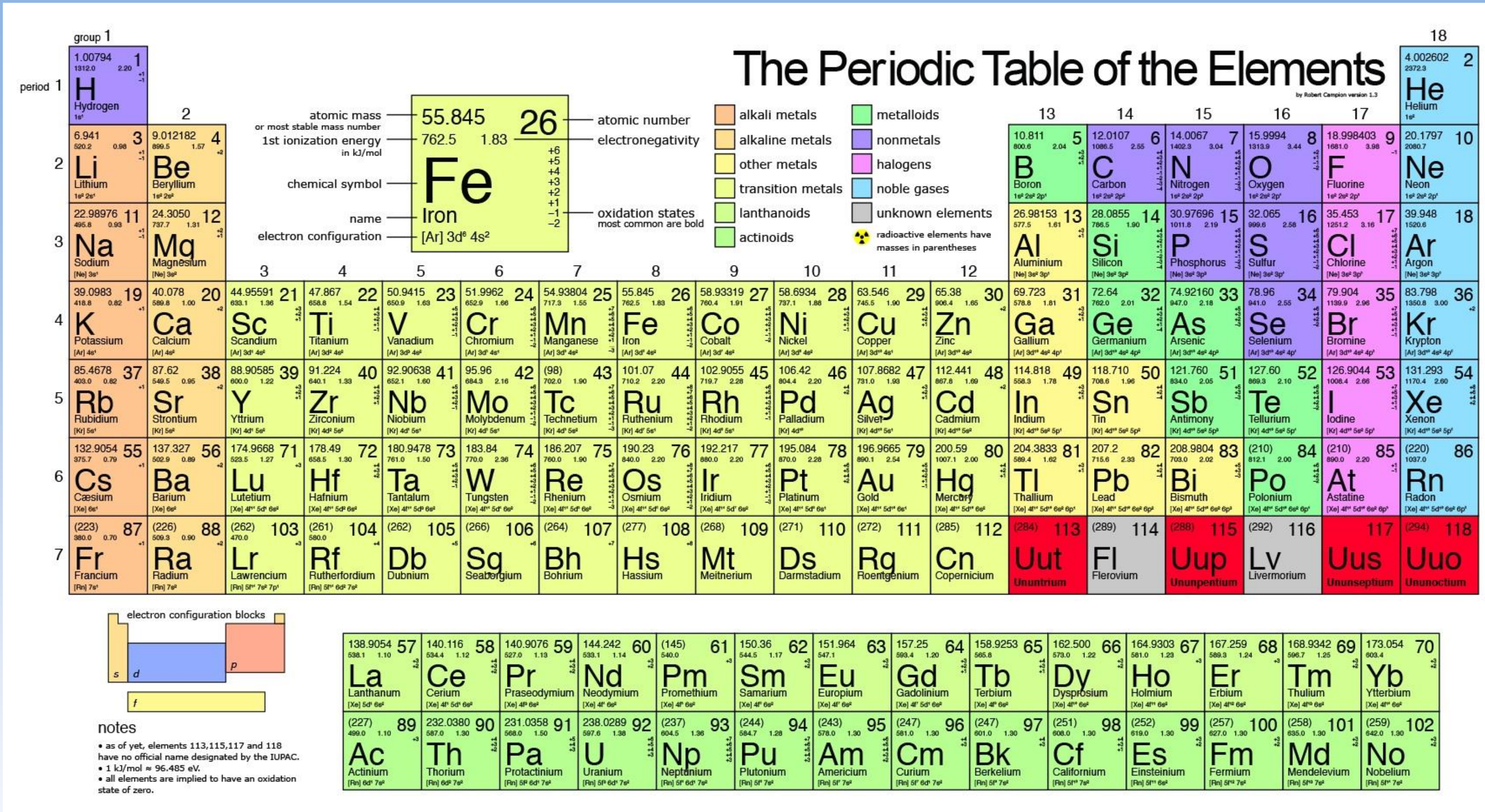
"Synthesis of the Elements in Stars"

Margaret Burbidge, Geoffrey Burbidge, Willie Fowler, & Fred Hoyle

Reviews of Modern Physics Vol. 29, # 4, October 1957, pp. 547-650.

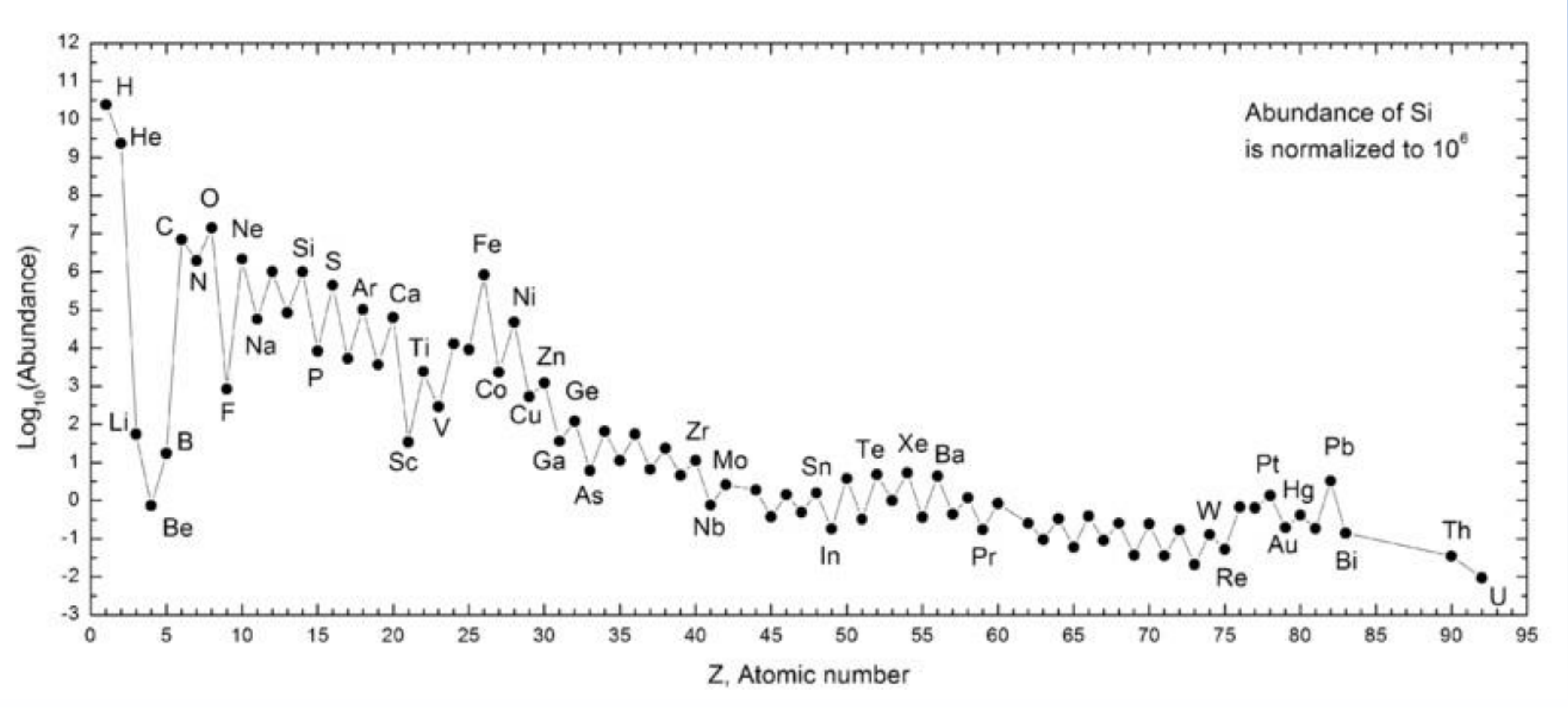
- Dr. David Batchelor



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

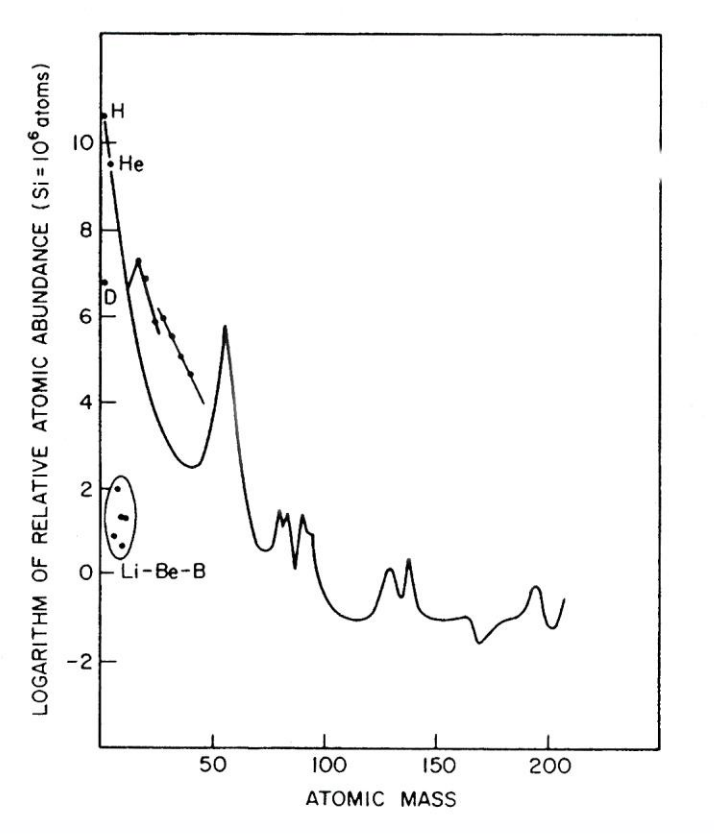
Abundance (where?) Curves

- 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?



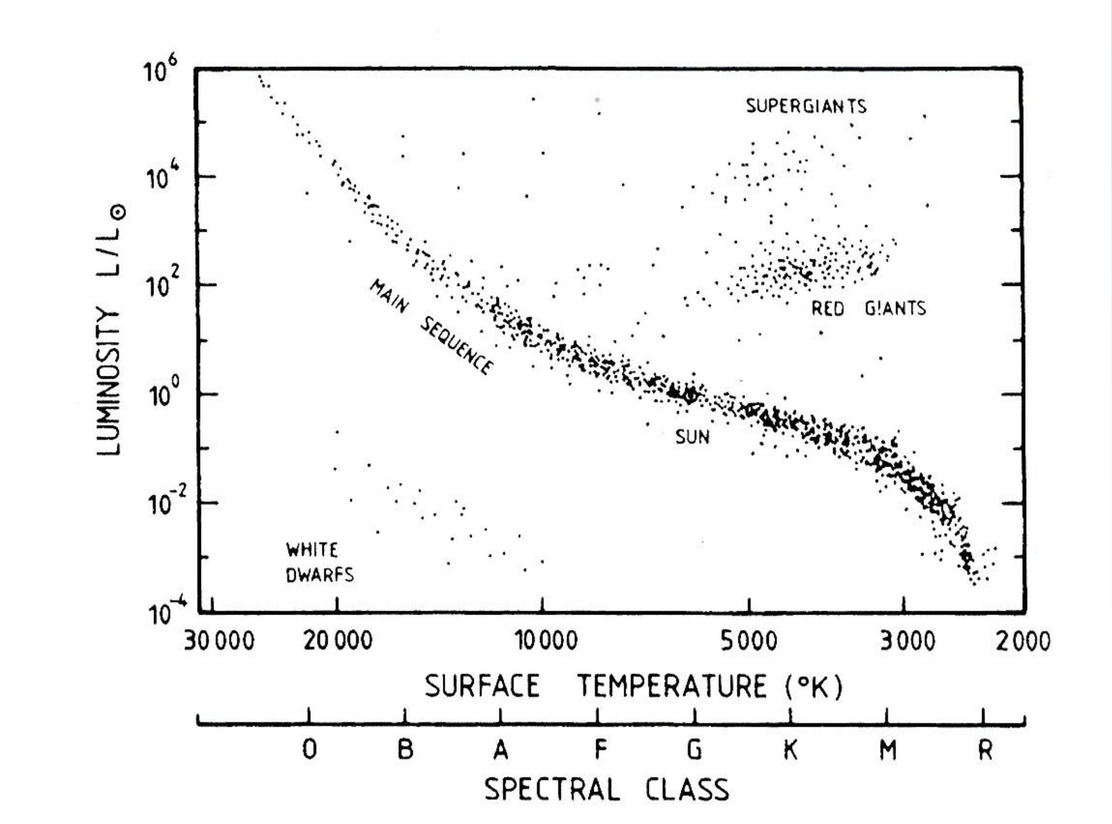
The Alpher-Bethe-Gamow letter in Physical Review

- 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 α, β, γ.

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…

$$^{1}H + {}^{12}C \rightarrow \gamma s + {}^{13}N \rightarrow {}^{13}C + \beta^{+} + \nu$$

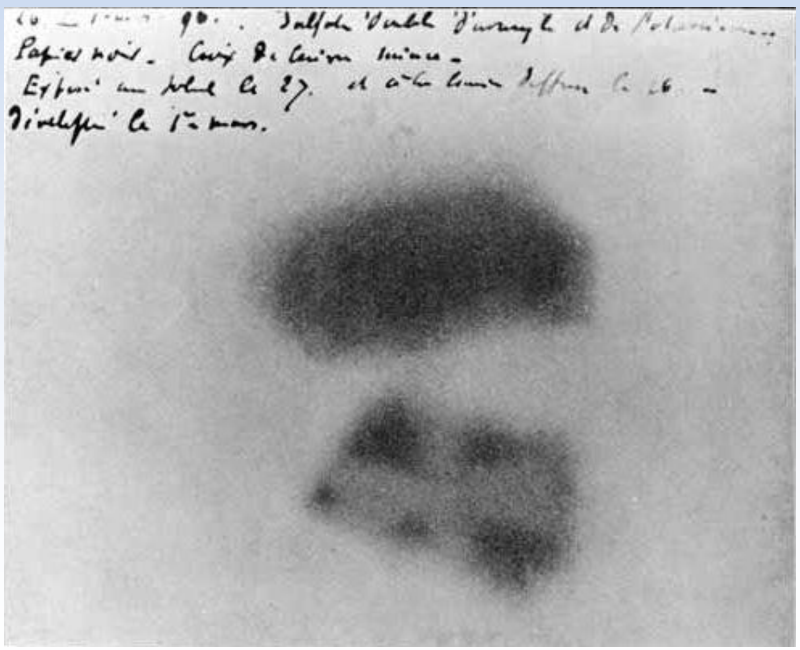
$$^{1}H + {}^{13}C \rightarrow {}^{14}N + \gamma s$$

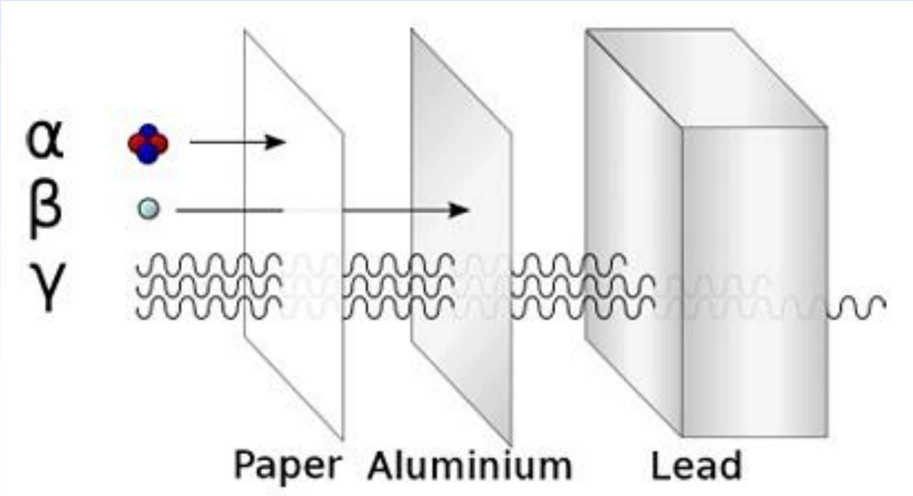
$$^{1}H + {}^{14}N \rightarrow \gamma s + {}^{15}O \rightarrow {}^{15}N + \beta^{+} + \nu$$

$$^{1}H + {}^{15}N \rightarrow {}^{12}C + {}^{4}He$$

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.

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

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

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

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

How Likely is a Nuclear Reaction?

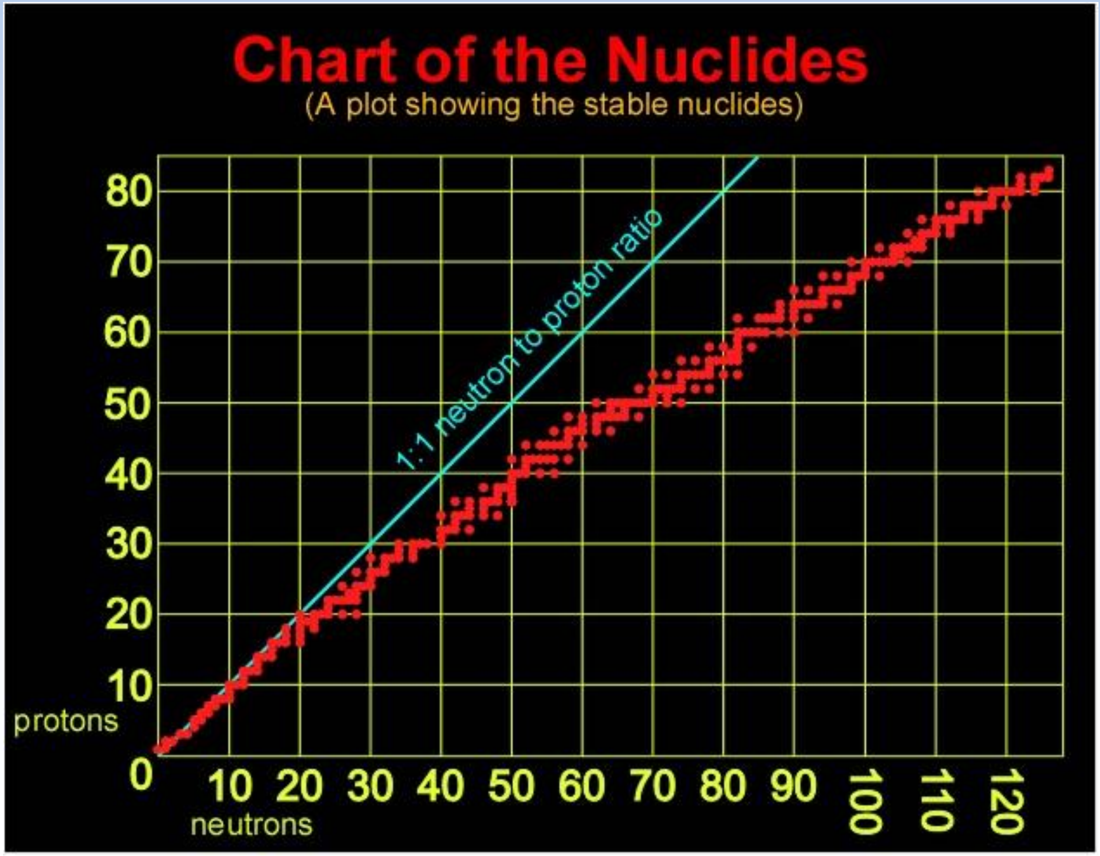
- How likely is a small particle to strike a nucleus and cause a reaction?
- The probability is expressed by the cross-section of the nucleus (as seen by the incoming particle).
- The standard unit is the cross-section area of a uranium nucleus, 10^{-24} cm^2.
- In the wartime code developed by Purdue 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^{-24}b 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. (^{50}V, 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. (^{4}He, 99.999866%; ^{16}O, 99.756%; ^{208}Pb, Z=82, N= 126)
- She also discovered *spin-orbit coupling* in nucleons, which explains the even-odd effect.
- She later worked on the "Super" with Teller.

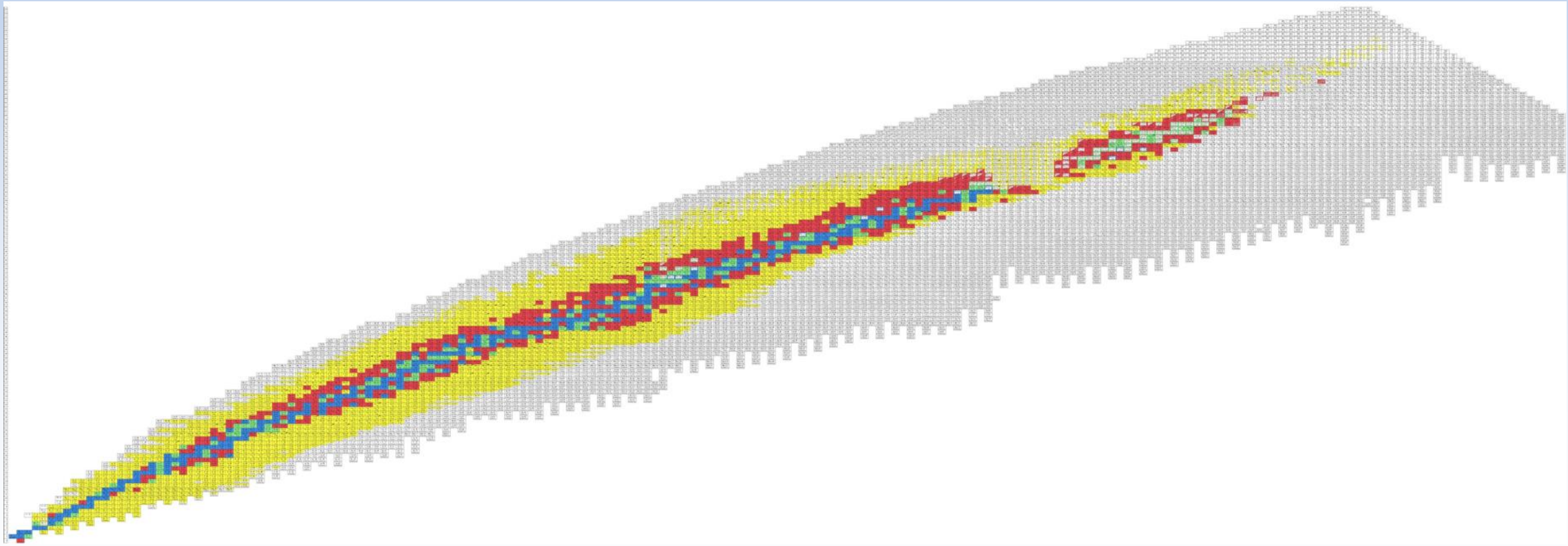
We'll also need the REAL periodic table, the *Chart of the Nuclides.*

- 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.

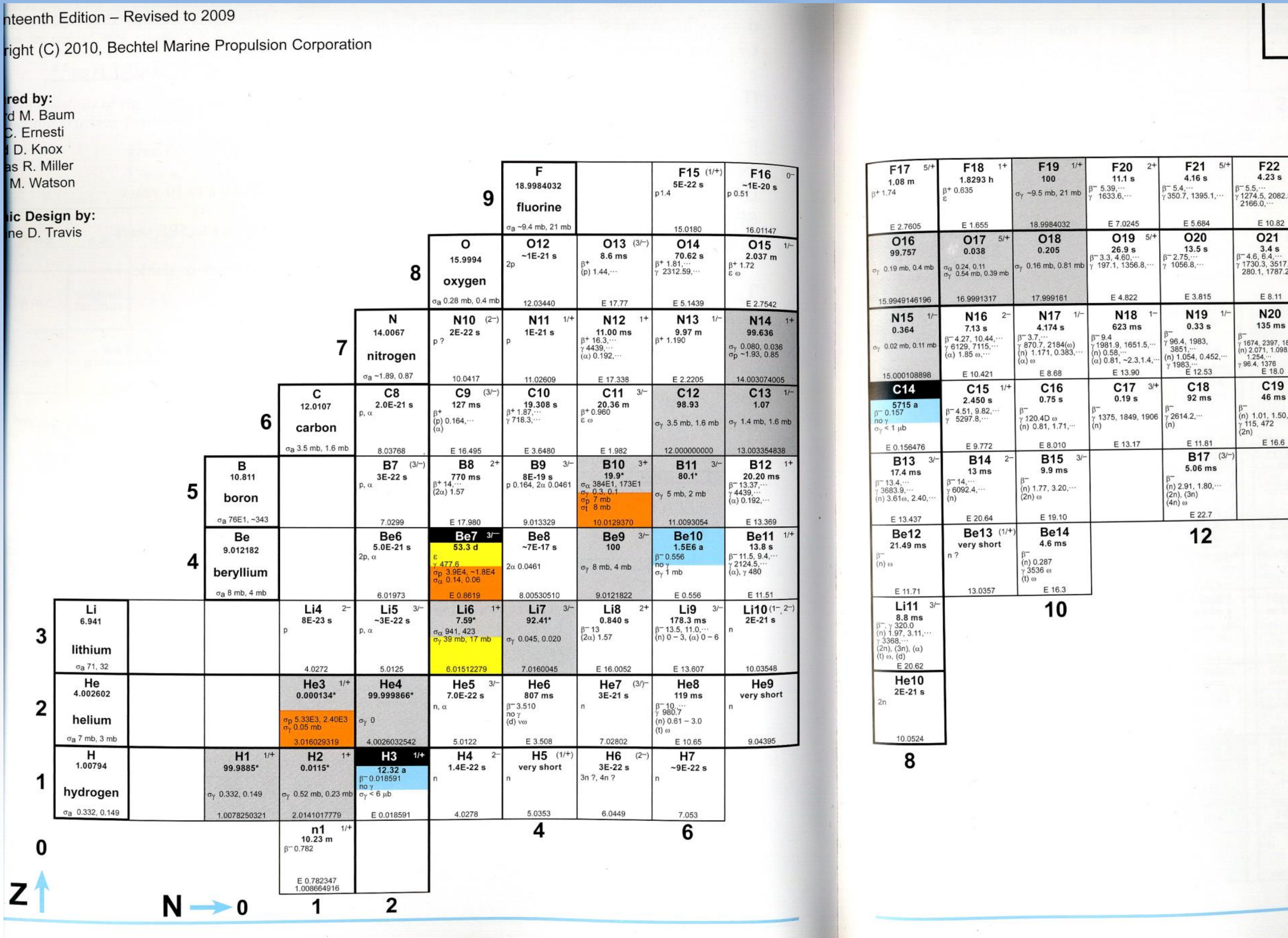


The *Chart of the Nuclides, cont'd.*

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



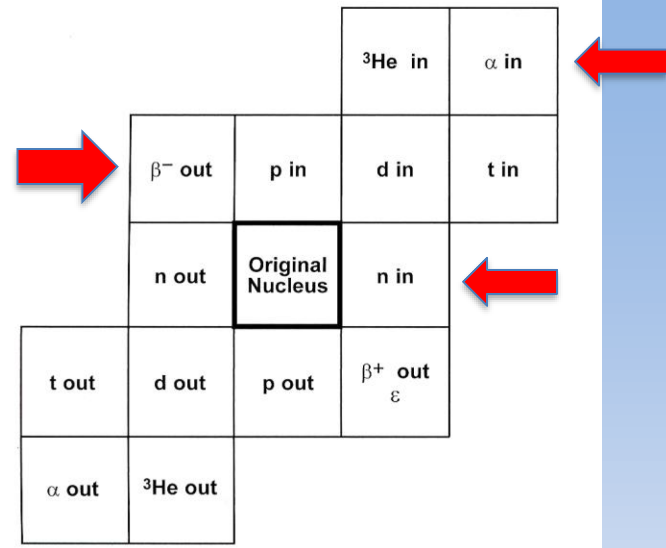
The *Chart of the Nuclides*, up close.



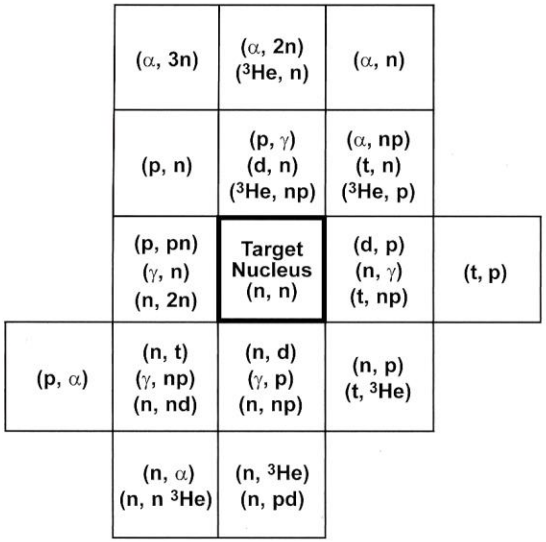
Nuclear Reactions on the *Chart of the Nuclides.*

- 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

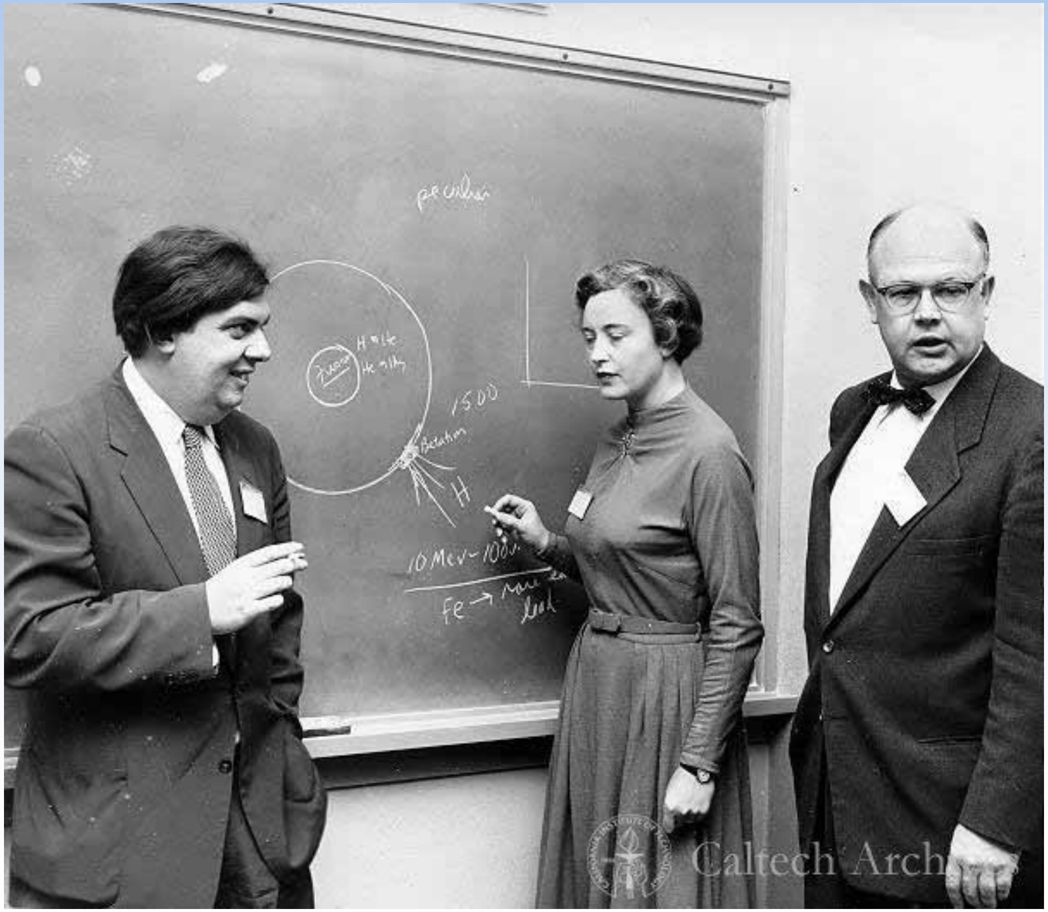


Displacement Caused by Nuclear Bombardment Reactions



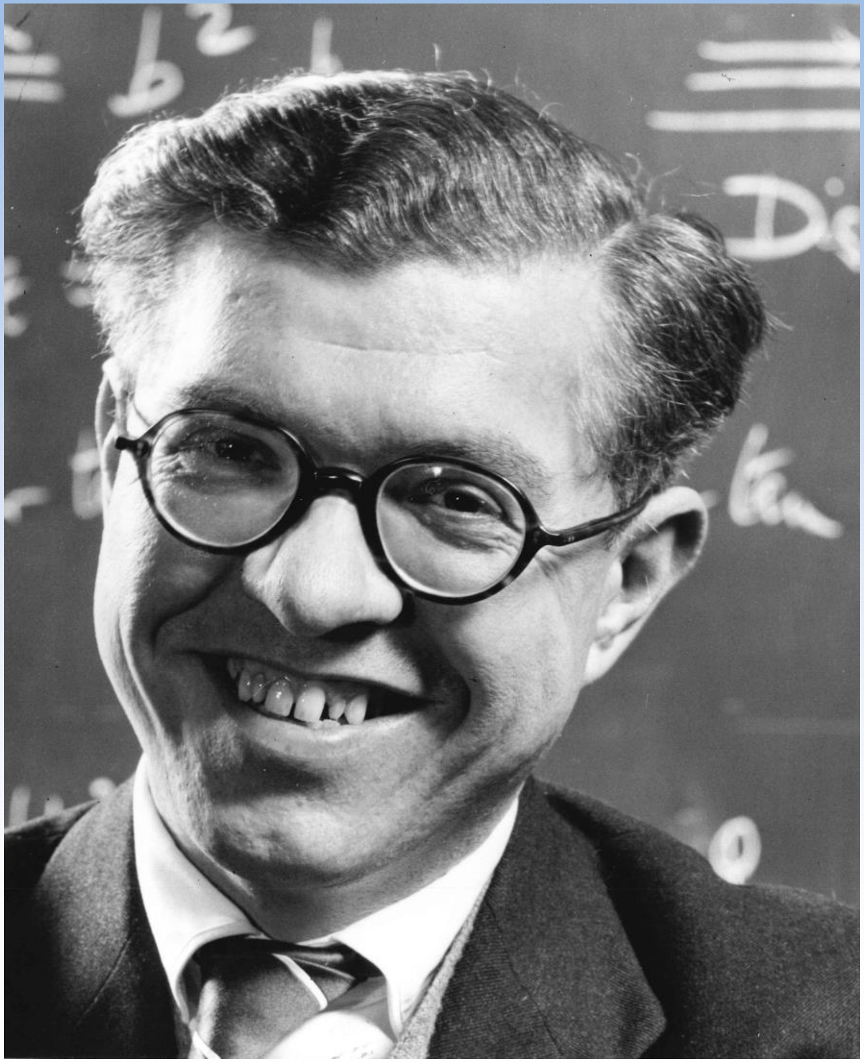
Meet the Authors

- 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 a 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 ^{12}C 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: https://en.wikipedia.org/wiki/Triple-alpha_process#Improbability_and_fine-tuning.

Triple-alpha process

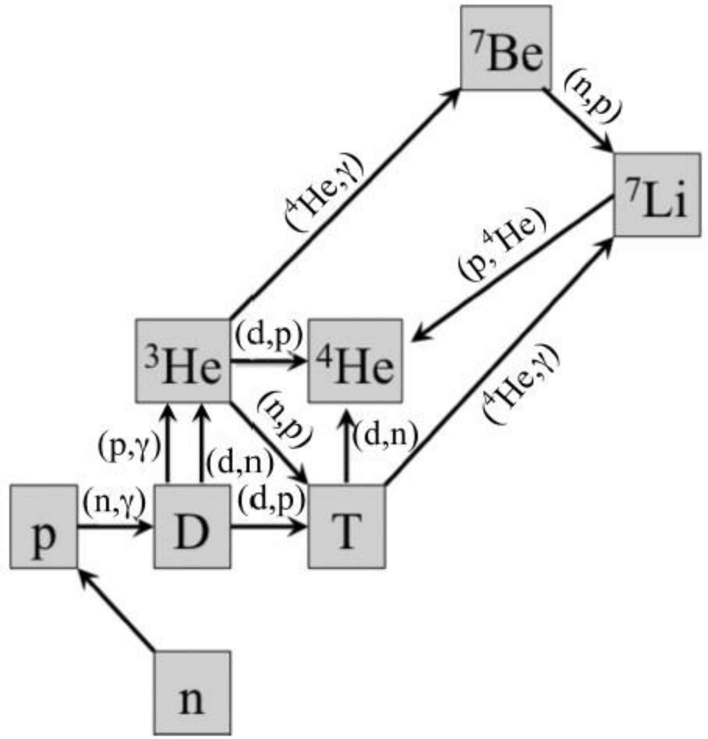
$$^{4}He + {}^{4}He \rightarrow {}^{8}Be$$

$$^{4}He + {}^{8}Be \rightarrow {}^{12}C + \beta^{-} + \beta^{+}$$

$$^{4}He + {}^{12}C \rightarrow {}^{16}O + \gamma$$

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 B^2FH.
- 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

- $^{12}C(\alpha,\gamma)^{16}O$
- $^{16}O(\alpha,\gamma)^{20}Ne$
- $^{20}Ne(\alpha,\gamma)^{24}Mg$
- $^{24}Mg(\alpha,\gamma)^{28}Si$
- $^{28}Si(\alpha,\gamma)^{32}S$
- $^{32}S(\alpha,\gamma)^{36}Ar$
- $^{36}Ar(\alpha,\gamma)^{40}Ca$
- $^{40}Ca(\alpha,\gamma)^{44}Ti$, which undergoes two β decays to ^{44}Ca
- $^{44}Ca(\alpha,\gamma)^{48}Ti$
- 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	*~1000 years*	0.6 GK
$^{12}C + {}^{12}C \rightarrow {}^{20}Ne + {}^{4}He$		
$^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma$		
$^{16}O + {}^{4}He \rightarrow {}^{20}Ne + \gamma$		
$^{20}Ne + {}^{4}He \rightarrow {}^{24}Mg + \gamma$		
Core contracts		
Neon burning	*years*	1.2 GK
$^{20}Ne + \gamma \rightarrow {}^{16}O + {}^{4}He$		
$^{20}Ne + {}^{4}He \rightarrow {}^{24}Mg + \gamma$		
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
$^{28}Si + {}^{4}He \rightarrow {}^{32}S$		
$^{32}S + {}^{4}He \rightarrow {}^{36}Ar$		
…*et cetera*, down to…		
$^{52}Fe + {}^{4}He \rightarrow {}^{56}Ni$		

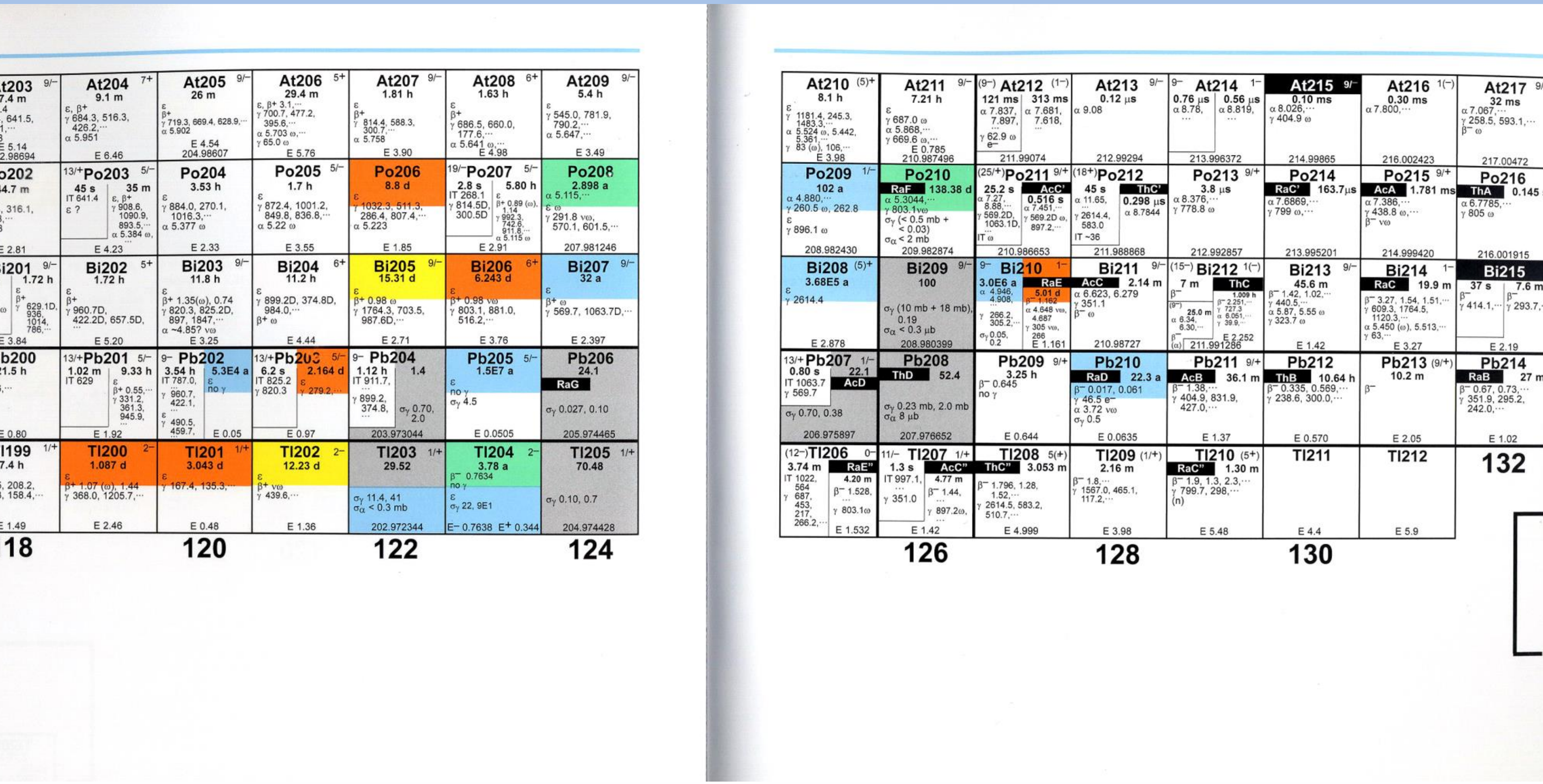
The Burbidges Decipher the Rest – the *s-Process*

- 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 next-heavier 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*

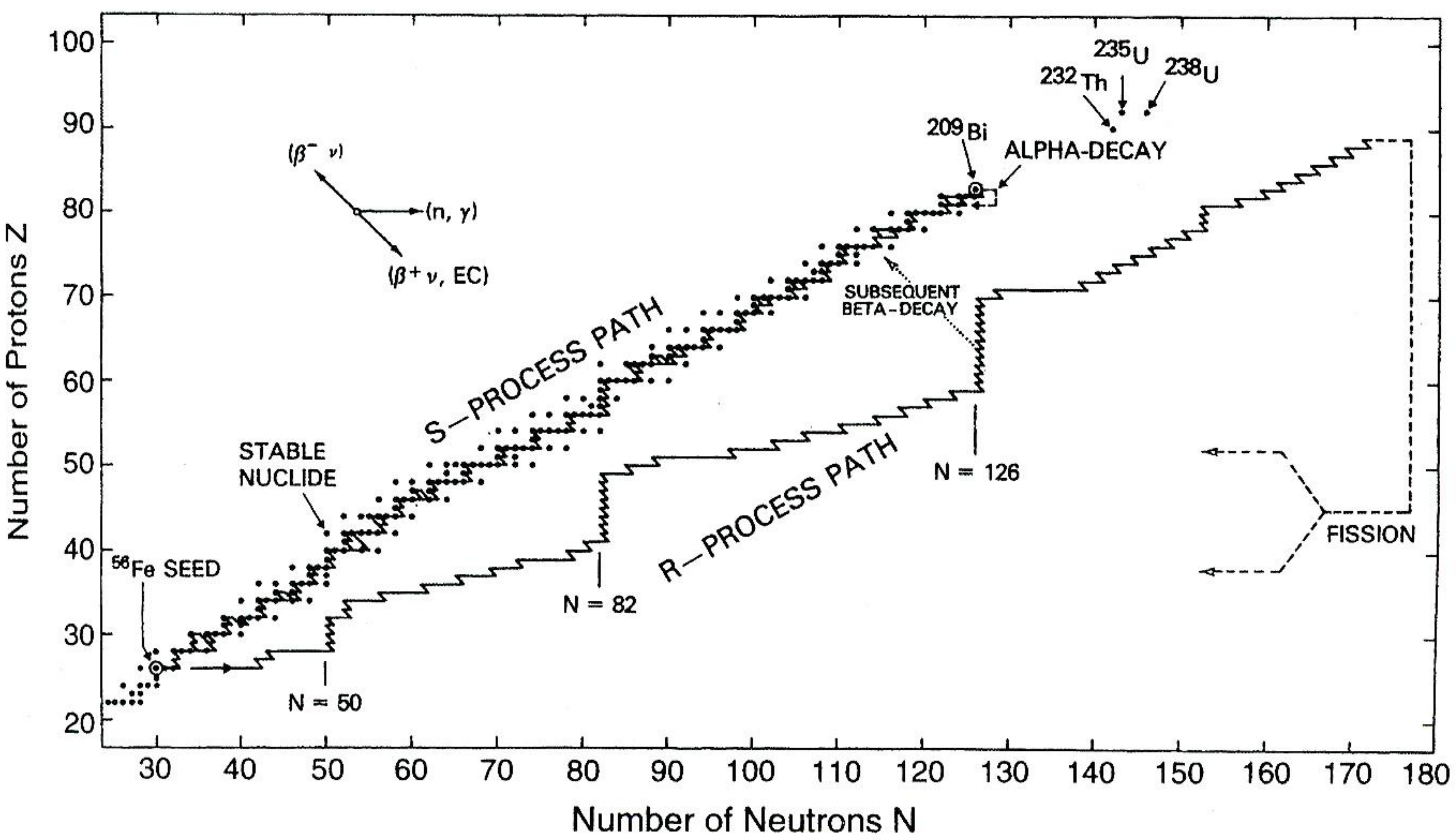
- The s-process is stopped at ^{209}Bi.
- ^{209}Bi(n,γ)^{210}Bi, which βs to ^{210}Po, which αs to ^{206}Pb, which 3(n,γ) to ^{209}Pb, which βs back to ^{209}Bi. We' re stuck.



The Burbidges Decipher the *r-Process*

- When the core become Fe, ^{56}Fe is the most stable nucleus, so no more α-captures 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*

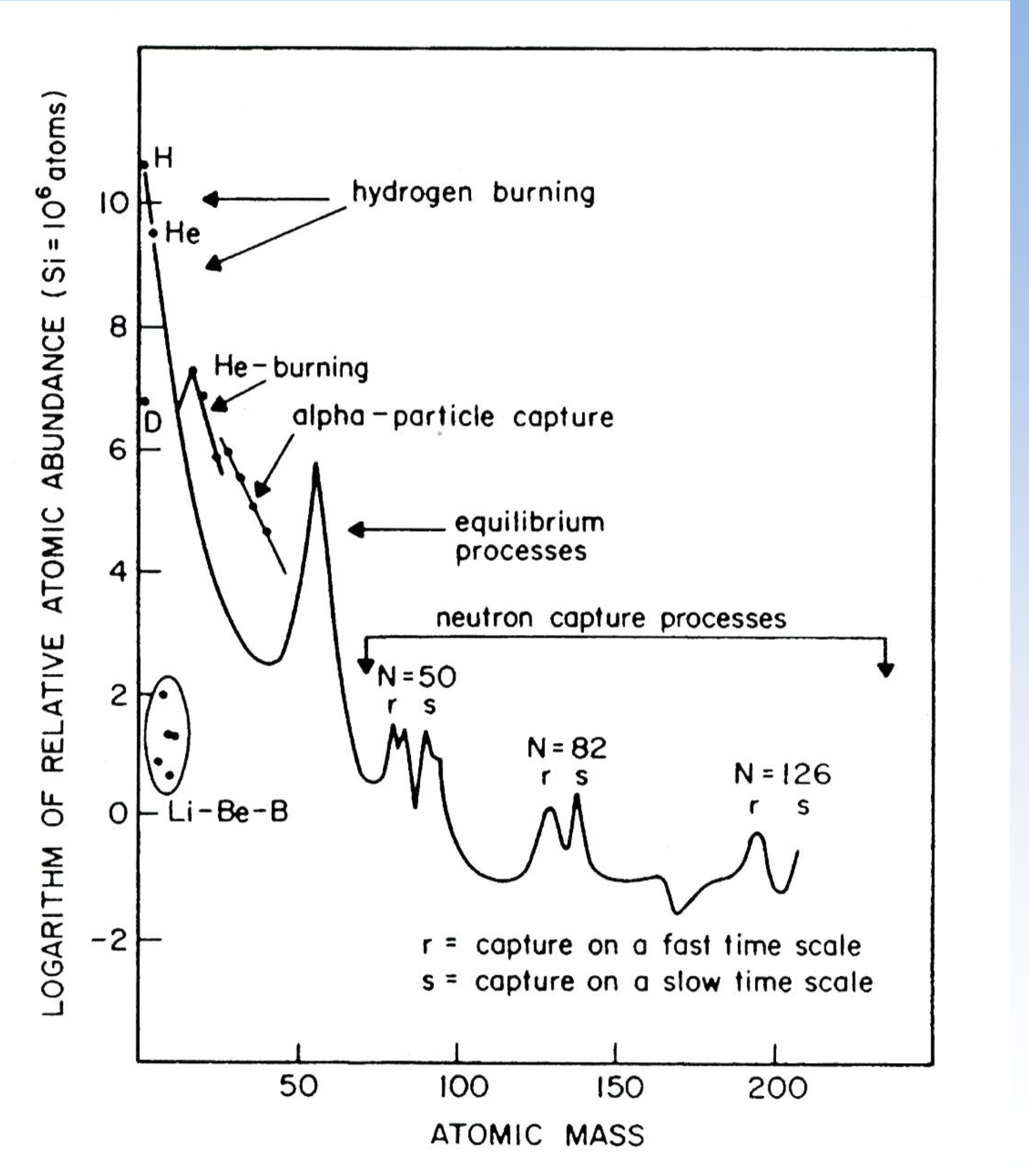


The p-process

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

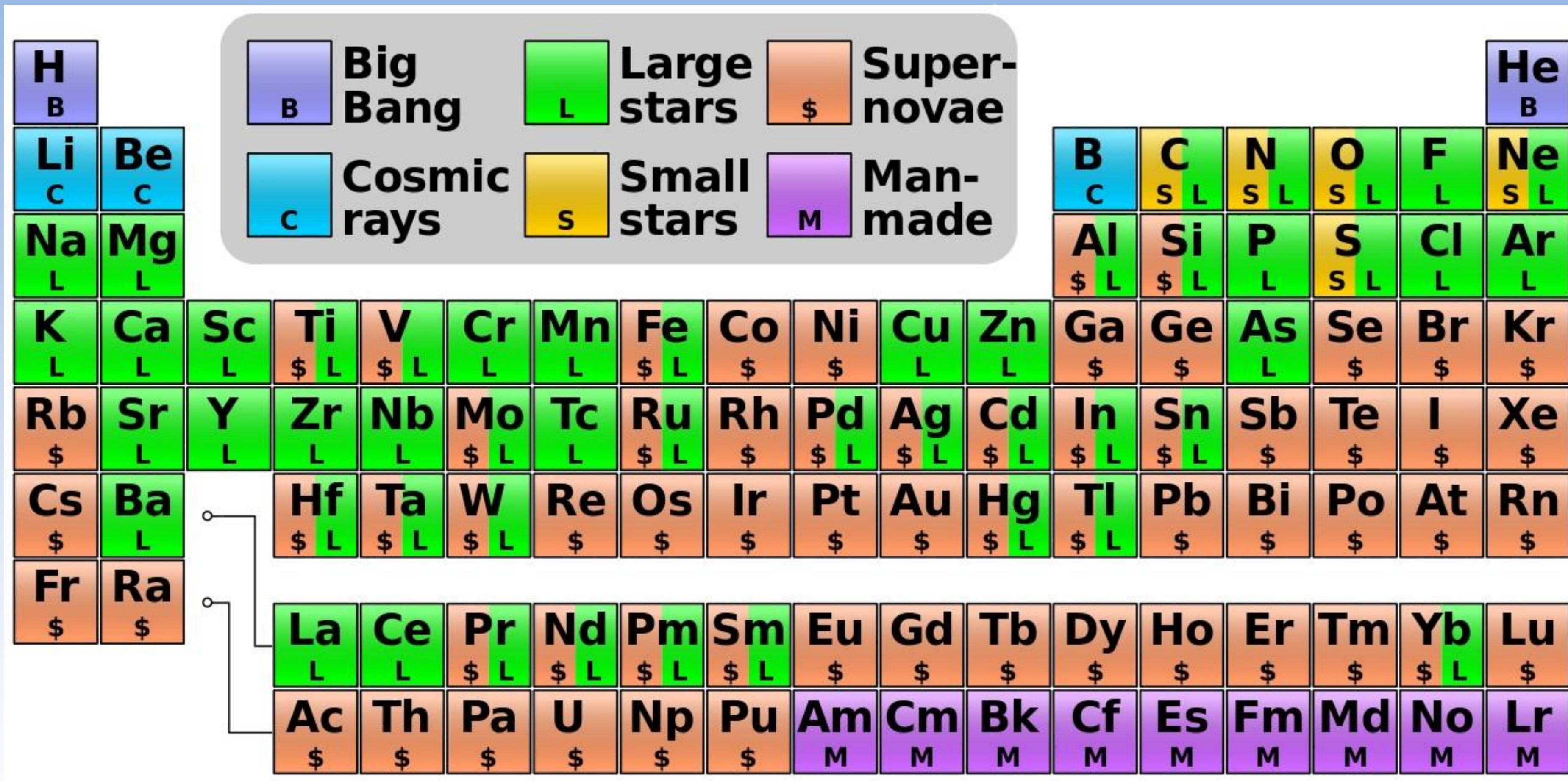
No ^{254}Cf

The Result



LOGARITHM OF RELATIVE ATOMIC ABUNDANCE (Si = 10^6 atoms)
ATOMIC MASS
H
He
D
Li-Be-B
hydrogen burning
He-burning
alpha-particle capture
equilibrium processes
neutron capture processes
N = 50
r s
N = 82
r s
N = 126
r s
r = capture on a fast time scale
s = capture on a slow time scale
10
8
6
4
2
0
-2
50
100
150
200

The Result



Big Bang
B
Large stars
L
Super-novae
$
Cosmic rays
C
Small stars
S
Man-made
M
H B
He B
Li C
Be C
B C
C S L
N S L
O S L
F L
Ne S L
Na L
Mg L
Al $ L
Si $ L
P L
S S L
Cl L
Ar L
K L
Ca L
Sc L
Ti $ L
V $ L
Cr L
Mn L
Fe $ L
Co $
Ni $
Cu L
Zn L
Ga $
Ge $
As L
Se $
Br $
Kr $
Rb $
Sr L
Y L
Zr L
Nb L
Mo $ L
Tc L
Ru $ L
Rh $
Pd $ L
Ag $ L
Cd $ L
In $ L
Sn $ L
Sb $
Te $
I $
Xe $
Cs $
Ba L
Hf $ L
Ta $ L
W $ L
Re $
Os $
Ir $
Pt $
Au $
Hg $ L
Tl $ L
Pb $
Bi $
Po $
At $
Rn $
Fr $
Ra $
La L
Ce L
Pr $ L
Nd $ L
Pm $ L
Sm $ L
Eu $
Gd $
Tb $
Dy $
Ho $
Er $
Tm $
Yb $ L
Lu $
Ac $
Th $
Pa $
U $
Np $
Pu $
Am M
Cm M
Bk M
Cf M
Es M
Fm M
Md M
No M
Lr M

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.


Thank You, and Good Night!