"Synthesis of the Elements in Stars"

Margaret Burbidge, Geoffrey Burbidge, Willie Fowler, & Fred Hoyle Reviews of Modern Physics Vol. 29, # 4, October 1957, pp. 547-650.



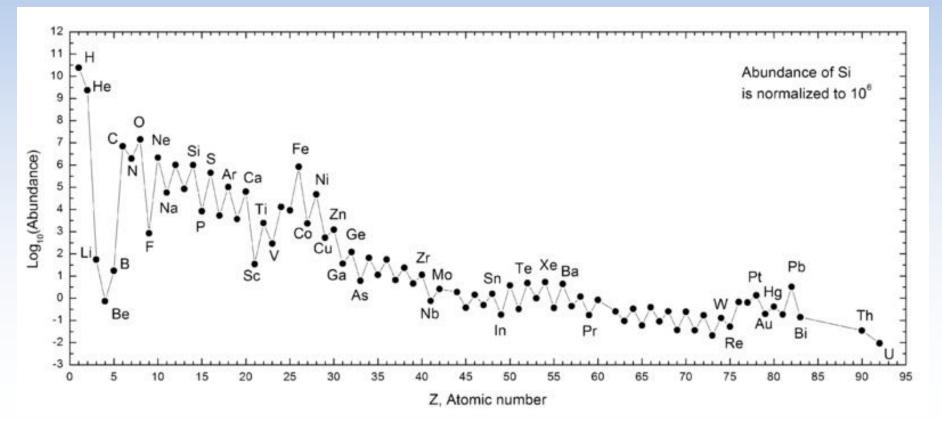
- Dr. David Batchelor

period 1	group 1 1.00794 1 1312.0 2.20 H Hydrogen	0									erioo					by Robert	Campion version 1.3	18 4.002602 23723 Heelium
2	6.941 0.88 3 520.2 0.88 3 Lithium	2 9.012182 899.5 1.57 4 989.5 1.57 4 *2 Beryllium	1st ioni	atomic mass whe mass number zation energy in kJ/mol emical symbol		⁴⁵ <u>2</u> 6	$\begin{array}{c c} 6 & & \text{atc} \\ & +6 & -+5 & -+4 \\ & +3 & +2 & +2 \\ & +2 & +1 & -+1 \\ \end{array}$	omic number ectronegativit	y 📃 alkali	metals ne metals metals ition metals	nonmeta halogens	lls s	13	14 12.0107 1096.5 2.55 Carbon	15 14.0067 1402.3 3.04 Nitrogen	16 15.9994 1313.9 3.44 0 Oxygen 19 ² 29'	17 18.998403 9 1681.0 3.98 -1 Fluorine 18 202 202	19 ⁴ 20.1797 10 Neon 19 ⁴ 29 ⁴ 20 ⁴
3	22.98976 11 495.8 0.93 11 Na Sodium (Ne) 391	24.3050 737.7 1.81 Mg Magnesium [Ne] 34 ²	electron 3	name configuration 4		^{1°} 4s ²	-1 ox	idation states st common are bo 8		anoids bids 10	radioactive of masses in particular for the m		26.98153 577.5 1.61 Aluminium [Ne] 3e ² 3p ²	28.0855 796.5 1.90 Silicon	30.97696 15 1011.8 2.19 15 Phosphorus	32.065 999.6 2.56 16 999.6 2.56 16 Sulfur [Ne] 3et 3pt		39.948 1520.6 18 Argon [No] 36* 3p*
4	39.0983 418.8 0.82 N Potassium (Ar) 44'	40.078 589.8 1.00 20 Calcium [Ar] 49 ²	44.95591 21 533.1 1.36 Scandium [Ar] 3d* 4e ²	47.867 658.8 1.54 22 Titanium (Ar) 3d ² 4e ²	650.9 1.63 20 Vanadium [Ar] 3d ² 48 ⁴	51.9962 652.9 1.66 24 Chromium [Ar] 3d* 44*	54.93804 25 717.3 1.55 Manganese (Ar) 3d* 4e ²	55.845 782.5 1.83 26 Fee Iron [A1] 36' 4st	58.93319 27 760.4 1.91 Cobalt [Ar] 3d' 4e ²	58.6934 737.1 1.88 28 Nickel (Ar) 3d* 484	63.546 29 Copper [Ar] 3d* 4s*	65.38 906.4 1.65 Zinc [Ar] 3d** 48 ²	69.723 578.8 1.81 31 Gallium [Ar] 34" 49 ² 4p ¹	72.64 762.0 2.01 32 Germanium [A1] 3d ¹¹ 48 ² 4p ²	74.92160 33 947.0 2.18 Arsenic [Ar] 36* 48 ² 4p ²	78.96 941.0 2.55 34 Selenium (Ar) 3d ⁴ 49 ⁴ 49 ⁴	79.904 1139.9 2.96 35 Bromine [Ar] 3d ¹¹ 49 ² 49 ¹	83.798 1350.8 3.00 36 Krypton [At] 3d** 4s² 4pf
5	85.4678 403.0 0.82 37 Rubidium (Kr) 54'	87.62 549.5 0.96 38 Strontium [K1] 56 ⁴	88.90585 39	91.224 640.1 1.33 40 Zirconium [Kr] 4d ⁶ 5e ⁴	92.90638 41 S2.1 1.60 41 Niobium (Kr) 4d ⁵ 5e ⁴	95.96 884.3 2.16 Molybdenum [Kr] 4d 5s ⁴	(98) 702.0 1.90 43 TC Technetium (Kr) 40° 58°	101.07 710.2 2.20 Ruthenium (Kr) 4d7 581	102.9055 45 Rh Rhodium [Ki] 44 ⁵ 54 ⁴	106.42 804.4 2.20 46 Palladium [Kr] 4d*	107.8682 47 Ag Silvet [Kr] 4d* 5e*	112.441 667.8 1.69 48 Cadmium [Kr] 4d* 562	114.818 49 558.3 1.78 49 Indium [Kr] 4d** 56* 5p*	118.710 50 708.6 1.96 50 Sn Tin [Kr] 4στ 5φ ² 5ρ ²	121.760 51 834.0 2.05 51 Sb Antimony [Ki] 44** 58* 5p*	127.60 609.3 2.10 52 Tellurium [Kr] 4d* 59* 5p*	126.9044 53 1008.4 2.66 ** I lodine [Kr] 4d** 5e* 5p*	131.293 54 Xenon (K0] 4d** 58° 59'
6	132.9054 55 375.7 0.79 55 Cæsium (Xe) 6e'	137.327 502.9 0.89 56 Barium [Xe] 66 ⁴	174.9668 71 523.5 1.27 *3 Lutetium (Xe) 4f" 5d" 88 ²	178.49 658.5 1.30 72 Hafnium [Xe] 41° 5d° 684	180.9478 73 761.0 1.50 73 Tantalum (Xe) 41" 5d ^e 6e ²	183.84 770.0 2.36 770.0 2.36 74 74 75 74 74 74 74 74 74 74 74 74 74 74 74 74	186.207 760.0 1.90 75 Ree Rhenium (Xe) 41" 5d" 68#	190.23 840.0 2.20 76 Osmium [Xe] 4f* 5d* 6e#	192.217 77 880.0 2.20 77 Iridium (Xe) 4f* 5d* 6s ²	195.084 870.0 2.28 Pt Platinum (Xe) 44" 54" 68"	196.9665 79 890.1 2.54 79 Gold [Xe] 4f* 5d* 6e*	200.59 1007.1 2.00 HC Mercory (Xe) 41° 54° 664	204.3833 81 589.4 1.62 31 Thallium [Xe] 4th* 5d* 6e* 6p*	207.2 715.6 2.33 82 Pb Lead (Xe) 41° 5d* 6e² 6p²	208.9804 83 703.0 2.02 55 Bismuth [Xe] 41 ^{sc} 5d ^{sc} 68 ^c 69 ^c	(210) 812.1 2.00 84 Polonium (Xe) 44" 5d" 68* 69'	(210) 890.0 2.20 85 Astatine [Xe] 41" 5d" 6e ² 6p ³	(220) 86 Rn Radon (Xe) 41° 5d° 6e ² 6p'
7	(223) 380.0 0.70 87 Francium (Rn) 781	(226) 509.3 0.90 88 Radium (Ph) 74 ⁰	(262) 103 470.0 3 Lawrencium (Rn) SI ^M 7e ² 7p ⁴	(261) 104 580.0 Rf Rutherfordium (Fn) 5F" 6d ² 7e ²	(262) 105 Db Dubnium	(266) 106 Sog Seaborgium	⁽²⁶⁴⁾ 107 Bh Bohrium	(277) 108 Hassium	(268) 109 Mt Meitnerium	⁽²⁷¹⁾ 110 DS Darmstadium	(272) 111 Rg Roentgenium	(285) 112 Copernicium	(284) 113 Uut Ununtrium	⁽²⁸⁹⁾ 114 Fl Flerovium	(288) 115 Uup Ununpentium	⁽²⁹²⁾ 116 LV Livermorium	117 UUS Ununseptium	(294) 118 Uuo Ununoctium
	$\frac{1}{100} \frac{1}{100} \frac{1}$																	
	• 1 kJ/mol	elements 113,115 cial name designa ≈ 96.485 eV. tts are implied to h o.	ted by the IUPAC.	Actiniur [Fin] 6d' 7e														្តរ ៣

- There are currently 118 known chemical elements; 27 are human-made, the rest are found in nature.
- Why? Where do they come from?

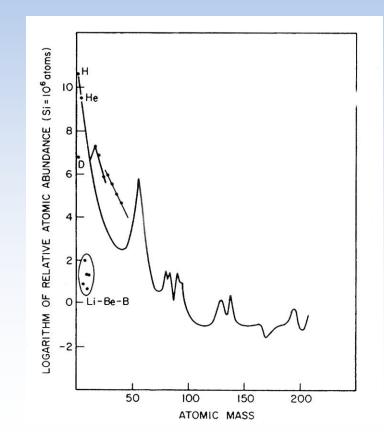
Abundance (where?) Curves

- All elements are not equally common; abundances differ by a factor of 5 trillion, dropping off with increasing atomic number.
- Even numbers more abundant than odd by factors of 10 to 100.
- Spikes near Fe, and at other, higher Zs.
- Clearly Cosmic Dragons have eaten most of the Li, Be, & B.



Abundance curves, continued

• Taking out the even/odd effect to smooth the data reveals some interesting patterns. Can those tell us what's produced the elements?



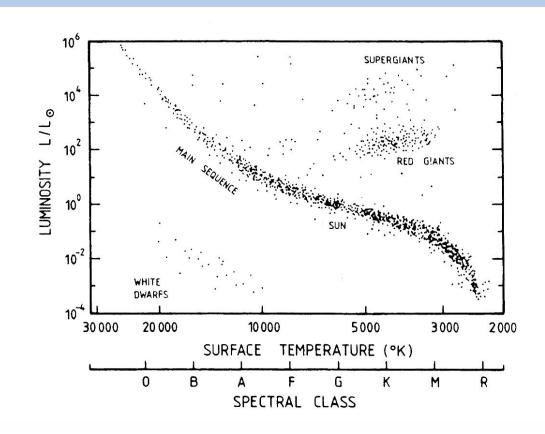
The Alpher-Bethe-Gamow letter in Physical Review

- In 1948, astronomer George Gamow had a grad. student named Ralph Alpher, who argued that all elements were produced during the Big Bang.
- Alpher proposed that the Big Bang produced neutrons. Neutrons are radioactive, and decay into protons and electrons with a $t_{1/2} = 10.23$ minutes.
- During the extremely hot universe following the Big Bang, neutron capture would have produced all the elements, with abundances decreasing with mass.
- Does not explain the spikes in the abundance curves.
- Does not explain why old stars have fewer heavy elements.
- Cannot proceed past He, as no element has a mass of 5 or 8.
- Hans Bethe's name was added by Gamow over Alpher's objections to play on $\alpha,\,\beta,\,\gamma.$

So if most elements weren 't made in the Big Bang, where were they made?

How About Stars?

- Most stars (the Main Sequence) roughly follow the Stefan-Boltzmann Law. A few (Giants, Supergiants and White Dwarfs) are very different.
- It was already known that Main Sequence stars fuse hydrogen into helium by one of two reaction chains, depending on the star's mass.



The pp Chain

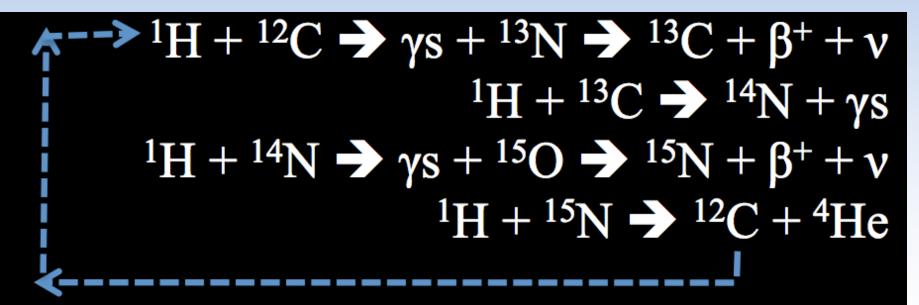
- In 1938, Hans Bethe and Charles L. Litchfield had derived the proton-proton chain (pp chain), the power source for small main sequence stars like our Sun.
- Superscripts are the mass number, A, the number of nucleons in the nucleus.

${}^{1}H + {}^{1}H \rightarrow {}^{2}H + \beta^{+} + \nu$ ${}^{1}H + {}^{2}H \rightarrow {}^{3}He + \gamma s$ ${}^{3}He + {}^{3}He \rightarrow {}^{4}He + {}^{1}H + {}^{1}H$

The CNO cycle

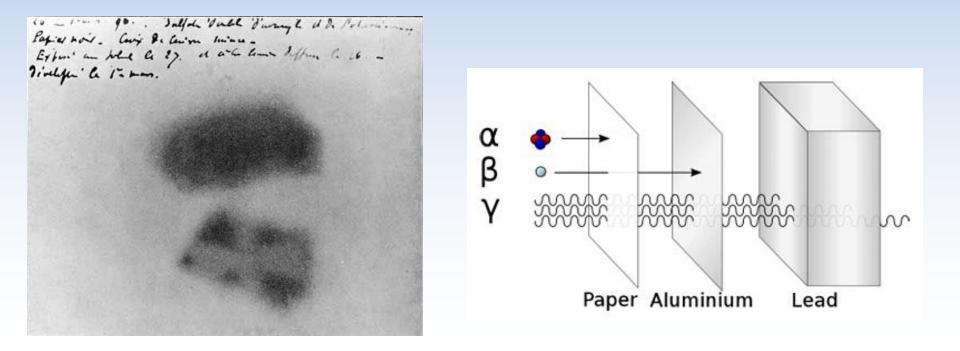
• Within a year, Baron Carl von Weizsäcker and Hans Bethe had independently derived another hydrogen-fusion chain catalyzed by carbon, nitrogen, and oxygen nuclei, the power source for more massive main sequence stars.

- Could such nuclear reactions in stars be the source of ALL chemical elements?
- If so, we'll need a bit of background about things nuclear...



Types of Radiation

- In 1896, Henri Becquerel discovered radioactivity.
- In 1899, Ernest Rutherford discovered alpha and beta rays. Beta particles were identified as electrons the same year, alpha particles as helium nuclei by 1908.
- In 1900, Paul Villard discovered gamma rays, which were so named by Rutherford in 1903, and identified as electromagnetic radiation by 1914.



Nuclear Reaction Shorthand

- Nuclear reactions usually involve a large nucleus being struck by a smaller particle, producing a different large nucleus and one or more small particles.
- It's easier and neater to write these reactions in a more condensed form than the sort borrowed from chemistry.

$${}^{14}_{7}N + {}^{1}_{1}H \rightarrow {}^{11}_{6}C + {}^{4}_{2}He \qquad {}^{14}N(p,\alpha)^{11}C$$

$${}^{27}_{13}Al + {}^{1}_{0}n \rightarrow {}^{27}_{12}Mg + {}^{1}_{1}H \qquad {}^{27}Al(n,p)^{27}Mg$$

$${}^{55}_{25}Mn + {}^{2}_{1}H \rightarrow {}^{55}_{26}Fe + {}^{1}_{0}n \qquad {}^{55}Mn(d,2n)^{55}Fe$$

• Easier, simpler, faster, better, more cromulent.

How Likely is a Nuclear Reaction?

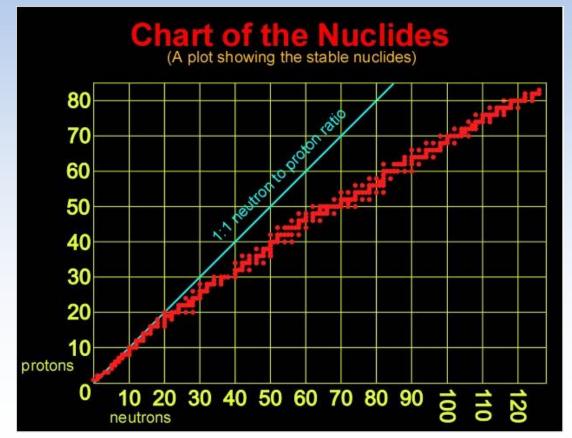
- How likely is a small particle to strike a nucleus and cause a reaction?
- The probability is expressed by the cross-section of the nucleus (as seen by the incoming particle).
- The standard unit is the cross-section area of a uranium nucleus, 10⁻²⁴ cm².
- In the wartime code developed by Purdue during WWII's Manhattan Project, this unit was known as a *barn* (from the expression, "He couldn't hit the broadside of a barn."). One microbarn (μb) is a *outhouse*, and 10⁻²⁴b is a *shed*. (Sometime (but not now), ask me about *pigs*, *cows*, and *shakes*.)

What are Magic Numbers?

- They are 2, 8, 20, 28, 50, 82, and 126.
- In 1950, Maria Göppert-Mayer published her nuclear shell model, in which nucleons orbit in shells analogous to those of electrons in an atom.
- The numbers represent the capacity of successive shells.
- Just as for electrons, nuclei with filled nuclear shells are more stable and abundant. (⁵⁰V, N=28, 99.765%; Sn, Z=50, ten stable isotopes; Pb, Z=82)
- Those with shells with one too many or one too few nucleons are less stable. (Sb, Z=51, two stable isotopes)
- Nuclei in which both neutron and proton shells are filled are termed "doubly magic", and are especially stable and abundant. (⁴He, 99.999866%; ¹⁶O, 99.756%; ²⁰⁸Pb, Z=82, N= 126)
- She also discovered *spin-orbit coupling* in nucleons, which explains the evenodd effect.
- She later worked on the "Super" with Teller.

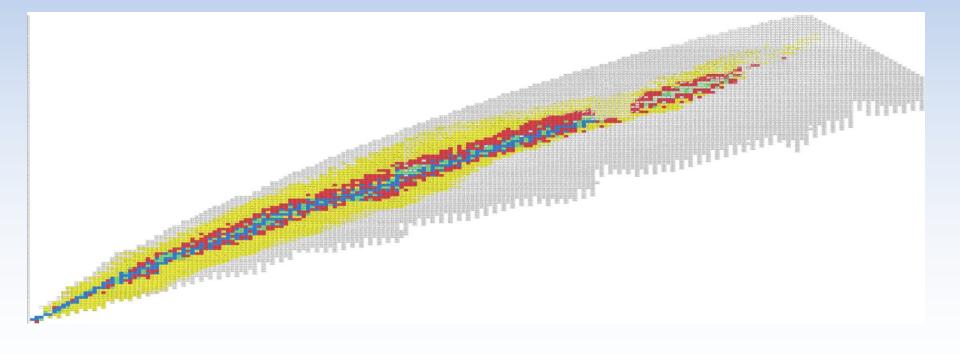
We'll also need the REAL periodic table, the Chart of the Nuclides.

- Here are all the stable isotopes, plotted as # of neutrons vs. # of protons (the mass number, Z).
- Notice they don't follow a 1:1 line, since extra neutrons are needed to beef up the strong nuclear force and counter the repulsion of the proton charges.



The Chart of the Nuclides, cont'd.

• Add in the radioactive nuclides, and it looks like this.



The Chart of the Nuclides, up close.

nteenth Edition - Revised to 2009

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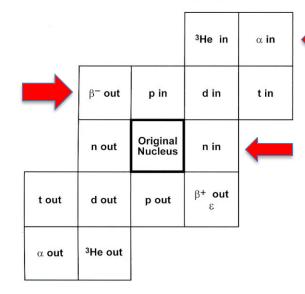
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as R. Mi	ller						F		F15 (1/+)	F1
M. Wat	son					0.000	18.9984032		5E-22 s	~1E-2
						9	fluorine		p1.4	p 0.51
ic Desi	gn by:					0.0000				
ne D. Ti	ravis						σa ~9.4 mb, 21 mb		15.0180	16.011
						0	O12 ~1E-21 s	O13 (3/-) 8.6 ms	O14 70.62 s	01
					8	15.9994	2p	β ⁺ (p) 1.44,…	β ⁺ 1.81,… γ 2312.59,…	β ⁺ 1.72 ε ω
					0	oxygen		(F)		0.0
						σ_a 0.28 mb, 0.4 mb	12.03440	E 17.77	E 5.1439	E 2.75
					N	N10 (2 ⁻)	N11 1/+	N12 1+	N13 1/-	N14
				_	14.0067	2E-22 s	1E-21 s	11.00 ms β ⁺ 16.3,···	9.97 m 6 ⁺ 1.190	99.63
				7	nitrogen	p,	P	γ 4439,… (α) 0.192,…	p 1.100	σ _γ 0.080, 0 σ _p ~1.93, 0
					l č	AND 1000 MILLS				
					σ _a ~1.89, 0.87	10.0417 C9 (3/-)	11.02609 C10	E 17.338 C11 3/-	E 2.2205	14.00307 C13
				C 12.0107	C8 2.0E-21 s	127 ms	19 308 s	20.36 m β ⁺ 0.960	98.93	1.0
			6	100000000	ρ, α	β ⁺ (p) 0.164,…	β ⁺ 1.87,… γ 718.3,…	β ⁺ 0.960 ε ω	σ _γ 3.5 mb, 1.6 mb	σ _γ 1.4 mb,
			v	carbon		(α)			-1	
				σ _a 3.5 mb, 1.6 mb	8.03768	E 16.495	E 3.6480	E 1.982	12.00000000	13.00335
			В		B7 (3/-)	B8 2+	B9 3/-	B10 3+	B11 3/-	B12
		5	10.811		3E-22 s p, α	770 ms β ⁺ 14,… (2α) 1.57	8E-19 s p 0.164, 2α 0.0461	19.9* σ _α 384E1, 173E1 σ ₂ 0.3, 0.1	80.1*	20.20 β 13.37,···· γ 4439.···
		J	boron			(20) 1.57		σp 7 mb σt 8 mb	σ_γ 5 mb, 2 mb	(α) 0.192,…
			σa 76E1, ~343		7.0299	E 17.980	9.013329	10.0129370	11.0093054	E 13.3
			Be		Be6	Be7 3/-	Be8	Be9 3/-	Be10	Be1
			9.012182		5.0E-21 s 2p, α	53.3 d ε	~7E-17 s	100	1.5E6 a β 0.556	13.8 β 11.5, 9.4
		4	beryllium			γ 477.6 σ _p 3.9E4, ~1.8E4	2α 0.0461	σ _γ 8 mb, 4 mb	noγ σγ1 mb	γ 2124.5,… (α), γ 480
			σa 8 mb, 4 mb			σα 0.14, 0.06	1000000000		1.52	
	Li		6a 6 mb, 4 mb	Li4 2-	6.01973 Li5 ^{3/-}	E 0.8619 Li6 1+	8.00530510 Li7 3/-	9.0121822 Li8 2+	E 0.556 Li9 3/-	E 11.6
	6.941			8E-23 s	~3E-22 s	7.59*	92.41*	0.840 s	178.3 ms	2E-21
3				p	ρ, α	σ _α 941, 423 σ _γ 39 mb, 17 mb	σγ 0.045, 0.020	β ⁻¹³ (2α) 1.57	β ⁻ 13.5, 11.0,… (n) 0 - 3, (α) 0 - 6	n
-	lithium				1					
	σ _a 71, 32			4.0272	5.0125	6.01512279	7.0160045	E 16.0052	E 13.607	10.035
	He 4.002602			He3 1/+ 0.000134*	He4	He5 3/-	He6	He7 (3/)-	He8	He
2	4.002002			0.000134	99.999866*	7.0E-22 s n, α	807 ms β 3.510	3E-21 s	119 ms β 10 y 980.7	very st
-	helium			σ _p 5.33E3, 2.40E3 σ _γ 0.05 mb	σγ 0		noγ (d) νω		(n) 0.61 - 3.0	
	σ _a 7 mb, 3 mb			3.016029319	4.0026032542	5.0122	E 3.508	7.02802	(t) ω E 10.65	9.043
	Н		H1 1/+	H2 1+	H3 1/+	H4 2-	H5 (1/+)	H6 (2-)	H7	
	1.00794		99.9885*	0.0115*	12.32 a β=0.018591	1.4E-22 s	very short	3E-22 s 3n ?, 4n ?	~9E-22 s	
1	hydrogen		σγ 0.332, 0.149	σ _γ 0.52 mb, 0.23 mb	00 7					
	σ _a 0.332, 0.149					1 0070	5 0252	6.0449		
. I	-a 0.552, 0.149		1.0078250321	2.0141017779 n1 1/+	E 0.018591	4.0278	5.0353	0.0449	7.053	J
0				10.23 m			4		6	
0				β-0.782						
				E 0.782347						
-				E 0.782347 1.008664916						

F17 ^{5/+} 1.08 m	F18 ¹⁺ 1.8293 h	F19 1/+ 100	F20 2+ 11.1 s	F21 5/+ 4.16 s β ⁻ 5.4	F22 4.23 s
β+ 1.74	β ⁺ 0.635 ε	σγ ~9.5 mb, 21 mb	β 5.39,… γ 1633.6,…	γ 350.7, 1395.1,···	β ⁻ 5.5,… γ 1274.5, 2082.5, 2166.0,…
E 2.7605	E 1.655	18.9984032	E 7.0245	E 5.684	E 10.82
016 99.757 σγ 0.19 mb, 0.4 mb	017 5/+ 0.038 σ _α 0.24, 0.11 σ _γ 0.54 mb, 0.39 mb	018 0.205 σ _γ 0.16 mb, 0.81 mb	O19 5/+ 26.9 s β ^{-3.3, 4.60,} γ 197.1, 1356.8,	O20 13.5 s β ⁻ 2.75, γ 1056.8,	021 (5 3.4 s β ⁻ 4.6, 6.4, γ 1730.3, 3517.4, 280.1, 1787.2,.
15.9949146196	16.9991317	17.999161	E 4.822	E 3.815	E 8.11
N15 1/- 0.364	N16 ²⁻ 7.13 s	N17 1/- 4.174 s B 3.7,	N18 1- 623 ms 8 ^{-9.4}	N19 1/- 0.33 s	N20 135 ms
σ _γ 0.02 mb, 0.11 mb	β ⁻ 4.27, 10.44,… γ 6129, 7115,… (α) 1.85 ω,…	γ 870.7, 2184(ω) (n) 1.171, 0.383,… (α) ω	γ 1981.9, 1651.5,… (n) 0.58,… (α) 0.81, ~2.3,1.4,…	γ 96.4, 1983, 3851, (n) 1.054, 0.452, γ 1983	γ 1674, 2397, 189 (n) 2.071, 1.098, 1.254,… γ 96.4, 1376
15.000108898	E 10.421	E 8.68	E 13.90	E 12.53	E 18.0
C14 5715 a	C15 1/+ 2.450 s	C16 0.75 s	C17 3/+ 0.19 s	C18 92 ms	C19 (46 ms
β= 0.157 no γ σγ < 1 μb	$\beta^{-4.51, 9.82, \cdots}_{\gamma 5297.8, \cdots}$	β [−] γ 120.4D ⇔ (n) 0.81, 1.71,…	β ⁻ γ 1375, 1849, 1906 (n)	β ⁻ γ 2614.2,… (n)	p (n) 1.01, 1.50, 0 γ 115, 472 (2n)
E 0.156476	E 9.772	E 8.010	E 13.17	E 11.81	E 16.6
B13 3/- 17.4 ms β ⁻ 13.4 γ 3683.9	B14 2 ⁻ 13 ms ^{β⁻14,···} γ 6092.4,··· (n)	B15 3/- 9.9 ms β ⁻ (n) 1.77, 3.20, (2n) ω		$\begin{array}{c} \textbf{B17} (3/-) \\ \textbf{5.06 ms} \\ \beta^- \\ (n) \ 2.91, \ 1.80, \cdots \\ (2n), \ (3n) \end{array}$	
(n) 3.610, 2.40,	(II) E 20.64	E 19.10		(4n) ω E 22.7	
E 13.437 Be12 21.49 ms	Be13 (1/+) very short			12	
β (n) ω	n ?	β ⁻ (n) 0.287			
		γ 3536 ω (t) ω			
E 11.71	13.0357	y 3536 w			
$\begin{array}{c} \mbox{Li11} & 3^{l-1} \\ 8.8 \mbox{ ms} \\ \beta^{-}, \gamma \ 320.0 \\ (n) \ 1.97, \ 3.11, \cdots \\ \gamma \ 3368, \cdots \\ (2n), \ (3n), \ (\alpha) \\ (1) \ \alpha, \ (d) \end{array}$		γ 3536 ω (t) ω			
Li11 3/- 8.8 ms (7) 1.97, 3.11, (2n), (3n), (a) (t) (b), (d) E 20.62 He10 2E-21 s		γ 3536 ω (t) ω Ε 16.3]		
Li11 3/- 8.8 ms (n) 197.3.11, 7 3368 (1) n, (2) E 20.62 He10 2E-21 s 2n		γ 3536 ω (t) ω Ε 16.3			
Li11 3/- 8.8 ms (7) 1.97, 3.11, (2n), (3n), (a) (t) (b), (d) E 20.62 He10 2E-21 s		γ 3536 ω (t) ω Ε 16.3			

Nuclear Reactions on the Chart of the Nuclides.

• The important ones for us are in the top chart; α in, n in, and β^{-} out.

Relative Locations of the Products of Various Nuclear Processes



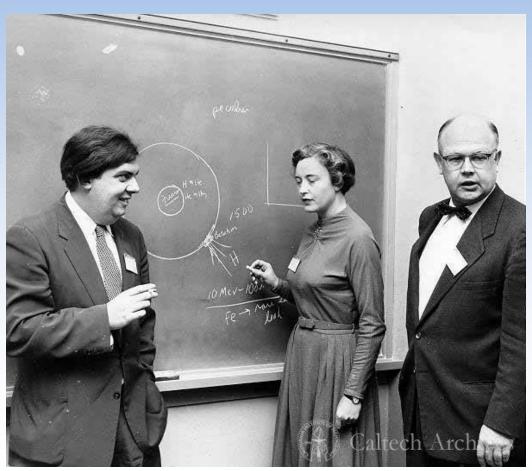
Displacement Caused by Nuclear Bombardment Reactions

	(α, 3n)	(α, 2n) (³ He, n)	(α, n)	
	(p, n)	(p, γ) (d, n) (³ He, np)	(α, np) (t, n) (³ He, p)	
	(p, pn) (γ, n) (n, 2n)	Target Nucleus (n, n)	(d, p) (n, γ) (t, np)	(t, p)
(p, α)	(n, t) (γ, np) (n, nd)	(n, d) (γ, p) (n, np)	(n, p) (t, ³ He)	
	(n, α) (n, n ³ He)	(n, ³ He) (n, pd)	e.	

Meet the Authors

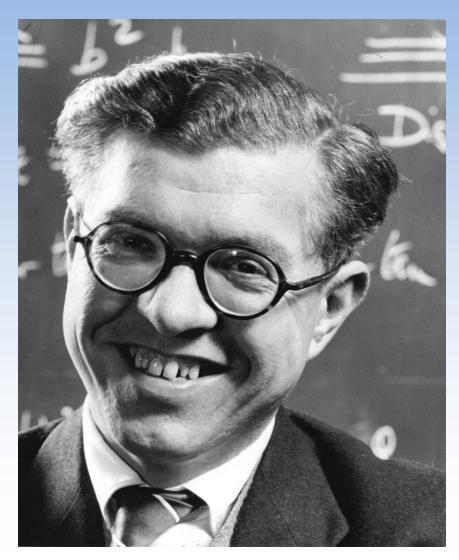
- That's Margaret Burbidge *née* Peachey, FRS, lead author, British astronomer, & champion of women in science. She's 96 years old now, and living in CA.
- To her left is her husband, Geoffrey Burbidge, FRS, also a British astronomer.
- On the right is Willie Fowler, American nuclear physicist, Nobel winner for this work, and former Director of Cal Tech's Kellogg Radiation Lab. (Yes, *that*

Kellogg.)



Meet the Authors, cont'd.

• This spiffy-looking gentleman is Sir Fred Hoyle, FRS, British astronomer, inventor of the term "Big Bang" (though he did not believe in it), science fiction author, and espouser of several odd hypotheses now known to be incorrect.



(Probably cost him Nobel Prize for this work.)

The Triple Alpha Process, aka He-Burning.

- In 1952, "Hoyle went boldly into...Fowler's lab...and said that there had to be a resonance of 7.69 MeV in the ¹²C nucleus, and that all the physicists in the world had missed it." Wikipedia. His reasoning was that the universe had lots of carbon, and the only way he could think of to make it was the reaction below, which requires that specific resonance. Stars doing this leave the Main Sequence and become Giant stars.
- Ward Whaling found it. Some argue this implies fine-tuning of the multiverse: <u>https://en.wikipedia.org/wiki/Triple-alpha_process#Improbability_and_fine-</u> <u>tuning</u>.

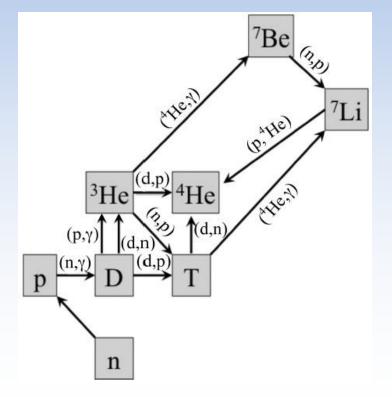
Triple-alpha process

$${}^{4}\text{He} + {}^{4}\text{He} \rightarrow {}^{8}\text{Be}$$

 ${}^{4}\text{He} + {}^{8}\text{Be} \rightarrow {}^{12}\text{C} + \beta^{-} + \beta^{+}$
 ${}^{4}\text{He} + {}^{12}\text{C} \rightarrow {}^{16}\text{O} + \gamma$

The Four-Way Collaboration.

- In 1953, Fowler and the Burbidges went to Cambridge to work with Hoyle. They began working on the details of whether *stellar nucleosynthesis* was a viable mechanism to produce the chemical elements. By 1957, they published
 B²FH.
- They assumed the Big Bang had produced H and He. It would be decades before the details of *Big Bang Nucleosynthesis* (BBN) were worked out.



Fowler Proposes the α-Capture Process, and Hoyle the e-(for equilibrium-) Process

- ¹²C(α,γ)¹⁶O
- ¹⁶O(α,γ)²⁰Ne
- ${}^{20}Ne(\alpha,\gamma){}^{24}Mg$
- ²⁴Mg(α,γ)²⁸Si
- ²⁸Si(α,γ)³²S
- ${}^{32}S(\alpha,\gamma){}^{36}Ar$
- ³⁶Ar(α,γ)⁴⁰Ca
- ${}^{40}Ca(\alpha,\gamma){}^{44}Ti$, which undergoes two β decays to ${}^{44}Ca$
- ⁴⁴Ca(α,γ)⁴⁸Ti
- Stars doing this become Supergiants.

• With each reaction, the star's core temperature increases; Hoyle reasoned that eventually the high temperatures would cause a plethora of nuclear reactions all in equilibrium, producing the elements near Fe.

Correction

• We now know they didn't get that bit quite right; here's what really happens.

Carbon burning $^{12}C + ^{12}C \rightarrow ^{20}Ne + ^{4}He$ $^{12}C + ^{4}He \rightarrow ^{16}O + \gamma$ $^{16}O + ^{4}He \rightarrow ^{20}Ne + \gamma$	~1000 years	0.6 GK
20 Ne + 4 He \rightarrow 24 Mg + γ		
Core contracts		
Neon burning	years	1.2 GK
$^{20}\text{Ne} + \gamma \rightarrow ^{16}\text{O} + {}^{4}\text{He}$	2	1.2 OK
20 Ne + 4 He \rightarrow 24 Mg + γ		
Core contracts		
Oxygen burning	months	1.5 GK
$^{16}O + ^{16}O \rightarrow ^{28}Si + ^{4}He$		
Core contracts		
Silicon burning	~ a day	2.7GK to 3.5 GK
$^{28}\text{Si} + ^{4}\text{He} \rightarrow ^{32}\text{S}$		
$^{32}S + {}^{4}He \rightarrow {}^{36}Ar$		
et cetera, down to		
52 Fe + 4 He \rightarrow 56 Ni		

The Burbidges Decipher the Rest – the s-Process

- They proposed the *s*-process, the slow neutron-capture process.
- The neutron sources are, first ${}^{13}C(\alpha,n){}^{16}O$, then ${}^{26}Ne(\alpha,n){}^{29}Mg$.
- As the star's core is working its way to Fe, each stable nucleus captures neutrons until it reaches a radioactive nucleus, which β -decays into the nextheavier element. This stairsteps up the *Chart of the Nuclides*, filling in many of the isotopes not made by the α -capture processes.
- At first, captures are every half-million years or so, but as heavier elements are made, core pressures and temperatures rise, until captures are happening roughly every decade.
- See the *Chart of the Nuclides* for the path.

Stopping the *s*-Process

- The s-process is stopped at ²⁰⁹Bi.
- ${}^{209}\text{Bi}(n,\gamma){}^{210}\text{Bi}$, which β s to ${}^{210}\text{Po}$, which α s to ${}^{206}\text{Pb}$, which $3(n,\gamma)$ to ${}^{209}\text{Pb}$, which β s back to ${}^{209}\text{Bi}$. We' re stuck.

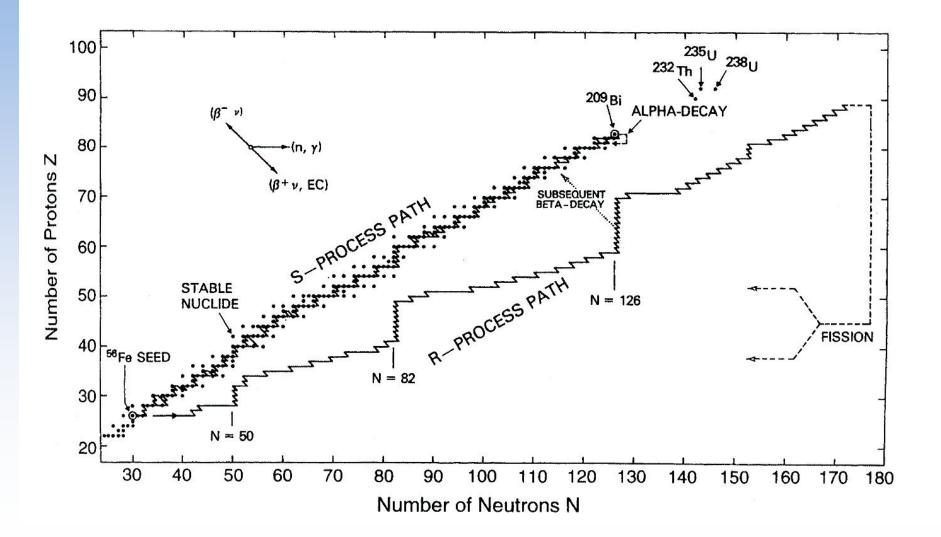
t203 9/- 7.4 m	At204 7+ 9.1 m	At205 9/- 26 m	At206 5+ 29.4 m 5. B+ 3.1	At207 ^{9/−} 1.81 h	At208 6+ 1.63 h	At209 9/- 5.4 h
4 641.5, 1,	$^{\epsilon, \beta^{+}}_{\gamma 684.3, 516.3, 426.2, \cdots}$ $^{\alpha 5.951}$	ε β+ γ 719.3, 669.4, 628.9,… α 5.902 Ε 4.54	γ 700.7, 477.2, 395.6, α 5.703 ω, γ 65.0 ω	β+ γ 814.4, 588.3, 300.7, α 5.758	β+ γ 686.5, 660.0, 177.6,… π 5.641 m …	ε γ 545.0, 781.9, 790.2,… α 5.647,…
2.98694	E 6.46	204.98607	E 5.76	E 3.90	E 4.98	E 3.49
202 4.7 m	^{13/+} Po203 ^{5/-} 45 s 35 m IT 641.4 ε, β ⁺ ε 2 γ 908.6,	Po204 3.53 h ^ε γ 884.0, 270.1,	Po205 5/- 1.7 h ε γ 872.4, 1001.2,	Po206 8.8 d ε 7 1032.3, 511.3,	19/- Po207 5/- 2.8 s 5.80 h IT 268.1 ε γ 814.5D, β ⁺ 0.89 (ω).	Po208 2.898 a α 5.115, ε φ
, 316.1,	α 5.384 ω,	α 5.377 ω E 2.33	α 5.22 ω E 3.55	286.4, 807.4,···· α 5.223 Ε 1.85	300.5D γ 992.3 742.6 911.8 α 5.115 ω E 2.91	γ 291.8 vo, 570.1, 601.5,… 207.981246
2.81	E 4.23			Contraction of the second		Provide Street Arrest
1.72 h	1.72 h	11.8 h	11.2 h	15.31 d	6.243 d	32 a ε
ω ^{β+} γ 629.1D, 936, 1014, 786,	β+ γ 960.7D, 422.2D, 657.5D,	β ⁺ 1.35(ω), 0.74 γ 820.3, 825.2D, 897, 1847, α ~4.85? νω	γ 899.2D, 374.8D, 984.0,… β ⁺ ω	β ⁺ 0.98 ω γ 1764.3, 703.5, 987.6D,…	β ⁺ 0.98 vo γ 803.1, 881.0, 516.2,…	β ⁺ ω γ 569.7, 1063.7D,…
3.84	E 5.20	E 3.25	E 4.44	E 2.71	E 3.76	E 2.397
b200 1.5 h	$\begin{array}{c} 13/+ \textbf{Pb201} 5/-\\ 1.02 \ m\\ 17 \ 629 \end{array} \begin{array}{c} 9.33 \ h\\ \epsilon\\ \beta^+ \ 0.55, \cdots\\ \gamma \ 331.2,\\ 361.3,\\ 945.9, \end{array}$	9- Pb202 3.54 h 17 787.0, ε 7 960.7, 422.1, ⁵ 490.5,	13/+ Pb20: 5/- 6.2 s IT 825.2 y 820.3 2.164 d s y 279.2,	9- Pb204 1.12 h 1.911.7, 7 899.2, 374.8, σ _γ 0.70, 2.0	Pb205 5/- 1.5E7 a ^ε πο γ σγ 4.5	Pb206 24.1 RaG σ _γ 0.027, 0.10
0.80	E 1.92	459.7, E 0.05	E 0.97	203.973044	E 0.0505	205.974465
1199 ^{1/+} 7.4 h	TI200 2- 1.087 d ε	TI201 1/+ 3.043 d ε	ΤΙ202 2- 12.23 d	TI203 1/+ 29.52	TI204 2- 3.78 a β 0.7634	TI205 1/+ 70.48
, 208.2, , 158.4,…	β+ 1.07 (ω), 1.44 γ 368.0, 1205.7,…	y 167.4, 135.3,···	β ⁺ νω γ 439.6,…	σ_{γ} 11.4, 41 σ_{α} < 0.3 mb	πο γ ε σ _γ 22, 9E1	σγ 0.10, 0.7
E 1.49	E 2.46	E 0.48	E 1.36	202.972344	E-0.7638 E+0.344	204.974428
18		120		122		124

α 4.880,… γ 260.5 ω, 262.8 ε	α 5.3044,… γ 803.1ve σ _γ (< 0.5 mb +	α 7.27, 8.88,···· γ 569.2D, 1063 1D γ 569.2D ω,	α 11.65, 0.298 μs γ 2614.4, α 8.7844	α 8.376,… γ 778.8 ω	α 7.6869,… γ 799 ω,…	α 7.386,… γ 438.8 ω,… β ⁻ νω	α 6.7785,… γ 805 ω
γ 896.1 ω 208.982430	< 0.03) $\sigma_{\alpha} < 2 \text{ mb}$ 209.982874	1063.1D, IT ω 210.986653	583.0 IT ~36 211.988868	212.992857	213.995201		
Bi208 (5)+	Bi209 9/-	9- Bi210 1-	Bi211 9/-	(15 ⁻) Bi212 ¹⁽⁻⁾	Bi213 9/-	214.999420 Bi214 ¹⁻	216.001915 Bi215
3.68E5 a	100	3.0E6 a α 4.946, 4.908, 6 1.162	AcC 2.14 m α 6.623, 6.279	7 m ThC	45.6 m	RaC 19.9 m	37 s 7.6 n β ⁻ β ⁻ β ⁻
γ 2614.4	σ _γ (10 mb + 18 mb), 0.19	γ 266.2, α 4.648 νω, 4.687	γ 351.1 β ω	(9 ^m) 25.0 m α 6.34. β ⁻ 2.251, γ 727.3 α 6.061,	γ 440.5,… α 5.87, 5.55 ω γ 323.7 ω	β 3.27, 1.54, 1.51, γ 609.3, 1764.5, 1120.3,	γ 414.1,… γ 293.7
E 2.878	σ _α < 0.3 μb 208.980399	σ _γ 0.05, 0.2 γ 305 vo, 266 E 1.161	210.98727	6.30, β (α) 211.991286	E 1.42	α 5.450 (ω), 5.513,… γ 63,… Ε 3.27	E 2.19
13/+ Pb207 1/- 0.80 s 22.1	Pb208	Pb209 9/+	Pb210	Pb211 9/+	Pb212	Pb213 (9/+)	Pb214
0.80 s 22.1 IT 1063.7 AcD γ 569.7	ThD 52.4	3.25 h β 0.645 no γ	RaD 22.3 a β 0.017, 0.061	AcB 36.1 m β ⁻ 1.38,···	ThB 10.64 h β 0.335, 0.569,	10.2 m β	RaB 27 r β 0.67, 0.73,…
σγ 0.70, 0.38	σ _γ 0.23 mb, 2.0 mb σ _α 8 μb	πο γ	γ 46.5 e ⁻ α 3.72 νω σ _v 0.5	γ 404.9, 831.9, 427.0,…	γ 238.6, 300.0,…		γ 351.9, 295.2, 242.0,…
206.975897	207.976652	E 0.644	σ _γ 0.5 E 0.0635	E 1.37	E 0.570	E 2.05	E 1.02
(12) TI206 0- 3.74 m RaE"	11/- TI207 1/+ 1.3 s AcC"	TI208 5(+) ThC" 3.053 m	TI209 (1/+) 2.16 m	TI210 (5+)	TI211	TI212	132
IT 1022, 4.20 m	IT 997.1, 4.77 m		β= 1.8,	RaC" 1.30 m β 1.9, 1.3, 2.3,…			102
γ 687, 453, 217 γ 803.1ω	γ 351.0 β ⁻ 1.44, γ 897.2ω,	γ 2614.5, 583.2,	γ 1567.0, 465.1, 117.2,…	γ 799.7, 298,… (n)			
217, 266.2,···· Ε 1.532	E 1.42	510.7,··· E 4.999	E 3.98	E 5.48	E 4.4	E 5.9	
					130		

The Burbidges Decipher the *r*-Process

- When the core become Fe, ⁵⁶Fe is the most stable nucleus, so no more αcaptures are possible. Fusion reactions stop, no more energy is generated in the core, so there's no energy release to fight gravity. The core implodes, then rebounds in a supernova explosion, tearing the star apart.
- They proposed the *r-process*, the rapid neutron-capture process; that happens during the supernova fireball.
- They proposed a neutron source, which we now know is wrong, but basically the high temperatures of the fireball photodisintegrate Fe and Ni into He and neutrons, while electron capture by protons produces more neutrons.
- Captures are every few milliseconds over roughly 100 seconds. This doesn't allow time for β-decay, and produces nuclei far to the right of stability, which then undergo serial β-decay.
- The r-process is stopped by fission at Pu.
- Some isotopes are produced by both the s- and r-processes, but some are unique to each one; see the paths on the *Chart of the Nuclides*.

The *r*- and *s*- *Processes*

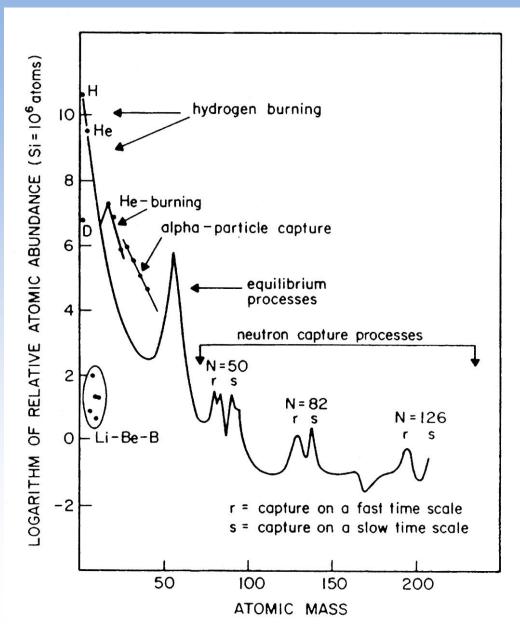


The p-process

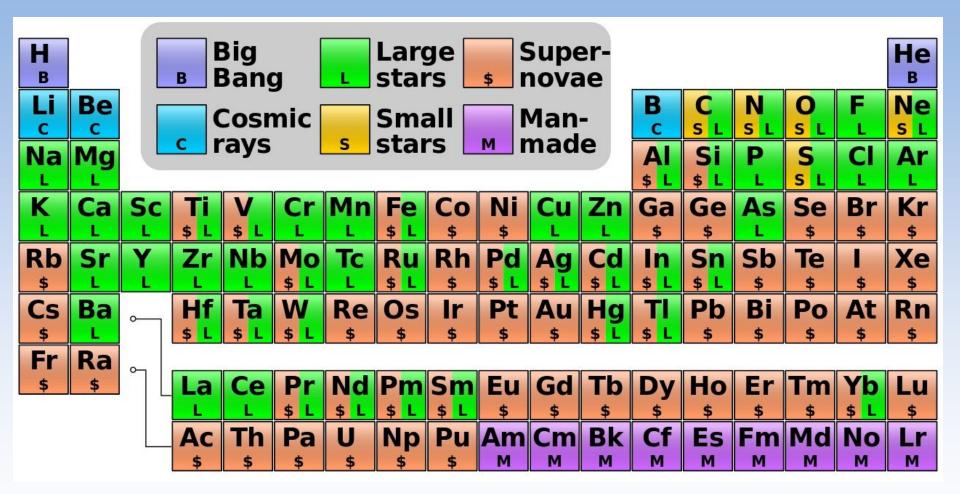
- Proton capture followed by β^+ decay.
- See the *Chart of the Nuclides* for the path.



The Result



The Result





Gratuitous fossil rugose coral, Monte Cristo Fm. (Mississippian), south of Goodsprings, NV. The Monte Cristo may be equivalent to the Redwall Limestone of the Grand Canyon.

