BETA-RADIOACTIVITY OF 5·3 YEAR Co^{60}.

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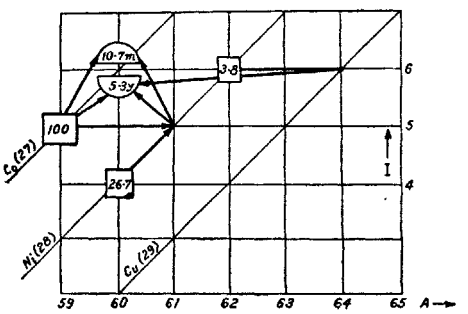
ABSTRACT.

A 180° *M-F* type of β-ray spectrometer has been set up in this laboratory and the constants of this instrument have been calculated according to a method proposed by A. K. Saha. The β-radiations of the 5·3 year period Co^{60} have been examined with it. The energy spectrum of these β-radiations was deduced from the experimental $N(H)$ curve by the method of Lawson and Tyler. The Kurie plot of these radiations showed that the Fermi formula is definitely valid. The value of the end point energy as deduced from the Kurie plot was found to be ·23 Mev. This is somewhat different from the value of ·30 Mev found by Deutsch *et al.* by the short magnetic lens type of β-ray spectrometer. The *ft* calculations indicated that the β emission of this nucleus belongs to the 2*B* class of Konopinski. Certain features of interest about Co^{60} from the point of view of nuclear stability have been discussed.

§1. *Introduction.*—The element Co has only one stable isotope Co^{59}, and a number of radioactive isotopes have been prepared in the laboratory. These are Co^{55}, Co^{56}, Co^{57}, Co^{58} and Co^{60}. The isotope Co^{57} was formerly supposed to be stable, having a frequency of about ·2%. But recent mass spectrographic studies of Mitchell, Brown and Fowler (1941) have completely disproved this, verifying a prediction of Saha, Sirkar and Mukherji (1940) on the basis of certain empirical rules of nuclear stability observed by them.

The β and γ-ray activities of the isotopes of Co have formed the subject of numerous investigations. We have in this paper examined the β-rays of the isotope Co^{60} having the half-life 5·3 years. The Co^{60} isotope has many interesting features and it is quite worth while to study it in detail. It is quite well known that this isotope has two isomeric states—one with a half-life 10·7 minutes and the other with a half-life 5·3 years. The methods of production of this isotope are illustrated in



The isotopes characterised by squares are stable and the figures given within the squares indicate percentage abundances.

FIG. 1. Transmutation Chart of Co^{60}.

the Saha, Sirkar and Mukherji chart as follows (fig. 1). The yields of the reactions Co^{59} (n, γ) and Ni^{60} (n, p) are not much, but that of the reaction Co^{59} (d, p) is several

thousand times greater. The sample examined by us has been prepared by the Co^{59} (d, p) reaction at the M.I.T. cyclotron laboratory at the request of Prof. M. N. Saha.

The disintegration schemes of the two isomeric states have been determined by Nelson *et al.* (1942) and Deutsch and Elliot (1942). According to absorption measurements of Nelson *et al.* each β-ray from the 10·7 min. Co^{60} is accompanied by the emission of one γ-ray. They measured also the end point energy of the β-rays with an *M-F* spectrometer and found that it was $1{\cdot}35\pm{\cdot}1$ Mev. The energy of the γ-ray was found to be $1{\cdot}5\pm{\cdot}2$ Mev. They studied also the 5·3 year period radiations and this was found to consist of a $1{\cdot}7\pm{\cdot}2$ Mev γ-ray and a negatron

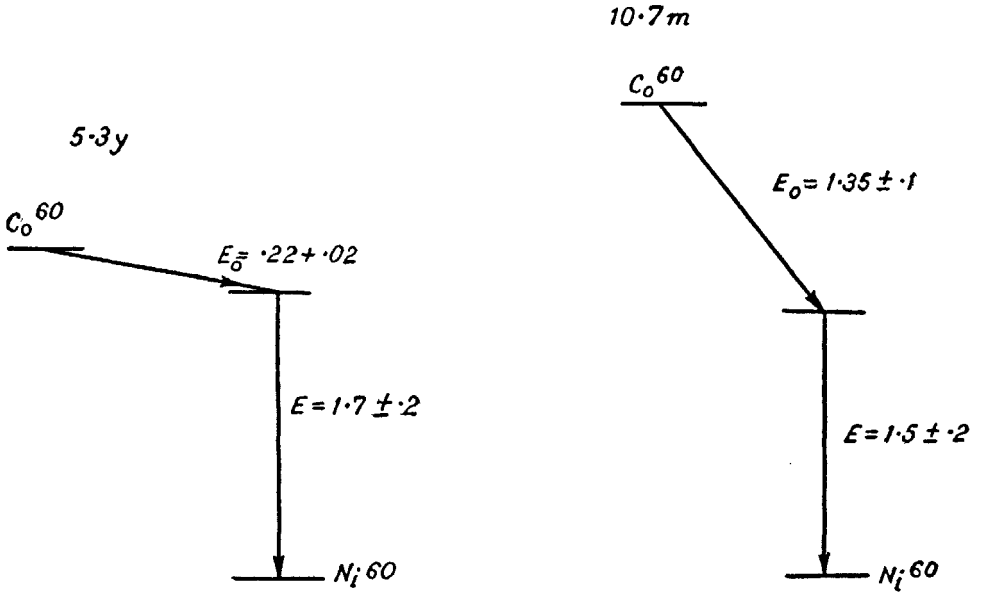


FIG. 2(*a*). Disintegration Scheme of Co^{60} (Nelson, Pool and Kurbatov).

spectrum with the end point at $\cdot220\pm{\cdot}02$ Mev. According to their investigations there is no genetic connection between these two isomers so that they decay independently. The disintegration schemes due to Nelson *et al.* are given in fig. 2(*a*). The order of emission of the β and γ-rays is still undecided, particularly so because there appears to be no conversion electrons in the β-spectra of either of these isomers. According to Deutsch and Elliot, however, the disintegration scheme is different from above. Thus the 5·3 year period Co^{60} emits first a simple negatron spectrum with the end point energy at $0{\cdot}300\pm0{\cdot}006$ Mev and then decays by the successive emission of two γ-rays of energies $1{\cdot}10\pm0{\cdot}02$ Mev and $1{\cdot}30\pm0{\cdot}02$ Mev. The decay of the 10·7 min. Co^{60} consists of two parts: 90% of the activity consists of a decay of this isomer to the 5·3 year period Co^{60} by the emission of an extremely soft γ-ray of energy $0{\cdot}056\pm0{\cdot}003$ Mev, and the remaining 10% consists of the emission of β-rays with the end point energy at $1{\cdot}50\pm0{\cdot}15$ Mev followed by the emission of a single γ-ray. The disintegration schemes which Deutsch and Elliot have in their minds are illustrated in fig. 2(*b*).

As Co^{59} has a spin of 9/2, the Co^{60} isomers which are produced either by the slow neutron reaction, viz. Co^{59} (n, γ) or by the Co^{59} (d, p) reaction, may be expected to have relatively large spins. Hence it is quite probable that this isotope has a large number of metastable states. The complete unravelling of the problems associated with Co^{60} requires a long programme of work, which we cannot carry out here at present with our limited means. Thus, for example, it is necessary to measure

accurately the mass of Co^{59}, measure the energies of the deuteron projectiles used in the Co^{59} (d, p) reaction and find out the energy of the protons liberated from this nuclear reaction. Since Ni^{60} is an even-even nucleus, it is expected to have a zero spin so that the γ-rays emitted from Co^{60} are expected to be high order multipole radiations. It is, however, difficult to determine the order of these γ-rays as they do not appear to be converted into conversion electrons. The β-radiations of 10·7 min. period have been found by Nelson *et al.* (1942) and Konopinski (1943) to be of the allowed type (0*B*-group of Konopinski), i.e. this isomeric state of the Co^{60} nucleus belongs to first Sargent curve. We have, in our paper, examined the β-radiations of the 5·3 year period Co^{60} and have tried to find out the class of this β-emission.

A 180° magnetic focussing type of β-ray spectrometer has been designed for this purpose. This instrument will be described in §2 and the experimental techniques will be explained there. The complete mathematical theory of the *M-F* β-ray

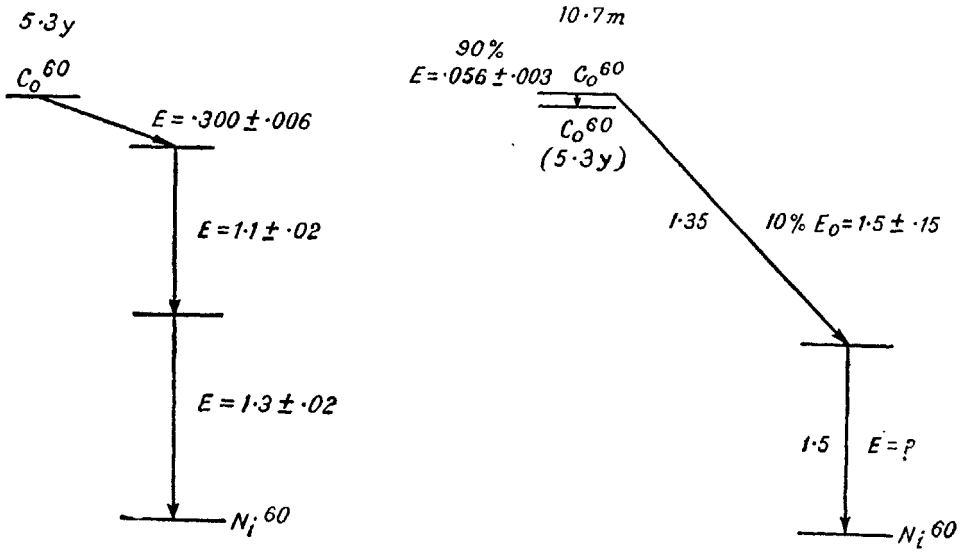


FIG. 2(*b*). Disintegration Scheme of Co^{60} (Deutsch and Elliot).

spectrometer and the method of deducing the energy spectrum of the β-rays investigated, from the experimental $N(H)$ curve have already been given in a paper by one of us (Saha, 1945).* The application of these methods to our specific problem is given in §3 and §4.

§2. *Design of the spectrometer.*—A sketch of the elevation and the plan of section of our spectrometer is given in fig. 3. We briefly describe the figure in what follows.

A—A $\frac{3}{8}$″ thick brass plate carrying the whole spectrometer assembly.

B—A chamber made of $\frac{1}{8}$″ thick brass sheets joined by soft soldering. The overall dimensions of the chamber are: length = 19 cm., width = 6·5 cm., height = 10·5 cm.

C—Soft rubber gasket.

D—Brass flange soldered round the outside of the upper edge of the chamber *B*. It supports the gasket *C*.

* This paper will be referred to hereafter as paper I.

E—Source holder arrangement. A thin aluminium foil E_1, from the centre of which a hole 1 cm. × 1 cm. is cut out, rests on four stout brass screws E_2 soldered to the top plate *A*. The height of the foil E_1 from *A* and its inclination can be controlled by the nuts E_3. The sample plate E_4 is a thin platinum foil of dimensions: length = 1 cm., width = ·2 cm., thickness = ·002 cm. It is fixed above the hole of the foil E_1 by some wax drops.

F—A lead block fixed on the top plate *A* by two stout screws F_1. It shields the detecting counter from direct radiations from the sample.

G—Central defining slit (source slit of paper I) made out of a thick brass plate. It is rectangular in shape of dimensions: 2 cm. × 1 cm., being fixed to the lead baffle *F* by two brass screws G_1 as shown in the figure.

H—The counter assembly. H_1 is a hollow brass cylinder having a flange H_2 at one end. It is screwed to the upper plate *A* as shown in the figure. H_3, the pyrex glass envelope of the detecting Geiger-Müller counter, passes through H_1 and is fixed into position by means of glass collar pressing against the flange H_2. The lower end H_3' of the glass envelope carries a brass cap H_4 with a rectangular slit of dimensions 1 cm. × ·2 cm. (counter slit of paper I). H_5, the counter cathode, is made of a copper foil and has the following dimensions: internal diameter = 2 cm., length = 8 cm. The anode H_6 of the G-M counter is a 3 mil. tungsten wire. At the end H_3' of the glass envelope a thin glass fibre H_7 is drawn out in the form of a diameter of circular section of this end and the central tungsten wire H_6 is tied to this fibre.

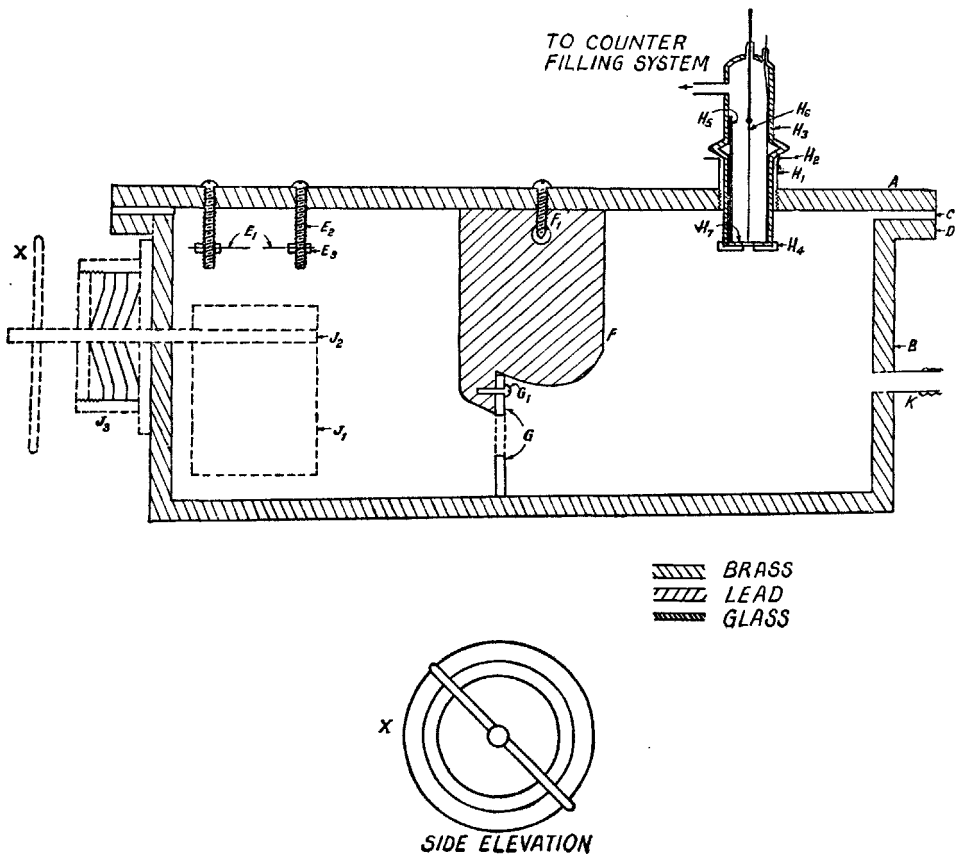


FIG. 3.

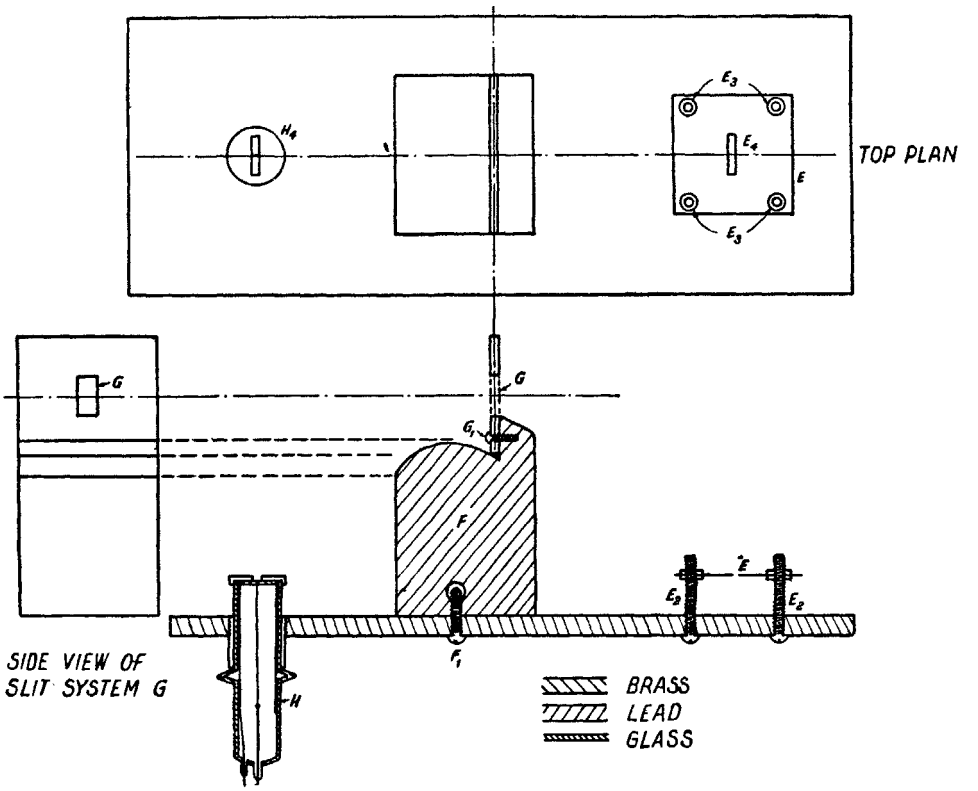


FIG. 3.

I—A thin screen to cover the counter slit on the brass cap H_4. At first thin mica screens were used but were later rejected on account of the fact that it is extremely difficult to detect small cracks between different layers of the mica. Moreover, the flaming necessary to seal the mica screens to the cap H_6 with sealing wax, or the small differences of pressure on the two sides of the screen during the process of evacuating the chamber *B* and filling the G-M counter with gas, cause small cracks to appear on the mica screens, unless great care is taken. We have therefore used the plastic known as 'Perspex' weighing 2·7 mg. per $cm.^2$ * To fix these screens on the brass cap H_4, a bed of a thin layer of sealing wax is first prepared on it. Next the screen is put in position and its edges are gently warmed by a flame from a distance. The edges melt and mix with the sealing wax and perfect sealing is attained when the assembly is cooled for some time. It has been found that the elastic nature of this plastic allows us to maintain quite considerable differences of pressure on the two sides of counter screen.

J—A shutter arrangement to cover the source when it is required to measure the variation of the background due to cosmic rays and local radioactivity with magnetic field. J_1 is a lead block fixed on a brass rod J_2, which passes through the Wilson seal arrangement J_3.

K—This leads to the pump, manometer and discharge tube. The vacuum produced inside the spectrometer chamber is of the order of 10^{-3} cm. of Hg.

* Supplied to us by the kind courtesy of Dr. Atma Ram, Officer-in-Charge, Central Glass and Ceramic Research Institute, Calcutta.

The diameter of the central circle passing through the centres of the sample plate, the source slit and the counter slit is 13 cm. To avoid scattering of the electrons, all metallic surfaces inside the spectrometer were thickly coated with Aquadag. To keep the spectrometer chamber vacuum tight and to prevent the counter gas from leaking out to the spectrometer, fine hard sealing wax was applied at the places where leaking is possible. A proper mixture of Bee's wax and rosin may be applied over the hard sealing wax layers to improve vacuum.

The chamber and the counter were connected in parallel and both were evacuated at the same time with the same pump so that the screen on the counter slit experienced the same pressure on both sides. Then the pump is cut off from the counter and the latter is filled with a mixture of helium and alcohol in the ratio of 7 : 2 at a total pressure of 5 cm. of Hg. The counter has a working plateau of length

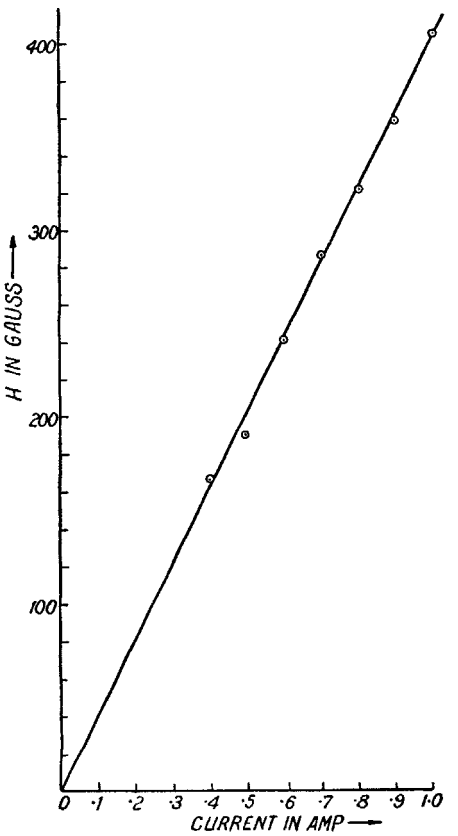


FIG. 4.

50 volts which is quite good for a small counter. The background without any magnetic field is 26 per minute. Argon could not be used as the counter gas as it was unavailable due to the war. Other gases tried were hydrogen, nitrogen, and air but these were found unsatisfactory. The counter was prepared in the usual manner (Dasgupta, 1942).

The detecting and recording circuit was a conventional single stage amplifier employing a sharp cut off pentode 6J7G and the thyratron 885. Pulses were registered by means of an A.T.C. call counter which was found to record without missing appreciably about 700 counts/min. This served our purpose well because the

maximum counts we could obtain with our source intensity was only 70/min. The high voltage stabiliser used to apply the cathode voltage of the G-M counter is a modification by Banerjee (1942) of the Neher-Pickering's circuit (1939).

The electromagnet used was of the iron core Rutherford type. The field of the magnet was explored in the usual manner with an exploring coil. The energising current for the electromagnet was drawn from the main supply without any special device to stabilise the current. However, since the current required to cut off all the electrons from the sample of Co^{60} investigated was only about ·8 amp., this current remained sufficiently steady during operations. The resistances controlling the current were air-cooled and could be varied at ·01 amp. steps. The field versus current curve is shown in fig. 4.

TABLE I.

η	0 cm.
δ	6·5 cm.
$l_2 = 2R_i$	12·9 cm.
$l_1 = 2R_i'$	13·1 cm.
α_B	·70222 rad.
α_A	·85675 rad.
s_B	8·5148 cm.
s_A	9·9247 cm.
$s_B \sec \alpha_B$	11·153 cm.
$s_A \sec \alpha_A$	15·152 cm.
t_{AB}	12·8462 cm.
$2R_s'$	13·062 cm.
$2R_s$	13·301 cm.
$2R_{Al_2}$	13·0479 cm.
$2R_{Al_1}$	13·220 cm.
$2\rho_{AB} = \frac{A \cdot s_B}{\delta}$	13·001 cm.

§3. *Calculations of the Transmission Factor and the constants of the spectrometer.*—The explanation of the symbols employed in what follows are given in paper I. The discussion closely follows that given on pp. 109–111, and in §6 of that paper. For our instrument we have

$$\left.\begin{aligned} &2\delta_0 = 13 \text{ cm.}, \ \sigma_1 = 2C_1 = 1 \text{ cm.}, \\ &\sigma_2 = 2C_2 = \cdot 2 \text{ cm.}, \ d_A = 7\cdot 5 \text{ cm.}, \\ &d_B = 5\cdot 5 \text{ cm.} \end{aligned}\right\} \quad .. \quad (3.1)$$

Let us take $\eta = 0$. Then the values of the quantities δ, l_2, l_1, etc. corresponding to this value of η appear in the Table I. Since $s_B \sec \alpha_B < l_2 < l_1 < s_A \sec \alpha_A$, it is clear that for the region we are interested in, $t_{\max} = 2\rho$. Consequently $2R_i$, $2R_i'$ are given by formula (4·2*a*), case (*c*) of paper I, being therefore respectively l_2 and l_1. Again since $t_{AB} < l_2 < l_1$, $2R_s'$ and $2R_s$ are respectively given by formula (4.2*b*), case (*d*). Evidently, $2R_i' > 2R_s'$, so that we have to discuss a figure like fig. 5(*b*) of paper I. The actual numerical values of the quantities $2R_i$, $2R_s'$, $2R_i$, $2R_s$, $2R_{Al_1}$ and $2R_{Al_2}$ for $\eta = 0$ are given in Table I. The function $T_1(\rho, 0)$ is therefore defined by the following:—

$$\left.\begin{aligned} &(a)\ 2R_i < 2\rho < 2R_{Al_2} : T_1(\rho, 0) = 2\Phi_{l_2}, \\ &(b)\ 2R_{Al_2} < 2\rho < 2R_s' : T_1(\rho, 0) = \Phi_A + \Phi_{l_2}, \\ &(c)\ 2R_s' < 2\rho < 2R_i' : T_1(\rho, 0) = \Phi_A - \Phi_B, \\ &(d)\ 2R_i' < 2\rho < 2R_{Al_1} : T_1(\rho, 0) = \Phi_A - \Phi_B - 2\Phi_{l_1}, \\ &(e)\ 2R_{Al_1} < 2\rho < 2R_s : T_1(\rho, 0) = -\Phi_B - \Phi_{l_1}. \end{aligned}\right\} \quad .. \quad (3.2)$$

The function $T_1(\rho, 0)$ is plotted against 2ρ in fig. 5. Now

$$T_2(D, \eta) = \int T_1(D, \eta) \sin\theta d\theta . \quad .. \quad .. \quad .. \quad (3.3)$$

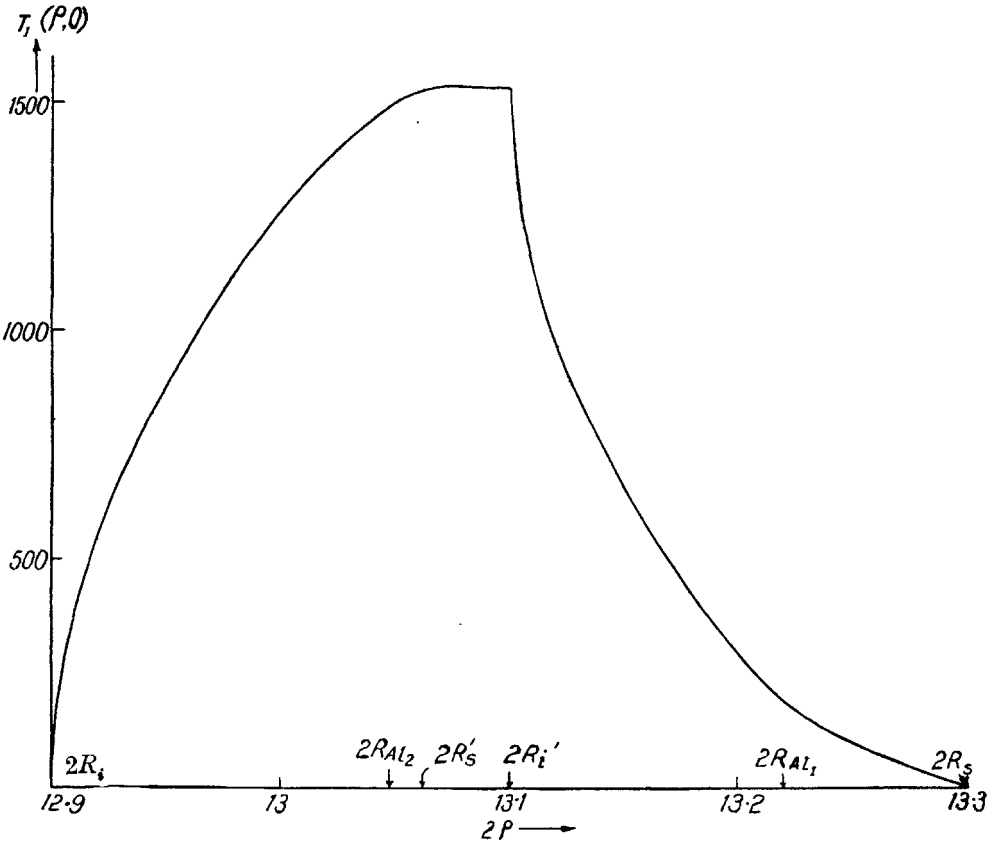


FIG. 5.

It has been shown in paper I [cf. equations (6.5a) and (6.5b) of paper I] that

$$T_2(D, \xi, \eta) = \text{const. } T_1(D, \eta) \quad .. \quad .. \quad .. \quad (3.4)$$

for all values of ξ in $\lambda_+ < \xi < \lambda_-$. Again

$$T_3(D, \eta) = \int T_2(D, \xi, \eta) d\xi = \text{const. } T_1(D, \eta), \quad .. \quad .. \quad (3.5)$$

as shown by equation (6.6) of paper I. The transmission factor function of the spectrometer is given by

$$T(D) = \int T_3(D, \eta) d\eta = \text{const.} \int T_1(D, \eta) d\eta. \quad .. \quad .. \quad (3.6)$$

It has been shown in paper I that the limits of the integral (3.6) are $2R_1(\eta = -\cdot1 \text{ cm.}) = 2R_1 = 12{\cdot}8$ cm. and $2R_s$ $(\eta = +\cdot1 \text{ cm.}) = 2R_2 = 13{\cdot}4$ cm. [cf. discussions in paper I, p. 115 below fig. 7(c)]. It has also been shown in paper I that

$$T_1(D, \eta) = T_1(D-\eta, \eta = 0 \text{ cm.}) \quad .. \quad .. \quad .. \quad (3.7)$$

[cf. formula (4·27) of paper I]. Thus for $2R_1 < D < 2R_i$ ($\eta = +\cdot 1$ cm.) we have to calculate the area under the $T_1(D, \eta = 0$ cm.) curve between $2R_i(\eta = 0$ cm.) and $D+\cdot 1$ cm. in order to find $T(D)$, whereas for $2R_s$ ($\eta = -\cdot 1$ cm.) $< D < 2R_2$ we have to find the area under $T_1(D, \eta = 0$ cm.) curve between $D-\cdot 1$ cm. and $2R_s$ ($\eta = 0$ cm.). For D in $2R_i(\eta = +\cdot 1$ cm.) $< D < 2R_s(\eta = -\cdot 1$ cm.) we have, however, to calculate the area under the $T_1(D, \eta = 0$ cm.) curve between $D-\cdot 1$ cm. and $D+\cdot 1$ cm. In this way the $T(D)$ curve has been constructed and is shown in fig. 6.

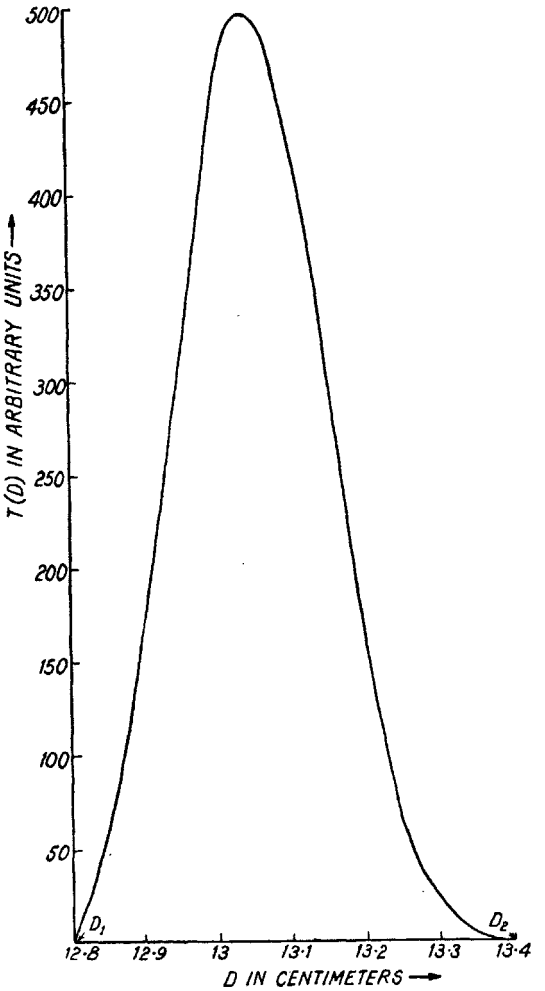


FIG. 6. The Transmission Factor Function of the Spectrometer.

The graphical solution of the equation

$$\int_{D_1}^{D_2} (D - D_3) T(D) dD = 0 \qquad \ldots \quad \ldots \quad \ldots \quad (3.8)$$

yields the following value for D_3, viz.

$$D_3 = 13{\cdot}054 \text{ cm.} \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3.9)$$

If P be defined by

$$D_3 = \frac{2P}{H} \qquad .. \quad .. \quad .. \quad .. \quad (3.10)$$

[cf. formula (7·2*b*), paper I] then the momentum spectrum of the radioactive sample under investigation may be deduced from the experimental $N(H)$ curve through the formula

$$n(P) \propto \frac{N(H)}{H} \qquad .. \quad .. \quad .. \quad .. \quad (3.11)$$

[cf. equation (7·5), paper I].

Since we could not vary the intensity of our sample the determination of the end point H_{max} of the $N(H)$ curve is not strictly accurate as shown in paper I, p. 118. Taking, however, the observed end point as true, the end point of the momentum spectrum of the electrons from the sample investigated is

$$p_{max} = \frac{D_1 H_{max}}{2} \qquad .. \quad .. \quad .. \quad .. \quad (3.12)$$

[cf. formula (7.11), paper I]. It has been shown in paper I that correspondence between the momentum spectrum and the experimental $N(H)$ curve expressed by equation (3.11) fails over a certain region $H_1 < H < H_{max}$, where H_1 is given by

$$H_1 = \frac{2p_{max}}{D_2} = \frac{D_1 H_{max}}{D_2}. \qquad .. \quad .. \quad .. \quad (3.13)$$

As H_1 in most cases is very near to H_{max}, the method suggested in paper I to deduce the momentum spectrum from $N(H)$ curve has not been employed.

To deduce the energy spectrum from the momentum spectrum we use the relations

$$E^2 = c \times 10^{-8} \left[\left(\frac{E_R}{e} \right)^2 + p^2 \right], \qquad .. \quad .. \quad .. \quad (3.14)$$

where E is the total energy (including the rest energy) of an electron with momentum $\frac{ep}{c}$, and E_R is the rest energy of an electron. All energies are expressed in electron volts. Thus

$$\frac{dp}{dE} \propto \frac{E}{p}.$$

Finally, the energy distribution and momentum distribution are connected by

$$n(E) = n(p) \frac{dp}{dE} \propto \frac{N(H)}{H} \cdot \frac{E}{p}. \qquad .. \quad .. \quad .. \quad .. \quad (3.15)$$

§4. *Experiment.*—The sample of Co^{60} of half-life 5·3 years was supplied to us in the form of cobalt chloride solution. A portion of this solution was spread over the platinum sample plate E_4 and evaporated.

At each field two sets of counter readings were taken, one with the source covered by the shutter J_1, and the other with the source uncovered. In this way it was found that the background due to cosmic rays and local radioactivity vary somewhat with the field. The $N(H)$ curve, the excess of the number of counts recorded by the counter with the source uncovered for any particular field H over the background corresponding to that field, is shown in fig. 7. No conversion electron

groups have been found, but we cannot be quite certain on this point as the magnetic field could not be changed at very small steps. The end point of the $N(H)$ curve

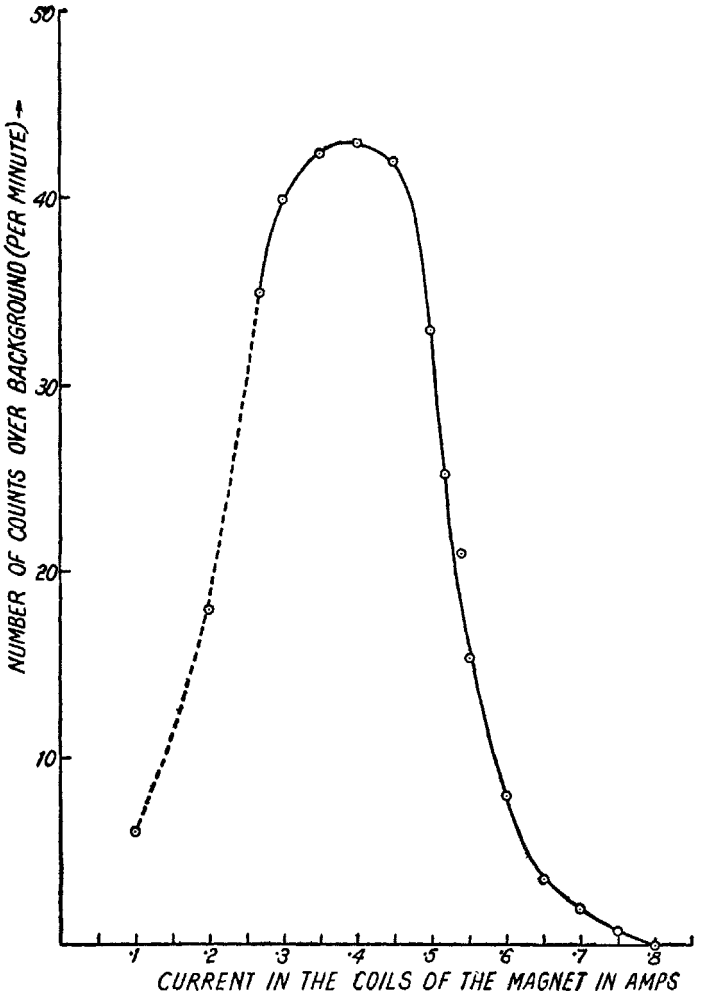


FIG. 7. The $N(H)$ curve.

is evidently at $H_{max} = 325{\cdot}52$ gauss, so that from equations (3.12) and (3.14) we obtain

$$E_{max} = {\cdot}296 \text{ Mev.} \quad .. \quad .. \quad .. \quad .. \quad (4.1)$$

The energy spectrum deduced from the $N(H)$ curve is shown in fig. 8.

§5. *Discussion.*—The best way to find out whether the energy spectrum deduced from the $N(H)$ curve follows the Fermi distribution formula or that due to Konopinski and Uhlenbeck is to construct the so-called Kurie-Richardson-Paxton plot. It is well known that the two formulae cited above for allowed transition may be condensed in a single formula

$$n(W)dW \propto F(Z, W)\,(W_{max} - W)^{2n}\,pWdW, \quad .. \quad .. \quad (5.1)$$

where W is the total energy of the electrons (including rest energy) in m_0c^2 units. The Fermi formula comes out if n is put equal to 1 whereas the Konopinski-Uhlenbeck formula is obtained if n is given the value 2. Consequently

$$\left[\frac{n(W)}{pWF(Z,W)}\right]^{\frac{1}{k}} \propto (W_{max}-W) \quad .. \quad .. \quad .. \quad (5.2)$$

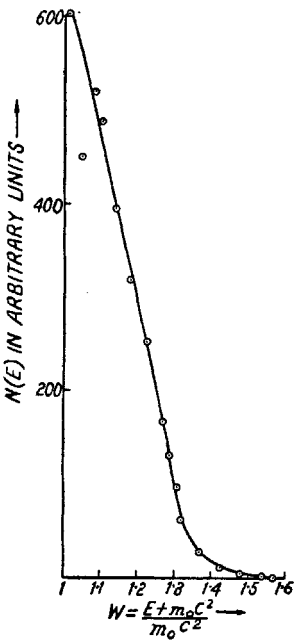


FIG. 8. The Energy Spectrum.

with $k = 2$ for Fermi formula and $k = 4$ for the Konopinski-Uhlenbeck distribution. Thus if we plot the left-hand side against W, and the resultant curve is linear and passes through W_{max} then the Fermi formula is definitely established. This plot generally goes by the name Kurie-Richardson-Paxton plot. The Kurie plot for the 5·3 year period Co^{60} is given in fig. 9. An approximation is used for $F(Z,W)$, viz.

$$F(Z,W) \propto \left[1-\frac{\pi\,|\,\gamma\,|}{|\,e^{2\pi\gamma}-1\,|}\cdot\frac{1}{W^2}\right]p^{2s-3}W \quad .. \quad .. \quad (5.3)$$

(cf. Nordheim and Yost, 1937) where $\gamma = \alpha Z$, $s = \sqrt{1-\gamma^2}$, α being the fine structure constant ($= \frac{1}{137}$). In fig. 9 it will be noticed that almost for the entire electron spectrum the Kurie plot corresponds to a straight line. It is only near the end point and the extreme soft energy portion of the spectrum that any deviation from linearity is found. It is reasonable to assume that the tail of the Kurie plot near the end point is due to stray electrons or Compton electrons knocked out by the γ-rays from the Co^{60}. Such a tail has also been found in the β-spectrum of 10·7 min. period Co^{60} by Nelson *et al.* The extrapolated end point of the β-spectrum of our sample of Co^{60} is given by

$$E_{max} = \cdot 23 \text{ Mev.} \quad .. \quad .. \quad .. \quad .. \quad (5.4)$$

The value for the end point found in §4 [cf. formula (4.1)] is therefore too high.

In order to know what is the spin transition taking place for the emission of the β-particles from the 5·3 year period Co^{60}, it is necessary to fix the so-called *class* of

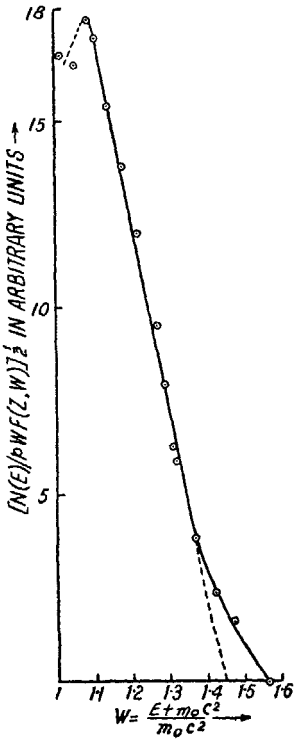


FIG. 9. The Kurie-Richardson-Paxton Plot.

the β-emission process. To do this, as is well known, it is necessary to calculate the ft function for this Co^{60} isomer. The quantity t is the half-life of Co^{60} expressed in seconds. The function f is, according to the approximation due to Nordheim and Yost cited above, given by

$$f=\frac{2^{2s}}{(2s\,!)^2}\cdot\frac{2\pi\,|\,\gamma\,|\,(1+\gamma^2)}{|1-e^{-2\pi\gamma}|}\cdot\left(\frac{mcR}{\hbar}\right)^{2s-2}\cdot(\overline{W}^2-1)^{s-1}\cdot$$
$$\cdot\left[\frac{W^5_{\max}-10\,W^2_{\max}+15\,W_{\max}-6}{30}-\frac{2\pi\,|\,\gamma\,|}{|e^{2\pi\gamma}-1|}\,\frac{(W_{\max}-1)^3}{3}\right]. \quad \ldots \quad (5.5)$$

The ft value for Co^{60}, calculated by us comes out to be $\sim 4{\cdot}4\times 10^7$. It should therefore be included in the $2B$-group of Konopinski (1943) so that the β^- emission from the 5·3 year period Co^{60} is of the second forbidden class.

Certain other features of interest may be noticed about this nucleus. In a paper prepared by Prof. M. N. Saha, D.Sc., F.R.S., in collaboration with one of us (Saha and Saha, 1946), it has been pointed out that in order to explain the empirical rules of Saha, Sirkar and Mukherji about nuclear stability, it is necessary to modify the binding energy formula of Weizsäcker and Bethe. It is well known that for stable nuclei with N even and Z even we may write down the binding energy of a nucleus as follows :—

$$\Delta M(Z,A)=\alpha A-\frac{\beta I^2}{A}-\gamma A^{2/3}-\frac{\delta Z^2}{A^{1/3}} \quad \ldots \quad \ldots \quad \ldots \quad (5.6)$$

[cf. Weizsäcker (1935), Bethe and Bacher (1936)] in analogy with the energy of a charged liquid drop. According to Saha and Saha for other types of nuclei we must add a certain term $\chi(Z, A)$ to the right-hand side of (5.6) to get the correct binding energy of the nucleus. In order to explain the empirical rules of nuclear stability mentioned above it has been found necessary to associate with $\chi(Z, A)$ the following properties: $\chi(Z, A)$ should be zero for the ground state of a nucleus if both Z and A are even. If, however, any one of these pairs is odd then $\chi(Z, A)$ should have a finite negative value. For different excited states of a nucleus, $\chi(Z, A)$ must have different values. It is perhaps reasonable on account of these properties to take $\chi(Z, A)$ to be really the spin dependent term in the binding energy formula. Saha and Saha have made a thorough study of all the nuclei from $I = -1$ to $I = 6$ from this point of view. We shall calculate the $\chi(Z, A)$ terms corresponding to the different energy levels of Co^{60} and Ni^{60} given in fig. 2(*b*). The order of the β, γ emission will be supposed to be the same as given there, although enough experimental facts are not still in our hands to justify this. It has been shown by Saha and Saha that a nucleus ${}_ZM^A$ will emit a β^--particle of kinetic energy E_{β^-} given by

$$E_{\beta^-} = M_n - M_p - m + \frac{4\beta(I-1)}{A} - \frac{\delta(A-I+1)}{A^{1/3}} + \chi(Z+1, A) - \chi(Z, A),$$

$$= A^- + \chi(Z+1, A) - \chi(Z, A). \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (5.7)$$

The difference of E_{β^-} and A^- gives us an estimate of the difference between the χ terms of the parent nucleus ${}_ZM^A$ and its daughter ${}_{Z+1}M^A$. If a nucleus ${}_ZM^A$ emits a γ-ray of energy E_γ then the difference of the χ terms corresponding to the two levels between which the γ-transition is taking place is given by E_γ. Using these two facts we have calculated the $\chi(Z, A)$ terms for the different energy levels of Co^{60} and Ni^{60}. These are as follows :—

10·7 min. period Co^{60} : $\chi_2(27, 60) = -3{\cdot}562$ Mev.

5·3 yr. period Co^{60} : $\chi_1(27, 60) = -3{\cdot}506$ Mev.

Ni^{60} : $\chi_2(28, 60) = -2{\cdot}4$ Mev. $\chi_1(28, 60) = -1{\cdot}3$ Mev. $\chi_0(28, 60) = 0$.

$\chi_0(28, 60)$ corresponds to the ground level of Ni^{60} and we have taken this to be zero as Ni^{60} is an even-even nucleus. $\chi_1(28, 60)$ and $\chi_2(28, 60)$ correspond to the two excited levels of this nucleus shown in the disintegration scheme of 5·3 yr. Co^{60} [fig. 2(*b*)].

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