A Correlation of Nuclear Disintegration Processes

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INTRODUCTION

THE publication of experimental results in nuclear physics has usually been limited to rather short reports of a very few transmutation processes. Disintegration has been produced by alphas, protons, deuterons, neutrons and photons and as products alphas, protons, neutrons, gammas, electrons (both positive and negative) and rare isotopes of hydrogen and helium have been observed. The techniques for producing and detecting these various radiations are so widely different and the field of research so broad that few results have been reported in a manner which stresses any correlation between the various processes. However, the development of the field has been brought to such a point that it is now possible to organize these data into representative processes. It is the purpose of this paper to summarize these correlations, to present charts which include all types of disintegrations observed to date and to draw from these correlations some suggestions which may be of assistance in further experimental and theoretical study.

LINE CHARTS

Any systematic graphical catalog of nuclear reactions involves a plot of all known nuclear species, in which one coordinate represents the nuclear charge or atomic number Z and the other coordinate shows the nuclear weight or mass number A. Such charts usually present a linear scale of Z as abscissae, but a wider choice is available for the scale of ordinates representing A. When a heavy nucleus is thought of as an aggregation of protons p and neutrons n (some of which may be combined into heavier units), a linear scale of A represents the sum of all n and p in the nucleus, that is $A=n+p$. A mass scale plotted as $A-Z$ represents n, the number of neutrons in the nucleus, and a mass scale plotted as $A-2Z$ represents $n-p$, the number of excess neutrons in the nucleus. We have chosen abscissae Z and ordinates linear in $A-2Z$ for the present charts because such a scale has a slope approaching zero for small Z, the geometrical representation of reactions is simpler and the ordinates show directly the number of excess neutrons required to form a stable nucleus. As is well known, an attractive force between neutrons and protons may be invoked to overcome the repulsive proton-proton forces and hence, for light nuclei, $n-p$ is nearly zero but for heavy nuclei $n-p$ rises to around 50.

Each stable nuclear species[1] found in nature is represented by a square on Fig. 1. The zero point of the linear ordinate scale $(n-p)$ is $2Z$ in every case, hence its numerical value varies with Z. Since $A=n+p=2p+(n-p)=2Z+(n-p)$, the mass of any isotope is obtained directly from the mass ordinates $2Z+(n-p)$ shown in Figs. 1, 2 and 3. For example, the single isotope of fluorine has a charge of $Z=9$, and a mass of $2Z+1=19$, while for beryllium $Z=4$ and hence its mass $2Z+1=9$. The naturally radioactive elements and the artificially radioactive elements produced by neutron bombardment are protrayed in Fig. 1 as circles and the course of their production and disintegration is shown by straight lines connecting the nuclear species involved. Those reactions whose course has been established by chemical separations, by energy measurements on each of the emitted particles, or by the agreement of disintegration data from two or more laboratories and the absence of any contrary evidence, are plotted in Figs. 1, 2 and 3. Unconfirmed and uncertain reactions are separately tabulated in Table I.

The known nuclear reactions involving elements from Z to 1 to 30 are plotted on Fig. 2. Isotopes whose atomic mass is twice the atomic number have a mass ordinate of $2Z$; those containing an extra neutron, $2Z+1$; those which have an extra proton, $2Z-1$; etc. It is to be noted that H^1 and He^3 are the only stable members of this last category. The legend on Fig. 2

[1] J. Mattauch, Physik. Zeits. **35**, 567 (1934); F. W. Aston, Proc. Roy. Soc. **149**, 396 (1935).

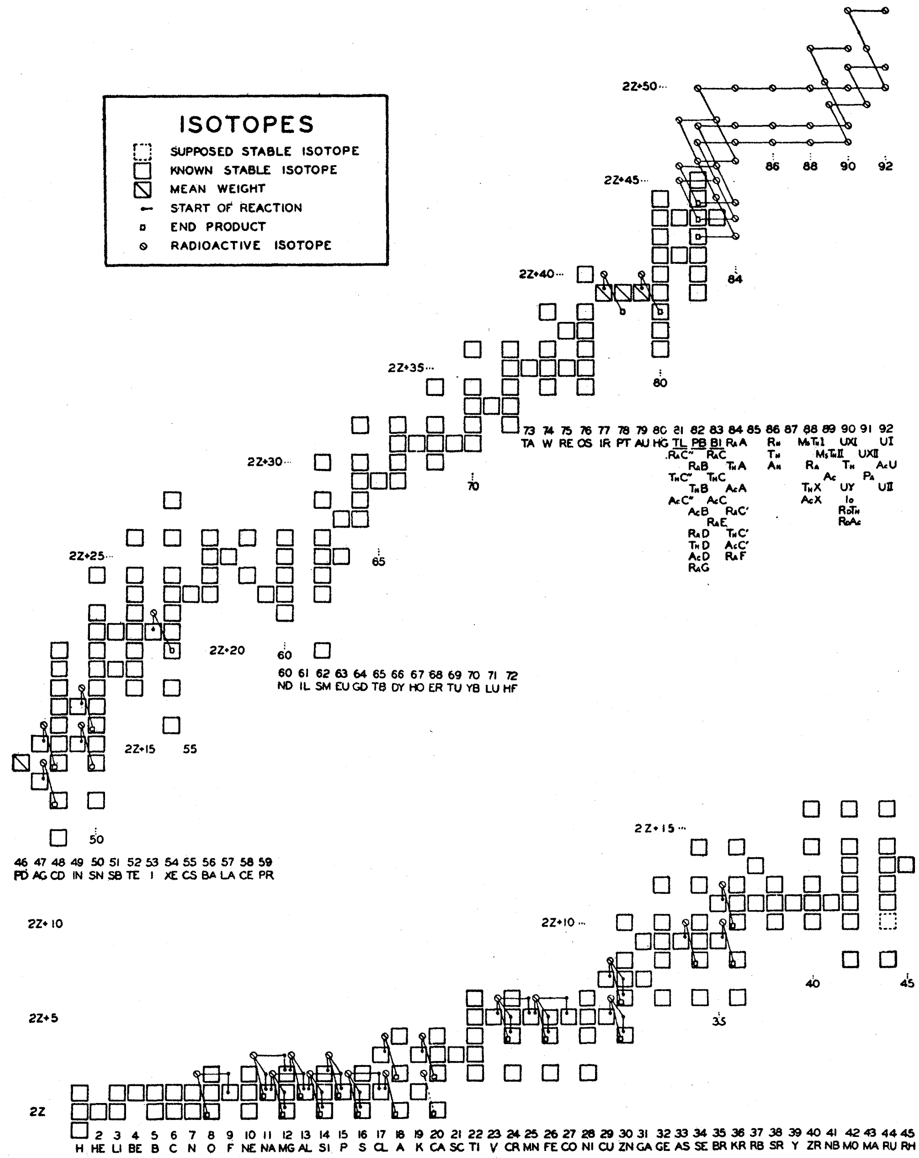

FIG. 1. Isotopes found in nature; abscissae, atomic number Z; ordinates, mass number A plotted in terms of $2Z+(n-p)$. The natural radioactive processes and those stimulated by neutron bombardment are indicated for those cases in which the active isotope has been identified.

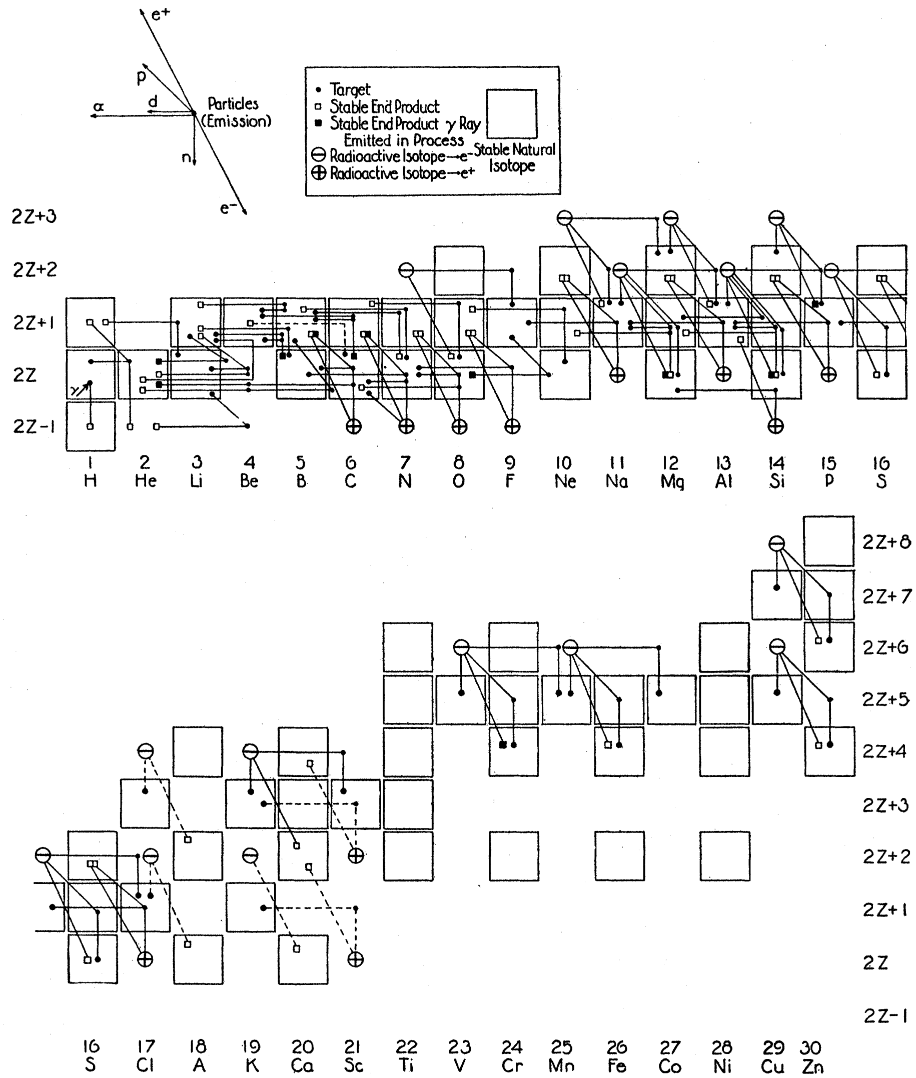

FIG. 2. All established reactions on targets having $Z=1$ to 30. Emission of γ-rays is indicated by a solid black small square representing the emitting nucleus.

TABLE I. *Observations of γ-rays are indicated by italics; disintegrations resulting in complete division of the product nucleus into α-particles are indicated by square brackets; doubtful, unconfirmed, or incompletely studied reactions are shown in parentheses closed by a question mark.* The naturally radioactive nuclei in the U, Th and Ac series are omitted in the interests of brevity. (Closed April 29, 1935.)

Reaction type	Target material: Reaction leads to a stable isotope	Target material: Reaction leads to a radioactive isotope	Type of rad.
$zM^A+\alpha\rightarrow P_i+{}_{z+1}M^{A+3}$	${}_5B^{10}$, ${}_7\mathrm{N}^{14}$, ${}_9\mathrm{F}^{19}$, ${}_{11}\mathrm{Na}^{23}$, ${}_{13}\mathrm{Al}^{27}$, ${}_{15}\mathrm{P}^{31}$ (${}_{10}\mathrm{Ne}^{20}$, ${}_{12}\mathrm{Mg}^{24}$, ${}_{16}\mathrm{S}$, ${}_{17}\mathrm{Cl}$, ${}_{18}\mathrm{A}$, ${}_{19}\mathrm{K}$?)	${}_{12}\mathrm{Mg}^{25}$ (${}_3\mathrm{Li}^7$, ${}_4\mathrm{Be}^9$?)	e^-
$zM^A+\alpha\rightarrow n+{}_{z+2}M^{A+3}$	${}_3Li^7$, ${}_4Be^9$, ${}_5\mathrm{B}^{11}$, (${}_{10}\mathrm{Ne}^{22}$?)	${}_5\mathrm{B}^{10}$, ${}_7\mathrm{N}^{14}$, ${}_9\mathrm{F}^{19}$, ${}_{11}\mathrm{Na}^{23}$, ${}_{12}\mathrm{Mg}^{24}$, ${}_{13}\mathrm{Al}^{27}$, ${}_{15}\mathrm{P}^{31}$, ${}_{19}\mathrm{K}$ (${}_3\mathrm{Li}^6$, ${}_{30}\mathrm{Zn}$, ${}_{12}\mathrm{Mg}^{25,\,26}$?)	e^+
$zM^A+d\rightarrow\alpha+{}_{z-1}M^{A-2}$	${}_3\mathrm{Li}^6$, ${}_4\mathrm{Be}^9$, [${}_5B^{10}$], ${}_7\mathrm{N}^{14}$, ${}_{11}\mathrm{Na}^{23}$, ${}_{13}\mathrm{Al}^{27}$ (${}_8\mathrm{O}^{16}$?)		
$zM^A+d\rightarrow p+zM^{A+1}$	${}_1\mathrm{H}^2$, ${}_3\mathrm{Li}^6$, ${}_5B^{10}$, ${}_6C^{12}$, ${}^7\mathrm{N}^{14}$ (${}_4\mathrm{Be}^9$, ${}_8\mathrm{O}^{16}$?)	${}_{11}\mathrm{Na}^{23}$, ${}_{13}\mathrm{Al}^{27}$, ${}_{29}\mathrm{Cu}$	e^-
$zM^A+d\rightarrow n+{}_{z+1}M^{A+1}$	${}_1\mathrm{H}^2$, [${}_3\mathrm{Li}^7$], ${}_4Be^9$, ${}_5\mathrm{B}^{11}$, ${}_{11}\mathrm{Na}^{23}$, ${}_{13}\mathrm{Al}^{27}$	${}_5\mathrm{B}^{10}$, ${}_6\mathrm{C}^{12}$, ${}_7\mathrm{N}^{14}$	e^+
$zM^A+p\rightarrow\alpha+{}_{z-1}M^{A-3}$	${}_3\mathrm{Li}^6$, ${}_3Li^7$, [${}_5\mathrm{B}^{11}$], ${}_7F^{19}$		
$zM^A+p\rightarrow(\gamma)+{}_{z+1}M^{A+1}$		${}_6C^{12}$, (${}_5B^{10}$?)	e^+
$zM^A+n\rightarrow\alpha+{}_{z-2}M^{A-3}$	${}_3\mathrm{Li}^6$, ${}_5\mathrm{B}^{10}$, ${}_7\mathrm{N}^{14}$, ${}_8\mathrm{O}^{16}$ ${}_{10}\mathrm{Ne}^{20}$ (${}_6\mathrm{C}^{12}$, ${}_{12}\mathrm{Mg}^{24}$?)	${}_9\mathrm{F}^{19}$, ${}_{12}\mathrm{Mg}^{26}$, ${}_{13}\mathrm{Al}^{27}$, ${}_{15}\mathrm{P}^{31}$, ${}_{17}\mathrm{Cl}^{35}$, ${}_{21}\mathrm{Sc}^{45}$, ${}_{25}\mathrm{Mn}^{55}$, ${}_{27}Co^{59}$	e^-
$zM^A+n\rightarrow p+{}_{z-1}M^A$		${}_{11}\mathrm{Na}^{23}$, ${}_{12}\mathrm{Mg}^{24}$, ${}_{13}\mathrm{Al}^{27}$, ${}_{14}\mathrm{Si}^{28}$, ${}_{15}\mathrm{P}^{31}$, ${}_{16}\mathrm{S}^{32}$, ${}_{24}\mathrm{Cr}^{52}$, ${}_{26}\mathrm{Fe}^{56}$, ${}_{30}\mathrm{Zn}^{64}$, ${}_{30}\mathrm{Zn}^{66}$, (${}_7\mathrm{N}^{14}$, ${}_8\mathrm{O}^{16}$, ${}_9\mathrm{F}^{19}$?)	e^-
$zM^A+n\rightarrow(\gamma)+zM^{A+1}$	${}_{39}Y$, ${}_{48}Cd$, ${}_{82}Hg$	${}_{11}\mathrm{Na}^{23}$, ${}_{12}\mathrm{Mg}^{23}$, ${}_{13}\mathrm{Al}^{27}$, ${}_{14}\mathrm{Si}^{30}$, ${}_{17}Cl$, ${}_{19}\mathrm{K}^{41}$, ${}_{23}\mathrm{V}^{51}$, ${}_{25}\mathrm{Mn}^{55}$, ${}_{29}\mathrm{Cu}^{63}$, ${}_{29}\mathrm{Cu}^{65}$, ${}_{31}\mathrm{Ga}$, ${}_{33}\mathrm{As}^{75}$, ${}_{34}\mathrm{Se}$, ${}_{35}\mathrm{Br}^{79}$, ${}_{35}\mathrm{Br}^{81}$, ${}_{47}\mathrm{Ag}$, ${}_{49}\mathrm{In}^{113}$, ${}_{49}\mathrm{In}^{115}$, ${}_{51}\mathrm{Sb}$, ${}_{53}\mathrm{I}^{127}$, ${}_{56}\mathrm{Ba}$, ${}_{74}\mathrm{W}$, ${}_{75}\mathrm{Re}$, ${}_{77}Ir$, ${}_{79}Au$, (${}_{32}\mathrm{Ge}$, ${}_{37}\mathrm{Rb}$, ${}_{42}\mathrm{Mo}$, ${}_{45}\mathrm{Rh}$, ${}_{46}\mathrm{Pd}$, ${}_{52}\mathrm{Te}$, ${}_{55}\mathrm{Cs}$, ${}_{59}\mathrm{Pr}$, ${}_{62}\mathrm{Sm}$, ${}_{63}\mathrm{Eu}$, ${}_{64}\mathrm{Gd}$, ${}_{65}\mathrm{Tb}$, ${}_{68}\mathrm{Er}$, ${}_{70}\mathrm{Yb}$, ${}_{73}\mathrm{Ta}$, ${}_{78}\mathrm{Pt}$, ${}_{82}\mathrm{Pb}$, ${}_{90}\mathrm{Th}$, ${}_{92}\mathrm{U}$?)	e^-
$zM^A+\gamma\rightarrow n+zM^{A-1}$	${}_1\mathrm{H}^2$, ${}_4\mathrm{Be}^9$		
	Radioactive isotopes		
$zR\rightarrow e^++{}_{z-1}R^A$	${}_6\mathrm{C}^{11}$, ${}_7\mathrm{N}^{13}$, ${}_8\mathrm{O}^{15}$, ${}_9\mathrm{F}^{17}$, ${}_{11}\mathrm{Na}^{22}$, ${}_{13}\mathrm{Al}^{26}$, ${}_{14}\mathrm{Si}^{27}$, ${}_{15}\mathrm{P}^{30}$, ${}_{17}\mathrm{Cl}^{34}$, ${}_{21}\mathrm{Sc}$, (${}_5\mathrm{B}^9$?)		
$zR^A\rightarrow e^-+{}_{z+1}R^A$	${}_7\mathrm{N}^{16}$, ${}_{10}\mathrm{Ne}^{23}$, ${}_{11}Na^{24}$, ${}_{12}\mathrm{Mg}^{27}$, ${}_{13}Al^{28}$, ${}_{14}Si^{31}$, ${}_{15}\mathrm{P}^{32}$, ${}_{17}\mathrm{Cl}$, ${}_{19}\mathrm{K}^{42}$, ${}_{23}V^{52}$, ${}_{25}Mn^{56}$, ${}_{29}\mathrm{Cu}^{64}$, ${}_{29}\mathrm{Cu}^{66}$, ${}_{31}\mathrm{Ga}$, ${}_{33}\mathrm{As}^{76}$, ${}_{34}\mathrm{Se}$, ${}_{35}\mathrm{Br}^{80}$, ${}_{35}\mathrm{Br}^{82}$, ${}_{47}\mathrm{Ag}$, ${}_{49}\mathrm{In}^{114}$, ${}_{49}\mathrm{In}^{116}$, ${}_{51}\mathrm{Sb}$, ${}_{53}\mathrm{I}^{128}$, ${}_{56}\mathrm{Ba}$, ${}_{74}\mathrm{W}$, ${}_{75}\mathrm{Re}$, ${}_{77}\mathrm{Ir}$, ${}_{79}\mathrm{Au}$; ${}_{19}\mathrm{K}$, ${}_{37}\mathrm{Rb}$, ${}_{60}\mathrm{Nd}$. (${}_4\mathrm{Be}^{10}$, ${}_6\mathrm{C}^{14}$, ${}_8\mathrm{O}^{19}$, ${}_9\mathrm{F}^{20}$, ${}_{32}\mathrm{Ge}$, ${}_{37}\mathrm{Rb}$, ${}_{42}\mathrm{Mo}$, ${}_{45}\mathrm{Rh}$, ${}_{46}\mathrm{Pd}$, ${}_{52}\mathrm{Te}$, ${}_{55}\mathrm{Cs}$, ${}_{59}\mathrm{Pr}$, ${}_{62}\mathrm{Sm}$, ${}_{63}\mathrm{Eu}$, ${}_{64}\mathrm{Gd}$, ${}_{65}\mathrm{Tb}$, ${}_{68}\mathrm{Er}$, ${}_{70}\mathrm{Yb}$, ${}_{73}\mathrm{Ta}$, ${}_{78}\mathrm{Pt}$, ${}_{82}\mathrm{Pb}$, ${}_{90}\mathrm{Th}$, ${}_{92}\mathrm{U}$, ${}_{93}\mathrm{X}$, ${}_{94}\mathrm{X}$?)		
$zR^A\rightarrow\alpha+{}_{z-2}R^{A-4}$	${}_{62}\mathrm{Sm}^{152}$?		

explains the interpretation of the line charts. Stable isotopes occurring in nature are shown as large squares. A disintegration reaction is indicated by a series of straight lines between the parent and product nuclei, each line indicating a particle used for bombardment or observed as a product. The diagram in the upper left corner of Fig. 2 indicates the magnitude and direction of a change as indicated in the charts for the emission of the various particles. A similar set of lines in the same directions but in the negative sense would indicate the capture of such particles when they were the bombarding projectiles. For example, when a bombarding neutron is absorbed the mass is increased by one, leaving the charge the same; conversely, a neutron emitted lowers the mass by one row. The beginning of a process, and hence the target material, is indicated by a dot, the final stable product by a small hollow square. The dotted Cl and K reactions indicate uncertainty as to the mass of the isotope which enters the reaction. The $C+n$ reaction is dotted because it rests on meager data. Other doubtful or unconfirmed reactions are omitted in Fig. 2,

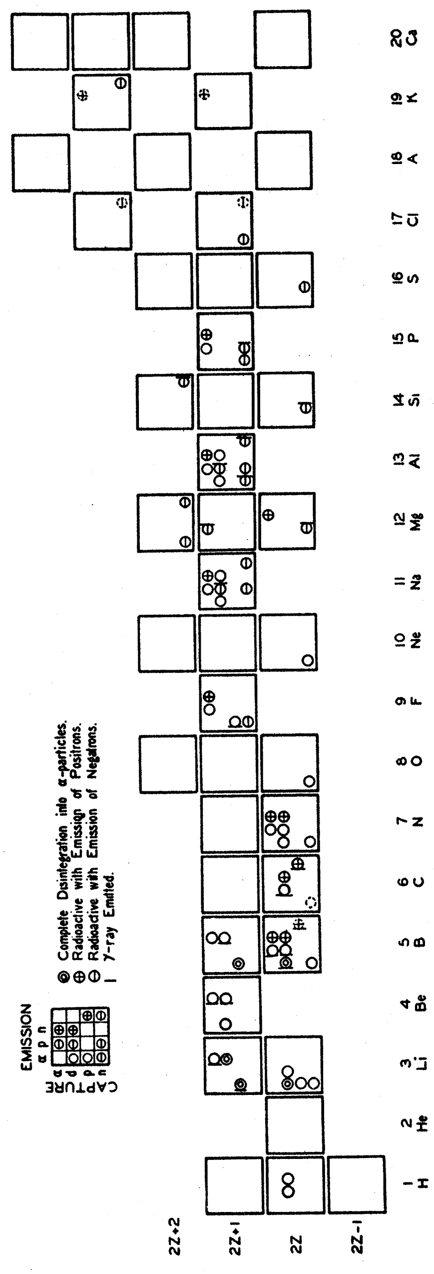

FIG. 3. Target catalog of all established reactions by α, d, p and for n when $Z \leq 20$.

but will be found in Table I. The artificially induced radioactive isotopes are indicated as small circles, enclosing a plus sign if they emit positrons, a minus sign if they emit negative electrons. Let us illustrate by the reaction of $_9F^{19}$ under neutron bombardment. The neutron is captured and an alpha-particle emitted, producing the radioactive nitrogen isotope $^*{}_7N^{16}$, which then emits an electron radioactively and ends as a stable $_8O^{16}$. Three straight lines therefore completely portray the reactions:

$$_9F^{19}+{}_0n^1\rightarrow{}_2\alpha^4+{}^*{}_7N^{16}\ :\ {}^*{}_7N^{16}\rightarrow{}_8O^{16}+e^-.$$

In many cases alternate processes occur, such as in the bombardment of H^2 by deuterons. One process gives H^3 with proton emission, while the other gives He^3 with neutron emission. On the chart these two reactions branch from the same line indicating the captured deuteron. In a similar manner there is multiple use of lines in cases where several reactions produce the same products. This is illustrated by two reactions leading to the radioactive $^*{}_7N^{13}$ isotope, one due to deuteron bombardment of $_6C^{12}$ and the other to alpha-bombardment of $_5B^{10}$.

A similar case of multiple use of lines is:

$$_3Li^7+\alpha\rightarrow{}_5B^{10}+n+\gamma,$$
$$_4Be^9+d\rightarrow{}_5B^{10}+n+\gamma,$$

where the gamma-rays have the same energy (0.6±0.1 MEV) in both cases. Many other examples will be found by inspection of Fig. 2.

The radioactive isotopes are found to occur both above and below the region of stable isotopes on the charts. All those above this region are characterized by having a larger number of excess neutrons $n-p$ than the stable isotopes having the same charge Z. In terms of the recent beta-ray theories of Fermi and others, one of these neutrons is converted into a proton plus electron plus neutrino, the proton remaining in the nucleus while the beta-ray and neutrino are emitted. Similarly, radioactive nuclei below the region of stable isotopes have too few binding neutrons and a proton switches to a neutron plus positron and antineutrino, resulting in positron radioactivity.

The charts accelerate the identification of processes in which chemical analysis or other techniques for identifying reactions have not been used or have not been successful. For example, Fermi reports an electron radioactivity of 40 sec. half-life when sodium or magnesium is bombarded by neutrons but does not identify chemically the radioactive isotope. Noticing that in this region of the atomic table the two most probable neutron processes are those giving alphas and protons as products, and that $*_{11}Na^{24}$ is excluded because of its 15 hr. half-life, it is readily seen that $*_{10}Ne^{23}$ must be the radioactive isotope, produced from magnesium with alpha-emission and from sodium with proton-emission, and that this is beta-active and results in stable $_{11}Na^{23}$ as a final end product. These reactions are indicated on the chart. With the accumulation of more experimental data it should be possible to apply similar rules for the verification of the unidentified radioactive isotopes and so to accelerate the experimental research. The cases of radioactive $*_{23}V^{52}$ and $*_{25}Mn^{56}$ are striking instances in which a single radioactive isotope is the result of each of the three neutron reactions, produced from three different elements. These two cases are supported by chemical evidence.

Of the three types of neutron reactions, that giving alpha-particles is predominant for very light elements; that giving protons is predominant around $Z=10$ to 30; the third, or radiative type, in which there is no particle emission, is predominant in the higher ranges of the atomic table; while all three processes occur in the region between $Z=20$ and 30. This grouping may be due to experimental difficulties or it may be that insufficient work has been done to identify these particles. However, it seems more probable that fundamental nuclear laws underly this orientation of processes. It is possible tentatively to ascribe the lack of charged particle emission from heavy nuclei to their high potential barriers, and its absence in the light element region to the ease with which heavy charged particles pass these lower barriers. The radiative neutron-capture type is sensitive to the so-called water-effect or proton-effect, having a very high probability for slow bombarding neutrons. A theory has recently been advanced by Bethe to account for these high yields.

Disintegration by gamma-radiation or x-rays has been obtained in only two of the lighter elements, $_1H^2$ and $_4Be^9$. These are both endo-energetic reactions and occur with emission of neutrons. The latter reaction is omitted from Fig. 2 because only the neutrons have been reported. The remaining products may either be $_4Be^8$ or, more probably, two alpha-particles.

Processes in which gamma-radiation is a product are of two kinds: (a) those for which the gamma-ray is a definite product and must be included in the mass and energy equations. The third, or radiative neutron type, is of this nature. This may occur in many of the type processes given in the next section, but in most instances energies have not been measured accurately enough to test this point. (b) Those for which the particles are occasionally emitted with energies lower than their maximum, resulting in an excited product nucleus which emits gamma-radiation as it returns to the normal state. This alternative gamma-radiation has varying probabilities for different elements and has been observed for those noted in Table I under each type process. Such radiation, if monochromatic, gives definite evidence of excitation states in the product nucleus. The importance of more complete and more accurate studies of the gamma-radiation accompanying nuclear processes cannot be stressed too strongly.

The geometrical arrangement of Figs. 1 and 2 facilitates a rapid survey of nuclear reactions and the prediction of new reactions. With charged particle projectiles of the present available energies, nuclear potential barriers permit the disintegration of most elements having $Z<20$. With neutrons as projectiles this limitation is removed. The disintegration of Cu by energetic deuterons, recently reported by Lawrence and his co-workers, suggests that in some cases the deuteron may behave like a neutron couplied to a proton, permitting acceleration to high velocity by virtue of its protonic charge, but capable of splitting at a nuclear potential barrier with capture of the neutron and rejection of the proton by the nucleus.

In predicting new reactions one must also consider the reaction energy, which should be calculated when the isotopic masses are known with sufficient accuracy, as well as the total switch in nuclear spin. If the reaction energy is negative, limits of energy of the bombarding particle may be set below which the process cannot occur. Thus, ${}_6C^{12}+\alpha\rightarrow n+{}^*{}_8O^{15}$; ${}_8O^{15}\rightarrow{}_7N^{15}+e^+$, has not been reported, but should occur if α-rays having over *ca.* 6 MEV are used, e.g. ThC′. Similar tests may be applied to all possible processes and experiments based on such predictions should be more rapidly and successfully performed than otherwise.

One example is noted in which proton bombardment does not emit a particle: ${}_6C^{12}+p\rightarrow{}^*{}_7N^{13}+\gamma$. It may be assumed with some certainty that this process does give a gamma-ray product in order that both momentum and energy may be conserved. Hafstad and Tuve have recently shown that the reaction probability is high for only a narrow band of incident proton energies, suggesting a type of resonance capture. One can infer from Fig. 2 that similar processes may be observed for other cases such as ${}_5B^{10}$, ${}_7N^{14}$, ${}_8O^{16}$. The case for ${}_5B^{10}$ is particularly suggestive for Crane and Lauritsen reported induced radioactivity for 0.9 MEV protons on boron, while Cockcroft, Gilbert and Walton found none with 0.6 MEV protons, a situation reminiscent of the carbon case a few months ago. Similarly the possibility of resonance capture of deuterons by ${}_{12}Mg^{24}$, ${}_{14}Si^{28}$ and ${}_{16}S^{32}$, with the emission of energetic γ-rays and the formation of radioactive ${}^*{}_{13}Al^{26}$, ${}^*{}_{15}P^{30}$ and ${}^*{}_{17}Cl^{34}$ should be examined experimentally.

By analogy with such parallel type reactions as

$$ {}_5B^{10}+\alpha\rightarrow n+{}^*{}_7N^{13}, $$
$$ {}_6C^{12}+d\rightarrow n+{}^*{}_7N^{13}, $$

it may be reasonably suggested that similar cases will be observed when more elements have been surveyed. The case of ${}_6C^{12}+\alpha$ has just been considered. ${}_{11}Na^{23}$, ${}_{13}Al^{27}$ and ${}_{15}P^{31}$ when bombarded by α-rays emit neutrons and give radioactive products. Consequently one should expect to find

$$ {}_{12}Mg^{25}+d\rightarrow n+{}^*{}_{13}Al^{26} : {}^*{}_{13}Al^{26}\rightarrow{}_{12}Mg^{26}+e^+, $$
$$ {}_{14}Si^{29}+d\rightarrow n+{}^*{}_{15}P^{30} : {}^*{}_{15}P^{30}\rightarrow{}_{14}Si^{30}+e^+, $$
$$ {}_{16}S^{33}+d\rightarrow n+{}^*{}_{17}Cl^{34} : {}^*{}_{17}Cl^{34}\rightarrow{}_{16}S^{34}+e^+, $$

when these targets are bombarded by sufficiently energetic deuterons.

TYPE REACTIONS

Certain geometrical patterns are apparent when the known disintegration processes are charted in this manner. There are many paralleling processes, which might be represented by type equations or generalizations, as has already been pointed out by other writers. With the exception of non-capture disintegrations, there prove to be just 14 type processes which have been observed, 2 with alpha-bombardment, 3 with deuterons, 2 with protons, 3 with neutrons, 1 with gamma-rays and 3 for radioactive processes. These type reactions are collected in Table I, and opposite each reaction are entered the target materials for which the reaction has been established. In addition, the targets for which the reaction has been reported by one author, but remains doubtful or unconfirmed, are tabulated with an accompanying question mark.

Table II classifies the established reactions according to the number of successfully dis-

TABLE II. *Numerical classification of the 140 established nuclear reactions, according to atomic number Z of the target and, below, Z of the radioactive nucleus; (as in Table I, the U, Ac and Th series are excluded).*

Reaction type	Target material: Reaction leads to a stable isotope, Z odd	Z even	Reaction leads to a radioactive isotope, Z odd	Z even	Type of rad.
$M+\alpha\rightarrow p$	6	0	0	1	e^-
$M+\alpha\rightarrow n$	2	1	7	1	e^+
$M+d\rightarrow\alpha$	5	1	0	0	
$M+d\rightarrow p$	4	1	3	0	e^-
$M+d\rightarrow n$	5	1	2	1	e^+
$M+p\rightarrow\alpha$	4	0	0	0	
$M+p\rightarrow\gamma$	0	0	0	1	e^+
$M+n\rightarrow\alpha$	3	2	7	1	e^-
$M+n\rightarrow p$	0	0	3	7	e^-
$M+n\rightarrow\gamma$	1	2	20	5	e^-
$M+\gamma\rightarrow n$	1	1	0	0	

Type of radioactivity	Radioactive isotopes: Z odd	Z even
$R\rightarrow e^+$	7	3
$R\rightarrow e^-$	24	7

integrated atomic species having odd and even atomic number.

In order to explain certain disintegration forks as observed in the cloud chamber, non-capture reactions have been postulated. In general these reactions are still under question, the evidence for them is meager and they are not included in the present correlations.

Circle Chart

The resolution of all disintegration processes into the type equations of Table I makes possible a simplified graphical target catalog such as Fig. 3. Here the large square representing each bombarded nucleus is subdivided into four rows, each representing a captured projectile, alpha α, deuteron d, proton p, or neutron n, and into four columns representing the emitted particle, α, p, n, or none (γ only). A circle within the square of a stable isotope denotes its successful disintegration, the circle's row and column disclose the captured and emitted particles, hence portray the reaction. A double circle denotes complete division of the products of disintegration into α-rays, while a plus or minus sign shows that the reaction is followed by an induced radioactive disintegration with the emission, respectively, of positrons or of negative electrons. A vertical bar to the left of the circle connotes γ-ray emission associated with the primary disintegration, while a bar to the right of the circle indicates γ-ray emission associated with the induced radioactive disintegration. Hence the position and form of each entry suffices for complete representation of the reaction. All established reactions within $Z=1$ to 20 are given on Fig. 3, with the exception of

$$d+\gamma\rightarrow p+n, \quad \text{and} \quad {}_4\mathrm{Be}^9+\gamma\rightarrow n+?.$$

A few inadequately established but very probable reactions are shown dotted. The entries in the caption square portray the known type reactions of Table I, the plus or minus indicating that positron or electron radioactivity is sometimes associated with the particular disintegration.

From Fig. 3, it is possible to collect rapidly all reactions conforming to any desired sub-classification. For example: to tabulate all reactions produced by alpha-rays one simply reads the entries along the top rows within all the isotope squares; to tabulate reactions which yield neutrons as products of disintegration one reads the entries in the third columns of all isotope squares; to tabulate all reactions yielding positron radioactivity one records all appearances of the plus sign within the various reaction circles.

The authors appreciate the value of a quantitative correlation of mass and energy in disintegration processes. They consider it outside the scope of this paper to attempt any such correlation but point out that isotopic plots on the coordinates of Figs. 1, 2, 3 have proved a very convenient form for such records.

No bibliography is here appended because, if complete, it would exceed a thousand references and, if incomplete, it might appear invidious to some. Moreover, most workers are already equipped with these details and our major concern in the present writing has been to report a method and an accurate catalog of established nuclear reactions.