72. ON THE STRUCTURE OF ATOMIC NUCLEI

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Ever since Heisenberg (1932) showed that the nucleus of the atom is to be regarded as composed of two fundamental particles, viz., the proton and the neutron, many investigations from the theoretical point of view have been carried out regarding the structure, stability and reactivity of nuclei. In the meantime, there have been large additions to the known number of nuclei by (1) the discovery of newer and rarer stable isotopes, and (2) the discovery of new unstable varieties of isotopes produced by bombardment of known nuclei by means of α-particles, deuterons, protons, neutrons and to a slight extent by photons. The recent discovery of fission of uranium and thorium by neutrons has led to the discovery of a number of β^--active nuclei which probably could not have been produced by any other existing method.

The enormous increase in our knowledge of nuclear phenomena within the last eight years has rendered it almost impossible for the average physicist to form a comprehensive picture of the present situation, much less than keep in living touch with progressing knowledge.

In this paper, an attempt has been made to present the existing knowledge of the known nuclei, stable, as well as radioactive, in the form of a chart. No attempt has been made to give any theoretical discussion on stability in this paper, but rules and regularities which are obvious have been duly noted and recorded. Probably we are justified, at this stage, in adopting this attitude in view of the following significant remark we came across in Gamow's 'Structure of Atomic Nuclei' (1938).

'One may hope that further investigations along these lines will add considerably to our understanding of more detailed problems of structure. Much has already been done with rather overlapping results by Bartlett, Gapon, Ivanenko, Elsasser, Guggenheimer and others; it is not referred to in detail here because the author was never able in studying these articles to remember the beginning when he was reading the end.'

Symbols used

We denote by

p .. the proton,
n .. the neutron,
Z .. the nuclear charge,
N .. the number of neutrons,
A .. the mass-number, so that $A=Z+N$.

$I=N-Z=A-2Z$ has been called the '*Isotope-number*' by Bethe and Bacher (1936).

According to this notation

$p^Z n^{Z+I}$ or $p^Z n^N$ denotes a nucleus composed of Z protons and N neutrons. Thus $_{38}Sr^{87}$ is $p^{38}n^{38+11}$, *i.e.* strontium 87 would be found in the isotope line $I=11$ of our chart.

In this connection, a comparison may be made between the chart given here and the other charts so far in use. Papers earlier than 1931 were written on the supposition that the nucleus was composed of protons and electrons. Nevertheless, many of the conclusions and regularities noted in earlier papers are very valuable, and have been utilized by subsequent workers:

(1) W. D. Harkins (1928) plotted an (I/Z)-curve in fig. 14, p. 113, and nuclei were classified into a few groups.

(2) Barton (1930) plots an (N/Z)-diagram up to $Z=61$, and notes a few regularities.

(3) W. D. Harkins (1931) plots an (N/Z)-diagram (fig. 1) and a number of (I/Z)-diagrams (figs. 2, 3, 4, 5) and an (N/P)/Z-diagram.

(4) Heisenberg (1932) first took the view that the nucleus is composed of neutrons and protons. He discussed nuclear stability by plotting (N/Z)/Z-diagrams.

(5) Gamow (1934) utilized (N/Z)/Z-diagrams for a discussion on nuclear stability and α- and β-emissions.

(6) Guggenheimer (1934) plotted an (N/Z)-diagram and classified nuclei into groups.

(7) Bethe and Bacher (1936) give on p. 97 an I/A-diagram on a small scale, comprising only stable nuclei. No isotopic lines (Z-lines) have been drawn, but some regularities regarding the stability of nuclei have been pointed out.

None of the above workers included β^{+-}-emitting nuclei in their diagrams.

(8) Hevesy and Levi (1936-37) have given a number of (I/Z)-diagrams of stable and radioactive isotopes.

(9) H. Brown (1938) has plotted an (I/Z)-diagram for finding out the range of occurrence of stable isotopes.

(10) Gregoire (1938*a*) has an (A/Z)-diagram for presenting the totality of our knowledge of nuclei, stable as well as radioactive. (The same diagram has been drawn more elaborately in '*Physique Nucleaire*' *of Tabelles Annuelles de Constant et Donneé's Numeriques No.* 26, 1938). Here the radioactive nuclei have been drawn in different colours, and percentages of isotopes have been indicated.

(11) In their paper on 'Mechanism of Nuclear Fission', Bohr and Wheeler (1939) published an (I/A)-diagram (Fig. 8, p. 445) for illustrating 'Nuclear Fission'. This paper came to our notice after our work was almost over. This figure contains only stable nuclei and is identical in principle with ours, but it has been drawn for a limited range, and for illustrating the successive β^- -emission products of fission of the uranium nucleus.

Explanation of the chart

The abscissa represents mass-number A, the ordinate represents I, the isotope number. The parallel lines at 45°, to be henceforward called the Z-lines, represent atomic number 'Z'. Thus all isotopes of 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 up, ♂, represent β^+ -emitting (positron) nuclei; when the arrow points down, ♀, they indicate β^- -emitting (electron) nuclei. Circles with arrows pointing both up and down, ⚥, like $_{29}Cu^{64}$ indicate that the nuclei are both β^+ and β^- -active. The percentage occurrence of any nucleus is given by the number on the top. For isotopes having small abundance, the actual percentage is given to the nearest fraction. The half lives of β-particle-emitting products are indicated. The following abbreviations have been used for indicating the half lives:

s .. .. seconds,
m .. .. minutes,
h .. .. hours,
d .. .. days,
mo .. .. months,
y .. .. years.

The nuclei represented by ♀ denote those obtained by fission of U or Th.

The reader may now refer to the symbolic diagram on the left of Chart 1. The N.W.-pointing arrow terminating in *p* denotes a proton-emission; an arrow in the opposite direction (S.E., not shown in fig.) denotes a proton-capture.

Similarly, the S.W.-pointing arrow ending in *n* denotes neutron-emission, and an arrow in the opposite direction (N.E., not shown in fig.) would denote a neutron-capture.

The west-pointing double-arrow terminating in α denotes an α-particle-emission.

Thus we can follow the reaction

$$B^{10}+H^1=C^{11}+h\nu, \quad C^{11}\rightarrow\beta^+=B^{11}$$

in the chart by putting our finger on B^{10}, and going diagonally downwards (S.E.) we reach C^{11}, and we find that C^{11} will emit a positron, and going vertically upwards we reach the stable nucleus B^{11}.

'Neutron-capture' takes a nucleus a step higher along the Z-line.

Thus

$$Be^9+n^1 = Be^{10}+h\nu \ (?)$$

$$Be^{10}\rightarrow\beta^- = B^{10}$$

We can follow this reaction easily in the chart. Let us take a reaction in which a nuclear particle is emitted, *e.g.*,

$$Ca^{42}+n^1\rightarrow C^{43*}\rightarrow K^{42}+H^1$$

$$K^{42}\rightarrow\beta^- = Ca^{42}$$

We put our finger on Ca^{42}—a neutron bombardment of Ca^{42} followed by capture takes us to Ca^{43*} along the Z-line,* denoting that it is an intermediate nucleus, of extremely short life, breaking up into K^{42} and H^1. K^{42} is obtained by going diagonally up in the *p*-direction. The chart shows that K^{42} is β^- -active and changes to Ca^{42}.

Deuteron-bombardment

Deuteron bombardment followed by capture will take a nucleus along the I-line (horizontal or East) to the next nucleus, and the chart tells us what reactions are to be expected. Thus

$$Si^{30}+H^2\rightarrow P^{32*}=Si^{31}+H^1$$

We put our finger on Si^{30}; capture of H^2 takes us to P^{32*} intermediate, which breaks up into Si^{31} and H^1. The chart shows that Si^{31} emits a β^- -particle and gives us P^{31}. Thus starting from Si^{31} one goes vertically one step downwards and reaches P^{31}. The reaction $P^{32}\rightarrow\beta^- = S^{32}$ is also possible, but its probability seems to be negligibly small.

α-ray bombardment

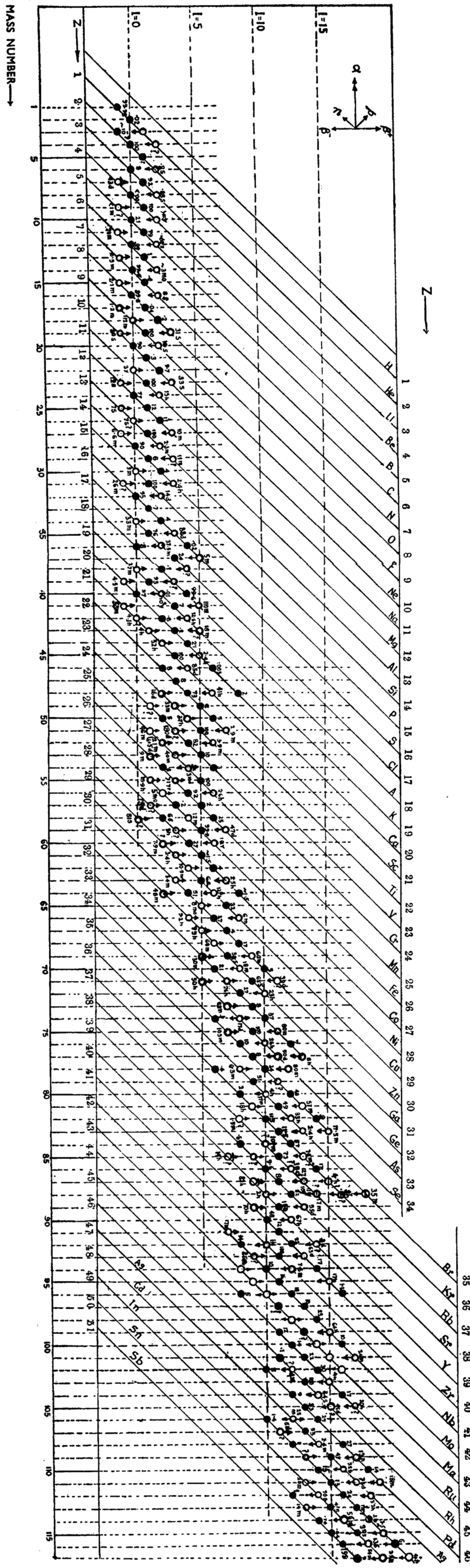
α-ray bombardment followed by capture will take a nucleus along the I-line two steps to the right; and *vice-versa*, if in a reaction, an α-ray is emitted, the nucleus will have to be taken two steps to the left along the same I-line.

Thus

$$N^{14}+He^4\rightarrow F^{18*} = O^{17}+H^1; \text{ or } F^{18*}\rightarrow\beta^+ = O^{18}$$

Thus we see that N^{14} on capturing He^4 will form an intermediate nucleus F^{18*}, which can either break up into O^{17} and H^1, or emit a β^+ -particle, and pass on to O^{18}. The former process is, however, much more probable and is observed usually.

For illustrating the use of the chart, we take sulphur,


α
β⁺
β⁻
n
I=15
I=10
I=5
I=0
Z
MASS NUMBER
H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
A 18
K 19
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Ma 43
Ru 44
Rh 45
Pd 46
Ag
Cd
In
Sn
Sb
1
5
10
15
20
25
30
35
40
45
50
55
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65
70
75
80
85
90
95
100
105
110
115

CHART 1

CHART 2

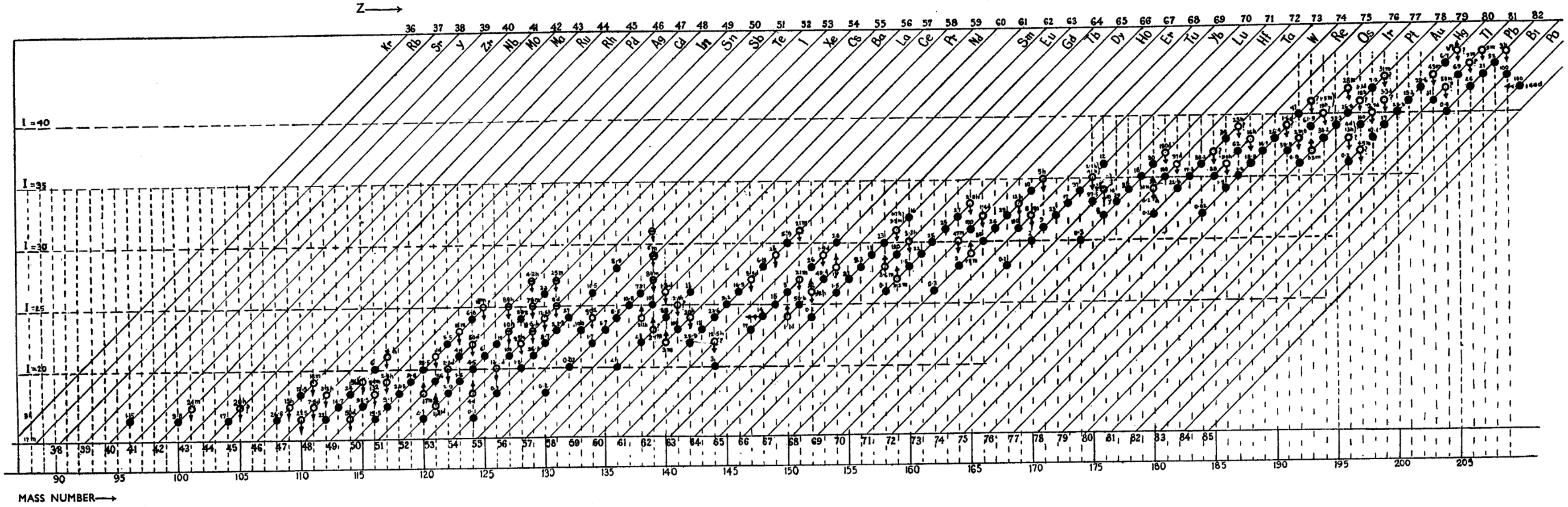
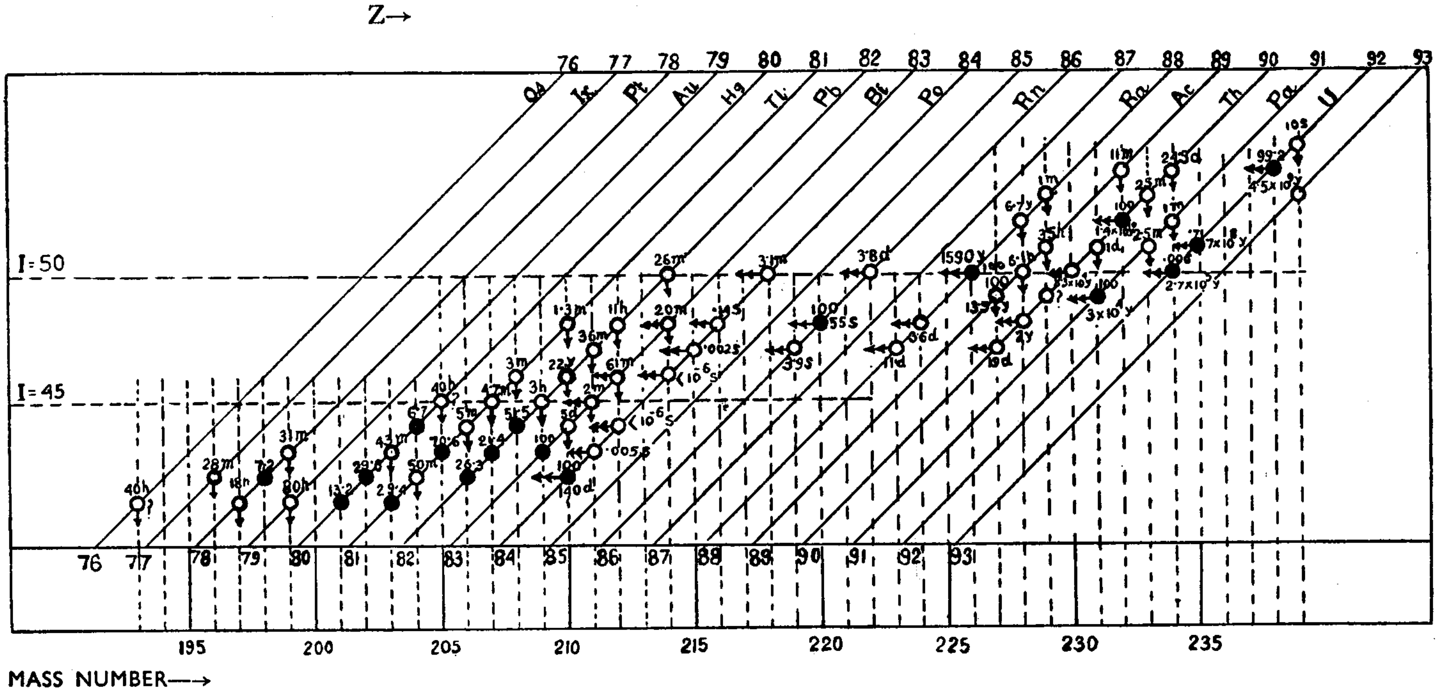

Z⟶
36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82
Kr Rb Sr Y Zr Nb Mo Ma Ru Rh Pd Ag Cd In Sn Sb Te I Xe Cs Ba La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tu Yb Lu Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po
I = 40
I = 35
I = 30
I = 25
I = 20
38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85
90 95 100 105 110 115 120 125 130 135 140 145 150 155 160 165 170 175 180 185 190 195 200 205
MASS NUMBER⟶

CHART 3


Z→
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Po
Rn
Ra
Ac
Th
Pa
U
I=50
I=45
195
200
205
210
215
220
225
230
235
MASS NUMBER→

Z=16. A glance at the Z-line 16 shows that sulphur has the following isotopes:

S^{31}	S^{32}	S^{33}	S^{34}	S^{35}	S^{36}	S^{37}
+	95	·7	4	—	·02	—
26*m* (?)				88*d*		5*m*

S^{31} is β^+-active, with half life of 26*m*. ? indicates that the estimate is doubtful. S^{35}, S^{37} are β^--active, with half lives 88 days and 5 min. respectively. S^{32}, S^{33}, S^{34}, S^{36} are stable isotopes occurring in the proportion 95: ·7 : 4 : ·02.

The symbol δ indicates that the nucleus $p^z n^{z+1}$ deos not actually emit a positron, but captures a K-electron, and passes on vertically up to the nucleus $p^{z-1} n^{z-1+1+2}$.

A glance at the chart at once shows its usefulness. It not only comprises all our present knowledge about isotopes, stable as well as radioactive, but, as will be shown presently, indicates definite rules for stability and for electron- and positron-emission. Further, it suggests new nuclear processes and predicts new stable isotopes, not yet discovered. For purposes of clarity, a number of I-lines at intervals of '5' have been drawn. These have no special significance.

Rules for Stability

For discussing this point, we have taken each horizontal row, corresponding to definite values of 'I'.

If we take I=0, we find that the nuclei are stable from Z=1, H^2, to Z=8, O^{16}. After that, the nucleus is stable for even values of Z, and β^+-active for odd values of Z. The group stops with Sc^{42}, which is β^+-active.

(**Rule 1**).

When I is even and > 2, we get alternation of stable and β-active nuclei. Stable nuclei are obtained for *even* values of Z, and β-active nuclei are obtained for *odd* values of Z. This rule is partly foreshadowed in a remark by Bethe and Bacher (1936, p. 104) and has been discussed in detail in §10, p. 100.

Illustration

Let us take I=4. We get the following:—

I=4; Z=	16	17	18	19	20	21	22	23
	S^{36}	Cl^{38}	A^{40}	K^{42}	Ca^{44}	Sc^{46}	Ti^{48}	V^{50}
	stable	—	stable	—	stable	—	stable	+
Z=	24	25	26	27	28	29	30	31
	Cr^{52}	Mn^{54}	Fe^{56}	Co^{58}	Ni^{60}	Cu^{62}	Ni^{64}	Ga^{66}
	stable	+ —	stable	+ ?	stable	+	stable	+

We observe that after approximately the middle of the series is passed, the nuclei to the right with odd Z become β^+-active. This rule is found to be obeyed right up to I=40, after which we enter the region of natural radioactivity, where also up to I=54, the rule is generally obeyed with a few exceptions (noted later).

For I=2, we observe that the first stable nucleus is Z=8, O^{18}, after which the rule of alternation holds all right. Before Z=8, we have a number of β^--emitting nuclei from Z=1 to Z=7. It is quite possible that in the other groups also, *e.g.* for the group I=4, we may have a number of β^--active elements before S^{36}, but special reactions will have to be devised to obtain them.

(**Rule 2**)· I is odd:

In these groups, we first find β^--active nuclei, and then arrive at *a number of succeeding stable nuclei*. These are followed by β^+-active nuclei. The number of succeeding stable nuclei has been found sometimes as small as 3, sometimes as large as 13, usually the nucleus in the midst of the stable group appears to be the most stable, though there appear to be exceptions.

Illustration

Let us take I=5. A glance at the chart shows that we have

I=5; Z=	16	17	18	19	20	21	22	23
	S^{37}		A^{41}	K^{43}	Ca^{45}		Ti^{49}	V^{51}
	—		—	—	—		6,	100,
Z=	24	25	26	27	28	29	30	31
	Cr^{53}	Mn^{55}	Fe^{57}	Co^{59}	Ni^{61}	Cu^{63}	Zn^{65}	Ga^{67}
	10,	100,	2,	99·8	1,	68,	+	+
Z=	32	33						
	Ge^{69}	As^{71}						
	+	+						

The stable nuclei start from Ti^{49} and extend up to Cu^{63}. The numbers below them here show the percentages. The elements to the left of the stable group are β^--active and those to the right are β^+-active. We have some gaps, *e.g.*, at Cl^{39} (β^-), Sc^{47} (β^- or stable), but these will probably be discovered if proper nuclear reactions are tried.

We now begin a detailed duscussion of the table, taking each I-line in turn. While studying these discussions, the reader is advised to have the chart at hand, as all references are to the chart.

I= −2:

A few nuclei like Li^4 have been postulated, but as knowledge about them is very meagre, we leave this group for the present out of our consideration.

I=−1:

In this line, H^1, He^3 (Alvarez and Cornog, 1939) are stable. Li^5 cannot be formed, energy-considerations are against it.

Absentees are:—Na^{21}, P^{29}, Cl^{33}, A^{35}, K^{37} which are expected to be β^+-active.

The series terminates at Sc^{41}.

It is probable that the 'absentee' nuclei may be obtained if proper nuclear reactions are tried. Let us take an example.

For Na^{21}, the following reactions are suggested:—

$$(1)\ Ne^{20}+H^1=Na^{21}+h\nu$$

This is suggested in analogy to the reaction $O^{16}+H^1=F^{17}+h\nu$ which has been observed by DuBridge *et al* (1937, 1938).

$$(2)\ Ne^{20}+H^2=Na^{21}+n^1$$

This is suggested in analogy to the reaction $O^{16}+H^2=F^{17}+n^1$, observed by Kurie *et al* (1936) and Newson (1937). But the reaction has been tried by Snell (1937) who, however, obtained $Ne^{20}+H^2=F^{18}+He^4$. Probably the chance of capture followed by γ-emission is negligible to that of particle emission, as has been found by Bethe (1939).

It is clear from this discussion that the suggestion of proper reaction to get a certain absentee nuclei will involve a good deal of work. Hence the subject is not further pursued in this paper.

It is not yet clear whether there will be any limit to the number of nuclei on any I-level. The last nuclei for $I=-1$ is Sc^{41}. It is possible that we may get the series continued to Ti^{43}, V^{45}, etc . . . , but the prospect of getting such nuclei will be diminished with larger Z, as *no* stable nuclei, which can act as the starting material for bombardment with H^1, He^4 and n^1 will be available.

$I=0$:

This line starts with H^2 and is stable up to O^{16}, after which the alternation rule holds: Nuclei are stable for Z=even, and β-active for Z=odd. The series terminates for Sc^{42}, but we have, after a long interval, Cu^{58}, which is stated by Delsasso (1939) to be β^+-active. The intermediate absent nuclei are:—

Ti^{44}	V^{46}	Cr^{48}	Mn^{50}	Fe^{52}	Co^{54}	Ni^{56}
St.	+	St.	+	St.	+	St.

which may be looked for.

$I=1$:

H^3 is β^--active, as has been shown by Alvarez and Cornog (1939*b*) changing probably to stable He^3, and after that we have stable elements up to Cl^{35} in an unbroken series. K^{39} has been shown to be definitely stable. Hence A^{37} ought to be stable, and may be a very rare isotope. Ca^{41} is still unknown, and as it is on the border line, we cannot say whether it will be stable or β^+-active. From Sc^{43} to Ni^{57}, all are β^+-active with the exception of Ti^{45} and V^{47} which have to be looked for.

$I=2$:

We have β^--active nuclei from H^4, (rather doubtful) to N^{16}, and then we have alternation of stable and radioactive nuclei beginning from O^{18}. From Sc^{44}, the radioactive nuclei in this group begin to become β^+-active and with the exception of Zn^{62}, which may be looked for, we have the group extended up to Ga^{44}.

$I=3$:

In this group, the stable nuclei start from Cl^{37} and end in Ti^{47}. On the left side, they are flanked by β^--active nuclei which, with gaps at F^{21}, Na^{25} and P^{33}, can be traced to O^{19}. The group contains the notable anomalous nucleus A^{39} which ought to be stable, but Nier (1936) who specially looked for it states that its abundance is less than 10^{-5} of the most abundant isotope A^{40}. Gregoire (1938*b*) gives it as β^--active, but doubtfully. The anomaly ought to be cleared up.

On the right side of the last stable isotope Ti^{47}, the nuclei are all β^+-active, with the exception of Co^{57} which according to Bleakney *et al* (1936) is stated to be stable with an abundance of ·18 per cent. If it is really stable, it forms a glaring anomaly which ought to be cleared up.

The line is continued to Zn^{63} at present, but further β-emitting particles may be discovered on both flanks.

$I=4$:

In this line, as in all with even values of I, the rule of alternation regarding stability is followed, without exception. The limits of the line at present are left S^{36} (stable) and right Ga^{66} (β^+-active). Co^{58} should be β^+-active, but the nature of the particles emitted has not yet been ascertained experimentally.

In this and all other groups with *even* values of I, it is still a moot question whether, if the line is extended on both flanks, the nuclei will continue to obey the law of alternation, *e.g.*, whether Si^{32} or Mg^{28}, if discovered, will be stable or β^--active. Similarly on the right flank whether Ge^{68} or Se^{72}, if discovered, will be stable or β^+-active. A third possibility is that like Li^5, they may be energetically impossible. These remarks apply to the subsequent discussions.

One difficulty in the formation of these 'flank' nuclei would be that of getting any 'starting'-point. This point may be illustrated by a concrete example. Let us take C^{16} and N^{18} which fall in the line $I=4$. Now C^{16} should be stable if rule (1) is obeyed, and N^{18} ought to be β^--active. But from what nucleus should we start to get C^{16} ? Since O^{18} is stable, it may be possible to produce N^{18}, but B^{14} will again be difficult to produce.

According to present ideas of stability, all such nuclei may be β^--active, but actual experiments can alone decide how far the rule of alternation will extend on both flanks.

As will be seen later, some 'flank' nuclei of the description given here have been obtained in the case of ${}_{52}Te$ to ${}_{58}Ce$ and ${}_{35}Br$ to ${}_{40}Zr$ by the fission of the uranium nucleus. But the fission process is probably possible only for the heaviest nuclei.

I=5:

We have in this line 8 stable nuclei from Ti^{49} to Cu^{63}, flanked by β^--emitting nuclei on the left, and β^+-emitting nuclei on the right. Sc^{47} may be a stable nucleus or β^--active. Cl^{39} will be β^--active.

From I=6, the rules we have stated appear to be followed rigorously. The remarks with respect to 'flank' nuclei are always to be taken subject to the observations made under I=4.

I=6:

Absentees are As^{72}, Br^{76}, both β^+-active.

I=7:

This line shows only three successive stable isotopes at Cu^{65}, Zn^{67}, Ga^{69}. There are gaps at V^{53}, Cr^{55}, Mn^{57}, Co^{61} (all β^--active) and at Br^{77}, Kr^{79}, Rb^{81}, Sr^{83}, Zr^{87} and Nb^{89} (all β^+-active) which may be looked for.

I=8:

This line is very much broken. We have the first stable isotope Ca^{48}, and then after a long pause Ni^{64}. Search may be made for

Sc^{50}	Ti^{52}	V^{54}	Cr^{56}	Mn^{58}	Fe^{60}	Co^{62}	Y^{83}	Zr^{88}	Nb^{90}
—	stable	—	stable	—	stable	—	+	stable	+

Some of these stable isotopes have been looked for by Nier (1938), but have not been obtained. He states that Ti^{52} is $<10^{-5}$, $Cr^{56} < 10^{-5}$, $Fe^{60} < 3 \times 10^{-5}$, $Zr^{88} < 10^{-5}$, of the respective most abundant isotopes, if they exist at all.

I=9:

We have here stable isotopes from Ga^{71} to Br^{79}. β^+-active isotopes are expected at Rb^{83}, and Nb^{91}.

I=10:

This series starts with the stable isotope Zn^{70} and is continued up to Cd^{106}. Ru^{98} ought to be stable and we may look for β^+-active nuclei at Rh^{100} and Ag^{104}.

I=11:

This group contains *11* successive stable isotopes from Br^{81} to Rh^{101}. To this group also belongs Ma^{97}, still undiscovered. The first β^+-active nucleus is Cd^{107} shown as doubtful. There are two intervening absent nuclei, Pd^{103} and Ag^{105}, which may be β^+-active. Ga^{73} may be β^--active.

I=12:

This group starts with the stable nucleus Ge^{76} and is continued up to Sn^{112}. There is one absentee at In^{110} which may be β^+-active.

I=13:

The stable group starts at Mo^{97} and is continued up to Ag^{107}. Ma^{99} is expected to be stable and one of the chief isotopes of the element, which is still undiscovered. As^{79}, Y^{91} and Nb^{95} may be β^--active.

I=14:

This group starts with stable isotope Se^{82} and ends with Sn^{114}. β^--active isotopes at Br^{84} and Nb^{96} are expected. Besides, a stable Sr^{90} is expected. Nier (1938) looked for the isotope and has found that if it exists its abundance is less than 3×10^{-5}.

I=15:

The first stable nucleus of this group is at Ag^{109} and the last one at Sn^{115}. The nucleus Pd^{107} may be also stable. Br^{85}, Rb^{89}, Sr^{91}, Y^{93} and Nb^{97} may be β^--active.

Masuriam.

The element '43' Masuriam has not yet been satisfactorily identified. Let us see what prediction can be made about it. It is expected to have isotopes of the following atomic weights

94	95	96	97	98	99	100	101	102	103
+	+	+−	St.	+−	St.	+−	−	−	−

The two stable isotopes are expected to have the masses 97 and 99. Of these 99 is expected to be more abundant. ${}_{43}Ma^{99}$, though not yet observed on the earth, has been detected by an indirect method by Abelson (1939*b*). He observed that Mo^{99}, which is β^--active (period 64 hrs.), has, besides, a branch activity, and one-fifth of Mo^{99} is converted to ${}_{43}Ma^{99}$ which emits a γ-ray and lapses to a stable isotope. The γ-ray is internally converted, which expels an electron from the K-shell, and $K\alpha$-line of Ma is emitted. This has been detected by Abelson.

I=16: (See Chart 2.)

The first stable isotope is at Zr^{96} and the last one so far detected is Xe^{124}. The following radioactive nuclei may be looked for:—

Nb^{98}	Ma^{102}	Rh^{106}	Sb^{118}	I^{122}
−	−	−	+	+

I=17:

There are only three stable nuclei Cd^{113}, In^{115} and Sn^{117} in this group. Sb^{119} is not yet known. It may be either stable or β^+-active. Ma^{103} and Rh^{107} may be β^--active.

I=18:

This group starts with Pd^{110} and is continued up to Ba^{130}. Cs^{128} may be β^+-active.

I=19:

The stable isotopes in this group are Sn^{119}, Sb^{121} and Te^{123}. After these we have neither stable nor radioactive nuclei in this group. I^{125} may be either stable or β^+-active; so is Xe^{127}.

I=20:

The group starts with the stable nucleus Cd^{116} and is continued up to Sm^{144}. There is a notable absentee amongst stable nuclei at Nd^{140}. Radioactive nuclei are expected at

In^{118}	Cs^{130}	La^{134}	Pr^{138}	${}_{61}X^{192}$
−	+ −	+	+	+

I=21:

We have got four stable nuclei in this group from Sb^{123} to Xe^{129}. It will be interesting to look for nuclei further beyond at Cs^{131}, Ba^{133}, La^{135} and Ce^{137}. I^{119} may β^--active.

I=22:

The first stable isotope is Sn^{122} and the stable series terminates at the stable isotope Nd^{142}. Radioactive nuclei can be looked for at Cs^{132}, (+ −), La^{136}(+ −).

I=23:

The first stable nucleus in this group is Xe^{131} and the last one is Sm^{147}. La^{137} is a notable absentee and Ce^{139} is anomalous. According to our rule this ought to be stable. As a matter of fact cerium shows anomaly in the next group I=25 and Ce^{139} as well as Ce^{141}, which are shown to be β^+-and β^--active respectively, ought to be stable according to our rule. The gap at ${}_{61}X^{145}$ is still to be filled up.

I=24:

This group shows the first stable nucleus at Sn^{124} and is continued up to Gd^{152}. Sb^{126} ought to be β^--active. Sm^{148} is α-active. This is indicated by the double arrow which shows that after the emission of α-ray it is transformed into Nd^{144}. According to our classification α-active substances are to be classed with stable nuclei.

I=25:

The first stable nucleus is at Ba^{137} and excepting for the anomaly at Ce^{141} this group is continued up to Eu^{151}. Xe^{133} and Cs^{135} may be either stable or β^--active. Pr^{143} ought to be a stable isotope, so should also be ${}_{61}X^{147}$. Gd^{153} may be stable or β^+-active.

I=26:

The first stable nucleus is at Te^{130} and the last is at Er^{162}. One may look for the radioactive nuclei at

I^{132}	Cs^{136}	Pr^{144}	${}_{61}X^{148}$	Tb^{156}	Ho^{160}
−	−	−	+	+	+

I=27:

This contains only two successive stable elements at Eu^{153} and Gd^{155}. The next element Tb^{157} is also probably stable. This group is flanked on both sides by radioactive nuclei which start from Sb^{129}. Search may be made for other radioactive neuclei at

I^{133}	Xe^{135}	Cs^{137}	La^{141}	Ce^{143}	Pr^{145}	${}_{61}X^{149}$	Tb^{157}	Ho^{161}	Er^{163}	Tu^{165}
−	−	−	−	−	−	−	+	+	+	+

I=28:

This group starts with the stable nucleus Xe^{136} and we should have stable nuclei at Ba^{140} and Ce^{144}. Others, which according to our rule should occur, are present up to Yb^{168}. We should expect the following radioactive nuclei:—

Cs^{138}	La^{142}	Pr^{146}	${}_{61}X^{150}$	Ho^{162}	Tu^{166}	Lu^{170} etc.
−	−	−	−	+	+	+

I=29:

We have three successive stable nuclei at Gd^{157}, Tb^{159}, Dy^{161}. Eu^{155} and Ho^{163} may be either stable or radioactive. The following radioactive nuclei may be looked for:—

${}_{61}X^{151}$	Eu^{155}	Ho^{163}	Tu^{167}	Lu^{171} etc.
−	−	+	+	+

I=30:

The group starts with the stable nucleus Nd^{150} and is continued up to Hf^{174}. W^{178} may be a stable isotope of tungsten. The following radioactive nuclei are expected:—

${}_{61}X^{152}$	Eu^{156}	Tu^{168}	Lu^{172}	Ta^{176}	Re^{180}
−	−	− +	+	+	+

Element 61.

The discovery of element '61' has been claimed and disputed. It is possible to make predictions regarding its number of stable isotopes, their abundance, and radioactive isotopes. The chart shows that we may expect isotopes having the mass-numbers:—

144	145	146	147	148	149	150	151	152
+	St.	+ −	St.	+ −	−	+ −	−	−

The two stable isotopes with A=145, 147 will have probably the same order of abundance.

I=31:

We have got five successive stable nuclei, viz., Dy^{163}, Ho^{165}, Er^{167}, Tu^{169}, Yb^{171}. They are flanked by a certain number of radioactive nuclei. Search may be made for

${}_{61}X^{153}$	Sm^{155}	Eu^{157}	Tb^{161}	Lu^{173}	Hf^{175}	Ta^{177}	W^{179}
−	−	−	− or St. ?	+	+	+	+

I=32:

The series starts with the stable nucleus Gd^{160} and terminates at Os^{184}. Search may be made for the following radioactive nuclei:—

Tb^{162}	Lu^{174}	Ta^{178}	Re^{182}
$-$	$-+$	$+$	$+$

I=33:

We have three successive stable nuclei at Yb^{173}, Lu^{175} and Hf^{177}. Tu^{171} and Ta^{179} may also probably be stable. Search may be made for the following radioactive elements:—

Ho^{167}	W^{181}	Re^{183}	Os^{185} etc.
$-$	$+$	$+$	$+$

It may be mentioned here, as a proof of the usefulness of the table, that it makes Lu^{175} stable and probably the most abundant isotope. But this nucleus is mentioned as β^--active in the Tables published by Gregoire (1938*b*). Mattauch and Lichtblau (1939) have subsequently shown that there is an isotope at Lu^{176} with abundance of 2·5% and it has been shown by Libby (1939) that it is Lu^{176} which is β^--active with the unusually long life of 10^{10} yrs. and not Lu^{175}. Lu^{176} is thus just like long-lived K^{40} and Rb^{87}.

I=34:

This series starts with the stable nucleus Er^{170} and terminates at the stable nucleus Os^{186}. The following radioactive nuclei may be looked for:—

Tu^{172}	Re^{184}
$-$	$-+$

I=35:

There are five successive stable isotopes beginning from Hf^{179} up to Os^{187}. They are flanked on the left by two β^--active nuclei and the following may be looked for:—

Tu^{173}	Lu^{177}	Ir^{189}	Pt^{191}
$-$	$-$ St. ?	$+$	$+$

I=36:

The series starts with the stable isotope Yb^{176} and ends with Hg^{196}. Search may be made for

Lu^{178}	Ir^{190}	Au^{194}	Tl^{198}
$-$	$+$	$+$	$+$

I=37:

There are three successive stable nuclei at Re^{187}, Os^{189} and Ir^{191}, flanked as usual on the left by the β^--active and on the right by β^+-active nuclei. Search may be made for

Ta^{183}	Au^{195}
$-$	$+$

I=38:

This series starts with W^{186} and ends with Hg^{198}. Au^{196} is shown as a β^--active nucleus with two periods 4 days and 13 hours.

I=39:

This series has four successive stable nuclei from Ir^{193} to Hg^{199}. There may be more stable nuclei to the right *e.g.* at Tl^{201}.

I=40:

This series starts with the stable nucleus Os^{192} and ends with Pb^{204}. Tl^{202} may be β^+-active.

I=41:

We have two successive stable nuclei, Hg^{201} and Tl^{203}. Pb^{205} may be a stable isotope. On the left side we have the β^--active nuclei Au^{199}, Pt^{197} and Os^{193}, but on the right side no representative has yet been obtained. We may have Ir^{195} (β^--active) and Bi^{207} and Po^{209} (β^+-active).

I=42:

From this series we enter the region of natural radioactivity, the α-emitting nuclei are treated as stable for our purpose. The rule of alternation is obeyed in this series and we have stable nuclei at Pt^{198}, Hg^{202}, Pb^{206} and Po^{210}, the last one being α-active. Au^{200} ought to be β^--active and Bi^{208} ought to be β^+-active. These have not yet been found.

I=43:

This series also obeys the laws stated, as we have successive stable isotopes at Tl^{205}, Pb^{207}, Bi^{209} and Po^{211} (α-active). The group is flanked on the left by β^--active nuclei in which Au^{201} is an absentee. On the right, β^+-active nuclei may be expected, such as ${}_{85}$X^{213} and Rn^{215}.

I=44:

Here also the rule of alternation is followed from Hg^{204} up to Po^{212} (α-active). No β-active nuclei on the left or right have yet been found.

I=45:

We have three β^--active nuclei and only one 'stable' (α-active) isotope at Bi^{211}. Both Po^{213} and ${}_{85}$X^{215} may be either stable or α-active nuclei.

I=46:

Only four isotopes are present which follow the rule, excepting Pb^{210} which is an anomaly. This nucleus is actually β^--active but ought to be stable or α-active according to our scheme. Rn^{218} may be stable.

I=47:

We have 'stable' nuclei at Po^{215}, Rn^{219}, Ra^{223} and Th^{227}, all being α-active. If the odd number rule is valid then probably $_{85}X^{217}$, $_{87}X^{221}$ and Ac^{225} should also be 'stable' or α-active.

$I=48$:

In this series Pb^{212} (Th B) should be stable, but actually it is β^--active. Bi^{214} (Ra C) should be β^--active but this actually emits, as is well known, both α-and β-rays. Apart from these two anomalies the other nuclei in this series follow the stability rule. These are Po^{216}, Rn^{220}, Ra^{224} and Th^{228}, all being α-active. We should expect $_{85}X^{218}$, $_{87}X^{222}$ and Ac^{226} to be all β^--active.

$I=49$:

This group is very small having only two stable isotopes at Th^{229} (which is doubtful) and Pa^{231} (which is α-active). U^{233}, if it could be obtained, would probably be α-active.

$I=50$:

Here also we have an exception to the rule in Pb^{214} (Ra B). It ought to emit α-particle, but actually it emits β-rays passing to Ra C. Other nuclei follow the rule. These are Po^{218}, Rn^{222}, Ra^{226}, Th^{230} and U^{234}, all being α-active. We ought to have β^--active nuclei at Bi^{216}, $_{85}X^{220}$ and $_{87}X^{224}$. Ac^{228} is found to be β^--active and Pa^{232} may be β^+-active.

$I=51$:

There is a single stable nucleus U^{235} flanked by three β^--active nuclei on the left. $_{93}X^{237}$, according to these rules, may be 'stable', *i.e.* α-active. It is now well known that U^{235} forms about 0·7% of the most abundant isotope U^{238}.

$I=52$:

Here also we start with an anomaly at Ra^{228} which instead of being α-active is β^--active. The other two nuclei in this group are Th^{232} which is α-active as it ought to be, and Pa^{234} which is β^--active. U^{236} ought to be stable (or α-active). $_{93}X^{238}$ ought to be β^+-active.

$I=53$:

There are only three nuclei in this group of which the first two, *e.g.*, Ra^{229} and Th^{233} are β^--active and $_{93}X^{239}$ is probably stable or α-active. U^{237} may be either α-or β-active. Ac^{231} and Pa^{235} will probably be β^--active.

$I=54$:

In this group the nucleus Th^{234} is an anomaly, because according to the rules it should be α-active, but actually it is β^--active. Pa^{236} ought to be β^--active.

Element 85—*Radio-Iodine.*

Element 85, still undiscovered, is expected to have isotopes of the following mass-numbers:—

212	213	214	215	216	217	218	219	220
—	St. (?)	—	St. (?)	—	St. or α-	—or α-	—	—

The stable isotope of element 85 should have an atomic mass of 217.

Element 87—*Radio-Caesium.*

This element is expected to have isotopes of the following mass-numbers:—

221	222	223	224
St. or α-	—	—	—

So it appears to have only one stable isotope of mass-number 221.

Fission of Uranium and Thorium

After a certain amount of progress had been made with this paper, we received the September (1939) number of the *Physical Review*, containing a paper by Bohr and Wheeler (1939) on the 'Mechanism of Nuclear Fission'. In this paper, the mechanism of nuclear fission is explained by using a (I)/A- diagram (Fig. 8, p. 445) which is very nearly identical with the one used here. As mentioned already, only a part of the diagram from Br^{98} to Sm^{140} is shown, and no other use is made of it, except to illustrate the mechanism of fission.

As few points regarding fission can be elucidated by means of our chart. It has been now proved that the effect of bombarding U or Th-nuclei with neutrons is probably: (1) to release a number of neutrons; estimates vary from 2 to 6 (see Zinn and Szilard, 1939); (2) to split up the remaining nucleus into almost two equal halves, which leave each other with energy of about 200 Mev. The energy of splitting can be calculated from theoretical considerations of the energy-formation of nuclei, and is found to be in accordance with experimental observations.

In some cases, the products of fission and the products of successive disintegrations have been correctly identified, in other cases all the links have not been satisfactorily traced. We give below in Table I a summary of the results so far obtained by different observers, showing the successive series which have been observed.

The tables have been compiled from recent works, particularly those due to Hahn and his co-workers (1939), and Abelson (1939*a*). We may add some notes regarding the establishment of each series of successive products, and identification of the mass of the nucleus, which is indicated at the top of each column.

The first series (second column of Table I)

$_{51}Sb^{127}$	$\rightarrow \beta^-$	$_{52}Te^{127}$	$\rightarrow \beta^-$	$_{53}I^{127}$
80*h*		10*h*		stable

has been cleared up by Abelson, and its mass, 127, was identified from the observation that a 10*h*-Te isomer was already discovered by Seaborg, Livingood, and Kennedy (1937).

TABLE I.

Products of Fission of Uranium.

Mass / Nuclei	127	129	131	133 ?	135 ?	137 ?	139	141 ?	143 ?
$_{50}$Sn	..	..	..	..	..	..	..	..	..
$_{51}$Sb	80*h*	4·2*h*	..	5*m*	< 10*m*	< 10*m*	..	..	..
$_{52}$Te	90*d* 10*h*	30*d* 70*m*	30*h* 25*m*	77*h*	43*m*	60*m*	..	..	..
$_{53}$I	I^{127} stable	18·5*h*	8*d*	2·4*h*	54*m*	22*h*	..	..	..
$_{54}$Xe	..	Xe^{129} stable	Xe^{131} stable	st. or —(?)	—	—	..	15*m*	
$_{55}$Cs	..	..	..	Cs^{-133} stable	st. or—	—	6*m*	33*m*	..
$_{56}$Ba	..	..	..	..	Ba^{135} stable	Ba^{137} stable	86*m*	300*h*	14*m*
$_{57}$La	..	..	..	..	..	..	La^{139} stable	36*h*	2·5*h*
$_{58}$Ce	..	..	..	..	..	..	..	Ce^{141}* stable ?	—
$_{59}$Pr	..	..	..	..	..	..	..	..	Pr^{143} stable
$_{60}$Nd	..	..	..	..	..	..	..	..	..

* *Vide* remarks, page 288

It should terminate with stable I^{127}. The fission nuclei are indicated by the symbol ♀ in the Chart. The nuclei under mass numbers against which there are query marks have not been shown in the Chart.

The mass of the second series (A = 129) was identified from the 70*m* (1 *h*)-Te discovered by Seaborg *et al.* It should end in Xe^{129} (stable—26%).

The mass of the third series (A = 131) was identified from the 8*d*-I, discovered by Seaborg *et al.* It should end in Xe^{131} (stable—2·2%).

The identification of the masses of the three remaining series is far from clear; but they cannot have the even masses, 132, 134, 136, as suggested by Abelson (1939*a*), for according to our chart (*vide* mass-lines 132, 134, 136), I^{132}, Te^{134} and I^{136} should be *stable.* One has merely to go up along the mass-lines 132, 134, 136 and it can at once be seen that the points I^{132}, Te^{134}, I^{136} would be stable according to the rules formulated by us.

These three unidentified series should have therefore the odd mass-numbers 133, 135, 137 respectively, but it is of course not possible to say which number refers to which group.

X^{133}-group should end in Cs^{133}, *i.e.* we should have in addition a β^--emitting Xe^{133} in this group. There is just a chance that Xe^{133} may be stable.

X^{135}-group should end in Ba^{135}, or Cs^{135} if the latter is stable. In any case, we should have a Xe^{135}, β^--emitting.

X^{137}-group should end in Ba^{137}. Hence this group should show a β^--emitting Cs^{137} and a β^--emitting Xe^{137}.

The end product of X^{139} has been definitely identified by Hahn *et al* (1939) with La^{139}.

The masses of the other two groups are not yet definite. But they cannot be even for the same reason as in the case of X^{133}, ^{135}, ^{137} but odd. They have probably the mass-members 141 and 143.

The group X^{141} should end in Ce^{141}, which as remarked already should be a stable isotope of Ce.

The group X^{143} should end in Pr^{143}, *i.e.* it should have β^--emitting Ce^{143}.

We have thus shown that according to Hahn *et al*, and Abelson, one of the immediate products of fission of uranium may be any odd mass from 127 to 143, 9 in number. These contain too large a proportion of neutrons, and therefore undergo successive β^--transformations till they end in stable nuclei which have invariably odd mass numbers. The highest number of β^--transformation so far detected is four (for X^{141}).

Since the starting nucleus was either U^{239} or U^{235}, and probably two neutrons are emitted before fission, the other component of fission would be a nucleus with an even mass. For example, the other component of the fission process which gives rise to ${}_{54}X^{143}$ should be ${}_{38}X^{90}$. The results on this side are rather confusing, and the different series have not been completely worked out. Only the following series appear to have been worked out fully:—

$$\underset{35m}{{}_{35}Br^{88}} \rightarrow \underset{3h\ (?)}{{}_{36}Kr^{88}} \rightarrow \underset{17m}{{}_{37}Rb^{88}} \rightarrow \underset{\text{Stable.}}{{}_{38}Sr^{88}}$$

This is based on the identification of ${}_{36}Kr^{88}$, which is, however, doubtful (Langsdorff, 1939).

SUMMARY

A chart has been drawn with A, the mass-number as abscissa, I, the isotope number which is defined as the excess of the number of neutrons over protons as ordinate, and Z-lines, at 45° to the abscissa or ordinate. In this chart, all nuclei, stable as well as radioactive, have been represented with their abundance (for stable nuclei) and half-lives. The chart enables one to form a complete picture of all nuclei so far known, as well as of the nuclear processes. Rules of stability have been noticed; in the case of nuclei with even mass-number, these have been partly foreshadowed by Bethe and Bacher; the rules for stability of odd nuclei which are noted here are believed to be new. A large number of predictions have been made regarding the occurrence of rare stable nuclei, and of radioactive nuclei. In the case of elements still undiscovered, Nos. 43, 61, 85, 87, predictions have been made regarding the number of isotopes and of the most stable varieties. A number of anomalies in the present list of stable elements have been pointed out which ought to be cleared up. The mass-numbers of the U-fission product series to which Abelson assigned the values 132, 134, 136 have been shown to be untenable. The correct mass-numbers appear to be 131, 133, 135 respectively. Further, two series have been shown to possess the mass-numbers 141 and 143 respectively.

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