(Nuclei + radioactivity)

Nuclear physics

[Hand out copies of nuclide chart from Bleth]

Z = atomic # = # of protons ⇒ charge of nucleus, identity of element

N = neutron # = # of neutrons ⇒ different isotopes

(1913: JJ Thomson: ^{20}Ne, ^{22}Ne)

▨ = stable, □ = unstable

[Some elements have several stable isotopes, some only one (Be)
and some have none
$Z = 43$, Tc made in cyclotron by bombarding Mo
$Z = 61$, Pm found in products of uranium fission
These were gaps in the periodic table of Mendeleev]

[Generally we characterize isotopes not by N but by]

$A = Z + N$ = mass # = # of nucleons = baryon #

Symbol $^{A}_{Z}X$

↑ redundant

[Let's look at bottom of table]

n [unstable: $T_{\frac{1}{2}} = ?$]

^{1}H, ^{2}H = heavy hydrogen = deuterium (0.015%)

^{3}H = tritium ($T_{\frac{1}{2}} \sim 12$ yrs)

^{3}He (0.0001 4%), ^{4}He

^{12}C, ^{13}C (~1%), ^{14}C ($T_{\frac{1}{2}} \sim 5730$ yrs ⇒ dating)

□· = naturally-occurring unstable ($T_{\frac{1}{2}} \sim$ billions of yrs)

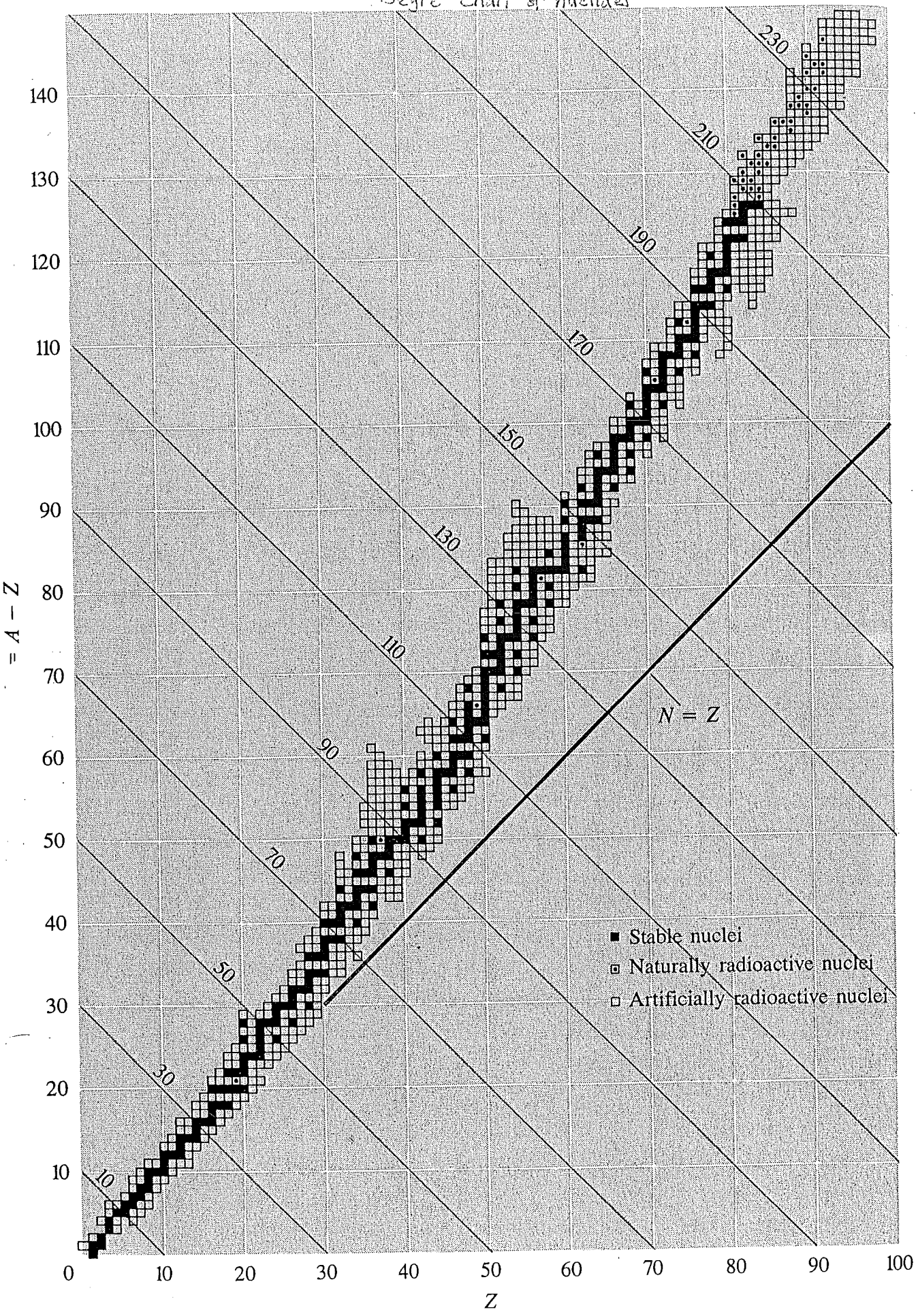
$^{40}_{19}K$ [intro II lab] $T_{\frac{1}{2}} = 1.3E9$ yrs

$^{87}_{37}Rb$ [earth dating] $T_{\frac{1}{2}} = 5E10$ yrs

$^{238}_{92}U$, $^{235}_{92}U$ (0.72%), $^{234}_{92}U$ (0.0055%) (heaviest naturally occurring)

$_{92}Pb$ = heaviest unstable, $^{209}_{93}Bi$ ($T_{\frac{1}{2}} = 2E19$ yrs) [2003 wikipedia], $^{210}_{94}Po$ unstable ($T_{\frac{1}{2}} = 140$ d)

Segré chart of nuclides



20
10
0
10
30
10

Line of stability

$Z \approx N$ for light nuclei

$Z > N$ for heavier

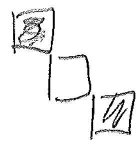
Why?

Why no stable nuclei beyond Pb?

Even-even nuclei more stable & ∴ more abundant [table]
(majority of stable nuclei: about 150 out of 250 are even-even though we'd expect 1/4)

Odd-odd nuclei less stable & ∴ rarer (∃ only 4!: ^2H, ^6Li, ^{10}B, ^{14}N, ..)
4n pos Fill Better Marrow

odd-even in middle

eg  At A = 50, 70

proton pair up w/ protons } ⇒ spin 0 state
neutrons pair up w/ neutrons }

Some even numbers of p & n are particularly stable

magic #s = 2, 8, 20, 28, 50, 82, 126

[look at Z = 50 relative to 49 & 51
Z = 20
Also N = 20 relative to 19 & 21]

Doubly magic nuclei ^4He = 2p + 2n
^{16}O = 8p + 8n
^{208}Pb = 82p + 126n

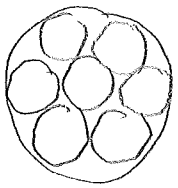
Radius of nuclei

Various experiments show that $R \propto A^{1/3}$

$$R = A^{1/3} r_0 \quad \text{where} \quad r_0 \cong 1.2 \times 10^{-15}\ m = 1.2\ fm$$

$$\text{Volume} = \frac{4}{3}\pi R^3 = \left(\frac{4}{3}\pi r_0^3\right) A$$

Nuclei act as a collection of close-packed nucleons of fixed volume



mass of nuclei

$m_p \approx m_n \approx 1\ u$

$\Rightarrow M \approx Z + N = A$

Recall $1\ u \Rightarrow 931.5\ MeV$

$E_{rest} = A\,(931.5\ MeV) + \Delta$ ← atomic mass, we include electrons to make atom neutral

Δ = "mass excess"

$\Delta \equiv 0$ for ^{12}C

$\Rightarrow M = A + \dfrac{\Delta}{(931.5\ MeV)}$

[Hand out nuclear wallet cards and curve of binding energy]

neutron: $E = 939.6\ MeV \Rightarrow \Delta = 8.1\ MeV$ [check]

proton $E = 938.3\ MeV$
electron $E = 0.5\ MeV$

^1H $E = 938.8\ MeV \Rightarrow \Delta = 7.3\ MeV$ => check

(neglect 13.6 eV!)

Isotope Z	El	A	Jπ	Δ (MeV)	T1/2 or Abundance	Decay Mode
0	n	1	1/2+	8.071	10.4 m *2*	β-
1	H	1	1/2+	7.289	99.985% *1*	
		2	1+	13.136	0.015% *1*	
		3	1/2+	14.950	12.33 y *6*	β-
		4?	2-	25.840		
2	He	3	1/2+	14.931	0.000137% *3*	
		4	0+	2.424	99.999863% *3*	
		5	3/2-	11.390	0.60 MeV *2*	α, n
		6	0+	17.592	806.7 ms *15*	β-
		7	(3/2)-	26.110	160 keV *30*	n
		8	0+	31.598	119.0 ms *15*	β-, β-n 16%
		9		40.810	very short	n
3	Li	4	2-	25.120		
		5	3/2-	11.680	≈1.5 MeV	α, p
		6	1+	14.085	7.5% *2*	
		7	3/2-	14.907	92.5% *2*	
		8	2+	20.945	838 ms *6*	β-, β-2α
		9	3/2-	24.954	178.3 ms *4*	β-, β-n 49.5%, β-n2α
		10		33.840	1.2 MeV *3*	n
		11	(1/2-)	40.900	8.7 ms *1*	β-, β-n, β-nα 0.027%
4	Be	6	0+	18.374	92 keV *6*	α, 2p
		7	3/2-	15.768	53.29 d *7*	ε
		8	0+	4.941	6.8 eV *17*	2α
		9	3/2-	11.347	100%	
		10	0+	12.607	1.51×10^{6} y *6*	β-
		11	1/2+	20.174	13.81 s *8*	β-, β-α 3.1%
		12	0+	25.077	24.4 ms *30*	β-, β-n<1%
		13	(1/2,5/2)+	35.000		n
		14	0+	40.100	4.2 ms *7*	β-
5	B	7	(3/2-)	27.870	1.4 MeV *2*	p, α
		8	2+	22.920	770 ms *3*	ε, εα, ε2α
		9	3/2-	12.415	0.54 keV *21*	p, 2α
		10	3+	12.050	19.9% *2*	
		11	3/2-	8.668	80.1% *2*	
		12	1+	13.369	20.20 ms *2*	β-, β-3α 1.58%
		13	3/2-	16.562	17.36 ms *16*	β-, β-n 0.28%
		14	2-	23.664	16.1 ms *12*	β-
		15		28.970	8.8 ms *6*	β-, β-n
		16	(0-)	37.140s		n
		17	(3/2-)	43.310s		β-
		18		52.280s		
		19		59.360s		
6	C	8	0+	35.094	230 keV *50*	α, p
		9	(3/2-)	28.913	126.5 ms *9*	ε, εp, ε2α
		10	0+	15.699	19.255 s *53*	ε
		11	3/2-	10.650	20.385 m *20*	ε
		12	0+		98.90% *3*	
		13	1/2-	3.125	1.10% *3*	
		14	0+	3.020	5730 y *40*	β-
		15	1/2+	9.873	2.449 s *5*	β-
		16	0+	13.694	0.747 s *8*	β-, β-n≥98.8%

Isotope Z	El	A	Jπ	Δ (MeV)	T1/2 or Abundance	Decay Mode
10	Ne	25	(1/2,3/2)+	-2.060	602 ms *8*	β-
		26	0+	0.440	230 ms *60*	β-
		27		6.960e		
		28	0+	11.000e		
11	Na	18		25.320s		p
		19		12.928	0.03 s *?*	p
		20	2+	6.839	447.9 ms *23*	ε, εα 21%
		21	3/2+	-2.189	22.48 s *3*	ε
		22	3+	-5.185	2.6088 y *14*	ε
		23	3/2+	-9.532	100%	
		24	4+	-8.420	14.9590 h *12*	β-
		24m	1+	-7.948	20.20 ms *7*	IT, β-≈0.05%
		25	5/2+	-9.360	59.1 s *6*	β-
		26	3+	-6.904	1.072 s *9*	β-
		27	5/2+	-5.650e	301 ms *6*	β-, β-n 0.13%
		28	1+	-1.140	30.5 ms *4*	β-, β-n 0.58%
		29	3/2	2.650	44.9 ms *12*	β-, β-n 22%
		30	2+	8.330e	48 ms *2*	β-, β-n 30%, β-2n 1.17%, β-α 0.0055%
		31	(3/2)	12.010e	17.0 ms *4*	β-, β-n 37%, β-2n 0.9%
		32		16.550	13.2 ms *4*	β-, β-n 39%, β-2n 1.2%
		33		21.470	8.2 ms *4*	β-, β-n 52%, β-2n 12%
		34		26.650	5.5 ms *10*	β-, β-n, β-2n
		35			1.5 ms *5*	β-, β-n
12	Mg	20	0+	17.570	0.1 s	ε, εp
		21	(3/2,5/2)+	10.913	122 ms *3*	ε, εp 32%
		22	0+	-0.397	3.857 s *9*	ε
		23	3/2+	-5.473	11.317 s *11*	ε
		24	0+	-13.933	78.99% *3*	
		25	5/2+	-13.192	10.00% *1*	
		26	0+	-16.214	11.01% *2*	
		27	1/2+	-14.586	9.462 m *11*	β-
		28	0+	-15.019	20.91 h *3*	β-
		29	3/2+	-10.728e	1.30 s *12*	β-
		30	0+	-9.070e	335 ms *17*	β-
		31		-3.400e	0.23 s *2*	β-
		32	0+	-0.790e	120 ms *20*	β-, β-n 2.4%
		33		5.090e	90 ms *20*	β-, β-n 17%
		34	0+	8.440s	20 ms *10*	β-, β-n
		35		14.680s		
13	Al	22		18.040e	70 ms *46*	ε, εp, ε2p
		23		6.767	0.47 s *3*	ε, εp
		24	4+	-0.055	2.053 s *4*	ε, εα 0.035%
		24m	1+	0.371	131.3 ms *25*	IT 82%, ε 18%, εα 0.026%
		25	5/2+	-8.915	7.183 s *12*	ε
		26	5+	-12.210	7.4×10^{5} y *3*	ε
		26m	0+	-11.982	6.3452 s *19*	ε
		27	5/2+	-17.197	100%	
		28	3+	-16.851	2.2414 m *12*	β-

Isotope Z	El	A	Jπ	Δ (MeV)	T1/2 or Abundance	Decay Mode
6	C	17		21.035	202 ms *17*	β-
		18	0+	24.920	66 ms *20*	β-, β-n
		19		32.630s		
		20	0+	37.070s		β-
7	N	10		39.700s		
		11	1/2-	24.890	0.74 MeV *10*	p
		12	1+	17.338	11.000 ms *16*	ε, ε3α 3.44%
		13	1/2-	5.345	9.965 m *4*	ε
		14	1+	2.863	99.63% *2*	
		15	1/2-	0.101	0.37% *2*	
		16	2-	5.682	7.13 s *2*	β-, β-α 0.0012%
		17	1/2-	7.871	4.173 s *4*	β-, β-n 95%
		18	1-	13.117	624 ms *12*	β-, β-n, β-α
		19		15.871	290 ms *90*	β-, β-n
		20		21.880s	100 ms *25*	β-, β-n
		21		25.150s	95 ms *13*	β-, β-n 84%
		22		31.990e	24 ms *7*	β-, β-n 35%
8	O	12	0+	32.060	400 keV *250*	p
		13	(3/2-)	23.113	8.90 ms *20*	ε, εp
		14	0+	8.006	70.606 s *18*	ε
		15	1/2-	2.855	122.24 s *16*	ε
		16	0+	-4.737	99.76% *1*	
		17	5/2+	-0.809	0.038% *3*	
		18	0+	-0.782	0.20% *1*	
		19	5/2+	3.332	26.91 s *8*	β-
		20	0+	3.796	13.57 s *10*	β-
		21	(5/2+)	8.066	3.42 s *10*	β-
		22	0+	9.440	2.25 s *15*	β-
		23		14.540s	82 ms *37*	β-, β-n 31%
		24	0+	18.790s	61 ms *26*	β-, β-n 58%
9	F	14	(2-)	33.610s		p
		15	(1/2+)	16.770	1.0 MeV *2*	p
		16	0-	10.680	40 keV *20*	p
		17	5/2+	1.951	64.49 s *16*	ε
		18	1+	0.873	109.77 m *5*	ε
		19	1/2+	-1.487	100%	
		20	2+	-0.017	11.00 s *2*	β-
		21	5/2+	-0.047	4.158 s *20*	β-
		22	(3,4)+	2.789e	4.23 s *4*	β-
		23	(3/2,5/2)+	3.350	2.23 s *14*	β-
		24		7.640e	340 ms *80*	β-
		25		11.330e		
		26		18.460e		
		27		25.600e		
10	Ne	16	0+	23.989	122 keV *37*	2p
		17	1/2-	16.480	109.0 ms *10*	ε, εp
		18	0+	5.319	1.672 s *8*	ε
		19	1/2+	1.751	17.22 s *2*	ε
		20	0+	-7.047	90.48% *3*	
		21	3/2+	-5.737	0.27% *1*	
		22	0+	-8.027	9.25% *3*	
		23	5/2+	-5.156	37.24 s *12*	β-
		24	0+	-5.950	3.38 m *2*	β-

Isotope Z	El	A	Jπ	Δ (MeV)	T1/2 or Abundance	Decay Mode
13	Al	29	5/2+	-18.215	6.56 m *6*	β-
		30	3+	-15.890	3.60 s *6*	β-
		31	(3/2,5/2)+	-14.967e	0.644 s *25*	β-
		32	1+	-11.190e	33 ms *4*	β-
		33		-8.610e		
		34		-3.250e	60 ms *18*	β-, β-n 27%
		35		-0.320e	0.15 s *5*	β-, β-n 40%
		36	0+	5.050s		
		37				
14	Si	22	0+		6 ms *3*	ε, εp
		23		23.530s		
		24	0+	10.755	102 ms *35*	ε, εp
		25	5/2+	3.827	220 ms *3*	ε, εp
		26	0+	-7.145	2.234 s *13*	ε
		27	5/2+	-12.385	4.16 s *2*	ε
		28	0+	-21.492	92.23% *1*	
		29	1/2+	-21.895	4.67% *1*	
		30	0+	-24.433	3.10% *1*	
		31	3/2+	-22.950	157.3 m *3*	β-
		32	0+	-24.081	172 y *4*	β-
		33		-20.556e	6.18 s *18*	β-
		34	0+	-19.992e	2.77 s *20*	β-
		35		-14.390e	0.78 s *12*	β-
		36	0+	-12.640e	0.45 s *6*	β-, β-n<10%
		37		-7.000s		
		38	0+	-5.360s		
15	P	25		22.080s		
		26		11.260s	≈20 ms	ε, εp, ε2p
		27	1/2+	-0.715e	0.26 s *8*	ε, εp
		28	3+	-7.161	270.3 ms *5*	ε
		29	1/2+	-16.951	4.140 s *14*	ε
		30	1+	-20.207e	2.498 m *4*	ε
		31	1/2+	-24.441	100%	
		32	1+	-24.305	14.262 d *14*	β-
		33	1/2+	-26.338	25.34 d *12*	β-
		34	1+	-24.557	12.43 s *8*	β-
		35	1/2+	-24.857	47.3 s *7*	β-
		36		-20.251	5.6 s *3*	β-
		37		-18.930e	2.31 s *13*	β-
		38		-13.430e	0.64 s *14*	β-
		39		-12.500s	≈160 ms	β-, β-n 41%
		40		-7.020s	0.26 s *8*	β-, β-n 30%
		41			0.12 s *2*	β-, β-n 30%
		42			0.11 s *3*	β-, β-n 50%
3	S	27		18.220s		
		28	0+	4.199e	125 ms *10*	ε, εp
		29	5/2+	-3.115e	0.187 s *4*	ε, εp 47%
		30	0+	-14.063	1.178 s *5*	ε
		31	1/2+	-19.045	2.572 s *13*	ε
		32	0+	-26.016	95.02% *9*	
		33	3/2+	-26.586	0.75% *1*	
		34	0+	-29.932	4.21% *8*	
		35	3/2+	-28.846	87.51 d *12*	β-
		36	0+	-30.664	0.02% *1*	

Reproduced from *Nuclear Wallet Cards* by J.K. Tuli (Brookhaven National Laboratory, 1990).

Instability

A nucleus X_0 can decay into $X_1 + X_2 + .. X_n$ if $\sum_{i=1}^{n} M_i < M_0$

Kinetic energy released $Q = M_0 c^2 - \sum M_i c^2$

$= (A_0 u + \Delta(X_0)) - \sum (A_i u + \Delta(X_i))$

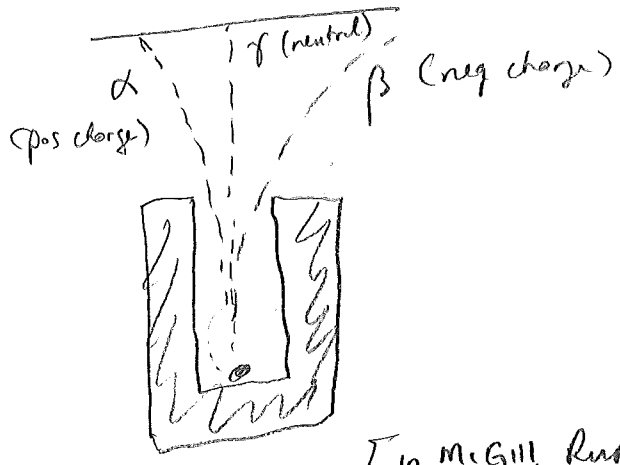
Baryon # cons $\Rightarrow$ $A_0 = \sum A_i$

$\Rightarrow$ $Q = \Delta(X_0) - \sum \Delta(X_i)$

Radioactivity

1896 Becquerel: [U blackens photographic plates
must be emitting particles

Rutherford [cloud chamber
particles bend in magnetic fields
different types of radioactivity : α, β, γ



[in McGill, Rutherford suspected $\alpha = {}^4He$]
[in Manchester, proved it w/ Royds in 1907]

$\alpha = {}^4He$ nuclei

$$Q = \Delta(X_0) - \Delta(X_1) - \Delta({}^4He)$$

[possible because $\Delta({}^4He) = 2.425$ MeV, rather low]

Curie [also discovered α-decay of radium + polonium]

[^4He found in natural gas due to decay of radioactive elements underground]

α-decay usually involves heavy nuclei [top of chart of nuclides]

Since α particle energies were ~ 5 MeV

could use them to probe atomic structure

→ first particle accelerators

1909 Rutherford, Marsden, Geiger: α + Au

expected slight scattering by e^-'s in plum pudding

instead found a massive nucleus

1919 Rutherford was able to use α's to transmute elements
w small Z (could overcome Coulomb barrier of nucleus)

$$\alpha + {}^{14}N \rightarrow {}^{17}O + p$$

1930 Walther Bothe & H Becker

$$\alpha + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C + \left(\begin{array}{c}\text{neutral penetrating} \\ \text{radiation}\end{array}\right)$$

thought by them (α by F. Joliot and I. Curie) to be γ

1932 Owen Chadwick discovers neutron

Fermi subsequently used n to probe nuclei (no Coulomb barrier)

β-decay

β^- = electrons [bent in opp. direction in mag field

same $\frac{e}{m}$ as cathode rays

cathode rays = atomic electrons

β^- from nucleus]

[simplest example] [did this before]

$$n \longrightarrow p + e^- + \bar{\nu}$$

$$Q = m_n c^2 - m_p c^2 - m_e c^2$$

$$= 939.6 - 938.3 - 0.5 = 0.8\ \text{MeV} > 0$$

∴ neutron unstable

[Alternatively]

$$Q = \Delta(n) - \Delta(^1H)$$

[$\Delta(^1H)$ includes recall the electron mass]

$$-[8.071 - 7.289 = 0.782]$$

A neutron inside a nucleus can be stable

$$\underbrace{^2H}_{pn e^-} \longrightarrow \underbrace{^1H}_{p e^-} + p + e^-$$

$$Q = \Delta(^2H) - \Delta(^1H) - \Delta(^1H) = -1.4\ \text{MeV} < 0$$

deuterium stable

$$[13.130 - 2(7.289) = -1.442]$$

Sometimes neutron inside a nucleus can decay

$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + e^- + \bar{\nu} $$

$$ Q = \left[M_{nuc}(X) - M_{nuc}(Y) - m_e \right] c^2 $$

$$ = \left[Au + \underset{\uparrow}{\Delta}(X) - Z m_e c^2 \right] - \left[Au + \Delta(Y) - (Z+1) m_e c^2 \right] - m_e c^2 $$

(↑ neutral atom)

$$ = \Delta(X) - \Delta(Y) $$

If $Q > 0$, nucleus is unstable

"neutron-rich" nuclei usually undergo β^- decay

~~β^- decay~~

~~$n \rightarrow p\, e^- \bar{\nu}$~~

~~${}^A_Z X \rightarrow {}^A_{Z+1} Y\, e^-\, \bar{\nu}$ possible~~

~~if $Q = \Delta(X) - \Delta(Y) > 0$~~

[$n + {}^{238}_{92}U \rightarrow {}^{239}_{92}U \xrightarrow[(23\,min)]{} e^- \bar{\nu} {}^{239}_{93}Np \xrightarrow[(2\,days)]{} e^- \bar{\nu} {}^{239}_{94}Pu \rightarrow$ fission
late
breeder reactor]

β^+ decay of proton rich nuclei

Normally $p \not\rightarrow n\, e^+ \nu$

but

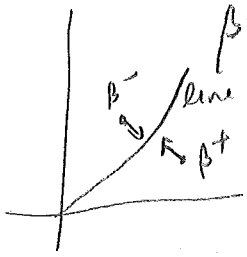
${}^A_Z X \rightarrow {}^A_{Z-1} Y\, e^+ \nu$ is possible if $Q > 0$

where $Q = \left(M_{nuc}(X) - M_{nuc}(Y) - m_{e^+} - \cancel{m_\nu}^{\,0}\right) c^2$

$= \left[A u + \Delta(X) - Z m_e c^2\right] - \left[A u + \Delta(Y) - (Z-1) m_e c^2\right] - m_e c^2$

$= \Delta(X) - \Delta(Y) - 2 m_e c^2$

β^+ decay is followed by $e^+ e^- \rightarrow \gamma\gamma$
(each γ has 0.511 MeV)



[F. Joliot-I. Curie discovered artificial radioactivity: 1934
$\alpha + {}^{27}_{13}Al \rightarrow n + {}^{30}p \rightarrow {}^{30}_{14}Si + e^+ + \nu_e$ (e^+ delayed)]

Electron capture (from K shell) $e^- p \not\rightarrow n\nu$ but

$e^- \; {}^A_Z X \rightarrow {}^A_{Z-1} Y\, \nu$ possible if $Q > 0$

where $Q = m_{nuc}(X) + m_e - m_{nuc}(Y)$

$= \left[A u + \Delta(X) - Z m_e c^2\right] + m_e c^2 - \left[A u + \Delta(Y) - (Z-1) m_e c^2\right]$

$= \Delta(X) - \Delta(Y)$

- EC is followed by emission of X-ray photon as outer shell (valence) electron falls into vacancy.

4 radioactive series

$A = 4n+2$	^{238}U	(4.5E9 yrs)	$\longrightarrow$	^{206}Pb
$4n+3$	^{235}U	(7.1E8 yrs)	$\longrightarrow$	^{207}Pb
$4n$	^{232}Th	(1.4E10 yrs)	$\longrightarrow$	^{208}Pb
$4n+1$	^{233}U	(1.6E7 yrs)	$\longrightarrow$	^{209}Bi

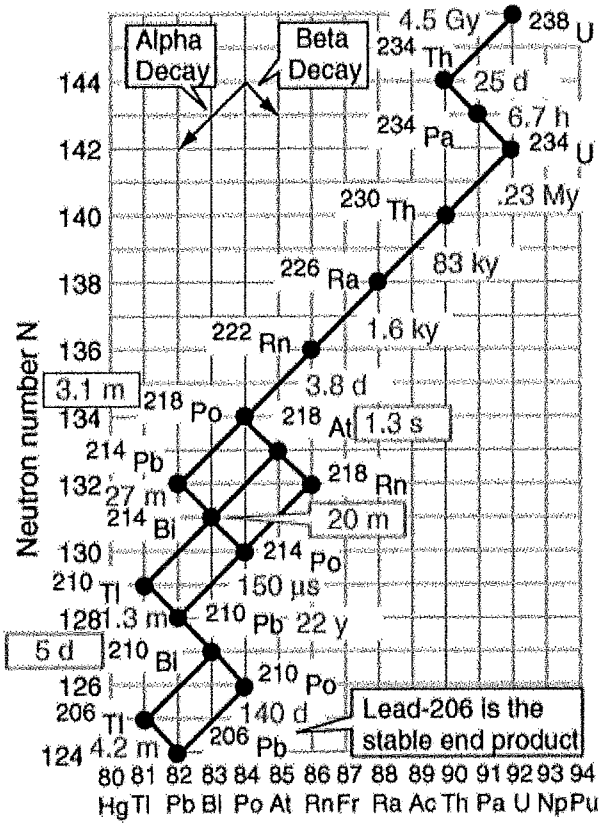
hyperphysics.phy-astr.gsu.edu/hbase/nuclear

(georgia state u.)

The Uranium-238 Decay Series

- ☐ ^{235}U Series
- ☐ ^{232}Th Series
- ☑ ^{238}U Series
- ☐ ^{237}Np Series

The four natural radioactive series



Boxed values for half-life are for multiple decay paths

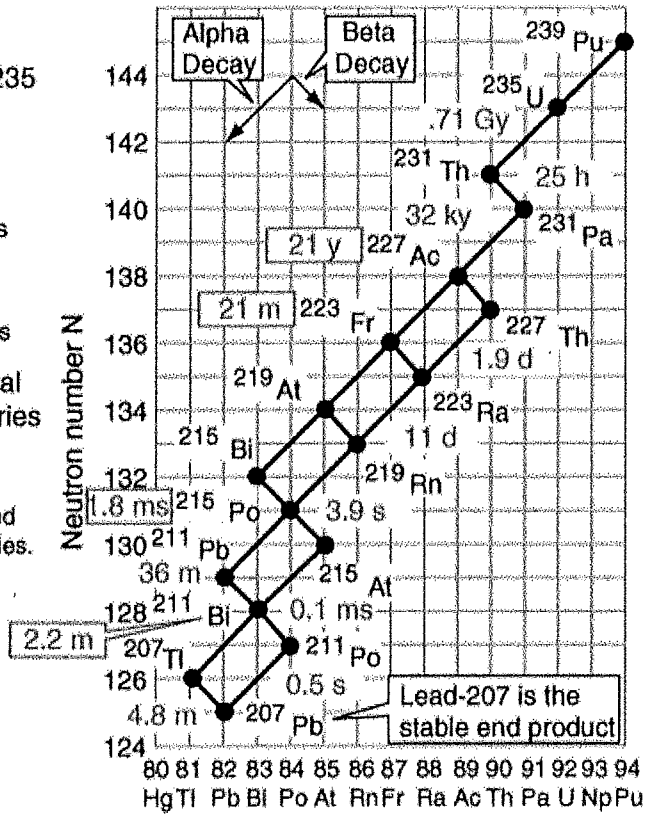
The Uranium-235 Decay Series

- [x] ^{235}U Series
- [ ] ^{232}Th Series
- [ ] ^{238}U Series
- [ ] ^{237}Np Series

The four natural radioactive series

This series is traditionally called the Actinium series.

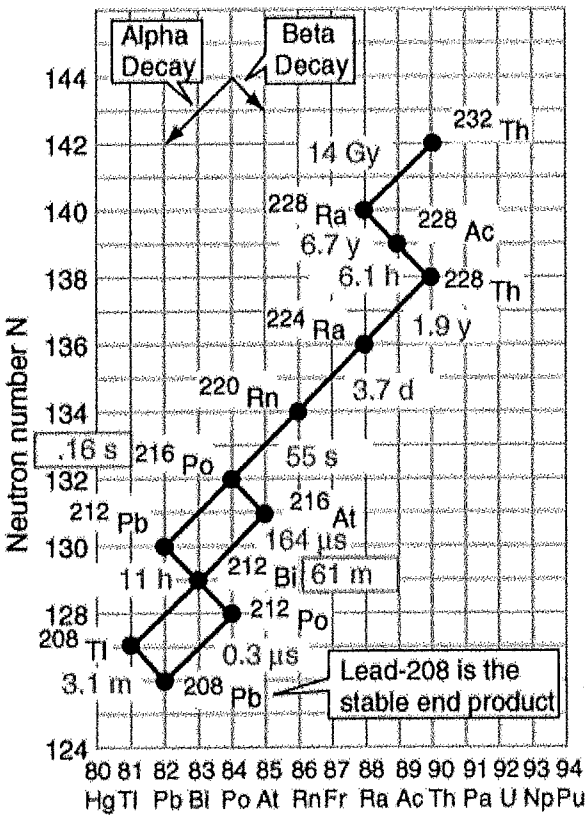
Boxed values for half-life are for multiple decay paths



The Thorium-232 Decay Series

- ☐ ^{235}U Series
- ☑ ^{232}Th Series
- ☐ ^{238}U Series
- ☐ ^{237}Np Series

The four natural radioactive series

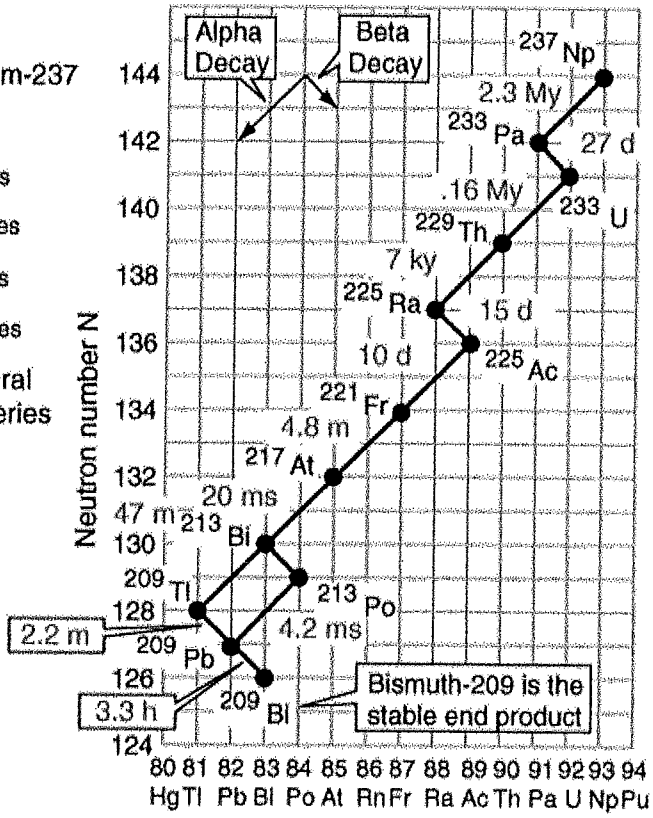


Boxed values for half-life are for multiple decay paths

The Neptunium-237 Decay Series

- ☐ ^{235}U Series
- ☐ ^{232}Th Series
- ☐ ^{238}U Series
- ☑ ^{237}Np Series

The four natural radioactive series

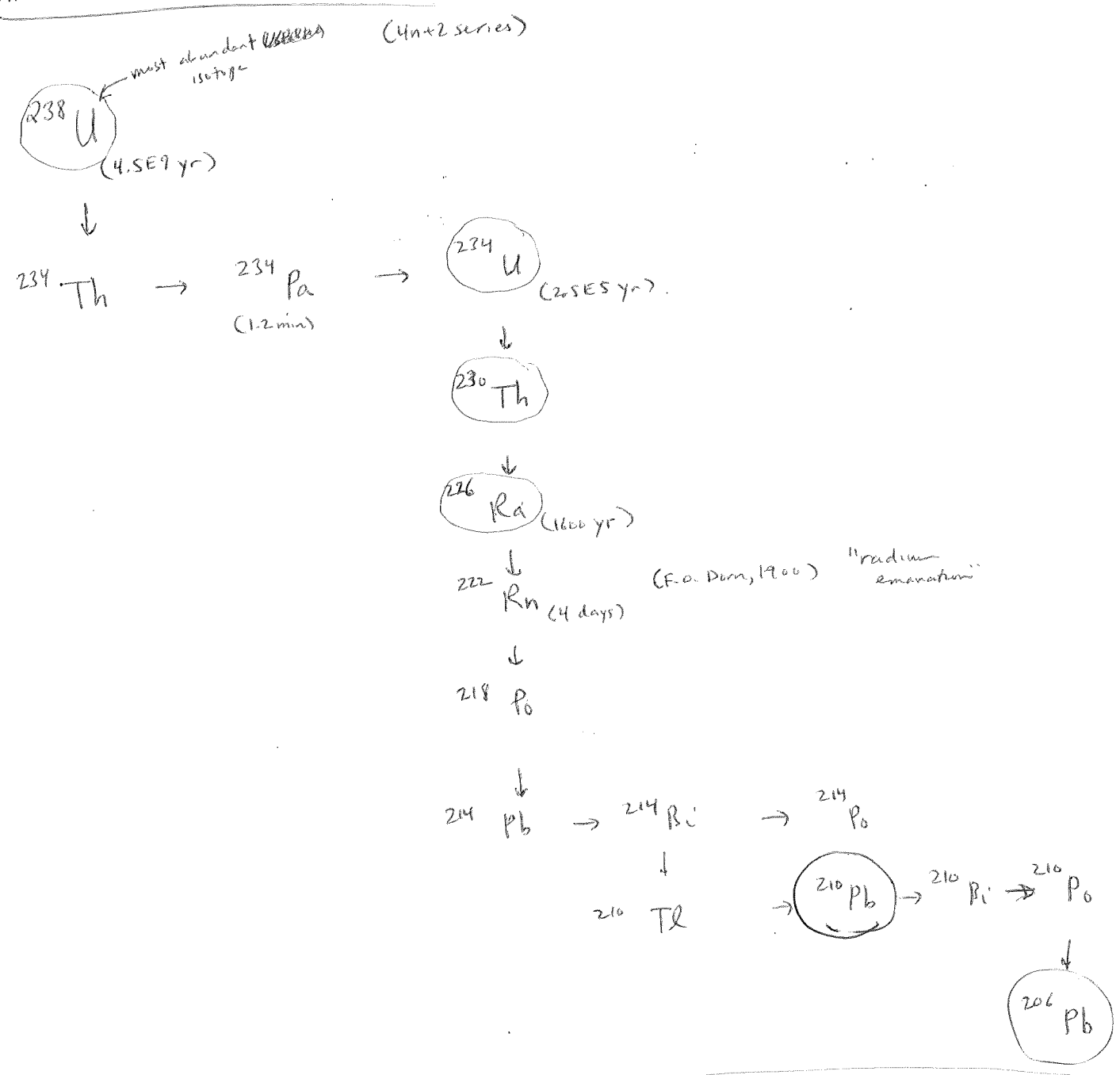


Radioactive transformations

URANIUM - RADIUM SERIES:

circled = longer-lived

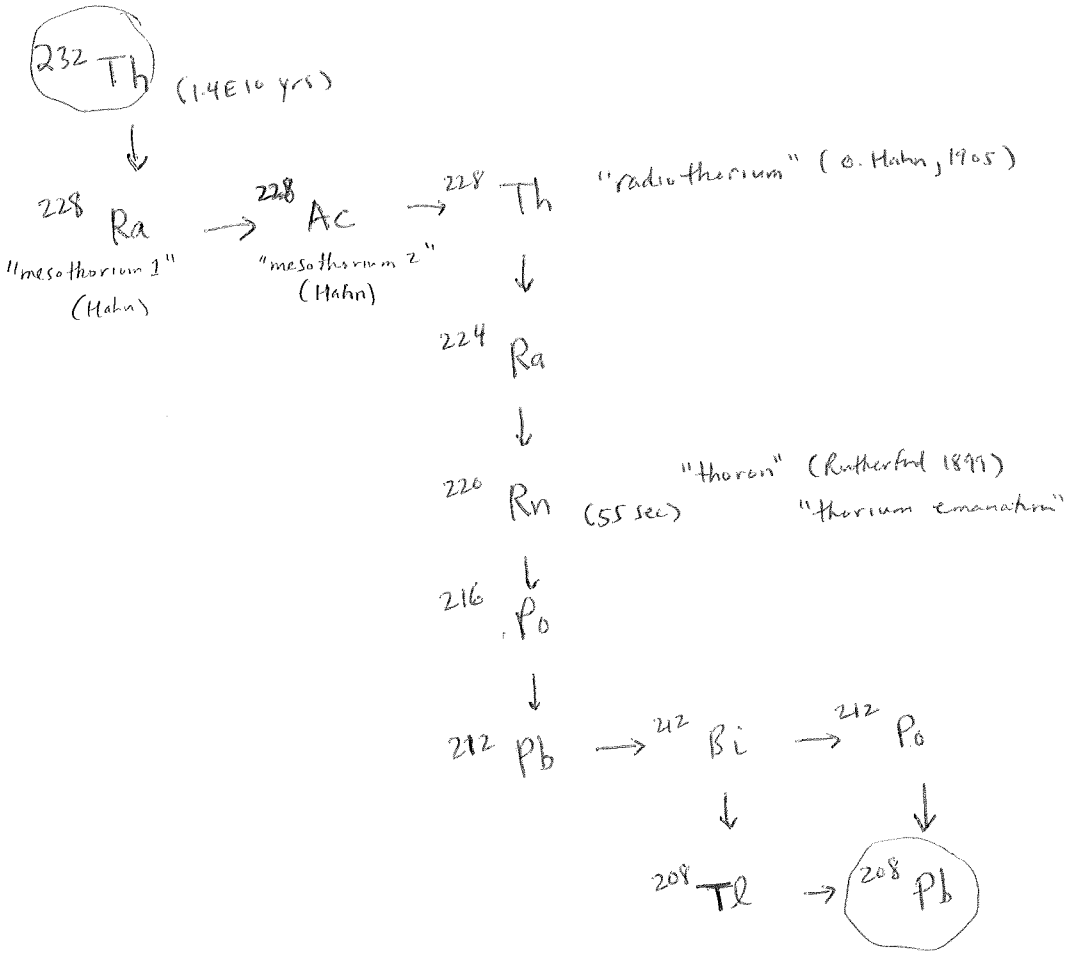
(4n+2 series)



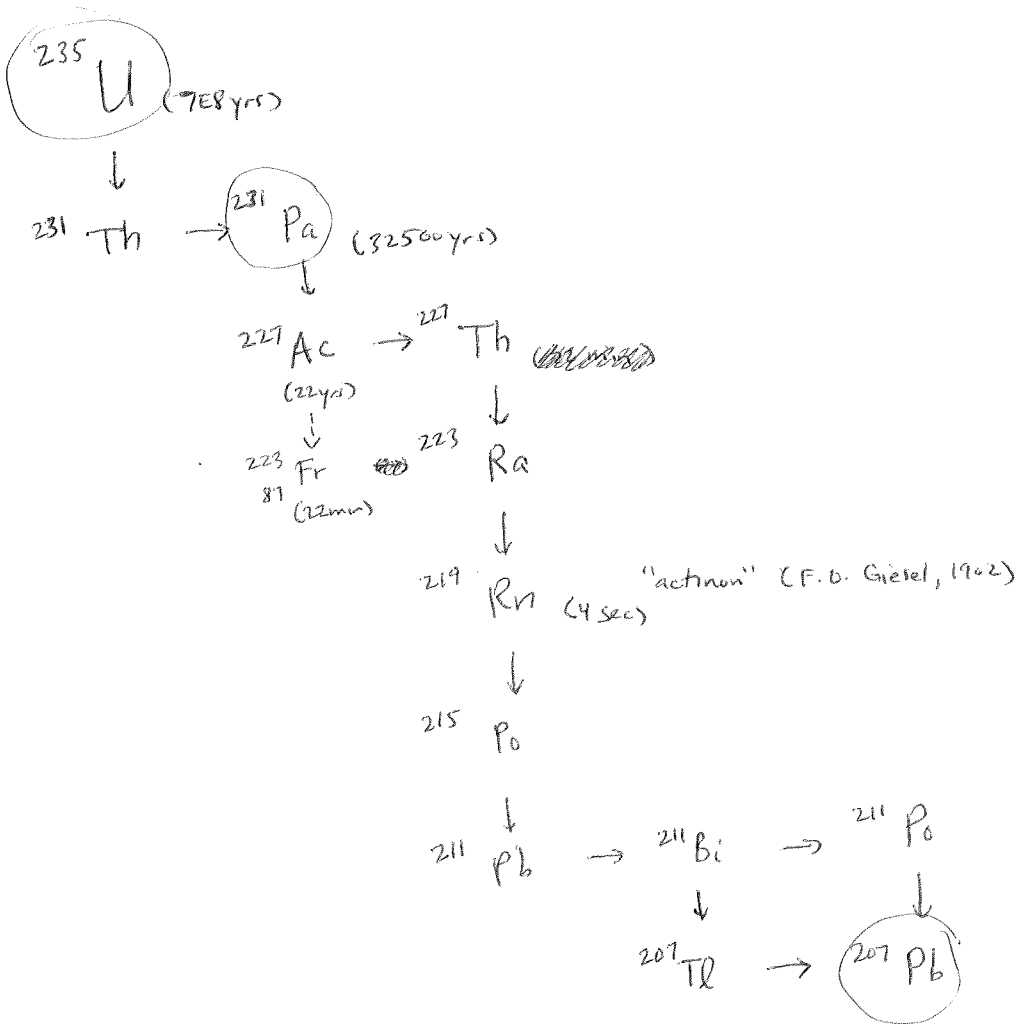
Pb	Bi	Po	At	Rn	Fr	Ra	Ac	Th	Pa	U	Np	Pu
(207)	(209)	(210)	(210)	(222)	(223)	(226)	(227)	(232)	(231)	(238)	~~(237)~~ (237)	(242)

↑ most stable isotope

Thorium series (4n series)



1) Actinium series (4n+3 series)



4n+1 Series

not naturally occurring

237 Np (2E6 yrs)

1 curie: activity of 1 g of ^{226}Ra (3.7×10^{10} disintegrats/sec)

^{226}Ra, $T = 1600$ yr

^{222}Rn $T = 4$ days

^{233}U

$^{232}_{90}Th + n \longrightarrow {}^{233}_{90}Th + \gamma$

$\downarrow \beta$

$^{233}_{91}Pa \xrightarrow{\beta} {}^{233}_{92}U \longrightarrow$ Fission $\longrightarrow$ produced neutrons

(Thorium cycle)

(1/140 g Natural U) $^{235}U \longrightarrow Ba + Kr + 2.5n$ (+200 MeV)

Fissionable

$^{233}U \longrightarrow$

^{239}Pu

(Neutron sources)

$^{9}Be + \alpha \longrightarrow {}^{12}C + n$ (Chadwick)

$^{27}Al + \alpha \longrightarrow {}^{30}P + n$ (Joliot-Curie)

$\hookrightarrow {}^{30}Si + e^+$

α from α-decay typically 5 MeV

eg Bi^{214}

$^{237}U + n \longrightarrow {}^{238}U$ ($T = 2$ days)

(Np, Pu produced in 1940)

^{244}Pu ($T = 8 \times 10^7$ yrs) most stable

^{238}Pu ($T = 85$ yrs) produced 1st in 1940

^{239}Pu ($T = 25000$ yrs)

Used to power lunar equipment

$n + {}^{238}U \longrightarrow {}^{239}U \longrightarrow {}^{239}Np \longrightarrow {}^{239}Pu$

(23 min.) ($T = 2$ days)

basis of their atomic weight; to-day we arrange them according to their " atomic number ", as we shall see below.

At the end of the periodic system stand the radioactive elements; these too can be arranged according to their chemical behaviour. The method, first applied by the Curies, for separating them and determining their chemical properties, consists in bringing the radioactive substance with other bodies into solution, and applying various precipitating agents. It is then tested whether the activity, recognizable by the radiating power, is in the precipitate or in the residual solution, or is divided between the two. Each portion is treated in a similar way, until one part of the products is free from radiation, and the other part shows an exponential decay with characteristic half-value period (§ 4, p. 31). Radium itself was isolated thus by the Curies (1898), starting from the mineral pitchblende; barium was left along with the radium to begin with, and could not be separated from it until the end. Radium therefore belongs to the group of alkaline earth metals, and so must be placed in the periodic table in the column under calcium and barium; radon Rn (or Ra emanation), on the other hand, behaves like a noble gas and so ranges under He, Ne, &c. The short-lived succeeding disintegration product RaA ($T = 3$ min.) is found to be chemically analogous to tellurium; the next, RaB ($T = 27$ min.), goes with lead, and so on.

From these and similar results the following important *law of radioactive transformation* has been deduced: emission of an α-particle (loss of charge $+2e$) shifts the residual atom two places to the left in the periodic table, i.e. in the direction towards lower H-valencies; thus radium on giving up an α-particle is transformed into radon (Ra emanation). On the other hand, escape of a β-particle (loss of charge $-e$) displaces the atom one place to the right (Russel, Soddy, Fajans, 1913). If we go through the three radioactive series according to this rule (fig. 13), we find that many places in the table are multiply occupied. To cite a particularly conspicuous example: into the place in the periodic table occupied by ordinary lead, there also come, according to the law of radioactive change, the end-products of the three radioactive series, viz. RaG, AcD and ThD, all three of which have undoubtedly the character of lead. Besides these, RaD, AcB, ThB and RaB also fall into the place mentioned. All these elements, in spite of their like chemical behaviour, have different masses, because in an α-emission the atom gives up the mass 4 of helium, while in a β-disintegration, on account of the small mass of the electron, the mass of the atom remains practically unchanged. The three elements of the radium

series mentioned above, RaB, RaD and RaG, must therefore have masses decreasing successively by 4.

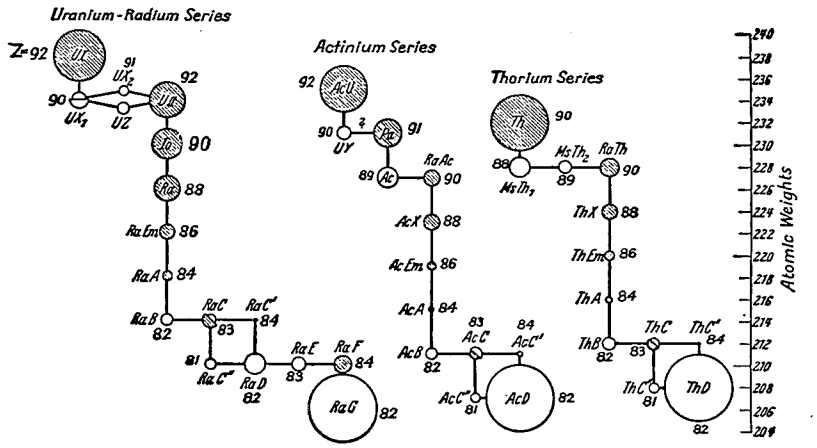


Fig. 13.—The radioactive transformation series. The changes indicated by vertical lines correspond to α-emission, by horizontal lines to β-emission; in the former the atomic weight falls by 4, the atomic number by 2; in the latter the atomic weight remains approximately constant, and the atomic number increases by 1. Shaded circles indicate α-rays; circles without shading, β-rays. The size of each circle corresponds to the half-value period.

It may also happen, we may add (e.g. in every β-disintegration), that two chemically different elements have the same atomic weight; these are called *isobars*.

After the existence of isotopes had been demonstrated in this way for radioactive substances, J. J. Thomson (1913), by deflection experiments on canal rays, succeeded in proving that isotopes occur even among ordinary elements, for instance neon. Ordinary chlorine, whose atomic weight is given by chemists as 35·5, consists of one kind of chlorine of weight 35·0, and another of weight 37·0. Thomson's investigations reached their highest development in the mass-spectrograph constructed by Aston (1919), which we have already mentioned (§ 2, p. 29), and which at present is the most exact method for determining atomic weights (Aston, Dempster (1918), Bainbridge).

By magnetic separation of canal rays of lithium, it has even been found possible (Oliphant, Shire and Crowther, 1934) to obtain visibly separated deposits of the two lithium isotopes (6 and 7). This method is now used for the separation of the two uranium isotopes (235 and 238) on a large scale (see § 9, p. 195).

Partial separation of isotopes can be obtained by any physical

process the rate of which depends directly or indirectly on the mass of the particles: ordinary diffusion and thermal diffusion (Appendix II, p. 277), diffusion assisted by centrifugation, chemical action, fractional distillation, evaporation, ionic migration and electrolysis (Chap. III, § 5, p. 65), photo-chemical action. As an example may be mentioned the partial separation of neon isotopes by Hertz (1933). By means of a suitably devised circulation process, he caused the mixture of isotopes to diffuse several times through a system of clay cylinders. Since the lighter components of the mixture diffuse more rapidly than the heavier, we obtain in this way, as the final products of the circulation process, two mixtures, one of which is richer in the lighter components, the other in the heavier. This method has also been applied successfully for the separation of the heavy isotope of hydrogen (see § 5, p. 65) and for the separation of the uranium isotopes (§ 9, p. 195).

The method of thermal diffusion was successfully applied by Clusius and Dickel (1938) to the cases of neon and chlorine (in the form HCl). With the help of a chemical reaction between HCN gas and a solution of NaCN in water Hutchinson, Stewart and Urey (1940) were able to increase the fraction of the isotope ^{13}C by a considerable amount.

The result of the detailed investigations on the occurrence of isotopes may be stated in the following form. Every element (in the chemical sense) has either a whole number for its atomic weight, or consists of a mixture of different kinds of atoms whose atomic weights are whole numbers. For practical reasons atomic weights have all along been referred, not to hydrogen equal to 1, but to oxygen equal to 16. This has proved fortunate as an aid to clearness, for the integral character of the isotopic weights stands out much more obviously than with the choice of $H = 1$. Hydrogen indeed, for $O = 16$, gets a value ($H = 1{\cdot}0081$) differing decidedly from 1, but the atomic weights of all other pure isotopes approximate closely to whole numbers.

To understand how this comes about, we must anticipate so far as to note that the masses of atoms are almost entirely concentrated in the *atomic nuclei*. Every atom consists of a nucleus, which is surrounded by a cloud of electrons (§ 3, p. 57). This nucleus is the essential part of the atom. The result of Aston's investigations must be referred to the nucleus: every nucleus consists of a whole number of hydrogen nuclei or *protons*; its mass (except for trifling divergencies) is an integral multiple of the mass of the proton.

These divergencies, which in spite of their slightness are of the highest importance, will be discussed later (§ 4, p. 67).

TABLE II.—TABLE OF ISOTOPES

The isotopes are arranged in each case where known in the order of frequency of occurrence; the radioactive isotopes are indicated by an asterisk. Radioactive isotopes produced artificially are not included.

Element	Z	Isotopes	Element	Z	Isotopes
H	1	1, 2, 3	Sb	51	121, 123
He	2	4, 3	Te	52	130, 128, 126, 125, 124, 122, 123, 127?
Li	3	7, 6			
Be	4	9	I	53	127
B	5	11, 10	Xe	54	132, 129, 131, 134, 136, 130, 128, 124, 126
C	6	12, 13			
N	7	14, 15	Cs	55	133
O	8	16, 18, 17	Ba	56	138, 137, 136, 135, 134, 130, 132
F	9	19			
Ne	10	20, 22, 21	La	57	139
Na	11	23	Ce	58	140, 142, 138, 136
Mg	12	24, 25, 26	Pr	59	141
Al	13	27	Nd	60	142, 144, 146, 143, 145, 148, 150
Si	14	28, 29, 30			
P	15	31	Sm	62	152, 154, 147, 149, 148, 150, 144
S	16	32, 34, 33			
Cl	17	35, 37	Eu	63	153, 151
A	18	40, 36, 38	Gd	64	156, 158, 155, 157, 160, 154, 152
K	19	39, 41, 40*			
Ca	20	40, 44, 42, 48, 43, 46	Tb	65	159
Sc	21	45	Dy	66	164, 162, 163, 161, 160, 158
Ti	22	48, 46, 47, 49, 50	Ho	67	165
V	23	51	Er	68	166, 168, 167, 170, 164, 162
Cr	24	52, 53, 50, 54	Tm	69	169
Mn	25	55	Yb	70	174, 172, 173, 176, 171, 170, 168
Fe	26	56, 54, 57, 58			
Co	27	59, 57	Lu	71	175, 176
Ni	28	58, 60, 62, 61, 64	Hf	72	180, 178, 177, 179 176, 174
Cu	29	63, 65	Ta	73	181
Zn	30	64, 66, 68, 67, 70	W	74	184, 186, 182, 183, 180
Ga	31	69, 71	Re	75	187, 185
Ge	32	74, 72, 70, 73, 76	Os	76	192, 190, 189, 188, 187, 186, 184
As	33	75			
Se	34	80, 78, 76, 82, 77, 74	Ir	77	193, 191
Br	35	79, 81	Pt	78	195, 194, 196, 198, 192
Kr	36	84, 86, 82, 83, 80, 78	Au	79	197
Rb	37	85, 87*	Hg	80	202, 200, 199, 201, 198, 204, 196
Sr	38	88, 86, 87, 84			
Y	39	89	Tl	81	205, 203, 207*, 208*, 210*
Zr	40	90, 92, 94, 91, 96			
Cb	41	93	Pb	82	208, 206, 207, 204, 203? 205?, 209?, 210*, 211*, 212*, 214*
Mo	42	98, 96, 95, 92, 94, 97, 100			
Ru	44	102, 101, 104, 100, 99, 96, 98?	Bi	83	209, 210*, 211*, 212*, 214*
Rh	45	103, 101	Po	84	210*, 211*, 212*, 214*, 215*, 216*, 218*
Pd	46	106, 108, 105, 110, 104, 102			
			Rn	86	222*, 219*, 220*
Ag	47	107, 109	Ra	88	226*, 223*, 224*, 228*
Cd	48	114, 112, 111, 110, 113, 116, 106, 108	Ac	89	227*, 228*
			Th	90	232*, 227*, 228*, 230*, 234*
In	49	115, 113			
Sn	50	120, 118, 116, 119, 117, 124, 122, 112, 114, 115	Pa	91	231*, 234*
			U	92	238*, 235*, 234*