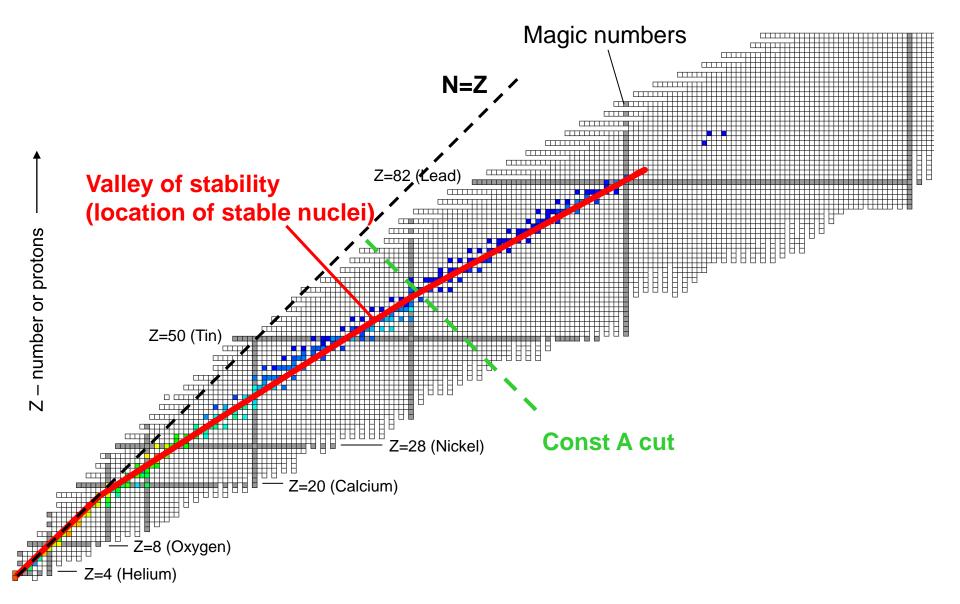


The valley of stability



Const. A cut:

Binding energy per nucleon along const A due to asymmetry term in mass formula

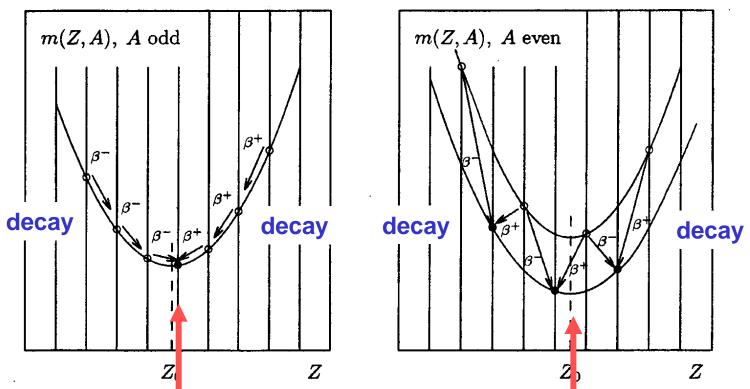


Fig. 4.2 - Mass of nuclei with a fixed A. The stable nuclei are represented by full circles.

(Bertulani & Schechter)

valley of stability

What happens when a nucleus outside the valley of stability is created? (for example in a nuclear reaction inside a star?)

Decay - energetics and decay law

Decay of A in B and C is possible if reaction A → B+C has positive Q-value (again – masses are critical!)

BUT: there might be a barrier that prolongs the lifetime

Decay is described by quantum mechanics and is a pure random process, with a constant probability for the decay of a single nucleus to happen in a given time interval.

N: Number of nuclei A (Parent)

 λ : decay rate (decays per second and parent nucleus)

$$dN = -\lambda Ndt$$

therefore

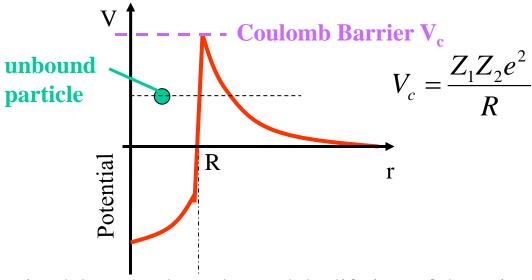
$$N(t) = N(t = 0) e^{-\lambda t}$$

lifetime $\tau=1/\lambda$

half-life $T_{1/2} = \tau \ln 2 = \ln 2/\lambda$ is time for half of the nuclei present to decay

Decay modes

for anything other than a neutron (or a neutrino) emitted from the nucleus there is a Coulomb barrier



If that barrier delays the decay beyond the lifetime of the universe (~ 14 Gyr) we consider the nucleus as being stable.

Example: for 197 Au -> 58 Fe + 139 I has Q ~ 100 MeV ! yet, gold is stable.

→ not all decays that are energetically possible happen

β decay

 $p \longleftrightarrow n$ conversion within a nucleus via weak interaction

Modes (for a proton/neutron in a nucleus):

Electron capture (or EC) of atomic electrons or, in astrophysics, of electrons in the surrounding plasma

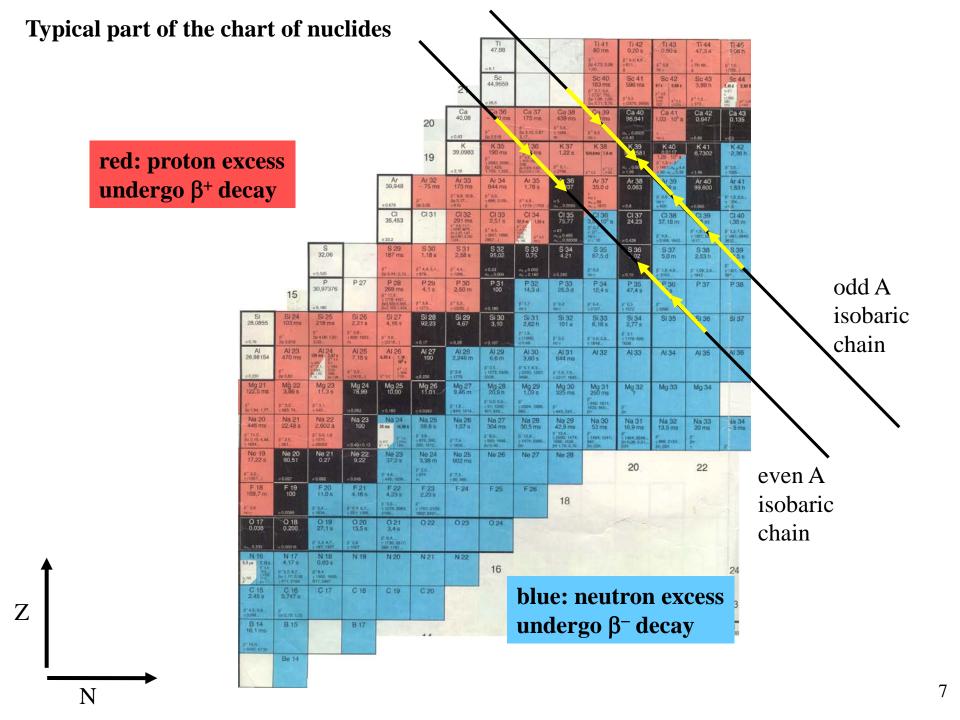
Q-values for decay of nucleus (Z,N)

with nuclear masses

with atomic masses

$$\begin{split} Q_{\beta+} \,/\,\, c^2 &= m_{nuc}(Z,N) \,-\, m_{nuc}(Z-1,N+1) \,-\, m_e \,\, = \mathbf{m}(\mathbf{Z},\mathbf{N}) \,-\, \mathbf{m}(\mathbf{Z}-1,N+1) \,-\, 2\mathbf{m}_e \\ Q_{EC} \,/\,\, c^2 &= m_{nuc}(Z,N) \,-\, m_{nuc}(Z-1,N+1) \,+\, m_e \,\, = \mathbf{m}(\mathbf{Z},\mathbf{N}) \,-\, \mathbf{m}(\mathbf{Z}-1,N+1) \\ Q_{\beta-} \,/\,\, c^2 &= m_{nuc}(Z,N) \,-\, m_{nuc}(Z+1,N-1) \,-\, m_e \,\, = \mathbf{m}(\mathbf{Z},\mathbf{N}) \,-\, \mathbf{m}(\mathbf{Z}+1,N-1) \end{split}$$

Note: $Q_{EC} > Q_{\beta+}$ by 1.022 MeV



Typical β decay half-lives:

very near "stability": occasionally Mio's of years or longer more common within a few nuclei of stability: minutes - days most exotic nuclei that can be formed: ~ milliseconds

Proton or neutron decay:

Usually, the protons and neutrons in a nucleus are bound

→ Q-value for proton or neutron decay is negative

For extreme asymmetries in proton and neutron number nuclei become proton or neutron unbound

→ Proton or neutron decay is then possible

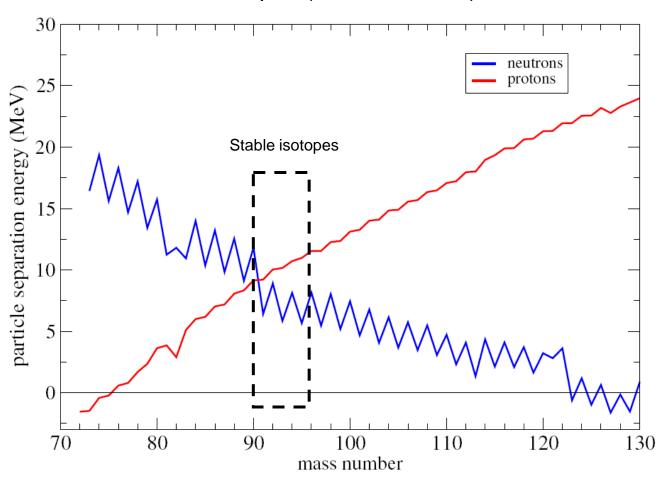
A nucleus that is proton unbound (Q-value for p-decay > 0) is beyond the "**proton drip line**"

A nucleus that is neutron unbound (Q-value for n-decay >0) is beyond the "neutron drip line"

NOTE: nuclei can exist beyond the proton and neutron drip line:

- for very short time
- for a "long" time beyond p-drip if Q-value for p-decay is small (Coulomb barrier!)
- for a long time beyond n-drip at extreme densities inside neutron stars

Zr isotopes (Z=40, N varies)



6.4. α decay

emission of an α particle (= ⁴He nucleus)

Coulomb barrier twice as high as for p emission, but exceptionally strong bound, so larger Q-value

emission of other nuclei does not play a role (but see fission!) because of

- increased Coulomb barrier
- reduced cluster probability

Q-value for α decay:

$$Q_{\alpha} = m(Z, A) - m(Z - 2, A - 4) - m_{\alpha}$$

$$= -B(Z, A) + B(Z - 2, A - 4) + m_{\alpha}$$

$$< 0, \text{ but closer to 0 with larger A,Z}$$

→ large A therefore favored

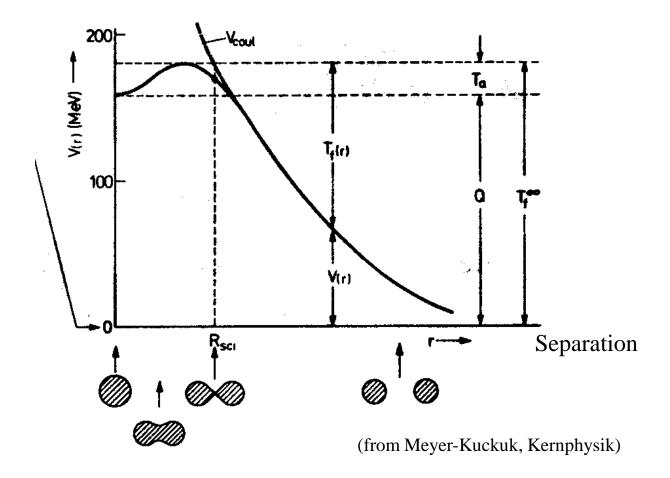
lightest α emitter: ¹⁴⁴Nd (Z=60) (Q α =1.9 MeV but still T_{1/2}=2.3 x 10¹⁵ yr) beyond Bi α emission ends the valley of stability!

The real Property lies and the least lies and the lies and the least lies and the least lies and the least lies and the least lies and the lies and the least lies an																		
C 0278	Ac 209 0,10 s	Ac 210 0,35 s	Ac 211 0,25 s	Ac 212 0,93 s	Ac 213 0.80 s	Ac 214 8,2 s	Ac 215 0,17 s	Ac 216 8,33ms -0,33ms	Ac 217	Ac 218 0,27 μs	Ac 219 7 μs	Ac 220 26 ms	Ac 221 52 ms	AC 222 66 s 4.1s	A			
	7,59		a.7,48			a 7,214; 7,082	α7,604	14.9.028; 14.9.07; 19.00	E E E E	α 9.21	a 8.66	α 7,85; 7,61; 7,68 γ 134	a 7,65; 7,44; 7,38	6.75. 6.89. 7.90. 1-7. c 6.87	a 6 6.5			
	Ra 208	a 7,46 Ra 209	Ra 210	a7,38 Ra 211	α7.36 Ra 212	Ra 213	Ra 214	Ra 215	Ra 216	Ra 217	Ra 218	Ra 219	Ra 220	Ra 221	B			
	1,4 s	4,6 s	3,7 s	13 \$	13 s	2,1 ms 2,74 m/ 1y 546; 0 6,624; 1063; 6,731;	2,46 s a.7,136	1,6 ms	7 ns 0,18 μs 17.688; 476; 344	1,6 µs	14 μs	10 ms	23 ms	28 s α.6,606; 6754;	α6.			
	7,133	α 7,010	α 7,019	0.8.911 £?	□ 8,9006 € 7	n 8,466; 2,7 (10), 8,367 215 6	5	a 8,699	11,828. a 9,349	a 8,99	a 8,39	α7,68; 7,98 Fr 218	α7,46. γ 465 Fr 219	6,661 y89; 152; 176 Fr 220	473	v. 11 c		
	Fr 207 14,8 s	Fr 208 58,6 s	Fr 209 50,0 s	Fr 210 3,18 m	Fr 211 3,10 m	Fr 212 20,0 m	Fr 213 34,6 s	Fr 214 3,35 ms 5,0 ms	Fr 215 0,09 μs	Fr 216 0,70 μs	Fr 217 22 μs	21 ms ? 0,7 ms	21 ms	27,4 5 a 6,68; 6,63 6,58		yello		
1 4	6,767	a 6,636 7,636, 779; 325	a 6,648	α.6.543 ε √644; 817	a 6.535 £ 7.540; 918; 281	6,102,6,364 6,400,6,340 /1074,227,1185	u 6,775	n 8,477; at 8,426; 8,547; 8,356	a 9,36	α9,01	α 8,315	a 4:7,867; by 7 7,572	α 7,313 γ (352; 530)	6,58 β γ45, 106, 152	7 2 100	are c	<i>e</i> mitter	
	Rn 206 5,67 m	Rn 207 9,3 m	Rn 208 24.4 m	Rn 209 28,5 m	Rn 210 2.4 h	Rn 211	Rn 212 24 m	Rn 213 25 ms	Rn 214	Rn 215 2,3 µs	Rn 216 45 µs	Rn 217 0,54 ms	Rn 218 35 ms	Rn 219 3,96 s	P			
263 (t	6,260,; r 498; 325;	ε; α 6,133 β γ,345; 747	a 6,141e y 251; 350; 287; 952	ε; α 6,039 β* 2,2; 2,6 γ 408, 746, 338; 689	α 6,040 ε γ 458; (571; 649; 73)	65.783.5,851 7.674; 1363, 678g	α 6.264	α 8,09	ly 182.	α 8,67	a 8,05		α 7,133	o. 8,619; 6 553; 6.425	α6, γ(5			
3	At 205	At 206	At 207	338; 689 At 208	649; 73) At 209	678g	At 211	At 212	a 10,63. a 9,04 At 213	At 214	At 215	α7,740 At 216	y (609) At 217	γ 271; 402 At 218	A			
2 m	26,2 m a 5,902	29,4 m	1,8 h	1,63 h	5,4 h	8,3 h e: a 5,524, 5,442; 5,361	7,22 h	119 ms 314 ms a7.68;	0,11 μs	565 ns 790 ns	0,1 ms	0,3 ms	32,3 ms a 7,069	~ 2 s a 6,694; 6,153	· ·			
6	719: 669: 529: g	r; p ⁺ 3,1; 3,5 n 5,703 y 701; 477; 396	α.5,759 γ.815; 588: 301; g	α 5,640 γ 686; 660; 177	7,545; 782; 790	y 1181; 245; 1483	α 5,867 γ (687)	7.90 7.63 7.63 8	α 9,08	α 8,819 g	α 8,026 γ (405)	α7,800;7,697 γ (115)	y (259; 334; 595)	β γ	β-1			
	Po 204 3,53 h	Po 205 1,80 h	Po 206 8,8 d	Po 207 2,8 s 5,84 h	Po 208 2,898 a	Po 209 102 a	Po 210 138,38 d α 5,30438	Po 211 25,2 s 0,516 s 0.7,270.	Po 212	Po 213 4,2 μs	Po 214 164 μs	Po 215 1,78 ms	Po 216 0,15 s	Po 217 < 10 s	3			
15,384 y 909 1091; 894	15,377 884; 270;	(; β*; α 5,22 γ 872; 1001; 850; 837	ε; α 5,2233 γ 1032; 511; 286; 807 ε; g	Fy 815; 14 5, 116 7 992; 268; 743; 301 912 g	α 5,1152 ε γ (292; 571)	α 4,881 ε γ (895; 261; 263)	γ (803) σ < 0,0005+ < 0,030	8,883. et 7,450. y 570; y (570, 1064; 898; (898.) 328)	11,65 405. 223 72615: a a 583 10,22 6,784	α 8,376 Υ	α 7,6869 γ (800; 298)	α 7,3862 β γ (439)	α 6,7783 γ (805)	α.6,539 β	α 6, β			
202	Bi 203 11,76 h	Bi 204 11,22 h	Bi 205 15,31 d	Bi 206 6,24 d	Bi 207 33,4 a	Bi 208 3,68 10 ⁵ a	Bi 209 100	Bi 210 3,0-10 ⁸ al 5,013 d	Bi 211 2,17 m	Bi 212	Bi 213 45,59 m	Bi 214 19,9 m	Bi 215 7,4 m					
	(; ß* 1,4 (820; 825; 897; 1848	y 899; 375; 984	β+ γ 1764; 703;	E +	β 9 570: 1064:			n 4,946; p 1,2 4,908. n 4,649; 7,286. 4,669 -1709	x 6,6229; 6,2788 β" y 351	6.30 a 6.051 6.09(. 5e t0.22 7/2/	β* 1,4 α 5,87 γ 440; (293; 1100)	(i 1.5, 3.3 (i 5.450; 5.513 (i 809; 1764; 1120						
9	Pb 202	9:m Pb 203	Pb 204	γ803,881,516, 17.19,537 Pb 205	Pb 206	Pb 207	e 0,014±0.019 Pb 208	Pb 209	Pb 210	Pb 211	Pb 212	Pb 213	Pb 214	Serveniel .				
	62 h ~ 3 961) 10 ⁵ a	6,2 s 51,9 h	1.4 67,2 m > 1.4-	1,5·10 ⁷ a	24,1	22,1	52,4	3,253 h	22,3 a 6 0,02; 0.06 7 47; e 6 3,72; g 6 0,5	36,1 m _{fi□ 1,4}	10,64 h 6 0.9:0,6 7 239:300	10,2 m	26,8 m	1 57				
7331 787 761 74 945 460	7 s 190; 0; 390. f no. T	hy 825. F 279.	912: a 2.67 375 a 0.661	ε no γ	a 0,0305	a 0,709	a 0,000487	рт 0,6 по у		7 405; 832. 427	γ 239, 300 9	p.	y 352, 295, 242					
200 i,1 h	TI 201 73,1 h	TI 202 12,23 d	TI 203 29,524	TI 204 3,78 a	TI 205 70,476	TI 206	TI 207	TI 208 3,053 m	TI 209 2,20 m	TI 210 1,30 m			132					
1206; E	v 167: 135	v 440: (520)	a 11,0	8 0.8 r no y 9 o 21,6	a 0.10	453, 216, 266, 1021, 7(803,)	17 1000; p 1.4 251 y(891)	(5° 1.8; 2.4 y 2615; 583; 511; 860; 277	(F 1.8 y 465; 1566; 117	β 1.9: 2.3 γ 800: 298 βn		1	102					
SECONO 1	Hg 200 23,1	Hg 201	Hg 202 29,65	Hg 203 46,59 d	Hg 204 6,8	Hg 205	Hg 206 8,15 m	Hg 207			T BE							
17.0	23,1	13,2	20,00		3 4		ß" 1,3 у 305; 650	B	128	130								
Distance of the last	o < 60 Au 199	o < 60 Au 200	a4,9 Au 201	β 0,2 γ 279 Au 202	o 0,43 Au 203	β 1.5 γ 204 Au 204	9	Y	_									
2,6935d	3, 139 d 8 0,3, 0,5 y 158; 208	18,7 h 48,4 m	26,4 m	28 s		40 s	126		4	the higher the Q-value the easier the Coulomb barrier can be overcome (Penetrability $\sim \exp(-\cosh \cdot E^{-1/2})$)								
y 412 G ir 25100 0	g n 30	(T 0 9 1366,498; 7 388; 579,256; 1226; 1283	γ 543; 517; 613; 167	β*3.5 γ 440: 1125: 1307: 1204		β" γ.437; 1511												
197 18,3 h	Pt 198 7,2	Pt 199 13,6 s 30,8 m	Pt 200 12,5 h	Pt 201 2,5 m	124				LISH,									
177	o 0.027 + 3.7	by 392 y543 494 32 317 186	β 0,6; 0,7 γ 76; 136; 244; 60; 227	β*2.7 γ 1760	124													
196	Ir 197	Ir 198 8 s							- 11									
52 s 8,5	.9 m 5,8 m	0.5		1						and the shorter the α-decay half-lives								

6.5. Fission

Very heavy nuclei can fission into two parts (Q>0 if heavier than ~iron already)

For large nuclei surface energy less important - large deformations less prohibitive. Then, with a small amount of additional energy (Fission barrier) nucleus can be deformed sufficiently so that coulomb repulsion wins over nucleon-nucleon attraction and nucleus fissions.

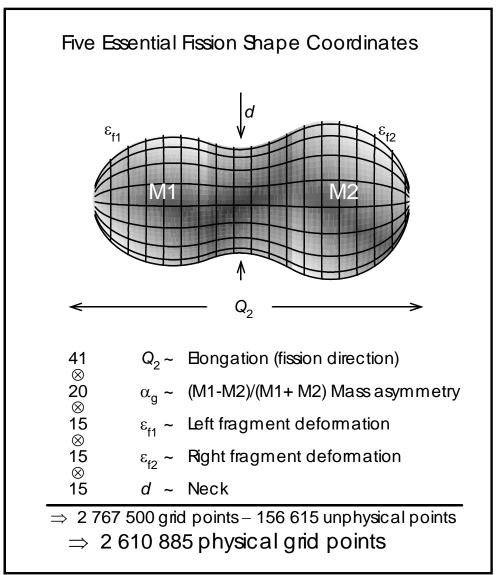


Real fission barriers:

Fission barrier depends on how shape is changed (obviously, for example. it is favourable to form a neck).

Real theories have many more shape parameters - the fission barrier is then a landscape with mountains and valleys in this parameter space. The minimum energy needed for fission along the optimum valley is "the fission barrier"

Example for parametrization in Moller et al. Nature 409 (2001) 485



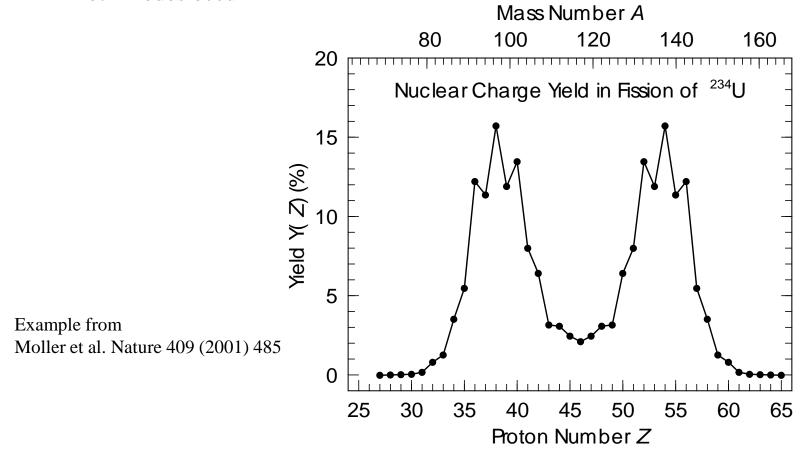
Fission fragments:

Naively splitting in half favourable (symmetric fission)

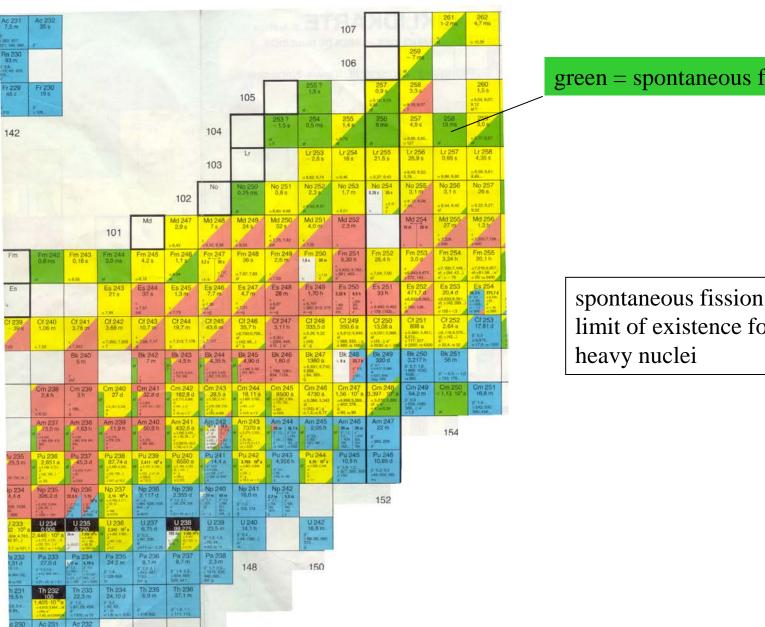
There is a asymmetric fission mode due to shell effects

(somewhat larger or smaller fragment than exact half might be favoured if more bound due to magic neutron or proton number)

Both modes occur



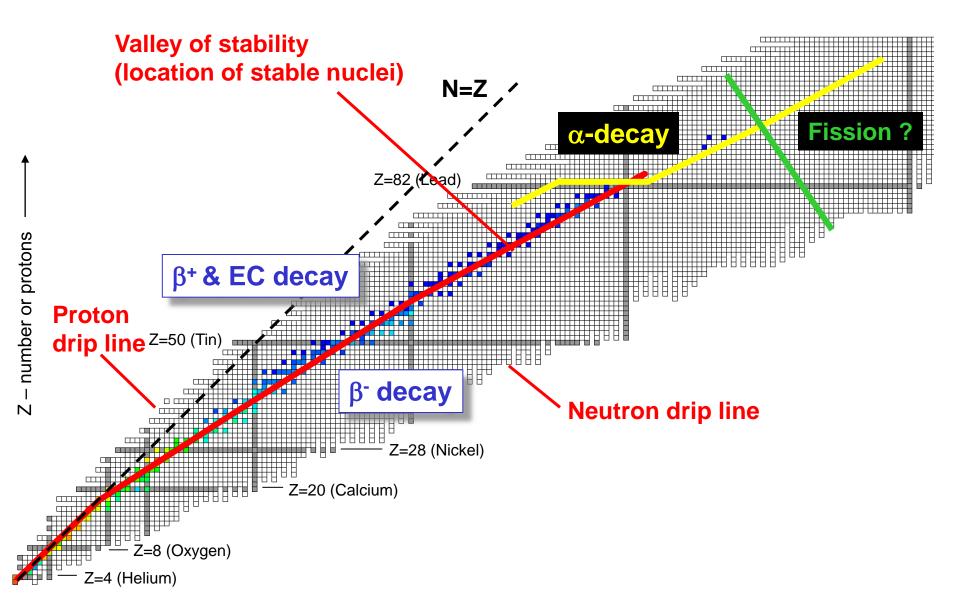
If fission barrier is low enough spontaneous fission can occur as a decay mode



green = spontaneous fission

spontaneous fission is the limit of existence for

Summary



Solar abundances and nuclear physics

