Nuclear physics

[Periodic table of elements does not tell all.
Position on periodic table is determined by

Z = atomic number = # protons in nucleus = electric charge of nucleus

[But a nucleus w/ given # of protons can have varying #s of neutrons]

N = neutron number

[Elements w/ different neutron numbers are called]

isotope = "same place" (on periodic table)

[disc. 1913 J.J. Thomson ^{20}Ne, ^{22}Ne]

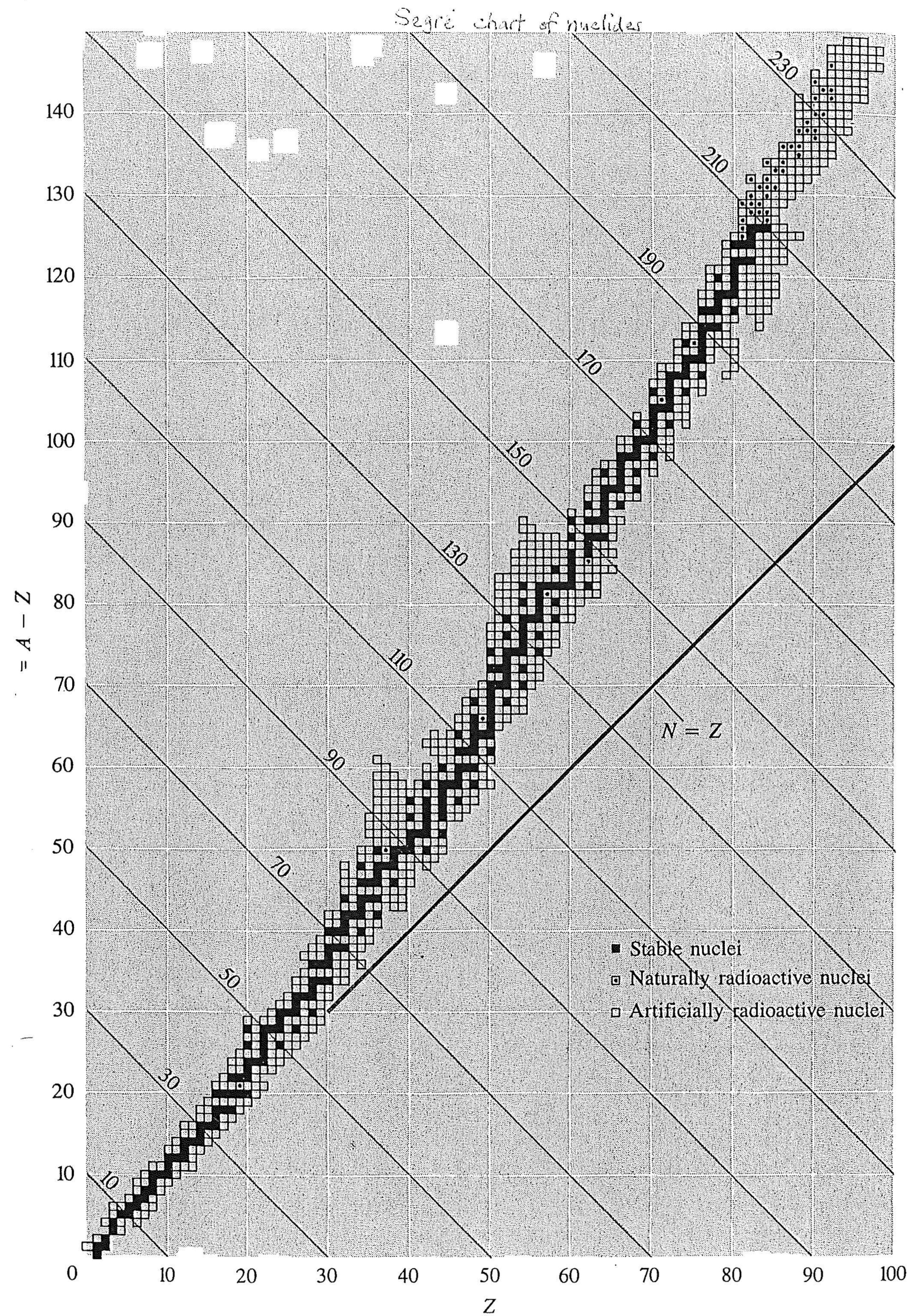
[Hand out and project Segré chart from Blatt]

[Since proton + neutron have ~ same mass, the mass of the nucleus is approx. given by the sum of Z and N]

A = Z + N = nucleon number = baryon number = mass number

Symbol for a nuclide $^{A}_{Z}X$ ← atomic symbol

Z ↑ redundant



Segrè chart of nuclides
N = A − Z
Z
N = Z
Stable nuclei
Naturally radioactive nuclei
Artificially radioactive nuclei
10
30
50
70
90
110
130
150
170
190
210
230

▨ = stable

□ = unstable (artificially created)

⊡ = unstable (naturally occurring)

[Isotopes are in vertical columns]

Fairly small # of stable isotopes for each element (on average 3)
[Bethe Morrison]

Some have several (calcium $Z = 20$ has 6)

Some have one only (scandium $Z = 21$)

Some have none (technetium $Z = 43$, bombard Mo in cyclotron,
promethium $Z = 61$, product of U fission)

[there were gaps in the periodic table before these were produced]

Isobars = same A (on diagonals)

isotones = same N

Patterns of stable nuclei

Lighter nuclei: $N \approx Z$ $\quad$ ^4He, ^{12}C, ^{16}O

Heavier nuclei $N > Z$ $\quad$ $^{238}_{92}U$

Valley of stability

[why?]

Staircase pattern.

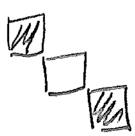
even-even most stable [150 of 250 stable]

suggests p's like to pair up w/ protons and n's w/ neutrons

odd-odd least stable [only 5: ^2_1H, ^6_3Li, $^{10}_5B$, $^{14}_7N$, $^{180}_{73}Ta$]

^ Das Ferbel

Isobars



< [at A = 50 and A = 70 etc]

stable isobars are (almost) always separated by an unstable one

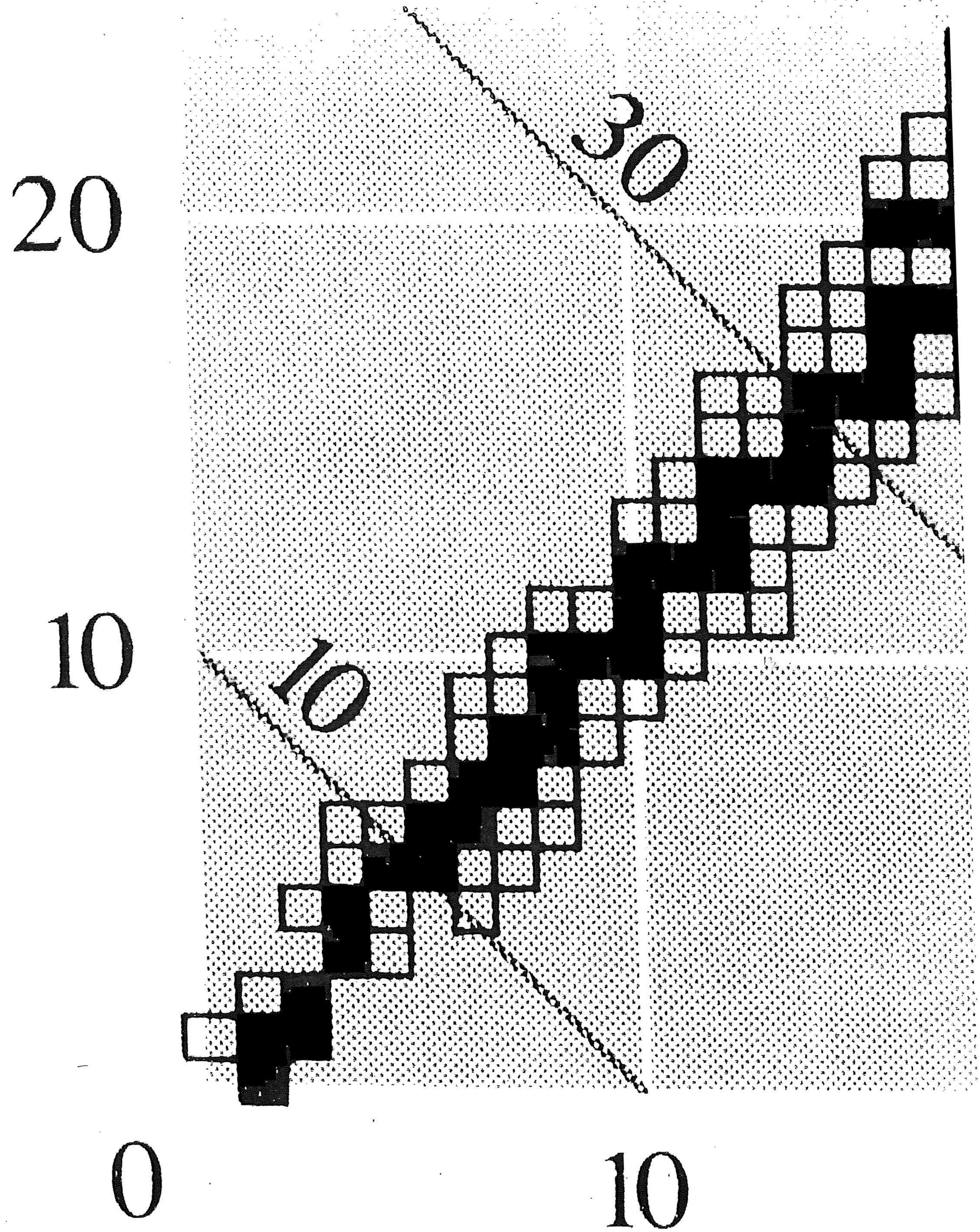
Some #s of p + n particularly stable

Magic numbers: 2, 8, 20, 28, 50, 82, 126

↑ (20) Z = 20 vs 19, 21; N = 20 vs 19, 21

↑ (50) Z = 50 vs 49, 51

doubly magic: ^4He, ^{16}O, $^{208}_{82}Pb$ (82 + 126)



20
10
0
10
30
10

Nuclear Wallet Cards

Isotope				Δ	T½, Γ, or	
Z	El	A	Jπ	(MeV)	Abundance	Decay Mode
0	n	1	1/2+	8.071	10.24 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–	25.9	4.6 MeV *9*	n
		5		36.8	5.7 MeV *21*	n
		6		41.9	1.4 MeV *3*	3n ?
2	He	3	1/2+	14.931	**0.000137% *3***	
		4	0+	2.425	**99.999863% *3***	
		5	3/2–	11.39	0.60 MeV *2*	α , n
		6	0+	17.594	806.7 ms *15*	β–
		7	(3/2)–	26.11	160 keV *30*	n
		8	0+	31.598	119.0 ms *15*	β– , β–n 16%
		9	(1/2–)	40.82	65 keV *37*	n
		10	0+	48.81	0.17 MeV *11*	2n ?
3	Li	4	2–	25.3	6.03 MeV	p
		5	3/2–	11.68	≈1.5 MeV	α , p
		6	1+	14.086	**7.59% *4***	
		7	3/2–	14.908	**92.41% *4***	
		8	2+	20.946	838 ms *6*	β– , β–α
		9	3/2–	24.954	178.3 ms *4*	β– , β–n 50.8%
		10	(1–,2–)	33.05	1.2 MeV *3*	n
		11	3/2–	40.80	8.5 ms *2*	β– , β–nα 0.027%, β–n
		12		50.1s	<10 ns	n ?
4	Be	5	(1/2+)	38.s		p
		6	0+	18.375	92 keV *6*	α , 2p
		7	3/2–	15.769	53.29 d *7*	ε
		8	0+	4.942	6.8 eV *17*	α
		9	3/2–	11.348	**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+	25.08	21.3 ms *1*	β– , β–n < 1%
		13	(1/2–)	33.7	0.17 MeV *11*	n
		14	0+	39.9	4.35 ms *17*	β– , β–n 81%, β–2n 5%
5	B	7	(3/2–)	27.87	1.4 MeV *2*	p , α
		8	2+	22.921	770 ms *3*	ε , εα
		9	3/2–	12.416	0.54 keV *21*	p ,
		10	3+	12.051	**19.8% *3***	
		11	3/2–	8.668	**80.2% *3***	
		12	1+	13.369	20.20 ms *2*	β– , β–3α 1.58%
		13	3/2–	16.562	17.36 ms *16*	β–
		14	2–	23.66	12.3 ms *3*	β– , β–n 6.04%
		15		28.97	9.87 ms *7*	β– , β–n 93.6%, β–2n 0.4%
		16	0–	37.08	<190 ps	n
		17	(3/2–)	43.7	5.08 ms *5*	β– , β–n 63%, β–2n 11%, β–3n 3.5%, β–4n 0.4%
		18	(4–)	52.3s	<26 ns	n ?

[Put up lower left portion of Segrè]

What is the first open box?

^1_0n free neutron is unstable

[PPB] $\tau = 880\,s \approx 15$ min [will estimate this later in semester]

[Put up nuclear wallet cards]

$T_{\frac{1}{2}} = 10.2$ min (half life)

Why discrepancy? — — — — — — — —

$$N(t) = N(0)\,e^{-Rt}$$

R = decay rate

Activity $A(t)$ = # particles that decay per unit time

$$= -\frac{dN}{dt}$$

$$= R\,N(0)\,e^{-Rt}$$

$$= R\,N(t)$$

= (rate)(# particles remaining)

[HW] show that mean life of particle $\tau = \frac{1}{R}$

$$\Rightarrow N(t) = N(0)\,e^{-\frac{t}{\tau}}$$

$$A = \frac{1}{\tau}N$$

$$N = \tau A$$

[HW] find relation between mean life and half-life

(natural abundance means fraction of the number of atoms not of the weight)

so 1g of hydrogen
≈ 1 mole ≈ 6×10^{23} atoms
× 0.015% → 9×10^{19} deuterium atoms

(not)
1g → 0.00015g deuterium
≈ 0.00007 mole
→ 4.5×10^{19} deuterium atoms

$^1H = p$ stable

$^2H = pn$ = deuterium (0.015%) "heavy-hydrogen"

ingredient in "heavy water"; D_2O
used as a moderator in fission reactors
[cf Heavy water war]

d = deuteron = deuterium nucleus [down quark?]

$^3H = pnn$ = tritium ($T_{\frac{1}{2}} \sim 12$ years)
produced in nuclear reactors

$^3He = ppn$. (0.000014%)
$^4He = ppnn$ (~100%) very stable nucleus

α-particle = ^4He nucleus

[If we were living in the very early universe, we could stop now. Primordial abundance has 75% H and 25% He. All heavier elements produced in supernovae much later. Of course we wouldn't be around if there were no heavier elements]

Nuclear Wallet Cards

Isotope Z	El	A	Jπ	Δ (MeV)	T½, Γ, or Abundance	Decay Mode
5	B	19	(3/2−)	59.4s	>200 ns	β− ?
6	C	8	0+	35.09	230 keV *50*	p , α
		9	(3/2−)	28.914	126.5 ms *9*	ε , εp 23%, εα 17%
		10	0+	15.699	19.255 s *53*	ε
		11	3/2−	10.651	20.39 m *2*	ε
		12	0+	0.000	98.89% *1*	
		13	1/2−	3.125	1.11% *1*	
		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 99%
		17		21.04	193 ms *13*	β− , β−n 32%
		18	0+	24.92	95 ms *10*	β− , β−n 19%
		19		32.8	49 ms *4*	β−n 61%, β−
		20	0+	37.6	14 ms *+6−5*	β− , β−n 72%
		21	(1/2+)	46.0s	<30 ns	n ?
		22	0+	52.6s	>200 ns	β− ?
7	N	10	(1−)	39.7s		p ?
		11m	1/2+	25.3	1.58 MeV *+75−52*	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	99.634% *20*	
		15	1/2−	0.101	0.366% *20*	
		16	2−	5.683	7.13 s *2*	β− , β−α 0.0012%
		17	1/2−	7.87	4.173 s *4*	β− , β−n 95.1%
		18	1−	13.12	624 ms *12*	β− , β−n 14.3%, β−α 12.2%
		19		15.86	290 ms *90*	β− , β−n 62.4%
		20		21.77	142 ms *19*	β− , β−n 66.1%
		21	(1/2−)	25.23	87 ms *6*	β− , β−n 80%
		22		32.1	18 ms *5*	β− , β−n 35%
		23	(1/2−)	37.7s	>200 ns	β− ?
		24		47.0s	<52 ns	n ?
8	O	12	0+	32.05	0.40 MeV *25*	p
		13	(3/2−)	23.111	8.58 ms *5*	ε , εp≈100%
		14	0+	8.007	70.606 s *18*	ε
		15	1/2−	2.855	122.24 s *16*	ε
		16	0+	−4.737	99.762% *16*	
		17	5/2+	−0.809	0.038% *1*	
		18	0+	−0.782	0.200% *14*	
		19	5/2+	3.334	26.91 s *8*	β−
		20	0+	3.797	13.51 s *5*	β−
		21	(1/2,3/2,5/2)+	8.06	3.42 s *10*	β−
		22	0+	9.28	2.25 s *15*	β− , β−n<22%
		23	(1/2+)	14.6	82 ms *37*	β− , β−n 31%
		24	0+	19.0	61 ms *26*	β− , β−n 58%
		25	(3/2+)	27.1s	<50 ns	n ?
		26	0+	35.2s	<40 ns	n ?
9	F	14	(2−)	33.6s		p
		15	(1/2+)	16.8	1.0 MeV *2*	p
		16	0−	10.680	40 keV *20*	p
		17	5/2+	1.952	64.49 s *16*	ε

^{12}C (99%)

^{13}C (1%)

^{14}C ($T_{\frac{1}{2}} \sim 5730$ years) used in historical dating

produced in bombardment of nitrogen by cosmic rays in upper atmosphere

$^{14}C \rightarrow {}^{14}N$

$^{39}_{19}K$ (93%)

$^{40}_{19}K$ $T_{\frac{1}{2}} = 1.3$ E 9 years

brick lab

$^{40}K \rightarrow {}^{40}Ca$, ^{40}Ar

$^{87}_{37}Rb$ $T_{\frac{1}{2}} = 4.75$ E 10 yrs

dating of age of earth

$^{87}Rb \rightarrow {}^{87}Sr$

$_{92}Pb$ heaviest element w/ stable nucleus (end-point of many radioactive chains)

$^{209}_{83}Bi$ stable in Segre chart but actually $T_{\frac{1}{2}} = 1.9E19$ yrs [2003]

$^{210}_{84}Po$ even in Segre chart: $T_{\frac{1}{2}} = 140$ days (not stable)

poisoning of Alexander Litvinenko in 2006

$^{238}_{92}U$ 99.3%, $T_{\frac{1}{2}} = 4.5$ E9 years; heaviest naturally-occurring element

[why no heavier ones? short range of color force]