

*Nuclear Spin of Radioactive Elements.*

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There seems at present to be rather definite evidence that the rate of radioactive disintegration, and excitation of the product-nucleus usually connected with it, is largely affected by the values of nuclear angular momenta.

It was shown by the author<sup>†</sup> that the existence of intense components of  $\alpha$ -ray-fine-structure indicates that the disintegrating-, and the product-nuclei possess different spins. The angular momenta received in this case by  $\alpha$ -particles of the normal group (transitions between normal states of both nuclei) will reduce its probability of escape in favour of other groups corresponding to the formation of the excited product.

From this point of view we have to accept the change of nuclear spins in normal disintegration of radioactive C-products (ThCC'' ; RaCC'' ; AcCC'') and also of most members of the actinium-family. Unfortunately the existing formula for decrease of probability does not take into account all the factors influenced by angular momenta of  $\alpha$ -particle (only the effect due to increase of potential barrier can be simply evaluated) and therefore the values of spin-differences cannot be exactly estimated.

The role of nuclear spin in the process of  $\beta$ -integration was recently indicated by Fermi<sup>‡</sup> in his theory of  $\beta$ -decay. According to this theory the decay constant  $\lambda$  for  $\beta$ -disintegrating bodies depends on the factor :

$$\left| \int u_n v_m^* d\omega \right|^2, \quad (1)$$

where  $u_n$  and  $v_m$  are the eigenfunctions of nuclear neutron and resultant proton. We may notice, however, that this result is not necessarily connected with the special form of Fermi's theory, and will hold for practically every theory treating the  $\beta$ -decay as the transformation of a nuclear neutron into a proton.

The factor (1) must be of the order of magnitude unity if the initial and resultant nuclei possess the same spin (permitted transitions) :

$$i = i' \quad (2)$$

<sup>†</sup> 'Nature,' vol. 129, p. 470 (1932); vol. 131, p. 618 (1933); Gamow and Rosenblum, 'C. R. Acad. Sci. Paris,' vol. 197, p. 1620 (1933).

<sup>‡</sup> 'Ric. Sci.,' vol. 2, No. 12 (1933); 'Z. Physik,' vol. 88, p. 161 (1934).

and be reduced to the value

$$\left( \frac{\text{radius of the nucleus}}{\text{wave-length of } \beta\text{-particle}} \right)^{2\Delta i} \sim \left( \frac{1}{100} \right)^{\Delta i}$$

if this condition is not fulfilled (non-permitted transitions):

$$i \neq i'. \quad (2')$$

This explains the result found by Sargent† that plotting the logarithms of decay constants against the logarithms of maximum energy of  $\beta$ -particles we get the experimental points distributed between two different curves. We must say that the  $\beta$ -spectra belonging to the class I (RaD, UX<sub>1</sub>, ThB, AcB, RaB, AcC'', ThC'', UX<sub>2</sub>) correspond to  $i = i'$  while those of the class II (RaE, MTh<sub>2</sub>, ThC, RaC) to  $i \neq i'$  (most probably  $i = i' \pm 1$ ). One would also expect the shape of continuous  $\beta$ -spectra to be different for permitted and non-permitted transitions, although the present experimental evidence is not sufficient to prove that.

Remembering that the product-nucleus can be formed in different excited states, with the energy-excess not greater than the total energy-difference between the two nuclei, we must consider the following possibility. The normal state of the product nucleus possesses a spin different from that of the original one ( $i_0 \neq i'_0$ ) but one of its excited states has the same value of spin ( $i_0 = i'_n$ ). In such cases we must expect that the observed  $\beta$ -spectra will correspond to a permitted transition leading to the formation of an excited nucleus and consequently will be accompanied by a strong  $\gamma$ -line with absolute intensity unity (or by several less strong  $\gamma$ -lines, if different radiative transitions from this completely excited level are equally possible). This has actually been observed by Ellis and Mott‡, for several  $\beta$ -disintegrating bodies (for example, for ThBC and ThC''D). The fact that there are no  $\beta$ -transformations belonging to the non-permitted class and at the same time possessing  $\gamma$ -lines of absolute intensity unity speaks in favour of the exclusion rules (2) and (2').

We shall now apply these considerations to the forking regions of three known radioactive families for which the experimental evidence is rather complete.

In fig. 1 is given the scheme of radioactive decay from ThA to ThD (lead). From the absence of intense fine structure in the  $\alpha$ -disintegration-row leading

† 'Proc. Roy. Soc.,' A, vol. 139, p. 659 (1933).

‡ 'Proc. Roy. Soc.,' A, vol. 139, p. 369 (1933).

to the formation of ThB, we conclude that all these nuclei (including ThB) possess the same value of spin, and one can hardly doubt that this value is zero ( $i_0(\text{ThB}) = 0$ ). Now ThB emits a continuous  $\beta$ -spectrum belonging to the class I and possesses a quadrupole  $\gamma$ -line,  $\gamma = 0.24 \times 10^6$  e.v., with absolute intensity unity.<sup>†</sup> Thus we must say that observed  $\beta$ -spectra (with  $E_{\text{max}} = 0.36 \times 10^6$  e.v.) represents the permitted transformation of the ThB-nucleus into the excited state of the ThC-nucleus, and that this later state

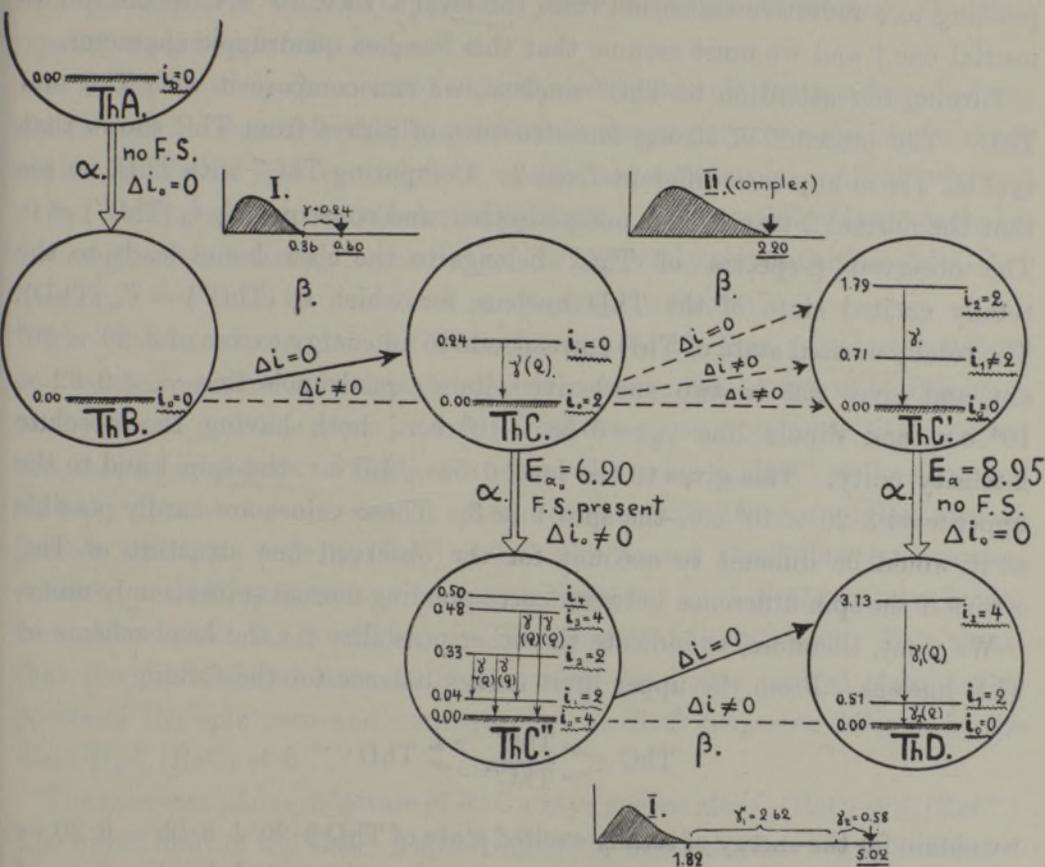


FIG. 1.

possesses the spin  $i_n(\text{ThC}) = 0$ . The spin of the normal state of ThC must be consequently  $i_0(\text{ThC}) = 2$  as the value 0 would permit the  $\beta$ -transformation between the normal state and the value 1 is excluded by the quadrupole character of the  $\gamma$ -ray,  $0.24 \times 10^6$  e.v.

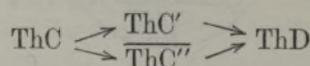
The second  $\beta$ -transformation leads from ThC to ThC'. The absence of the fine-structure of  $\alpha$ -rays from ThC' shows that the normal state of this nucleus possesses the same spin as the normal state of ThD. But from spectro-

<sup>†</sup> 'Proc. Roy. Soc.,' A, vol. 139 p. 639 (1933).

scopic evidence it seems very plausible that  $\text{ThD} = {}^{208}\text{Pb}$  possesses no spin. Thus:  $i_0(\text{ThC}') = 0$  and the normal  $\beta$ -transformation  $\text{ThCC}'$  must be not-permitted in agreement with the fact that the observed  $\beta$ -spectra of  $\text{ThC}$  belongs to the class II. The two levels  $0.71 \times 10^6$  e.v. and  $1.79 \times 10^6$  e.v. estimated from  $\text{ThC}'$  long-range  $\alpha$ -groups, correspond respectively to the permitted and not-permitted  $\beta$ -transformations. Thus the corresponding spins are  $i_2 = 2$  and  $i_1 \neq 2$ . There seems to exist in the  $\gamma$ -spectra of  $\text{ThC}'$  a weak line corresponding to a radiative transition from the level  $1.79 \times 10^6$  e.v. to the fundamental one,† and we must assume that this line has quadrupole character.

Turning our attention to  $\text{ThC}''$  nucleus, we can compare it with  $\text{ThC}$  and  $\text{ThD}$ . The presence of strong fine-structure of  $\alpha$ -rays from  $\text{ThC}$  shows that  $i_0(\text{ThC}'')$  is in any case different from 2. Comparing  $\text{ThC}''$  with  $\text{ThD}$ , we see that the normal  $\beta$ -transition is not-permitted, and consequently  $i_0(\text{ThC}'') \neq 0$ . The observed  $\beta$ -spectra of  $\text{ThC}''$  belongs to the class I and leads to the totally excited state of the  $\text{ThD}$  nucleus, for which  $i_0(\text{ThC}'') = i'_n(\text{ThD})$ . The totally excited state of  $\text{ThD}$  corresponds to an energy-excess of  $3.20 \times 10^6$  e.v. and gives rise to two successive  $\gamma$ -lines: quadrupole line  $\gamma_1 = 2.62 \times 10^6$  e.v. and dipole line  $\gamma_2 = 0.58 \times 10^6$  e.v., both having the absolute intensity unity. This gives to the level  $0.58 \times 10^6$  e.v. the spin 1 and to the upper level  $3.20 \times 10^6$  e.v. the spin 1 or 3. These values are hardly possible as it would be difficult to account for the observed fine structure of  $\text{ThC}$   $\alpha$ -rays if the spin-difference between corresponding normal states is only unity.

We want, therefore, to indicate the other possibility for the level scheme of  $\text{ThD}$  nucleus. From the upper limit energy-balance for the forking



we obtain for the energy of totally excited state of  $\text{ThD}$   $2.20 + 8.95 - 6.20 - 1.82 = 3.13 \times 10^6$  e.v., which is more nearly represented by the sum of  $\gamma_1 = 2.62 \times 10^6$  e.v. and the other  $\gamma$ -line  $\gamma_2 = 0.51 \times 10^6$  e.v., corresponding to the quadrupole-transition and having the absolute intensity 0.3. If we accept the  $\gamma$ -line  $0.51 \times 10^6$  e.v. instead of  $0.58 \times 10^6$  e.v. we must give to the first level ( $0.51$ ) the spin 2 and to the top-level ( $3.13$ ) the spins 0 or 4. As the value 0 is excluded (otherwise the normal  $\beta$ -transformation  $\text{ThC}''\text{D}$  would be permitted), we must accept for the upper level of  $\text{ThD}$  and, consequently for the normal state of  $\text{ThC}''$ , the spin 4, as is indicated in our diagram. This would give the spin-difference  $\Delta i_0 = 4 - 2 = 2$  to the normal  $\alpha$ -group of  $\text{ThC}$ .

† Skobelzyn, 'C. R. Acad. Sci. Paris,' vol. 194, p. 1486 (1932).

As, on the other hand, the group  $\alpha_3$  seems to possess the same  $\Delta i$  as  $\alpha_0$ † we must accept for the excited state 0.48 of ThC'' nucleus also the value  $i_3 = 4$ . This fits with the fact that the  $\gamma$ -transition from this level to a fundamental one has quadrupole character. The levels 0.04 and 0.33, connected with 0.00 and 0.48 by quadrupole  $\gamma$ -transitions, may have  $i = 2$  or  $i = 4$ ; we choose  $i = 2$ , as the corresponding fine-structure  $\alpha$ -components are relatively strong. The evidence about the level 0.50 is indecisive as the only known  $\gamma$ -transition can be a quadrupole as well as a dipole one; the extremely high intensity of corresponding  $\alpha_4$ -group is also surprising.‡

It must, however, be noticed that the selection-rule for quadrupole transitions used in the article of Ellis and Mott is correct only for a model of a single radiating particle in a central field, and is not necessarily applicable to real nuclei consisting of a great number of particles. The possibility is not excluded (although not necessarily required) that for real nuclei the transitions  $\Delta i = \pm 1$  (except  $0 \rightarrow 1$ ) may be permitted in quadrupole radiation.

The evidence concerning the two other radioactive families is less complete, and we shall mention only the main points. As the  $\beta$ -spectrum of RaB belongs to the class I and also some intense  $\gamma$ -lines are present we must either regard this case as analogous to ThB, and accept the value  $i_0$  (RaC)  $\neq 0$  or suppose that the normal and also one or several of the excited states of RaC nucleus possess the spins zero ( $i_0$  (RaC) = 0). The second possibility is, however, excluded as RaC' possesses a transition from the level 1.414 to the fundamental one which is, as well known, not permitted in radiation. This means that the fundamental state of RaC' nucleus (and also excited state 1.414) possesses the spin zero and consequently, as RaC  $\beta$ -spectrum belongs to the class II,  $i_0$  (RaC)  $\neq 0$ .

The existence of fine structure of RaC  $\alpha$ -rays give us also  $i_0$  (RaC)  $\neq i_0$  (RaC''). The upper limit of the RaC''  $\beta$ -spectrum is not measured but can be estimated from upper-limit energy balance and belongs to the class II. Thus

† Gamow and Rosenblum, *loc. cit.*

‡ [Note added in proof, May 23, 1934,—The detailed investigation of the relative intensities of different components of  $\beta$ -spectra has shown that it is difficult to account for the observed intensity of the normal  $\beta$ -group of ThC accepting the spin-difference  $i_0$  (ThC) -  $i_0$  (ThC') to be equal to 2 units; it seems necessary to accept for it the value 1. As the value for  $i_0$  (ThC) = 2 seems to be rather definite we must accept for  $i_0$  (ThD) the value 1 and explain the absence of hyperfine structure in the optical spectra of lead by the vanishing of the corresponding Landé-factor. This will change our arguments concerning this part of the diagram and the spins of the normal and two excited states of ThD-nucleus will now be: 1; 2; 4 (accepting the level 0.58) or 1; 1; 3 (accepting the level 0.51). The first hypothesis seems now to be more probable.]

$i_0(\text{RaC}'') \neq i_0(\text{RaD})$ . For RaD we probably have a situation analogous to RaB, and for the RaEF transformation we get  $i_0(\text{RaE}) \neq i_0(\text{RaF})$ .

The actinium-family is rather analogous to that of thorium and radium with the difference, however, that both the AcCC' and AcC''D  $\beta$ -transformations (upper limit of AcC  $\beta$ -spectra being again estimated from energy-balance†) seems here to belong to permitted transitions. One must, however, be very careful with the upper limits of  $\beta$ -spectra estimated in the above way.

In speaking about the energy-distribution in continuous  $\beta$ -spectra we must conclude that  $\beta$ -spectra of ThB and ThC'' must be simple. On the other hand the spectra of ThC must be constructed from different  $\beta$ -components corresponding to the excitation of different ThC' levels; the same kind of complexity we must also ascribe to continuous  $\beta$ -spectra of RaC leading to strongly excited RaC' nucleus. Ellis and Mott‡ tried to construct these complex spectra from different components with relative intensities defined by the percentage of excitation of corresponding levels of C'-products. Their constructions, however, may not be quite correct, as they assumed that all  $\beta$ -components have the same shape as the second class spectra of RaE, when it seems that some of these components belong to first class transitions (ThC'' component in the mixture ThC-ThC'' and the slowest components of ThC and RaC spectra) and, consequently, may have different shape.

The author is very glad to express his thanks to Professor N. Bohr for the kind interest and helpful discussion of this paper.

† Beck, 'Nature,' vol. 132, p. 967 (1933).

‡ 'Proc. Roy. Soc.,' A, vol. 141, p. 502 (1933).