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 of 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 Segrè chart from Blatt]

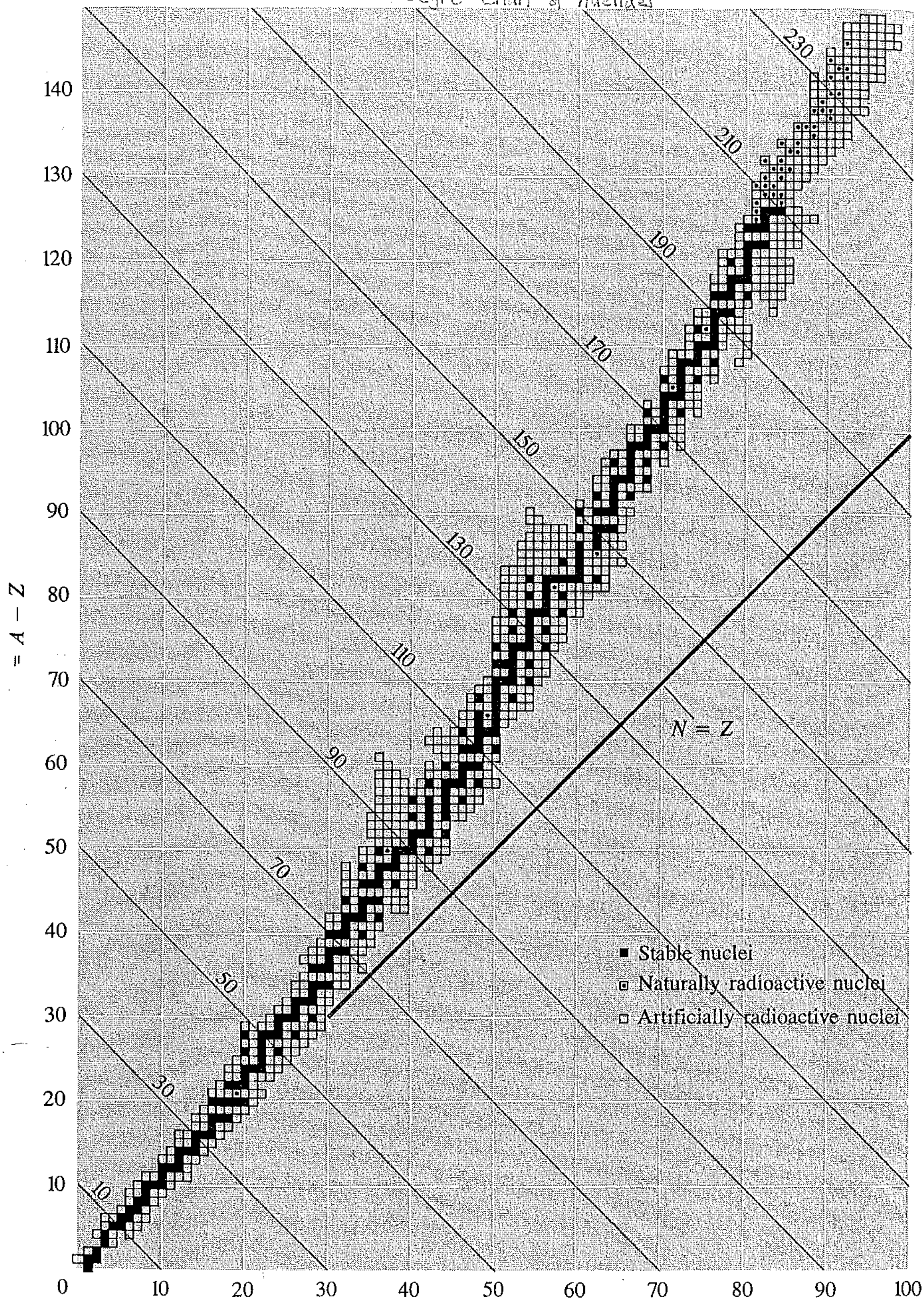
[Since proton + neutron have ~ same mass, the mass of a nucleus is approx. given by the sum of Z and N]

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

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

Z ↑ redundant

Segré chart of nuclides



▨ = stable

□ = unstable (artificially created)

⊡ = unstable (naturally occurring)

[Isotopes are in vertical columns]

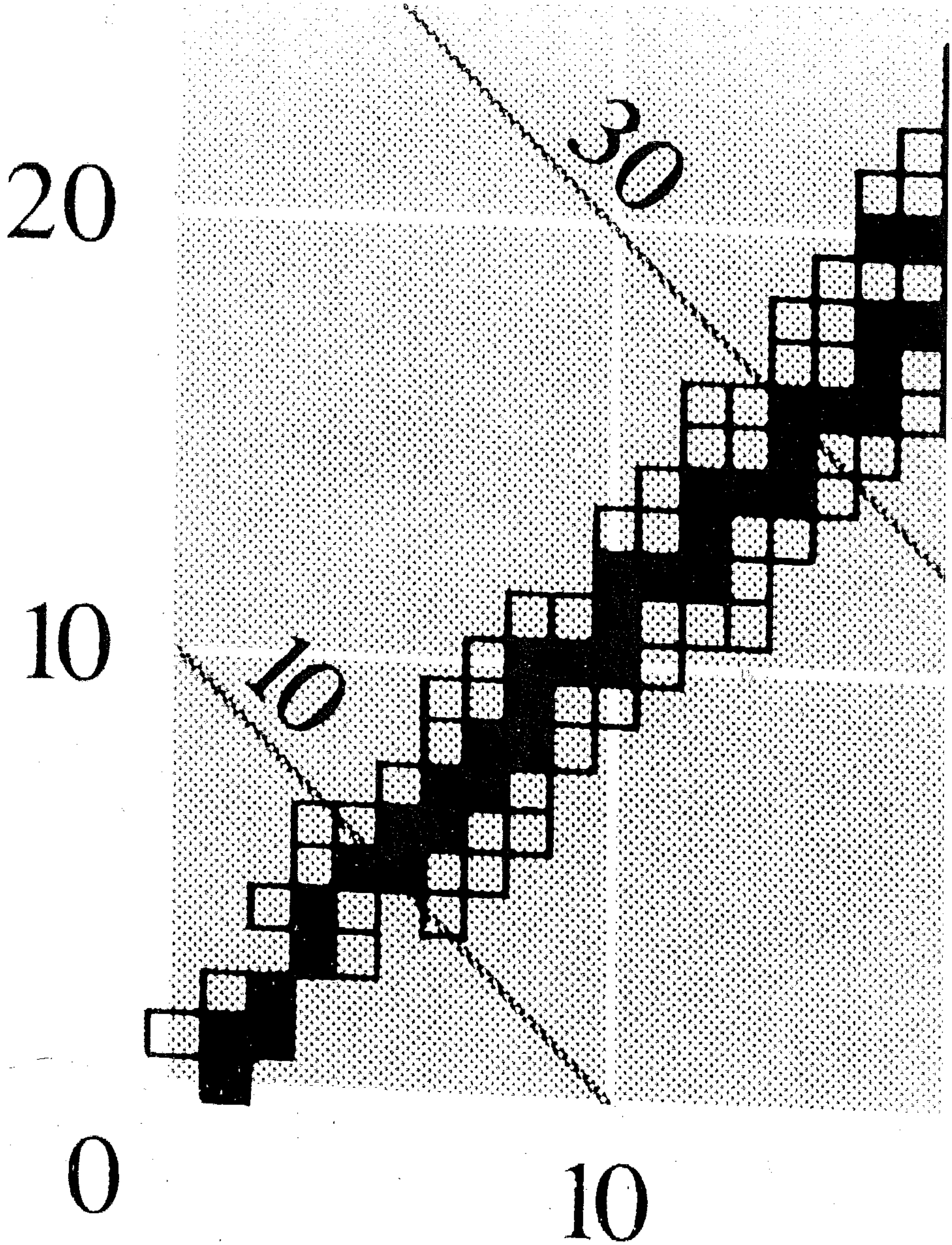
Fairly small # of stable isotopes for each element (on average 3)
[Bethe Morrison]

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]


30
20
10
10
0
10

[Put up lower left portion of Segrè]

What is the first open box?

$^1_0 n$ free neutron is unstable

[PPB] $\tau = 880\,s \approx 15$ min

[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

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%

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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-

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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 45	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 0.028%
		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-

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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%
16	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	

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

$^1H = p$ 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

$^3He = ppn$. (0.00014%)
$^4He = ppnn = \alpha$ (~100%) very stable nucleus
α-particle = ^4He nucleus

[If we were living in the very early universe, we could stop now. Primordial abundance was 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

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

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

$^{40}_{19}K$ $T_{\frac{1}{2}} = 1.3$ E9 years — brick lab
$^{40}K \to {}^{40}Ca$, ^{40}Ar

$^{87}_{37}Rb$ $T_{\frac{1}{2}} = 4.75$ E 10 yrs — dating of age of earth
$^{87}Rb \to {}^{87}Sr$

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

$^{209}_{93}Bi$ stable in Segre chart but actually $T_{\frac{1}{2}} = 1.9$E19 yrs

$^{210}_{84}Po$ error in Segre chart : $T_{\frac{1}{2}} = 140$ days
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]

Patterns of stable nuclei

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

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

Valley of stability

[why?]

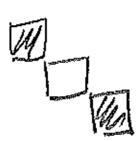
Staircase pattern:

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}H, ^{6}Li, ^{10}B, ^{14}N, ?]

↑ Das Ferbel



← at $A = 50$ and $A = 70$ etc

Some #s of p + n particularly stable

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

↑ $Z=20$ vs 19, 21; $N=20$ vs 19, 21

↑ $Z=50$ vs 49, 51

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