistor can carry the largest currents used with a temperature increase of less than 1°C, consequently its resistance will stay constant to almost 1 in 10^5. The voltage developed across the standard resistance is compared to a voltage determined by the setting of a Student's Potentiometer and the difference amplified 100 db. by a two channel amplifier. One channel amplifies the frequency range of0-10 cycles per second, the other 5-1000 cycles per second. The two signals are reunited at the grid of a 6L6 which in turn drives the grids of a bank of eight 6AS7's in series with the magnet and the standard resistor. At low fields the 6AS7's carry the full magnet current

but for higher settings they must be shunted by external resistors. These resistors were calculated on the basis that the power dissipation in the regulator tubes should not exceed their rated capacity of 168 watts. A series resistor was also included in the circuit so that low currents could be drawn safely from the 250 watt D.C. mains. If a current of less than 4 amperes is conducted through the tubes from a supply of more than 150 volts, serious damage will certainly result.

The calibration of the potentiometer is checked periodically by comparison with a standard cell. The magnet current is broken by throwing the main switch, the galvanometer sensitivity switch turned past 2 megohms to open the circuit and the 'voltage check' switch depressed. The potentiometer is adjusted to the voltage of the standard cell and the sensitivity of the galvanometer increased. The galvanometer is brought back to zero by manipulating the 'voltage adjust' controls.

A block diagram of the regulating system is shown in Fig.26 and a circuit diagram in Fig.27.

The potentiometer output voltage can be made to agree with the setting to 5 parts in 10^4 and the voltage across the standard resistor is held equal to this within one part in 10^4. Any deviations of low frequency can be observed by the action of the amplifier meters or by the galvanometer. During the original adjustment of the system a measurement was made of the amount of high frequency (greater than 30 cycles per second) A.C. passing through the coil. It was found to be about 1 m.a. over the range of D.C. currents and

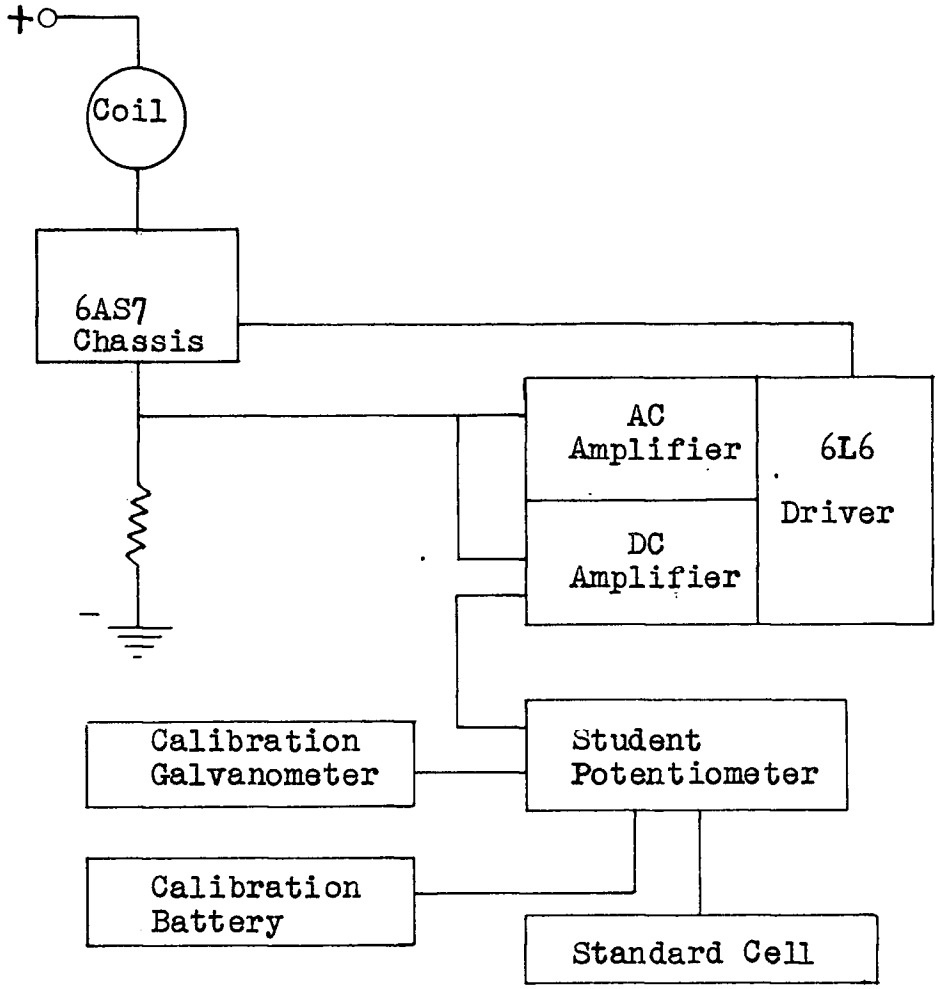

FIGURE 26.

BLOCK DIAGRAM OF CURRENT
REGULATING SYSTEM

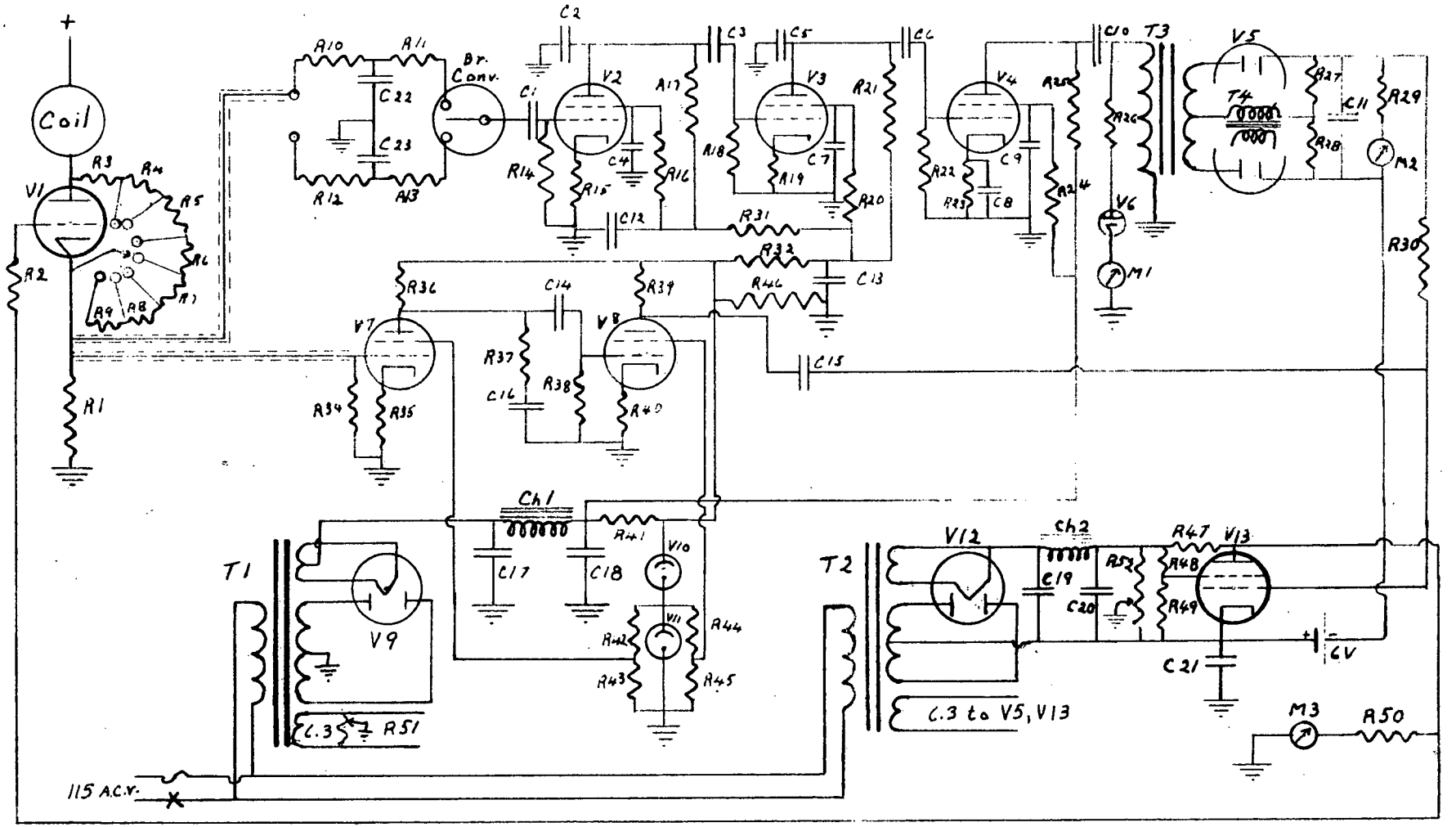

FIGURE 27.

CIRCUIT DIAGRAM OF CURRENT REGULATING SYSTEM

COMPONENTS OF FIGURE 27

Tubes

V1	8-6AS7's in parallel	V5	6H6	V10	VR105
V2	6SJ7	V6	1N34	V11	VR150
V3	6SJ7	V7	6SJ7	V12	5Y3G
V4	6V6	V8	6SJ7	V13	6L6
		V9	SY3G		

Meters

M1	100 microamperes full scale.
M2	1 milliampere, center reading.
M3	150 microamperes full scale.

Transformers and Chokes

T_1	Hammond 276	T_3	Hammond 337
T_2	" 270	T_4	" 51
Ch_1 and Ch_2	Hammond 10-100x		

Resistors (All 1/2 watt unless otherwise stated)

R1	St.r.about 0.1ohm	R18	1.5 M ohms	R35	3 K ohms
R2	1000 ohms	R19	3 K "	R36	500 K "
R3	12.8 " 1200 w.	R20	2 M "	R37	1 M "
R4	30.1 " 230 w.	R21	500 K "	R38	2 M "
R5	30.5 " 210 w.	R22	500 K "	R39	150 K "
R6	40.4 " 200 w.	R23	250 " 2 w.	R40	2.5 K "
R7	50.7 " 200 w.	R24	5 K "10 w.	R41	1 K " 2 w.
R8	8.0 " 200 w.	R25	5 K "10 w.	R42	30 K "
R9	11.5 " 190 w.	R26	150 K "	R43	40 K "
R10	30 K "	R27	50 K "	R44	30 K "
R11	20 K "	R28	50 K "	R45	40 K "
R12	30 K "	R29	100 K "	R46	100 K " 1 w.
R13	20 K "	R30	100 K "	R47	10 K "10 w.
R14	1 M "	R31	25 K "	R48	18 K " 5 w.
R15	3 K "	R32	50 K "	R49	7.5 K " 2 w.
R16	2 M "	R33	5 K "	R50	2 M "
R17	500 K "	R34	2 M "	R51	100 ohm pot.
				R52	100 K ohm pot.

Condensers

C1	0.1 mf	400 v.	C12	16 mf	450 v.
C2	.005 mf	500 v.	C13	16 mf	450 v.
C3	0.1 mf	500 v.	C14	1.0 mf	500 v.
C4	0.1 mf	500 v.	C15	1.0 mf	500 v.
C5	.005 mf	500 v.	C16	0.1 mf	500 v.
C6	.006 mf	500 v.	C17	30 mf	450 v.
C7	0.1 mf	500 v.	C18	30 mf	450 v.
C8	100 mf	50 v.	C19	30 mf	450 v.
C9	16 mf	450 v.	C20	30 mf	450 v.
C10	1.0 mf	500 v.	C21	30 mf	450 v.
C11	2.0 mf	500 v.	C22	1.0 mf	400 v.
			C23	1.0 mf	400 v.

thus is only 0.1% in the worst case.

B. H.T. Regulation.

Since the plateau in the counting rate curve of Heptane filled counters had considerable slope it was necessary to provide a very stable high voltage supply. Fig.28 is a circuit diagram of the regulating system finally developed.

The plate voltage of the amplifier tube (V2) is taken from the regulated side of V1 instead of the unregulated side. This results in considerably improved performance. The error signal fed into the grid of the amplifier tube is taken partly from the imput voltage and partly from the output. By adjustment of R18 and R19 the circuit can be made to under-compensate, over-compensate or regulate perfectly. R17 controls the screen voltage of V2 and thus the grid bias on V1.

The adjustment was made initially by feeding 6.3 volts A.C. in series with R1 and R2. The controls were set for a ripple in the output of less than 1 millivolt. With the circuit in operating condition there was no observable ripple in the output. The output voltage drifted about 3 volts per hour for 4 hours after the supply was turned on, after this any changes were of the order of 1 volt.

C. Pulse Amplifier and Scalar.

A circuit of the pulse amplifier is shown in Fig.29. The output of this circuit was fed into an Atomic Instrument Company scale of 64 scalar.

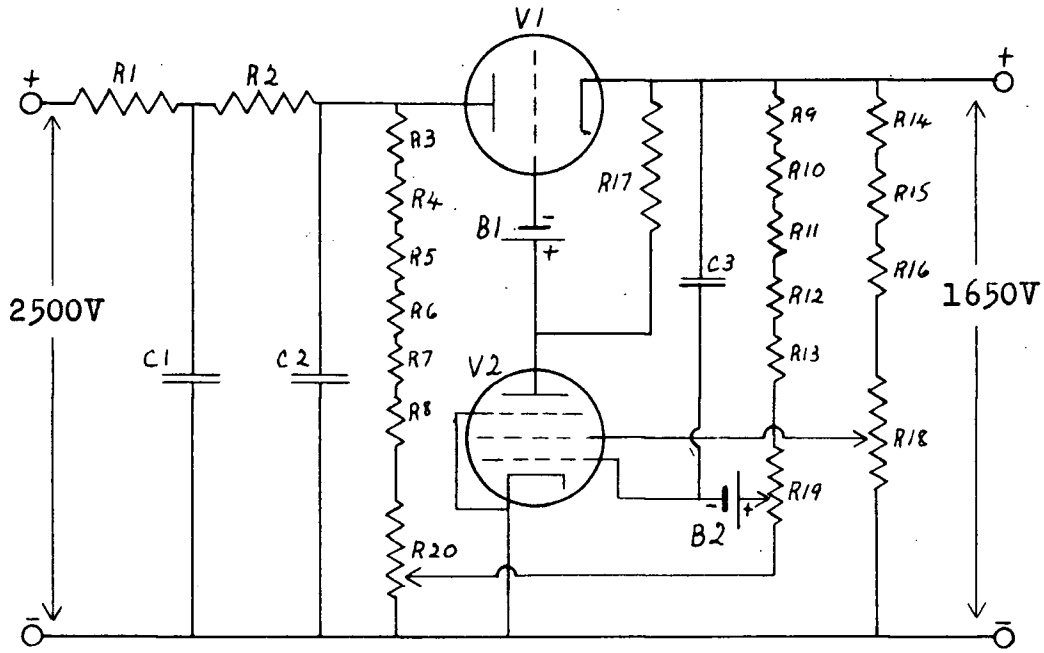

FIGURE 28.

H. T. REGULATING CIRCUIT

List of Components

V1 -- 6J5

V2 -- 6SJ7

R1, R2 -- 100 K ohm
R3-R13 -- 500 K ohm
R14-R16 - 1 M ohm

R17 -- 500 K ohm
R18 -- 100 K pot.
R19 -- 500 K pot.
R20 -- 500 K pot.

All resistors 2 watts

C1, C2 1 mf 3000 volts
C3 .01 mf 3000 volts

B1 90 volt battery
B2 300 volt battery

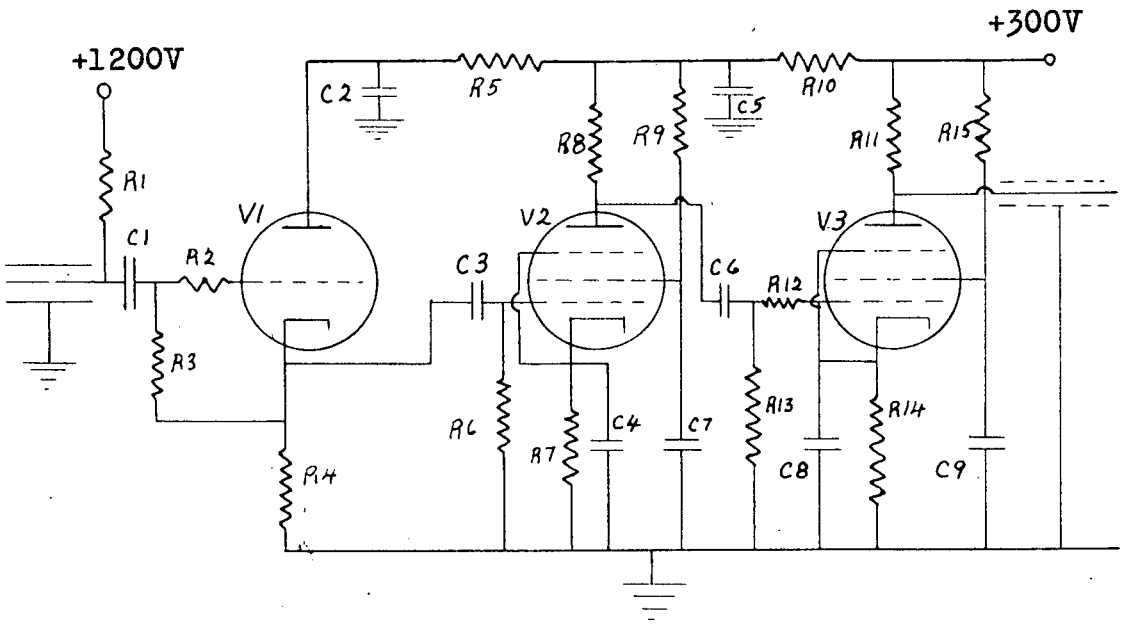

FIGURE 29.

CIRCUIT DIAGRAM OF PULSE AMPLIFIER

R1	1 M ohm	R6	50 K ohm	R11	1 K ohm
R2	50 ohm	R7	200 ohm	R12	1 K ohm
R3	330 K ohm	R8	5 K ohm	R13	100 K ohm
R4	10 K ohm	R9	60 K ohm	R14	200 ohm
R5	50 K ohm	R10	10 K ohm	R15	60 K ohm

All resistros 1/2 watt

V1	6J6	V2	6AK5	V3	6AC7

C1	.001 mf 2500V	C4	.1 mf 400V	C7	.001 mf 400V
C2	.002 mf 400V	C5	.01 mf 400V	C8	.1 mf 400V
C3	.0001 mf 400V	C6	.0001 mf 400V	C9	.001 mf 400V

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