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Synthesis of the elements

Introduction : Getting past Nickel

- Although low-mass stars generate C, O and even up to Ne, Mg the new elements are trapped in the WD

- Therefore elements up to Nickel that reach the ISM come from core collapse supernovae.

- ~~Loots~~ Lots of elements around Nickel come from thermonuclear supernova (about 50%)

- We find in nature ~~in nature~~ essentially every isotope with a half-life of ~~less than~~ greater than a billion years and many with shorter ones

- They had to be made in stars.

- We have seen many binary, trinary and reactions add an alpha particle but there are other possibilities.

Remember:

The most stable nuclei have about the same number of protons and neutrons with the neutron fraction increasing for larger nuclei.

Let's look near the valley of stability around Fe-56

Ni			56	57	58	59	60	61	62
Co		54	55	56	57	58	59	60	61
Fe	52	53	54	55	56	57	58	59	60
Mn		52	53	54	55	56	57	58	59

Rules of the game:

(1) Add a proton to go up

(2) Add a neutron to go right

Either repeat or wait for β-decay

Add neutrons slowly yields the s-process; some "happy" nuclei have really low neutron σ so these build up. (a) Nothing Bi to Th

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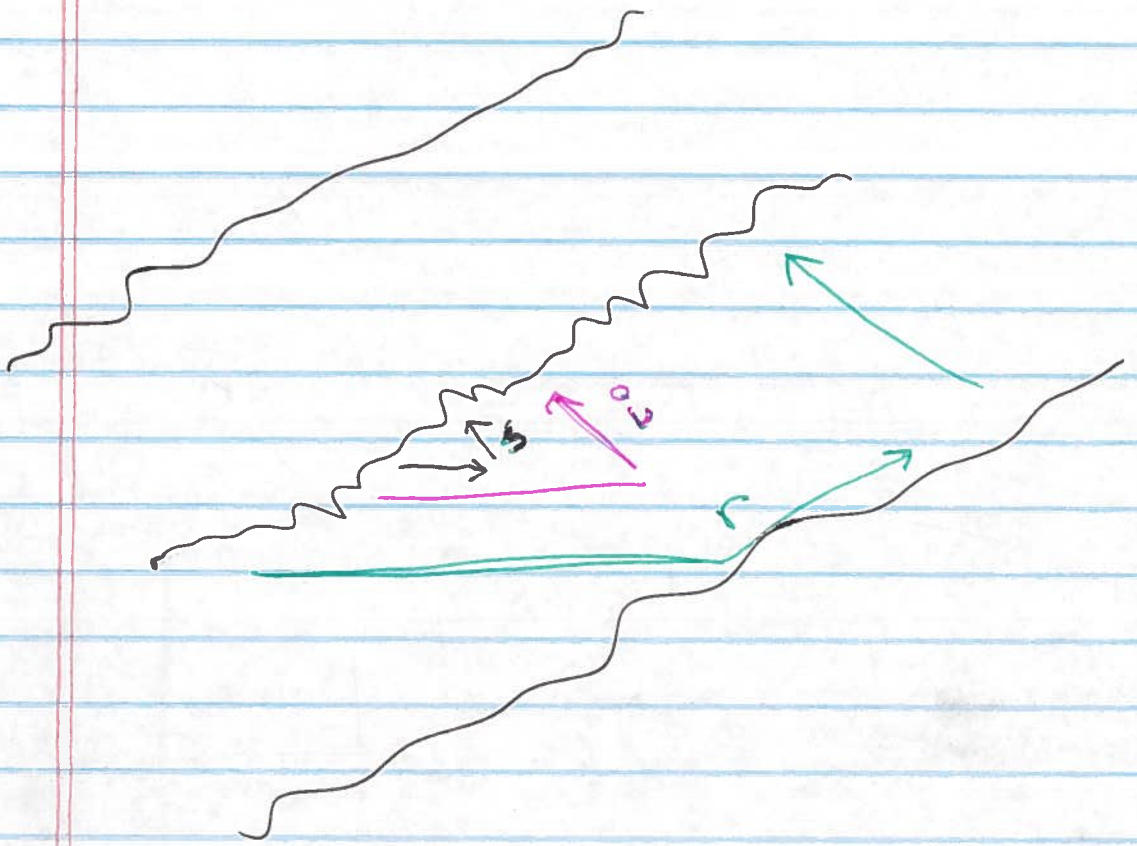
Neutron Capture Schematically



- slow-neutron capture can only access nuclei on ~~the~~ the right side of the ridge of stability $\tau_\beta << \tau_{n\gamma}$
  - Cannot access proton-rich side
  - Cannot access stable nuclei that are isolated
- faster neutron capture $\tau_{n\gamma} << \tau_\beta$
  - can access all neutron-rich stable nuclides
  - can go past Pb to U.
  - But where is it?

The s-process (in general)

$$\tau_\beta << \tau_{n\gamma} = (\rho Y_n \lambda_{n\gamma})^{-1}$$

Small neutron densities

in massive star: $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$

suppose equilibrium between production and capture

$$\frac{dY_n}{dt} \simeq 0 \sim Y(^{22}\mathrm{Ne})\rho\lambda_{\alpha n}(^{22}\mathrm{Ne})Y_\alpha - Y(^{56}\mathrm{Fe})Y_n\rho\lambda_{n\gamma}(^{56}\mathrm{Fe})$$

T_8	$\lambda_{\alpha n}$	$\lambda_{n\gamma}$	$n=\rho N_A Y_n$
2.5	$2.4\cdot10^{-13}$	$1.9\cdot10^{6}$	$10^{8}\ \mathrm{cm}^{-3}$
3	$1.9\cdot10^{-11}$	$1.9\cdot10^{6}$	$10^{10}\ \mathrm{cm}^{-3}$
3.5	$5.6\cdot10^{-10}$	$1.9\cdot10^{6}$	$3\cdot10^{11}\ \mathrm{cm}^{-3}$

- Typical timescale for neutron additions is days to years

- Some nuclides have $\lambda_{n\gamma}$ 100x $\lambda_{n\gamma}(^{56}\mathrm{Fe})$

Reaction Rates

- $Q_{n\gamma} \approx 8\,\text{MeV}$ so reaction yields a new nucleus excited by 8 MeV

- No electrostatic repulsion so

$$\sigma_{n\gamma} \sim \pi \bar{\lambda}^2 \frac{\overset{\text{prob to make}\rightarrow}{\Gamma_n} \Gamma_\gamma \leftarrow \text{decay as photon}}{\Gamma_n + \Gamma_\gamma \leftarrow \text{all ways to decay}}$$

- usually $\Gamma_p + \Gamma_\alpha$ not important

- For low energies $\lesssim \text{keV}$ $\Gamma_n \ll \Gamma_\gamma$ so

$$\sigma_{n\gamma} \sim \pi \lambda^2 \Gamma_n \qquad \Gamma_n \propto E^{1/2}$$

$$\langle \sigma v \rangle \sim \frac{1}{E} E^{1/2} E^{1/2} \approx \text{constant}$$

- For large energies $E_n \gg 1\,\text{keV}$ $\Gamma_\gamma \ll \Gamma_n$ so

$$\sigma_{n\gamma} \sim \pi \lambda^2 \Gamma_\gamma$$

Γ_γ depends on
- phase space for photon
- # levels to decay
- matrix elements

Two things to know

(1) Γ_γ increases dramatically with $Q_{n\gamma}$

- capture onto magic + even-even nuclei is small
- capture onto odd $\overset{N}{\ }$nuclei large especially if going to magic

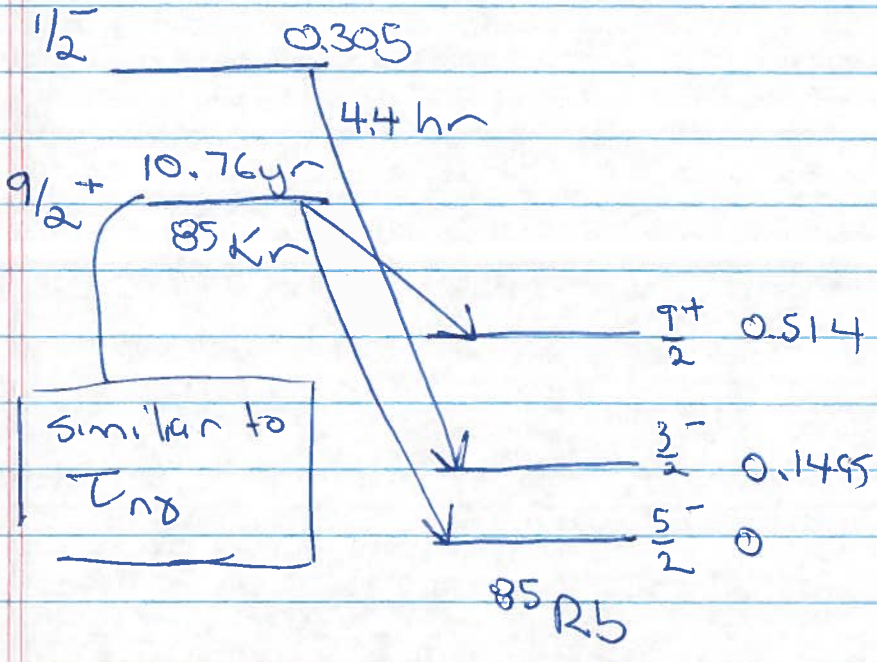
(2) Γ_γ doesn't depend much on temperature $E_n \sim 30\,\mathrm{keV} << Q_n \approx 8\,\mathrm{M}$

$$\langle \sigma v \rangle \sim E_n^{1/2} \frac{1}{E_n} \Gamma_\gamma \sim \frac{\Gamma_\gamma}{E_n^{1/2}}$$

E_n varies by a factor of four and Γ_γ does increase slightly so $\langle \sigma v \rangle$ is about constant!

Usually β-decay aren't sensitive to temperature but sometimes can be important!

- Measure the temperature of s-process!



Other examples ^{93}Zr, ^{113}Cd, ^{134}Cs, ^{151}Sm

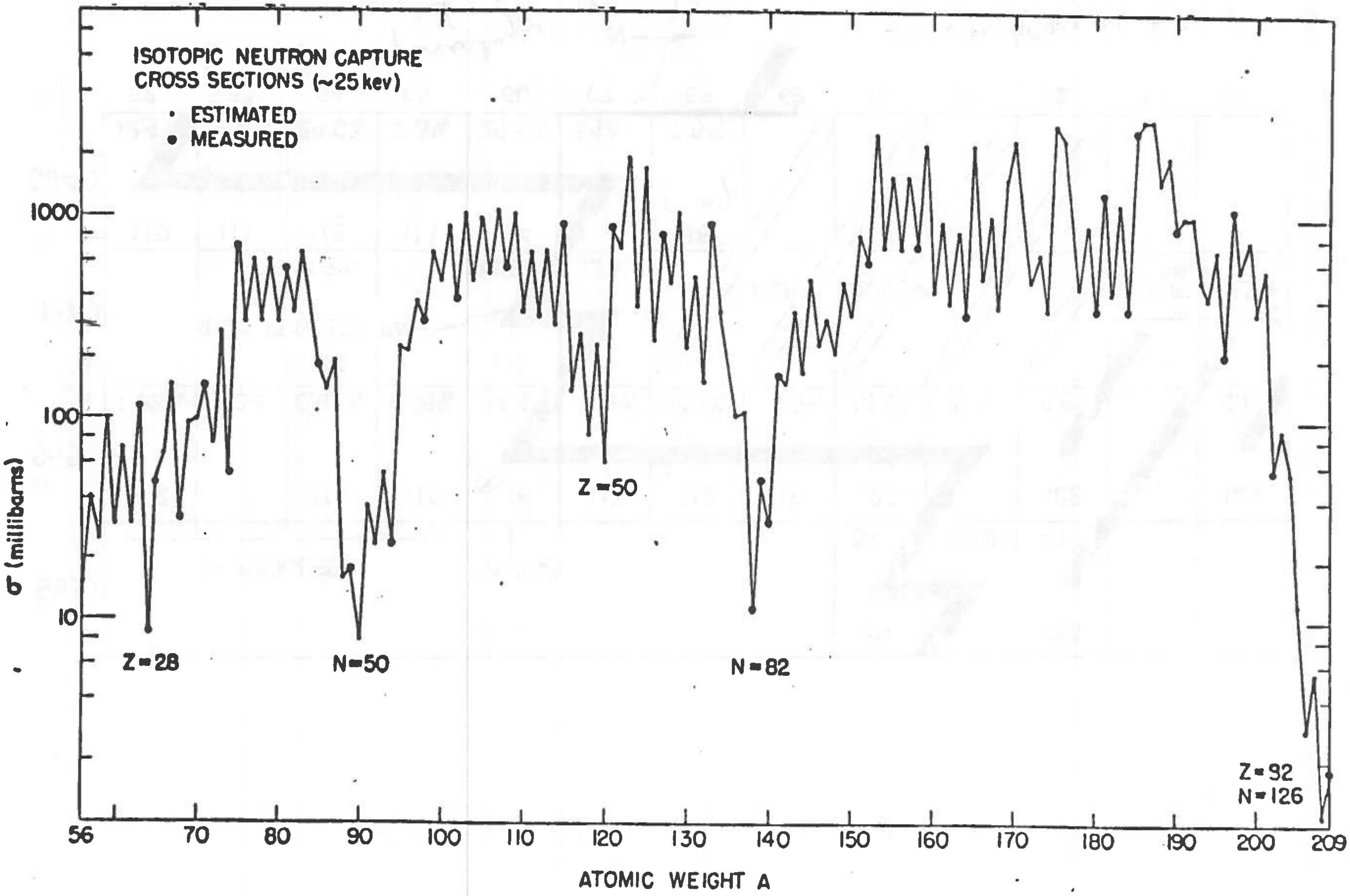
- - -

∘ Neutron capture ~~so~~ cross sections vary ~~for~~ from about 10^{-2} barn for magic nuclei (N = 28, 50, 82, 126 $Z=50$ to 1 barn for nuclei ~~far~~ from magic

- broad minima around magic nucle
- odd-even variation by a factor of three

∘ Nuclei with low $\sigma_{n\gamma}$ ~~accumulate~~ build up

∘ Nuclei with high $\sigma_{n\gamma}$ move along


ISOTOPIC NEUTRON CAPTURE CROSS SECTIONS (~25 kev)
· ESTIMATED
● MEASURED
σ (millibarns)
1000
100
10
Z=28
N=50
Z=50
N=82
Z=92
N=126
56
70
80
90
100
110
120
130
140
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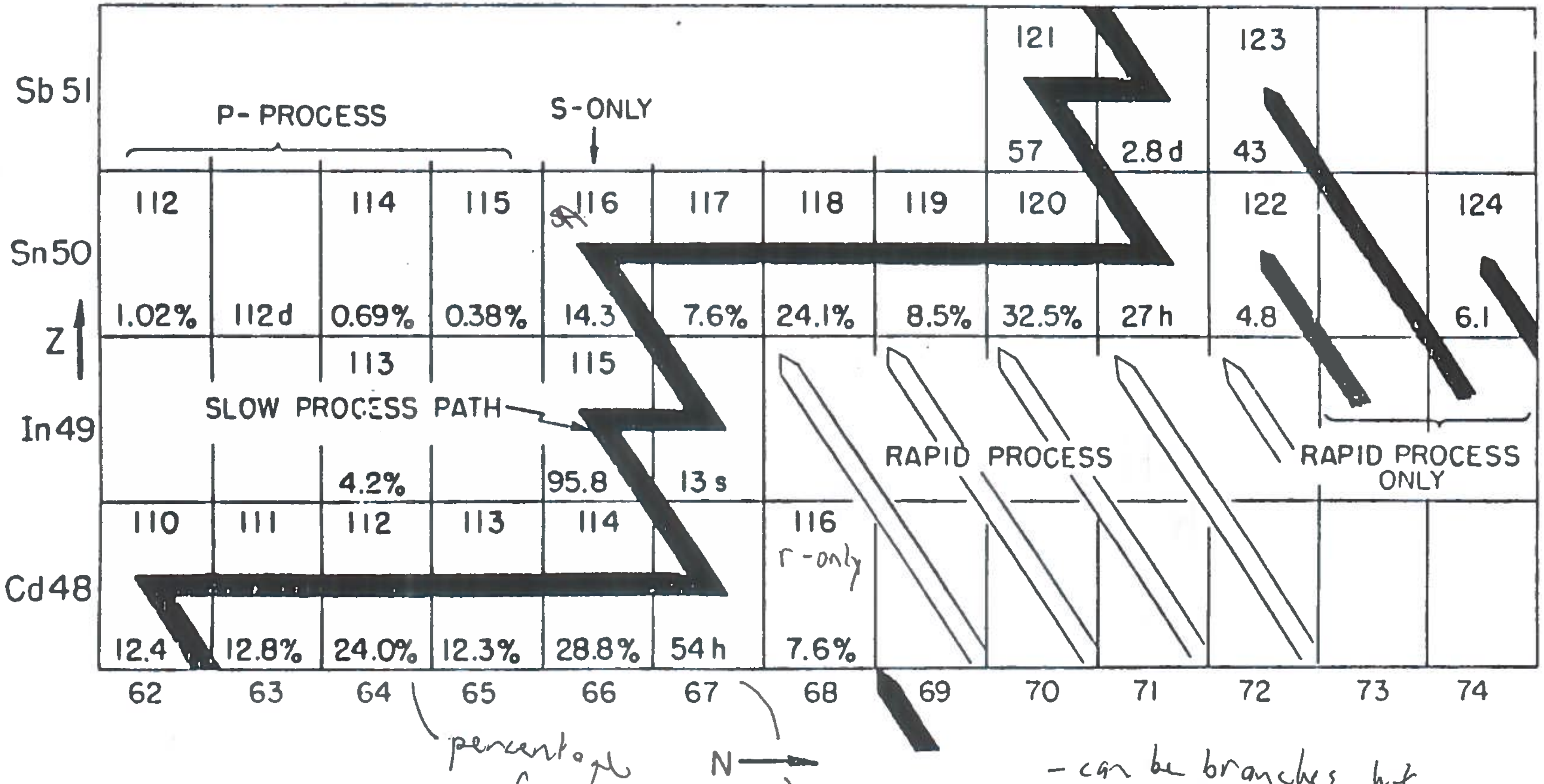
160
170
180
190
200
209
ATOMIC WEIGHT A



percentage of Cd in nature as ^{64}Cd

half-life

- can be branches, but to zeroth order there is only one s-process element per A-value.

K. Cosner PhD Urbana 1982

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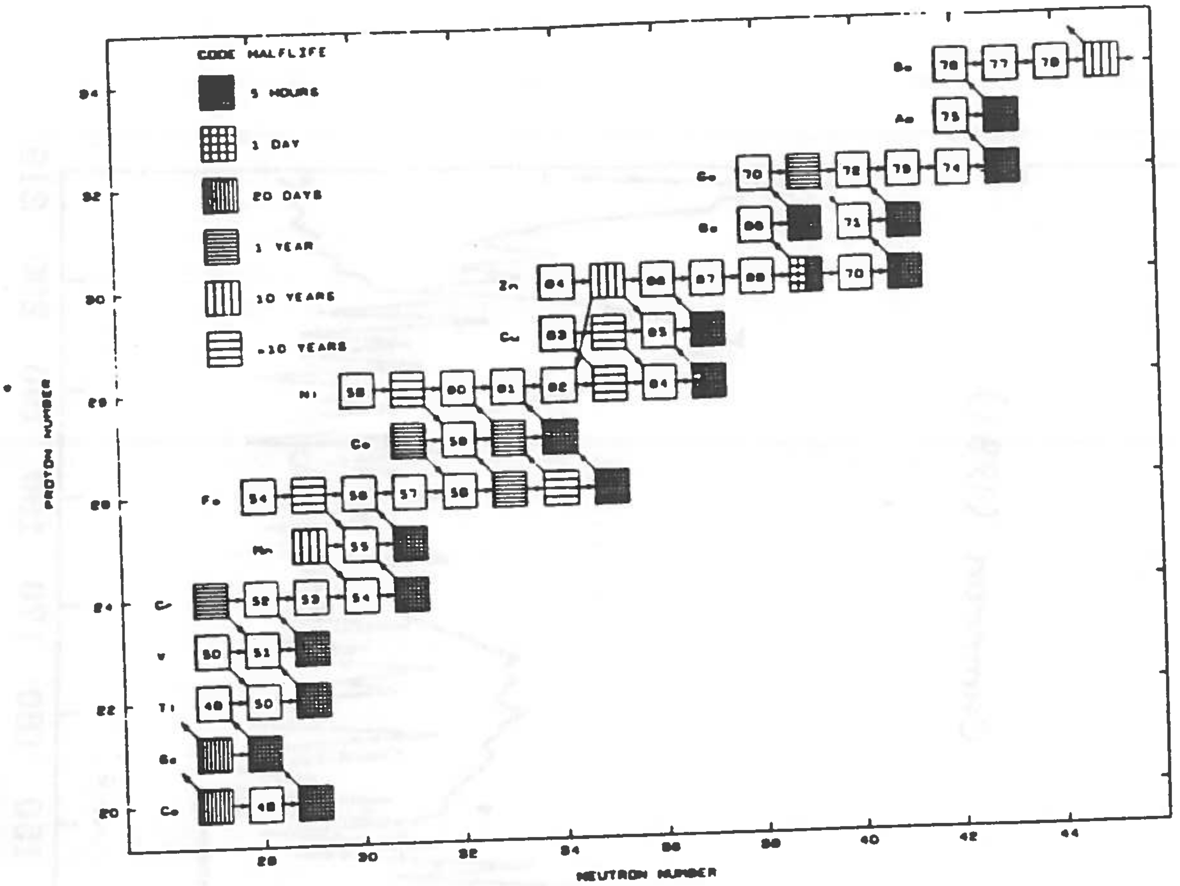

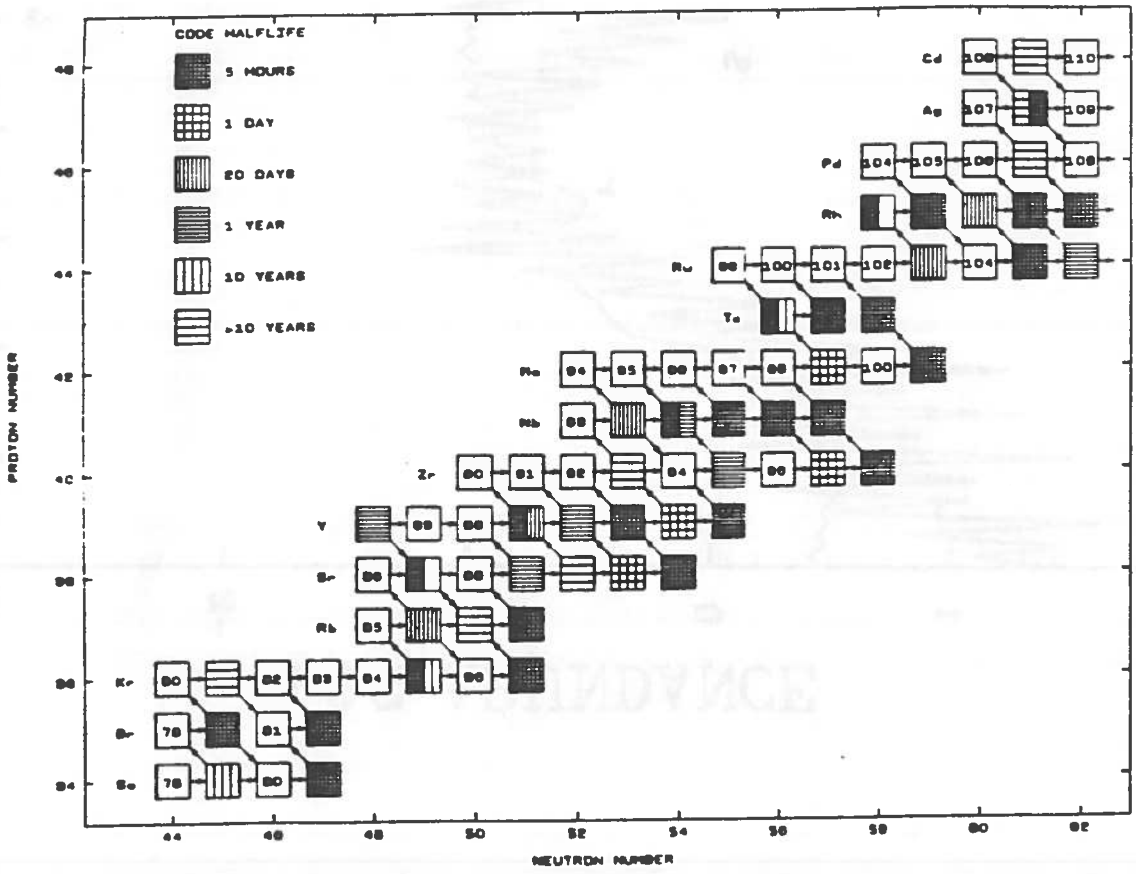

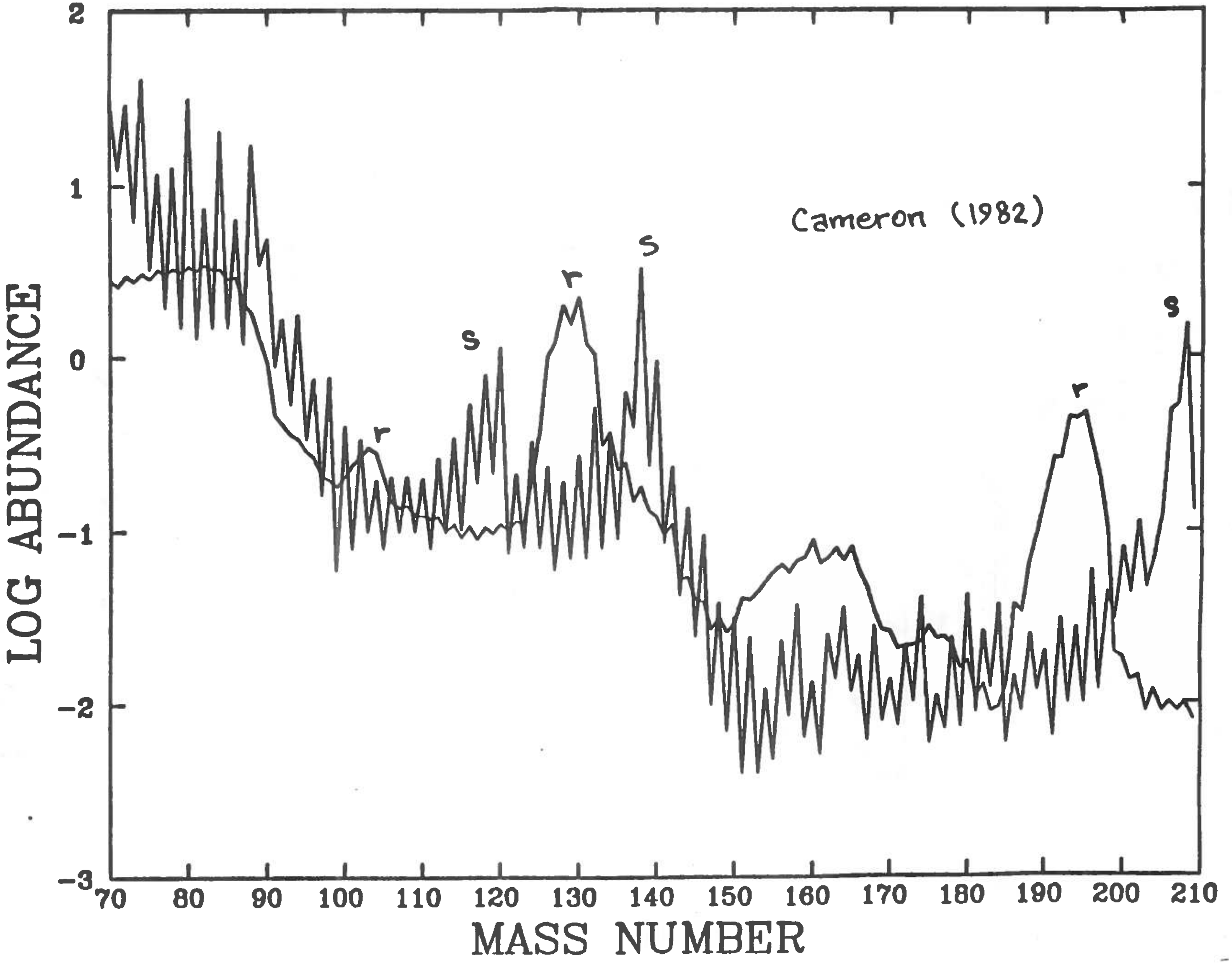
Cameron (1982)
s
r
s
r
r
s
LOG ABUNDANCE
2
1
0
−1
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MASS NUMBER
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80
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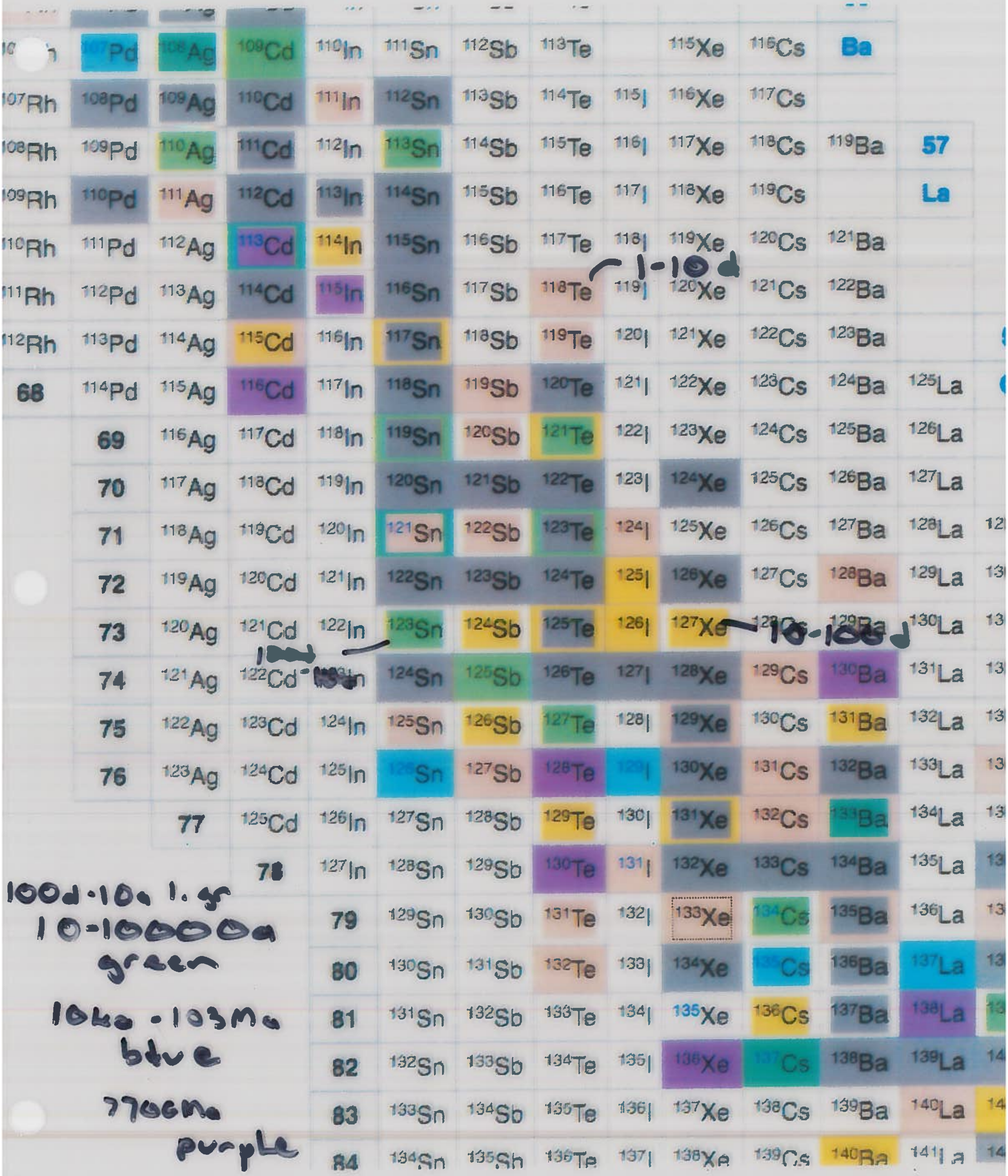


^{10}Rh	^{107}Pd	^{108}Ag	^{109}Cd	^{110}In	^{111}Sn	^{112}Sb	^{113}Te		^{115}Xe	^{116}Cs	Ba		
^{107}Rh	^{108}Pd	^{109}Ag	^{110}Cd	^{111}In	^{112}Sn	^{113}Sb	^{114}Te	^{115}I	^{116}Xe	^{117}Cs			
^{108}Rh	^{109}Pd	^{110}Ag	^{111}Cd	^{112}In	^{113}Sn	^{114}Sb	^{115}Te	^{116}I	^{117}Xe	^{118}Cs	^{119}Ba	57	
^{109}Rh	^{110}Pd	^{111}Ag	^{112}Cd	^{113}In	^{114}Sn	^{115}Sb	^{116}Te	^{117}I	^{118}Xe	^{119}Cs		La	
^{110}Rh	^{111}Pd	^{112}Ag	^{113}Cd	^{114}In	^{115}Sn	^{116}Sb	^{117}Te	^{118}I	^{119}Xe	^{120}Cs	^{121}Ba		
^{111}Rh	^{112}Pd	^{113}Ag	^{114}Cd	^{115}In	^{116}Sn	^{117}Sb	^{118}Te	^{119}I	^{120}Xe	^{121}Cs	^{122}Ba		
^{112}Rh	^{113}Pd	^{114}Ag	^{115}Cd	^{116}In	^{117}Sn	^{118}Sb	^{119}Te	^{120}I	^{121}Xe	^{122}Cs	^{123}Ba		
68	^{114}Pd	^{115}Ag	^{116}Cd	^{117}In	^{118}Sn	^{119}Sb	^{120}Te	^{121}I	^{122}Xe	^{123}Cs	^{124}Ba	^{125}La	
	69	^{116}Ag	^{117}Cd	^{118}In	^{119}Sn	^{120}Sb	^{121}Te	^{122}I	^{123}Xe	^{124}Cs	^{125}Ba	^{126}La	
	70	^{117}Ag	^{118}Cd	^{119}In	^{120}Sn	^{121}Sb	^{122}Te	^{123}I	^{124}Xe	^{125}Cs	^{126}Ba	^{127}La	
	71	^{118}Ag	^{119}Cd	^{120}In	^{121}Sn	^{122}Sb	^{123}Te	^{124}I	^{125}Xe	^{126}Cs	^{127}Ba	^{128}La	12
	72	^{119}Ag	^{120}Cd	^{121}In	^{122}Sn	^{123}Sb	^{124}Te	^{125}I	^{126}Xe	^{127}Cs	^{128}Ba	^{129}La	13
	73	^{120}Ag	^{121}Cd	^{122}In	^{123}Sn	^{124}Sb	^{125}Te	^{126}I	^{127}Xe	^{128}Cs	^{129}Ba	^{130}La	13
	74	^{121}Ag	^{122}Cd	[illegible]	^{124}Sn	^{125}Sb	^{126}Te	^{127}I	^{128}Xe	^{129}Cs	^{130}Ba	^{131}La	13
	75	^{122}Ag	^{123}Cd	^{124}In	^{125}Sn	^{126}Sb	^{127}Te	^{128}I	^{129}Xe	^{130}Cs	^{131}Ba	^{132}La	13
	76	^{123}Ag	^{124}Cd	^{125}In	^{126}Sn	^{127}Sb	^{128}Te	^{129}I	^{130}Xe	^{131}Cs	^{132}Ba	^{133}La	13
		77	^{125}Cd	^{126}In	^{127}Sn	^{128}Sb	^{129}Te	^{130}I	^{131}Xe	^{132}Cs	^{133}Ba	^{134}La	13
			78	^{127}In	^{128}Sn	^{129}Sb	^{130}Te	^{131}I	^{132}Xe	^{133}Cs	^{134}Ba	^{135}La	13
				79	^{129}Sn	^{130}Sb	^{131}Te	^{132}I	^{133}Xe	^{134}Cs	^{135}Ba	^{136}La	13
				80	^{130}Sn	^{131}Sb	^{132}Te	^{133}I	^{134}Xe	^{135}Cs	^{136}Ba	^{137}La	13
				81	^{131}Sn	^{132}Sb	^{133}Te	^{134}I	^{135}Xe	^{136}Cs	^{137}Ba	^{138}La	13
				82	^{132}Sn	^{133}Sb	^{134}Te	^{135}I	^{136}Xe	^{137}Cs	^{138}Ba	^{139}La	14
				83	^{133}Sn	^{134}Sb	^{135}Te	^{136}I	^{137}Xe	^{138}Cs	^{139}Ba	^{140}La	14
				84	^{134}Sn	^{135}Sb	^{136}Te	^{137}I	^{138}Xe	^{139}Cs	^{140}Ba	^{141}La	14

~1-10 d

~10-100 d

1[illegible]

100d-10a l. gr

10-10000a
green

10ka-103Ma
blue

770GMa
purple

- For a particular element the s-process yield $\propto (\sigma)^{-1}$

e.g. Tellurium		$Z=52$	n_0 (rel 10^6 Si)	σN
^{120}Te	p	484	$5.8 \cdot 10^{-3}$	2.8
^{122}Te	s only	295	0.159	46.9
^{123}Te	s-only	822	0.058	47.7
^{124}Te	s-only	162	0.295	48.4
^{125}Te	s, r	444	0.454 (0.3405)	201 (150 r)
^{126}Te	s, r	80	1.22 (0.61)	98 (50 r)
^{128}Te	r	39	2.07	81
^{129}Te	r	15.5	2.24	35

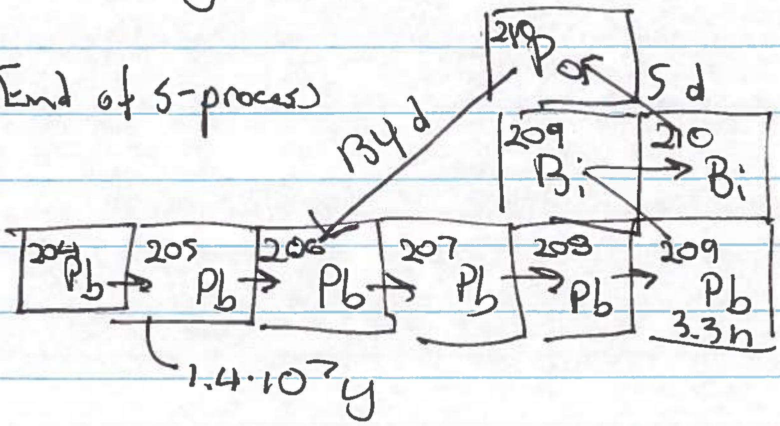
~~substr.~~ subtract s to get r

^{130}Ce		**Nd**								
^{131}Ce	^{132}Pr		**61**	**62**	**63**					
^{132}Ce	^{133}Pr	^{134}Nd	**Pm**	**Sm**	**Eu**					
^{133}Ce	^{134}Pr	^{135}Nd		^{137}Sm		**64**				
^{134}Ce	^{135}Pr	^{136}Nd	^{137}Pm	^{138}Sm	^{139}Eu	**Gd**				
^{135}Ce	^{136}Pr	^{137}Nd	^{138}Pm	^{139}Sm	^{140}Eu					
^{136}Ce	^{137}Pr	^{138}Nd	^{139}Pm	^{140}Sm	^{141}Eu	^{142}Gd				
^{137}Ce	^{138}Pr	^{139}Nd	^{140}Pm	^{141}Sm	^{142}Eu	^{143}Gd	**65**	**66**	**67**	
^{138}Ce	^{139}Pr	^{140}Nd	^{141}Pm	^{142}Sm	^{143}Eu	^{144}Gd	**Tb**	**Dy**	**Ho**	
^{139}Ce	^{140}Pr	^{141}Nd	^{142}Pm	^{143}Sm	^{144}Eu	^{145}Gd	^{146}Tb	^{147}Dy		
^{140}Ce	^{141}Pr	^{142}Nd	^{143}Pm	^{144}Sm	^{145}Eu	^{146}Gd	^{147}Tb	^{148}Dy		1
^{141}Ce	^{142}Pr	^{143}Nd	^{144}Pm	^{145}Sm	^{146}Eu	^{147}Gd	^{148}Tb	^{149}Dy	^{150}Ho	1
^{142}Ce	^{143}Pr	^{144}Nd	^{145}Pm	^{146}Sm	^{147}Eu	^{148}Gd	^{149}Tb	^{150}Dy	^{151}Ho	1
^{143}Ce	^{144}Pr	^{145}Nd	^{146}Pm	^{147}Sm	^{148}Eu	^{149}Gd	^{150}Tb	^{151}Dy	^{152}Ho	1
^{144}Ce	^{145}Pr	^{146}Nd	^{147}Pm	^{148}Sm	^{149}Eu	^{150}Gd	^{151}Tb	^{152}Dy	^{153}Ho	1
^{145}Ce	^{146}Pr	^{147}Nd	^{148}Pm	^{149}Sm	^{150}Eu	^{151}Gd	^{152}Tb	^{153}Dy	^{154}Ho	1
^{146}Ce	^{147}Pr	^{148}Nd	^{149}Pm	^{150}Sm	^{151}Eu	^{152}Gd	^{153}Tb	^{154}Dy	^{155}Ho	1
^{147}Ce	^{148}Pr	^{149}Nd	^{150}Pm	^{151}Sm	^{152}Eu	^{153}Gd	^{154}Tb	^{155}Dy	^{156}Ho	1
^{148}Ce	^{149}Pr	^{150}Nd	^{151}Pm	^{152}Sm	^{153}Eu	^{154}Gd	^{155}Tb	^{156}Dy	^{157}Ho	1
^{149}Ce	^{150}Pr	^{151}Nd	^{152}Pm	^{153}Sm	^{154}Eu	^{155}Gd	^{156}Tb	^{157}Dy	^{158}Ho	1
^{150}Ce	^{151}Pr	^{152}Nd	^{153}Pm	^{154}Sm	^{155}Eu	^{156}Gd	^{157}Tb	^{158}Dy	^{159}Ho	1
93			^{154}Pm	^{155}Sm	^{156}Eu	^{157}Gd	^{158}Tb	^{159}Dy	^{160}Ho	1
	94	^{154}Nd		^{156}Sm	^{157}Eu	^{158}Gd	^{159}Tb	^{160}Dy	^{161}Ho	1
		95		^{157}Sm	^{158}Eu	^{159}Gd	^{160}Tb	^{161}Dy	^{162}Ho	1
			96		^{159}Eu	^{160}Gd	^{161}Tb	^{162}Dy	^{163}Ho	1

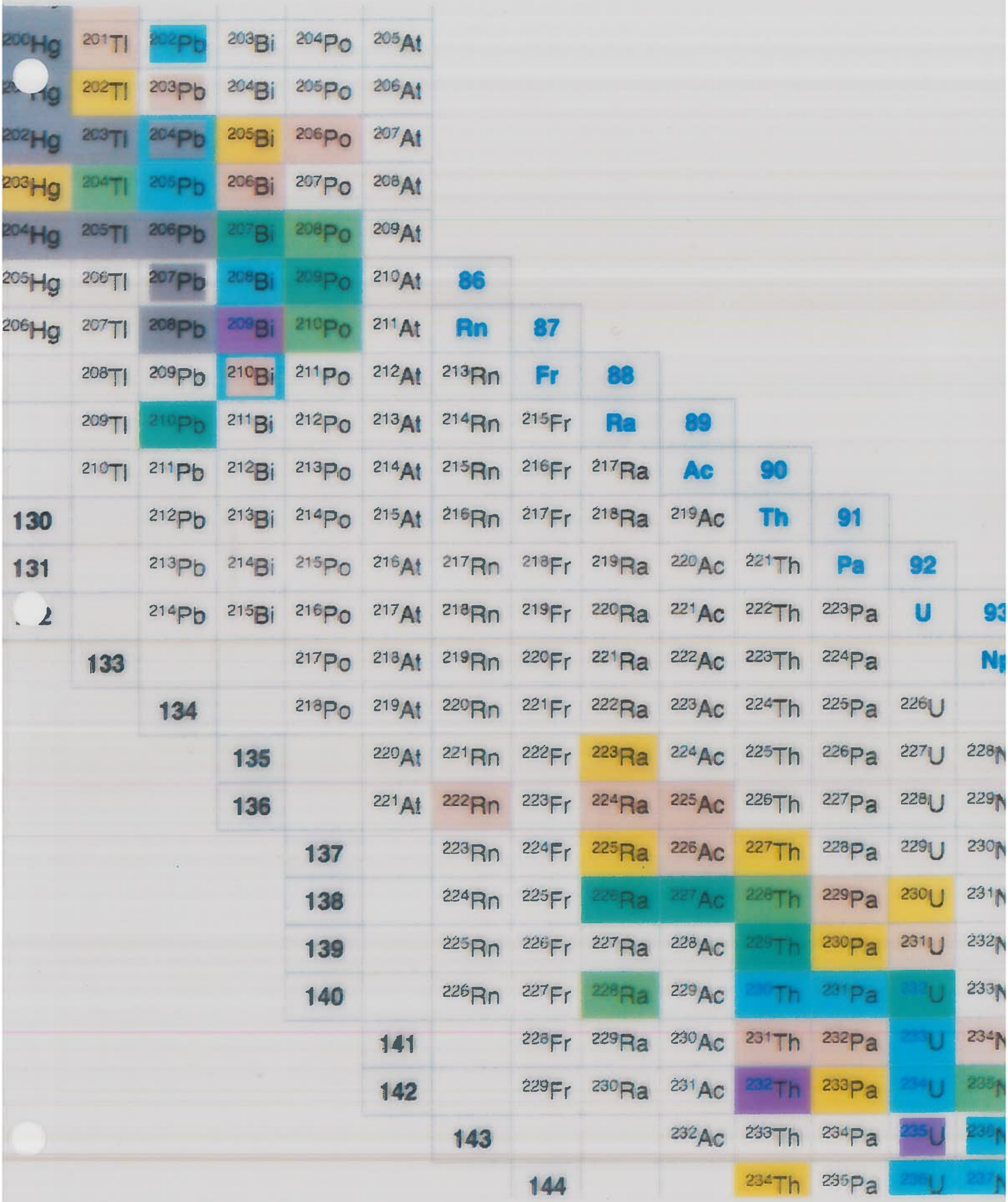
eg Samarium $Z=62$

			(rel 10^6 Si)	σN
^{144}Sm	p	92	$7.42 \cdot 10^{-3}$	0.65
^{147}Sm	r, s	1000	$3.71 \cdot 10^{-2}$	37
^{148}Sm	s	267	$2.70 \cdot 10^{-2}$	7.2
^{149}Sm	r, s	1454	$3.32 \cdot 10^{-2}$	48.3
^{150}Sm	s	447	$1.79 \cdot 10^{-2}$	8.0
^{152}Sm	s, r	375	$6.41 \cdot 10^{-2}$	24.2
^{154}Sm	r	293	$5.45 \cdot 10^{-2}$	16.0

- Require a range of exposures; in fact much less at high exposure than low!
- Repeat shell flashes of C-13 pocket where only a fraction joins in the next flash!
- End of s-process



^{209}Bi decays by α in $2 \cdot 10^{19}$ y



^{200}Hg	^{201}Tl	^{202}Pb	^{203}Bi	^{204}Po	^{205}At								
^{2}[illegible]Hg	^{202}Tl	^{203}Pb	^{204}Bi	^{205}Po	^{206}At								
^{202}Hg	^{203}Tl	^{204}Pb	^{205}Bi	^{206}Po	^{207}At								
^{203}Hg	^{204}Tl	^{205}Pb	^{206}Bi	^{207}Po	^{208}At								
^{204}Hg	^{205}Tl	^{206}Pb	^{207}Bi	^{208}Po	^{209}At								
^{205}Hg	^{206}Tl	^{207}Pb	^{208}Bi	^{209}Po	^{210}At	**86**							
^{206}Hg	^{207}Tl	^{208}Pb	^{209}Bi	^{210}Po	^{211}At	**Rn**	**87**						
	^{208}Tl	^{209}Pb	^{210}Bi	^{211}Po	^{212}At	^{213}Rn	**Fr**	**88**					
	^{209}Tl	^{210}Pb	^{211}Bi	^{212}Po	^{213}At	^{214}Rn	^{215}Fr	**Ra**	**89**				
	^{210}Tl	^{211}Pb	^{212}Bi	^{213}Po	^{214}At	^{215}Rn	^{216}Fr	^{217}Ra	**Ac**	**90**			
130		^{212}Pb	^{213}Bi	^{214}Po	^{215}At	^{216}Rn	^{217}Fr	^{218}Ra	^{219}Ac	**Th**	**91**		
131		^{213}Pb	^{214}Bi	^{215}Po	^{216}At	^{217}Rn	^{218}Fr	^{219}Ra	^{220}Ac	^{221}Th	**Pa**	**92**	
[illegible]2		^{214}Pb	^{215}Bi	^{216}Po	^{217}At	^{218}Rn	^{219}Fr	^{220}Ra	^{221}Ac	^{222}Th	^{223}Pa	**U**	**93**
	133			^{217}Po	^{218}At	^{219}Rn	^{220}Fr	^{221}Ra	^{222}Ac	^{223}Th	^{224}Pa		**N**
		134		^{218}Po	^{219}At	^{220}Rn	^{221}Fr	^{222}Ra	^{223}Ac	^{224}Th	^{225}Pa	^{226}U	
			135		^{220}At	^{221}Rn	^{222}Fr	^{223}Ra	^{224}Ac	^{225}Th	^{226}Pa	^{227}U	^{228}N
			136		^{221}At	^{222}Rn	^{223}Fr	^{224}Ra	^{225}Ac	^{226}Th	^{227}Pa	^{228}U	^{229}N
				137		^{223}Rn	^{224}Fr	^{225}Ra	^{226}Ac	^{227}Th	^{228}Pa	^{229}U	^{230}N
				138		^{224}Rn	^{225}Fr	^{226}Ra	^{227}Ac	^{228}Th	^{229}Pa	^{230}U	^{231}N
				139		^{225}Rn	^{226}Fr	^{227}Ra	^{228}Ac	^{229}Th	^{230}Pa	^{231}U	^{232}N
				140		^{226}Rn	^{227}Fr	^{228}Ra	^{229}Ac	^{230}Th	^{231}Pa	^{232}U	^{233}N
					141		^{228}Fr	^{229}Ra	^{230}Ac	^{231}Th	^{232}Pa	^{233}U	^{234}N
					142		^{229}Fr	^{230}Ra	^{231}Ac	^{232}Th	^{233}Pa	^{234}U	^{235}N
						143			^{232}Ac	^{233}Th	^{234}Pa	^{235}U	^{236}N
							144			^{234}Th	^{235}Pa	^{236}U	^{237}N

We see that some nucleides are just s-process, just r-process and just p-process.

- Magic nuclei are hang up points for s-process e.g. Ba
  so if neutron dose is sufficient to past Ba go all the way to Pb.

  . Other big s-process Sr, Y, Sn

- r-process : rapid additional of ~~nuclei~~ neutrons to nuclei to get past Pb and away from s-process path

(1) Originally thought to be in ~~SN~~ core collapse SN but too few n per Fe can only get to Rb or so.
BUT if Z is really low, could go further!

(2) Now mostly thought to be in mergers of neutron stars

Nuclei in crust already neutron rich and lots of neutrons!

Neutron Star Crust Nuclei

		ρ_{max}		
^{56}Fe	up to	$8 \cdot 10^6$		
⋮				
^{78}Ni	up to	10^{11}		
^{126}Ru		$1.3 \cdot 10^{11}$	→	^{126}Te
^{124}Mo		$2 \cdot 10^{11}$	→	~~^{124}Te~~ ^{124}Sn r-only
⋮				
^{118}Kr		$4 \cdot 10^{11}$	→	^{118}Sn

But expect to add neutrons as well to get actinides (and lanthanide

↳ actinides e.g. U powers the Earth's interior (very important

GW170817 NS merger; saw lanthanid

GRB130603B kilonova after short GRB
↳ $0.01 M_\odot$ ejected; $10 M_\oplus$ of Au!

Can also make new elements on the proton rich side but

$\sigma_{p\gamma} << \sigma_{n\gamma}$ because of electrostatic repulsion

★ By rapidly adding protons e.g. 10^{28} protons/cm^3 and 2 GK
run along proton-drip line until ^{107}Te (that α decays)
- thermonuclear explosions on neutron stars
- have to wait for β-decays along drip lin

★ Regular p-process in supernovae
(~~Type I~~ core collapse and thermonucl

Also have γ-process in SN $(\gamma,n),(\gamma,\alpha),(\gamma,$
to move down toward p nuclei

★ Origin of p nuclei still uncertain

What's left?

Li	$^3He(\alpha,\gamma)^7Be(\beta^+\nu)^7Li$ (novae)
Be	Cosmic ray spallation
B	Cosmic ray spallation
He-3	Cosmic ray spallation
H-2	Cosmic ray spallation

Also many radioactive nuclides are produced by CR spallation because they exist on Earth but $\tau_{1/2} << \tau_{\oplus}$