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RADIOACTIVE NUCLEI PRODUCTION FROM RELATIVELY ABUNDANT NATURAL ELEMENTS

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GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

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by
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INTRODUCTION

The function of this data is to furnish a guideline in evaluating potential radioactive nuclei production that could affect experiments or personnel in the Goddard Space Flight Center accelerator laboratory. The elements given in the table have been selected based upon the following criteria:

a. Theoretical reaction threshold energies less than 17.0 Mev.
b. Half-life time greater than 0.2 second.
c. Natural element abundance greater than 1%.

The use of the table is intended to serve accelerator personnel by estimating decay half-life for materials placed within the accelerator beam. The beam energy and particle type are taken into account for each material in determining if the reaction goes to completion. Since activation cross-section data is not provided, the table cannot provide reaction yields, it being a monumental task to obtain cross-section data for each threshold energy and particle type.

Since the cross-section data is not readily obtainable, it does not necessarily mean the particular reactions shown in Table II do or do not constitute a radiological hazard. The table shows that the potential reaction exists.

DEFINITION

The following list of definitions are headings as listed left to right in Table II.

Target Nuclide: The element bombarded by the accelerated beam. The superscript refers to the atomic weight. Most elements exist in the form of several isotopes - some radioactive, some stable.

Natural Abundance: The percentage of the particular isotope which is found in any sample of the element.

Radioactive Nuclei: The radioactive product formed when the accelerated beam interacts with the target nuclide.

Production Scheme: The method of interaction to form the radioactive product. The first symbol in parentheses names the accelerated beam particle which interacts with the target nuclide to yield the radioactive nuclei. The second symbol names the subatomic particle which is produced by the interaction in addition to the radioactive nuclei.

Decay Scheme: Defines the type of radiation produced by the radioactive nuclei during its decay. In some cases, there are multiple modes by which the radioactive nuclei may decay, and these are listed by their symbols.

Half-Life: The time required for one half of all the nuclei in a given sample to decay exponentially. The activity never reaches zero, but becomes very small after several half lives. For example, after ten half lives the activity has reduced to ~ 0.1% of the original amount.

Threshold Energy: The theoretical minimum energy in the center of mass, in million electron volts, an accelerated particle must have to interact with the target nucleus to produce a radioactive nucleus. In practice, the numbers quoted must be increased by 10% to 15% to give the corresponding laboratory energies. For example, light nuclei with heavy bombarding particles will have a large center of mass correction. Conversely heavy nuclei with light bombarding particles will have a small correction.

SYMBOLS

The following symbols are used in Table II:

α : alpha particle

β^- : electron emission

β^+ : positron emission

γ : Gamma ray or x-ray

∂ : deuteron (heavy hydrogen nucleus)

d : days (under half-life heading only)

e : electron

ex : exothermic (the accelerated particle does not need any energy to trigger the reaction) h : hours

IT : isometric transition (γ-ray emission)

K : K shell electron capture (γ-ray emission)

L : L shell electron capture (γ-ray emission)

m : minutes

Mev : million electron volts

n : neutron

p : proton

s : seconds

t : triton (double heavy hydrogen nucleus)

y : years

TABLE UTILIZATION

A typical example of using the tables would be in evaluating the activation hazard of a proton beam on an aluminum target. The relative hazard can be obtained as follows:

1. Find Al in Table I, note it is the seventh element listed in Table II.

2. Find Al as the seventh element in Table II.

3. Choose the correct atomic weight of the element. (Typically, the highest percent of the natural abundance.)

4. Seek the correct production scheme, in this case protons or the (p, n) reaction. Note that neutrons should be anticipated if the threshold voltage is reached.

5. Find the corresponding threshold energy and add 10% to be conservative. In our case, the final value would be about 6.1 Mev.

6. If the planned accelerated proton beam is to exceed 6.1 Mev, the resulting decay half-life is 4.4 seconds. This element should not constitute a hazard since in an accelerator run the element will decay typically before the accelerator voltage is reduced to ground potential.

Table I

ORDER OF TABLE II ELEMENT LISTING

1. Li	10. Ar	19. Ge
2. N	11. K	20. Zr
3. O	12. Ca	21. Sn
4. Ne	13. Ti	22. Sb
5. Na	14. Cr	23. Ta
6. Mg	15. Fe	24. Au
7. Al	16. Ni	25. Pb
8. Si	17. Cu	26. Th
9. P	18. Zn	27. U

Table II

TARGET NUCLIDE	NATURAL ABUNDANCE	RADIOACTIVE NUCLEI	PRODUCTION SCHEME	DECAY SCHEME	HALF LIFE	THRESHOLD ENERGY
Li^6	7.4%	${}_2He^6$	(n,p)	β^-	0.82 s	2.74
Li^6		${}_2He^6$	(e,γ)	β^-	0.82 s	ex
Li^6		${}_4Be^7$	(p,γ)	K	53.0 d	ex
Li^7	92.6%	${}_4Be^7$	(p,n)	K	53.0 d	1.66
Li^7		${}_3Li^8$	(n,γ)	$\beta^-, 2\alpha$	0.84 s	ex
Li^7		${}_4Be^{10}$	(t,γ)	β^-	2.7×10^6 y	ex
N^{14}	99.6%	${}_8O^{14}$	(p,n)	β^+, γ	72.0 s	5.97
N^{14}		${}_6C^{14}$	(n,p)	β^-	5730.0 y	ex
N^{14}		${}_7N^{13}$	(γ,n)	β^+	10.0 m	10.56
N^{14}		${}_8O^{15}$	(p,γ)	β^+	2.1 m	ex
N^{14}		${}_9F^{18}$	(α,γ)	β^+	1.87 h	ex
O^{16}	99.0%	${}_7N^{16}$	(n,p)	β^-, γ	7.4 s	9.60
O^{16}		${}_8O^{15}$	(γ,n)	β^+	2.1 m	15.60
O^{16}		${}_9F^{17}$	(p,γ)	β^+	66.0 s	ex
O^{16}		${}_9F^{18}$	(∂,γ)	β^+	1.87 h	ex
Ne^{20}	90.0%	${}_{11}Na^{20}$	(p,n)	β^+, α	0.3 s	16.2
Ne^{20}		${}_9F^{20}$	(n,p)	β^-, γ	11.0 s	6.25
Ne^{20}		${}_{10}Ne^{19}$	(γ,n)	β^+	18.5 s	16.92
Na^{23}	100.0%	${}_{12}Mg^{23}$	(p,n)	β^+, γ	12.0 s	4.89
Na^{23}		${}_{10}Ne^{23}$	(n,p)	β^-, γ	40.0 s	3.58
Na^{23}		${}_{10}Ne^{23}$	(e,γ)	β^-, γ	40.0 s	3.38
Na^{23}		${}_{11}Na^{24}$	(n,γ)	β^-, γ	15.0 h	ex
Mg^{24}	79.0%	${}_{13}Al^{24}$	(p,n)	β^+, γ	2.1 s	14.85
Mg^{24}		${}_{11}Na^{24}$	(n,p)	β^-, γ	15.0 h	4.71
Mg^{24}		${}_{12}Mg^{23}$	(γ,n)	β^+, γ	12.0 s	16.57
Mg^{24}		${}_{11}Na^{24}$	(e,γ)	β^-, γ	15.0 h	7.69
Mg^{24}		${}_{13}Al^{25}$	(p,γ)	β^+, γ	7.3 s	ex
Mg^{24}		${}_{13}Al^{26}$	(∂,γ)	$\beta^+; \beta^+, \gamma$	6.5 s; 10^6 y	ex
Mg^{25}	10.0%	${}_{13}Al^{25}$	(p,n)	β^+, γ	7.3 s	5.05
Mg^{25}		${}_{11}Na^{25}$	(n,p)	β^-, γ	60.0 s	2.92
Mg^{25}		${}_{11}Na^{24}$	(γ,p)	β^-, γ	15.0 h	12.07
Mg^{25}		${}_{11}Na^{25}$	(e,γ)	β^-, γ	60.0 s	3.22
Mg^{25}		${}_{13}Al^{26}$	(p,γ)	$\beta^+; \beta^+, \gamma$	6.5 s; 10^6 y	ex
Mg^{25}		${}_{13}Al^{28}$	(t,γ)	β^-, γ	2.3 m	ex
Mg^{26}	11.0%	${}_{11}Na^{25}$	(γ,p)	β^-, γ	1.0 m	14.07
Mg^{26}		${}_{13}Al^{26}$	(p,n)	β^+ β^+, γ	6.5 s 10^6 y	4.83
Mg^{26}		${}_{12}Mg^{27}$	(n,γ)	β^-, γ	9.5 m	ex
Mg^{26}		${}_{13}Al^{28}$	(∂,γ)	β^-, γ	2.3 m	ex
Mg^{26}		${}_{13}Al^{29}$	(t,γ)	β^-, γ	6.6 m	ex
Al^{27}	100.0%	${}_{14}Si^{27}$	(p,n)	β^+, γ	4.4 s	5.62
Al^{27}		${}_{12}Mg^{27}$	(n,p)	β^-, γ	9.5 m	1.79

Table II (Continued)

TARGET NUCLIDE	NATURAL ABUNDANCE	RADIOACTIVE NUCLEI	PRODUCTION SCHEME	DECAY SCHEME	HALF LIFE	THRESHOLD ENERGY
Al^{27}		$_{12}Mg^{27}$	(e,γ)	β^-,γ	9.5 m	2.18
Al^{27}		$_{13}Al^{28}$	(n,γ)	β^-,γ	2.3 m	ex
Si^{28}	92.0%	$_{15}P^{28}$	(p,n)	β^+,γ	0.28 s	14.55
Si^{28}		$_{13}Al^{28}$	(n,p)	β^-,γ	2.3 m	3.86
Si^{28}		$_{13}Al^{28}$	(e,γ)	β^-,γ	2.3 m	4.16
Si^{28}		$_{15}P^{29}$	(p,γ)	β^+,γ	4.5 s	ex
Si^{28}		$_{15}P^{30}$	(∂,γ)	β^+,γ	2.5 s	ex
Si^{29}	5.0%	$_{15}P^{29}$	(p,n)	β^+,γ	4.5 s	5.76
Si^{29}		$_{13}Al^{29}$	(n,p)	β^-,γ	6.6 m	1.95
Si^{29}		$_{13}Al^{28}$	(γ,p)	β^-,γ	2.3 m	12.35
Si^{29}		$_{13}Al^{29}$	(e,γ)	β^-,γ	6.6 m	3.40
Si^{29}		$_{15}P^{30}$	(p,γ)	β^+,γ	2.5 m	ex
Si^{29}		$_{15}P^{32}$	(t,γ)	β^-	14.5 d	ex
Si^{30}	3.0%	$_{15}P^{30}$	(p,n)	β^+,γ	2.5 m	5.12
Si^{30}		$_{13}Al^{29}$	(γ,p)	β^-,γ	6.6 m	13.79
Si^{30}		$_{14}Si^{31}$	(n,γ)	β^-,γ	2.6 h	ex
Si^{30}		$_{15}P^{32}$	(∂,γ)	β^-	14.5 d	ex
Si^{30}		$_{15}P^{33}$	(t,γ)	β^-	25.0 d	ex
P^{31}	100.0%	$_{16}S^{31}$	(p,n)	β^+,γ	2.6 s	6.24
P^{31}		$_{14}Si^{31}$	(n,p)	β^-,γ	2.6 h	0.68
P^{31}		$_{15}P^{30}$	(γ,n)	β^+,γ	2.5 m	12.40
Ar^{40}	99.6%	$_{19}K^{40}$	(p,n)	β^-; K	10^9 y	2.29
Ar^{40}		$_{18}Ar^{41}$	(n,p)	β^-,γ	1.82 h	cx
K^{39}	93.2%	$_{20}Ca^{39}$	(p,n)	β^+	1.0 s	7.61
K^{39}		$_{18}Ar^{39}$	(n,p)	β^-	260.0 y	ex
K^{39}		$_{19}K^{38}$	(γ,n)	$\beta^+;\beta^+,\gamma$	7.7 m ; 0.95 s	12.88
Ca^{40}	96.9%	$_{21}Sc^{40}$	(p,n)	β^+,γ	0.2 s	14.72
Ca^{40}		$_{19}K^{40}$	(n,p)	β^-; K	10^9 y	0.53
Ca^{40}		$_{19}K^{40}$	(e,γ)	β^-; K	10^9 y	0.83
Ca^{40}		$_{21}Sc^{41}$	(p,γ)	β^+	0.87 s	ex
Ca^{40}		$_{20}Ca^{41}$	(n,γ)	K	10^5 y	ex
Ca^{40}		$_{21}Sc^{42}$	(∂,γ)	$\beta^+,\gamma;\beta^+$	62.0 s ; 0.66 s	ex
Ca^{40}		$_{21}Sc^{43}$	(t,γ)	β^+,γ	3.9 h	ex
Ca^{40}		$_{22}Ti^{44}$	(α,γ)	K	10^3 y	ex
Ca^{42}	0.64%	$_{19}K^{42}$	(n,p)	β^-,γ	12.5 h	2.87
Ca^{42}		$_{19}K^{42}$	(e,γ)	β^-,γ	12.5 h	3.2
Ca^{42}		$_{21}Sc^{43}$	(p,γ)	β^+,γ	3.9 h	ex
Ca^{42}		$_{21}Sc^{44}$	(∂,γ)	IT ; β^+, K	2.4 d ; 4.0 h	ex
Ca^{44}	2.1%	$_{21}Sc^{44}$	(p,n)	IT ; β^+, K	2.4 d ; 4.0 h	4.45
Ca^{44}		$_{19}K^{44}$	(n,p)	β^-,γ	22.0 m	5.35
Ca^{44}		$_{19}K^{43}$	(γ,p)	β^-,γ	22.0 h	12.24
Ca^{44}		$_{19}K^{44}$	(e,γ)	β^-,γ	22.0 m	6.1

Table II (Continued)

TARGET NUCLIDE	NATURAL ABUNDANCE	RADIOACTIVE NUCLEI	PRODUCTION SCHEME	DECAY SCHEME	HALF LIFE	THRESHOLD ENERGY
Ca^{44}		$_{20}Ca^{45}$	(n,γ)	β^-	160.0 d	ex
Ca^{44}		$_{21}Sc^{46}$	(∂,γ)	IT, K; β^-, γ	20.0 s ; 85.0 d	ex
Ca^{44}		$_{21}Sc^{47}$	(t,γ)	β^-, γ	3.4 d	ex
Ti^{46}	8.0%	$_{23}V^{46}$	(p,n)	β^+	0.4 s	8.17
Ti^{46}		$_{21}Sc^{46}$	(n,p)	IT, K; β^-, γ	20.0 s ; 85.0 d	1.56
Ti^{46}		$_{22}Ti^{45}$	(γ,n)	β^+; K	3.1 h	13.4
Ti^{48}	74.0%	$_{23}V^{48}$	(p,n)	β^+; K	16.2 d	4.83
Ti^{48}		$_{21}Sc^{48}$	(n,p)	β^-, γ	44.0 h	3.24
Ti^{48}		$_{21}Sc^{47}$	(γ,p)	β^-, γ	82.0 h	11.4
Ti^{49}	5.5%	$_{23}V^{49}$	(p,n)	K (no γ)	1 y	1.41
Ti^{49}		$_{21}Sc^{49}$	(n,p)	β^-, γ	57.0 m	1.19
Ti^{49}		$_{21}Sc^{48}$	(γ,p)	β^-, γ	44.0 h	11.4
Ti^{50}	5.3%	$_{23}V^{50}$	(p,n)	—	10^{14} y	3.21
Ti^{50}		$_{21}Sc^{49}$	(γ,p)	β^-, γ	57.0 m	12.2
Cr^{50}	4.4%	$_{25}Mn^{50}$	(p,n)	IT, β^+; β^+	2.0 m ; 0.28 s	8.60
Cr^{50}		$_{23}V^{50}$	(n,p)	—	10^{14} y	0.60
Cr^{50}		$_{24}Cr^{49}$	(γ,n)	β^+, γ	42.0 m	13.2
Cr^{50}		$_{25}Mn^{51}$	(p,γ)	β^+, γ	45.0 m	ex
Cr^{50}		$_{24}Cr^{51}$	(n,γ)	K	27.0 d	ex
Cr^{50}		$_{25}Mn^{52}$	(∂,γ)	IT, β^+; K	21.0 m ; 57 d	ex
Cr^{50}		$_{25}Mn^{53}$	(t,γ)	K	140.0 y	ex
Cr^{52}	84.0%	$_{25}Mn^{52}$	(p,n)	IT, β^+; K	21.0 m ; 5.7 d	5.50
Cr^{52}		$_{23}V^{52}$	(n,p)	β^-, γ	3.8 m	3.10
Cr^{52}		$_{23}V^{52}$	(e,γ)	β^-, γ	3.8 m	3.40
Cr^{52}		$_{25}Mn^{53}$	(p,γ)	K (no γ)	10^6 y	ex
Cr^{52}		$_{25}Mn^{54}$	(∂,γ)	K	314 d	ex
Cr^{53}	9.5%	$_{25}Mn^{53}$	(p,n)	K (no γ)	10^6 y	1.40
Cr^{53}		$_{23}V^{52}$	(γ,p)	β^-, γ	3.8 m	11.1
Cr^{53}		$_{25}Mn^{54}$	(p,γ)	K	314 d	ex
Cr^{53}		$_{25}Mn^{56}$	(t,γ)	β^-, γ	2.6 h	ex
Cr^{54}	2.4%	$_{25}Mn^{54}$	(p,n)	K	314 d	2.00
Cr^{54}		$_{24}Cr^{55}$	(n,γ)	β^-	3.6 m	ex
Cr^{54}		$_{25}Mn^{56}$	(∂,γ)	β^-, γ	2.6 h	ex
Cr^{54}		$_{25}Mn^{57}$	(t,γ)	β^-, γ	1.7 m	ex
Fe^{54}	6.0%	$_{27}Co^{54}$	(p,n)	β^+	0.18 s	9.70
Fe^{54}		$_{25}Mn^{54}$	(n,p)	K	314 d	ex
Fe^{54}		$_{26}Fe^{53}$	(γ,n)	β^+, γ	9.0 m	13.6
Fe^{54}		$_{25}Mn^{54}$	(e,γ)	K	314 d	0.1
Fe^{54}		$_{27}Co^{55}$	(p,γ)	β^+, K	18.0 h	ex
Fe^{54}		$_{26}Fe^{55}$	(n,γ)	K (no γ)	2.9 y	ex
Fe^{54}		$_{27}Co^{56}$	(∂,γ)	K, β^+	77.0 d	ex
Fe^{54}		$_{27}Co^{57}$	(t,γ)	K	267.0 d	ex

Table II (Continued)

TARGET NUCLIDE	NATURAL ABUNDANCE	RADIOACTIVE NUCLEI	PRODUCTION SCHEME	DECAY SCHEME	HALF LIFE	THRESHOLD ENERGY
Fe^{56}	92.0%	$_{27}Co^{56}$	(p,n)	K , β^+	77.0 d	5.40
Fe^{56}		$_{25}Mn^{56}$	(n,p)	β^-, γ	2.6 h	2.90
Fe^{56}		$_{25}Mn^{56}$	(e,γ)	β^-, γ	2.6 h	3.20
Fe^{56}		$_{27}Co^{57}$	(p,γ)	K	267.0 d	ex
Fe^{56}		$_{27}Co^{58}$	(∂,γ)	IT ; β^+, K	9.0 h ; 71.0 d	ex
Fe^{57}	2.0%	$_{27}Co^{57}$	(p,n)	K	267.0 d	1.30
Fe^{57}		$_{25}Mn^{56}$	(γ,p)	β^-, γ	156.0 m	10.6
Fe^{57}		$_{27}Co^{58}$	(p,γ)	IT ; K , β^+	9.0 h ; 71.0 d	ex
Fe^{57}		$_{27}Co^{60}$	(t,γ)	β^-, γ	5.2 y	ex
Fe^{58}	0.3%	$_{27}Co^{58}$	(p,n)	IT ; K , β^+	9.0 h ; 71.0 d	3.10
Fe^{58}		$_{26}Fe^{59}$	(n,γ)	β^-, γ	45.0 d	ex
Fe^{58}		$_{27}Co^{60}$	(∂,γ)	β^-, γ	5.2 y	ex
Fe^{58}		$_{27}Co^{61}$	(t,γ)	β^-, γ	1.65 h	ex
Ni^{58}	68.0%	$_{29}Cu^{58}$	(p,n)	β^+, γ	3.2 s	10.80
Ni^{58}		$_{27}Co^{58}$	(n,p)	IT ; K , β^+	9.0 h ; 71.0 d	ex
Ni^{58}		$_{28}Ni^{57}$	(γ , n)	β^+; K	36.0 h	11.8
Ni^{58}		$_{27}Co^{58}$	(e,γ)	IT ; K, β^+	9.0 h ; 71.0 d	ex
Ni^{58}		$_{29}Cu^{59}$	(p,γ)	β^+, γ	81.0 s	ex
Ni^{58}		$_{28}Ni^{59}$	(n,γ)	K (no γ)	10^5 y	ex
Ni^{58}		$_{29}Cu^{60}$	(∂,γ)	β^+, γ	24.0 m	ex
Ni^{58}		$_{29}Cu^{61}$	(t,γ)	β^+, γ	3.3 h	ex
Ni^{58}		$_{30}Zn^{62}$	(α,γ)	K , β^+	9.0 h	ex
Ni^{60}	26.0%	$_{29}Cu^{60}$	(p,n)	β^+, γ	24.0 m	7.1
Ni^{60}		$_{27}Co^{60}$	(n,p)	β^-, γ	5.2 y	2.0
Ni^{60}		$_{27}Co^{60}$	(e,γ)	β^-, γ	5.2 y	0.80
Ni^{60}		$_{29}Cu^{61}$	(p,γ)	β^+, γ	3.3 h	ex
Ni^{60}		$_{29}Cu^{62}$	(∂,γ)	K , $\beta^\pm$	9.9 m	ex
Ni^{60}		$_{28}Ni^{59}$	(γ , n)	K (no γ)	10^5 y	ex
Ni^{61}	1.1%	$_{29}Cu^{61}$	(p,n)	β^+, γ	3.3 h	3.0
Ni^{61}		$_{27}Co^{61}$	(n,p)	β^-, γ	1.7 h	0.6
Ni^{61}		$_{27}Co^{61}$	(e,γ)	β^-, γ	1.7 h	2.40
Ni^{61}		$_{29}Cu^{62}$	(p,γ)	β^+, γ	9.9 m	ex
Ni^{61}		$_{27}Co^{60}$	(γ,p)	β^-, γ	5.2 y	ex
Ni^{62}	4.0%	$_{29}Cu^{62}$	(p,n)	β^+, γ	9.9 m	4.70
Ni^{62}		$_{27}Co^{62}$	(n,p)	β^-; β^-, γ	1.6 m ; 14.0 m	3.70
Ni^{62}		$_{27}Co^{61}$	(γ,p)	β^-, γ	96.0 m	11.0
Ni^{62}		$_{27}Co^{62}$	(e,γ)	β^-; β^-, γ	1.6 m ; 14.0 m	4.5
Ni^{62}		$_{28}Ni^{63}$	(n,γ)	β^-	80.0 y	ex
Ni^{62}		$_{29}Cu^{64}$	(∂,γ)	K , $\beta^\pm$	12.8 h	ex
Ni^{64}	1.0%	$_{29}Cu^{64}$	(p,n)	K , $\beta^\pm$	12.8 h	2.50
Ni^{64}		$_{28}Ni^{65}$	(n,γ)	β^-, γ	2.56 h	ex
Ni^{64}		$_{29}Cu^{66}$	(∂,γ)	β^-, γ	5.1 m	ex

Table II (Continued)

TARGET NUCLIDE	NATURAL ABUNDANCE	RADIOACTIVE NUCLEI	PRODUCTION SCHEME	DECAY SCHEME	HALF LIFE	THRESHOLD ENERGY
Ni^{64}		${}_{29}Cu^{67}$	(t,γ)	β^-,γ	61.0h	ex
Cu^{63}	69.0%	${}_{30}Zn^{63}$	(p,n)	β^+,γ	38.0m	4.20
Cu^{63}		${}_{28}Ni^{63}$	(n,p)	β^-,γ	92.0y	ex
Cu^{63}		${}_{29}Cu^{62}$	(γ,n)	β^+,γ	10.0m	10.6
Cu^{63}		${}_{28}Ni^{63}$	(e,γ)	β^-,γ	92.0y	ex
Cu^{63}		${}_{29}Cu^{64}$	(n,γ)	K, $\beta^\pm$	12.8h	ex
Cu^{63}		${}_{30}Zn^{65}$	(∂,γ)	K, β^+	245.0d	ex
Cu^{63}		${}_{31}Ga^{67}$	(α,γ)	β^+, K	78h	ex
Cu^{65}	31.0%	${}_{28}Ni^{65}$	(e,γ)	β^-,γ	2.6h	0.1
Cu^{65}		${}_{29}Cu^{66}$	(n,γ)	β^-,γ	5.1m	ex
Cu^{65}		${}_{30}Zn^{65}$	(p,n)	K, β^+	245.0d	2.15
Cu^{65}		${}_{28}Ni^{65}$	(n,p)	β^-,γ	2.6h	1.28
Cu^{65}		${}_{29}Cu^{65}$	(γ,n)	K, $\beta^\pm$	13.0h	9.8
Zn^{64}	49.0%	${}_{31}Ga^{64}$	(p,n)	β^+,γ	2.5m	8.1
Zn^{64}		${}_{29}Cu^{64}$	(n,p)	K, $\beta^\pm$	12.8h	ex
Zn^{64}		${}_{29}Cu^{64}$	(e,γ)	K, $\beta^\pm$	12.8h	0.5
Zn^{64}		${}_{31}Ga^{65}$	(p,γ)	IT, β^+, K	15.0m	ex
Zn^{64}		${}_{30}Zn^{65}$	(n,γ)	K, β^+	245.0d	ex
Zn^{64}		${}_{31}Ga^{66}$	(∂,γ)	β^+, K	9.4h	ex
Zn^{64}		${}_{31}Ga^{67}$	(t,γ)	K	78.0d	ex
Zn^{64}		${}_{30}Zn^{63}$	(γ,n)	β^+; K	38.0m	11.9
Zn^{66}	28.0%	${}_{31}Ga^{66}$	(p,n)	β^+; K	9.4h	6.0
Zn^{66}		${}_{29}Cu^{66}$	(n,p)	β^-,γ	5.1m	1.8
Zn^{66}		${}_{29}Cu^{66}$	(e,γ)	β^-,γ	5.1m	2.1
Zn^{66}		${}_{31}Ga^{67}$	(p,γ)	K	78.0h	ex
Zn^{66}		${}_{31}Ga^{68}$	(∂,γ)	β^+, K	68.0m	ex
Zn^{67}	4.0%	${}_{31}Ga^{67}$	(p,n)	K	28.0h	1.9
Zn^{67}		${}_{29}Cu^{67}$	(n,p)	β^-,γ	61.0h	ex
Zn^{67}		${}_{29}Cu^{67}$	(e,γ)	β^-,γ	61.0h	0.1
Zn^{67}		${}_{31}Ga^{68}$	(p,γ)	β^+; K	68.0m	ex
Zn^{67}		${}_{31}Ga^{70}$	(t,γ)	β^-,γ	21.0m	ex
Zn^{67}		${}_{32}Ge^{71}$	(α,γ)	K	12.0d	ex
Zn^{67}		${}_{29}Cu^{66}$	(γ,p)	β^-,γ	5.1m	8.9
Zn^{68}	19.0%	${}_{31}Ga^{70}$	(p,n)	β^+; K	68.0m	3.70
Zn^{68}		${}_{29}Cu^{67}$	(γ,p)	β^-,γ	61.0h	9.4
Zn^{68}		${}_{30}Zn^{69}$	(n,γ)	IT; β^-	14.0h; 52.0m	ex
Zn^{68}		${}_{31}Ga^{70}$	(∂,γ)	β^-,γ	21.0m	ex
Zn^{70}	0.6%	${}_{31}Ga^{70}$	(p,n)	β^-,γ	21.0m	1.40
Zn^{70}		${}_{30}Zn^{71}$	(n,γ)	β^-,γ; β^-,γ	3.0h; 2.5m	ex
Zn^{70}		${}_{31}Ga^{72}$	(∂,γ)	β^-,γ	14.1h	ex
Zn^{70}		${}_{31}Ga^{73}$	(t,γ)	β^-,γ	5.0h	ex
Ge^{70}	21.0%	${}_{31}Ga^{70}$	(n,p)	β^-,γ	21.0m	0.8

Table II (Continued)

TARGET NUCLIDE	NATURAL ABUNDANCE	RADIOACTIVE NUCLEI	PRODUCTION SCHEME	DECAY SCHEME	HALF LIFE	THRESHOLD ENERGY
Ge^{70}		$_{31}Ga^{70}$	(e, γ)	β^-, γ	21.0 m	1.1
Ge^{70}		$_{33}As^{71}$	(p, γ)	β^+, γ	62.0 h	ex
Ge^{70}		$_{32}Ge^{71}$	(n, γ)	K	12.0 d	ex
Ge^{70}		$_{33}As^{72}$	(∂, γ)	β^+, γ	26.0 h	ex
Ge^{70}		$_{33}As^{73}$	(t, γ)	K	76.0 d	ex
Ge^{72}	27.0%	$_{33}As^{72}$	(p, n)	β^+, γ	26.0 h	5.20
Ge^{72}		$_{31}Ga^{72}$	(n, p)	β^-, γ	14.1 h	3.20
Ge^{72}		$_{31}Ga^{72}$	(e, γ)	β^-, γ	14.1 h	3.50
Ge^{72}		$_{33}As^{73}$	(p, γ)	K	76.0 d	ex
Ge^{72}		$_{33}As^{74}$	(∂, γ)	IT; K , $\beta^\pm$	8.0 s ; 18.0 d	ex
Ge^{73}	7.8%	$_{33}As^{73}$	(p, n)	K	76.0 d	1.20
Ge^{73}		$_{31}Ga^{73}$	(n, p)	β^-, γ	5.0 h	0.6
Ge^{73}		$_{31}Ga^{73}$	(e, γ)	β^-, γ	5.0 h	0.6
Ge^{73}		$_{33}As^{74}$	(p, γ)	IT; K , $\beta^\pm$	8.0 s ; 18.0 d	ex
Ge^{73}		$_{33}As^{76}$	(t, γ)	β^-, γ	26.7 h	ex
Ge^{74}	36.5%	$_{33}As^{74}$	(p, n)	IT; K , $\beta^\pm$	8.0 s ; 18.0 d	3.4
Ge^{74}		$_{32}Ge^{75}$	(n, γ)	IT ; β^-, γ	49.0 s ; 82.0 m	ex
Ge^{74}		$_{33}As^{76}$	(∂, γ)	β^-, γ	26.7 h	ex
Ge^{74}		$_{33}As^{77}$	(t, γ)	β^-, γ	39.0 h	ex
Ge^{76}	7.8%	$_{33}As^{76}$	(p, n)	β^-, γ	26.7 h	1.90
Ge^{76}		$_{33}As^{77}$	(p, γ)	β^-, γ	39.0 h	ex
Ge^{76}		$_{32}Ge^{77}$	(n, γ)	IT, $\beta^-, \gamma; \beta^-, \gamma$	52.0 s ; 12.0 h	ex
Ge^{76}		$_{33}As^{78}$	(∂, γ)	IT; β^-, γ	6.0 m ; 90.0 m	ex
Ge^{76}		$_{33}As^{79}$	(t, γ)	β^-, γ	9.0 m	ex
Zr^{90}	52.0%	$_{41}Nb^{90}$	(p, n)	IT ; β^+, γ	24.0 s ; 14.6 h	5.20
Zr^{90}		$_{39}Y^{90}$	(n, p)	IT ; β^+, γ	3.2 h ; 64.2 h	1.40
Zr^{90}		$_{39}Y^{90}$	(e, γ)	IT ; β^+, γ	3.2 h ; 64.2 h	2.0
Zr^{90}		$_{41}Nb^{91}$	(p, γ)	IT , K ; K	62.0 d ; long	ex
Zr^{90}		$_{41}Nb^{92}$	(∂, γ)	K	10.1 d	ex
Zr^{91}	11.0%	$_{41}Nb^{91}$	(p, n)	IT, K ; K	62.0 d ; long	2.20
Zr^{91}		$_{39}Y^{91}$	(n, p)	IT ; β^-, γ	50.0 m ; 58.0 d	0.70
Zr^{91}		$_{39}Y^{91}$	(e, γ)	IT ; β^-, γ	50.0 m ; 58.0 d	1.0
Zr^{91}		$_{41}Nb^{92}$	(p, γ)	K	10.1 d	ex
Zr^{91}		$_{41}Nb^{94}$	(t, γ)	IT, $\beta^-, \gamma; \beta^-, \gamma$	6.6 m , 10^4 y	ex
Zr^{92}	17.1%	$_{41}Nb^{92}$	(p, n)	K	10.1 y	2.50
Zr^{92}		$_{39}Y^{92}$	(n, p)	β^-, γ	3.5 h	2.70
Zr^{92}		$_{39}Y^{92}$	(e, γ)	β^-, γ	3.5 h	3.0
Zr^{92}		$_{40}Zr^{93}$	(n, γ)	β^-, γ	10^6 y	ex
Zr^{92}		$_{41}Nb^{94}$	(∂, γ)	IT, $\beta^-, \gamma; \beta^-, \gamma$	6.6 m ; 10^4 y	ex
Zr^{92}		$_{41}Nb^{94}$	(t, γ)	IT, $\beta^-, \gamma; \beta^-, \gamma$	6.6 m ; 10^4 y	ex
Zr^{94}	17.4%	$_{41}Nb^{94}$	(p, n)	IT, $\beta^-, \gamma; \beta^-, \gamma$	6.6 m ; 10^4 y	1.50
Zr^{94}		$_{39}Y^{94}$	(n, p)	β^-, γ	20.0 m	4.60

Table II (Continued)

TARGET NUCLIDE	NATURAL ABUNDANCE	RADIOACTIVE NUCLEI	PRODUCTION SCHEME	DECAY SCHEME	HALF LIFE	THRESHOLD ENERGY
Zr^{94}		$_{39}Y^{94}$	(e,γ)	β^-,γ	20.0 m	4.90
Zr^{94}		$_{41}Nb^{95}$	(p,γ)	IT ; β^-,γ	90.0 n ; 35.0 d	ex
Zr^{94}		$_{40}Zr^{95}$	(n,γ)	β^-,γ	65.0 d	ex
Zr^{94}		$_{41}Nb^{96}$	(∂,γ)	β^-,γ	23.0 h	ex
Zr^{94}		$_{41}Nb^{97}$	(t,γ)	IT ; β^-,γ	1.0 m ; 72.0 m	ex
Zr^{96}	3.0%	$_{41}Nb^{96}$	(p,n)	β^-,γ	23.0 h	0.50
Zr^{96}		$_{41}Nb^{97}$	(p,γ)	IT ; β^-,γ	1.0 m ; 72.0 h	ex
Zr^{96}		$_{40}Zr^{97}$	(n,γ)	β^-,γ	17.0 h	ex
Sn^{112}	1.0%	$_{49}In^{112}$	(e,γ)	IT IT K , $\beta^\pm$	0.04 s 21.0 m 14.0 m	ex
Sn^{112}		$_{49}In^{112}$	(n,p)	IT IT K , $\beta^\pm$	0.04 s 21.0 m 14.0 m	ex
Sn^{116}		$_{49}In^{116}$	(e,γ)	IT; β^-,γ β^-,γ	2.2 s ; 54.0 m 14.0 s	2.8
Sn^{116}	14.3%	$_{51}Sb^{118}$	(∂,γ)	β^+, K K	3.5 m 5.1 h	ex
Sn^{116}		$_{51}Sb^{119}$	(t,γ)	K	38.0 h	ex
Sn^{116}		$_{51}Sb^{116}$	(p,n)	β^+,K β^+, K	60.0 m 15.0 m	5.50
Sn^{116}		$_{49}In^{116}$	(n,p)	IT; β^-,γ β^-,γ	2.2 s ; 54.0 m 14.0 s	2.50
Sn^{117}	7.6%	$_{49}In^{117}$	(e,γ)	β^- , IT β^-,γ	1.9 h 45.0 m	1.00
Sn^{117}		$_{51}Sb^{118}$	(p,γ)	β^+, K K	3.5 m 5.1 h	ex
Sn^{117}		$_{51}Sb^{119}$	(∂,γ)	K	38.0 h	ex
Sn^{117}		$_{51}Sb^{120}$	(t,γ)	K β^+,K	5.8 d 17.0 m	ex
Sn^{117}		$_{49}In^{117}$	(n,p)	β^- , IT β^-,γ	1.9 h 45.0 m	0.70
Sn^{118}	24.0%	$_{51}Sb^{120}$	(∂,γ)	K β^+,K	5.8 d 17.0 m	ex
Sn^{118}		$_{51}Sb^{118}$	(p,n)	β^+, K K	3.5 m 5.1 h	4.90
Sn^{119}	8.5%	$_{51}Sb^{120}$	(p,γ)	K β^+,K	5.8 d 17.0 m	ex
Sn^{119}		$_{51}Sb^{122}$	(t,γ)	IT $\beta^\pm$, K	3.5 m 2.8 d	ex
Sn^{120}	32.5%	$_{50}Sn^{121}$	(n,γ)	β^-,γ β^-	25.0 y 27.0 h	ex
Sn^{120}		$_{51}Sb^{122}$	(∂,γ)	IT K , $\beta^\pm$	3.5 m 2.8 d	ex
Sn^{120}		$_{51}Sb^{120}$	(p,n)	K β^+,K	5.8 d 17.0 m	3.50
Sn^{122}	4.8	$_{50}Sn^{123}$	(n,γ)	β^-,γ β^-,γ	130.0 d 40.0 m	ex

Table II (Continued)

TARGET NUCLIDE	NATURAL ABUNDANCE	RADIOACTIVE NUCLEI	PRODUCTION SCHEME	DECAY SCHEME	HALF LIFE	THRESHOLD ENERGY
Sn^{122}		$_{51}Sb^{124}$	(∂, γ)	IT β^-, γ β^-, γ	21.0 m 1.3 m 60.0 d	ex
Sn^{122}		$_{51}Sb^{125}$	(t, γ)	β^-, γ	2.7 y	ex
Sn^{122}		$_{51}Sb^{122}$	(p, n)	IT K , $\beta^{\pm}, \gamma$	3.5 m 2.8 d	2.30
Sn^{124}	6.1%	$_{51}Sb^{125}$	(p, γ)	β^-, γ	2.7 y	ex
Sn^{124}		$_{50}Sn^{125}$	(n, γ)	β^-, γ β^-, γ	9.5 m 10.0 d	ex
Sn^{124}		$_{51}Sb^{126}$	(∂, γ)	β^-, γ ; β^-, γ	19.0 m ; 12.5 d	ex ?
Sn^{124}		$_{51}Sb^{127}$	(t, γ)	β^-, γ	93.0 h	ex ?
Sn^{124}		$_{51}Sb^{124}$	(p, n)	IT β^-, γ β^-, γ	21.0 m 1.3 m 60.0 d	1.40
Sn^{124}		$_{50}Sn^{123}$	(γ, n)	β^-, γ β^-, γ	130.0 d 40.0 m	8.4
Sb^{121}	57.0%	$_{50}Sn^{121}$	(γ, n)	β^-, γ β^-, γ	25.0 y 27.0 h	ex
Sb^{121}		$_{51}Sb^{120}$	(γ, n)	K β^+, K	5.8 d 17.0 m	9.3
Sb^{123}	43.0%	$_{50}Sn^{123}$	(e, γ)	β^-, γ β^-, γ	130.0 d 40.0 m	0.9
Sb^{123}		$_{51}Sb^{124}$	(n, γ)	IT β^-, γ β^-, γ	21.0 m 1.3 m 60.0 d	ex
Sb^{123}		$_{50}Sn^{123}$	(n, p)	β^-, γ β^-, γ	130.0 d 40.0 m	0.6
Ta^{181}	99.99%	$_{72}Hf^{181}$	(n, p)	β^-, γ	46.0 d	0.20
Ta^{181}		$_{73}Ta^{180}$	(γ, n)	β^- K	8.0 h	7.7
Au^{197}	100.0%	$_{78}Pt^{197}$	(n, p)	IT ; β^-, γ β^-, γ	2.8 h ; 82.0 m 19.0 h	0.00
Au^{197}		$_{78}Pt^{197}$	(e, γ)	IT ; β^-, γ β^-, γ	2.8 h ; 82.0 m 19.0 h	0.30
Au^{197}		$_{79}Au^{198}$	(n, γ)	β^-, γ	2.7 d	ex
Au^{197}		$_{81}Tl^{201}$	(α, γ)	K	3.0 d	ex ?
Pb^{204}	1.3%	$_{81}Tl^{204}$	(e, γ)	β^- , K	4.1 y	0.30
Pb^{204}		$_{82}Pb^{205}$	(n, γ)	K	3×10^7 y	ex
Pb^{204}		$_{83}Bi^{206}$	(∂, γ)	K	6.4 d	ex
Pb^{204}		$_{83}Bi^{207}$	(t, γ)	K , L	30.0 y	ex
Pb^{204}		$_{84}Po^{208}$	(α, γ)	α , γ	2.9 y	5.19
Pb^{204}		$_{81}Tl^{204}$	(n, p)	β^- , K	4.1 y	0.0
Pb^{206}	26.0%	$_{81}Tl^{206}$	(e, γ)	β^-	4.2 m	1.02
Pb^{206}		$_{83}Bi^{207}$	(p, γ)	K , L	30.0 y	ex
Pb^{206}		$_{84}Po^{210}$	(α, γ)	α , γ	138.0 d	5.41
Pb^{206}		$_{83}Bi^{206}$	(p, n)	K	6.4 d	4.35
Pb^{206}		$_{81}Tl^{206}$	(n, p)	β^-	4.2 m	0.72

Table II (Continued)

TARGET NUCLIDE	NATURAL ABUNDANCE	RADIOACTIVE NUCLEI	PRODUCTION SCHEME	DECAY SCHEME	HALF LIFE	THRESHOLD ENERGY
Pb^{207}	21.0%	$_{83}Bi^{207}$	(p,n)	K	30.0 y	3.20
Pb^{207}		$_{81}Tl^{207}$	(n,p)	β^-, γ	4.8 m	0.65
Pb^{207}		$_{81}Tl^{206}$	(γ, p)	β^-	4.2 m	7.5
Pb^{208}	52.0%	$_{81}Tl^{207}$	(γ, p)	β^-, γ	4.8 m	8.0
Pb^{208}		$_{83}Bi^{208}$	(p,n)	K , L	3.7×10^5 y	3.73
Pb^{208}		$_{81}Tl^{208}$	(n,p)	β^-, γ	3.1 m	4.20
Th^{232}	100.0%	$_{91}Pa^{232}$	(p,n)	β^-, γ	1.3 d	1.16
Th^{232}		$_{90}Th^{231}$	(γ, n)	β^-, γ	26.0 h	6.4
U^{238}	99.3%	$_{93}Nb^{238}$	(p,n)	β^-, γ	2.1 d	0.90
U^{238}		$_{91}Pa^{237}$	(γ, p)	β^-, γ	39.0 m	7.5

ADDITIONAL REFERENCES TO OBTAIN NUCLEAR DATA:

1. National Bureau of Standards
   Circular #499 - Nuclear Data
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2. Table of Isotopes
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