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An Electron Lens Type of Beta-Ray Spectrometer*†

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A beta-ray spectrometer utilizing the focusing action of the homogeneous magnetic field produced by a long solenoid is described. The theory of the action of an instrument of this type is considered in some detail for the case of a point source of beta-rays, and the extension of the theory to cover the case of an actual source of finite area is discussed. Details of design are given, together with a number of experimental tests which have been made on the instrument. These tests include measurements of the absorption of beta-rays in the Cellophane window of the G-M counter used for detection, measurement of the resolution and efficiency of the spectrometer, calibration of the instrument, and an examination of the beta-ray spectrum of radium E. The beta-spectra of phosphorus ${}_{15}P^{32}$ and iridium ${}_{77}Ir^{194}$ have been investigated. The forms of the distribution curves all agree better with the Fermi than the K-U theory. It is concluded that the spectrometer operates satisfactorily and possesses some definite advantages over the conventional designs.

INTRODUCTION

THE most common methods for investigating beta-ray energies which have been in use for the past three decades are: (1) absorption measurements, (2) measurements with a cloud chamber in a magnetic field, and (3) measurements with a magnetic spectrometer essentially like the type developed by Rutherford and Robinson[1] in 1913.

The suggestion that a large solenoid might be used as an electron lens to focus beta-rays of determinate energy upon some sort of detecting device appears to have been first made by Kapitza[2] in 1923. In 1924 an instrument of this type was built by Tricker.[3] More recently Klemperer[4] has constructed an electron lens type of spectrometer, using the focusing properties of a flat coil.[5]

If one considers the operation of a spectrometer utilizing the electron lens properties of a solenoid, it soon becomes evident that, if a satisfactory instrument of this type could be designed, it would possess several marked advantages compared to the conventional spectrometer,[6] among which might be mentioned the following: (1) The efficiency of the spectrometer can be relatively high, since a larger solid angle at the source can be utilized without sacrifice of resolving power. (2) Source material can be distributed over the surfaces of thin films of collodion or some similar substance, covering an area much larger than that generally possible in the conventional type of spectrometer. It is thus possible for an instrument of this type to furnish data on materials whose activity cannot be concentrated sufficiently for use in the usual type. (3) Only one layer of absorbing material (the window of the G-M counter) is present in the electron path. (4) The source can be located relatively far from any scattering material except that of the source holder itself. (5) The relatively large distance between source and detector, together with the large amount of absorbing material interposed by a central baffle system, should practically eliminate detection of gamma-rays.

THEORY OF SPECTROMETER

A. General considerations

The theory of the action of magnetic electron lenses has been treated at length by various workers.[4, 7, 8] The present discussion is confined to

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[1] E. Rutherford and H. Robinson, Phil. Mag. **26**, 717 (1913).

[2] P. Kapitza, Proc. Camb. Phil. Soc. **22**, pt. 3.

[3] R. A. R. Tricker, Proc. Camb. Phil. Soc. **22**, 454 (1924).

[4] O. Klemperer, Phil. Mag. **20**, 545 (1935).

[5] A flat coil type of electron lens spectrometer has been constructed recently by M. Deutsch, Phys. Rev. **59**, 684A (1941).

[6] Witcher, O'Conor, Haggstrom and Dunning, Phys. Rev. **55**, 1135A (1939).

[7] W. Glaser, Zeits. f. Physik **109**, 700 (1938).

[8] J. H. McMillen and G. H. Scott, Rev. Sci. Inst. **8**, 288 (1937).

the simple treatment of a few of the relations which have the most direct bearing on the use of the uniform solenoid lens for the examination of beta-ray spectra.

We consider an electron which is initially projected with momentum p,

$$p = m_0\beta c/\sqrt{(1-\beta^2)}$$

in a direction making an angle α with the direction of a uniform magnetic field H. The electron's path will have the form of a circular helix of radius

$$\rho = (p/He)\sin\alpha \tag{1}$$

and pitch

$$L = (2\pi p/He)\cos\alpha. \tag{2}$$

If z denotes the displacement of the electron from the initial position in the direction of H, and r its displacement perpendicular to H, it is readily shown that:

$$r = (L/\pi)\tan\alpha \sin(\pi z/L). \tag{3}$$

To examine this equation it is convenient to introduce the variable

$$D = L/(\pi \cos\alpha) = 2p/He,$$

whereupon (3) takes the form:

$$r = D\sin\alpha \sin[z/(D\cos\alpha)]. \tag{4}$$

With the condition that the field H is initially fixed, this equation indicates (1) how r varies with z along the path of any particular electron (D and α constant), or (2) how, at a specified distance z from the initial position of the electron, the displacement r varies with departure angle α for electrons of the same momentum (z and D constant), or (3) how, for fixed z and α, r varies with electron momentum.

The first case is obvious, and case (3) need not be considered in this discussion.

As α increases from 0 to $\pi/2$, z and D constant, r starts from 0 and oscillates between a succession of positive and negative maxima, these being located at the values of α for which $\partial r/\partial\alpha = 0$. The zeros of $|r|$ lying between successive maxima are at the α values for which

$$z/(D\cos\alpha) = n\pi, \quad n = 1, 2, \cdots.$$

Physically, this behavior of $|r|$ corresponds to the fact that electrons with the same momentum, but leaving the source with larger and larger departure angles, may cross the plane determined by z during the first, second, third, etc., turns of their helical paths. Further investigation indicates that the successive maxima of $|r|$ in the direction of increasing α are consecutively greater, approaching the limiting value D as α approaches $\pi/2$. Physically this expresses the fact that, as α increases, the pitch of the helix contracts, its diameter becoming correspondingly greater. For $\alpha = \pi/2$, the helix becomes a circle of diameter $D = 2p/He$.

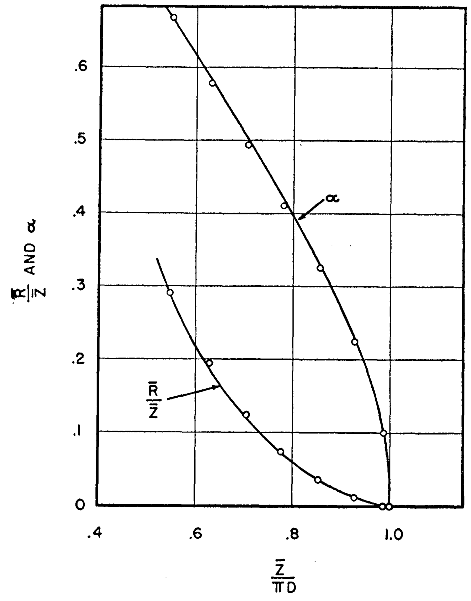

FIG. 1. Geometrical design functions.

B. Intensity and resolution for a point source

It is difficult to obtain a general treatment of the problems of intensity and resolution when the source of electrons has a finite area in the plane perpendicular to the magnetic field. However, the treatment for a point source may be used to suggest the features of the more general problem.

Consider a source at the point $(r, z) = 0$ emitting electrons with all possible momenta from 0 to some upper limit, the emission being assumed isotropic. We first wish to examine the distribution of the current arising from electrons whose momenta lie in the neighborhood of a given value p in the plane determined by assigning to z the value $\bar{z}$. From the analysis given above for the case z and D constant, it appears that at each

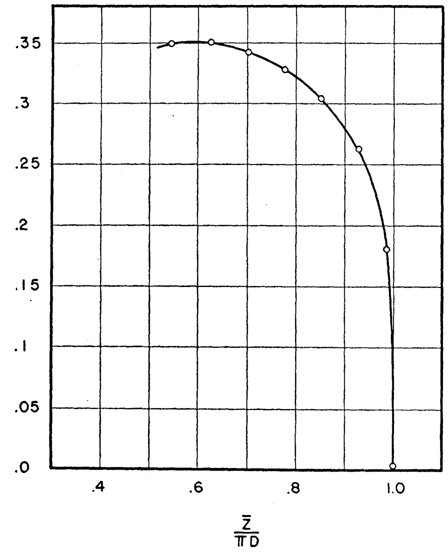

FIG. 2. Intensity function J.

value of r there will be contributions to the current arising from an infinite set of α values, extending from some definite lower limit to $\pi/2$. Let $I(r, \alpha)$ denote the contribution to the density of current at r due to any specified value of α from this set. Then $I(r, \alpha)$ must be proportional to $\sin\alpha$, and also to $\partial\alpha/\partial r$. It therefore follows that I will become infinite at the points where $\partial r/\partial\alpha = 0$, *viz.*, the maxima of $|r|$ as function of α considered previously. The current distribution due to electrons of the same momentum will therefore be characterized by the existence of a set of concentric "focal rings," upon which its density becomes infinite. The smallest ring will occur at the smallest value of r for which $\partial r/\partial\alpha$ vanishes. If this derivative vanishes concurrently with r, we may speak of a "point focus." We have, from (4):

$$\partial r/\partial\alpha = D\cos\alpha\sin[z/(D\cos\alpha)] + z\tan^2\alpha\cos[z/(D\cos\alpha)] = 0. \quad (5)$$

On setting $y = z/(D\cos\alpha)$, this gives:

$$\bar{\alpha} = \tan^{-1}\sqrt{[-(1/y)\tan y]}. \quad (6)$$

The symbol $\bar{\alpha}$ is used to identify the α value as that corresponding to a maximum of $|r|$. (It is convenient to consider y as a parameter in this and the succeeding two relations.) Combining the last relation with (4) and (5) and using $\bar{r}$ to denote the maximum value of r thus obtained, we have:

$$\bar{r}/\bar{z} = [(\sin y)/y]\tan\bar{\alpha}, \quad (7)$$

$$\bar{z}/\pi D = (1/\pi)y^{\frac{3}{2}}/\sqrt{(y - \tan y)}. \quad (8)$$

By use of the last three relations, with y as a parameter, the curves of Fig. 1 are obtained. These curves exhibit $\bar{\alpha}$ (corresponding to the *first* maximum of r) and $\bar{r}/\bar{z}$ as functions of $\bar{z}/\pi D$ from $\bar{z}/\pi D = 0.5$ to 1.0. ($\bar{\alpha}$ is plotted in radians, on the same scale as that of $\bar{r}/\bar{z}$.) If $\bar{z}$ is regarded as fixed, these curves indicate the variation of $\bar{\alpha}$ and of the radius of the first focal ring as functions of electron momentum. The first point focus occurs at $\bar{z}/\pi D = 1$, $\alpha = 0$. As $\bar{z}/\pi D$ decreases, this opens up into the first ring focus, as indicated in Fig. 1. For $\bar{z}/\pi D = 0.9$, $\bar{\alpha} = 15°$ approximately, and $\bar{r}/\bar{z} = 0.020$. For $\bar{z}/\pi D = 0.8$, $\bar{\alpha} = 22.5°$ and $\bar{r}/\bar{z} = 0.063$.

Intensity relations.—The current flowing through the annular area of radii $\bar{r} - \Delta r$ and $\bar{r}$ will be proportional to

$$\int_{\bar{\alpha}-\Delta\alpha_1}^{\bar{\alpha}+\Delta\alpha_2} \sin\alpha d\alpha \approx (\sin\bar{\alpha})(\Delta\alpha_1 + \Delta\alpha_2),$$

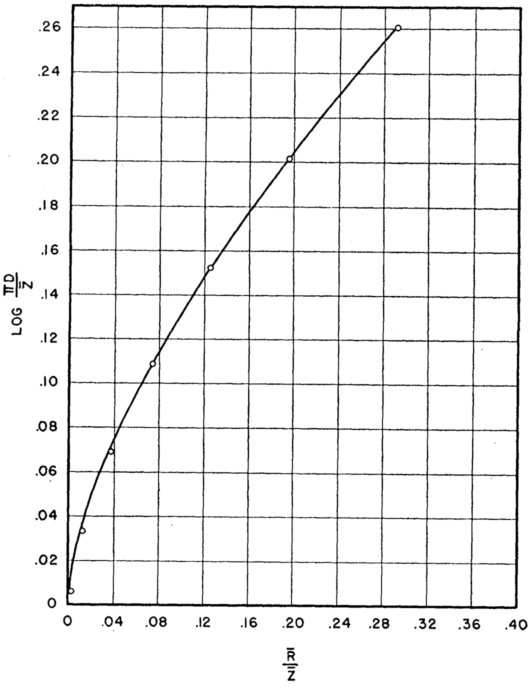

FIG. 3. Resolution function.

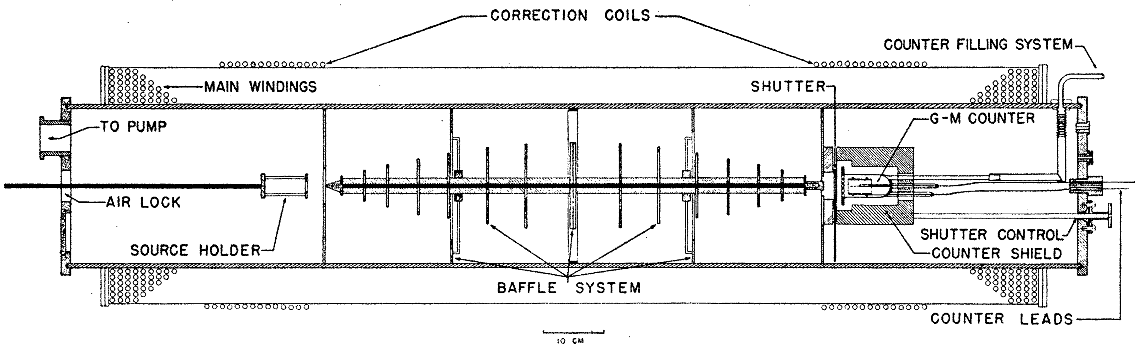

FIG. 4. Solenoidal beta-ray spectrometer.

where

$$\Delta\alpha_1+\Delta\alpha_2=2\sqrt{[-\Delta r/(\tfrac{1}{2})(\partial^2 r/\partial\alpha^2)_{\bar{\alpha}}]}. \quad (9)$$

The intensity function

$$J=\sin\bar{\alpha}/\sqrt{(-\partial^2 r/\partial\alpha^2)_{\bar{\alpha}}} \quad (10)$$

is plotted against $\bar{z}/\pi D$ in Fig. 2. This function gives an indication of the variation with $\bar{z}/\pi D$ of the current to be expected through a ring of constant width Δr and outer radius $\bar{r}$, $\bar{r}$ being the radius of the first focal ring. Note that J is a maximum at $\bar{z}/\pi D=0.6$, and that it begins to drop rather sharply above $\bar{z}/\pi D=0.85$.

Resolving power.—A convenient criterion of resolving power is the rate of variation of D (i.e., of electron momentum) with $\bar{r}$, expressed as a fraction of D itself. We accordingly consider

$$(1/D)(dD/d\bar{r})=(d/d\bar{r})(\log D). \quad (11)$$

In Fig. 3, $\log_{10}(\pi D/\bar{z})$ is plotted against $\bar{r}/\bar{z}$. The resolving power, as indicated by the slope of this curve, is greatest for $\bar{r}/\bar{z}=0$, decreasing rapidly until $\bar{r}/\bar{z}=0.10$, and then becoming approximately constant.

DESIGN OF SPECTROMETER

A. Design criteria

The utility of any beta-ray spectrometer will depend in general upon the following three criteria: (1) the range in energy over which the instrument can be used; (2) the sharpness of resolution; (3) the efficiency, as measured by the fraction actually detected of the beta-rays which leave the source with energies lying in the band passed by the instrument.

B. Maximum energy

Equation (2) in the form

$$HL/\cos\alpha=2\pi p/e$$

indicates that the maximum momentum (and hence the maximum energy) which it is possible to measure with an instrument of this type will depend on (1) the maximum obtainable field strength and (2) the length and diameter of the region in which the field can be considered uniform; i.e., the region between source and counter. In fact, the maximum energy increases with each of these factors.

C. Efficiency and resolution

From the theory outlined above, the electrons are brought to a focus at the plane $\bar{z}$ in a ring of radius $\bar{r}$. The geometry of the instrument may therefore be determined by a diaphragm provided with an annular slit of suitable radius and width equal to a small fraction of its radius, together with a baffle system which will allow only electrons with the correct angle of emergence $\bar{\alpha}$ to pass through the spectrometer.

The consideration of an extended beta-ray source in the form of a disk perpendicular to the magnetic field shows that the momentum values passed by the instrument are a function of (1) the distance from the axis to the initial position of the electron and (2) the azimuthal angle of its initial direction of motion. Since the resolving power decreases somewhat from the center of the source to its edge, the final design is a compromise between the resolution, the efficiency, and the area of the active material. Equation (4) and the curves in Figs. 2 and 3 permit approximate selection of the actual geometrical design factors for a given resolution and efficiency.

DESCRIPTION OF APPARATUS

A. General features of spectrometer

The general features of the spectrometer as finally designed[6] are shown in Fig. 4. Essentially, it consists of a long solenoid having the source of beta-radiation placed on the axis near one end and a G-M counter for detection placed 90 cm distant in the analogous position near the other end. Between source and counter are interposed a series of Duralumin disks and rings, which serve to specify, within definite limits, the dimensions of the helical paths which the electrons may follow in passing from source to counter.

The dimensions of the instrument were primarily determined by the power supply, a 600-ampere 30-volt d.c. generator, which was available before design of the spectrometer was begun. The theoretical considerations outlined indicate that for a specified power supply, the solenoid should be designed for (1) maximum field strength, (2) maximum length of homogeneous field region, and (3) maximum ratio of diameter to length.

B. Solenoid

The solenoid was made by winding six layers of $\frac{1}{4}$-inch diameter copper tubing (0.035-inch wall thickness) on a brass tube 10.5 inches o.d., 10 inches i.d., and 66 inches long. The actual length of winding is 60 inches, and there are 220 turns per layer. The tubing for each layer was fabricated in one piece (lengths ranging up to 700 feet) by the manufacturers and has double cotton insulation 4.0 mils thick. All six layers of the winding are connected in parallel electrically by bus bars and also in parallel hydraulically by manifolds. The waterflow through the coil at 50 lb./in.^{2} pressure is adequate for cooling under full load conditions (18 kw). To improve the homogeneity of the field inside the solenoid, correcting coils consisting of 90 turns of No. 12 wire were wound 12 inches from each end of the main winding. These correcting coils, together with a rheostat, are connected across the main winding.

Careful comparison measurements with a standard solenoid showed that this solenoid gives a field of 1.859 oersteds/ampere, corresponding to a field of 1115 oersteds with 600 amperes through the coil. Investigation of field distribution showed that the homogeneity of the field at all points between the positions of source and counter is better than 1 percent.

C. Baffle system

The construction of the baffle system is shown in Fig. 4. The positions and diameters of the disks forming the central baffle were calculated so that the edges of the disks lie on a surface of revolution formed by rotating about the axis of the instrument a sine curve of amplitude 7.16 cm and half-period 90 cm, starting from the source position. The middle diaphragms have openings whose edges lie on a similar surface of amplitude 12.5 cm and half-period 90 cm and intersecting the instrument axis at the same points as the previous surface. The over-all length of the baffle system is 82 cm, there being a space of 4 cm between the source position and the annular opening in the first ring. The edges of the annular slit at the counter end also lie on the two surfaces of revolution previously described, and the slit is 3 cm o.d. and 2 cm i.d. The resolution and efficiency of the spectrometer for a source of 2-cm diameter are determined almost entirely by this final annular slit.

The central series of disks, together with their spacers, are held together by a Duralumin rod which passes through them. This central disk system is supported by the outer system of ring baffles through the two sets of radial rods. The baffle system was made of Duralumin to minimize electron scattering, and the further precaution was taken of painting all surfaces with thick colloidal graphite (Aquadag).

D. Source holder

The source holder is designed to minimize all possible scattering from the support and to permit quick introduction through an air lock. In this spectrometer, the radioactive material may be deposited on an area 2 cm in diameter without materially reducing the resolution, which permits the use of very thin sources. The thin collodion layer on which the source is deposited is mounted on a thin aluminum ring 3.5 cm in diameter, which is in turn supported by three thin aluminum rods attached by a plate to the end of a rod which enters the instrument through a Neoprene seal of the type described by Wilson and Kamen.[9] The gate valve air lock is essential to facilitate quick operation without destroying the vacuum, since the vacuum must be maintained at about 10^{-4} mm Hg by an oil diffusion pump in order to prevent discharges from occurring between the G-M counter leads.

E. The G-M counter

A single G-M counter is adequate for this type of spectrometer. Coincidence methods are unnecessary, since gamma-radiation from the source can contribute virtually nothing because of the large distance from source to counter and the interposed baffles.

The design of the counter used in this spectrometer has necessarily been somewhat unconventional: (1) because the window through which the beta-rays were to enter had to be placed at one end of the counter rather than in the side wall, and (2) because it was desired to construct a window which should be at least 3.0 cm in diameter and as thin as possible. The final design adopted is shown in Fig. 5. The cylindrical copper cathode is 3 cm i.d. and 4 cm long, and the central wire is 4-mil tungsten with a glass bead on the free end.[10] A glass sleeve covers the counter wire to within 1.5 cm of the end in order to minimize the active volume and reduce the background. The counter windows used thus far have been of Cellophane 0.5 mil thick (1.75 mg/cm^2), but considerably thinner films of collodion may be used to facilitate more accurate measurements at low energies. The window is clamped between a brass ring and a 1.6 mm thick brass grille, a very thin rubber gasket being interposed between the ring and the Cellophane. This assembly is cemented to the front end of the counter with picein. (Note that the grille is on the outside of the Cellophane.) The grille was made by drilling holes 0.32 cm in diameter in a brass plate, and its open area is 73 percent.

A mixture of 9 cm argon, and 1 cm ethyl alcohol[11] has proved satisfactory for operation over periods as long as several weeks. The counter filling system with appropriate argon and alcohol reservoirs is permanently connected to the counter, but a stopcock operable through a Neoprene seal permits the counter to be isolated from the filling system.

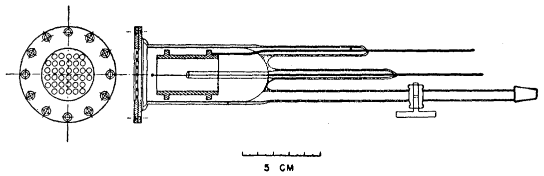

FIG. 5. G-M counter.

While the geometrical proportions of the counter were necessarily bad, very satisfactory operation at high speeds was achieved by a capacitance coupled multi-vibrator quenching circuit which is a modification of that described by Getting.[12] An amplifier tube preceding a biased low impedance multi-vibrator circuit resulted in positive operation under all conditions. A scale-of-eight demultiplying circuit utilizing three pairs of 6SJ7 tubes permitted counting at high rates. It was observed that much more satisfactory quenching of the counter pulses was obtained when the metal grille was held at about $\frac{1}{3}$ the potential of the anode.

When shielded by lead 2.5 cm thick to minimize stray radiation effects, the natural background of the counter system was approximately 10 counts/min. The counter threshold was approximately 1300 volts, and the "plateau" about 300 volts broad with a slight positive slope. Counter operation was regularly checked with a small radium source placed in a standard position, but over periods of many weeks no deviations were observed beyond those expected statistically.

As shown in the drawing, a shutter operable from outside was placed in front of the counter. Four holes in the shutter permitted absorption measurements to be made on selected materials for electrons having any desired energy.

F. Spectrometer power supply

The current for the solenoid windings from the 600-ampere 30-volt d.c. generator is stabilized by a voltage regulator similar to the type described

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[9] R. R. Wilson and M. D. Kamen, Phys. Rev. **54**, 1031 (1938).

[10] J. R. Dunning and S. M. Skinner, Rev. Sci. Inst. **6**, 243 (1935).

[11] A. Trost, Zeits. f. Physik **105**, 399 (1937).

[12] I. A. Getting, Phys. Rev. **53**, 103 (1938).

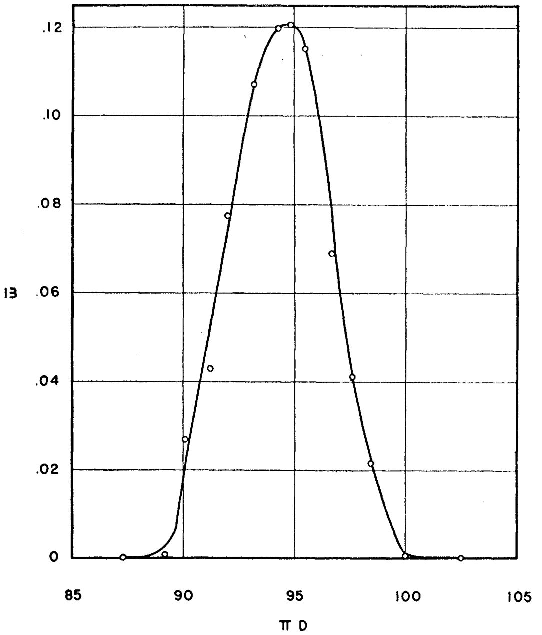

FIG. 6. Theoretical resolution curve and experimental points.

by Anderson, Dunning and Mitchell,[13] current fluctuations being not greater than 0.2 percent. Currents are measured by calibrated shunts connected to an ammeter or potentiometer.

EXPERIMENTAL TESTS OF INSTRUMENT

A. Test of resolving power—theoretical resolution

The *absolute* minimum and maximum values of πD (most convenient geometrical quantity for use in all discussions of resolution) can readily be calculated from Eq. (4), taking the source diameter as 2 cm and the baffle dimensions given previously. They are: $\pi D_{\text{min}} = 88.15$ cm, $\pi D_{\text{max}} = 100.19$ cm. The maximum and minimum starting angles for electrons are 23° 30′ and 12° 36′, respectively. What may be called the "resolution curve" of the instrument is obtained by a calculation of the effective solid angle $\bar{\omega}$, averaged over the entire source area, for electrons which pass through the baffle system as a function of πD over the range of this quantity. The ordinates on the theoretical resolution curve (Fig. 6) are the values (obtained by a process of numerical integration) of $\bar{\omega}$. The maximum value of $\bar{\omega}$ is approximately 0.122, giving a theoretical maximum efficiency of detection of approximately $0.122/4\pi = 1$ percent. The value of πD at the peak of the curve is 94.7 cm. The estimated error in $\bar{\omega}$ introduced by numerical approximations does not exceed 1 percent in the neighborhood of the maximum of the curve and 4 percent near the extreme ends of the curve.

Experimental resolution.—To obtain an experimental test of the resolution of the instrument, the well-known beta-ray line of Th B+C+C′+C″ at $H\rho$1387.5 (mean value from the measurements of Ellis[14] and Wang[15]) was used.

The source was prepared by collecting recoil nuclei from thoron on a collodion film 1 to 2 microns thick. The deposit was confined to an area 2 cm in diameter by a diaphragm shield with a negatively charged collecting disk immediately behind the film, the holder itself being positively charged to minimize collection outside the desired source area.

The plotted points of Fig. 6 show the results of the experimental resolution measurements on the Th B line. The statistical error in $\bar{\omega}$ is approximately 1 percent at the peak, and the continuous beta-ray spectrum has been allowed for by subtracting its contribution, which is approximately 20 percent in the neighborhood of the line.

The agreement between the theoretical resolution curve and the experimental points (which have been matched at the peak) is seen to be very good. The total range of πD is about 12.5 percent of the mean value (94.7 cm), but 80 percent of the area of the experimental curve lies within a band extending about 3 percent on each side of the peak. Higher resolution may readily be obtained by redesigning the baffle system as suggested previously with smaller annular slits. The present baffle system, however, represents a good compromise between reasonably high resolution and large effective solid angle.

B. Test of spectrometer efficiency

The efficiency of the spectrometer was determined approximately by direct measurement in the following way. The number of α-particles

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[13] Anderson, Dunning, and Mitchell, Rev. Sci. Inst. **8**, 497 (1937).

[14] C. D. Ellis, Proc. Roy. Soc. **138**, 318 (1932).

[15] K. C. Wang, Zeits. f. Physik **87**, 633 (1934).

emitted per second from a Th B source of the type described was first directly measured by counting, with a linear amplifier-ion chamber system, the number of particles emerging through a small foil-covered hole (of known diameter) at the end of a long evacuated tube which contained the source at a measured distance from the hole. The number of beta-particles emitted per second in the line $H\rho 1387.5$ could then be calculated by using the present accepted value for the coefficient of internal conversion for that line ($P\alpha = 0.25$). The number of electrons actually detected in the line when the source was placed in the spectrometer (after allowing for the opaque section of the brass counter grille) was then determined. These results gave a value for the effective solid angle in reasonably good agreement with the peak value of 0.12 shown in Fig. 6. The large solid angles for which the lens spectrograph should be effective were therefore achieved.

C. Correction for absorption in counter window

The absorption of electrons in the counter window was determined by making measurements of the transmission through 0, 1, 2, and 3 additional layers of 0.5-mil Cellophane, when these were interposed in front of the counter by means of the shutter system described. Figure 7 shows the correction factors by which the observed counting rates are to be multiplied, as obtained by extrapolation of the data for eight values of electron momentum to zero total absorber thickness. These correction factors should be fairly reliable down to $H\rho$ 854, but are probably not trustworthy below this value, although some electrons are still passing through the foils at $H\rho$ 640.

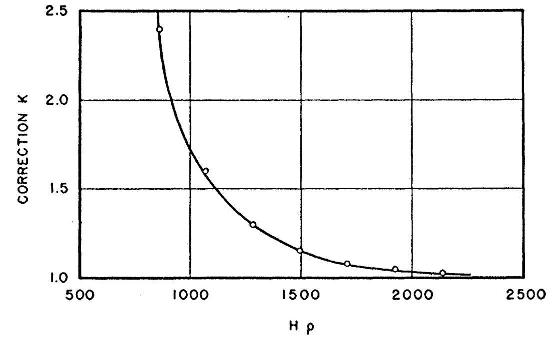

FIG. 7. Correction factor for counter window absorption.

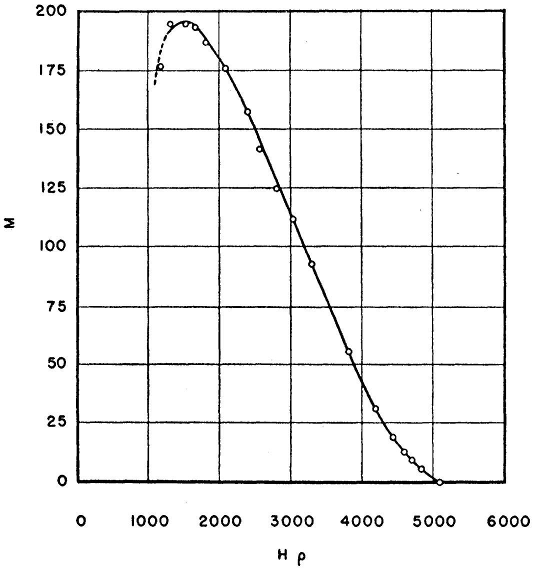

FIG. 8. Radium E spectrum.

There is little evidence for scattering in the baffle system. With zero field, no counts above background are observed.

D. Magnetic field measurements and calibration

Measurements of the field within the solenoid at various points, both on and off the axis, were made by a flip coil which had been calibrated previously with a standard solenoid. These measurements gave for the field at the center of the solenoid a value of 1.830±2 percent oersteds/ampere. As stated previously, the homogeneity of the field was better than 1 percent throughout the region between source and counter.

If we take $\pi D = 94.7$ cm at the peak of the resolution curve and use 1387.5 for the $H\rho$ value of the Th B line, a comparison determination of the field may be obtained. If πD is assumed to be reliable to within ±0.2 percent, the value of 1.859±0.4 percent oersteds/ampere is obtained. This is considered to be reasonable agreement with the previous value.

The value 1.859 oersteds/ampere obtained from the Th B line has been used as a standard for the subsequent spectrometer measurements. The maximum field obtainable with the present power supply is thus 1115 oersteds at 600 amperes, corresponding to a beta-ray energy of 4.44 Mev.

It should be noted that in such an instrument the effect of the earth's field (or other stray fields) cannot be completely neglected in the very low energy region. The axis of the instrument has been placed in the direction of the horizontal component of the earth's field to minimize any effect due to this component. There is no evidence that the operation of the instrument is appreciably affected by the vertical component of the earth's field at the lowest energies so far used (100 kev.) However, a compensating coil for the vertical component is being installed for work down to 10 to 25 kev.

INVESTIGATION OF BETA-SPECTRA

A. Measurements on radium E

The beta-spectrum of Ra E was selected for a general test of the spectrometer, since so many data are now available on it.

The Ra E source was prepared from a purified Ra D+E+F solution by successive deposition on Ni foil followed by successive solutions in hot HCl to insure freedom from Ra D. The final highly purified Ra E solution was distributed as uniformly as possible over a 2-cm diameter area in the center of a thin collodion film mounted on the source holder.

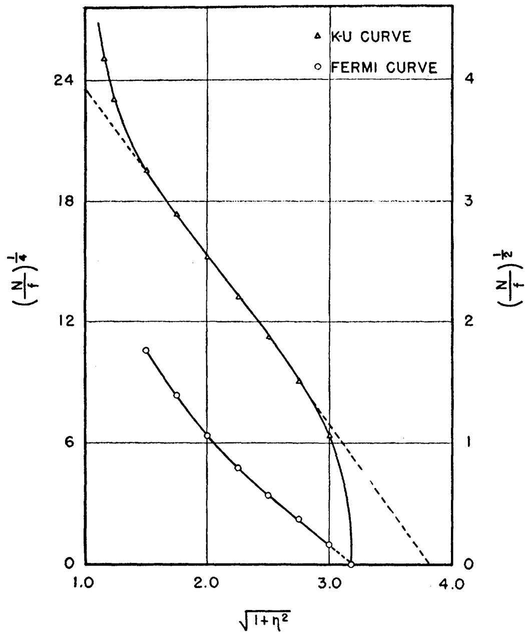

FIG. 9. Fermi and K-U plots for radium E.

Figure 8 shows the data obtained with such a source after correcting for counter window absorption. The individual points have a statistical error of 2 percent or less. Knowing the form of the resolution curve of the instrument, one can accurately determine the upper end point of any beta-spectrum by a process of successive approximations, provided that the source is reasonably strong. The value of the end point for the Ra E spectrum, after account is taken of the effect of the resolution curve, was computed to be $H\rho$ 5100 (1.11 Mev), corresponding to a total energy of 3.18 in m_0c^2 units. Plots of these data on the basis of the Fermi[16] and Konopinski-Uhlenbeck[17] theories are shown in Fig. 9. Neither theory is seen to give a straight line over the complete range of the data, but the Fermi plot is much better. The extrapolated K-U end point is at a total energy of $3.83m_0c^2$ units, in excellent agreement with the results of Flammersfeld,[18] Neary,[19] and other recent measurements.[20,21] These tests with Ra E indicate that the instrument can be regarded as reliable at least above $H\rho$ 1300 (135 kev).

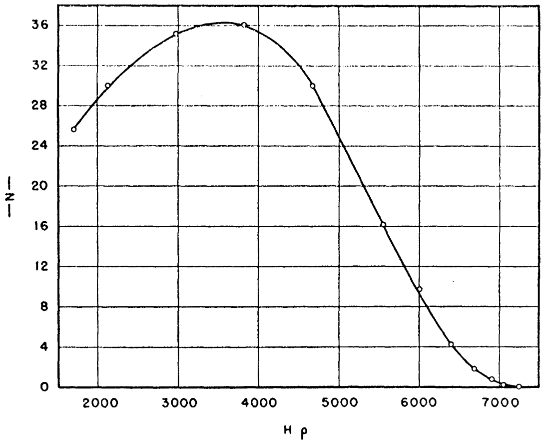

FIG. 10. Spectrum of $_{15}P^{32}$.

B. Beta spectrum of $_{15}P^{32}$

The source of $_{15}P^{32}$ was prepared by distributing a few drops of dilute Na_2HPO_4 solution

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[16] E. Fermi, Zeits. f. Physik **88**, 161 (1934).

[17] E. J. Konopinski and G. E. Uhlenbeck, Phys. Rev. **48**, 7 (1935).

[18] A. Flammersfeld, Zeits. f. Physik **112**, 727 (1939).

[19] G. J. Neary, Proc. Roy. Soc. **175**, 71 (1940).

[20] L. H. Martin and A. A. Townsend, Proc. Roy. Soc. **A170**, 190 (1939).

[21] J. S. O'Conor, Phys. Rev. **52**, 303 (1937).

containing the active phosphorus over the source film, as in the case of Ra E. Some of the $_{15}P^{32}$ was kindly supplied by Professor E. O. Lawrence and his associates during a period when the Columbia cyclotron was not in operation. In all sources, the activity of the phosphorus was such that the total weight of the deposit over an area 2 cm in diameter was less than 0.5 mg.

The results of the measurements are shown in Fig. 10, where the statistical error of the points is less than 1 percent. The observed end point is at $H\rho$ 7357 (1.75±0.02 Mev). This is in good agreement with values since published, of Lawson[22] (1.72 Mev) and Lyman[23] (1.70±0.04 Mev).

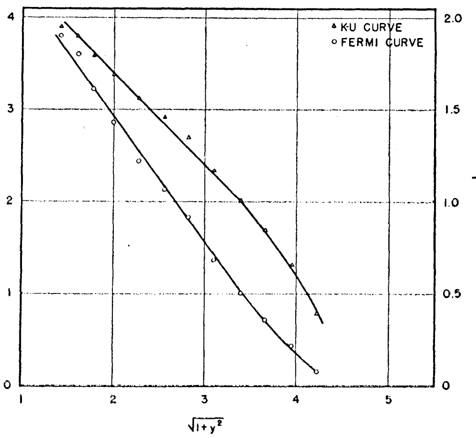

FIG. 11. Fermi and K-U plots for $_{15}P^{32}$.

The Fermi and K-U plots for $_{15}P^{32}$ are shown in Fig. 11. Again neither are straight lines over the entire range, although the Fermi plot is nearly so and shows less departure at the upper end.

C. Beta-spectrum of $_{77}Ir^{194}$

The source of $_{77}Ir^{194}$ was prepared through a concentration process of the Szilard-Chalmers[24] type developed by Dr. J. Steigman.[25] Approximately 5 g of Ir in the form of a Werner complex compound of iridium and ethylene diamine were irradiated with neutrons from the cyclotron. After separation of the active Ir as Ir metal with approximately 1 mg Ir as a carrier, the active material was deposited as a colloidal suspension on the source film.

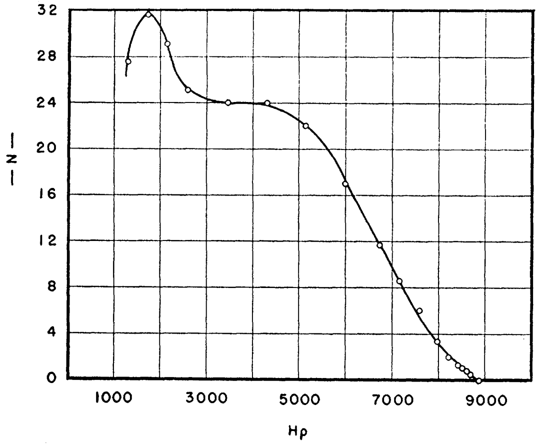

FIG. 12. $_{77}Ir^{104}$ spectrum.

The spectrum obtained is shown in Fig. 12, where the points have a precision of at least ±2 percent. The end point is concluded to be at $H\rho$ 8870 (2.18±0.04 Mev), in fair agreement with previous estimates by other methods.[26] The curve strongly suggests that the spectrum is complex. If only one weak lower energy group is assumed, its end point would correspond to 3000 to 3500 $H\rho$. Measurements of the half-life in various parts of the spectrum gave the same value, 19.5 hours, to within the limits of error.

The Fermi and K-U plots for Ir in Fig. 13 indicate the Fermi plot to be very straight in the upper region. A complex spectrum is likewise suggested by these plots.

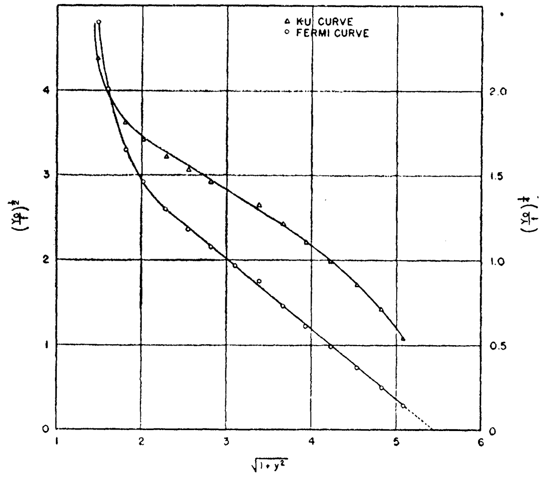

FIG. 13. Fermi and K-U plots for $_{77}Ir^{194}$.

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[22] J. L. Lawson, Phys. Rev. **56**, 131 (1939).

[23] E. M. Lyman, Phys. Rev. **51**, 1 (1937).

[24] L. Szilard and T. A. Chalmers, Nature **134**, 462 (1934).

[25] J. Steigman, Phys. Rev. **59**, 498 (1941).

[26] M S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 359 (1937).

A series of measurements of the absorption of the Ir beta-rays in Al were made using an ion chamber with 1-mil aluminum window filled with Freon (CCl_2F_2) at 1 atmosphere, and which was connected to an FP-54 amplifier. The range obtained was 0.970 ± 0.030 g/cm^2. From Feather's empirical range-energy relation, as recently corrected by Widdowson and Champion,[27] we have energy (Mev) $= [0.165 \pm \text{range (g/cm}^2)]/0.536$. This gives a value of 2.11 ± 0.07 Mev for the end point, in good agreement with the spectrometer value. The absorption curve gives evidence for the presence of a soft gamma-radiation almost completely stopped by 3-mm of Pb.

The author would like to express his sincere thanks to Professor J. R. Dunning for the suggestion of designing the lens spectrometer described here, and for his constant advice and encouragement. He is likewise indebted to Dr. C. J. Davisson of the Bell Telephone Laboratories for his invaluable contributions to the theory outlined. The cooperation of Mr. M. Hartley Dodge and Mr. W. W. Kelley in supplying the copper tubing and the brass cylinder for the spectrometer is gratefully acknowledged.

The author wishes to express his sincere appreciation of the assistance given him throughout the work by his co-workers Miss E. Haggstrom and Father J. S. O'Conor; of the aid given by Dr. J. Steigman and Dr. A. V. Grosse in the chemical processes, and to the many others in the Department of Physics who have helped in designing and building the instrument.

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[27] E. E. Widdowson and F. C. Champion, Phys. Soc. Proc. **50**, 185 (1938).

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The Scattering of One- to Three-Mev Protons by Helium

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The scattering of protons of from one- to three-Mev energy by helium has been experimentally examined for the existence of resonance scattering analogous to the neutron-helium resonance observed for one-Mev neutrons by Staub and Stephens. If *n-n* and *p-p* nuclear forces are equal, such a resonance should occur in *p*-He scattering for protons of approximately two Mev. The number of protons scattered through 140° were observed as a function of their energy. This number passed through a maximum at two Mev as expected, but the sharpness and height of the maximum were several times less than for the *n*-He resonance. However, this greater width and lesser intensity can be qualitatively justified. The number of protons scattered through 76° did not show the presence of a resonance scattering as the energy was varied. Observations of the angular distribution of the scattered protons for angles of scattering between 30° and 140° for proton energies of 1.0, 1.5, 2.0, 2.5 and 3.0 Mev, respectively, have been obtained.

Introduction

PROTON-helium scattering experiments for protons of energy one- to three-million electron volts are of especial interest because of the similarity of the proton-helium scattering problem to that of neutron-helium scattering. The dependence of the neutron-helium scattering cross section upon the neutron energy has been investigated experimentally by Staub and Stephens.[1] They have found that the ratio of the *n*-He cross section for the production of recoils to the similar *n-p* cross section is a maximum for neutrons of about one-Mev energy. This maximum they attribute to a resonance in the compound He^5 nucleus. The existence of this large amount of scattering of one-Mev neutrons by He has since been confirmed by a number of workers,[2]

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[1] H. Staub and W. E. Stephens, Phys. Rev. **55**, 131–139 (1939).

[2] E. Hudspeth and H. Dunlap, Phys. Rev. **57**, 971–975 (1940).