ENERGIES AND PRODUCTS INVOLVED IN NUCLEAR DISINTEGRATION AND SYNTHESIS

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INTRODUCTION

There seems to be running through the multitude of experiments that have been performed in the last year or so on nuclear disintegration, a strong demand for certain fundamental nuclear building blocks. These building blocks with their properties and their current scientific standing are listed in Table I (1).

TABLE I
BUILDING BLOCKS

	Mass	Charge	Symbol	Reputability
Electron	Very small	neg.	e	Long standing
Neutrino	Very small	zero	n'	Questionable
Positron	Very small	pos.	e^+	Recently established
Negatron	Large	neg.	p	Questionable
Neutron	Large	zero	n	Recently established
Proton	Large	pos.	p	Long standing

It is noticed that there are two major groups; a group of three with small masses and a group of three with large masses. The relative size of the masses in these two groups is about 1/1850 to 1.

A few years ago when only the two particles, the electron and the proton, were known, many attempts were made to build consistent arrays of the known nuclei out of these two constituents. However, when the reality of the neutron was established (2) and when sufficient experimental data on how nuclei disintegrate were accumulated, it became obvious that the previous concepts on nuclear building were inadequate and erroneous.

STABLE NUCLEI

Since only protons and neutrons (or combinations of these; for example, an alpha particle which consists, let us say, of two protons and two neutrons) are found ejected when a nucleus is made to disintegrate, it is natural to expect the nuclei of the various elements to be made up of a logical sequence of protons and neutrons (3). Table II shows a possible arrangement.

TABLE II

ATOMIC MASSES

	Composition	Bethe	Oliphant	Aston et al.
$_0n^1$	n	1.00850 (50)*	1.0083 (3)	1.0089
$_1H^1$	p	1.00807 (07)	1.0081 (1)	*1.0081*
$_1H^2$	n p	2.01423 (15)	2.0142 (2)	*2.0148*
$_1H^3$	n p n	3.01610 (33)	3.0161 (3)	3.0151
$_2He^4$	α	4.00336 (23)	4.0034 (4)	*4.0041*
$_2He^5$	α n	.....	5.010 ...	5.0060
$_3Li^6$	α n p	6.01614 (50)	6.0163 (6)	6.0175
$_3Li^7$	α n p n	7.01694 (48)	7.0170 (7)	7.0176
$_4Be^8$	2α	.....	8.007 ...	.....
$_4Be^9$	2α n	9.0135 (7)	9.0138 (5)	9.0164
$_5B^{10}$	2α n p	10.0146 (10)	10.0143 (3)	10.0135
$_5B^{11}$	2α n p n	11.0111 (11)	11.0110 ...	11.0121
$_6C^{12}$	3α	12.0037 (7)	12.0027 (3)	*12.0048*
$_6C^{13}$	3α n	13.0069 (7)	.....	13.0051
$_7N^{14}$	3α n p	14.0076 (4)	.....	14.0042
$_7N^{15}$	3α n p n	15.0053 (5)	.....	15.0032
$_8O^{16}$	4α	16.0000 (0)	16.0000 (0)	16.0000
$_8O^{17}$	4α n	17.0040 (2)	.....	17.0024
$_8O^{18}$	4α n n	.....	.....	18.0065
$_9F^{19}$	4α n n p	.....	.....	18.9931
$_2He^3$	p n p	3.01699 (46)	3.0172 (3)	3.0164

*The numbers in parentheses indicate the probable error; for example, 1.00850 + .00050.

First, there is the neutron and the proton separately. Next, there is the combination of neutron and proton, called the deuteron or nucleus of the heavy hydrogen atom of which heavy water is made. By adding a neutron to this nucleus there is obtained a still heavier nucleus of hydrogen. The addition of a proton to this nucleus then gives the alpha particle or the nucleus of the helium atom. It is obvious that the

nuclei following from here on may be arrived at by merely adding alternately a neutron and proton—until oxygen, atomic number 8, atomic weight 16, is reached. Then the scheme is to add neutron, neutron, proton, proton.

As may be seen in Table III this scheme continues to argon. Beyond argon a more complicated scheme involving the negatron seems to work more satisfactorily (4). In Table II are listed also the nuclear masses as given by three different workers. The masses given by the first two are based on nuclear disintegration data, the last based on mass spectrograph data (5). It is unfortunate that there is such a wide spread in the data available and that no definite values as yet can therefore be decided upon.

TABLE III

STABLE NUCLEI

Nucleus	Composition	Mass	Abundance
$_1H^1$	p	1.00807	99.99
$_1H^2$	n p	2.01423	.025
$_1H^3$	n p n	3.01610	10^{-6}
$_2He^4$	α	4.00336	100
$_2He^5$	α n	5.010	.....
$_3Li^6$	α n p	6.01614	8.3
$_3Li^7$	α n p n	7.01694	91.7
$_4Be^8$	2α	8.007	.05
$_4Be^9$	2α n	9.0135	99.99
$_5B^{10}$	2α n p	10.0146	20.
$_5B^{11}$	2α n p n	11.0111	80
$_6C^{12}$	3α	12.0037	99.75
$_6C^{13}$	3α n	13.0069	.25
$_7N^{14}$	3α n p	14.0076	99.86
$_7N^{15}$	3α n p n	15.0053	.14
$_8O^{16}$	4α	16.0000	99.81
$_8O^{17}$	4α n	17.0040	.03
$_8O^{18}$	4α n n	18.0065	.16
$_9F^{19}$	4α n n p	19.0031	100
$_{10}Ne^{20}$	5α	19.99671	90.4
$_{10}Ne^{21}$	5α n	.....	0.6
$_{10}Ne^{22}$	5α n n	21.99473	9.0
$_{11}Na^{23}$	5α n n p	.....	100
$_{12}Mg^{24}$	6α	.....	77.4
$_{12}Mg^{25}$	6α n	.....	11.5
$_{12}Mg^{26}$	6α n n	.....	11.1
$_{13}Al^{27}$	6α n n p	.....	100
$_{14}Si^{28}$	7α	27.9818	94

TABLE III—(Continued)

Nucleus	Composition	Mass	Abundance
$_{14}Si^{29}$	7α n	.....	4
$_{14}Si^{30}$	7α n n	.....	2
$_{15}P^{31}$	7α n n p	30.9825	100
$_{16}S^{32}$	8α	.....	96
$_{16}S^{33}$	8α n	.....	1
$_{16}S^{34}$	8α n n	.....	3
$_{17}Cl^{35}$	8α n n p	34.893	76
$_{18}A^{36}$	9α	35.976	0.6
$_{18}A^{37}$	9α n	.....	.....
$_{18}A^{38}$	9α n n	.....	.....
$_{19}K^{39}$	9α n n p	.....	5.4
$_{18}A^{36}$	9α	35.976	0.6
$_{17}Cl^{37}$	9α p	36.980	24
$_{18}A^{38}$	9α p p	.....	.01
$_{18}A^{39}$	9α p p n	.....	.....
$_{18}A^{40}$	9α p p n n	39.971	99.4
$_{20}Ca^{40}$	10α	.....	97
$_{19}K^{41}$	10α p	.....	94.6
$_{20}Ca^{42}$	10α p p	.....	.8
$_{20}Ca^{43}$	10α p p n	.....	.2
$_{20}Ca^{44}$	10α p p n n	.....	2.3
$_{22}Ti^{44}$	11α	.....	.....
$_{21}Sc^{45}$	11α p	.....	100
$_{22}Ti^{46}$	11α p p	.....	.01
$_{22}Ti^{47}$	11α p p n	.....	.01
$_{22}Ti^{48}$	11α p p n n	.....	99
$_{22}Ti^{49}$	11α p p n n n	.....	.01
$_{22}Ti^{50}$	11α p p n n n n	.....	.01
$_{24}Cr^{50}$	12α 2n	.....	4.9
$_{23}V^{51}$	12α 2n p	.....	100
$_{24}Cr^{52}$	12α 2n p p	.....	81.6
$_{24}Cr^{53}$	12α 2n p p n	.....	10.4
$_{24}Cr^{54}$	12α 2n p p n n	.....	3.1
$_{26}Fe^{54}$	13α 2n	.....	95
$_{25}Mn^{55}$	13α 2n p	.....	100
$_{26}Fe^{56}$	13α 2n p p	.....	5
$_{26}Fe^{57}$	13α 2n p p n	.....	.....
$_{26}Fe^{58}$	13α 2n p p n n	.....	.....
$_{28}Ni^{58}$	14α 2n	57.942	66
$_{27}Co^{59}$	14α 2n p	.....	100
$_{28}Ni^{60}$	14α 2n p p	.....	34
$_{28}Ni^{61}$	14α 2n p p n	.....	.01
$_{28}Ni^{62}$	14α 2n p p n n	.....	.01
$_{29}Cu^{63}$	14α 2n p p n n p	.....	68
$_{30}Zn^{64}$	15α 4n	63.937	50.4
$_{29}Cu^{65}$	15α 4n p	.....	32

TABLE III—(Continued)

Nucleus	Composition	Mass	Abundance
$_{30}Zn^{66}$	15α 4n *p* p	.....	27.2
$_{30}Zn^{67}$	15α 4n *p* p n	.....	4.2
$_{30}Zn^{68}$	15α 4n *p* p n n	.....	17.4
$_{31}Ga^{69}$	15α 4n *p* p n n p	.....	60
$_{30}Zn^{70}$	15α 4n *p* p n n p *p*	.....	0.4
$_{32}Ge^{70}$	16α 6n	.....	21.2
$_{31}Ga^{71}$	16α 6n *p*	.....	40
$_{32}Ge^{72}$	16α 6n *p* p	.....	27.3
$_{32}Ge^{73}$	16α 6n *p* p n	.....	7.9
$_{32}Ge^{74}$	16α 6n *p* p n n	.....	37.1
$_{33}As^{75}$	16α 6n *p* p n n p	74.934	100
$_{32}Ge^{76}$	16α 6n *p* p n n p *p*	.....	6.5

NEUTRONS

By glancing over Table III several points of interest are noticed; for example, beryllium, atomic number 4, atomic weight 9, is the only nucleus with any appreciable abundance that has attached to its alpha-particle kernel only one single extra neutron. As might be expected this extra neutron (under violent bombardment with alpha rays from polonium) would easily be shaken loose and neutron emission observed. In fact this is the very way neutrons were first discovered by Chadwick in 1932. Consequently, were it not for the existence of this particular isotope of beryllium which copiously emits neutrons, the field of nuclear physics would undoubtedly be less advanced and less fruitful than it is today and nuclear physicists would be deprived of one of their most powerful tools for prying into the secrets of the nucleus.

Table IV has been prepared in order to show clearly what is meant by the terms *isotopes*, *isobars*, and *isomers*.

TABLE IV

ISOTOPES, ISOBARS, ISOMERS

	Weight of Nucleus	Chemical Properties of Atom	Structure of Nucleus	Examples
Isotopes	Different...	Same.....	Different...	$_1H^1$, $_1H^2$, $_1H^3$
Isobars	Same.....	Different...	Different...	$_1H^3$, $_2He^3$
Isomers	Same.....	Same.....	Different...	$_{91}UX_2$,^{234} $_{91}UZ^{234}$

Since the advent of neutrons through the bombardment of beryllium by alpha rays, many attempts have been made to discover or develop other methods that would give strong neutron sources. The three most successful methods are deuteron bombardment of beryllium, deuteron bombardment of the heavier lithium isotope, and deuteron bombardment of deuterons. With four strong neutron sources available, much progress in nuclear transformations has been made by using the neutrons obtained from nuclear disintegration to bombard and thereby disintegrate other nuclei.

SYNTHESIZED RADIOACTIVE NUCLEI

When a nucleus is disintegrated, or rather transmuted, into some other nucleus, it frequently occurs that the nucleus which is formed is of a new species and has never been observed before. In order to show how fruitful this particular phase of the general nuclear problem is, there is collected in Table V a list of nuclei which were not known to either chemists or physicists before February, 1934. F. Joliot and I. Curie (6) announced then that alpha-ray bombardment of boron produces a product which is radioactive. This product is nitrogen, atomic number 7, atomic weight 13 (see eleventh row), composed of three alpha particles and one proton, has a half life of 11 minutes, emits positrons with energies up to 1.5 million volts, and as may be seen in the last column of the table, can be produced also by proton bombardment of carbon or by deuteron bombardment of carbon.

TABLE V

SYNTHESIZED RADIOACTIVE NUCLEI

Nucleus	Composition	Life	Energy of e	+or—	Method of Production
$_2He^3$	p n p	.....	.....	.....	p Li^6; d (H^2, B^9)
$_2He^6$	α n n	.....	.....	.....	.....
$_3Li^5$	α p	.....	.....	.....	.....
$_3Li^8$	α n n p n	0.5 s	9. mV max	—	d Li^7
$_4Be^7$	α p n p	.....	.....	.....	.....
$_4Be^{10}$	2α n n	.....	.3 mV av	—	d Be^9; α Li^7
$_5B^9$	2α p	1. m	.5 mV av	+	α Li^6
$_5B^{12}$	2α n n p n	.02 s	11. mV max	—	d B^{11}
$_6C^{11}$	2α p n p	20. m	1.3 mV max	+	d B^{10}
$_6C^{14}$	3α n n	.....	.....	.....	.....
$_7N^{13}$	3α p	11. m	1.5 mV max	+	p C^{12}; d C^{12}; α B^{10}

TABLE V—(Continued)

Nucleus	Composition	Life	Energy of e	+or—	Method of Production
$_{7}N^{16}$	3α n n p n	9. s	.....	—	n F^{19}
$_{8}O^{15}$	3α p n p	126. s	1.2 mV max	+	d N^{14}
$_{8}O^{19}$	4α n n n	40 s	.....	—	n F^{19}
$_{9}F^{17}$	4α p	1.16 s	.....	+	α N^{14}
$_{9}F^{18}$	4α n p	.....	.....	+	.....
$_{9}F^{20}$	4α n n p n	12. s	4.5 mV max	—	n Na^{23}; d F^{19}
$_{10}Ne^{19}$	4α p n p	.....	.....	+	.....
$_{10}Ne^{23}$	5α n n n	40. s	.....	—	n (Na^{23}, Mg^{26})
$_{11}Na^{22}$	5α n p	.....	.4 mV av	+	α F^{19}
$_{11}Na^{24}$	5α n n p n	15. h	1.0 mV av	—	n (Na^{23}, Mg^{24}, Al^{27}) d Na^{23}
$_{12}Mg^{23}$	5α p n p	.....	.....	+	.....
$_{12}Mg^{27}$	6α n n n	10. m	.6 mV av	—	n (Mg^{26}, Al^{27})
$_{13}Al^{26}$	6α n p	.....	.....	+	.....
$_{13}Al^{28}$	6α n n p n	2.3 m	1.3 mV av	—	n (Al^{27}, Si^{28}, P^{31}); d Al^{27}; α Mg^{25}
$_{14}Si^{27}$	6α p n p	14.5 m	.....	+	α Mg^{24}
$_{14}Si^{31}$	7α n n n	2.4 h	1.25 mV av	—	n (Si^{30}, P^{31})
$_{15}P^{30}$	7α n p	3.25 m	3. mV max	+	α Al^{27}
$_{15}P^{32}$	7α n n p n	14. d	.8 mV av	—	n (S^{32}, Cl^{35})
$_{16}S^{31}$	7α p n p	.....	.....	+	.....
$_{16}S^{35}$	8α n n n	.....	.....	—	.....
$_{17}Cl^{34}$	8α n p	.....	.....	+	.....
$_{17}Cl^{36}$	8α n n p n	50. m	2. mV max	—	n Cl^{35}
$_{17}Cl^{38}$	9α *p* n	.....	.....	—	n Cl^{37}
$_{18}A^{35}$	8α p n p	.....	.....	+	.....
$_{18}A^{39}$	9α n n n	.....	.....	—	.....
$_{19}K^{38}$	9α n p	.....	.....	+	.....
$_{19}K^{42}$	10α *p* n	16. h	1.6 mV av	—	n (K^{41}, Sc^{45}, Ca^{42})
$_{20}Ca^{41}$	10α n	4. h	.....	—	n Ca^{40}
$_{20}Ca^{45}$	10α *p* p n n n	3. m	.....	—	n Ti^{48}
$_{21}Sc^{46}$	11α *p* n	.....	.....	.....	n Sc^{45}
$_{23}V^{52}$	.....	3.75 m	1.4 mV av	—	n (V^{51}, Cr^{52}, Mn^{55})
$_{25}Mn^{56}$	.....	2.5 h	1.2 mV av	—	n (Mn^{55}, Fe^{56}, Co^{59})
$_{29}Cu^{64}$	.....	5. m	.....	—	n (Cu^{63}, Zn^{64})
$_{29}Cu^{66}$	.....	10. h	.....	—	n (Cu^{65}, Zn^{66})
$_{31}Ga^{70}$	.....	20. m	1.4 mV av	—	n Ga^{69}
$_{31}Ga^{72}$	.....	23. h	.....	—	n Ga^{71}
$_{32}Ge^{75}$	.....	30. m	.....	—	n Ga^{74}
$_{33}As^{76}$	.....	26. h	1.3 mV av	—	n As^{75}
$_{34}Se^{81}$	.....	35. m	.....	—	n Se^{80}
$_{35}Br^{80}$	.....	30. m	2.1 mV max	—	n Br^{79}
$_{35}Br^{82}$	.....	6. h	2.1 mV max	—	n Br^{81}
$_{40}Zr^{95}$	.....	4. h	1.1 mV av	—	n Zr^{94}
$_{42}Mo^{99}$	.....	30. m	.....	—	n Mo^{98}
$_{42}Mo^{101}$	.....	36. h	.....	—	n Mo^{100}

TABLE V—(Continued)

Nucleus	Composition	Life	Energy of e	+or—	Method of Production
$_{45}Rh$	.....	44. s	1.2 mV av	—	n Rh
$_{45}Rh$	.....	3.9 m	.....	—	n Rh
$_{47}Ag^{108}$	.....	22. s	.....	—	n Ag^{107}
$_{47}Ag^{110}$	.....	2.3 m	.7 mV av	—	n Ag^{109}
$_{49}In^{114}$	.....	54. m	.7 mV av	—	n In^{113}
$_{49}In^{116}$	.....	3. h	.....	—	n In^{115}
$_{51}Sb^{122}$	.....	2.5 d	.7 mV av	—	n Sb^{121}
$_{52}Te^{131}$	.....	45. m	.....	—	n Te^{130}
$_{53}I^{128}$	.....	30. m	2.1 mV max	—	n I^{127}
$_{55}Cs^{134}$	.....	1.5 h	.....	—	n Cs^{133}
$_{56}Ba^{139}$	.....	80. m	.....	—	n Ba^{138}
$_{58}Ca^{141}$	.....	5. m	.....	—	n Pr^{141}
$_{59}Pr^{142}$	.....	19. h	1. mV av	—	n Pr^{141}
$_{60}Nd^{147}$	.....	1. h	.....	—	n Nd^{146}
$_{62}Sm^{153}$	.....	40. m	.....	—	n Sm^{152}
$_{64}Gd^{159}$	.....	8. h	.....	—	n Gd^{158}
$_{72}Hf^{181}$	.....	2. mo	.....	—	n Hf^{180}
$_{74}W^{185}$	.....	1. d	.....	—	n W^{184}
$_{75}Re^{186}$	.....	20. h	1. mV av	—	n Re^{185}
$_{77}Ir$	.....	19. h	1. mV av	—	n Ir
$_{78}Pt$	.....	50. m	.....	—	n Pt
$_{79}Au$	.....	2.7 d	.4 mV av	—	n Au
$_{90}Th$	.....	1. m	.....	—	n Th^{232}
$_{90}Th$	.....	24. m	.....	—	n Th^{232}
$_{92}U$	.....	15. s	.....	—	n U^{238}
$_{92}U$	.....	40. s	.....	—	n U^{238}
?	.....	13. m	1.2 mV av	—	n U^{238}
?	.....	100. m	.6 mV av	—	n U^{238}

Helium, atomic number 2, atomic weight 3 (see first row), has not been observed to be radioactive, nevertheless it is listed in this table with the synthesized nuclei because it fits in with their scheme of nuclear composition. Every nucleus in this table does not fit in with the scheme for stable nuclei in Table III. However, there apparently is no great fundamental difference between stable nuclei and unstable nuclei since the half life of the synthesized nucleus hafnium is two months.

It is interesting to notice that the lighter synthesized nuclei can be obtained in several ways while the heavier synthesized nuclei must be obtained only with neutron bombardment (7). To make somewhat more clear the implication of the shorthand of the last column of Table V, there is written out in

Table VI the details for the various ways in which radioactive sodium, or rather radio-sodium, can and may be synthesized. Similar information in regard to radio-aluminum is given in Table VII. The upper group of reactions in each of these tables are those reactions that have been observed to work satisfactorily; the lower group are those that might work if the various nuclei involved existed or existed in sufficient abundance.

TABLE VI

RADIO-SODIUM

$$
\left.\begin{array}{l}
{}_0n^1 + {}_{11}Na^{23} \longrightarrow {}_{11}Na^{24} \\
{}_0n^1 + {}_{12}Mg^{24} \longrightarrow {}_{11}Na^{24} + {}_1p^1 \\
{}_0n^1 + {}_{13}Al^{27} \longrightarrow {}_{11}Na^{24} + {}_2He^4 \\
{}_1d^2 + {}_{11}Na^{23} \longrightarrow {}_{11}Na^{24} + {}_1p^1 \\
{}_1d^2 + {}_{12}Mg^{26} \longrightarrow {}_{11}Na^{24} + {}_2He^4 \\
{}_2\alpha^4 + {}_{10}Ne^{21} \longrightarrow {}_{11}Na^{24} + {}_1p^1 \\
{}_2\alpha^4 + {}_9F^{21} \longrightarrow {}_{11}Na^{24} + {}_0n^1 \\
{}_1d^2 + {}_{10}Ne^{23} \longrightarrow {}_{11}Na^{24} + {}_0n^1 \\
{}_1p^1 + {}_{10}Ne^{24} \longrightarrow {}_{11}Na^{24} + {}_0n^1 \\
{}_1p^1 + {}_{12}Mg^{27} \longrightarrow {}_{11}Na^{24} + {}_2\alpha^4
\end{array}\right\} \quad {}_{11}Na^{24} \xrightarrow[15h]{} {}_{12}Mg^{24} + -{}_1e^0
$$

TABLE VII

RADIO-ALUMINUM

$$
\left.\begin{array}{l}
{}_0n^1 + {}_{13}Al^{27} \longrightarrow {}_{13}Al^{28} \\
{}_0n^1 + {}_{14}Si^{28} \longrightarrow {}_{13}Al^{28} + {}_1H^1 \\
{}_0n^1 + {}_{15}P^{31} \longrightarrow {}_{13}Al^{28} + {}_2He^4 \\
{}_1d^2 + {}_{13}Al^{27} \longrightarrow {}_{13}Al^{28} + {}_1H^1 \\
{}_2\alpha^4 + {}_{12}Mg^{25} \longrightarrow {}_{13}Al^{28} + {}_1H^1 \\
{}_1d^2 + {}_{14}Si^{30} \longrightarrow {}_{13}Al^{28} + {}_2He^4 \\
{}_1d^2 + {}_{12}Mg^{27} \longrightarrow {}_{13}Al^{28} + {}_0n^1 \\
{}_2\alpha^4 + {}_{11}Na^{25} \longrightarrow {}_{13}Al^{28} + {}_0n^1 \\
{}_1p^1 + {}_{12}Mg^{28} \longrightarrow {}_{13}Al^{28} + {}_0n^1 \\
{}_1p^1 + {}_{14}Si^{31} \longrightarrow {}_{13}Al^{28} + {}_2He^4
\end{array}\right\} \quad {}_{13}Al^{28} \xrightarrow[2.3m]{} {}_{14}Si^{28} + -{}_1e^0
$$

If one is to prohibit electrons and positrons from being constituents in the building up of the nucleus, perhaps the necessity of accounting for the actual experimentally observed ejections of electrons and positrons from these radioactive nuclei would consequently produce some embarrassment. However, one is able to account satisfactorily for the emission of light from an atom without the necessity of saying that atoms are composed, in part at least, of light. Likewise, when a nucleus changes from one energy state to another of lower energy, the energy difference may be carried from the nucleus

in the form of a gamma ray or if there is sufficient excess energy in the form of an electron (or positron) which is created out of this energy in accord with the Einstein relativistic relation that energy equals mass multiplied by the square of the velocity of light.

SLOWED NEUTRONS

It is the common opinion that the faster the impinging bombarding particle is made to go, the more likely it is upon collision for a disintegration to take place. This idea has recently been shown to be grossly wrong in a large number of the reactions where neutron bombardment is concerned. In Table VIII there are listed some of the elements which show a marked increase of effectiveness of slow neutrons compared to the effectiveness of fast neutrons in the production of radioactive nuclei (8). Other elements which do not yield radioactive nuclei when bombarded with neutrons evidence their reactional tendencies by strongly absorbing a beam of slow neutrons.

TABLE VIII

SLOW-NEUTRON EFFECTIVENESS

Element Bombarded	Effectiveness of Slow Neutrons Over That of Fast
Vanadium	40
Silver	30
Manganese	23
Rhodium	15
Tungsten	15
Copper	15
Indium	12
Bromine	10

TABLE IX

ABSORBERS OF SLOW NEUTRONS (7)

Element	Thickness Required to Decrease Intensity of a Beam of Slow Neutrons to Half
Cadmium	.015 mm., .13 mm. (14)
Boron	.022 mm.
Yttrium	.040 mm.
Lithium	.094 mm.

For example, the substances in Table IX are considered opaque to slow neutrons. However, some other substances such as aluminum, tin, zinc, and iron are comparatively transparent to slow neutrons. Almost all substances are easily penetrated by fast neutrons.

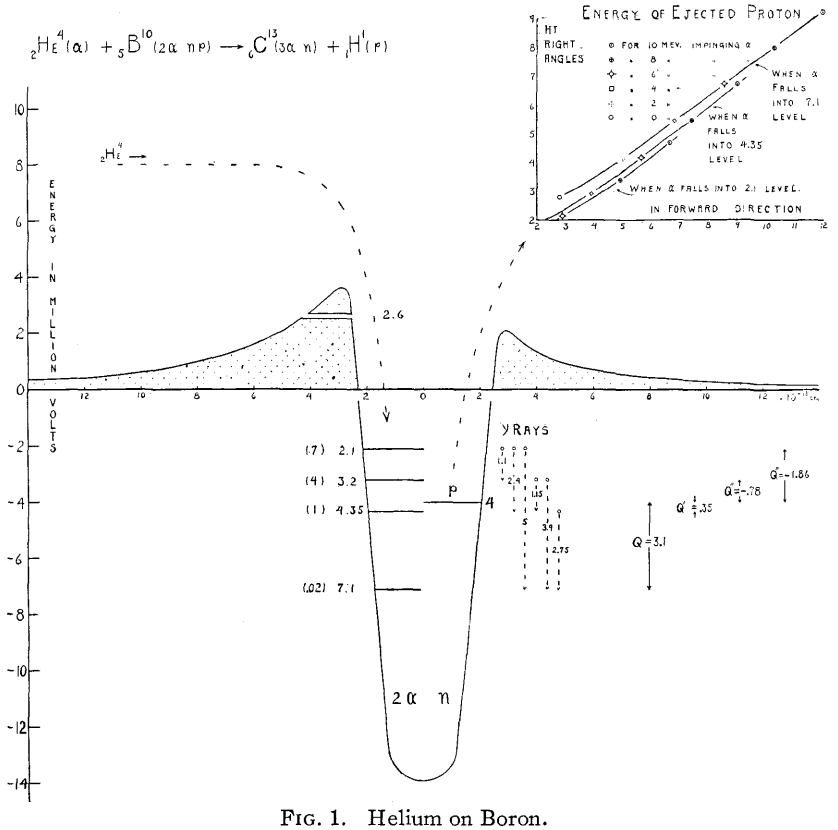

FIG. 1. Helium on Boron.

TRANSMUTATION DIAGRAMS

Since it is quite evident by now that there is a large quantity of information available concerning nuclear transmutations in general and concerning the behavior of any one nucleus in a transmutation, a collection, therefore, of a portion of this information condensed as much as possible into a single diagram or schematic picture would possibly be desirable.

With this purpose in mind consider Fig. 1 for the transmutation of boron into carbon and hydrogen (9). Along the

vertical axis is plotted energy in million volts and along the horizontal axis is plotted nuclear distance in 10^{-13} cm. The left half of the diagram represents the potential energy curve

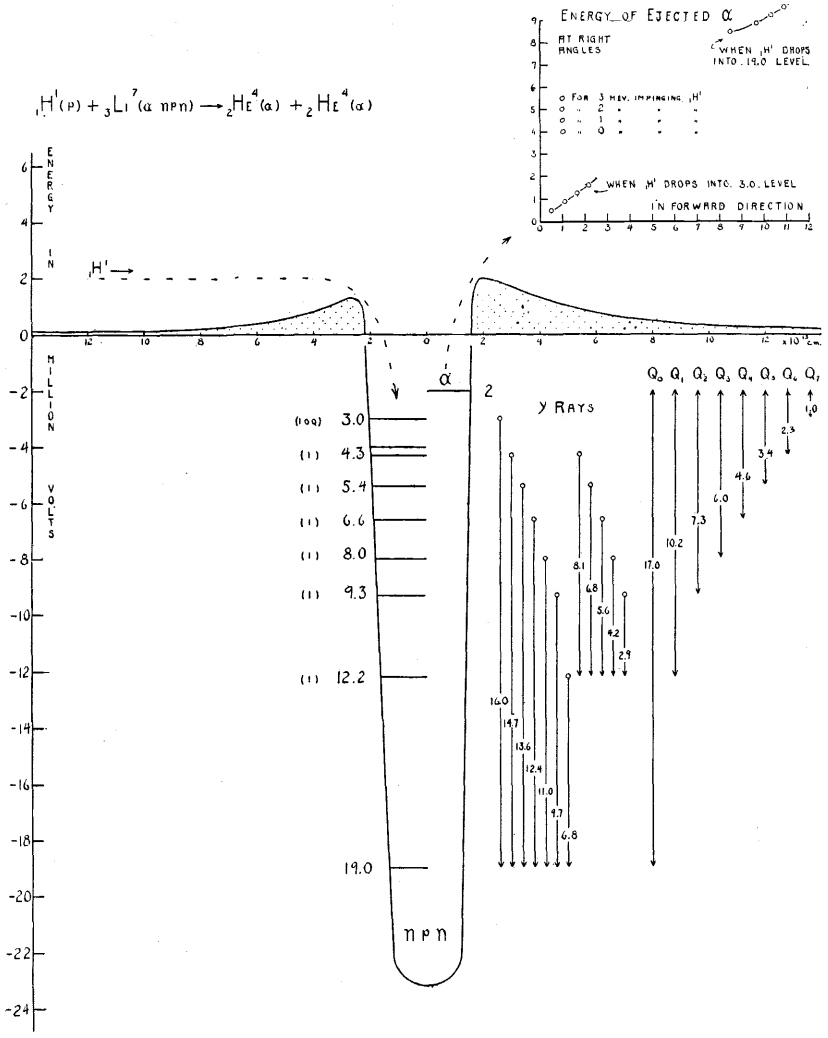

FIG. 2. Protons on Lithium.

or potential barrier of an alpha particle in the presence of a boron nucleus. This is the situation before the transmutation. The right-hand curve represents the potential energy curve or potential barrier of a proton in the presence of a carbon

nucleus. This is the situation after transmutation. The diagram is then to be read as follows: The alpha particle approaches the boron nucleus and is repulsed by the strong electric fields. If the alpha particle has enough energy to get over the barrier, which here is about 3.6 million volts, it then falls into the interior of the nucleus. There are four levels (2.1, 3.2, 4.35, and 7.1 million volt) on which the alpha particle may choose to stop. If the alpha particle drops to the lowest

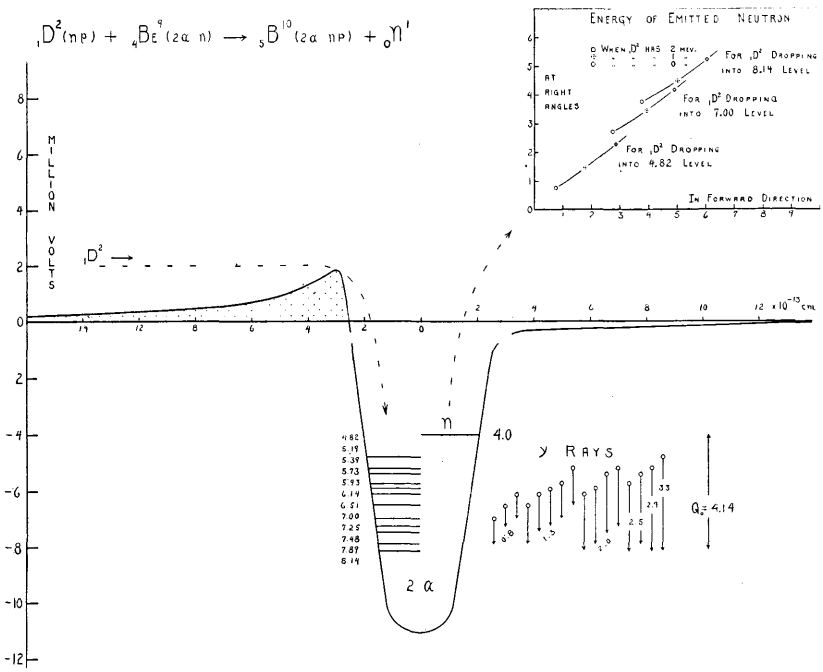

FIG. 3. Deuterons on Beryllium.

level, the greatest amount of energy is available to eject the proton from its four-million-volt level.

The proton may be ejected in the same direction as the impinging alpha particle or at right angles to this direction. Due to the conservation of momentum the proton will receive a little more energy if it comes off in the forward direction. Taking into consideration the momentum of the impinging alpha particle, the recoil of the residual carbon nucleus and the true transmutation energy Q, calculations were made for the energies of the protons in both the forward and the right-angle directions when the impinging alpha particle has various

energies up to ten million volts. These results are plotted in the inset graph where both the horizontal and vertical axes represent energy in million volts.

Consequently, if one wishes to know how energetically protons would be emitted at right angles when eight-million-volt

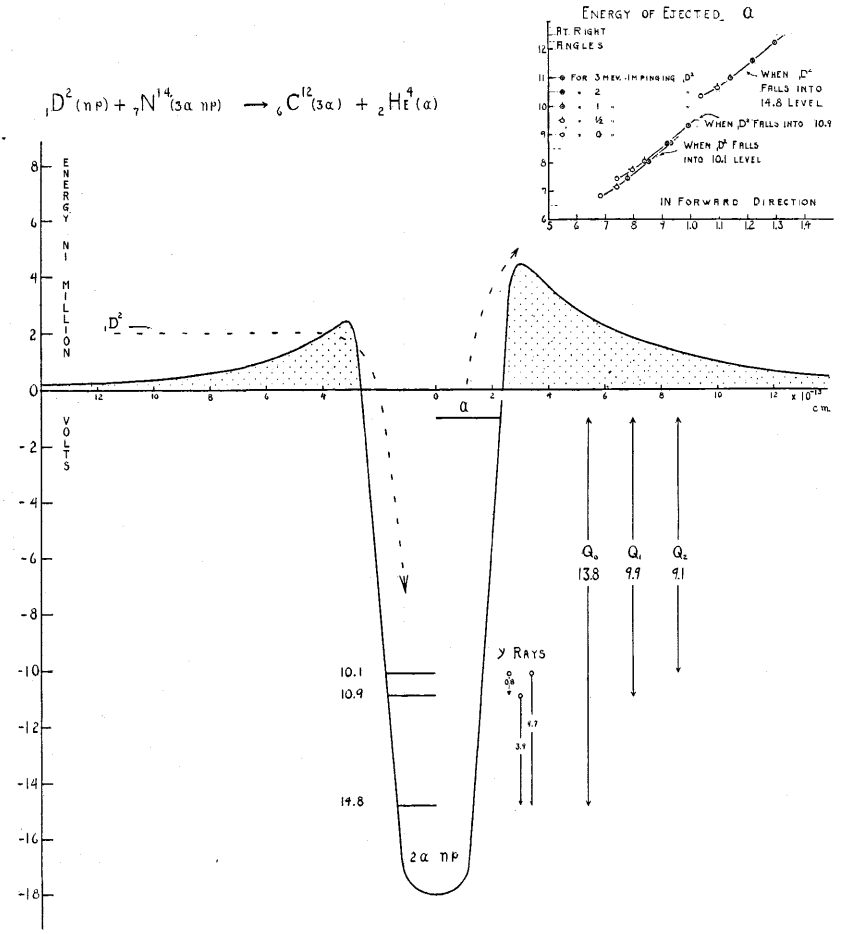

FIG. 4. Deuterons on Nitrogen.

alpha particles bombard boron, one can immediately see from the inset graph that there will be an eight-million-volt proton group if the alpha particles fall into the lowest level, or a 3.4-million-volt group if the alpha particles fall into the highest level. For protons emitted in the forward direction these two

numbers would be changed to 10.3 and 4.9, respectively. In general for a given alpha-particle energy, there are four proton groups emitted, since there are four levels into which the alpha particle may fall. The number in parentheses opposite each of these levels represents the relative chance that the alpha particle falls to that particular level.

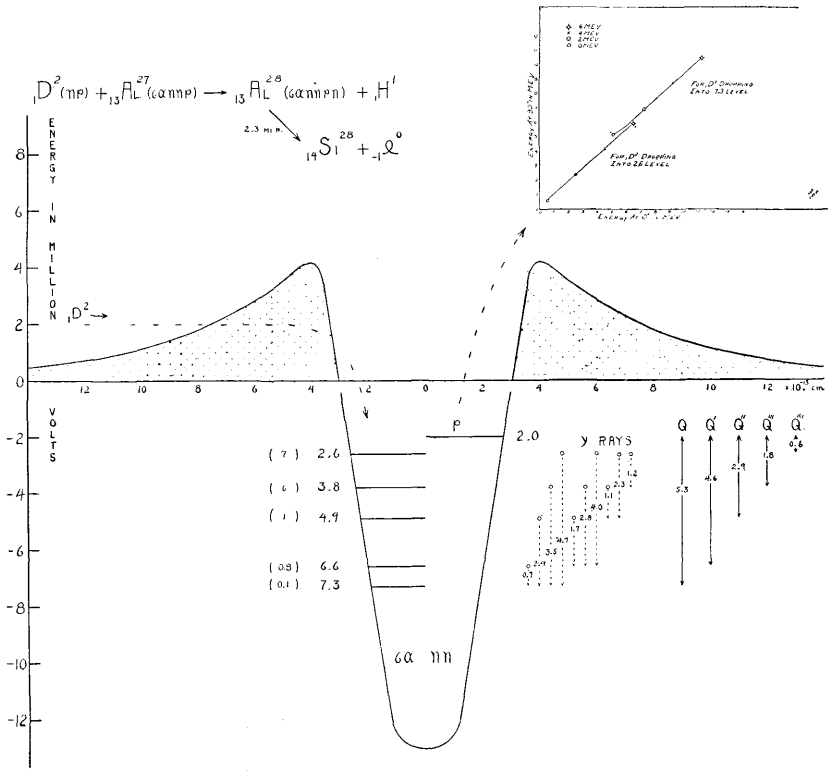

FIG. 5. Deuterons on Aluminum.

It seems to be true in this reaction as well as in most others that the impinging particle infrequently falls to the lowest level or ground level of the nucleus (10). When the alpha particle falls into a level other than the ground level the nucleus is thereby left in an excited state and later, perhaps in 10^{-20} sec., the alpha particle continues on down to the ground level. The energy difference is emitted as gamma ray. The possible gamma-ray energies are shown on the right side opposite the nuclear energy levels. In Fig. 1 all the transitions are dotted,

indicating that the expected gamma rays have not yet been observed. In some of the other figures gamma rays have been observed and are drawn in full line.

The true transmutation energy Q can be checked from the individual masses. For example, before transmutation

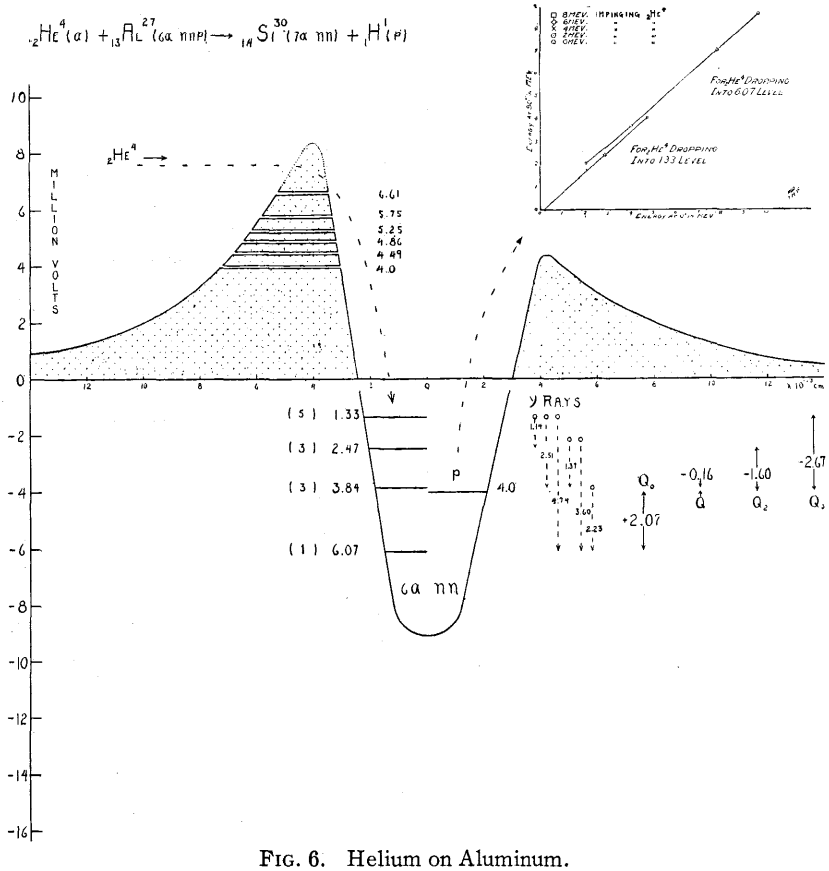

FIG. 6. Helium on Aluminum.

4.00336 + 10.0146 = 14.01796; after transmutation 13.0069 + 1.00807 = 14.01497. The decrease in mass is 0.00299. Using the Einstein mass-energy relation mentioned previously, this decrease in mass must now appear in the form of energy and in this case corresponds to 2.8 million volts of energy. This value is in only fair agreement with the observed energy gain of 3.1 million volts as shown by Q in the figure.

Only for alpha-particle bombardment does the potential barrier frequently exhibit a peculiar channeled structure. Through these channels (see also Fig. 6) the alpha particle

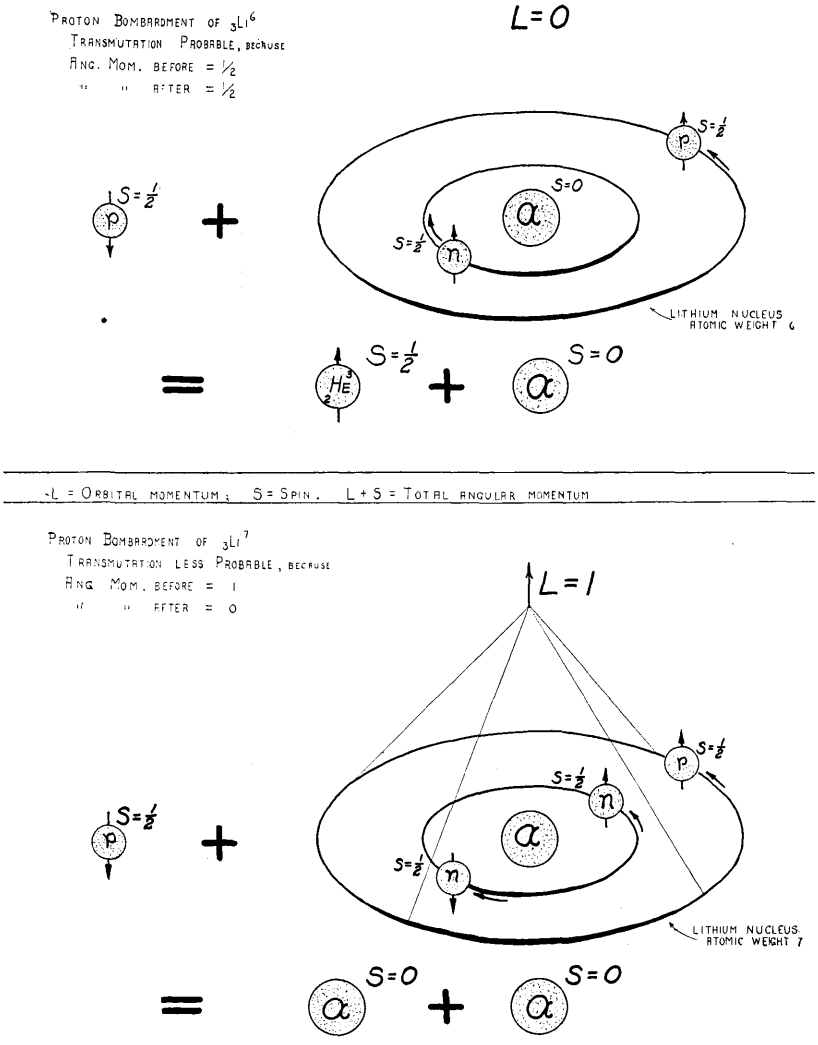

FIG. 7. Transmutation probabilities for protons on lithium 6, and on lithium 7.

seems to pass easily and the probability of a nuclear transmutation by alpha particles bombarding the nucleus with these particular energies is thereby greatly enhanced (11).

Fig. 2 shows the energy-level diagram (one of three) of an alpha particle itself and the large number of gamma rays observed (12). Notice how narrow and deep this nucleus is compared to the aluminum nucleus of Fig. 5.

NUCLEAR SPINS

So far we have used, although not explicitly expressed, three of the four conservation laws of nuclear physics. These laws are:

a). Conservation of electric charge.
b). Conservation of mass-energy.
c). Conservation of momentum.
d). Conservation of angular momentum.

The conservation of angular momentum is useful in explaining why some reactions are more probable than others (13). For example, consider Fig. 7 in which for proton bombardment the disintegration of lithium, atomic weight 6 (upper half of figure), is shown to be more probable than the disintegration of lithium, atomic weight 7 (lower half of figure). Assuming lithium, atomic weight 6, to consist of an alpha particle, a proton and neutron as shown, the total nuclear angular momentum is therefore $\frac{1}{2} + \frac{1}{2} = 1$. A proton with spin $\frac{1}{2}$ gives a resultant angular momentum before disintegration of $1 - \frac{1}{2} = \frac{1}{2}$, which is equal to the angular momentum after disintegration, $\frac{1}{2} + 0 = \frac{1}{2}$. This equality does not hold in the lower half of the figure, however, since before disintegration the total nuclear angular momentum is $(1 + \frac{1}{2} - \frac{1}{2} + \frac{1}{2}) - \frac{1}{2} = 1$ and after disintegration the angular momentum is $0 + 0 = 0$. The former reaction is about 30 times more probable than the latter. If sometimes, however, one of the alpha particles in the latter reaction is left in an excited state as indicated in Fig. 2, then the considerations just mentioned probably will not apply.

In closing, a word of caution should be said in regard to the tables and the figures presented here. They should not be read too closely or interpreted too literally because changes are being made from time to time in the data and in the interpretation of the data.

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