77. ON NUCLEAR ENERGETICS AND BETA-ACTIVITY

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Abstract

The following is an attempt to discover regularities in the energetics of the β^+, β^- and γ-emissions, and of K-capture of different nuclei. It follows an earlier attempt by the senior author, S. C. Sirkar and K. C. Mukherjee (1940) to find out empirical rules of stability of nuclei. The authors have deduced, from the Weizsäcker-Bethe formula, expressions for energy-release in the case of β-transitions and K-capture, which involve only the isotopic number term, the coulomb-interaction terms, and spin-dependent terms in the mass-defect formula. The nuclei have been classified into group having a definite value of I, and the theoretical results have been compared to the observed ones. Generally good agreement has been obtained in the case of nuclei belonging to the seven groups $I=-1$ to $I=6$ whose properties are well determined. A few glaring anomalies have been pointed out, e.g. Ca^{48} announced as a rare stable isotope of calcium by Nier, cannot possibly exist as a stable nucleus. This has also been pointed out by I. Curie. Many apparent anomalies from empirical rules of stability have been explained. The present work covers all nuclei from $I=-1$ to $I=6$, and further work is contemplated.

Introduction

Ever since the discovery by the Joliot-Curies of the phenomenon of induced radioactivity, a very large number of radioactive nuclei (exceeding 400) has been prepared in the laboratory in addition to those existing naturally. In recent years, new types of radioactive nuclei have been obtained from fission of heavy nuclei like U, Th and Pa. The data so far collected in the different laboratories of the world form a rather bewildering mass, as can be easily seen from a glance at the comprehensive tables of isotopes given by Turner (1940), Livingood and Seaborg (1944) and Seaborg (1944). In many cases, the designation of a new isotope by mass is not quite unambiguous; indeed this is a very acute problem for fission products.

Several attempts at a regularisation of data have been made by previous workers, but we may start with a paper by Saha, Sirkar and Mukherjee (1940) where references to previous works will be found. In the present paper the notation used in the previous work will be employed, but it is repeated in order to spare the reader the trouble of constantly looking back for reference.

The chart of atomic nuclei—The essence of the paper by Saha *et al.* is a comprehensive chart of atomic nuclei, hereinafter called the Nuclear Chart. A section of it is shown in Fig. 1. In this the abscissa represents mass-number A, the ordinate represents the isotope number $I=N-Z$, which represents the excess of neutrons over protons in any nucleus. A ranges from 1 to 239, and I from -1 to about 54. The section of the chart reproduced here extends from $I=-1$ to $I=8$. We have attempted to make the chart as up-to-date as possible. The parallel lines at 45° to be henceforth called the Z-lines, represent the atomic number Z. Thus all isotopes of the element Z are to be found on the same Z-line. Each isotope is represented by a circle. Solid circles (●) represent 'Stable nuclei'. Hollow circles (♂) with an arrow pointing upwards represent β^+ (positron) emitting nuclei. When the arrow points down (♀), it indicates that the nucleus is β^- (electron) emitting. Circles with arrows pointing both up and down like ⚥ indicate that the nucleus emits both negatrons and positrons, e.g. Cu^{64}. ♂ denotes that the nucleus decays by K-capture only. ⚲ denotes that the nucleus decays by K-capture as well as by positron-emission. ♀ denotes that the nucleus has been obtained in 'fission'; such nuclei are all β^--emitting. If any particular isotope has two different half-lives (isomers), both half-lives are given (cf. Co^{60}). Saha, Sirkar and Mukherjee (1940) gave the following rules of stability, some of which have been previously known.

Rule 1.—I=even: When I is even, say 4, we get alternation of stable and β-active nuclei. All even-even nuclei having Z=even, N=even are stable. All odd-odd nuclei (Z=odd, N=odd) are unstable. This rule has also been given by Bethe and Bacher (1936). Exceptions are (*a*) for even-even nuclei: He^6, Be^{10}, C^{14}, Pb^{210} (RaD) which are all β^--emitting, (*b*) for odd-odd nuclei: H^2, Li^6, B^{10}, N^{14} which are all stable.

Rule 2.—I=odd: If in any of the odd groups, we arrange the nuclei in order of their mass-number, we first find β^--active nuclei, then arrive at a number of succeeding stable nuclei, which are followed by nuclei decaying by β^+-emission or K-capture. The number of stable nuclei in any group has been found sometimes as large as 13, and sometimes as small as 3. There are a few exceptions to this rule which will be mentioned in proper places.

These rules apply only to known nuclei. Supposing for any particular I, say $I=4$, which starts from P^{34} and ends at Ga^{66}, the membership is extended on both sides. Would they continue to obey this rule ? Would Na^{26}, Al^{30}, Si^{32}, As^{70}, Br^{74}, and Rb^{78}, etc. which are at present unknown be found stable when they are made in the laboratory or would they be unstable ?

In this paper, attempt has been made to obtain an explanation of the above rules and at a quantitative expression for the energy-release of β-emission of nuclei.

§1. Notation and Formulae used

Let us now explain the notation and formulae used for explaining the empirical rules of stability, and further, as we shall see, for arriving at some regularity in the nature of β-emissions. We use the following symbols:—

${}_ZM^A$ =mass of the bare nucleus 'M' with mass-number A and atomic number Z.

$M(Z, A)$ =mass of the full-atom (i.e. of the nucleus plus the Z-electrons),

$$={}_ZM^A+Zm. \quad .. \quad (1.1)$$

Energetics of β-emission:

(A) β^--emission—A nucleus ${}_ZM^A$ when emitting a β^--particle, and transforming to ${}_{Z+1}M^A$ will release the energy E^- given by

$$E^-={}_ZM^A-{}_{Z+1}M^A-m=M(Z,A)-M(Z+1,A)\ldots \quad (1.2)$$

This energy E^- is the total energy released in the β^--transition, i.e. it is the sum of the end-energy of the liberated electrons and the total sum of the energies of the γ-rays genetically connected with these electrons.

(B) β^+-emission—A nucleus ${}_ZM^A$ when emitting a β^+ -particle and transforming to ${}_{Z-1}M^A$ will release a total amount of energy E^+ given by

$$E^+={}_ZM^A-{}_{Z-1}M^A-m=M(Z,A)-M(Z-1,A)-2m. \quad (1.3)$$

(C) K-capture—The K-capture phenomenon was first discovered by Alvarez (1938) and its theory was earlier given by Yukawa and Sakata (1935) and independently by Möller (1937). An account is included in the report on β-decay by Konopinski (1943). When a K-electron is captured by a nucleus ${}_ZM^A$, it changes to ${}_{Z-1}M^A$ and the total energy released E^K is given by

$$E^K={}_ZM^A+m(1-\alpha^2Z^2)^{\frac{1}{2}}-{}_{Z-1}M^A,$$
$$=M(Z,A)-M(Z-1,A)-m\{1-(1-\alpha^2Z^2)^{\frac{1}{2}}\}. \quad (1.4)$$

Here $m(1-\alpha^2Z^2)^{\frac{1}{2}}$ represents the total mass of the captured K-electron, according to Dirac. Combining (1.3) and (1.4) we observe that if

$$2m>M(Z,A)-M(Z-1,A)>m\{1-(1-\alpha^2Z^2)^{\frac{1}{2}}\}\simeq m\alpha^2Z^2, \quad (1.5)$$

for light elements, then only K-capture will take place. But if

$$2m<M(Z,\ A)-M(Z-1,\ A), \quad .. \quad (1.6)$$

K-capture as well as positron-emission may take place. In fact there is a competition between the two processes. As the difference $M(Z,\ A)-M(Z-1,\ A)$ becomes larger and larger than $2m$, positron-emission predominates over K-capture. The point has been discussed in detail by Konopinski (1943).

To obtain the exact value of E^+, E^-, and E^K we have to know the value of the masses $M(Z,\ A)$, $M(Z+1,\ A)$, $M(Z-1,\ A)$ correctly. The empirical method of doing so is to measure the atomic mass correctly in the mass-spectrograph, as has been done by Aston and others. These workers express the exact value of $M(Z,\ A)$ in terms of a packing fraction f defined by

$$f=\frac{M(Z,\ A)-A}{A},\ \text{i.e.}\ M(Z,\ A)=A(1+f). \quad .. \quad (1.7)$$

Tables of $M(Z,\ A)$ and f are given by Aston (1942), Dempster (1936), Mattauch and Flügge (1942), Graves (1939) and Duckworth (1942).

Though f has been determined for a large number of nuclei, there are many important gaps and some of the older determinations have to be revised. The masses of radioactive nuclei have to be obtained from the energetics of reactions used to produce them.

Binding energy of nuclei.—The binding energy of a nucleus ${}_ZM^A$ is given by

$$\triangle M(Z,\ A)=NM_n+ZM_p-ZM^A=(\cdot 00853-f)A+\cdot 0004I. \quad (1.8)$$

Thus whenever the packing fraction is given, we may calculate the binding energy $\triangle M(Z,\ A)$ for the formation of a nucleus out of Z-protons and N-neutrons.

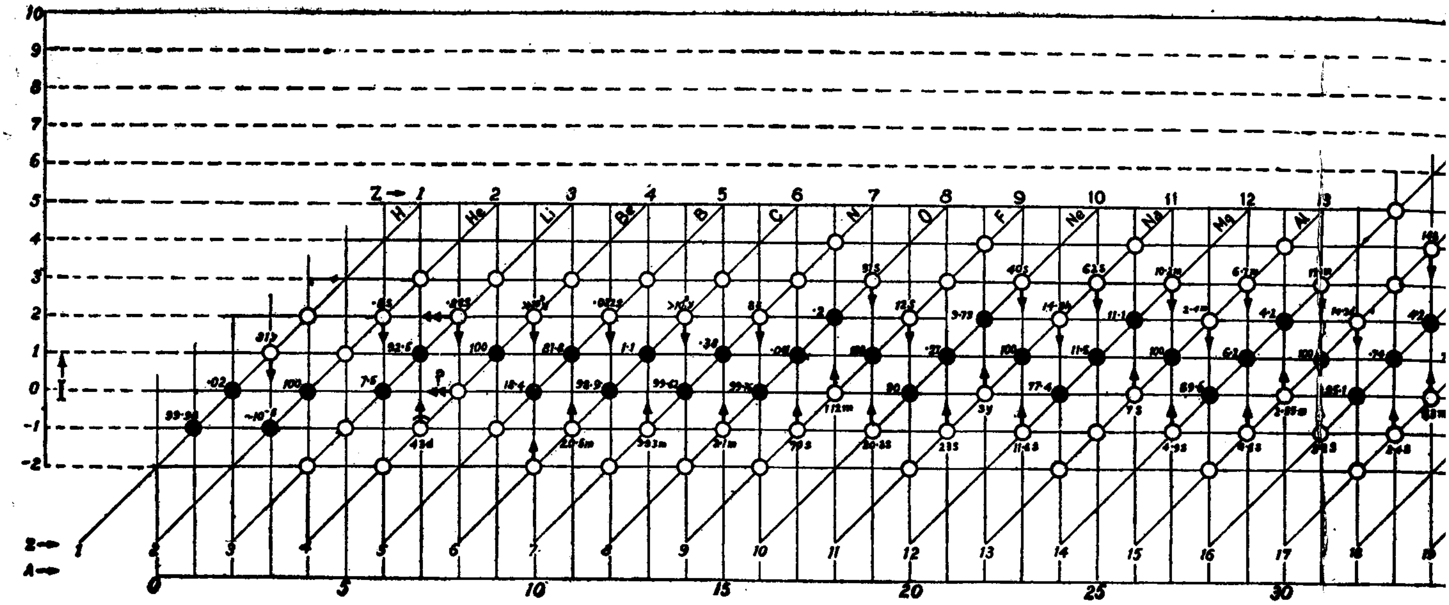
The binding energy formula based on the classical liquid drop model.—Several semi-empirical formulae for binding energy have been given. We have used in this paper the formula used by Bethe (1936) which is a modified form of one first introduced by Weizsäcker (1935), and we have added to it a term $\chi\ (Z,\ A)$ presently to be explained. The formula is

$$\triangle M(Z,\ A)=\phi(Z,\ A)+\chi(Z,\ A), \quad .. \quad (1.9)$$

where $\phi(Z,\ A)$ is the part due to Weizsäcker and Bethe, viz.

$$\phi(Z,\ A)=\alpha A-\beta\frac{I^2}{A}-\gamma A^{\frac{2}{3}}-\delta\frac{Z^2}{A^{\frac{1}{3}}}. \quad .. \quad (1.10)$$

330 (1)



THE NUCLEAR CHART

330 (2)

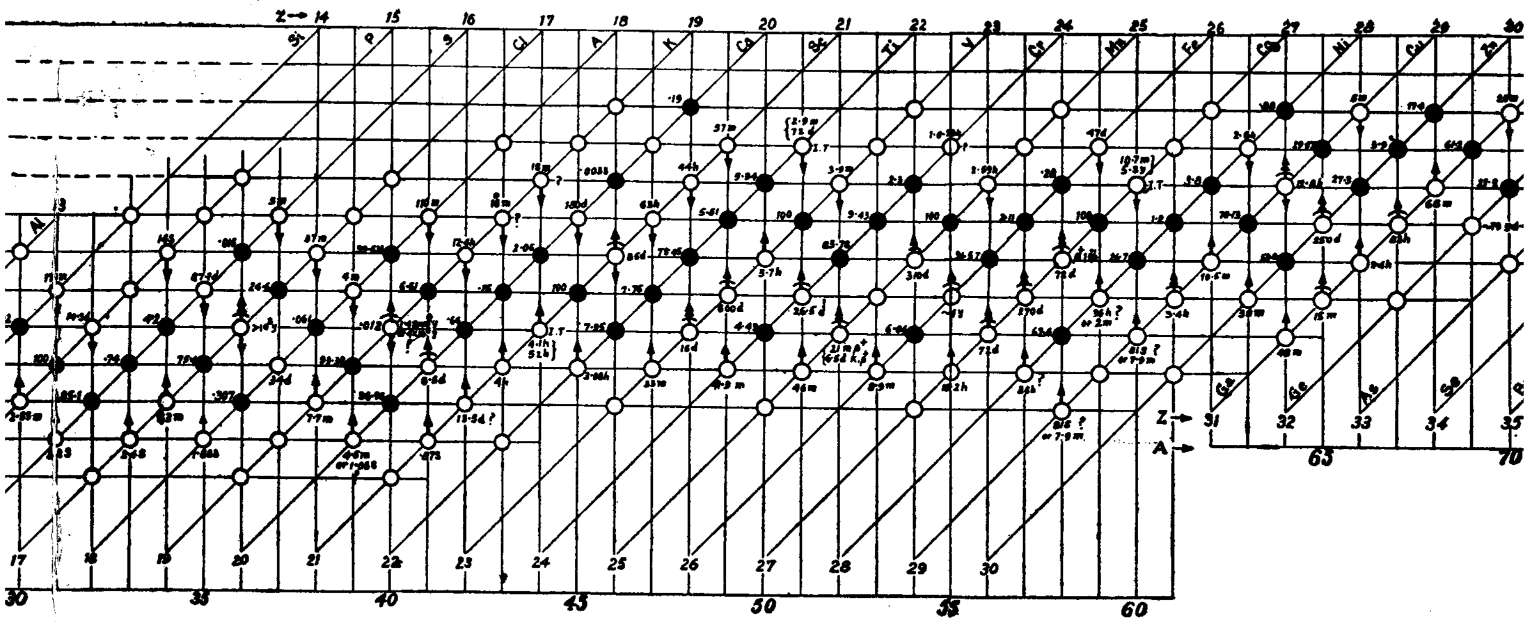
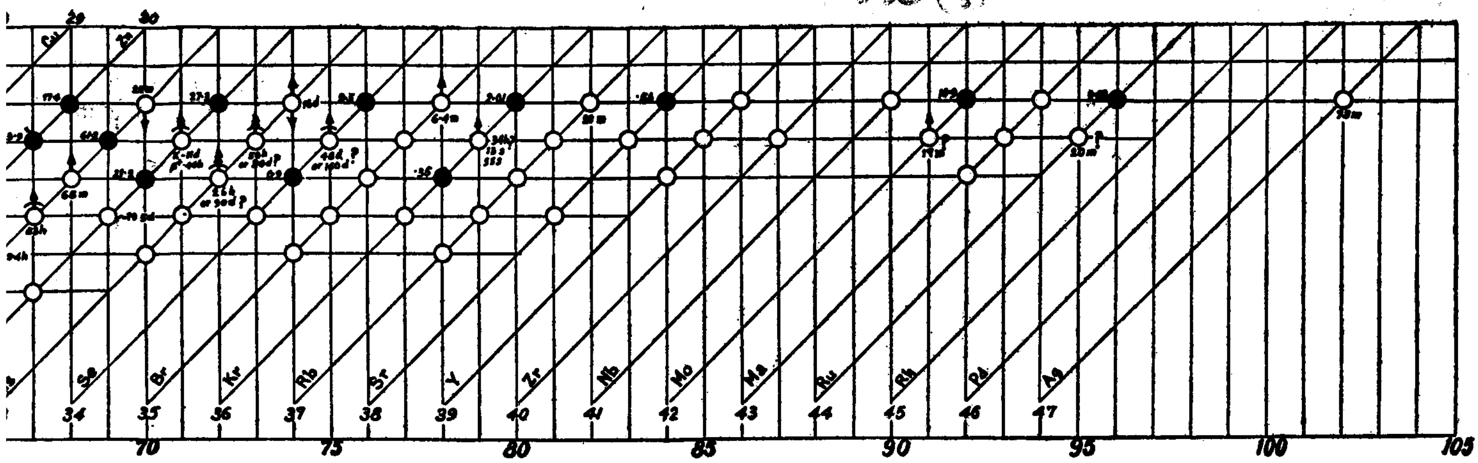


FIG. 1.

330 (3)



It is known empirically that $\triangle M(Z, A) = \phi(Z, A)$, i.e. $\chi(Z, A) = 0$ only for even Z, and even N for which the nuclear spin i is generally zero. All other nuclei have finite spin. For them $\chi(Z, A)$ will be finite. We shall call $\chi(Z, A)$ the spin-dependent part of nuclear binding energy. Usually this part was neglected as being too small compared to the other terms in the mass-defect formula. Our work will show, however, that this term, although negligible compared to the other terms in the binding energy formula, viz. ($\alpha A, \gamma A^{\frac{2}{3}}$), being of the order of 3 Mev in most cases, grows in importance when one applies the binding energy formula to explain the energy-release in β-decay processes, for the terms αA, $\gamma A^{\frac{2}{3}}$ cancel out.

It is also known that a nucleus may have different values of spin i, in other words $\chi(Z,A)$ may be *multivalued.* This brings us to the question of nuclear levels and isomeric states which will be taken up later.

The spin-independent part of $\triangle M(Z,A)$ contains four constants

$$\alpha, \beta, \gamma, \delta.$$

Of these only δ is known from theory with certain amount of definiteness. It is given by

$$\delta = \frac{3}{5}\frac{e^2}{r_0}, \text{ where } r_0 = \text{a nuclear constant} \simeq \frac{e^2}{m_0 c^2}.$$

The other constants are obtained in such a way that $\triangle M(Z, A)$ calculated from the Weizsäcker-Bethe formula fit with the experimental values. For details, see Bethe and Bacher (1936). Bethe gives the following values for the mass-defect constants

$\alpha = 13{\cdot}86$ Mev, $\beta = 19{\cdot}5$ Mev, $\gamma = 13{\cdot}2$ Mev, $\delta = {\cdot}58$ Mev.

It should be noted, however, that he took the neutron and proton masses to be 1·00845 MU and 1·00807 MU respectively. Repeating his calculations with the more recent values of the masses, viz. $M_n = 1{\cdot}00893$ MU and the mass of H^1 atom $= 1{\cdot}00813$ MU we get

$\alpha = 14{\cdot}058$ Mev, $\beta = 18{\cdot}9$ Mev, $\gamma = 13{\cdot}08$ Mev, $\delta = {\cdot}58$ Mev.

In what follows we have, however, taken $\beta = 19{\cdot}5$ Mev for it will be clear from subsequent discussions that for the groups at the beginning of the nuclear chart we need a value of β much greater than 18·9 Mev to explain the experimental facts. However, it is possible that for the groups $I = 6$ and groups beyond it, $\beta = 18{\cdot}9$ Mev, the standard value, will explain better the β-activity of the different members of these groups.

There are other mass-defect formulae, e.g. those due to Wigner (cf. Wigner and Feenberg, 1941), which has been used by Barkas (1939) in an attempt to obtain a finer analysis of nuclear binding energies. Probably by using these formulae, our results for energy-release would be improved, but we have not tried to use these formulae, as they are very complicated. We have, however, pointed out the defects arising from our formula in relevant places.

The masses and binding energies can be expressed in in terms of either

(*a*) Mass units or millimass units.
(*b*) Electron volts.
(*c*) Units of $m_0 c^2$(electron rest mass units).

We use the following conversion table:—

1 mMU $= {\cdot}9317$ Mev.
1 electron rest energy unit $= {\cdot}000549$ MU $= {\cdot}5112$ Mev.
1 Mev $= 1{\cdot}074$ mMU.

We have made use of Birge's (1941) summary of the general physical constants.

§2. Total Energy-release in β-emission

Let us now obtain values of E^-, E^+. and E^K. We have from (1.2)

$$E^- = M_n - M_p - m + \triangle M(Z+1, A) - \triangle M(Z, A).$$

Now using the mass-defect formula (1.9), it can be easily shown that

$$E^- = A^- + \chi(Z+1, A) - \chi(Z, A), \quad \text{.. (2.1)}$$

where A^- is the spin-independent part, being given by

$$A^- = M_n - M_p - m + \frac{4\beta(I-1)}{A} - \frac{\delta(A-I+1)}{A^{\frac{1}{3}}}. \quad \text{.. (2.2)}$$

In million electron volts, we have

$$A^- = {\cdot}766 + \frac{78(I-1)}{A} - \frac{{\cdot}58(A-I+1)}{A^{\frac{1}{3}}}, \quad \text{.. (2.3)}$$

where we have generally taken for β the value given by Bethe, viz. 19·5 Mev.

In a similar way, we have, for the energy-release in positron-emission

$$E^+ = -M_n + M_p - m + \triangle M(Z-1, A) - \triangle M(Z, A),$$
$$= A^+ + \chi(Z-1, A) - \chi(Z, A), \quad \text{.. (2.4)}$$

$$\text{where } A^+ = -M_n + M_p - m - \frac{4\beta(I+1)}{A} + \frac{\delta(A-I-1)}{A^{\frac{1}{3}}}. \quad \text{(2.5)}$$

In million electron volts, we have

$$A^+ = -1{\cdot}788 - \frac{78(I+1)}{A} + \frac{{\cdot}58(A-I-1)}{A^{\frac{1}{3}}}. \quad \text{.. (2.6)}$$

In the above derivations, we have taken β to be constant in the different groups. If we admit the possibility that

β may be a function of I, i.e. it changes from group to group, then we get

$$A^-=M_n-M_p-m+\frac{\beta(I)I^2-\beta(I-2)\,(I-2)^2}{A}-\frac{\delta(A-I+1)}{A^{\frac{1}{3}}},$$

$$A^+=-M_n+M_p-m+\frac{\beta(I)I^2-\beta(I+2)\,(I+2)^2}{A}+\frac{\delta(A-I-1)}{A^{\frac{1}{3}}}. \quad \ldots (2.7)$$

In this paper we shall, however, make no use of these formulae.

Lastly, we have

$$E^K=E^++m\{1+(1-\alpha^2Z^2)^{\frac{1}{2}}\}, \quad \ldots (2.8)$$
$$\simeq E^++2m-\tfrac{1}{2}m\alpha^2Z^2.$$

According to formulae (2.1) and (2.4), the values of E^+ and E^- depend on I, A, and the spin-dependent terms denoted by χ. It is therefore best to classify the nuclei into groups defined by definite values of the isotopic number I as Saha *et al.* (1940) have already done. We have, in the following, considered only a few groups at the beginning of the chart ranging from $I=-1$ to $I=6$. For each group, we have drawn the A^+ and A^- curves, with the values of A^+ and A^- defined by (2.3) and (2.6) as ordinate and A as abscissa.

The groups with I=even, may be divided into two classes.

1. Even-even nuclei (Z=even, N=even): For such nuclei we have

$$\left.\begin{aligned}E^-&=A^-+\chi(Z+1,\ A)<A^-,\\ E^+&=A^++\chi(Z-1,\ A)<A^+,\end{aligned}\right\} \quad \ldots (2.9)$$

because as has already been pointed out by Bohr and Wheeler (1939), $\chi(Z,\ A)$ is generally negative when Z is odd.

2. Odd-odd nuclei (Z=odd, N=odd): For these we have

$$\left.\begin{aligned}E^-&=A^--\chi(Z,\ A)>A^-,\\ E^+&=A^+-\chi(Z,\ A)>A^+,\end{aligned}\right\} \quad \ldots (2.10)$$

because Z being odd, $\chi(Z,\ A)$ is negative.

When I=odd, we have to use the original formulae (2.1) and (2.4) as none of the χ-functions vanish. As we shall see later $\chi(Z\mp1,\ A)$ and $\chi(Z,\ A)$ for odd-even or even-odd nuclei are in general nearly of the same order of magnitude so that $E^+\simeq A^+$, $E^-\simeq A^-$ or may differ by only few units.

It is obvious that a nucleus is stable with respect to β^--emission, when E^- is negative, and with respect to β^+-emission when E^+ is negative. But K-capture can take place even if E^+ is negative but $>-2m$. The ratio between the frequencies of these two processes, in the case of allowed transitions may be estimated as follows. They are expressed by the two factors f^K and f^+ where (see Konopinski, *loc. cit.*, pages 241 and 224)

$$f^K=2\pi(\alpha Z)^{2s+1}\,(2R)^{2s-2}\left[1+\frac{s}{(2s\,!)^2}\right](E^K)^2, \quad (2.11)$$

and $$f^+=u_+(Z)(\bar{p})^{2s-2}[v(W_0)-w_+(Z)(W_0-1)^3], \quad (2.12)$$

where $s=\sqrt{1-\alpha^2Z^2}$, W_0-1 =end-energy of the β^+-spectrum in m_0c^2 units. The definitions of the functions $u_+(Z)$, $v(W_0)$, $W_+(Z)$, $\bar{p}$ may be found in Nordheim and Yost (1937). Numerical values of these functions will be found in the review by Konopinski (1943). A formula similar to (2.12) holds for negatron-emission. For small Z

$$f^K\simeq2\pi(\alpha Z)^3(E^K)^2. \quad \ldots (2.13)$$

Deduction of E^-, E^+ and E^K from experimental data.—Radioactive nuclei release their energy in the form of energies of electrons, positrons, neutrinos, and γ-rays. In cases where we can be sure that no γ-rays are emitted, it is an easy matter to determine E^+ and E^-. These are, on current theories, merely equivalent to the end-energies of the β-ray spectra emitted by the nuclei, and whenever these end-energies have been correctly determined (this is by no means always the case) we have correct values of E^+ and E^-. It is more difficult to calculate E^K. This in the case of simple allowed K-capture is merely equivalent to the energy carried always by the 'neutrino', which is, however, unobservable. E^K has therefore in such cases to be determined from the energetics of the reaction, but this is possible only in a few cases (e.g. see the determination of E^K by Haxby *et al.*, 1940). In some cases E^+ and E^- also may be obtained from the energetics of the reaction which produces the nucleus in question.

When γ-rays are emitted, the situation becomes extremely complex. A satisfactory scheme of nuclear levels has to be devised to fit in with experimental results. These cases have been dealt with in their proper places. In such cases the energy liberated E is the sum of the end-energies of the emitted β-particles and the energies of the γ-rays genetically connected to these β-particles.

Let us now take up the different groups one by one and see how the inclusion of the term $\chi(Z,\ A)$ in the mass-defect formula of Weizsäcker and Bethe serves to explain the empirical rules of stability mentioned above. We shall see that the discussion for the odd groups is entirely different from that for the even groups so that we shall have to treat them separately. We shall first take up the odd groups $I=-1$, $I=1$, $I=3$, and $I=5$ in §3. In §4 the even groups $I=0$, $I=2$, $I=4$ and $I=6$ will be discussed. In the discussion of each group we give a table in which all available information about the members of this group have been included. The methods of productions have been clearly indicated. The reactions characterised by the corresponding target nuclei being underlined, have been actually tried and the

TABLE I

$I = -1$

Nucleus	Percentage abundance	Mass	Spin	Magnetic moment	Half-life	E_{β^-} in Mev	E_K in Mev	E_{β^+} in Mev	E_γ in Mev	E^- in Mev	EK in Mev	E^+ in Mev	ft	Class
H^{1}	99·98	1·00813	1/2	+2·7896	..	..	..	..	..	..	..	..	..	..
He^{3}	$\sim 10^{-5}$	3·01711	..	..	..	..	..	..	..	..	..	..	..	..
Li^{5}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Be^{7}	..	..	..	..	43 d.	..	*	..	0·45	..	..	..	(1) 2300 (2) 5610	0A
B^{9}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
C^{11}	..	..	..	..	20·5 m.	..	..	0·95	..	..	..	0·95	3460	0A
N^{13}	..	..	..	..	9·93 m.	..	..	0·92 1·20	0·28	..	..	1·20	(1) 5480 (2) 8100?	0A
O^{15}	..	..	..	..	2·1 m.	..	..	1·7	..	..	..	1·7	4160	0A
F^{17}	..	..	..	..	70 s.	..	..	2·1	..	..	..	2·1	3350	0A
Ne^{19}	..	..	..	..	20·3 s.	..	..	2·2	..	..	..	2·2	1840	0A
Na^{21}	..	..	..	..	23 s.	..	..	..	..	..	..	..	5300	0A
Mg^{23}	..	..	..	..	11·6 s.	..	..	2·82	..	..	..	2·82	3090	0A
Al^{26}	..	..	..	..	7 s. ?	..	..	2·99 ?	..	..	..	2·99 ?	2400	0A
Si^{27}	..	..	..	..	4·9 s.	..	..	3·74 3·54	..	..	..	3·54	3550	0A
P^{29}	..	..	..	..	4·6 s.	..	..	3·63	..	..	..	3·63	3800	0A
S^{31}	..	..	..	..	3·2 s.	..	..	3·85	..	..	..	3·85	3260	0A
Cl^{33}	..	..	..	..	2·4 s.	..	..	4·13	..	..	..	4·13	3420	0A
A^{35}	..	..	..	..	1·88 s.	..	..	4·4	..	..	..	4·4	3450	0A
K^{37}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Ca^{39}	..	..	..	..	4·5 m. 1·06 s.	..	..	*	..	..	..	..	..	..
Sc^{41}	..	..	..	..	0·87 s.	..	..	4·94	..	..	..	4·94	2480	0A
Ti^{43}	..	..	..	..	..	..	..	..	..	..	..	..	..	..

Nucleus	Transmutation Table (TARGET NUCLEI.) (γ, n)	$(n, 2n)$	(p, γ)	(p, n)	(p, α)	(d, n)	$(d, 2n)$	(d, H^{3})	(α, n)	Remarks and special reactions
H^{1}	..	..	..	..	..	..	..	..	..	....
He^{3}	..	..	..	..	..	..	..	..	..	....
Li^{5}	Li^{6}	Li^{6}	He^{4}	..	..	He^{4}	..	Li^{6}	..	....
Be^{7}	..	..	Li^{6}	$\underline{Li^{7}}$	$\underline{B^{10}}$	$\underline{Li^{6}}$	Li^{7}	..	He^{4}	....
B^{9}	B^{10}	B^{10}	..	Be^{9}	C^{12}	..	Be^{9}	B^{10}	Li^{6}	....
C^{11}	C^{12}	$\underline{C^{12}}$	$\underline{B^{10}}$	$\underline{B^{11}}$	$\underline{N^{14}}$	$\underline{B^{10}}$	B^{11}	C^{12}	..	....
N^{13}	N^{14}	$\underline{N^{14}}$	$\underline{C^{12}}$	C^{13}	O^{16}	$\underline{C^{12}}$	C^{13}	$\underline{N^{14}}$	$\underline{B^{10}}$	....
O^{15}	$\underline{O^{16}}$	$\underline{O^{16}}$	$\underline{N^{14}}$	N^{15}	..	$\underline{N^{14}}$	N^{15}	O^{16}	$\underline{C^{12}}$	....
F^{17}	..	..	$\underline{O^{16}}$	O^{17}	Ne^{20}	$\underline{O^{16}}$	O^{17}	..	$\underline{N^{14}}$	....
Ne^{19}	Ne^{20}	Ne^{20}	..	$\underline{F^{19}}$	..	..	F^{19}	Ne^{20}	O^{16}	....
Na^{21}	..	..	Ne^{20}	$\underline{Ne^{21}}$	Mg^{24}	$\underline{Ne^{20}}$	Ne^{21}	..	..	....
Mg^{23}	$\underline{Mg^{24}}$	Mg^{24}	..	$\underline{Na^{23}}$	..	..	Na^{23}	Mg^{24}	Ne^{20}	....
Al^{26}	..	..	Mg^{24}	$\underline{Mg^{25}}$	Si^{28}	Mg^{25}	Mg^{25}	..	..	....
Si^{27}	Si^{28}	Si^{28}	..	$\underline{Al^{27}}$	..	..	Al^{27}	Si^{28}	Mg^{24}	....
P^{29}	..	..	Si^{28}	$\underline{Si^{29}}$	S^{32}	Si^{28}	Si^{29}	..	..	....
S^{31}	S^{32}	S^{32}	..	$\underline{P^{31}}$	..	..	P^{31}	S^{32}	$\underline{Si^{28}}$	..
Cl^{33}	..	..	S^{32}	$\underline{S^{33}}$	A^{36}	S^{32}	S^{33}	..	..	....
A^{35}	A^{36}	A^{36}	..	$\underline{Cl^{35}}$	..	..	Cl^{35}	A^{36}	$\underline{S^{32}}$	....
K^{37}	..	..	A^{36}	..	Ca^{40}	A^{36}	..	..	..	....
Ca^{39}	$\underline{Ca^{40}}$	$\underline{Ca^{40}?}$	..	K^{39}	..	..	K^{39}	C^{40}	A^{36}	....
Sc^{41}	..	..	Ca^{40}	..	..	$\underline{Ca^{40}}$	..	..	..	....
Ti^{43}	..	..	..	..	..	..	..	..	Ca^{40}	....

*Stars indicate that evidence for the emission has been found, but no measurement has been made.

Targets underlined indicate that the corresponding nuclear reaction has been tried. Targets not underlined indicate that the corresponding nuclear reaction has yet to be tried.

TABLE 2

$I=1$

Nucleus	Percentage abundance	Mass	Spin	Magnetic moment	Half-life	E_{β^-} in Mev	E_x in Mev	E_{β^+} in Mev	E_γ in Mev	E^- in Mev	EK in Mev	E^+ in Mev	ft	Class
H^3	..	..	..	..	31 y.	0·015	..	..	..	0·015	..	..	1410	0A
He^6	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Li^7	92·5	7·01818	3/2	+3·253	..	..	..	..	..	..	..	..	..	..
Be^9	100	9·01494	3/2	−1·176	..	..	..	..	..	..	..	..	..	..
B^{11}	81·6	11·01295	3/2	..	..	..	..	..	..	..	..	..	..	..
C^{13}	1·1	13·00766	1/2	+0·701	..	..	..	..	..	..	..	..	..	..
N^{15}	0·38	15·00495	1/2	+0·280	..	..	..	..	..	..	..	..	..	..
O^{17}	0·041	17·00449	..	..	..	..	..	..	..	..	..	..	..	..
F^{19}	100	19·00452	1/2	+2·622	..	..	..	..	..	..	..	..	..	..
Ne^{21}	0·27	20·99968	..	..	..	..	..	..	..	..	..	..	..	..
Na^{23}	100	22·99680	3/2	+2·216	..	..	..	..	..	..	..	..	..	..
Mg^{25}	11·5	24·99277	..	..	..	..	..	..	..	..	..	..	..	..
Al^{27}	100	26·9916	5/2	+3·628	..	..	..	..	..	..	..	..	..	..
Si^{29}	6·2	28·9864	..	..	..	..	..	..	..	..	..	..	..	..
P^{31}	100	30·9839	1/2	..	..	..	..	..	..	..	..	..	..	..
S^{33}	0·74	32·9818	..	..	..	..	..	..	..	..	..	..	..	..
Cl^{35}	75·4	34·97903	5/2	+1·368	..	..	..	..	..	..	..	..	..	..
A^{37}	..	..	..	..	34 d.	..	..	..	..	..	..	..	..	..
K^{39}	93·38	38·97518	3/2	+0·391	..	..	..	..	..	..	..	..	..	..
Ca^{41}	..	..	..	..	8·5 d.	..	*	..	1·1	..	..	..	..	..
Sc^{43}	..	..	..	..	3·92 h.	..	*	{0·4 1·4 / 1·11}	1·65	..	..	..	12×10^4	0B
Ti^{45}	..	..	..	..	3·08 h.	..	..	1·2	..	..	..	1·2	$5·5\times10^4$	0B
V^{47}	..	..	..	..	33 m.	..	..	1·9	..	..	..	1·9	$6·9\times10^4$	0B
Cr^{49}	..	..	..	..	41·9 m.	..	..	1·45	{0·18 / 1·55}	..	..	..	..	..
Mn^{51}	..	..	..	..	46 m.	..	..	2·0	..	..	..	2·0	$11·3\times10^4$	0B
Fe^{53}	..	..	..	..	8·9 m.	..	..	*	..	..	..	..	..	..
Co^{55}	..	..	..	..	18·2 h.	..	..	1·50	{0·16, 0·21, / 0·08, 1·2}	..	..	..	..	..
Ni^{57}	..	..	..	..	{36 h. ? / 2 m. ?}	..	..	0·67	..	..	..	..	..	..
Cu^{59}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Zn^{61}	..	..	..	..	..	..	..	..	..	..	..	..	..	..

TRANSMUTATION TABLE

Nucleus	(γ, n)	(γ, p)	(n, γ)	$(n, 2n)$	(n, p)	(n, α)	(p, γ)	(p, n)	(p, α)	(d, n)	$(d, 2n)$	(d, p)	(d, H^3)	(d, α)	(α, n)	(α, p)	Remarks and special reactions
H^3	..	He^4	H^2	..	He^3	Li^6	..	..	..	..	..	$\underline{H^2}$	$\underline{Be^9}$	..	..	..	{Li—n—H^3 / B—n—H^3 / N—n—H^3}
He^6	..	Li^6	He^4	..	..	..	..	..	..	..	..	He^4	..	Li^7	..	H^3	....
Li^7	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Be^9	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
B^{11}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
C^{13}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
N^{15}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
O^{17}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
F^{19}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Ne^{21}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Na^{23}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Mg^{25}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Al^{27}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Si^{29}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
P^{31}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
S^{33}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Cl^{35}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
A^{37}	A^{38}	..	A^{36}	A^{38}	..	$\underline{Ca^{40}}$	..	$\underline{Cl^{37}}$	..	..	$\underline{Cl^{37}}$	A^{36}	A^{38}	$\underline{K^{39}}$	$\underline{S^{34}}$	..	....
K^{39}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Ca^{41}	Ca^{42}	..	Ca^{40}	$\underline{Ca^{42}}$	..	..	..	K^{41}	..	..	K^{41}	$\underline{Ca^{40}}$	Ca^{40}	..	A^{38}	..	....
Sc^{43}	..	..	..	..	..	..	Ca^{42}	$\underline{Ca^{43}}$	Ti^{46}	$\underline{Ca^{42}}$	Ca^{42}	..	..	..	..	$\underline{Ca^{40}}$	....
Ti^{45}	$\underline{Ti^{46}}$	..	..	$\underline{Ti^{46}}$	..	..	..	$\underline{Sc^{45}}$	..	..	$\underline{Sc^{45}}$	..	Ti^{46}	..	$\underline{Ca^{42}}$	..	....
V^{47}	..	..	..	..	..	..	Ti^{46}	$\underline{Ti^{47}}$	Cr^{50}	$\underline{Ti^{46}}$	Ti^{47}	..	..	..	..	..	....
Cr^{49}	Cr^{50}	..	..	$\underline{Cr^{50}}$	..	..	..	..	..	..	..	..	Cr^{50}	..	$\underline{Ti^{46}}$	..	....
Mn^{51}	..	..	..	..	..	..	$\underline{Cr^{50}}$	..	Fe^{54}	$\underline{Cr^{50}}$	..	..	..	..	..	..	....
Fe^{53}	$\underline{Fe^{54}}$	..	..	$\underline{Fe^{54}}$	..	..	..	..	..	..	..	..	Fe^{54}	..	$\underline{Cr^{50}}$	..	....
Co^{55}	..	..	..	..	..	..	$\underline{Fe^{54}}$	..	Ni^{58}	$\underline{Fe^{54}}$	..	..	..	..	..	..	....
Ni^{57}	$\underline{Ni^{58}}$	..	..	$\underline{Ni^{58}}$	..	..	..	..	..	..	..	..	Ni^{58}	..	$\underline{Fe^{54}}$	..	{Assignment incomplete.
Cu^{59}	..	..	..	..	..	..	Ni^{58}	..	..	Ni^{58}	..	..	..	..	..	..	....
Zn^{61}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Ni^{58}	..	....

TARGET NUCLEI.

*Stars indicate that evidence for the emission has been found, but no measurement has been made.

Targets underlined indicate that the corresponding nuclear reaction has been tried. Targets not underlined indicate that the corresponding nuclear reaction has yet to be tried.

references will almost in all cases be found in Seaborg's Table (Seaborg, 1944). When the target nucleus is not underlined, the corresponding reaction has not yet been tried.

§3. The Odd Groups

A. *The Group* $I=-1$. (Fig. 2, Table 1.)

This group ranges from He^3 to Sc^{41}, leaving aside the proton which also algebraically belongs to this group. The nuclei Li^5, B^9, K^{37} have not yet been prepared. As will be clear from the transmutation chart in Table 1, we may perhaps produce Ti^{43} by the Ca^{40} (α, n)-reaction. He^3 is stable; all the rest are unstable, being either positron-emitting or decaying by K-capture.

The curve A^+ has been shown in Fig. 2. The points enclosed in small circles represent the experimentally observed values of E^+. It will be noticed that the experimental points lie quite close to the A^+-curve showing that $\chi(Z, A)$ and $\chi(Z-1, A)$ for these groups are nearly of the same magnitude. The β^+-emission process for this group falls under the $0A$ class of Konopinski (1943). The difference of A^+ and the experimental value of E^+ gives us an estimate of $\chi(Z-1, A)-\chi(Z, A)$.

Let us now consider the nuclei one by one.

Li^5: This nucleus is not yet known. It is theoretically very interesting because it formed the kernel of certain very remarkable astrophysical speculations. But neither Li^5 nor any other nucleus having the mass-number 5 has been

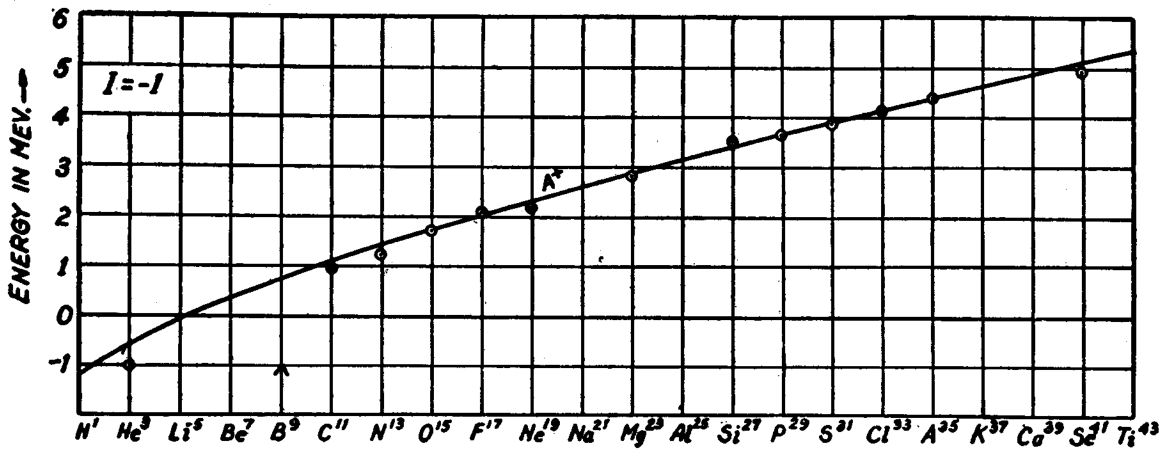


Fig. 2

It is easily seen that this group can have no β^--activity, for A^- for this group is highly negative. The energy-release for positron-emission is given by the simple formula

$$E^+=-1{\cdot}788+{\cdot}58A^{\frac{2}{3}}+\chi(Z-1, A)-\chi(Z, A).$$

The formula for E^+ does not contain the mass-defect constant β. It may be noticed in passing that the expected theoretical energy-release from the nuclei of these groups has been expressed in a somewhat different formula by White *et al.* (1940). According to them

$$E^+=-1{\cdot}788+\frac{{\cdot}6(A-1)}{A^{\frac{1}{3}}}.$$

They have assumed that the Coulomb energy term is given by

$$\frac{1{\cdot}27Z(Z-1)}{A^{\frac{1}{3}}}mc^2$$

(in electron-energy units) whereas we have followed Bethe who neglects 1 in comparison with Z and gets the usual expression

$$\frac{3}{5}\,\frac{Z^2}{r_0A^{\frac{1}{3}}}$$

which in million volts is given by $\cdot58\ Z^2/A^{\frac{1}{3}}$.

found so far. Since the abundance of Li^6 is only 7·5%, the Li^6 (n, $2n$)-reaction would unambiguously be convenient if separated Li^6 could be available. The other two reactions are difficult to carry out on account of the fact that it is not easy to prepare a suitable target of He. The experiment may be tried, however, by bombarding solid or liquid helium with a proton or a deuteron beam. If Li^5 is found it will probably turn out to be either stable, or decaying by extremely slow K-capture process to He^5, about which again there are very interesting speculations. We have shown later that if Li^5 is stable against break-up into He^4, n it will decay by K-capture to He^5 in about five years' time.

Be^7: According to investigations by Haxby *et al.* (1940) who studied Be^7 produced by the Li^7 (p, n)-reaction, the atomic mass-difference Be^7-Li^7, in our notation $M(4, 7)-M(3, 7)={\cdot}87$ Mev. The nucleus shows K-capture as well as emission of a γ-ray of energy ·450 Mev, the number of γ-rays to K-capture being 1:10 roughly. Attempt has been made by Breit and Knipp (1938) to explain the data on the basis that Li^7 has two nuclear states which can be designated as $P_{\frac{1}{2}}$, $P_{\frac{3}{2}}$; this is independently supported. Be^7, which is supposed to have the state $P_{\frac{3}{2}}$, can have an allowed K-capture producing Li^7 normal ($P_{\frac{3}{2}}$-state) or a forbidden K-capture, producing Li^7 excited with $P_{\frac{1}{2}}$-state. This excited Li^7, while making a transition to normal $P_{\frac{3}{2}}$-state, produces the γ-ray of energy ·450 Mev. Breit *et al.* have given a theory of the phenomenon which has been revised by Konopinski. The $f^K t$ for Be^7 comes out to be $\simeq 2300$, so that it supports the contention that the K-capture is allowed.

B^9: This nucleus has not yet been found though the Be^9 (p, n)-reaction was studied by Haxby *et al.* (1940) and $M(5, 9)-M(4, 9)$ was given as 1·08 Mev, which would enable B^9 to emit positrons of energy ·06 Mev, or decay by K-capture to Be^9. It is suggested by Bethe that B^9, immediately on formation, breaks up into Be^8, H^1 or into $2He^4$, H^1, as the mass of B^9 is ·20 Mev higher than the Be^8+H^1-mass.

C^{11}: According to Haxby *et al.* (1940), the $M(6, 11)$ $-M(5, 11)$ difference is 1·97 Mev corresponding to positron-emission of maximum energy ·95 Mev, which, as Haxby *et al.* remark, is in perfect agreement with the observed values of end-energy of β^+-spectrum.

N^{13}: The emission of this nucleus has been studied by a large number of workers. We may refer to the work of Watase (1940). The nucleus emits also a weak γ-ray of energy ·285 Mev and a β-spectrum of complicated type. Watase has given us an energy-level diagram from which it appears that the energy-release is 1·21 Mev, and the transition from the initial state of N^{13} to the final state of C^{13} is allowed. This is in accordance with the findings of Haxby *et al.* (1940). The γ-ray is from an excited state of C^{13}. It may be mentioned that the findings of Watase are in contradiction to those of previous workers, reference to whose works would be found in Watase's paper. These contradictions, however, refer to the γ-emission, not the value of the energy-release.

The value for end-energies of the β^+-spectra for the nuclei O^{15}, F^{17}, Ne^{19} and Mg^{23} have been obtained by the cloud-chamber method and ought to be revised. No data are available about Na^{21} yet. The 7 sec. half-period assigned to Al^{25} by White *et al.* is not quite certain as yet. They have tried the reaction Mg (p, n) so that they are not sure if the half-life observed is due to Al^{25} or Al^{26}. The β^+-spectra of P^{29}, S^{31}, Cl^{33}, A^{35} have been studied in the cloud-chamber by White *et al.* (1941), who have given a theoretical discussion of this group. The figure for the last nucleus of this group Sc^{41} has been given by Elliot and King (1941). Though the spectra of all these nuclei, with the exception of that of N^{13}, appear to be of a simple type, detailed and accurate investigations about the form of the spectra are still lacking.

B. *The Group* $I=1$. (Fig. 3, Table 2.)

The group extends from H^3 to Ni^{57}. The methods of production are reviewed in Table 2. It appears possible from Table 2 to produce nuclei of this group beyond Ni^{57}, viz. Cu^{59} and Zn^{61}. We first review the known properties of these nuclei. The only β^--emitting nucleus in this group is H^3, for, as will subsequently be shown, He^5 if ever discovered will perhaps be stable. The stable nuclei extend in unbroken sequence from Li^7 to K^{39}, with the exception of A^{37}. This is a mild violation of Rule 2 of Saha *et al.* From Ca^{41} all are either β^+-emitting or K-active. Let us consider the unstable nuclei in greater detail.

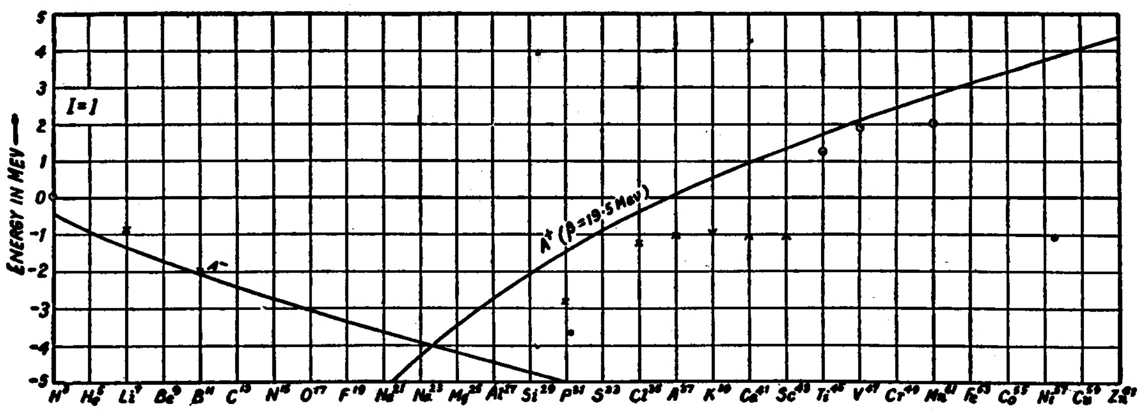


Fig. 3

A^{37}: All that is known about this nucleus is from a brief note by Weimer *et al.* (1941) who state that it decays, presumably to Cl^{37}, with a long period of 34 days. Probably it decays by K-capture, but nothing is yet reported about the emissions.

Ca^{41}: This has been shown by Walke *et al.* (1940) to decay by K-capture to K^{41} with a life of 8·5 days. A γ-ray of energy 1·1 Mev, which is internally converted to an extent of 10^{-1}, is also emitted. The large conversion shows that spin-change in the transition is probably high. No positrons are yet recorded, though the γ-ray energy value indicates that positrons of low energy should be emitted.

Sc^{43}: This nucleus has been studied by Hibdon, Pool and

Kurbatov (1945) who found that it decays with a half-life of 3·92 hrs. to Ca^{43} by positron-emission, the end-energy being given as 1·11 Mev. It also decays by K-capture and a γ-ray of energy 1·65 Mev is emitted. The probability of positron-emission to K-capture is stated to be 4 : 1. The transition is of the $0B$-type.

Ti^{45}: This nucleus has been prepared by Allen *et al.* (1941), by the process Sc^{45} (p, n) and its spectrum has been found to have the end-energy of 1·2 Mev, with a life of 3·08 hrs., the transition being of the $0B$-type. No γ-rays have yet been detected.

V^{47}: A 33-minute activity of radioactive vanadium has been ascribed to V^{47} by O'Connor *et al.* (1941) and the end-energy of the β^+-spectrum has been found to be 1·90 Mev. The transition is of the $0B$-type.

Cr^{49}: A 41·9 min. activity of radioactive chromium has been ascribed to Cr^{49} by O'Connor *et al.* (1941). The β^+-spectrum was found to have the end energy 1·45 Mev, but a number of γ-rays with energies ·18 Mev and 1·55 Mev have also been found. Cr^{49} decays to V^{49} which is radioactive and decays by K-capture to Ti^{49}. This sort of two-stage β^+-emission happens in the case of every other subsequent nuclei of this class.

Mn^{51}: According to a preliminary report by Livingood and Seaborg (1938), this nucleus emits a simple β^+-spectrum of end-energy 2 Mev (absorption). No γ-rays are reported. The transition is of the $0B$-type. They did not observe the product Cr^{51} to decay. This was probably due to the fact that Cr^{51} (see $I=3$) decays mainly by K-capture, and emits no positron of measurable energy. The energy-release is of simple type and may be taken to be $\simeq 2$ Mev. The nucleus merits reinvestigation.

Fe^{53}: An 8·9 min. nucleus obtained by the process Cr^{50} (α, n) has been ascribed by Ridenour and Henderson (1937) to Fe^{53} and supported by others. The life is in agreement with expectations but nothing is yet known of β-emission.

Co^{55}: The identification of this nucleus which has been produced only by the processes Fe^{54} (d, n) and Fe^{54} (p, γ) would be considered doubtful, as Fe^{54} has a small percentage. It does not appear possible to prepare it with any other starting material, hence confirmation has to be sought by increasing the concentration of Fe^{54}. The identification has, however, been confirmed by Livingood and Seaborg (1941) from the observation that Fe^{55} with a long life of 5·3 yrs. grows from this nucleus, but the nature of emission from Co^{55} is more complex than that from any other nucleus of this group. The positron-spectrum was found to be complex by Lawson (1939) with end-energy at 1·50 Mev, but the observations were not refined enough for splitting the curve into its constituents. A number of γ-rays have been obtained in the cloud-chamber by Curtis (1939) giving lines at ·16 Mev, ·21 Mev, ·8 Mev and 1·2 Mev, with intensities ·1, ·1, ·5 and ·1 of the annihilation radiation. The complexity of emission from Co^{55} renders it difficult to make any deduction about its energy-release in the transition from $Co^{55} \rightarrow Fe^{55}$. The problem merits more detailed investigation.

Ni^{57}: Radioactive nickel, produced by the processes indicated in Table 2, does not allow a clear assignment of mass, vide the discussion on Ni^{59} in the group $I=3$. We have assigned the 2 min.-period nickel to Ni^{57}, in accordance with the views of several workers, but in opposition to the views of Nelson *et al.* (1941), where previous references and a discussion of the problem will be found. Nothing appears yet to be known about the emission from Ni^{57}, but the best way for the identification of Ni^{57} would be to see if Co^{57} of 270 days' life grows from it.

Cu^{59}: An 81 sec. copper obtained by Delsasso *et al.* (1939) from the process Ni (p, n) has been assigned by the authors to Cu^{59}, but the assignment lacks confirmation. It would be interesting to observe the growth of Ni^{59} from the 81 sec. copper. Nothing as yet is known of its β^+-emission.

Zn^{61}: It is not yet known. There is a possibility that it can be prepared by the process Ni^{58} (α, n). It does not appear probable to prepare any heavier nuclei of this group by an ordinary reaction.

Let us now compare the positron-emitters of the group $I=-1$ with the electron-emitters of the group $I=+1$. For the positron-emission of a nucleus ${}_ZM^A$ of any particular group I, we have

$$E^+(Z, A) = A^+(Z, A) + \chi(Z-1, A) - \chi(Z, A), \qquad (3.1)$$

whereas for electron-emission of the nucleus $Z_{-1}M^A$ of the group $I+2$, we have

$$E^-(Z-1, A) = A^-(Z-1, A) + \chi(Z, A) - \chi(Z-1, A), \qquad (3.2)$$

so that

$$E^+(Z, A) + E^-(Z-1, A) = A^+(Z, A) + A^-(Z-1, A), \\ = -2m. \qquad (3.3)$$

It is easily seen that the right-hand side is independent of β. It is only necessary that β should be the same for the groups I and $I+2$. Thus taking the nuclei He^3 and H^3, we get

$$E^+(2, 3) = -1{\cdot}038 \text{ Mev} < -2m,$$

provided we take $E^-(1, 3) = {\cdot}015$ Mev as given by Nielson (1941). Thus He^3 is definitely stable against K-capture decay as well as β^+-decay. It is difficult to compare the energy-release of Li^5 with that of He^5, for nothing definite is known about He^5. We may, however, make a rough estimate of the E^- corresponding to He^5 and E^+ for Li^5. Before doing this let us compare the energy-releases of Be^7 and Li^7. As mentioned earlier Haxby *et al.* (1940) give

$$E^+(4, 7) = -{\cdot}153 \text{ Mev},$$

so that from (3.3)

$$E^{-}(3, 7) = -\cdot 87 \text{ Mev}.$$

Thus Li^7 should be stable against electron-emission as is actually the case. From (3.1) we get

$$\chi(4, 7) - \chi(3, 7) = \cdot 488 \text{ Mev},$$

whereas from (3.2) we get

$$\chi(2, 3) - \chi(1, 3) = \cdot 457 \text{ Mev}.$$

This suggests that $\chi(3, 5) - \chi(2, 5)$ may be of the same order of magnitude so that setting it equal to the mean of the above two values we get from (3.2)

$$E^{-}(2, 5) = -\cdot 462 \text{ Mev},$$

so that He^5 should be definitely stable against β^--emission. On the other hand from (3.1) we get

$$E^{+}(3, 5) = -\cdot 561 \text{ Mev},$$

so that Li^5 should be stable against β^+-activity but should decay by K-capture. From equation (2.13), we get

$$f^K(3, 7) \simeq 1\cdot 37 \times 10^{-5}.$$

If K-capture decay for Li^5 is allowed, we may take $f^K t$ for this nucleus to be of the same order of magnitude as that for Be^9, viz. 2300, so that for Li^5 the period of decay is expected to be

$$t(3, 5) \simeq 5 \text{ years}.$$

Next we may compare the energy-releases of B^9 and Be^9. Since Be^9 is stable we may take $E^{-}(4, 9) < 0$, i.e. from (3.3) we get

$$E^{+}(5, 9) > -1\cdot 022 \text{ Mev}.$$

Thus the nucleus B^9 may be expected to decay by K-capture or β^+-emission. In this way the discussion may be continued for the heavier members of these two groups and it will be found that the fact that the remaining nuclei of the group $I=1$ are not β^--active is consistent with the property that the corresponding nuclei of the group $I=-1$ decay by β^+-emission or K-capture.

C. *The Group* $I=3$. (Fig. 4, Table 3.)

This group extends from O^{19} to Ga^{65} of which the nuclei from O^{19} to S^{35} are β^--emitting. From Cl^{37} to Ti^{47} all are stable with the exception of A^{39}, a β^--emitting nucleus. From V^{49} to Ga^{65} we have nuclei decaying by K-capture or positron-emission. A glance at the transmutation table (Table 3) will show that it is possible to extend this group on the lighter side to He^7 by the Li^7 (n, p)-reaction. On the heavier side we may extend the group up to Ge^{67} by the $Zn^{64}(\alpha, n)$-reaction.

Let us now examine the members one by one in detail.

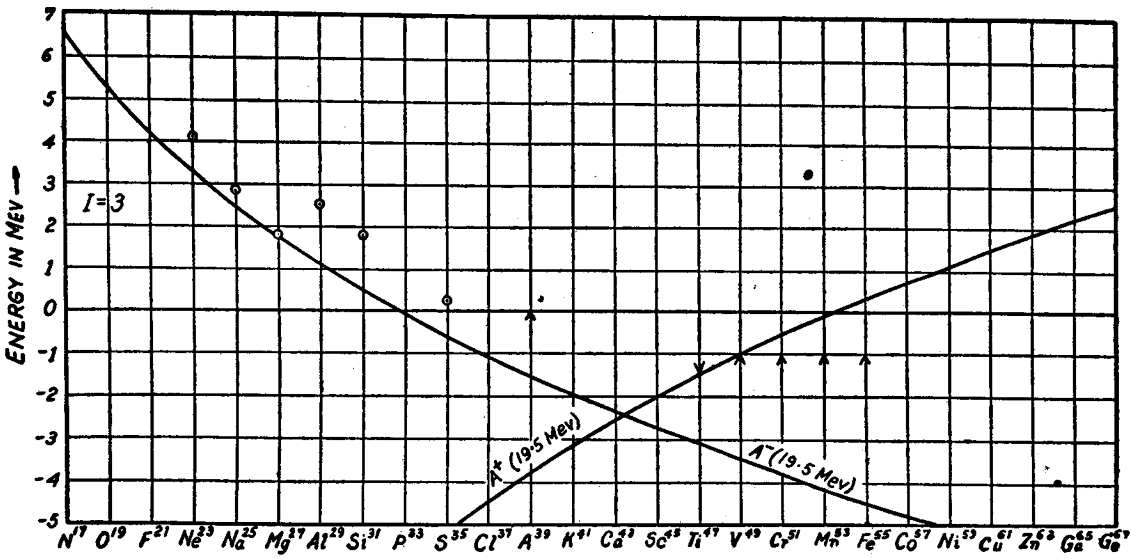


Fig. 4

O^{19}: Nothing is known of this nucleus, beyond a mere statement that it has a life of 31 sec. and that $E^{-} > 3\cdot 2$ Mev (Huber *et al.*, 1944). Probable methods of production are given in Table 3.

Ne^{23}: Huber *et al.* (1943) have produced the nucleus by the reaction Mg^{26} (n, α) and give a life of 40 sec., with $E^{-} = 4\cdot 1$ Mev.

Na^{25}: This has been investigated by Huber *et al.* (1943) who get a life of 62 sec. and $E^{-} = 2\cdot 8$ Mev.

Mg^{27}: The β^--spectrum was investigated by the cloud-chamber method (Crittenden, 1939) and found to be $1\cdot 8$ Mev. Other values are $2\cdot 05$ Mev (Henderson, 1935) by absorption experiments and $1\cdot 96$ Mev (Widdowson and Champion, 1938). No γ-rays are yet reported.

Al^{29}: As the end-energy of the β^--spectrum has been obtained (Bethe and Henderson, 1939) by the cloud-chamber

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TABLE 3

$I=3$

Nucleus	Percentage abundance	Mass	Spin	Magnetic moment	Half-life	E_{β^-} in Mev	E_K in Mev	E_{β^+} in Mev	E_γ in Mev	E^- in Mev	E^K in Mev	E^+ in Mev	ft	Class
He^7	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Li^9	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Be^{11}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
B^{13}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
C^{15}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
N^{17}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
O^{19}	..	..	..	..	31 s.	>3·2	..	..	..	..	..	..	..	..
F^{21}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Ne^{23}	..	..	..	..	40 s.	4·1	..	..	..	4·1	..	..	$1{\cdot}0\times10^5$	1*A*
Na^{25}	..	..	..	..	62 s.	2·8	..	..	0·035	2·835	..	..	..	..
Mg^{27}	..	..	..	..	10·2 m.	1·8	..	..	{0·64, 0·84, 1·02}	..	..	..	$0{\cdot}4\times10^5$	1*A*
Al^{29}	..	..	..	..	6·7 m.	2·5	..	..	..	2·5	..	..	$1{\cdot}0\times10^5$	1*A*
Si^{31}	..	..	..	..	170 m.	1·8	..	..	..	1·8	..	..	$7{\cdot}6\times10^5$	1*A*
P^{33}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
S^{35}	..	..	..	..	87·1 d.	0·103	..	..	0·13	0·233	..	..	$2{\cdot}37\times10^4$	0*B*
Cl^{37}	24·6	36·97786	5/2	+1·136	..	..	..	..	..	..	..	..	..	..
A^{39}	..	..	..	..	4 m.	..	..	..	..	..	..	..	..	..
K^{41}	6·61	40·9739	3/2	+0·215	..	..	..	..	..	..	..	..	..	..
Ca^{43}	0·15	42·9723	..	..	..	..	..	..	..	..	..	..	..	..
Sc^{45}	100	44·9701	7/2	+4·6	..	..	..	..	..	..	..	..	..	..
Ti^{47}	7·75	..	..	..	..	..	..	..	..	..	..	..	..	..
V^{49}	..	..	..	..	600 d.	..	*	..	..	..	..	..	..	..
Cr^{51}	..	..	..	..	26·5 d.	..	*	..	{0·5, 1·01 ·330}	..	..	..	..	..
Mn^{53}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Fe^{55}	..	..	..	..	~4 y.	..	*	..	..	..	..	..	..	..
Co^{57}	..	..	..	..	270 d.	..	*	0·26	{0·117, 0·130, 0·202, 0·215}	..	..	..	..	..
Ni^{59}	..	..	..	..	36 h. ?	..	..	0·67	..	..	..	..	$6{\cdot}5\times10^4$	0*B*
Cu^{61}	..	..	..	..	3·4 h.	..	*	1·125	..	..	..	..	{$f^+t>2{\cdot}4\times10^4$, $f^Kt>1\times10^4$}	0*B*
Zn^{63}	..	..	..	..	38 m.	..	..	2·3	1·5?	..	..	..	$15{\cdot}5\times10^4$	0*B*
Ga^{65}	..	..	..	..	15 m.	..	..	..	..	..	..	..	..	..
Ge^{67}	..	..	..	..	..	..	..	..	..	..	..	..	..	..

TRANSMUTATION TABLE — TARGET NUCLEI.

Nucleus	(γ,n)	(γ,p)	(n,γ)	$(n,2n)$	(n,p)	(n,α)	(p,γ)	(p,n)	(p,α)	(d,n)	$(d,2n)$	(d,p)	(d,H^3)	(d,α)	(α,n)	(α,p)	Remarks and special reactions
He^7	..	..	..	..	Li^7	..	..	..	..	..	..	..	..	..	..	..	....
Li^9	..	..	..	..	Be^9	..	..	..	..	..	..	..	..	..	..	..	....
Be^{11}	..	..	..	..	B^{11}	..	..	..	..	..	..	..	..	..	..	..	....
B^{13}	..	..	..	..	C^{13}	..	..	..	..	..	..	..	..	..	..	..	....
C^{15}	..	..	..	..	N^{15}	..	..	..	..	..	..	..	..	..	..	..	....
N^{17}	..	O^{18}	..	..	O^{17}	..	..	..	..	..	..	..	..	..	..	..	....
O^{19}	..	..	O^{18}	..	$\underline{F^{19}}$	Ne^{22}	..	..	..	..	..	O^{18}	..	..	..	..	....
F^{21}	..	Ne^{22}	..	..	Ne^{21}	..	..	..	..	..	..	..	..	..	..	O^{18}	....
Ne^{23}	..	..	..	..	$\underline{Na^{23}}$	$\underline{Mg^{26}}$	..	..	..	..	..	$\underline{Ne^{22}}$	..	..	..	..	....
Na^{25}	..	$\underline{Mg^{26}}$	..	..	Mg^{25}	..	..	..	..	..	..	..	..	..	..	Ne^{22}	....
Mg^{27}	..	..	$\underline{Mg^{26}}$	..	$\underline{Al^{27}}$	Si^{30}	..	..	..	..	..	$\underline{Mg^{26}}$	..	..	..	..	....
Al^{29}	..	Si^{30}	..	..	Si^{29}	..	..	..	..	..	..	..	..	..	..	$\underline{Mg^{26}}$	....
Si^{31}	..	..	$\underline{Si^{30}}$	..	$\underline{P^{31}}$	$\underline{S^{34}}$	..	..	..	..	..	$\underline{Si^{30}}$	..	..	..	..	....
P^{33}	..	S^{34}	..	..	S^{33}	..	..	..	S^{36}	..	..	..	..	..	..	Si^{30}	....
S^{35}	S^{36}	..	S^{34}	S^{36}	$\underline{Cl^{35}}$	A^{38}	..	..	..	..	..	$\underline{S^{34}}$	S^{36}	$\underline{Cl^{37}}$	..	..	....
Cl^{37}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
A^{39}	A^{40}	..	A^{38}	A^{40}	$\underline{K^{39}}$	Ca^{42}	..	..	..	..	..	A^{38}	A^{40}	K^{41}	S^{36}	..	....
K^{41}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Ca^{43}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Sc^{45}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Ti^{47}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
V^{49}	..	Cr^{50}	..	..	..	..	Ti^{48}	Ti^{49}	Cr^{52}	$\underline{Ti^{48}}$	Ti^{49}	..	..	..	..	Ti^{46}	....
Cr^{51}	Cr^{52}	..	$\underline{Cr^{50}}$	$\underline{Cr^{52}}$	..	Fe^{54}	..	$\underline{V^{51}}$	..	..	V^{51}	$\underline{Cr^{50}}$	Cr^{52}	..	$\underline{Ti^{49}}$	..	....
Mn^{53}	..	Fe^{54}	..	..	..	..	Cr^{52}	Cr^{53}	Fe^{56}	Cr^{52}	Cr^{53}	..	..	..	..	Cr^{50}	....
Fe^{55}	Fe^{56}	..	Fe^{54}	Fe^{56}	..	Ni^{58}	..	$\underline{Mn^{55}}$	..	..	Mn^{55}	$\underline{Fe^{54}}$	Fe^{56}	..	Cr^{52}	..	$Co^{55}-\beta^+$ decay
Co^{57}	..	Ni^{58}	..	..	..	..	$\underline{Fe^{56}}$	Fe^{57}	Ni^{60}	$\underline{Fe^{56}}$	Fe^{57}	..	..	..	..	Fe^{54}	....
Ni^{59}	$\underline{Ni^{60}}$	..	Ni^{58}	$\underline{Ni^{60}}$	..	..	..	Co^{59}	..	..	Co^{59}	Ni^{58}	Ni^{60}	..	$\underline{Fe^{56}}$	..	{Assignment Incomplete.
Cu^{61}	..	..	..	..	..	..	$\underline{Ni^{60}}$	$\underline{Ni^{61}}$	Zn^{64}	$\underline{Ni^{60}}$	Ni^{61}	..	..	..	..	Ni^{58}	....
Zn^{63}	$\underline{Zn^{64}}$	..	..	$\underline{Zn^{64}}$	..	..	..	$\underline{Cu^{63}}$	..	..	$\underline{Cu^{63}}$	..	Zn^{64}	..	$\underline{Ni^{60}}$	..	....
Ga^{65}	..	..	..	..	..	..	$\underline{Zn^{64}}$	..	..	$\underline{Zn^{64}}$	..	..	..	..	..	..	....
Ge^{67}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Zn^{64}	..	....

*Stars indicate that evidence for the emission has been found, but no measurement has been made.

Targets underlined indicate that the corresponding nuclear reaction has been tried. Targets not underlined indicate that the corresponding nuclear reaction has yet to be tried.

only, the problem needs reinvestigation. The transition being of the 1A-type, there might be undetected γ-rays.

Si^{31}: The end-energy of the β^--spectrum has been obtained by the cloud-chamber (Kurie *et al.*, 1936) to be 1·08 Mev, and no γ-rays have been recorded. Evidently it needs reinvestigation.

S^{35}: Kamen (1941) gives end-energy of the β^--spectrum as ·120 Mev and A. K. Saha (1946) as ·103 Mev. The f^-t-value given by the latter is $2{\cdot}37\times10^4$ and the transition is of 0B-class. Giebert *et al.* (1944) have studied the energetics of the reaction Cl^{35} (n, p) S^{35}, and find that there should be a γ-ray of energy ·130 Mev, which is emitted in cascade, but is difficult to detect on account of its feeble intensity. The energy-release may be taken to be ·233 Mev.

We now turn to positron-emitting and K-capturing nuclei.

V^{49}: A number of radioactive vanadium nuclei has been prepared by reactions with Ti, but as Ti has as many as 5 isotopes, it has been found difficult to assign the mass-number of the products correctly. According to Turner (1940) only V^{48} is unambiguously assigned. A 600-day vanadium has been assigned to be V^{49} by Turner after a good deal of argument. It has been found to emit neither β^+ nor γ-rays, but decays only by K-capture. This shows that $M(23, 49)$ has almost the same values as $M(22, 49)$. On the supposition that the energy of the neutrino released on K-capture is $x.mc^2$, where $x \ll 1$, we can calculate f^K. We have

$$f^K = 2\pi(\alpha Z)^3.x^2,$$

so that $f^K t = 1{\cdot}56.10^6.x^2$. If the K-capture process of V^{49} is supposed to be of the allowed type then its $f^K t$ should be of the order 10^4, i.e. we must have $x \simeq {\cdot}1$.

Cr^{51}: Walke *et al.* (1940) have shown that Cr^{51} mainly decays by K-capture but positron-emission is also indicated by the emission of strong annihilation γ-rays of ·5 Mev and 1·01 Mev. But no positrons were detected in the cloud-chamber. Recently Bradt *et al.* (1944) have given some new data about Cr^{51}. It gives vanadium K-rays indicative of K-capture, and a γ-ray of energy ·330 Mev, which is converted to the extent of 2-3% in the K and L-levels, which indicate, using Dancoff's formula, that $\triangle i = 2$. It is estimated that only 3% of the transformations lead to the excited level of V^{51} which gives us the γ-ray. These authors contradict the report by Walke *et al.* that there is any γ-ray of energy $\simeq 1$ Mev. From these data, it is difficult to deduce any value for E^+. It appears to be a small quantity.

Mn^{53}: This nucleus is not yet known. The probable methods of production are reviewed in Table 3. It should be easy to get this nucleus.

Fe^{55}: All that is known about this nucleus is from a short note by Livingood and Seaborg (1939) who state that according to private communication from Van Voorhis, it has a long life of 4 yrs. It is stated to decay by K-capture mainly.

Co^{57}: A radioactive cobalt due to the reactions Fe^{56} (d, n) and Fe^{56} (p, γ) has been assigned to be Co^{57} by Livingood and Seaborg (1941). It emits β^+-rays of end-energy ·26 Mev and γ-rays of energies ·117 Mev, ·130 Mev, ·202 Mev, and ·215 Mev, whose internal conversions have been studied by Plesset (1941). It apparently decays by K-capture, but more extended investigations are necessary to disentangle the results.

Ni^{59}: On account of the methods of production of radioactive Ni-nuclei, it has been found difficult to assign the mass-number correctly. The 36 hrs.-half-life has been assigned to Ni^{57} by Livingood and Seaborg (1938) but to Ni^{59} by Doran and Henderson (1941). The latter assignment is more in agreement with our views and is adopted here. Ni^{59} does not appear to have been yet well investigated, but it is said to decay with the emission of a positron-spectrum of end-energy ·67 Mev (absorption). According to Konopinski (1943) the transition is of 0B-type, with $ft = 6{\cdot}5.10^4$, so that the energy-release in the transition $Ni^{59} \rightarrow Co^{59}$ can be taken to be ·67 Mev. This nucleus should also decay by K-capture, but no observation appears to have been made so far.

Cu^{61}: This nucleus has been found to decay both by positron-emission and K-capture (Alvarez, 1938). The end-energy of the β^+-spectrum of Cu^{61} was given by Ridenour and Henderson (1937) at ·94 Mev, but the spectrum has been reinvestigated by Bradt *et al.* (1945) who find $E^- = 1{\cdot}225$ Mev. Calculation with this value shows $f^K/f^+ \simeq {\cdot}278$ and the ratio of the number of Ni K-quanta to the number of annihilation quanta was found to be ·33.

Zn^{63}: Townsend (1941) found the positron-spectrum end-point at 2·30 Mev and a γ-ray of energy 1·50 Mev was also suspected. According to our calculation $f^+/f^K \simeq 20$ so that K-capture is expected to be very feeble. In fact it is not reported at all. $ft \simeq 1{\cdot}55.10^5$ and the transition is assigned to the 0B-class, but it is really midway between 0B and 1B. The energy-release may be taken to be 2·30 Mev.

Ga^{65}: A 15-minute gallium produced by the processes Zn (d, n) and Zn (p, γ) has been provisionally assigned to be Ga^{65}, but the investigations are rather preliminary.

We may now compare the positron-emitters of the group $I=1$ with the electron-emitters of the group $I=3$. To compare P^{31} with Si^{31} we put $E^-(14, 31) = 1{\cdot}8$ Mev in (3.3) and get thereby

$$E^+(15, 31) = -1{\cdot}359 \text{ Mev} < -2m.$$

Thus P^{31} is stable against β^+-decay as well as K-capture as is actually observed. Next we take the isobaric pair S^{33} and

P^{33}. Since S^{33} is stable we may put $E^{+}(16, 33) < -1{\cdot}022$ Mev, and consequently from (3.3)

$$E^{-}(15, 33) > -{\cdot}003 \text{ Mev.}$$

Thus we cannot definitely say whether P^{33}, if ever prepared, will show β^{-}-activity or be stable against it. But it is very likely that this nucleus would be β^{-}-active decaying to S^{33}. Next pair is Cl^{35} and S^{35}. If $E^{-}(16, 35)$ is taken to be ·233 Mev, then from (3.3)

$$E^{+}(17, 35) = -1{\cdot}257 \text{ Mev} < -2m,$$

so that Cl^{35} should be stable as actually observed. We may now try to explain the anomalous behaviour of A^{37}. To do

D. *The Group* $I=5$. (Fig. 5, Table 4.)

This group extends from S^{37} to Ge^{69}. We have five β^{-}-emitting nuclei from S^{37} to Sc^{47}. From Ti^{49} to Cu^{63}, we have eight stable nuclei, followed by two K-active and positron-emitting nuclei. The methods of production of the radioactive nuclei are reviewed in Table 4. It appears possible to extend the group on both flanks. Attempts may be made to produce Cl^{39} by the S^{36} (α, p)-reaction. S^{36} (frequency ·016%) has to be concentrated. Beyond S^{37}, it appears possible to go up to Si^{33}. On the other flank, it will be possible to go up to Sr^{81}.

Let us review the β^{-}-emitting nuclei one by one.

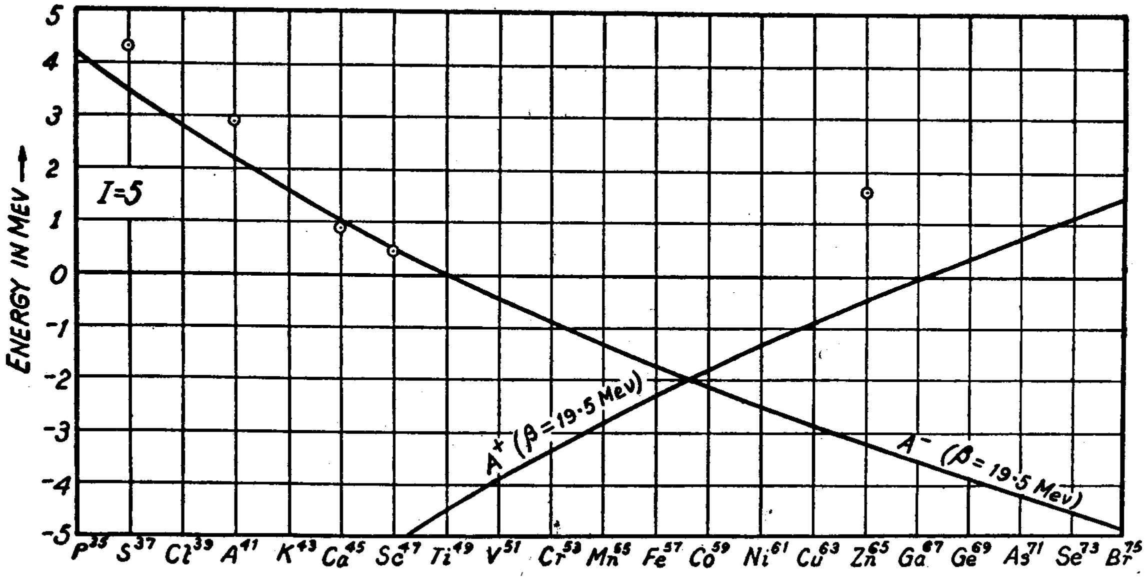

Fig. 5

this we put $E^{-}(17, 37) < 0$, as Cl^{37} is stable. Thus from (3.3) we have

$$E^{+}(18, 37) > -1{\cdot}023 \text{ Mev} \simeq 2m.$$

Thus A^{37} should show β^{+}-emission or K-capture, and this is in concord with experimental facts. We can estimate $E^{K}(18, 37)$ on the hypothesis that the K-capture of A^{37} is allowed. If $f^{K}t$ is taken to be of the order 3450 (the value for Sc^{41}) then we have $E^{K}(18, 37) \simeq {\cdot}15$ Mev and consequently $E^{+}(18, 37) \simeq -{\cdot}87$ Mev showing that A^{37} will most probably not show β^{+}-decay. We may next explain the anomalous behaviour of A^{39} by comparing this nucleus with K^{39}. As K^{39} is stable against β^{+}-decay as well as K-capture, we have $E^{+}(19, 39) < -1{\cdot}022$ Mev so that from (3.3)

$$E^{-}(18, 39) > 0,$$

showing that A^{39} should show β^{-}-activity, which fact is in harmony with the finding that there is no stable isotope of A having the mass-number 39. In this way we may continue our discussion for the heavier members of the two groups.

S^{37}: It has been identified by Giebert *et al.* (1944) in a Cl+n-reaction with a 5 min. product. It shows a complex β^{-}-spectrum, 10% decaying with the end-energy 4·3 Mev, 90% with the energy 1·6 Mev, and a strong γ-ray of energy 2·8 Mev has been found. Apparently, the end-energy is 4·3 Mev.

A^{41}: According to a rather old investigation by Richardson and Kurie (1936) with the cloud-chamber, this nucleus emits a β^{-}-spectrum with the end-energy of 1·5 Mev and a γ-ray of energy 1·37 Mev. The genetic connection has not yet been investigated. The β-transition has been found to be of the 1A-type as $ft = 2{\cdot}7.10^{5}$. If the two rays follow in succession, $E^{-} = 2{\cdot}87$ Mev.

K^{43}: Nothing is known about this nucleus.

Ca^{45}: This emits a composite β^{-}-spectrum of end-energies ·19 Mev (95%) and ·91 Mev (5%) and a γ-ray of ·71 Mev. Evidently the energy-release is ·91 Mev.

Sc^{47}: Hibdon and Pool (1945) have given reasons for assigning the 63 hrs. radioactive scandium to Sc^{47}. The end-energy according to them is at ·46 Mev. There are

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TABLE

$I=5$

Nucleus	Percentage abundance	Mass	Spin	Magnetic moment	Half-life	E_{β^-} in Mev	E_K in Mev	E_{β^+} in Mev	$E\gamma$ in Mev	E^- in Mev	EK in Mev	E^+ in Mev	ft	Class	(γ, n)	(γ, p)	(n, γ)	$(n, 2n)$	(n, p)	(n, α)	(p, γ)	(p, n)	(p, α)	(d, n)	$(d, 2n)$	(d, p)	(d, H^3)	(d, α)	(α, n)	(α, p)	Remarks and special reactions
															Transmutation Table — Target nuclei																
Si^{33}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	S^{36}	..	..	..	..	..	..	..	..	..	..	....
P^{35}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	S^{36}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
S^{37}	..	..	..	..	5 m.	1·6 (90%) 4·3 (10%)	..	..	2·8	4·3	..	..	..	..	..	..	S^{36}	..	Cl^{37}	A^{40}	..	..	..	..	..	S^{36}	..	..	..	..	....
Cl^{39}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	A^{40}	..	..	..	..	..	..	..	..	..	..	..	..	..	S^{36}	....
A^{41}	..	..	..	..	110 m.	1·5	..	..	1·37	2·87	..	..	$2{\cdot}7\times10^5$	1*A*	..	..	A^{40}	..	K^{41}	Ca^{44}	..	..	..	..	..	A^{40}	..	..	..	..	....
K^{43}	..	..	..	..	18 m. ?	*	..	..	..	..	..	..	..	..	..	Ca^{44}	..	..	Ca^{43}	..	..	..	Ca^{46}	..	..	..	..	..	..	A^{40}	....
Ca^{45}	..	..	..	..	180 d.	·19 (95%) ·91 (5%)	..	..	0·71	·91	..	..	(1) $>10\times10^7$ (2) $>5\times10^5$	2*A* 1*A*	Ca^{46}	..	Ca^{44}	Ca^{46}	Sc^{45}	Ti^{48}	..	..	..	..	..	Ca^{44}	Ca^{46}	..	..	..	....
Sc^{47}	..	..	..	..	63 h.	·46	..	..	..	·46	..	..	$3{\cdot}1\times10^6$	1*B*	..	Ti^{48}	..	..	Ti^{47}	..	C^{46}	..	Ti^{50}	Ca^{46}	..	..	..	Ti^{49}	..	Ca^{44}	....
Ti^{49}	5·51	48·9664	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
V^{51}	100	50·9567	7/2	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Cr^{53}	9·43	52·9572	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Mn^{55}	100	54·965	5/2	+3	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Fe^{57}	2·11	56·9609	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Co^{59}	100	..	7/2	(+2)− (+3)	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Ni^{61}	1·2	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Cu^{63}	70·13	62·956	3/2	+2·5	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Zn^{65}	..	..	..	..	250 d.	..	*	0·4	0·45, 0·65, 1·0, 1·14	..	1·4 1·6	..	..	..	Zn^{66}	..	Zn^{64}	Zn^{66}	..	..	..	Cu^{65}	..	..	Cu^{65}	Zn^{64}	Zn^{66}	..	Ni^{62}	..	Ga^{65} *K*-decay.
Ga^{67}	..	..	..	..	83 h.	..	*	..	·094, ·174, ·187, ·292, ·301	..	..	..	..	..	..	..	..	..	..	..	Zn^{66}	Zn^{67}	Ge^{70}	Zn^{66}	Zn^{67}	..	..	..	..	Zn^{64}	....
Ge^{69}	..	..	..	..	~195 d.	..	..	..	..	..	..	..	..	..	Ge^{70}	..	..	Ge^{70}	..	..	..	Ga^{69}	..	..	Ga^{69}	..	Ge^{70}	..	Zn^{66}	..	....
As^{71}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Ge^{70}	..	Se^{74}	Ge^{70}	..	..	..	..	..	..	....
Se^{73}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Se^{74}	..	..	Se^{74}	..	..	..	..	..	..	..	..	Se^{74}	..	Ge^{70}	..	....
Br^{75}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Se^{74}	..	Kr^{78}	Se^{74}	..	..	..	..	..	..	....
Kr^{77}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Kr^{78}	..	..	Kr^{78}	..	..	..	..	..	..	..	..	Kr^{78}	..	Se^{74}	..	....
Rb^{79}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Kr^{78}	..	..	Kr^{78}	..	..	..	..	..	..	....
Sr^{81}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Kr^{78}	..	....

*Stars indicate that evidence for the emission has been found, but no measurement has been made.
Targets underlined indicate that the corresponding nuclear reaction has been tried. Targets not underlined indicate that the corresponding nuclear reaction has yet to be tried.

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TABLE 5

$I=0$

Nucleus	Percentage abundance	Mass	Spin	Magnetic moment	Half-life	E_{β^-} in Mev	E_K in Mev	E_{β^+} in Mev	$E\gamma$ in Mev	E^- in Mev	E^K in Mev	E^+ in Mev	ft	Class	Transmutation Table (γ, n)	(γ, p)	(n, γ)	$(n, 2n)$	(n, p)	(n, α)	(p, γ)	(p, n)	(p, α)	(d, n)	$(d, 2n)$	(d, p)	(d, H^3)	(d, α)	(α, n)	(α, p)	Remarks and special reactions
H^2	0·02	2·014726	1	+·855	..	..	..	..	..		..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
He^4	100	4·00391	0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Li^6	7·5	..	1	+·820	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Be^8	..	?	?	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Li^7	..	..	Li^7	..	..	..	..	..	..	....
B^{10}	18·4	10·01633	1	+·598	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
C^{12}	98·9	12·00387	0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
N^{14}	99·62	14·00756	1	+·402	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
O^{16}	99·76	16·00000	0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
F^{18}	..	..	..	..	112 m.	..	..	0·7	..	..	..	0·7	$5{\cdot}85\times10^3$	0*A*	$\underline{F^{19}}$	..	..	$\underline{F^{19}}$	..	..	O^{17}	$\underline{O^{18}}$	Ne^{21}	$\underline{O^{17}}$	O^{18}	..	$\underline{F^{19}}$	$\underline{Ne^{20}}$	N^{15}	..	....
Ne^{20}	90·00	19·99896	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Na^{22}	..	..	..	..	3 y.	..	..	0·58	1·3	..	..	1·88	$>1{\cdot}5\times10^7$	2*A*	Na^{23}	..	..	Na^{23}	..	..	Ne^{21}	Ne^{22}	Mg^{25}	$\underline{Ne^{21}}$	Ne^{22}	..	Na^{23}	$\underline{Mg^{24}}$	$\underline{F^{19}}$	..	....
Mg^{24}	77·4	23·99189	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Al^{26}	..	..	..	..	7 s.	..	..	2·99	..	..	..	2·99	$2{\cdot}4\times10^3$	0*A*	$\underline{Al^{27}}$	..	..	Al^{27}	..	..	$\underline{Mg^{25}}$	$\underline{Mg^{26}}$	Si^{29}	Mg^{25}	Mg^{26}	..	Al^{27}	Si^{28}	$\underline{Na^{23}}$	..	....
Si^{28}	89·6	27·9866	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
P^{30}	..	..	..	..	2·55 m.	..	..	$\left\{\begin{matrix}3{\cdot}0\\3{\cdot}50\end{matrix}\right\}$	..	..	..	3·50	$\cdot5\times10^5$	1*A*	$\underline{P^{31}}$	..	..	$\underline{P^{31}}$	..	..	Si^{29}	$\underline{Si^{30}}$	S^{33}	Si^{29}	Si^{30}	..	P^{31}	$\underline{S^{32}}$	$\underline{Al^{27}}$	..	$Si^{28}-He^3-p$
S^{32}	95·1	31·9823	0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Cl^{34}	..	..	..	..	33 m.	..	..	2·5	..	..	..	..	$2{\cdot}8\times10^5$	1*A*	$\underline{Cl^{35}}$	..	..	$\underline{Cl^{34}}$	..	..	S^{33}	$\underline{S^{34}}$	..	$\underline{S^{33}}$	S^{34}	..	Cl^{35}	A^{36}	$\underline{P^{31}}$	..	$\left\{\begin{matrix}S^{32}-\alpha-(n,p)\\S^{32}-\alpha-d\end{matrix}\right.$
A^{36}	0·307	35·9785	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
K^{38}	..	..	..	..	7·7 m.	..*	..	2·3	..	..	..	..	$0{\cdot}4\times10^5$	1*A*	$\underline{K^{39}}$	..	..	$\underline{K^{39}}$	..	..	..	A^{38}	..	..	A^{38}	..	K^{39}	$\underline{Ca^{40}}$	$\underline{Cl^{35}}$	..	....
Ca^{40}	96·96	39·9745	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Sc^{42}	..	..	..	..	13·5 d.	..	..	1·4	..	..	..	..	$1{\cdot}3\times10^7$	2*A*	..	..	..	..	..	..	..	Ca^{42}	..	..	Ca^{42}	..	..	..	$\underline{K^{39}}$	..	....
Ti^{44}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
V^{46}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Ti^{46}	..	..	Ti^{46}	..	..	..	..	..	....
Cr^{48}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Mn^{50}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Cr^{50}	..	..	Cr^{50}	..	..	..	..	..	....
Fe^{52}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Co^{54}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Fe^{54}	..	..	Fe^{54}	..	..	..	..	..	....
Ni^{56}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....
Cu^{58}	..	..	..	..	$\left\{\begin{matrix}81\text{ s.}\\7{\cdot}9\text{ m.}\end{matrix}\right\}?$	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	$\underline{Ni^{58}}$	..	..	Ni^{58}	..	..	..	..	..	....

TARGET NUCLEI.

*Stars indicate that evidence for the emission has been found, but no measurement has been made.
Targets underlined indicate that the corresponding nuclear reaction has been tried. Targets not underlined indicate that the corresponding nuclear reaction has yet to be tried.

apparently no γ-rays. $ft \simeq 1{\cdot}6.10^5$, so that the class is $0B$. Energy-release may be taken to be ·46 Mev.

We now turn to the positron-emitting and K-capturing nuclei.

Zn^{65}: This nucleus has been investigated by a large number of workers, but we may take only the work of Watase *et al.* (1940). They found that it emits a positron-spectrum ending at ·46 Mev and a number of γ-rays at ·45 Mev, ·65 Mev and 1·0 Mev. They have established that Zn^{65} decays mainly by K-capture, because the nucleus emits the K-line of Cu^{65}. The γ-lines are evidently due to excited Cu^{65}, produced by K-capture. The ratio of K-capture to positron-emission is given as 70 : 1. The total energy-release is given by these authors as either 1·4 Mev or 1·6 Mev.

Ga^{67}: Though this nucleus has been studied by numerous investigators, its spectrum has not yet been cleared up. It emits a number of γ-rays whose energies are given by Cork *et al.* (1942) as ·094 Mev, ·174 Mev, ·187 Mev and ·301 Mev, and other workers give nearabout figures. Of these ·094 Mev γ-ray is the most heavily converted. The nucleus is presumed to decay by K-capture but from the present data, it does not appear possible to obtain any idea of the energy-release in the transition Ga^{67} to Zn^{67}.

Ge^{69}: Nothing is known about this nucleus beyond the mere statement that it has a long life of $\simeq$ 195 days. The report appears to be extremely doubtful.

The comparison between the positron-emitting nuclei of the group $I=3$ with the electron-emitting nuclei of the group $I=5$ may be done in the same manner as has been shown for the other groups.

Four exceptions to the empirical rules of stability are found in this group. These are shown with their spins and magnetic moments in Table 5*a*. These nuclei in spite of having both N and Z odd are not unstable. But the other odd-odd nuclei of the group follow Rule I, i.e. all the known odd-odd nuclei from F^{18} onwards are all β^+-active. All the even-even nuclei of this group are stable as required by Rule I. The facts find ready explanation on the theory proposed. The course of the A^+-curve are shown in Fig. 6. The A^--curve, not shown in the figure, is so far down in the negative energy domain that even for odd-odd nuclei, for which $E^- > A^-$, we cannot have E^- positive. This explains why we have no β^--emitting nuclei in this group.

TABLE 5*a*.

	H^2	Li^6	B^{10}	N^{14}	F^{18} (β^+-active).
Spin i ..	1	1	1	1	1?
Magnetic moment ..	·8565	·8213	·598	·403	

§ 4. The Even Groups.

A. *The Group* $I=0$. (Fig. 6, Table 5.)

This group extends from He^2 to Cu^{58}, the last nucleus being rather doubtful. Be^8 does not occur in nature and probably breaks up into two α-particles (He^4) as soon as it is formed, and nuclei from Ti^{44} to Ni^{56} have neither been found in nature nor have been artificially produced.

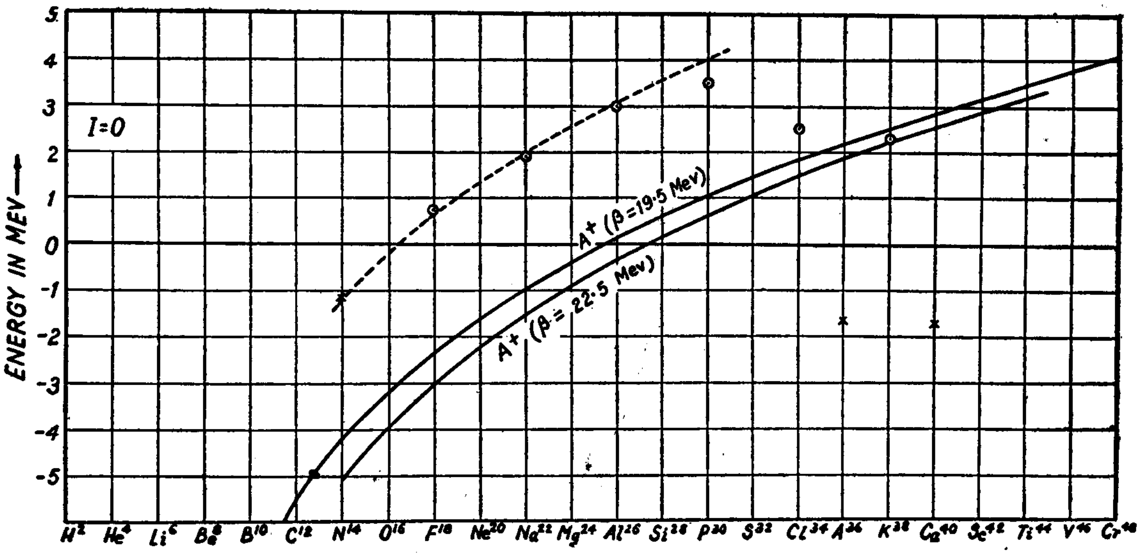

Fig. 6

We have, as mentioned in § 1, for even-even nuclei $E^+ < A^+$ and for od-odd nuclei $E^+ > A^+$, where

$$A^+ = -1{\cdot}788 - \frac{4\beta}{A} + \frac{\delta(A-1)}{A^{\frac{1}{3}}}.$$

The stability of Li^6, B^{10}, N^{14} is explained on the supposition that for these nuclei $A^+ - \chi(Z, A)$ continues to be negative because A^+ is negative and $|A^+| > -\chi(Z, A)$. Only from F^{18} onwards, $A^+ - \chi(Z, A)$ becomes positive.

Let us review the different members one by one.

F^{18}: It appears to show a simple β^+-spectrum of the $0A$-type, but more extended investigations are desirable. We have assumed that there are no γ-rays and $E^+ = \cdot 70$ Mev, as given by Yasaki and Watanabe (1938) in a short note. It is quite possible that F^{18} may also decay by K-capture to O^{18}, for according to calculation for allowed transition $f^K/f^+ \simeq \frac{1}{5}$.

Na^{22}: This emits both β^+-rays of end-energy $\cdot 58$ Mev and a γ-ray of energy 1·3 Mev. According to an extensive investigation by Maier-Leibnitz (1944), there is one γ-ray per β-ray, hence the energy-release is in cascade and equals $\cdot 58 + 1\cdot 30 = 1\cdot 88$ Mev. The β-transition therefore is to an excited state of Ne^{22}.

Al^{26}: This appears to emit, according to cloud-chamber investigations of White *et al.* (1939), a β^+-spectrum with end-energy at 2·99 Mev, the transition being of the $0A$-type. Hence we have to take the total energy-release to be 2·99 Mev.

P^{30}: This nucleus emits, according to Magnan (1941) a β^+-spectrum with end-energy at 3·5 Mev, the transition being of the $1A$-type. A γ-ray emission is therefore probable, though it has not yet been detected.

Cl^{34}: The end-value of the β^+-spectrum (2·5 Mev) is available only from absorption experiments and requires revision. On the present data, the transition is of the $1A$-type, so that a γ-ray is possible. The value of E^+ cannot therefore be found from present data.

K^{38}: This does not appear to be well-studied.

Sc^{42}: A radioactive scandium of 13·5 days period produced by the reaction K^{39} (α, n) was reported by Walke (1940), but this has not been confirmed by Hibdon, Pool and Kurbatov (1945). It appears also unlikely that Sc^{42} can have such a long period as 13·5 days.

A smooth curve can be drawn through the E^+-values of F^{18}, Na^{22}, Al^{26} and P^{30} and it is worthwhile investigating, when more complete data about Cl^{34} and K^{38} are obtained, whether this curve can be extended through their E^+-points.

We have, as yet, no knowledge of any attempt to produce heavier nuclei of this group. But it appears possible to produce some heavier nuclei with odd Z, viz. V^{46}, Mn^{50}, Co^{54} and Cu^{58} by using the (p, n)-reactions. They are expected to decay by the emission of positrons of very high energy. Will it be possible to produce nuclei of even Z, heavier than Ca^{40}, e.g. Ti^{44}, Cr^{48}, etc. ? We have not yet been able to think of any method. But if they can be produced, they will not be stable, for we have

$$E^+(20, 40) = 2\cdot 90 + \chi(19, 40) \text{ Mev}$$

whereas

$$E^+(22, 44) = 3\cdot 51 + \chi(21, 44) \text{ Mev}.$$

Since Ca^{40} is stable, and does not decay by K-capture — $\chi(19, 40) < 2\cdot 9$ Mev and we can put also $-\chi(21, 44)$ to be of this order. Hence E^+ for $Ti^{44} \simeq -\cdot 4$ Mev, i.e. Ti^{44} will probably decay by K-capture to Sc^{44} which will then decay by positron-emission to Ca^{44}. Other nuclei having $I=0$, beyond Ti^{44}, all nuclei would have E^+-positive, even if N and Z are even. But while odd-odd nuclei are expected to emit positrons of great energies, the even-even ones will emit positrons of much smaller energies and the earlier ones in the even-even group will mostly decay by K-capture.

B. *The Group* $I=2$. (Fig. 7, Table 6.)

This group extends from the doubtful nucleus H^4 to Ga^{64}. Of this group, all odd-odd nuclei are unstable as

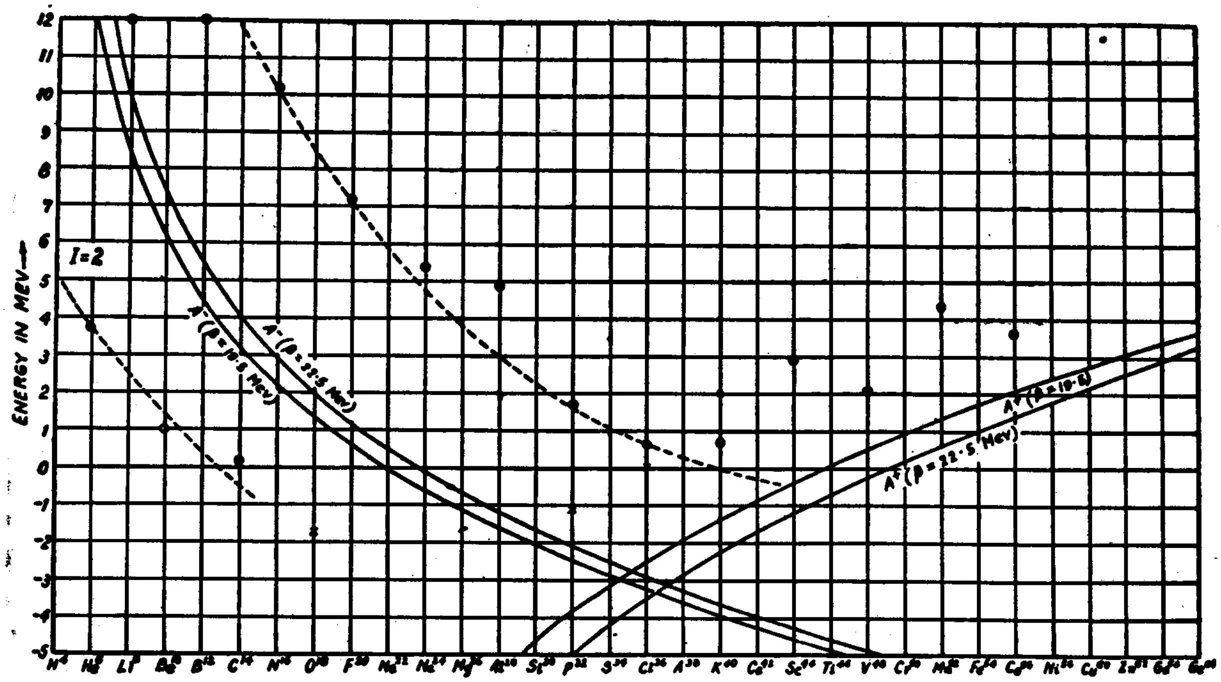

Fig. 7

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TABLE 6

$I=2$

Nucleus	Percentage abundance	Mass	Spin	Magnetic moment	Half-life	E_{β^-} in Mev	E_K in Mev	E_{β^+} in Mev	$E\gamma$ in Mev	E^- in Mev	EK in Mev	E^+ in Mev	ft	Class
H^4	..	..	..	..	..	..	..	..	..	..	..	..	..	..
He^6	..	..	..	..	·8 s.	3·7	..	..	..	3·7	..	..	$1·16\times10^3$	0*A*
Li^8	..	..	..	..	·88 s.	12	..	..	..	12	..	..	$2·8\times10^5$	1*A*
Be^{10}	..	..	..	..	$\gg 10^3$ y.	~0·5	..	..	< 0·5	~1		..	$·6\times10^{13}$	5*A*
B^{12}	..	..	..	..	·022 s.	12	..	..	..	12	..	..	$6·6\times10^3$	0*A*
C^{14}	..	..	..	..	$>10^3$ y.	·145	..	..	..	·145	..	..	$>4\times10^9$	3*A*
N^{16}	..	..	..	..	7·3 s.	{ 4 (75%) 10·2(25%) }	..	..	6·2	10·2	..	..	$1·0\times10^5$	1*A*
O^{18}	0·20	18·0037	..	..	..	..	..	..	..	..	..	..	..	..
F^{20}	..	..	..	..	12 s.	5·0	..	..	2·2	7·2	..	..	$0·7\times10^5$	1*A*
Ne^{22}	9·73	21·99864	..	..	..	..	..	..	..	..	..	..	..	..
Na^{24}	..	..	..	..	14·8 h.	1·4	..	..	..	?	..	..	$12·7\times10^5$	..
Mg^{26}	11·1	25·99062	..	..	..	..	..	..	..	..	..	..	..	..
Al^{28}	..	..	..	..	2·4 m.	3·3	..	..	1·8	5·1	..	..	{ (1) $>1·5\times10^5$ (2) $>1·1\times10^3$	1*A* O*A* }
Si^{30}	4·2	29·9832	..	..	..	..	..	..	..	..	..	..	..	..
P^{32}	..	• ..	..	..	14·3 d.	1·72	..	..	..	1·72	..	..	$8·6\times10^7$	2*A*
S^{34}	4·2	33·987	..	..	..	..	..	..	..	..	..	..	..	..
Cl^{36}	..	..	..	..	$>10^3$ y.	·64	*	*	..	·64	..	..	$f\text{-}t>\times10^8$	3*A*
A^{38}	0·061	37·9751	..	..	..	..	..	..	..	..	..	..	..	..
K^{40}	0·012	39·975	4	—1·290	{ $1·42\times10^9$ y. 4×10^8y.	·4, ·725 1.3 }	..	..	2	..	..	..	$9·9\times10^{16}$	7*A*
Ca^{42}	0·64	41·9711	..	..	..	..	..	..	..	..	..	..	..	..
Sc^{44}	..	..	..	..	3·92 h.	..	..	1·33	1·35	..	..	..	$1·9\times10^5$	1*A*
Sc^{44}	..	..	..	..	{ 52 h. I.T.	..	..	..	·28 1·33 }	..	..	..	..	..
Ti^{46}	7·95	45·9678	..	..	..	..	..	..	..	..	..	..	..	..
V^{48}	..	..	..	..	16 d.	..	* {	1·0 ·58	1·05 1·5 }	..	..	2·08	$>3·4\times10^6$	1*B*
Cr^{50}	4·49	..	..	..	..	..	..	..	..	..	..	..	..	..
Mn^{52}	..	..	..	..	21 m.	..	..	2·2	1·2			} 5·4	$6·2\times10^4$	0*B*
Mn^{52}	..	..	..	..	6·5 d.	..	*	·77	1·0					..
Fe^{54}	6·04	53·960	..	..	..	..	..	..	..	..	..	..	..	..
Co^{56}	..	..	..	..	72 d.	..	.. {	1·2 1·5 {	1·05, ·845, 1·26, 1·74, 2·01 2·55, 3·25 }	..	..	3·605	6×10^8	2*B*
Ni^{58}	67·4	57·9516	..	..	..	..	..	..	..	..	..	..	..	..
Cu^{60}	..	..	..	..	{ 81 s. 7·9 m.	}?	..	..	..	..	..	..	..	..
Zn^{62}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Ga^{64}	..	..	..	..	48 m.	..	..	..	..	..	..	..	..	..

TRANSMUTATION TABLE

Nucleus	(γ,n)	(γ,p)	(n,γ)	$(n,2n)$	(n,p)	(n,α)	(p,γ)	(p,n)	(p,α)	(d,n)	$(d,2n)$	(d,p)	(d,H^3)	(d,α)	(α,n)	(α,p)	Remarks and special reactions
H^4	..	He^5	..	..	He^4	Li^7	..	..	..	..	..	..	..	..	..	..	..
He^6	..	Li^7	..	..	$\underline{Li^6}$	$\underline{Be^9}$	..	..	..	..	..	He^5	..	..	..	..	..
Li^8	..	Be^9	$\underline{Li^7}$	..	..	$\underline{B^{11}}$	..	..	..	..	..	$\underline{Li^7}$	..	..	..	He^5	..
Be^{10}	..	B^{11}	Be^9	..	B^{10}	C^{13}	..	..	..	..	..	$\underline{Be^9}$	..	..	..	Li^7	..
B^{12}	..	C^{13}	B^{11}	..	C^{12}	N^{15}	..	..	..	..	..	$\underline{B^{11}}$	..	..	..	Be^9	..
C^{14}	..	N^{15}	C^{13}	..	$\underline{N^{14}}$	O^{17}	..	..	..	..	..	$\underline{C^{13}}$	..	..	..	B^{11}	..
N^{16}	..	O^{17}	N^{15}	..	$\underline{O^{16}}$	$\underline{F^{19}}$	..	..	..	..	..	$\underline{N^{15}}$	..	O^{18}	..	C^{13}	..
O^{18}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
F^{20}	..	Ne^{21}	$\underline{F^{19}}$	..	Ne^{20}	$\underline{Na^{23}}$	..	..	..	..	..	$\underline{F^{19}}$	..	Ne^{22}	..	O^{17}	..
Ne^{22}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Na^{24}	..	Mg^{25}	$\underline{Na^{23}}$	..	$\underline{Mg^{24}}$	$\underline{Al^{27}}$	..	..	..	..	..	$\underline{Na^{23}}$	..	$\underline{Mg^{26}}$	..	Ne^{21}	..
Mg^{26}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Al^{28}	..	Si^{29}	$\underline{Al^{27}}$	..	$\underline{Si^{28}}$	$\underline{P^{31}}$	..	..	..	..	..	$\underline{Al^{27}}$	..	Si^{30}	..	$\underline{Mg^{25}}$	..
Si^{30}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
P^{32}	..	S^{33}	$\underline{P^{31}}$	..	$\underline{S^{32}}$	$\underline{Cl^{35}}$	..	..	..	..	..	$\underline{P^{31}}$	..	$\underline{S^{34}}$	..	$\underline{Si^{29}}$	..
S^{34}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Cl^{36}	Cl^{37}	..	$\underline{Cl^{35}}$	Cl^{37}	A^{36}	K^{39}	..	S^{36}	..	..	S^{36}	$\underline{Cl^{35}}$	Cl^{37}	A^{38}	..	S^{33}	
A^{38}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
K^{40}	K^{41}	..	K^{39}	K^{41}	Ca^{40}	..	..	A^{40}	Ca^{43}	..	A^{40}	K^{39}	K^{41}	Ca^{42}	Cl^{37}	..	Natural sources.
Ca^{42}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Sc^{44}	$\underline{Sc^{45}}$	..	..	$\underline{Sc^{45}}$	..	..	Ca^{43}	$\underline{Ca^{44}}$	Ti^{47}	$\underline{Ca^{43}}$	Ca^{44}	..	Sc^{45}	$\underline{Ti^{46}}$	$\underline{K^{46}}$	..	..
Sc^{44}	$\underline{Sc^{45}}$	..	..	$\underline{Sc^{45}}$	..	..	Ca^{43}	$\underline{Ca^{44}}$	Ti^{47}	$\underline{Ca^{43}}$	Ca^{44}	..	Sc^{45}	$\underline{Ti^{46}}$	$\underline{K^{41}}$	..	..
Ti^{46}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
V^{48}	..	..	..	..	..	..	Ti^{47}	$\underline{Ti^{48}}$	..	$\underline{Ti^{47}}$	Ti^{48}	..	..	$\underline{Cr^{50}}$	$\underline{Se^{45}}$	..	..
Cr^{50}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Mn^{52}	..	..	..	..	..	..	..	$\underline{Cr^{52}}$	..	..	Cr^{52}	..	..	$\underline{Fe^{54}}$	..	..	..
Mn^{52}	..	..	..	..	..	..	..	$\underline{Cr^{52}}$	..	..	Cr^{52}	..	..	$\underline{Fe^{54}}$	..	..	..
Fe^{54}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Co^{56}	..	..	..	..	..	..	..	Fe^{56}	..	..	$\underline{Fe^{56}}$	..	..	$\underline{Ni^{58}}$	..	..	Fe^{44}—α—(n.p)
Ni^{58}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Cu^{60}	..	..	..	..	..	..	..	$\underline{Ni^{60}}$	..	..	Ni^{60}	..	..	..	..	..	..
Zn^{62}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Ga^{64}	..	..	..	..	..	..	..	$\underline{Zn^{64}}$	..	..	Zn^{64}	..	..	..	..	..	..

TARGET NUCLEI.

[illegible]dicate that evidence for the emission has been found, but no measurement has been made.

[illegible] underlined indicate that the corresponding nuclear reaction has been tried. Targets not underlined indicate that the corresponding nuclear reaction has yet to be tried.

stated in §1, but as already mentioned He^6, Be^{10}, C^{14} are unstable, though both N and Z are even. But it may be noticed that the total energy-releases E^- for these even-even nuclei are much less than those of immediate neighbours with Z odd and N odd, e.g. E^- for Be^{10} is 1 Mev while that for B^{12} is 12 Mev. The general explanation of these facts may be obtained from formulae (2·9) and (2·10). It has been proved there that for the even-even-nuclei of an even group, $E^- < A^-$ whereas for the odd-odd nuclei of the same group, $E^- > A^-$. A glance at Fig. 7 will show that such is indeed the case. In this figure, the $A^\pm$-curves have been drawn for two values of β, viz. 19·5 Mev and 22·5 Mev. In both cases we find that points indicating E^- for the even-even nuclei He^6, B^{10}, C^{14} lie below the $A\pm$-curve, whereas for the odd-odd nuclei Li^8, B^{12}, N^{16}, F^{20}, etc. the points indicating E^- lie above the A^--curve. In Table 6*a*, we have calculated A^- for the nuclei He^6 to F^{20}, taking $\beta = 22{\cdot}5$ Mev. Probably the formula is not applicable to the lightest elements, but that does not matter much. We observe that the spin-independent part is large to start with and diminishes gradually as A is increased, while $\chi(Z, N)$ remains almost of the same magnitude.

Be^{10}: All that is known about this nucleus is a private communication from Macmillan to Seaborg (1944). The nucleus requires reinvestigation. It is a long-lived product with life$\simeq 10^3$ years, with a small end-energy because A^- and χ are now subtractive.

B^{12}: All the remarks made with respect to Li^8 apply to this nucleus.

C^{14}: The emission of this nucleus has been studied by Ruben and Kamen (1940) who conclude from absorption experiments that the value of the end-energy of the β^--spectrum is $\cdot 145 \pm \cdot 015$ Mev. They could detect no γ-rays. In view of the limitations of such extrapolation formula for such low energy β-rays it is desirable that the limit be redetermined with the screen-cathode β-ray spectrometer (Saha, 1944). The transition $C^{14} \rightarrow N^{14}$ appears to be highly forbidden, like that of Be^{10}, while that of He^6 is allowed. It is quite probable that there are undetected γ-rays from C^{14} though Ruben and Kamen could not detect any of greater energy than ·1 Mev.

N^{16}: It has been recently investigated by Sommers Jr. and Scherr (1946) who find that the β^--spectrum emitted by it is complex. The total energy-release appears to be $E^- = 10{\cdot}2 \pm {\cdot}5$ Mev. 25% of the disintegration consists of a direct transition from the initial level of N^{16} to the final level of O^{16} but for the remaining 75%, we have first a β^--transition to an intermediate level of 4 Mev, which is followed by a γ-ray of energy 6·2 Mev.

TABLE 6*a*.

Nucleus	Odd-Odd								Even-Even		
	Li^8	B^{12}	N^{16}	F^{20}	Na^{24}	Al^{28}	P^{32}	Cl^{36}	He^6	Be^{10}	C^{14}
A^- in Mev	9·98	5·48	2·93	1·20	−·11	−1·18	−2·09	−2·89	14·17	7·34	4·06
E^- in Mev	$12+x$	12	10·2	7·2	5·4	5·1	1·72	·64	3·5	1	·145
$-\chi$ (Z, A) in Mev	$2{\cdot}02+x$	6·52	7·27	6	5·51	6·28	3·81	3·53	10·67	6·34	4·915
(Z, A)	(3, 8)	(5, 12)	(7, 16)	(9, 20)	(11, 24)	(13, 28)	(15, 32)	(17, 36)	(3, 6)	(5, 10)	(7, 14)

Let us consider the electron-emitters of this group one by one.

He^6: This interesting nucleus, first reported by Bjerge and Broström (1936) has recently been studied by Sommers Jr. and Scherr (1946) who confirm the earlier findings that $E^- = 3{\cdot}5 \pm {\cdot}6$ Mev. The transition is allowed as $ft \simeq 1160$, according to Konopinski (1943).

Li^8: The value of end-energy is very large because the A^--term and χ-term are now additive. A reference to the original work by Bayley and Crane (1937) shows that the determination of the end-energy of the β^--spectrum by cloud-chamber method carried out by them needs revision both for Li^8 and B^{12}. It is quite possible that in addition to β-rays, Li^8 may emit also γ-rays.

F^{20}: This nucleus has been studied by Bower and Burcham (1940) who find that the end-energy of the β^--spectrum is about 5 Mev, but this is followed by a γ-ray of energy 2·2 Mev. The total energy-release may therefore be taken to be 7·2 Mev, though more extended investigations are necessary to elucidate the problem.

Na^{24}: This very famous nucleus emits a β^--spectrum and number of γ-rays, which have been the subject of numerous investigations. The latest are those by Krüger and Ogle (1945), and by Maier-Leibnitz (1944) who have given level schemes. According to the latter, the total energy-release in the transition $Na^{24} \rightarrow Mg^{24}$ is 5·4 Mev whereas according to Krüger and Ogle it is 5·28 Mev. There is not much difference between these two values, and we have taken 5·4 Mev as the energy-release.

Al^{28}: Itoh (1941) has given a discussion of the β^- and γ-ray spectrum of this nucleus in a paper where all previous references would be found. The best value of the end-energy of the β^--spectrum is 3·3 Mev and the γ-ray energy is 1·8 Mev. According to the β-γ coincidence experiments of Watase (1941), one γ-ray is emitted per β^--transition, hence the energy-release is 5·1 Mev. Mass-data of Barkas as well as our investigations would, however, indicate that the energy-release is $\simeq$3·2 Mev.

P^{32}: According to Lawson (1939), this nucleus has a simple β^--ray spectrum with an end-point at 1·72 Mev. Searching investigations have failed to show any γ-ray. The spectrum certainly creates theoretical difficulties and has been the subject of numerous investigations.

Cl^{36}: All information about this nucleus are from a note by Grahame and Walke (1941), who say that the β^--spectrum is simple with the end-point at ·64 Mev. There are apparently no γ-rays. A few tracks apparently of low-energy positrons from the source were obtained in the cloud-chamber, as well as γ-rays which are supposed to indicate K-capture. A more detailed and accurate investigation of Cl^{36} is very much desirable for it apparently decays on one side by β^--emission to A^{36}, and on the other side by K-capture and positron-emission to S^{36}. So Cl^{36} is the first nucleus which, like Cu^{64}, decays on two sides. As we shall see later, Cl^{36} is one of the key-nuclei which can give us very useful information.

K^{40}: This nucleus occurs in nature with a frequency of 1/8000, and accounts for the natural radioactivity of potassium, discovered since 1906. It may also be artificially produced, but none of the methods suggested in Table 6 has yet been tried. On account of the long life of this nucleus and its low abundance, it is difficult to make accurate measurements with K^{40}. A large quantity of material is required so that all measurements become inaccurate due to self-absorption. Hence, measurements given by different observers have been widely different, e.g. the end-value of β^--spectrum is given as ·725 Mev by Libby and Lee (1939) while Henderson (1938) gives 1·3 Mev. The nucleus decays by β^--emission to Ca^{40} and Thomson and Holt (1944) have given arguments to show that it decays by K-capture to A^{40}, the proportion of the K-capture to β^--emission being given as 4 : 1. As we shall see shortly, the possibility of positron-emission cannot be excluded. The spin of K^{40} has been directly measured and found to have the abnormally large value of 4 (Zacharias, 1941). This short review shows the extremely unsatisfactory nature of our knowledge of K^{40} and attempts may be made to produce this nucleus by artificial methods, e.g. by the K^{39} (d, p)-reaction, and see whether the properties of K^{40} so obtained are similar to those of K^{40} occurring in nature. Isomeric forms of K^{40} having shorter life are quite possible.

All the odd-odd nuclei after K^{40} decay definitely by K-capture and β^+-emission. We may take them for detailed examinations.

Sc^{44}: A large amount of work has been done with this nucleus, but we may refer only to the recent work of Hibdon, Pool and Kurbatov (1945), for this work is quite elaborate and contains all references to earlier works. They have found that Sc^{44}, as derived from K^{41} (α, n) and Sc^{45} $(n, 2n)$-reactions, consists of two isomers, having lives of 3·92 hrs. and 52 hrs. The 52 hrs. isomer decays into the 3·92 hrs. one by emitting a γ-ray of energy ·28 Mev which is highly converted. The 3·92 period Sc^{44} emits a β^+-spectrum of end-energy 1·33 Mev and a γ-ray of energy 1·35 Mev. K-capture decay for Sc^{44} is indicated but it has not been definitely proved by X-ray investigations. According to calculations we have for allowed transitions $f^K = ·479, f^+ = ·588$ so that $f^K/f^+ = ·8$. The positron-emission is of the $1A$-type, as $f^+t = 1·19 \times 10^5$. The number of γ-rays to β^+-emission is given as 3 : 1, which does not agree with our ratio of f^K/f^+ showing that the process is more complicated. All that we can say from these investigations is that the energy-release is $> 1·61$ Mev.

V^{48}: According to the recent work of Hibdon *et al.* (1944), the end-energy of β^+-emission is ·58 Mev. The transition is of the $1B$-type. There is only one γ-ray of energy 1·5 Mev. This is the only radioactive isotope of vanadium which according to Turner (1940) is unambiguously identified. V^{48} has been observed to decay by K-capture and the probability of K-capture decay to that of β^+-emission has been found to be 18 : 1 (Hibdon *et al.*, 1944). It is found on our calculation that $f^+ = ·154, f^K = ·292$. The ratio of $f^K/f^+ = 2 : 1$, and not 18 :1.

Mn^{52}: This nucleus has been investigated in detail by Hemmendinger (1940) and has been found to consist of two isomers having periods of 21 min. and 6·5 days. The 21 min.-isomer emits a positron spectrum of end-energy 2·2 Mev with a transition of the $0B$-type and the 6·5 days-isomer, one of end-energy ·77 Mev with a transition of the class $1B$. A number of γ-rays are emitted by each isomer and K-capture is also inferred. It does not, however, appear to us that the level scheme suggested by Hemmendinger (Hemmendinger, *loc. cit.*, Fig. 9, p. 934) is correct. The energy-release according to this scheme is 5·4 Mev which appears to be too high. Mn^{52} appears to be one of the most interesting nuclei for investigation, for it gives a lot of data not yet cleared up.

Co^{56}: This nucleus has been the subject of many investigations which have been summed up by Elliot and Deutsch (1943). They have also given a level scheme (Figure on p. 324 of their paper). According to this paper, the total energy-release in the transition $Co^{56} \rightarrow Fe^{56}$ is 3·605 Mev, which occurs in the form of a β^+-spectrum of end-energy 1·5 Mev, followed by two γ-rays in cascade, of energies 1·26 Mev and ·845 Mev respectively. The last ray is found in the spectrum of Mn^{56} as well and must be from an excited state of Fe^{56}. Co^{56} also is suspected to decay by K-capture and the ratio of f^K/f^+ for allowed transitions =·25. On account of K-capture, a large number of γ-rays are emitted.

Cu^{60} and Ga^{61} have been claimed to have been produced by the processes Ni^{60} (p, n) and Zn^{64} (p, n) respectively, but nothing is known yet about their emissions. It does not appear possible to produce Zn^{62}, Ge^{66}, etc. which are not yet known amongst the stable nuclei of this group, artificially by any of the commoner nuclear processes. But unfamiliar processes like Ni $(\alpha, 2n)$, Cu^{63} $(p, 2n)$ may be thought of. But if these nuclei are formed, they will appear to be unstable (cf. discussion on Ti^{44} in the group $I=0$) and decay with β^+-emission and K-capture to Cu^{62} and Ga^{66} respectively, which will again decay by β^+-emission to Ni^{62} and Zn^{66}.

Discussion: It has been found difficult in this group to compare the theoretical formulae with the experimental results, because the latter are extremely confusing, and incapable of unique interpretation. For many nuclei, the knowledge is extremely defective. We shall show, however, that we may fix the value of the mass-defect constant β by a close analysis of the data collected for the nuclei P^{32}, Cl^{36} and K^{40}. It is clear that the value of β affects the two curves to different degrees and in opposite senses, e.g. for $I=2$ we have

$$A^- = \cdot 766 + \frac{4\beta}{A} - \frac{\delta(A-1)}{A^{\frac{4}{3}}}, \quad A^+ = -1\cdot 788 - \frac{12\beta}{A} + \frac{\delta(A-3)}{A^{\frac{4}{3}}},$$

so that any increase in the value of β will depress the A^+-curve thrice as much as it elevates the A^--curve. Now from equation (2·10) we have for odd-odd nculei

$$\frac{E^-(Z, A) - E^+(Z, A)}{2} = \frac{A^-(Z, A) - A^+(Z, A)}{2}$$

$$= 1\cdot 227 + \frac{4\beta I}{A} - \frac{\delta(A-I)}{A^{\frac{4}{3}}}. \qquad (4.1)$$

If $\beta = 19\cdot 5$ Mev, then for the nucleus P^{32} we have, since $E^-(15, 32) = 1\cdot 72$ Mev,

$$E^+ (15, 32) = \cdot 379 \text{ Mev},$$

so that P^{32} ought to decay by K-capture and β^+-decay, a fact which is not borne out by experimental observations. To make P^{32} stable against β^+-emission and K-capture we take

$$E^+(15, 32) = -1\cdot 022 - y \text{ Mev},$$

where $y > 0$. From equation (4.1) we get

$$\beta = 22\cdot 118 + 2y \text{ Mev}.$$

In Fig. 7 we have drawn the $A^\pm$-curves for $\beta = 22\cdot 5$ Mev. Let us now see whether the fact that Cl^{36} exhibits double activity is consistent with this new value of β. Using equation (4.1) we have, taking $E^-(17, 36) = \cdot 64$ Mev,

$$E^+(17, 36) = \cdot 034 \text{ Mev} > 0,$$

i.e. Cl^{36} ought to decay by both β^+-decay as well as by K-capture as is actually observed. For K^{40} we do not have any exact evaluation of E^- (19, 40); but if we take it to be ·7 Mev, we get

$$E^+(19, 40) = 2\cdot 04 \text{ Mev},$$

so that K^{40} ought to decay not only by K-capture but also by β^+-emission. The difficulties about the measurements for K^{40} have already been mentioned. It is quite possible that this energy $E^+(19, 40)$ may be released in the form of positrons and γ-rays. This deduction is supported by Klemperer (1934) who gives two γ-rays of energies ·5 Mev and 2 Mev. The former appears to be annihilation radiation, which is a strong proof that K^{40} actually decays by β^+-emission. K^{40} is thus seen to be full of unsolved problems, though it was the oldest light radioactive element discovered.

We may now compare the isobaric pairs of the groups $I=0$ and $I=2$. To do this we have drawn in Fig. 6 the A^+-curve for $I=0$ corresponding to $\beta = 22\cdot 5$ Mev. First we have the isobaric pairs N^{14} and C^{14}. Since $E^-(6, 14) = \cdot 145$ Mev we get using (3.3)

$$E^+(7, 14) = -1\cdot 169 \text{ Mev} < -2m.$$

Thus N^{14} should be stable against β^+-emission or K-capture as is observed. Next taking $E^+(9, 18) = \cdot 7$ Mev, we get from (4·1)

$$E^-(8, 18) = -1\cdot 727 \text{ Mev} < 0,$$

i.e. O^{18} ought to be stable as is actually observed. In a similar manner the discussion may be continued for heavier members of the two groups.

C. *The Group* $I=4$. (Fig. 8, Table 7.)

This group extends from P^{34} to Ga^{66}. From the review of the methods of production given in Table 7, it appears possible to extend the group on both sides very considerably. On the left side, it appears possible to get Al^{30}, Na^{26}, F^{22} and N^{18} by (n, p)-reactions, e.g. N^{18} by the reaction O^{18} (n, p), if the starting material could be concentrated. On the right side, it may be possible to prepare As^{70}, Br^{74}, Rb^{78} by (p, n)-reactions provided protons of sufficient energy are available, and the starting material, viz. Se^{74} (·9%), Kr^{78} (·35%), can be concentrated.

We first review the electron-emitters in details.

P^{34}: Giebert *et al.* (1944) have studied n-reactions with Cl and have identified a 14 sec. product with P^{34}. It shows a complex β-ray spectrum, 90% having the end-energy of 5 Mev, and 10% having 3·2 Mev. The energy-release may be taken to be $E^- \simeq 5$ Mev.

Cl^{38}: The spectrum of this nucleus has been extensively investigated by Itoh (1941), Watase (1941) and Curran *et al.* (1940). Itoh has given a level scheme of Cl^{38} on the basis of these measurements which appear to be quite satisfactory. According to Itoh, the β^--spectrum is a composite one of two components, having the end-energies of 4·99 Mev and 1·08 Mev. The difference is 3·91 Mev, which is the sum of the two observed γ-energies 2·19 Mev and 1·64 Mev. It appears therefore that the 1·08 Mev β-rays are emitted to an intermediate level, which descend to the lowest level of A^{38} after cascade emission of two successive γ-rays. The results of β-γ and γ-γ coincidence experiments of Watase are in agreement with these views. No spin-assignment of the levels has yet been made. Konopinski gives the 4·99 Mev-transition as of 2*A*-type, and 1·08 Mev-transition as of the allowed type. The maximum energy-release may be taken to be 4·99 Mev.

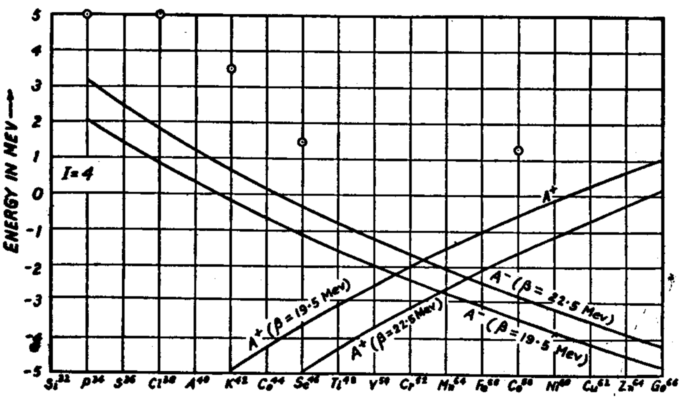

Fig. 8

K^{42}: This nucleus emits a β^--spectrum whose end-energy has been fixed at 3·5 Mev by Kurie *et al.* (1936). It requires reinvestigation. The transition has been given to be of the 2*A*-type. We have taken the energy-release to be 3·5 Mev.

Sc^{46}: The disintegration-scheme of this long-lived nucleus (85-day) has been studied by Meitner (1945). She has shown that Sc^{46} emits a β^--ray of end-energy ·26 Mev which is followed by a γ-ray of 1·26 Mev energy. The energy-release in the transition $Sc^{46} \rightarrow Ti^{46}$ is therefore 1·51 Mev. She has disproved the earlier hypothesis of Mattauch and Flugge (Kernphysikalishe Tabellen, 1942) that there is a second β-ray spectrum of end-energy 1·5 Mev. Meitner has also proved that Sc^{46} decays by *K*-capture to Ca^{46}. The ratio of *K*-capture to β^--emission is given as 3 : 2, but the results are stated to be preliminary. We have $f^- \simeq ·8$ for allowed transition and $f^-.t \simeq 5·6 \times 10^6$. This *ft*-value is nearly 1,000 times larger than the allowed *ft*-value. Hence actual f^- for this transition $\simeq 8 \times 10^{-4}$. We have $f^K \simeq 2\pi(\alpha Z)^3$. $(E^K/mc^2)^2 \simeq 2·5 \times 10^{-2}.x^2$ if $E^K = x.mc^2$. Taking $f^K/f^- = \frac{3}{2}$, we ought to have $f^K = 1·2 \times 10^{-3}$. So we get $x = \frac{1}{5}$ or ·2 Mev.

V^{50}: Nothing is known about this nucleus except its life, which is given as 3·7 hrs. (Walke, 1937). It is not even known whether it emits β^- or β^+-rays, or decays by *K*-capture and nothing is known of the end-energy of β-spectrum.

Let us now take up the β^+-emitting and *K*-capturing nuclei.

Mn^{54}: This interesting nucleus, which has a long life of 310 days, decays only by *K*-capture, and positrons were not obtained, even though looked for. It emits a single γ-ray of energy ·835 Mev which is due to an excited state of Cr^{54}. Deutsch and Elliot (1942) showed by coincidence experiments of the γ-ray, and the K_α-line of Cr^{54} which is the daughter nucleus, that every X-ray is followed by γ-ray. The *K*-capture therefore takes place in an excited level of Cr^{54}, but the energy-release to this excited level is not yet known.

Co^{58}: This nucleus which has been unambiguously identified as it has been produced by the reaction Mn^{55} (α, n) and has a life of 72 days. It was found by several workers to emit a positron-spectrum, and a γ-ray of energy ·805 Mev in addition to the annihilation radiation of ·505 Mev. The end-energy of the positron-spectrum which marks transition to an excited state of Fe^{58} was found to be ·47 Mev. Deutsch and Elliot (1942) showed the ratio of $f^+/f^K \simeq ·1$. This is in accordance with Fermi's theory of allowed transition. The γ-ray is from the excited state of Fe^{58} to a normal state. The energy-release in the transition $Co^{58} \rightarrow Fe^{58}$ is 1·275 Mev.

Discussion: Nuclei of this group give rise to some fundamental difficulties which may be grasped from the following representation (cf. Fig. 8*a*). It is generally found that in an arrangement of isobaric triplets as above, if

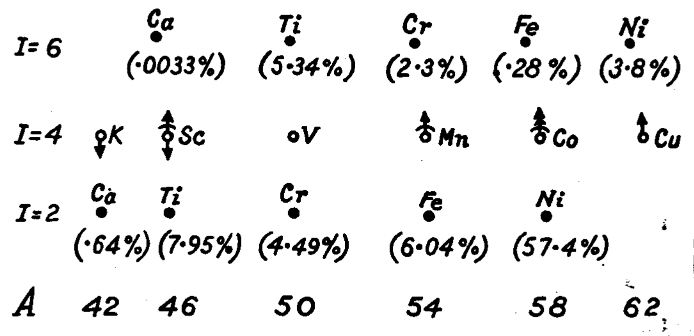

Fig. 8*a*

the isobars on the two extreme ends are stable, then the isobar in the middle is generally unstable showing of decay by both β^--activity and β^+-activity or *K*-capture.

344(1)

TABLE 7

$I = 4$

Nucleus	Percentage abundance	Mass	Spin	Magnetic moment	Half-life	E_{β^-} in Mev	E_K in Mev	E_{β^+} in Mev	E_γ in Mev	E^- in Mev	E^K in Mev	E^+ in Mev	ft	Class
N^{18}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
O^{20}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
F^{22}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Ne^{24}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Na^{26}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Mg^{28}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Al^{30}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Si^{32}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
P^{34}	..	..	..	..	14 s.	5 (90%) 3·2 (10%)	..	..	..	5	..	..	..	..
S^{36}	0·016	..	..	..	..	..	..	..	..	..	..	..	..	..
Cl^{38}	..	..	..	..	37 m.	4·99 1·08	..	..	2·19 1·64	4·99	..	..	(1) $2·1\times10^7$ (2) $1·1\times10^4$	2A 0A
A^{40}	99·632	39·97564	..	..	..	..	..	..	..	..	..	..	..	..
K^{42}	..	..	..	..	12·4 h.	3·5	..	..	..	3·5	..	..	$6·8\times10^7$	2A
Ca^{44}	2·06	..	..	..	..	..	..	..	..	..	..	..	..	..
Sc^{46}	..	..	..	..	85 d.	·26	*	..	1·26	1·51	..	..	$>5·6\times10^6$	1B
Ti^{48}	73·45	47·9651	..	..	..	..	..	..	..	..	..	..	..	..
V^{50}	..	..	..	..	3·7 h	..	..	..	..	..	..	..	..	..
Cr^{52}	83·78	51·9582	..	..	..	..	..	..	..	..	..	..	..	..
Mn^{54}	..	..	..	..	310 d.	..	*	..	·835	..	..	..	..	..
Fe^{56}	91·57	55·9572	..	..	..	..	..	..	..	..	..	..	..	..
Co^{58}	..	..	..	..	72 d.	..	* (90%)	0·47 (10%)	·6 ·805	..	..	1·275	..	..
Ni^{60}	26·7	..	..	..	..	..	..	..	..	..	..	..	..	..
Cu^{62}	..	..	..	..	10·5 m.	..	..	..	..	..	..	..	$8·4\times10^4$	0B
Zn^{64}	50·9	63·956	..	..	..	..	..	..	..	..	..	..	..	..
Ga^{66}	..	..	..	..	9·4 h.	..	..	..	..	..	..	..	$1·2\times10^6$	1B
Ge^{68}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
As^{70}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Se^{72}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Br^{74}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Kr^{76}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Rb^{78}	..	..	..	..	..	..	..	..	..	..	..	..	..	..

Nucleus	Transmutation Table (Target nuclei) (γ, n)	(γ, p)	(n, γ)	$(n, 2n)$	(n, p)	(n, α)	(p, γ)	(p, n)	(p, α)	(d, n)	$(d, 2n)$	(d, p)	(d, H^3)	(d, α)	(α, n)	(α, p)	Remarks and special reactions
N^{18}	..	..	..	..	O^{18}	..	..	..	..	..	..	..	..	..	..	..	..
O^{20}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
F^{22}	..	..	..	..	Ne^{22}	..	..	..	..	..	..	..	..	..	..	..	..
Ne^{24}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Na^{26}	..	..	..	..	Mg^{26}	..	..	..	..	..	..	..	..	..	..	..	..
Mg^{28}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Al^{30}	..	..	..	..	Si^{30}	..	..	..	..	..	..	..	..	..	..	..	..
Si^{32}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
P^{34}	..	..	..	..	$\underline{S^{34}}$	$\underline{Cl^{37}}$	..	..	..	..	..	..	..	S^{36}	..	..	..
S^{36}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Cl^{38}	..	..	$\underline{Cl^{37}}$	..	A^{38}	$\underline{K^{41}}$	..	..	..	..	..	$\underline{Cl^{37}}$	..	A^{46}	..	..	..
A^{40}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
K^{42}	..	Ca^{43}	$\underline{K^{41}}$	..	$\underline{Ca^{42}}$	$\underline{Sc^{45}}$	..	..	..	..	..	$\underline{K^{41}}$	..	Ca^{44}	..	..	..
Ca^{44}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Sc^{46}	..	Ti^{47}	$\underline{Sc^{45}}$	..	$\underline{Ti^{46}}$	..	..	Ca^{46}	Ti^{49}	..	Ca^{46}	$\underline{Sc^{45}}$	..	$\underline{Ti^{48}}$	..	$\underline{Ca^{43}}$	..
Ti^{48}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
V^{50}	V^{51}	..	..	$\underline{V^{51}}$	Cr^{50}	..	Ti^{49}	Ti^{50}	Cr^{53}	$\underline{Ti^{49}}$	Ti^{50}	..	V^{51}	Cr^{52}	..	$\underline{Ti^{47}}$	..
Cr^{52}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Mn^{54}	Mn^{55}	..	..	Mn^{55}	Fe^{54}	..	Cr^{53}	$\underline{Cr^{54}}$	Fe^{57}	$\underline{Cr^{53}}$	Cr^{54}	..	Mn^{55}	$\underline{Fe^{56}}$	$\underline{V^{51}}$	..	..
Fe^{56}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Co^{58}	Co^{59}	..	..	Co^{59}	$\underline{Ni^{58}}$	..	$\underline{Fe^{57}}$	$\underline{Fe^{58}}$	Ni^{61}	$\underline{Fe^{57}}$	Fe^{58}	..	Co^{59}	$\underline{Ni^{60}}$	$\underline{Mn^{55}}$	..	$Fe^{56}-\alpha-(n, p)$
Ni^{60}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Cu^{62}	$\underline{Cu^{63}}$	..	..	$\underline{Cu^{63}}$	..	..	$\underline{Ni^{61}}$	$\underline{Ni^{62}}$	Zn^{65}	Ni^{61}	Ni^{62}	..	$\underline{Cu^{63}}$	Zn^{64}	$\underline{Co^{59}}$	..	..
Zn^{64}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Ga^{66}	..	..	..	..	..	..	..	$\underline{Zn^{66}}$	..	..	Zn^{66}	..	..	..	$\underline{Cu^{63}}$	..	..
Ge^{68}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
As^{70}	..	..	..	..	..	..	..	Ge^{70}	..	..	Ge^{70}	..	..	..	..	..	..
Se^{72}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Br^{74}	..	..	..	..	..	..	..	Se^{74}	..	..	Se^{74}	..	..	..	..	..	..
Kr^{76}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Rb^{78}	..	..	..	..	..	..	..	Kr^{78}	..	..	Kr^{78}	..	..	..	..	..	..

TARGET NUCLEI.

*Stars indicate that evidence for the emission has been found, but no measurement has been made.

Targets underlined indicate that the corresponding nuclear reaction has been tried. Targets not underlined indicate that the corresponding nuclea reaction has yet to be tried.

We can easily verify from formulae (1.2) and (1.4) that this must be so. Thus

$$E^-(Z, A) = M(Z, A) - M(Z+1, A),$$

and $$E^K(Z+1, A) = M(Z+1, A) - M(Z, A) - m\{1-\sqrt{1-\alpha^2 Z^2}\},$$

$$\simeq -E^-(Z, A) - \tfrac{1}{2}m\alpha^2 Z^2. \quad .. \quad (4.2)$$

Thus if the nucleus $_ZM^A$ is stable against β^--decay, i.e. if $E^-(Z, A) < 0$, then

$$E^K(Z+1, A) > 0,$$

showing that the nucleus $_{Z+1}M^A$ ought to decay by K-capture unless of course if

$$-E^-(Z, A) < \tfrac{1}{2}m\alpha^2 Z^2, \qquad (4.3)$$

in which case $_{Z+1}M^A$ may be stable against K-capture decay. But in general $\frac{1}{2}m\alpha^2 Z^2$ is of the order of a few thousand electron volts only so that the probability of (4.3) being satisfied is very small. If $_ZM^A$ is β^--active, then $_{Z+1}M^A$ should be a stable nucleus. In Fig. 8 we find that apparently Mn^{54}, Co^{58} do not satisfy this rule, since these have not yet been found to decay by β^--emission. If we take $\beta = 19{\cdot}5$ Mev, then since $E^+(27, 58) = 1{\cdot}275$ Mev, we have

$$E^-(27, 58) = -1{\cdot}6 \text{ Mev}.$$

Thus Co^{58} should on no account decay by β^--emission. In that case Ni^{58} should exhibit K-capture decay. But Ni^{58} is, as is well known, a very stable nucleus having a large abundance. Nothing is known about E^+ for Mn^{54} or V^{50} so that we cannot examine whether E^- for these nuclei can have positive values. If, however, we take $\beta = 22{\cdot}5$ Mev, we find that

$$E^-(27, 58) = {\cdot}055 \text{ Mev} > 0,$$

so that Co^{58} may emit extremely soft electrons to detect which we shall have to employ special technique. If we take $\beta = 22{\cdot}5$ Mev we meet, however, another kind of difficulty. Taking the nucleus Sc^{46}, we have, provided $E^-(21, 46) = 1{\cdot}52$ Mev,

(*a*) $E^+(21, 46) = -0{\cdot}996$ Mev $> -2m$, $(\beta = 19{\cdot}5$ Mev),

(*b*) $E^+(21, 46) = -3{\cdot}083$ Mev $< -2m$, $(\beta = 22{\cdot}5$ Mev).

Thus whereas for $\beta = 19{\cdot}5$ Mev we can expect K-capture decay for Sc^{46}, $\beta = 22{\cdot}5$ Mev will rule out any such possibility. It appears therefore necessary to repeat Meitner's work on Sc^{46} from this point of view and also examine Co^{58} for soft β^--radiations. If the K-capture decay of Sc^{46}, which has been observed, is illusory then we cannot expect to have a stable Ca^{46}. The discovery of Ca^{46} and Ca^{48} has been claimed by Nier (1938) and their abundances have been given as ·0033% and ·2%. We shall take up this question again when we discuss Sc^{48}.

D. *The Group* $I=6$. (Fig. 9, Table 8.)

This group extends from the doubtful nucleus K^{44} to the stable nucleus Kr^{78} (·35%). The odd-odd nuclei are all unstable, but all have not yet been produced or studied. The methods of production are reviewed in Table 8. There are possibilities of extending the unstable nuclei on both flanks. It should certainly be possible to prepare Cl^{40} by the A^{40} (n, p)-reaction and P^{36} by the S^{36} (n, p)-reaction if S^{36} (abundance ·016%) can be concentrated. It does not appear possible to go beyond P^{36} to Al^{32}. On the other flank, it should be possible to prepare Br^{76}, Rb^{80}, Y^{84}, Ma^{92} by Se^{76} (9·5%), Kr^{80} (2%), Sr^{84} (·56%) and Mo^{92} (41·9%) (p, n)-reactions if the target nuclei could be concentrated, and protons of sufficient energy can be obtained. The properties of these nuclei would be very useful for the testing of the theory because there are many

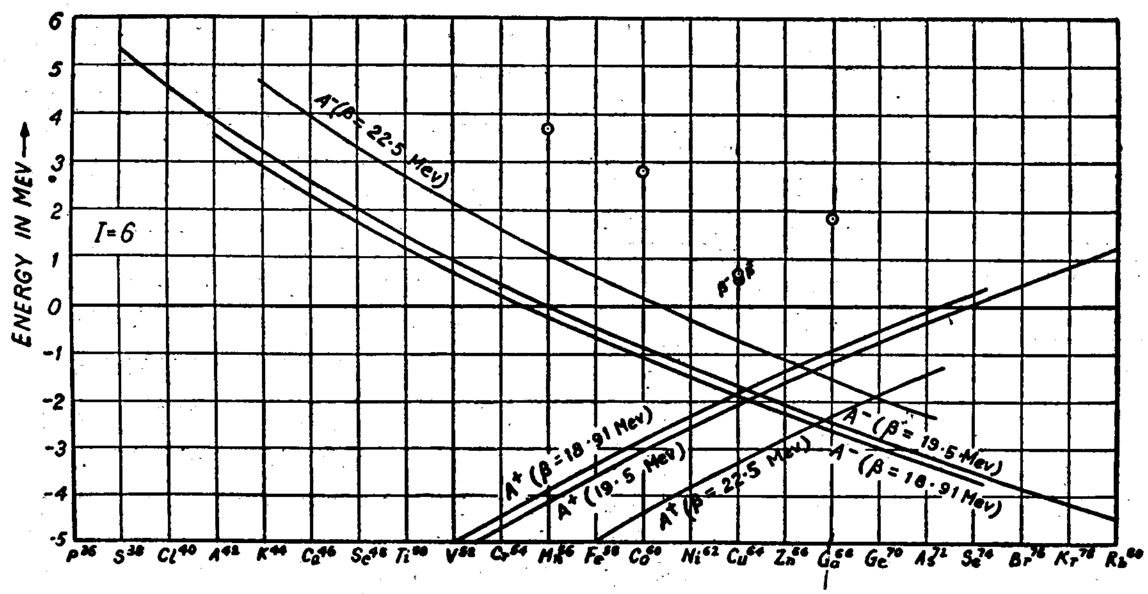

Fig. 9

lacunae in our knowledge of the group, which can be filled up only from data about the heavier nuclei. The knowledge of this group as a whole is rather too meagre.

Let us examine the β-emitters of this group one by one. The first radioactive nucleus reported is K^{44}, about which nothing is known, except a bare statement that it is β^--emitting, with a life of 18 min.

Sc^{48}: The next nucleus Sc^{48}, having a life of 44 hrs., forms the subject of a paper by Hibdon and Pool (1945), and is reported to give a β^--spectrum with end-energy of ·57 Mev and a γ-ray of energy 1·35 Mev. The γ-ray is attributed to K-capture, the existence of which is not proved clearly, and it is said that 14 γ-rays are emitted per nuclear electron. We have reasons which we give later to differ very essentially from the conclusions of Hibdon and Pool.

V^{52}: We have no information about this nucleus except that it emits only γ-rays of energy 2·05 Mev.

Mn^{56}: This nucleus has been the subject of many investigations which have been summed up by Elliot and Deutsch (1943) where all references to older works would be found. They have given a level scheme which apparently explains all facts (Fig. 4*a*, p. 324 of their paper). Mn^{56} emits a composite β^--spectrum which has been decomposed into three Fermi-curves with end-energies at ·73 Mev, 1·05 Mev and 2·86 Mev, with the relative abundance of 15 : 25 : 60. Three γ-rays were observed with energies of ·845 Mev, 1·81 Mev, 2·45 Mev. The γ-line ·845 Mev is found also in the spectrum in Co^{56} which is a β^+-emitting body, so that this level may be ascribed to Fe^{56} to which both Mn^{56} and Co^{56} decay. The energy-release in the transition $Mn^{56} \rightarrow Fe^{56}$ is given as 3·705 Mev. This has been accepted in this paper. No spin-assignment to these levels has yet been made. No positron-emission or K-capture is reported.

Co^{60}: This is a very interesting β^--emitting nucleus consisting of two isomers, having lives of 5·3 yrs. and 10·7 min. respectively. Many level schemes have been given but it will suffice to mention that of Deutsch *et al.* (1945), who have given references to earlier papers. Each isomer has its own β^--spectrum and γ-rays. The 5·3 yrs. Co^{60} emits a positron-spectrum with end-energy which is given as ·3 Mev by Deutsch *et al.* and ·23 Mev by Das and Saha (1946). This is followed by γ-rays of energy 1·10 Mev and 1·30 Mev. The 10·7 min. Co^{60} emits a β^--spectrum with end-energy of 1·28 Mev, followed by a single γ-ray of energy 1·5 Mev. There is besides a γ-ray of energy ·056 Mev which is very strongly converted. It is assured on plausible grounds that 90% of the 10·7 min. Co^{60} decays by the emission of ·056 Mev γ-ray to the 5·3 yrs. Co^{60}. It cannot yet be said that the level schemes have been well worked out. According to these works, however, the energy-release in the transition $Co^{60} \rightarrow Ni^{60}$ appears to be $\simeq$2·8 Mev. There is no evidence yet of β^+-emission or K-capture decay by this nucleus.

Cu^{64}: This was the first nucleus which was found to emit both β^- and β^+ rays and almost in equal proportion but Cl^{36} was found later to emit also simultaneously electrons and positrons. Both the positron and negatron spectra were very carefully investigated by Tyler (1939) in his precision magnetic spectrometer, and found to yield simple allowed type of Fermi spectra with end-energies at ·659 Mev and ·578 Mev respectively. There is departure from the ideal form on the low-energy side which is greater for the positron than for the electron-spectrum. These points were recently investigated by Backus (1946), who found actually a larger number of positrons on the low-energy side (below ·5 Mev) than one can get from the Fermi theory. On the whole, the evidence so far available does not enable us to postulate the existence of any γ-ray from Cu^{64}, but as it is expected to decay by K-capture, γ-rays may be emitted. Using the standard formula, we get f^K/f^+ for Cu^{64}=2·26, and an investigation by Bradt *et al.* (1945) gives for the ratio of Ni-K quanta to annihilation radiation from Cu^{64}, the value 1·82. From experiments on γ-γ coincidence, the above authors find no γ-ray from Cu^{64}. Assuming that E^-=·58 Mev and E^+=·66 Mev for Cu^{64}, we can apply formula (4.1) to calculate β. We find that

$$\beta \simeq 18{\cdot}91 \text{ Mev}.$$

The value of β is now the standard value (cf. §1).

Ga^{68}: The cloud-chamber investigation of spectrum of Ga^{68} (Mann, 1937) has shown the energy of the positron-spectrum to be 1·86 Mev. Ga^{68} is also expected to emit β^--particles of small energy, but no such rays are known, and if stable Ge^{68} does not exist, Ga^{68} cannot be β^--emitting. But it is one of the border line cases and ought to be more carefully investigated.

Discussion: We have seen that if E^+ and E^- for Cu^{64} are taken as ·66 Mev and ·58 Mev respectively then β should have the value 18·91 Mev. We have drawn in Fig. 9 the $A^{\pm}$-curves for the group with three values of β, viz. β=18·91 Mev, 19·5 Mev and 22·5 Mev. β=18·91 Mev, though explaining the energetics of Cu^{64}, presents us with certain serious difficulties. Taking $E^-(25, 56)$=3·705 Mev, we have from equation (4.1)

$$E^+(25, 56) = {\cdot}106 \text{ Mev},$$

so that Mn^{56} should decay by K-capture as well as β^+-emission. Similarly taking $E^-(27, 60)$=2·8 Mev, we get

$$E^+(27, 60) = 1{\cdot}124 \text{ Mev},$$

and if we take $E^+(31, 68)$=1·86 Mev, we get

$$E^-(31, 68) = {\cdot}138 \text{ Mev}.$$

We find therefore Co^{60} ought to exhibit β^+-decay as well as decay by K-capture, whereas Ga^{68} should decay by β^--emission. None of these statements are borne out by observations. We therefore try β=22·5 Mev which has

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Table 8

$I = 6$

Nucleus	Percentage abundance	Mass	Spin	Magnetic moment	Half-life	E_{β^-} in Mev	E_K in Mev	E_{β^+} in Mev	E_γ in Mev	E^- in Mev	E^K in Mev	E^+ in Mev	ft	Class
P^{36}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
S^{38}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Cl^{40}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
A^{42}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
K^{44}	..	..	..	..	18 m. ?	..	..	..	..	..	..	..	..	..
Ca^{46}	·0033	..	..	..	..	..	..	..	..	..	..	..	..	..
Sc^{48}	..	..	..	..	44 h.	·57	..	..	1·35	..	..	..	$2·8 \times 10^5$	1*A*
Ti^{50}	5·34	49·963	..	..	..	..	..	..	..	..	..	..	..	..
V^{52}	..	..	..	..	3·9 m.	2·05	..	..	..	..	..	..	$4·2 \times 10^4$	0*B*
Cr^{54}	2·3	53·960	..	..	..	..	..	..	..	..	..	..	..	..
Mn^{56}	..	..	..	..	2·59h.	·73 (15%) 1·05 (25%) 2·86 (60%)	..	..	·845 1·81 2·45	3·705	..	..	(1) $8·8 \times 10^6$ (2) $9·6 \times 10^4$	1*B* 0*B*
Fe^{58}	·28	..	..	..	..	..	..	..	..	..	..	..	..	..
Co^{60}	..	..	..	..	10·7 m. (I.T.)	1·28	..	..	1·5 ·056	2·8	..	..	$3·6 \times 10^4$	0*B*
Co^{60}	..	..	..	..	5·3 y.	·300	..	..	1·10 1·30		..	..	..	..
Ni^{62}	3·8	..	..	..	..	..	..	..	..	..	..	..	..	..
Cu^{64}	..	..	..	..	12·8 h.	·578	*	·659	..	..	..	..	$f^-t > 6·6 \times 10^4$ $f^+t > 2·2 \times 10^4$ $f^Kt > 2·2 \times 10^4$	0*B*
Zn^{66}	27·3	65·952	..	..	..	..	..	..	..	..	..	..	..	..
Ga^{68}	..	..	..	..	68 m.	..	..	1·86	..	..	..	1·86	$12·0 \times 10^4$	0*B*
Ge^{70}	21·2	..	..	..	..	..	..	..	..	..	..	..	..	..
As^{72}	..	..	..	..	26 h. 90 d. ?	..	.. *?	* ..	·052	..	..	..	..	..
Se^{74}	0·9	..	..	..	..	..	..	..	..	..	..	..	..	..
Br^{76}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Kr^{78}	0·35	77·945	..	..	..	..	..	..	..	..	..	..	..	..
Rb^{80}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Sr^{82}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Y^{84}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Zr^{86}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Nb^{88}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Mo^{90}	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Mo^{92}	..	..	..	..	..	..	..	..	..	..	..	..	..	..

Transmutation Table (Target nuclei.)

Nucleus	(γ, n)	(γ, p)	(n, γ)	(n, 2n)	(n, p)	(n, α)	(p, γ)	(p, n)	(p, α)	(d, n)	(d, 2n)	(d, p)	(d, H^3)	(d, α)	(α, n)	(α, p)	Remarks and special reactions
P^{36}	..	..	..	..	S^{36}	..	..	..	..	..	..	..	..	..	..	..	..
S^{38}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Cl^{40}	..	..	..	..	A^{40}	..	..	..	..	..	..	..	..	..	..	..	..
A^{42}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
K^{44}	..	..	..	..	$\underline{Ca^{44}}$	..	..	..	..	..	..	..	..	Ca^{46}	..	..	..
Ca^{46}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Sc^{48}	..	Ti^{49}	..	..	$\underline{Ti^{48}}$	$\underline{V^{51}}$	..	$\underline{Ca^{48}}$	..	..	$\underline{Ca^{48}}$	..	..	$\underline{Ti^{50}}$	..	..	..
Ti^{50}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
V^{52}	..	Cr^{53}	$\underline{V^{51}}$	..	$\underline{Cr^{52}}$	$\underline{Mn^{55}}$	..	..	..	..	..	$\underline{V^{51}}$	..	Cr^{54}	..	Ti^{49}	..
Cr^{54}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Mn^{56}	..	Fe^{57}	$\underline{Mn^{55}}$	..	$\underline{Fe^{56}}$	$\underline{Co^{59}}$	..	..	..	..	..	$\underline{Mn^{55}}$	..	$\underline{Fe^{58}}$	..	$\underline{Cr^{53}}$	..
Fe^{58}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Co^{60}	..	Ni^{61}	$\underline{Co^{59}}$	..	$\underline{Ni^{60}}$	Cu^{63}	..	..	..	..	..	$\underline{Co^{59}}$	..	..	..	Fe^{57}	..
Co^{60}	..	Ni^{61}	$\underline{Co^{59}}$	..	Ni^{60}	Cu^{63}	..	..	..	..	..	$\underline{Co^{59}}$	..	$\underline{Ni^{62}}$	..	Fe^{57}	..
Ni^{62}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Cu^{64}	$\underline{Cu^{65}}$	..	$\underline{Cu^{63}}$	$\underline{Cu^{65}}$	$\underline{Zn^{64}}$	..	..	$\underline{Ni^{64}}$	Zn^{67}	..	Ni^{64}	$\underline{Cu^{63}}$	Cu^{65}	Zn^{66}	..	Ni^{61}	..
Zn^{66}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Ga^{68}	$\underline{Ga^{69}}$	..	..	Ga^{69}	..	..	Zn^{67}	$\underline{Zn^{68}}$	..	$\underline{Zn^{67}}$	Zn^{68}	..	Ga^{69}	$\underline{Ge^{70}}$	Cu^{65}	..	..
Ge^{70}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
As^{72}	..	..	..	..	..	..	..	$\underline{Ge^{72}}$	..	..	Ge^{72}	..	..	..	Ga^{69}	..	..
Se^{74}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Br^{76}	..	..	..	..	..	..	..	Se^{76}	..	..	Se^{76}	..	..	..	..	..	..
Kr^{78}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Rb^{80}	..	..	..	..	..	..	..	Kr^{80}	..	..	Kr^{80}	..	..	..	..	..	..
Sr^{82}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Y^{84}	..	..	..	..	..	..	..	Si^{84}	..	..	Sr^{84}	..	..	..	..	..	..
Zr^{86}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Nb^{88}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Mo^{90}	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Mo^{92}	..	..	..	..	..	..	..	Mo^{92}	..	..	Mo^{92}	..	..	..	..	..	..

TARGET NUCLEI.

*Stars indicate that evidence for the emission has been found, but no measurement has been made.

Targets underlined indicate that the corresponding nuclear reaction has been tried. Targets not underlined indicate that the corresponding nuclear reaction has yet to be tried.

been so successful for the preceding groups. We get then

$$E^{+}(25, 56) = -2{\cdot}97 \text{ Mev}, \quad E^{+}(27, 60) = -1{\cdot}748 \text{ Mev},$$

$$E^{-}(31, 68) = 2{\cdot}672 \text{ Mev},$$

so that the stability of Mn^{56} and Co^{60} against decay by K-capture or β^{+}-decay is well explained, although we find that Ga^{68} should decay by β^{-}-emission. The investigations of Mn^{56} and Co^{60} appear to be thorough while that of Ga^{68} is not of the same standard. The product nucleus of a possible β^{-}-decay process of Ga^{68}, viz. Ge^{68} is, however, not known. For Cu^{64} if we take $E^{-}(29, 64) = {\cdot}578$ Mev as correct then

$$E^{+}(29, 64) = -2{\cdot}026 \text{ Mev},$$

so that Cu^{64} should not exhibit β^{+}-emission or K-capture. On the other hand, if we take $E^{+}(29, 64) = {\cdot}659$ Mev as correct then we get

$$E^{-}(29, 64) = 3{\cdot}263 \text{ Mev}.$$

Thus the energy 2·685 Mev should be emitted as γ-rays. It may be quite possible that a number γ-rays of approximate energy ·5 Mev are emitted in cascades. It would be difficult to detect them unambiguously on account of the presence of annihilation radiation.

It is therefore seen that all the nuclei, except Sc^{48} and perhaps Ga^{68}, conform in a general way to our scheme. Sc^{48}, however, is a glaring anomaly and we proceed to consider this nucleus carefully. As Sc^{48} is placed between the stable nuclei Ti^{48} (abundance 73·45%) and Ca^{48} (abundance ·19%), both K-capture and β^{-}-emission must take place if Ca^{48} really exists. Ca^{48} belongs to the group $I=8$, which starts from stable Ca^{48}. After Ca^{48}, however, there is a long gap and the nuclei Ti^{52} and Cr^{56} which may be expected to be stable are not found. None of the expected isotopes are obtained until we come to Ni^{60} (·88%). The artificially produced nuclei of the group $I=6$ after Sc^{48} are V^{52}, Mn^{56}, Co^{60}. V^{52} as already mentioned is not well-investigated but Mn^{56}, Co^{60} have been very thoroughly studied. It is therefore surprising that while Mn^{56}, Co^{60} do not decay by K-capture or β^{+}-emission, Sc^{48} does so. Let us examine Sc^{48} on the basis of our theory. If β is taken to be 22·5 Mev, then $A^{+}(21, 48) = -8{\cdot}374$ Mev, so that if Sc^{48} shows K-capture we must have

$$-\chi(21, 48) > 7{\cdot}352 \text{ Mev}.$$

In the case, however, $E^{-}(21, 48)$ should have a relatively high value, viz.

$$E^{-}(21, 48) > 10{\cdot}628 \text{ Mev}$$

which is not borne out at all by observations. The whole tangle can be solved at one stroke if we assume that a stable Ca^{48} does not exist. Nier (1938) who claimed to have found evidence for Ca^{48} and Ca^{46} in his mass-spectrograph had apparently some doubt whether these mass-numbers were really due to Ca and gave a discussion on these points. Apparently he satisfied himself that these isotopes of Ca do exist. Our suggestion is that γ-ray reported from Sc^{48} are not due to K-capture but are emitted in cascades after β^{-}-emission. In that case the E^{-} energy-release in the transition $Sc^{48} \rightarrow Ti^{48}$ would be quite large. This suggestion was made by Pollard (1938), but has been rejected by Hibdon *et al.* But since other nuclei of this group, viz. Mn^{56}, Co^{60}, emit very soft β^{-}-rays followed by a large number of γ-rays in cascade, we may expect the same kind of process for Sc^{48}. After this paper was written we came across a paper by Curie (1945) who is also of the opinion that there cannot be any stable Ca^{48}.

Conclusion: We have thus found that β-activity of nuclei may be neatly explained by the inclusion of a spin-dependent term in the Weizsäcker-Bethe mass-defect formula. We have not as yet arrived at any analytic dependence of this term $\chi(Z, A)$ on the spin or the magnetic moment of the nucleus (Z, A). It appears from the above discussion that $\chi(Z, A)$ is generally of the order of a few million electron volts. According to classical theory, it should, however, be $\simeq \frac{Zev}{cr^2}\mu_N$, where v = velocity of a nucleon inside the nucleus, μ_N=the magnetic moment of the nucleus, and r=the nuclear radius. Making plausible assumptions regarding these quantities, we find that $\frac{Zev}{cr^2}$ should be of order of 10 kiloelectronvolts. This shows that we have to consider some type of meson theory to find out the right order of value of the spin-dependent part of the nuclear binding energy.

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References

Allen, Pool, Kurbatov and Quill (1941). Artificial radioactivity of Ti^{45}. *Phy. Rev.*, **60**, 425.

Alvarez (1938). The capture of orbital electrons by nuclei. *Phy. Rev.*, **54**, 486.

Aston (1942). Mass-spectra and isotopes. E. Arnold & Co., London.

Backus (1946). The β-rays of Cu^{64} at low energies. *Phy. Rev.*, **68**, 59.

Barkas (1939). The analysis of nuclear binding energies. *Phy. Rev.*, **55**, 691.

Bayley and Crane (1937). The β-ray spectra of Li^{8} and B^{12}. *Phy. Rev.*, **52**, 604.

Bethe and Bacher (1936). Nuclear physics. *Rev. Mod. Phy.*, **8**, 90.

Bethe and Henderson (1939). Evidence for incorrect assignment of the supposed Si^{27} radioactivity of 6·7 min. half life. *Phy. Rev.*, **56**, 1060.

Birge (1941). The general physical constants. *Rep. Prog. Phy.*, **8**, 90.

Bjerge and Broström (1936). β-ray spectrum of radio-He. *Nat.*, **38**, 400.

Bohr and Wheeler (1939). The mechanism of nuclear fission. *Phy. Rev.*, **56**, 426.

Bower and Burcham (1940). Experiments on the transmutation of F by deuterons. *Proc. Roy. Soc. Lond.*, A, **173**, 379.

BRADT *et al.* (1944) and (1945). *Helv. Phy. Acta.*

BREIT and KNIPP (1938). Note on electron capture in Be^7. *Phy. Rev.*, **54,** 652.

CORK, HADLEY and KENT (1942). Relative probability of $(d, 2n)$-reaction in Ni and Zn. *Phy. Rev.*, **61,** 388.

CRITTENDEN (1939). The β-ray spectra of Mg^{27}, Cu^{62} and the nuclear isomers of Rh^{104}. *Phy. Rev.*, **56,** 709.

CURAN, DEE and STROTHERS (1940). Some measurements of β-ray energies. *Proc. Roy. Soc. Lond.*, A, **174,** 546.

CURIE (1945). Empirical determination of the atomic number Z_A corresponding to the maximum stability of atoms of mass *A. Jour. Phy. Rad. Series* 8, **6,** 209.

CURTIS (1939). The γ-radiations from radioactive Co. *Phy. Rev.*, **55,** 1136.

DAS and SAHA (1946). Radioactivity of 5·3 year Co^{60}. *Proc. Nat. Inst. Sci.* (in course of publication).

DELSASSO, RIDENOUR, SHERR and WHITE (1939). Artificial radioactivity produced by proton. *Phy. Rev.*, **55,** 113.

DEMPSTER (1936). Energy Content of Heavy Nuclei. *Phy. Rev.*, **53,** 869.

DEUTSCH and ELLIOT (1942). Disintegration schemes of radioactive substances. VII. Mn^{54} and Co^{58}. *Phy. Rev.*, **65,** 211.

DEUTSCH, ELLIOT and ROBERTS (1945). Disintegration schemes of radioactive substances. VIII. Co^{60}. *Phy. Rev.*, **68,** 193.

DORAN and HENDERSON (1941). New reactions in Ni. *Phy. Rev.*, **60,** 411.

DUCKWORTH (1942). New packing fraction curves. *Phy. Rev.*, **62,** 19.

ELLIOT and DEUTSCH (1943). Disintegration schemes of radioactive substances. VI. Mn^{65} and Co^{56}. *Phy. Rev.*, **64,** 321.

ELLIOT and KING (1941). Radioactive Sc^{41}, A^{35} and S^{31}. *Phy. Rev.*, **59,** 403.

GIEBERT, ROGGEN and ROSSEL (1944). Nuclear reactions of chlorine with neutrons. *Helv. Phy. Acta.*, **17,** 97.

GRAHAME and WALKE (1941). Preparation and properties of long-lived radio-chlorine. *Phy. Rev.*, **60,** 909.

GRAVES (1939). Packing fraction differences among heavy elements. *Phy. Rev.*, **55,** 863.

HAXBY, SHOUPP, STEPHENS and WELLS (1940). Thresholds for proton-neutron reactions of Li, Be, B and C. *Phy. Rev.*, **58,** 1035.

HEMMENDINGER (1940). Proton induced activity of Mn. *Phy. Rev.*, **58,** 929.

HENDERSON (1935). *Phy. Rev.*, **48,** 855.

HENDERSON (1938). The energy of the β-rays from K. *Phy. Rev.*, **55,** 238.

HIBDON, POOL and KURBATOV (1944). Radioactivity of V. *Bul. Amer. Phy. Soc.*, **19** (No. 2), 13.

HIBDON, POOL and KURBATOV (1944). Transmutation of Ti. *Phy. Rev.*, **65,** 351.

HIBDON, POOL and KURBATOV (1945). Radioactive Sc. I. *Phy. Rev.*, **67,** 289.

HIBDON and POOL (1945). Radioactive Sc. II. *Phy. Rev.*, **67,** 313.

HUBER, LIENARD, SCHERRER and WÄFFLER (1943). *Helv. Phy. Acta.*, **16,** 146; **16,** 431.

HUBER, LIENARD, SCHERRER and WÄFFLER (1944). *Helv. Phy. Acta.*, **17,** 224.

ITOH (1941). Radioactivity of Cl^{38}. *Proc. Phy. Math. Soc. Jap.*, **23,** 605.

KAMEN (1941). Production and isotopic assignment of long-lived radioactive sulphur. *Phy. Rev.*, **60,** 537.

KLEMPERER (1934). Radioactivity of K and Rb. *Proc. Roy. Soc. Lond.*, A, **148,** 638.

KONOPINSKI (1943). β-decay. *Rev. Mod. Phy.*, **15,** 209.

KRÜGER and OGLE (1945). γ-rays emitted during radioactive transitions. *Phy. Rev.*, **67,** 273.

KURIE, RICHARDSON and PAXTON (1936). Radiations emitted from artificially produced bodies radioactive substances. Part I. Upper limits and shapes of β-ray spectra for several elements. *Phy. Rev.*, **49,** 368.

LAWSON (1939). The β-ray spectra of P, Na and Co. *Phy. Rev.*, **56,** 131.

LIBBY and LEE (1939). Energies of soft β-radiations of Rb and other bodies, method of their determination. *Phy. Rev.*, **55,** 245.

LIVINGOOD and SEABORG (1938). Radioisotopes of Ni. *Phy. Rev.*, **53,** 765.

LIVINGOOD and SEABORG (1938). Radioactive Mn isotopes. *Phy. Rev.*, **54,** 391.

LIVINGOOD and SEABORG (1939). Longlived radioactive Fe^{55}. *Phy. Rev.*, **55,** 1268.

LIVINGOOD and SEABORG (1940). Table of induced radioactivities. *Rev. Mod. Phy.*, **12,** 30.

LIVINGOOD and SEABORG (1941). Radioactive isotopes of Co. *Phy. Rev.*, **60,** 913.

MAGNAN (1941). Radioactivity of P^{30}. *Ann. d. Phy.*, **15,** 5.

MAIER-LEIBNITZ (1944). Coincidence measurements of radioactive Na isotopes. *Zeits. Phy.*, **122,** 233.

MANN (1937). Nuclear transformation in Cu. *Phy. Rev.*, **52,** 405.

MATTAUCH and FLÜGGE (1942). Isotopenbericht, Berlin.

MEITNER (1945). On the radioactivity of Sc^{46}. *Arkiv. Math. Phy.*, **32,** 2.

MÖLLER (1937). On the capture of optical electrons by nuclei. *Phy. Rev.*, **51,** 84.

NELSON, POOL and KURBATOV (1941). Radioactive isotopes of Ni. *Phy. Rev.*, **61,** 428.

NIELSON (1941). Energy spectrum of H^3 β-rays. *Phy. Rev.*, **60,** 160.

NIER (1938). The isotopic constitution of Ca, Ti, S and A. *Phy. Rev.*, **53,** 282.

NORDHEIM and YOST (1937). On the matrix element in Fermi's theory of β-decay. *Phy. Rev.*, **51,** 942.

O'Cnnor, Pool and Kurbatov (1941). Artificial radioactivity of Cr^{49}. *Phy. Rev.*, **62,** 413.

PLESSET (1941). Nuclear excitations resulting from radioactive decay. *Phy. Rev.*, **62,** 181.

POLLARD (1938). Transmutation of Sc by ThC-particles. *Phy. Rev.*, **54,** 411.

RICHARDSON and KURIE (1936). The radiations emitted from artificially produced radioactive substances. II. γ-rays from several elements. *Phy. Rev.*, **50,** 999.

RIDENOUR and HENDERSON (1937). Artificial radioactivity produced by α-particles. *Phy. Rev.*, **52,** 889.

RUBEN and KAMEN (1940). Long-lived radioactive C. *Phy. Rev.*, **59,** 349.

SAHA, A. K. (1944). The theory of the screen cathode β-ray spectrometer. *Proc. Nat. Inst. Sci. Ind.*, **10,** 355.

SAHA, A. K. (1946). Radioactivity of S^{35}, Rb^{87} and RaD. *Proc. Nat. Inst. Sci. Ind.*, **12,** 159.

SAHA, M. N., SIRKAR and MUKHERJEE (1940). On the structure of atomic nucleus. *Proc. Nat. Inst. Sci. Ind.*, **6,** 45.

SEABORG (1944). Table of isotopes. *Rev. Mod. Phy.*, **16,** 1.

SOMMERS (JR.) and SCHERR (1946). Activity of N^{16} and He^6. *Phy. Rev.*, **69,** 2.

THOMPSON and HOLT (1944). Radioactivity of K^{40}. *Nat.*, **153,** 103.

TOWNSEND (1941). β-spectra of light elements. *Proc. Roy. Soc. Lond.*, A, **177,** 357.

TURNER (1940). Nuclear fission. *Rev. Mod. Phys.*, **12,** 1.

TURNER (1940). Radioactive isotopes of V. *Phy. Rev.*, **58,** 179.

TYLER (1939). β-and γ-radiations from Cu^{64} and Eu^{152}. *Phy. Rev.*, **56,** 125.

THOMPSON and ROWLANDS (1943). *Nat.*, **152,** 103.

WALKE (1937). Induced radioactivity of Ti and V. *Phy. Rev.*, **52,** 777.

Walke, Thompson and Holt (1940). *K*-capture and internal conversion in Cr^{51}. *Phy. Rev.*, **57,** 171.

Walke, Thompson and Holt (1940). Radioactive isotopes of Ca and their suitability as indicator. *Phy. Rev.*, **57,** 177.

Watase (1940). On the disintegration of N^{13} nucleus. *Proc. Phy. Math. Soc. Jap.*, **22,** 639.

Watase (1941). *Proc. Phy. Math. Soc. Jap.*, **23,** 618.

Watase, Itoh and Takada (1940). Radiations from radioactive Zn^{65}. *Proc. Phy. Math. Soc. Jap.*, **22,** 90.

Weimer, Kurbatov and Pool (1941). Radioactive argon A^{37}. *Phy. Rev.*, **60,** 469.

Weizsäcker (1935). On the theory of nuclear masses. *Zeits. Phy.*, **96,** 431.

White, Creutz, Delsasso and Wilson (1941). Positrons from light nuclei. *Phy. Rev.*, **59,** 63.

White, Delsasso, Fox and Creutz (1939). Short-lived radioactivities induced in F, Na, and Mg by high energy protons. *Phy. Rev.*, **56,** 512.

Widdowson and Champion (1938). Upper limits of continuous β-ray spectra. *Proc. Roy, Soc. Lond.*, A, **50,** 185.

Wigner and Feenberg (1941). Symmetry properties of nuclear levels. *Rep. Prog. Phy.*, **8,** 274.

Yasaki and Watanabe (1938). Deuteron induced radioactivity in O. *Nat.*, **141,** 787.

Yukawa and Sakata (1935). On the interaction of heavy particle I. *Proc. Phys. Math. Soc. Jap.*, **17,** 48.

Zacharias (1941). Nuclear spin and magnetic moment of K^{40}. *Phy. Rev.*, **61,** 270.

78. ON NUCLEAR ENERGETICS AND BETA-ACTIVITY*

M. N. Saha and A. K. Saha

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Ever since the discovery by Joliot and Curie of the phenomenon of induced radioactivity in 1934, a very large number of radioactive nuclei, exceeding 450, has been prepared in the laboratory. In recent years, new types of radioactive nuclei have been obtained from fission of heavy nuclei like $_{92}U$, $_{90}Th$ and $_{91}Pa$, and possibly also of $_{93}Np$ and $_{94}Pu$; which have, however, not yet been released for publication. Extensive studies of the β^- and β^+ activities of these nuclei have been made in the various laboratories of the world. The data so far collected, though they have reached vast magnitudes, are by no means sufficient, but already they form a rather bewildering mass (for example, see tables by Seaborg[1]), reminding one of the vast collection of spectroscopical data, before the rise of the modern theories of the electron-structure of the atom reduced them to a few simple laws like Pauli's exclusion principle.

In addition to the nuclei like C^{14} which have been prepared in the laboratory, we have nuclei, mostly stable, occurring in Nature the number of which now reach nearly 250. In the case of nuclei derived from fission, the designation of a new isotope by mass is occasionally not quite unambiguous; indeed, this is a very acute problem for fission products.

Several attempts at a regularization of data have been made by previous workers, but here we shall refer to a chart prepared by Saha, Sarkar and Mukherjee[2], a section of which is shown in Fig. 1; the full chart is too large to be reproduced here. This is a synthesis of several charts already published by different authors. In this, the abscissa represents mass-number M, the ordinate represents the isotope number $I=N-Z$, which represents the excess of neutrons over protons in any nucleus. M ranges from 1 to 239, and I from -1 to about 54. The section of the chart reproduced here extends from $I=-1$ to $I=8$. We have attempted to make the chart as up to date as possible. The parallel lines at 45°, henceforth to be called the Z-lines, represent the atomic number Z. Thus all isotopes of the element Z are to be found on the same Z-line. Each isotope is represented by a circle. Solid circles, ●, represent 'stable nuclei'. Hollow circles, ♂, with an arrow pointing upwards represent β^+- (positron)-emitting nuclei. When the arrow points down, ♀, it indicates that the nucleus is β^--(electron)-emitting. Circles with arrow pointing both up and down, ⚥, indicate that the nucleus emits both negatrons and positrons, for example, Cu^{64}. ♂ denotes that the nucleus decays by K-capture only. ♂ denotes that the nucleus decays by K-capture as well as by positron-emission. ♀ denotes that the nucleus has been obtained in 'fission'; such nuclei are all β^--emitting. If any particular isotope has two different half-lives (isomers), both half-lives are given (compare Co^{62}). Saha, Sirkar and Mukherjee[2] gave the following rules of stability, some of which were previously known:

Rule 1: I is even.

When I is even, say 4, we get alternation of stable and β-active nuclei, as shown below:

Z:	15*	16	17	18	19	20	21	22	23	24	25	26	27
	P^{34}	S^{36}	K^{38}	A^{40}	K	Ca^{44}	Sc^{46}	Ti^{48}	V^{50}	Cr^{52}	Mn^{54}	Fe^{56}	Co^{58}
	—	S	—	S	—	S	—	S	—	S	—	S	+

*Summary of a paper by M. N. Saha and A. K. Saha, "On Nuclear Energetics and β-Activity," *Trans. Nat. Inst. Sci. India*, **2,** 193 (1946.)