THE INVESTIGATION OF THE SPECTRA OF THE BETA RADIATIONS OF S^{35}, Rb^{87} AND RaD WITH THE SCREEN CATHODE BETA RAY SPECTROMETER.

By AJIT KUMAR SAHA, *M.Sc., Palit Laboratory of Physics, University College of Science, Calcutta.*

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ABSTRACT.

A screen cathode β-ray spectrometer has been constructed in this laboratory. Experimental investigations of the maximum energies of β-radiations of S^{35}, Rb^{87}, and RaD (all soft β-ray emitters) have been carried out with this spectrometer. A new type of scaling circuit, developed in this connection, has been briefly described. The values of the end point energies of these β-ray emitters obtained by the writer have been employed in the calculations of the function *ft*. The *ft* value for S^{35} makes this nucleus a member of the *OB* group of Konopinski. Rb^{87} has been placed in the *2B* group. The *ft* value for RaD places this nucleus in the *OC* group. A discussion has been given about the possibility of the existence of a metastable isomeric state of RaE with spin 1.

§1. *Introduction.*—In a previous paper (Saha, 1944),* a rigorous mathematical theory of the Screen Cathode β-Ray Spectrometer has been developed. A spectrometer of this type has been set up in the Palit Laboratory. This spectrometer is described in this paper and the experimental techniques that have been developed are completely given in what follows. Experimental investigations of the maximum energies of the β-radiations emitted by S^{35}, Rb^{87} and RaD have been carried out with our spectrometer, though the shapes of their spectra have not been determined on account of great mathematical difficulties, so that this part of the work remains to be completed. The results obtained will be reported in §7 and §8. The nuclei investigated were chosen, because they give β-rays of small energies and cannot be studied with ordinary 180° magnetic focussing type of β-ray spectrographs, as the diaphragms covering Geiger Müller Counters in such spectrographs, however thin they may be, are impervious to soft β-rays.

§2. *The clearing field between the sample cylinder and the cathode.*—Before proceeding to describe the spectrometer, certain remarks may be made about the electrostatic field applied between the sample cylinder and the cathode. A perusal of Paper I will show that the entire mathematical theory developed there hinges upon the fact that the sensitive volume or what Libby and Lee (1939) call the counting volume of the G-M counter in the spectrometer is confined within the cathode. The electrons which are confined in the intervening region between the cathode and the sample cylinder are assumed not to be registered. It has been shown experimentally by Korff and Ramsey (1940), and Libby and Lee (1939) that the counting volume will be confined within the cathode if the sample cylinder be kept at a positive electrostatic potential with respect to the cathode. Presumably therefore no ions which are formed outside the cathode can be accumulated within the space between the sample cylinder and the cathode on account of this clearing action of this electrostatic field so that none of these ions can move forward into the cathode space and make the counter register counts. It has also been observed by these workers that if the sample cylinder be kept at a negative potential with respect to the cathode, the assembly behaves essentially as if the counting volume was that of the sample cylinder. In fact, the ratio of the counting rates for these two cases is approximately that of the cylindrical surface areas of the sample cylinder

* Referred to hereafter as paper I.

and the cathode. Finally, if the sample cylinder is electrically connected to the cathode the counter breaks down into a continuous discharge. Obviously on account of the field free nature of the space between the sample cylinder and the cathode there is a constant supply of ions drifting towards the central wire, each initiating a counter action. This discussion shows therefore that in order to count only those electrons emitted from the sample cylinder which enter the cathode space we should keep the sample cylinder at a positive electrostatic potential with respect to the cathode. Furthermore, it appears that the magnitude of this clearing field is of no importance over quite a wide range (cf. Libby and Lee, 1939, fig. 2). However, Korff and Ramsey point out that the effective recovery time of such a counter depends on a time interval necessary for clearing all the ions away from the region between the sample cylinder and the cathode. This time interval becomes very long for a low field between the sample cylinder and the cathode. So we use, for high counting rate, a relatively high clearing field prescribed by Korff and Ramsey, viz. 50 volts.

§3. *The design of the spectrometer.*—A sketch of the elevation and the section of our spectrometer has been given in fig. 1. We shall briefly describe the figure

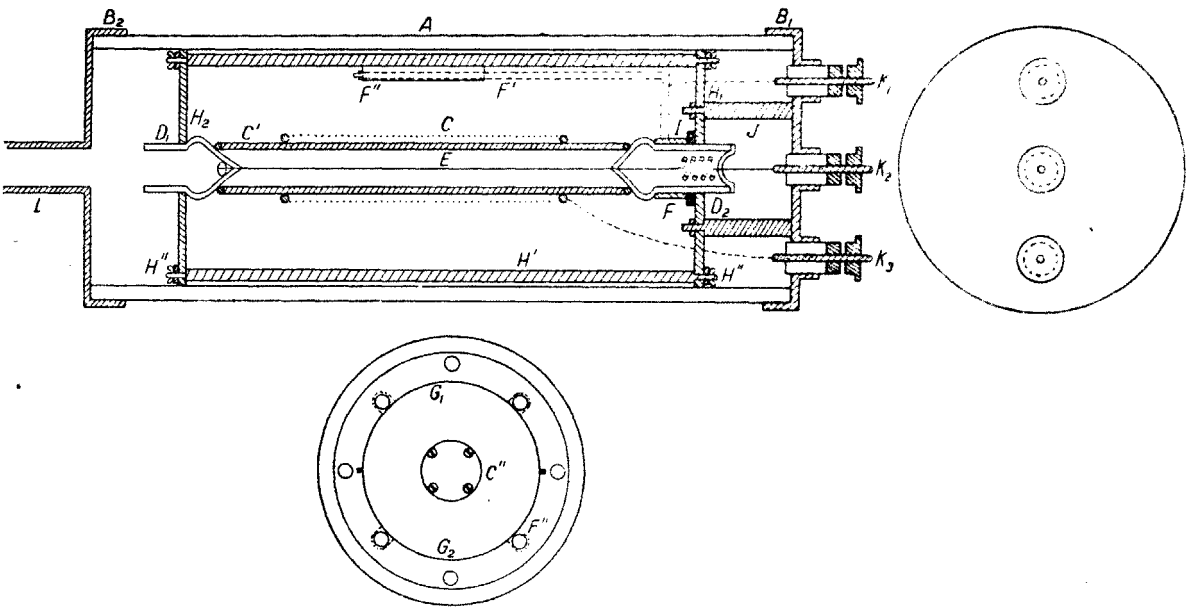

FIG. 1.

in what follows:—

A—A cylinder made of Pyrex glass.

B_1, B_2—Metal caps, in which fit closely the two ends of *A*.

C—Cathode cylinder made of a copper mesh having 7 wires per cm. each of diameter 0·031 cm. The external diameter of the cathode cylinder is 2 cm., and length is 10 cm.

C'—Four stout copper wires fixed symmetrically inside the cathode. These wires preserve the cylindrical shape of the cathode and increase the latter's rigidity.

C''—Two copper rings fixed on the ends of the wires.

D_1, D_2—Glass tubes with conically tapered ends carrying the rings *C* as shown in fig. 1.

E—Central wire made of tungsten of 4 ml. gauze. It passes through the tubes *D* and is fixed in position by means of a spring as shown in fig. 1.

F—A brass collar, through which the glass tube *D* passes. It carries the sample cylinder as shown in fig. 1.

G_1, G_2—Aluminium half-cylinders which together constitute the sample cylinder. They fit in each other as shown in fig. 1. They may be detached

from the rods F' carrying them by unscrewing the screw nuts F''. The internal diameter of the sample cylinder is 6 cm. and length is 4 cm.

H—Two brass cross pieces through the centre of which the tubes D_1, D_2 pass. They are fixed to each other by the rods H' and fly nuts H''. In this way they keep the whole assembly rigid. The rods H' serve to guide the whole assembly within the glass cylinder A.

I—Mica washers juxtaposed between the collars F and the cross pieces H_1 to insulate these electrically from each other.

J—Four brass pillars fixed on the cap B_1. They are also fixed to the cross piece H_1 and thus the cap B_1 carries the whole spectrograph assembly. Whenever it is necessary to introduce or take out the radioactive material we have only to release the cap B_1 from the cylinder and the whole spectrograph assembly comes out of A with the cap B_1.

K_1, K_2, K_3—Binding screws passing through amber plugs which are closely fitted in three collars on the cap B_1. K_1, K_2, K_3 are electrically connected to the sample cylinder, the central wire, and the cathode respectively.

L—Inlet for counter gas mixture. The gas may also be taken out through L by means of a pump when so desired.

The whole assembly is kept vacuum tight in the usual manner by laying fine hard sealing wax on the ends of the caps and the sides of the glass cylinder A. A proper mixture of Bee's wax and Rosin may be made and applied with flame over the hard sealing wax layer to improve vacuum. To prevent leak through the collars supporting the amber plugs some sealing material like Picein with high electrical insulation property may be applied.

The cathode surface is treated as follows for obtaining a satisfactory plateau. It is first thoroughly washed with strong chromic acid and then rinsed in distilled water to remove grease and other organic impurities. Chromic acid is then removed by washing with concentrated ammonium hydroxide followed by washing again in distilled water. Oxide layers and ammonia are then removed by washing in 5% nitric acid. The cathode cylinder is next put in an electric furnace and heated to 600–700°C. for several hours until the cathode is uniformly oxidised, when it is ready for use. The above procedure is customary in our laboratory and gives generally very satisfactory counters.

All metal surfaces in the spectrograph assembly are thoroughly washed with strong chromic acid and then rinsed in distilled water. A heavy coating of aquadag is then laid over these surfaces. This reduces scattering of β-particles from these surfaces.

A mixture of dry hydrogen and vapours of absolute alcohol is used as the counter gas. The hydrogen is dried by passing through calcium chloride towers. Any remaining traces of water vapour may be removed by allowing the hydrogen to stand for some time over phosphorus pentoxide. The ratio of hydrogen to alcohol in the gas mixture is about 9 : 1 and the total pressure of this mixture used in the spectrograph is 10 cm. of mercury. The plateau obtained in this way is about 80 volts in length and the starting potential is at 980 volts. The plateau may have been improved with a larger proportion of alcohol in the counter gas mixture. But as we shall see later, radioactive matter is kept in position on the sample cylinder by a thin layer of cellulose acetate, so that a large proportion of alcohol will dissolve this layer and the radioactive matter will spread everywhere rendering the counter unfit for action. The cosmic ray background is about 200 per minute.

§4. *Electrical circuits.*—The complete diagram of the electrical circuits used in this experiment is given in fig. 2. The circuit consists of six parts. These are described completely one by one below:—

A—This shows the electrical connections within the spectrometer together with the clearing field between the sample cylinder and the cathode.

B—This is the high voltage stabiliser giving voltage to the cathode of the spectrometer. The circuit is a modification by Banerjee (1942) of the usual Neher-Pickering type (1939).

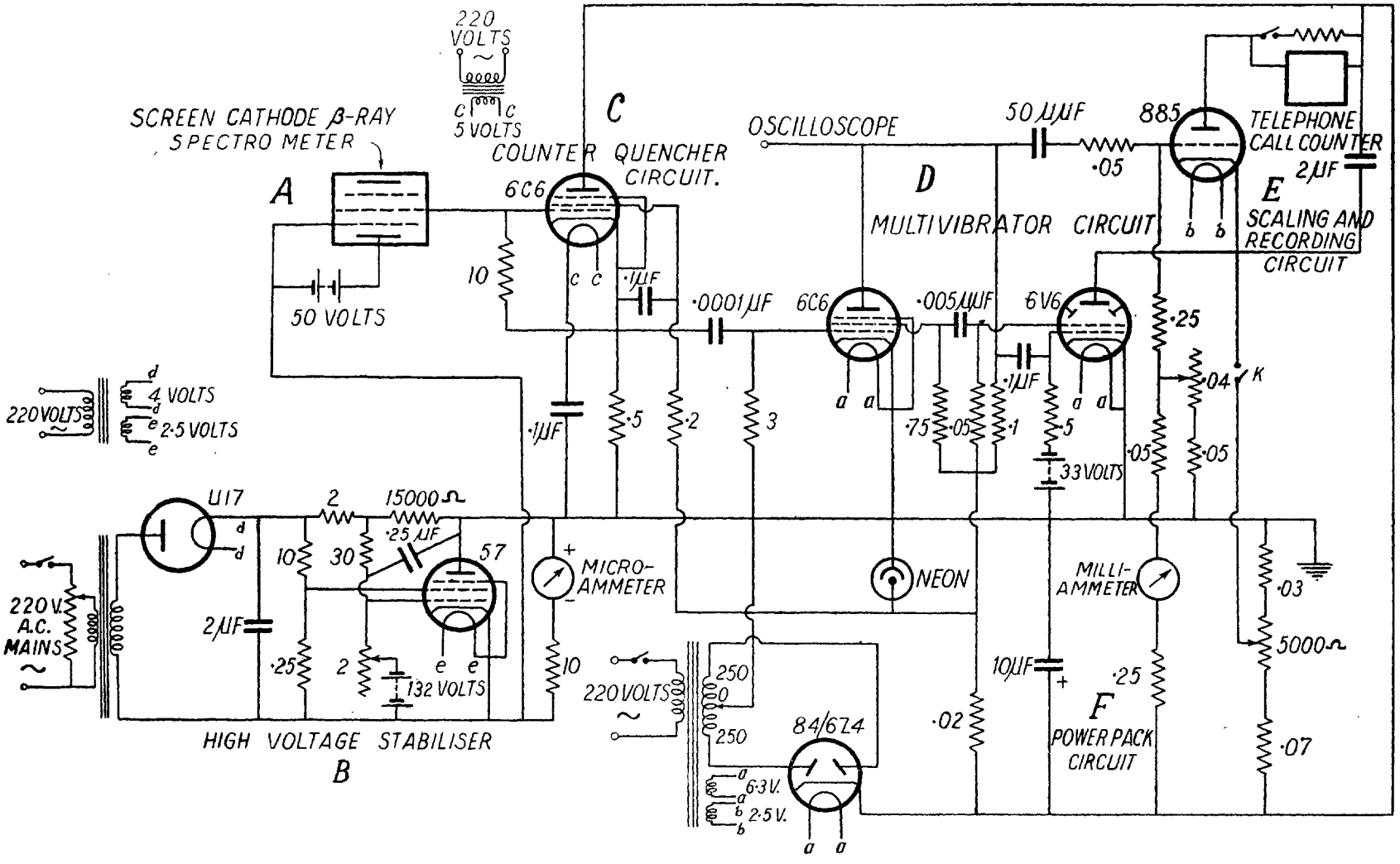

FIG. 2. All resistances are in megohms.

C—This is a counter quenching circuit devised by Johnson (1938). The voltage of the heater of the 6C6 valve used is only 5 volts instead of the usual 6·3 volts and is taken from a separate transformer as shown in the figure.

D, *E*—These are respectively a multivibrator circuit and a scaling circuit.

F—This is a power pack circuit feeding the circuits *D* and *E*.

Circuits *D*, *E* and *F* have been devised by Banerjee, Saha and Ghosh, being essentially a novel modification of the condenser charging type of scaling circuit of Johnson (1938). The salient features of this new circuit are briefly described below, while full details will be published in the forthcoming publication by Banerjee *et al.*

The pulses from the counter are applied to the multivibrator circuit *D*, the second tube of which delivers a current pulse of a fixed constant shape and size for every pulse applied to the grid of the first tube. As is usual with a properly adjusted multivibrator circuit, the amount of charge delivered in the second tube is practically independent of the input pulse shape and size provided the input pulse has a magnitude sufficient to trip the circuit and a duration smaller than that of the output pulse. As will be clear from fig. 2, the current pulse delivered by the multivibrator, while passing through the $2\mu F$ condenser of the circuit *E* charges it by a definitely fixed amount. This condenser is connected between the plate and the cathode of a thyratron. A discharge will start in the thyratron when the condenser voltage has increased sufficiently so that the plate potential of the thyratron reaches above the value V_1 volts, which is the plate potential necessary to start the discharge in the thyratron at the given grid bias. The discharge will automatically stop when the plate potential attains a value V_2, the extinction potential of the thyratron. Thus the thyratron discharge takes place when the scaling condenser receives a charge $C(V_1 - V_2)$ from the multivibrator. If the charge delivered for every input pulse is Q, then one thyratron discharge takes place for n input pulses, n being an integer just greater than $C(V_1 - V_2)/Q$. This scaling ratio can therefore be set at any desired value by adjusting C, Q and the grid bias applied to the thyratron. The condenser discharge, as will be apparent from fig. 2, has been arranged to operate the call counter directly. The circuit constants have been so arranged that the scaling ratio is just 10. It may be noticed, in passing, that we can use the circuit as a plain recording circuit, when so desired by switching on the key *K*. When this is done the thyratron cathode gets connected to the variable arm of the 5,000 Ω potentiometer and receives a voltage varying between 80–100 volts. As the grid is connected to a 30,000 Ω variable resistance which adjusts the bias over a range of 40–65 volts, the grid receives negative voltage with respect to the cathode. Thus the thyratron may be kept in a non-conducting state. When a negative pulse falls on the input terminal of the circuit, the thyratron grid receives a negative pulse through the $50\mu\mu F$ condenser, while simultaneously the cathode receives a negative pulse from the 6V6 tube of the multivibrator. Consequently, the thyratron flashes for every input pulse. The arc established within the thyratron is extinguished automatically due to the grid becoming highly negative with respect to the cathode after discharge and also due to the fact that the grid control of the thyratron is regained at low anode-cathode voltages as soon as the anode current drops below some low value.

§5. *Magnet.*—The spectrograph is placed coaxially inside the coils of a Weiss magnet from which the pole pieces were removed. This magnet is of Helmholtz coil pattern of about 10 cm. internal diameter with a gap of 10 cm. between the two parallel coils. The magnetic field in this gap has been measured in the usual manner with an exploring coil and is found to be quite uniform. The field depends linearly on the current in the coil, the slope of the field-current curve being 65 Gauss per ampere (fig. 3). The coils of this magnet are cooled by circulating water round them.

§6. *Preparation of the radioactive samples.*—

(A) S^{35}—The sulphur examined by us has been prepared and chemically separated in the M.I.T. Cyclotron Department. It is in the form of $BaSO_4$

and consequently insoluble in water and acids. It is therefore ground to fine powder and shaken in water and spread over a small region of the sample cylinder of lateral length 3 cm. It is kept in position by depositing a very thin layer of cellulose acetate dissolved in ethyl acetate.

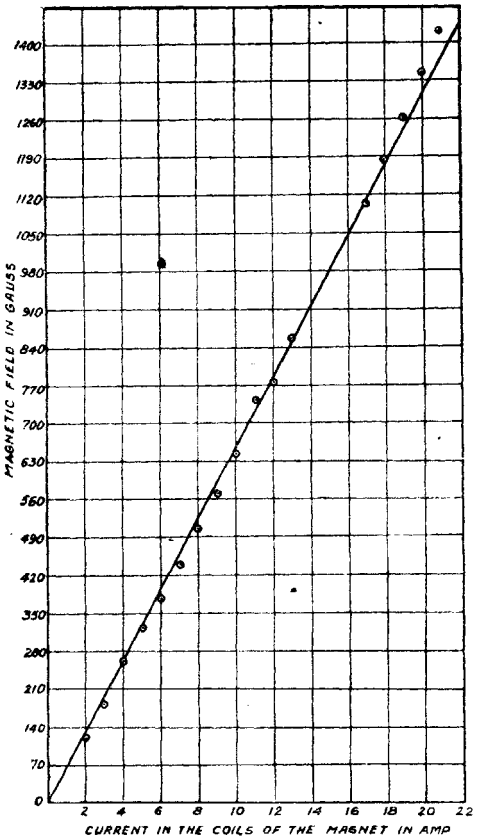

FIG. 3.

(B) RaD—This has been extracted from a radon tube about three to four years old. The method of extraction follows strictly a procedure recommended by Lee and Libby (1939). Their procedure is described below in almost their own words. The radon tube is first washed in concentrated nitric acid and then in water, and then crushed under 5 c.c. of concentrated HNO_3. The whole thing is heated and the glass particles are allowed to settle down, after which the solution is decanted and diluted by addition of about 3 c.c. of distilled water. From this final solution small portions were taken for individual preparations. One c.c. of this solution is evaporated twice with excess of concentrated HCl and the residue dissolved in about 5 c.c. of ·1N HCl, and heated to 90°–100°C. Then 99% of Po in this solution is removed by rotating in this solution at a speed of about 2-3 revolutions per min. an Ag foil (area 2 sq. cm.) for 4-5 hrs. The remaining Po is removed in the same way with another Ag foil. RaE in this solution is removed by rotating a Ni foil (of the same area as the Ag foil used) at the same speed. To remove the final traces of RaE we proceed as follows. ·1 c.c. of a solution containing 10 gm./c.c., each of Pb and Bi chlorides, is added to prevent the loss of RaE or RaD by occlusion on dust particles, etc. The solution was allowed to stand overnight. The RaE left in the solution by the previous treatment and that produced subsequently by the decay of RaD is removed by rotating in a hot solution a Ni foil similar to the one already used. The solution is then evaporated with excess of HNO_3 and then

twice with distilled water. The final residue is digested with 5 c.c. of a two per cent solution of NH_4NO_3 to insure the solution of the Pb content. The $BiONO_3$ residue is filtered off to remove last traces of RaE. RaD is removed from the filtrate by precipitating the Pb as PbS. This is stirred in water and spread uniformly over a small region of the sample cylinder of lateral length of 1·9 cm. A thin layer of a solution of cellulose acetate in ethyl acetate is spread over the PbS deposit to keep the latter in position.

(C) Rb^{87}—The investigation of the β-ray spectrum of this nucleus was carried out with another *S-C* spectrometer designed by Sen-Chowdhury (1942). The cathode of this instrument was 20 cm. in length but had a diameter of 2 cm. like the one already described. The sample of Rb was placed on a cylindrical tray of dimensions length = 10 cm., lateral length = 4 cm. and placed at a distance of 2 cm. from the cathode cylinder. The sample of Rb was prepared by dissolving 12 gms. of RbCl in water and the solution was spread over the tray. The water was evaporated and the sample was kept in position in the same way as the other two samples.

§7. *The $N(H)$ curves and p_{max}.*—Fig. 4 shows the $N(H)$ curves for S^{35} and RaD and fig. 5 that for Rb^{87}. The values of the field for which the $N(H)$ curves

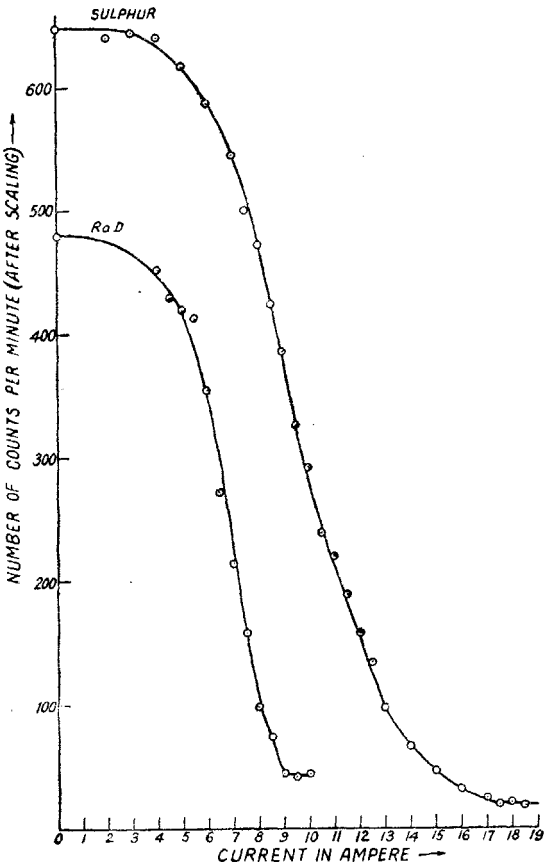

FIG. 4.

fall to zero is 1137·5 Gauss for S^{35}, 585 Gauss for RaD and 1365 Gauss for Rb^{87}. Now it has been proved in paper I that the maximum momentum of β-particles emitted from a sample is connected to H_{max} by

$$p_{max} = \frac{d-b}{2} \frac{e}{c} H_{max}$$

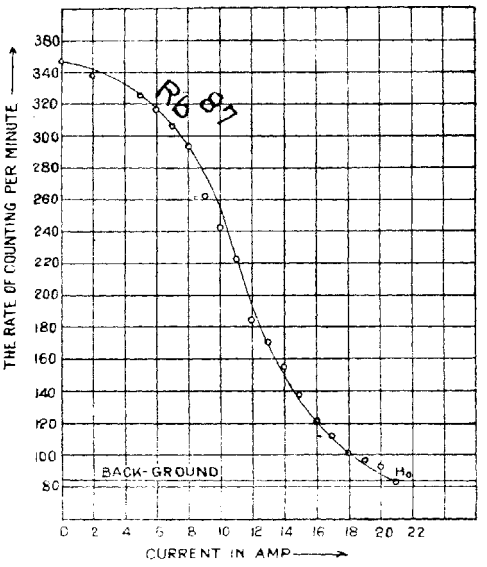

FIG. 5.

[cf. eqn. (8.2) paper I]. Corresponding kinetic energy in electron volts is given by

$$T_{\max} = c \times 10^{-8} \cdot \left[\sqrt{\left(\frac{m_0 c^2}{e}\right)^2 + \left(\frac{d-b}{2}\right)^2 H_{\max}^2} - \frac{m_0 c^2}{e} \right] \text{ev.}$$

The dependence of $T_{\max}$ on the current in the coils of the magnet for our apparatus

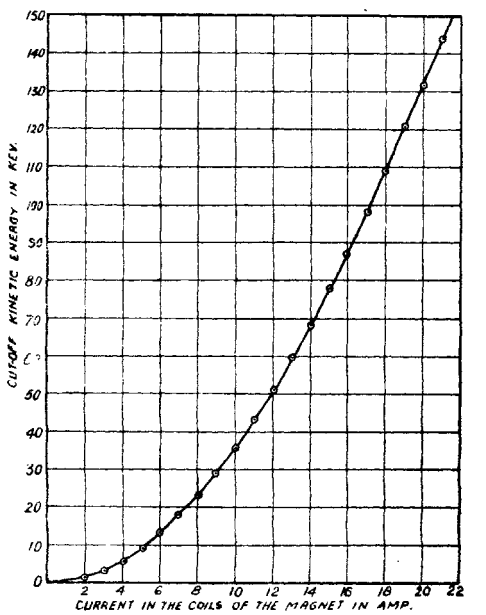

FIG. 6.

is shown clearly in fig. 6. Evidently for S^{35} $T_{\max} = 103{\cdot}3$ Kev., for RaD $T_{\max} = 29{\cdot}2$ Kev., and for Rb^{87} $T_{\max} = 143{\cdot}8$ Kev.

§8. *Discussion.*—The numerical calculations for the deduction of the shape of the momentum spectrum from the experimental $N(H)$ curve have not been carried out yet, as the difficulties of the method of solution of the integral equation of the spectrometer

$$N(H) = M \int_{p_{cut}}^{p_{max}} n(p)T(p/H)\,dp$$

[cf. equation (10.2) of paper I] suggested in §12 of paper I appear to be of a formidable nature. In this method, we neglected terms in the Taylor expansion of $n(p)$ over a small range $p_r > p > p_{r-1}$ containing powers of $p-p_r$ higher than the first. In practice, it has been found, this introduces serious errors in calculations on account of the fact that the range p_r, p_{r-1} is not small enough. Attempts are being made to solve the integral equation by some other more suitable method.

It can be claimed, however, that the determination of the end points of the different β-spectra investigated have been carried with utmost precision and the results obtained are perhaps much more correct than the results obtained previously by absorption experiments or by the usual magnetic focussing spectrometer. It has been found by the writer in another paper (Saha, 1945) that the transmission factor of the *S-C* spectrometer is of a much higher order than the *M-F* spectrometer, so that the $N(H)$ curves determined by the *S-C* spectrometer fall to zero much more steeply than those obtained by using the *M-F* spectrometer. It is true, however, that the solution of the integral equation of the *M-F* spectrometer can be carried out with extreme ease so that the deduction of the momentum spectrum from the $N(H)$ curve obtained with this apparatus gives no trouble whatever. Our results have been compared in the following table with earlier results, as reported in a table compiled by Seaborg (1944). The values of the half lives put down in Table I are also taken from Seaborg's table excepting that for Rb^{87}, the half life of which was measured in our laboratory by Sen-Chowdhury (1941) with the help of an *S-C* spectrometer. In this table we have also the products of the experimental half lives in seconds, with a function f, which is a measure of the expected half lives according to Fermi's theory of the allowed transition (Fermi, 1934). According to an approximation by Nordheim and Yost (1937) the function f has been found to have the form

$$f(W_0) = \frac{2^{2s}}{(2s!)^2} \cdot \frac{2\pi|\gamma|(1+\gamma^2)}{|1-e^{-2\pi\gamma}|} \cdot \left(\frac{mcR}{\hbar}\right)^{2s-2} \cdot (\bar{W}-1)^{s-1} \cdot \left[\frac{W_0{}^5-10W_0{}^2+15W_0-6}{30} - \frac{\pi|\gamma|}{|e^{2\pi\gamma}-1|} \cdot \frac{(W_0-1)^3}{3}\right],$$

where W_0 = the maximum energy (including the rest energy) of the β-rays in units of m_0c^2,

R = nuclear radius = $1{\cdot}5\times10^{-13}\,A^{\frac{1}{3}}$ cm. (A = atomic weight),

γ = αZ ($\alpha = \frac{1}{137}$ = fine structure constant, Z = atomic charge),

s = $\sqrt{1-\gamma^2}$

$\bar{W}$ = mean value of the energies (including the rest energy) of the particles in units of m_0c^2.

For the meaning of the symbols in the last column, see Konopinski (1943). A, B, C denote a rough classification of the radioactive nuclei according to atomic weight, A describing the lightest nuclei, B more heavier ones, and C the heaviest ones which are almost exclusively natural radio elements. The symbols 0, 1, 2, ... denote the class of β-transition, 0 representing allowed transition, 1 the first forbidden transition, 2 the second forbidden transition and so on.

TABLE I.

Nucleus.	W_0 = Maximum energy of β-particles (including rest energy) in m_0c^2 units.		Konopinski's calculations.			Writer's calculations.		Class.
	Value.	Reference.	W_0.	Half Life.	(ft) Fermi.	Half Life.	(ft) Fermi.	
$_{16}S^{35}$	1·209 1·234 1·201	Libby & Lee (1939) with S-C spectrometer. Kamen (1941) by absorption measurement. Writer with S-C spectrometer.	1·21	$7·6\times10^6$	$1·9\times10^4$	87·1 days	$2·372\times10^4$	OB.
$_{37}Rb^{87}$	1·258 1·489 1·254 1·281	Libby & Lee (1939) with S-C spectrometer. Klemperer (1935) Ollano (1941) Writer with S-C spectrometer.	1·26	6×10^{18} secs.	$4·8\times10^{16}$	$2·35\times10^{18}$ secs.	$3·106\times10^{16}$	$2B$ according to Konopinski. Values of ft for other members of the group is much smaller, being $\sim10^8$.
$_{82}RaD^{210}$	1·05 1·057	Lee & Libby (1939) with S-C spectrometer. Writer with S-C spectrometer.				22 years.	$2·401\times10^6$	OC.

Let us examine these β-emitters more closely one by one.

A. S^{35}—Certain interesting features are revealed if we examine the position of this nucleus in the chart of nuclei prepared by Saha, Sarkar and Mukherji (1940). Saha *et al.* have noticed the empirical rule that if we arrange the nuclei having a certain definite value for the isotopic number $I = A-2Z$ successively in order of increasing atomic weight, then if the value of the isotopic number selected is odd, then the nuclei situated towards the lighter atomic side are β^--active, the nuclei placed on the heavier atomic side are either β^+-active or show evidence for K-capture, and the stable nuclei are juxtaposed in between these two groups. Now I for S^{37} is 3. The corresponding group of nuclei are as follows:

TABLE II.

Nucleus	$_8O^{19}$	$_9F^{21}$	$_{10}Ne^{23}$	$_{11}Na^{25}$	$_{12}Mg^{27}$	$_{13}Al^{29}$	$_{14}Si^{31}$	$_{15}P^{33}$	$_{16}S^{35}$	$_{17}Cl^{37}$ to $_{22}Ti^{47}$	$_{23}V^{49}$ to $_{30}Zn^{63}$
Nature of Radioactivity	←				β^-				→	Stable	β^+ and K-capture.
T_{max}	..	..	4·1	2·8	1·8	2·5	1·8	..	·1033	..	..
Half life	31 sec.	..	40 sec.	62 sec.	10·2 min.	6·7 min.	170 min.	..	87·1 days	..	..

The stable group contains A^{39} which is β^--active. The anomalous behaviour of this nucleus remains unexplained. It will be observed from above that in general the nuclei in the β^--active group are characterised by the fact that the half life of the activity increases and the maximum energy T_{max} of the β^--radiations diminishes as the atomic number is increased. S^{35} is the last nucleus in this β^--active group and our determination of T_{max} makes it fit nicely in the above scheme. A detailed explanation of this empirical rule on the basis of the mass defect formula will be found in a future paper. We note, in passing, that the value of $(ft)_{Fermi}$ calculated on our data is $2{\cdot}37 \times 10^4$, whereas Konopinski obtained the value $1{\cdot}9 \times 10^4$ for the same quantity. This nucleus belongs to the group *OB* of Konopinski.

B. Rb^{87}—This nucleus probably has the distinction of being the first nucleus for which the spin change taking place during the β-transmission has been accurately measured by direct experimental methods. The spin of Rb^{87} has been found to be 3/2 by Kopfermann and Krüger (1936) and that of its daughter Sr^{87} has been shown to be 9/2 by Heyden and Kopfermann (1938). Consequently, $\Delta i = +3$. Greuling (1942) has dealt with this nucleus quite thoroughly, taking however the value $W_0 = 1{\cdot}26$ for the maximum energy of the β^--radiations. Konopinski (1943) considers that as Greuling's calculations involve high powers of nuclear radius and of the end point energy, the result is very sensitive to these quantities. Consequently, a repetition of Greuling's work with our data is perhaps necessary and this will be done in future. Briefly, we may summarise Greuling's result as follows. Greuling believes that this β^--ray transition is certainly not second forbidden according to the G-T rule: $\Delta i = 2$ (with no parity change) because the corresponding procedure gives a half life 2,000 times too short. For the calculations on the basis of the transition being third forbidden, obeying the G-T rule, $\Delta i = 3$ with parity change, Greuling obtains a half life of 6×10^{17} sec. using $\frac{v}{c} = \cdot 1$, v being the nucleon velocity. This half life is nearly four times less than the best determined half life of Rb^{87}, viz. $2{\cdot}35 \times 10^{18}$ sec. obtained by Sen-Chowdhury (1941) whose value agrees closely with the value of Hahn and Rothenbech (1919). A repetition of Greuling's calculations using our data is therefore necessary, but this must be postponed for the future. In passing we note that $(ft)_{Fermi}$, that we have obtained is $3{\cdot}11 \times 10^{16}$ whereas Konopinski (*loc. cit.*) has obtained the value $4{\cdot}8 \times 10^{16}$ for the same quantity using half life $= 6 \times 10^{18}$ sec. and $W_0 = 1{\cdot}26$.

C. RaD—The isotopic number I for this nucleus $= 46$ and the following nuclei with this value for I are known:—

TABLE III.

Nucleus	$_{81}Tl^{208}$ (ThC″)	$_{82}Pb^{210}$ (RaD)	$_{83}Bi^{212}$ (ThC)	$_{84}Po^{214}$ (RaC′)	$_{85}$Ra Hal^{216}
Nature of Radioactivity	β^-, γ	β^-, γ	α, β^-, γ	α	α

Since I is even for this group, we should expect on the basis of another empirical rule noticed by Saha *et al.*, that these nuclei should be alternately stable (α-activity is considered stable here) and β-active (β^+ and β^- active) or show signs of K-capture. Hence RaD which has even Z and even A should be stable. This rule is apparently not followed by this group. This anomaly of RaD is perhaps due to its possession of a finite spin. To prove this let us examine the following portion of the U-Ra series.

$$_{82}Pb^{210}(RaD) \xrightarrow{\gamma, \beta^-} {}_{83}Bi^{210}(RaE) \xrightarrow{\beta^-} {}_{84}Pb^{210}(RaF).$$

Δi 0 +2

i 2 0

According to a discussion given by Konopinski and Uhlenbeck (1941), the RaE β-transition belongs to the second forbidden class. They have decided that the spin change taking place here is $\Delta i = 2$. As RaF is an even-even nucleus, Konopinski and Uhlenbeck have taken its spin to be zero in its normal state so that the spin of RaE comes out to be 2. Our value for $(ft)_{\text{Fermi}}$, for RaD, given in Table I is $2{\cdot}4 \times 10^6$ so that this nucleus is placed in the *OC* group of Konopinski's classification of β-emitters, or in other words the RaD β-transition is allowed. The spin change of this class of β-transition is 0 according to Fermi selection rule, and 0, ± 1 with ($0 \rightarrow 0$ forbidden) according to Gamow-Teller selection rule. Further proof is given below of the existence of an isomeric state for RaE with spin 1 from which the state of RaE with spin 2 is reached by a γ-emission. It is well known that RaD is associated with a γ-ray with energy 47·2 Kev. The emission of this γ-ray and its internal conversion has been discussed at great length by Hulme *et al.* (1936), on the basis of Stahel's (1931) * experimental studies. Stahel's conclusions have been summarised by Hulme *et al.* as follows: 100% excitation of the product nucleus after β^--emission from RaD, produces about 60% emission of conversion electrons from the *L* shell, 36% from the *M* and the *N* shells and 4% emission of γ-quanta. This suggests, according to Hulme *et al.*, that field of the γ-ray is of the magnetic dipole type. When such a γ-ray is emitted it is well known that the spin change of the nucleus is $\Delta i = \pm 1$. Thus the isomeric level of RaE from which the γ-transition is taking place must have a spin 1. The spin of RaD is therefore 1 according to the Fermi selection rule, and 0 or 1 according to the Gamow-Teller

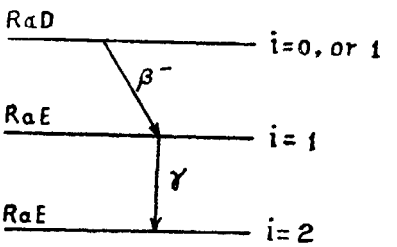

FIG. 7.

selection rule. If we take spin of RaD to be 0, it ought to be ordinarily a stable element. If however, we take its spin to be 1, then it will be clear from the following arguments that RaD will not be stable. Hulme *et al.* have pointed out that when a nucleus possesses magnetic moment, its energy is changed by an amount of the first order,

$$\pm ig(i) \cdot \frac{eh}{4\pi Mc} \cdot \frac{Zev}{cR^2} \simeq 60\, kev$$

where i = the spin, $g(i)$ = the Landé factor, M = proton mass, R = nuclear radius, v = velocity of nucleons inside the nucleus. The exact value of this increment of energy will depend on a correct knowledge of $ig(i)$. Which sign must be taken will depend on whether the magnetic moment has the same direction as the spin or whether it is in the opposite direction. We cannot go further into an elucidation of these points with the present state of our knowledge, but we may say roughly that RaD with $i = 1$ may have energy different from that with RaD with $i = 0$.

The conclusion that RaD, even though it is an even-even nucleus, possesses finite spin. This is probably not unjustified when we remember how RaD is produced in the U-Ra series by rather complicated branch processes. The transition

* Stahel's conclusions have been disputed by Lee and Libby, but they base their arguments on the earlier paper on Fisk (1934), whereas Hulme *et al.* (*loc. cit.*) have in their most recent paper upheld the findings of Stahel. The problem is certainly worth re-investigation.

RaC'→RaD emits a large number of long range α-particles and γ-rays, some of which have been shown to be due to transitions between levels left excited by α-emission.* Hence it is quite possible that RaD is largely left in an excited condition which starts β and γ emissions.

On the basis of our present knowledge it is not possible to distinguish between Fermi selection rule and Gamow-Teller selection rule for the RaD β-emission. Apparently both are probable and more detailed calculations based on Konopinski and Uhlenbeck line of thought are necessary before anything definite can be said.

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* Cf. discussion by Gamow (1937), pp. 118 and 150.

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Errata for Paper I.

p. 356, line 16th—the word 'positive' should read as 'negative'.
p. 356, line 17th—equation '$z = 0$' should be replaced by 'ZX'.
p. 361, line 10th—the word 'fig. 5' should read as 'fig. 4'.
p. 362, the right side of formula (6·4) should be

$$\cos^{-1}\left[\frac{d^2-b^2+\sin^2\psi \cdot D^2\sin^2\theta}{2d\sin\psi \cdot D\sin\theta}\right].$$

p. 362, line 21st—the words 'greater than' should read as 'less than'.