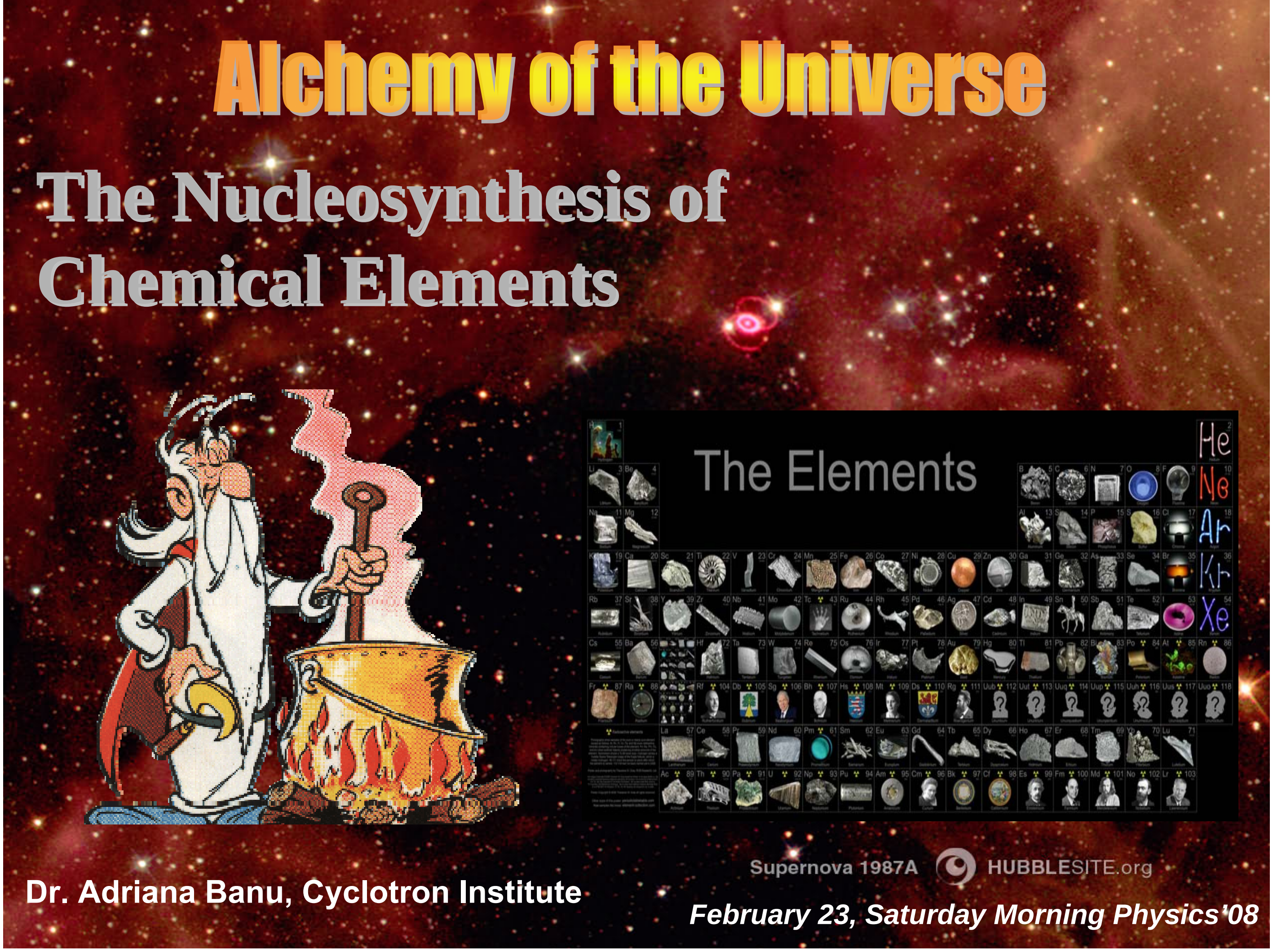


Outline

- History of chemical elements
- Origin of chemical elements
- Primordial nucleosynthesis
- Stellar nucleosynthesis
- Explosive nucleosynthesis
- Summary

• From Aristotle to Mendeleyev

In search of the building blocks of the universe…

Greek philosophers   4 building blocks

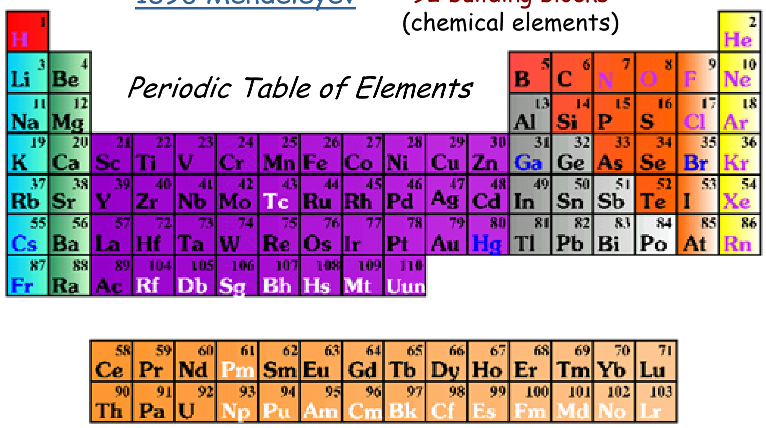

water
air
fire
earth

18th-19th century Lavoisier, Dalton, …

distinction between compounds and pure elements

atomic theory revived

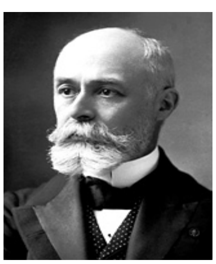
1896 Mendeleyev   92 building blocks (chemical elements)



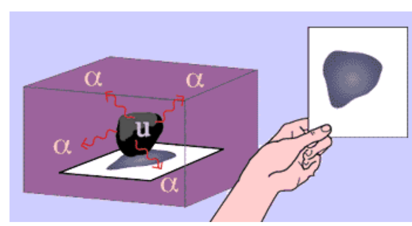
History of chemical elements

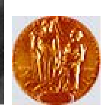
• Modern "Alchemy": **radioactivity**

1896 Becquerel discovers *radioactivity*



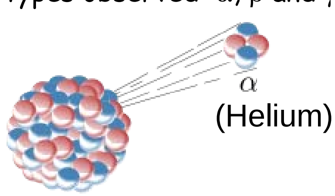
A. H. Becquerel   Pierre Curie   Marie Curie

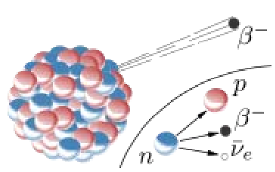


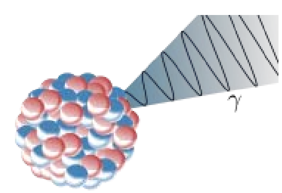

The Nobel Prize in Physics 1903

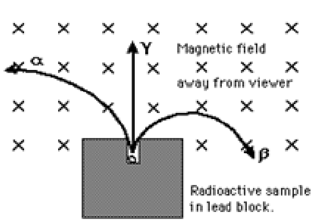
⇒ emission of radiation from atoms
⇒ 3 types observed: α, β and γ

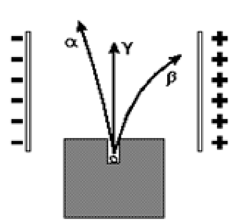
"transmutation"











α and β deflected in opposite direction ⇒ opposite charge
α deflected less than β ⇒ α must have larger mass
γ not deflected ⇒ uncharged

α and β emissions change nature of element
α's charge = +2e   α's mass ~ 4H
β radiation = electrons
γ = electromagnetic radiation (photons)

• Chart of the Nuclides

Z \ N	64	65	66	67	68	69	70	71	72
52	116Te 2.49 H ε: 100.00%	117Te 62 M ε: 100.00% ε: 25.00%	118Te 6.00 D ε: 100.00%	119Te 16.05 H ε: 100.00% ε: 2.06%	120Te >2.2E+16 Y 0.09% 2ε	121Te 19.16 D ε: 100.00%	122Te STABLE 2.55%	123Te >9.2E+16 Y 0.89% ε: 100.00%	124Te STABLE 4.74%
51	115Sb 32.1 M ε: 100.00%	116Sb 15.8 M ε: 100.00%	117Sb 2.80 H ε: 100.00% ε: 1.70%	118Sb 3.6 M ε: 100.00%	119Sb 38.19 H ε: 100.00%	120Sb 15.89 M ε: 100.00%	121Sb STABLE 57.21%	122Sb 2.7238 D β-: 97.59% ε: 2.41%	123Sb STABLE 42.79%
50	114Sn STABLE 0.66%	115Sn STABLE 0.34%	116Sn STABLE 14.54%	117Sn STABLE 7.68%	118Sn STABLE 24.22%	119Sn STABLE 8.59%	120Sn STABLE 32.58%	121Sn 27.03 H β-: 100.00%	122Sn STABLE 4.63%
49	113In STABLE 4.29%	114In 71.9 S β-: 99.50% ε: 0.50%	115In 4.41E+14 Y 95.71% β-: 100.00%	118 Sn			119In 2.4 M β-: 100.00%	120In 3.08 S β-: 100.00%	121In 23.1 S β-: 100.00%
48	112Cd STABLE 24.13%	113Cd 7.7E+15 Y 12.22% β-: 100.00%	114Cd >6.4E+18 Y 28.73% 2β-	β-: 100.00%	7.49% 2β-	β-: 100.00%	118Cd 50.3 M β-: 100.00%	119Cd 2.69 M β-: 100.00%	120Cd 50.80 S β-: 100.00%

Z ↑ N →

A chemical element is uniquely identified by the atomic number ***Z***: $^{A}_{Z}X_{N}$

Nuclides that have the same ***Z*** but different ***N*** are called *isotopes* !

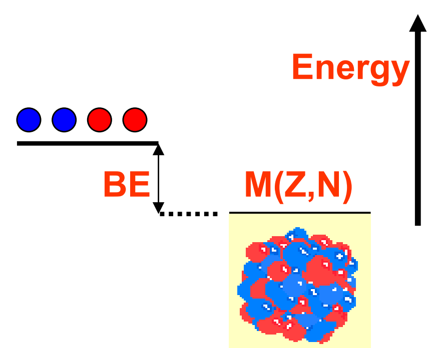
• need to understand the physics of nuclei to explain the origin of chemical elements

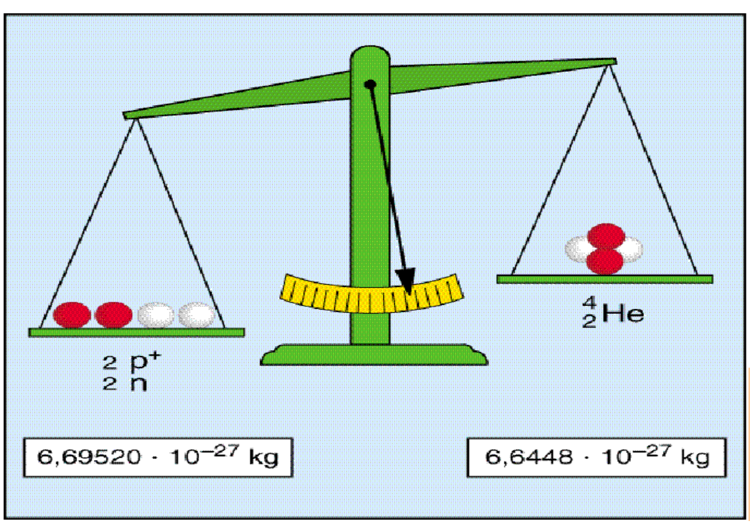
• Nuclear Masses and Binding Energy

$$M(Z,N) = Zm_p + Nm_n - BE$$

m_p = proton mass, m_n = neutron mass,
m(Z,N) = mass of nucleus with ***Z*** protons and ***N*** neutrons

The binding energy is the energy required to dissassemble a nucleus into protons and neutrons. It is derived from the strong nuclear force.





A bound system has a lower potential energy than its constituents !

⇓

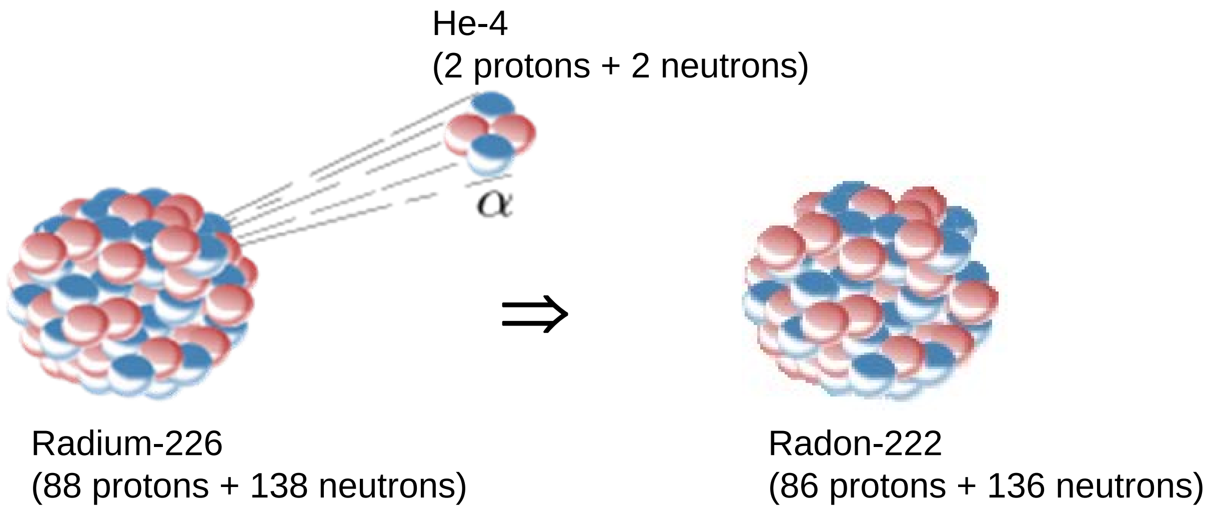
positive binding energy (BE)

• in atoms: BE ~ eV
• in nuclei: BE ~ MeV

$M_{nucl} < \Sigma m_p + \Sigma m_n$ ➡ $\Delta E = \Delta M \cdot c^2$

enormous energy stored in nuclei!

Thanks to $E=mc^2$,
tiny amounts of mass convert into huge energy release…



1 kg of radium would be converted into 0.999977 kg of radon and alpha particles.

The loss in mass is only *0.000023 kg*.

Energy = mc^2 = mass x (speed of light)^2
= $0.000023 \times (3 \times 10^8)^2 = 2.07 \times 10^{12}$ joules.
Equivalent to the energy from over 400 tonnes of TNT!!!

1 kg Ra (nuclear) ↔ $4 \cdot 10^5$ kg TNT (chemical)

- Nuclear Reactions

History of chemical elements

- **origin of chemical elements**
- **origin of stellar energies**

$$ {}^{A1}_{Z1}X + {}^{A2}_{Z2}Y \Rightarrow {}^{A3}_{Z3}A + {}^{A4}_{Z4}B $$

Conservation laws:

- **A1 + A2 = A3 + A4** (mass numbers)
- **Z1 + Z2 = Z3 + Z4** (atomic numbers)

Amount of energy liberated in a nuclear reaction (Q-value):

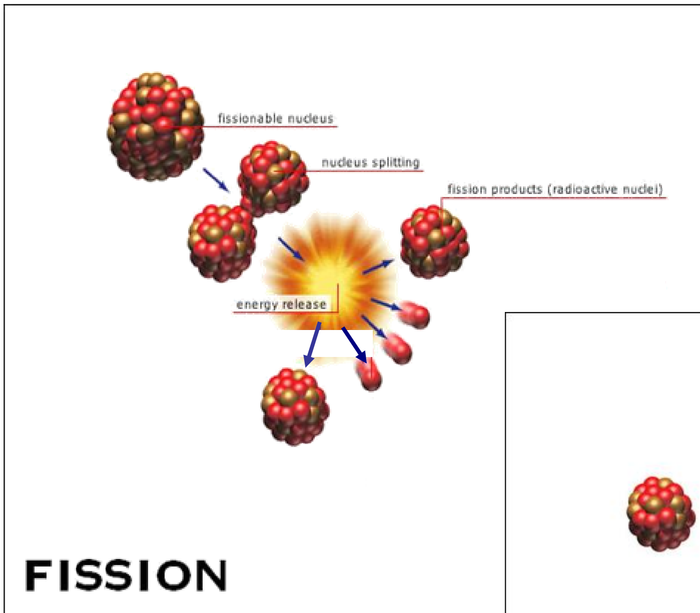
$$ Qval = [(m1 + m2) - (m3 + m4)]c^2 $$ **definition**

(m1 + m2): *initial*; (m3 + m4): *final*

Qval > 0: exothermic process (release of energy) **in stars**
Qval < 0: endothermic process (absorption of energy)

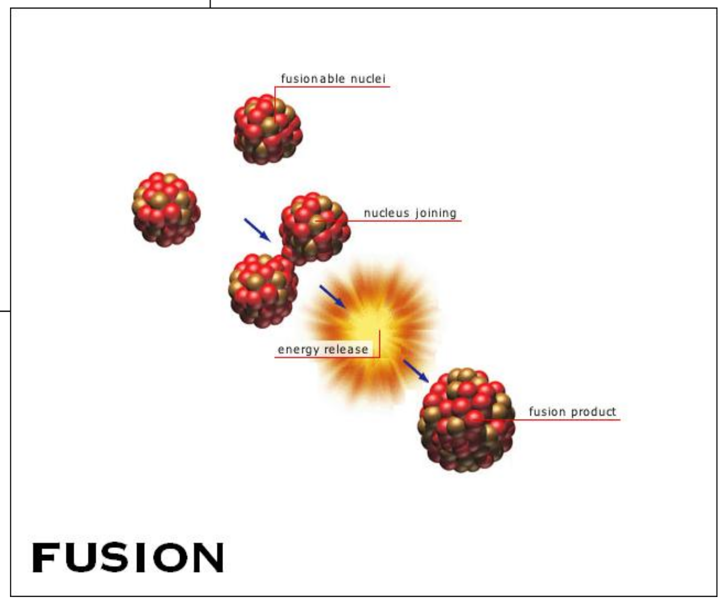
History of chemical elements

• Modern "Alchemy": **nuclear fusion and fission**



The process through which a large nucleus is split into smaller nuclei is called **fission**.

Fusion is a reverse process.

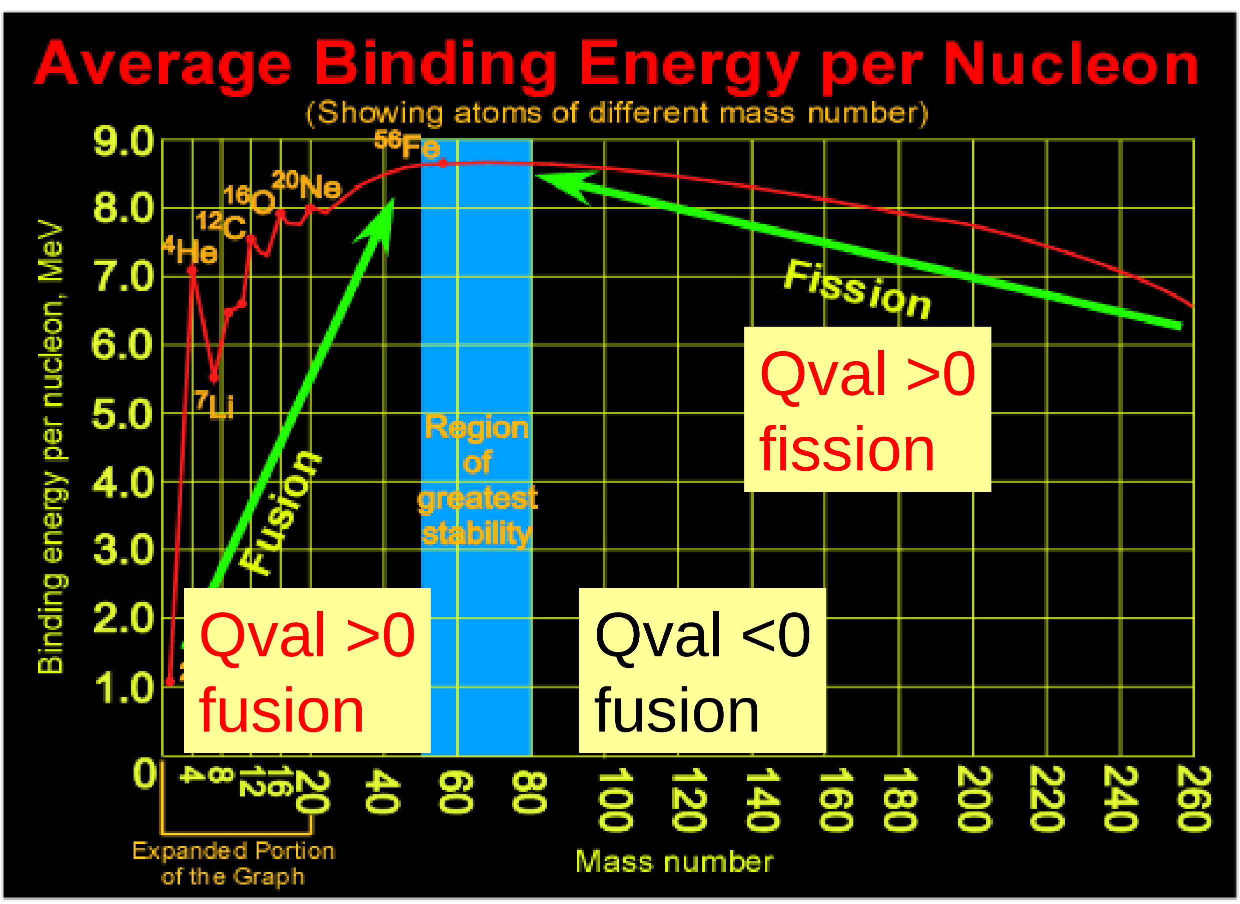


Fission and ***fusion*** are a form of elemental transmutation because the resulting fragments are not the same element as the original nuclei.

Nuclear fusion occurs naturally in stars !

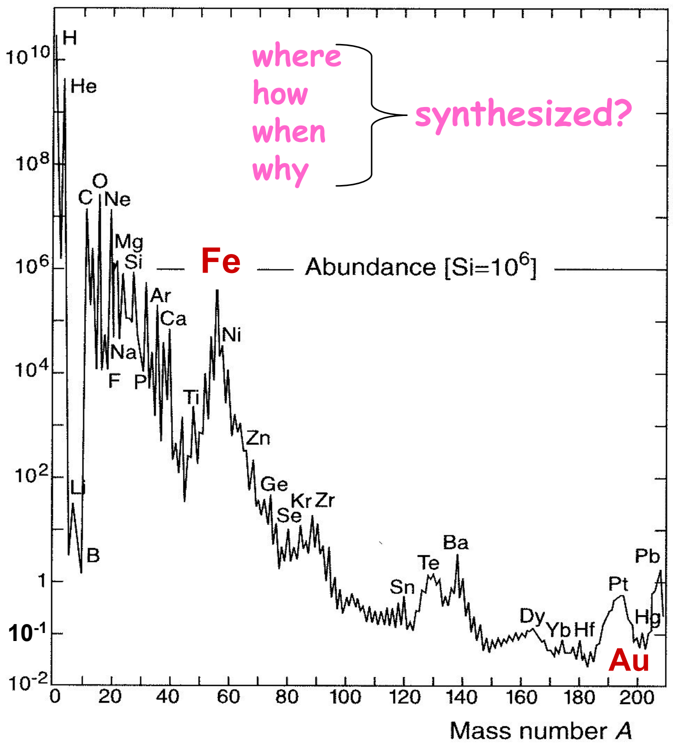
History of chemical elements

• Stability and Binding Energy Curve



• Abundance of the Elements

Origin of chemical elements



Data sources:

Earth, Moon, meteorites,
stellar (Sun) spectra, cosmic rays...

Features:

- 12 orders-of-magnitude span
- H ~ 75%
- He ~ 23%
- C → U ~ 2% (“metals”)
- D, Li, Be, B under-abundant
- O the third most abundant
- C the fourth most abundant
- exponential decrease up to Fe
- peak near Fe
- almost flat distribution beyond Fe

why does one kilogram of gold cost so much more than one kilogram of iron?

7 orders of magnitude less abundant ! + properties (it shines…)

CHEMICAL ELEMENTS IN YOUR BODY BY WEIGHT

Oxygen (65%)
Carbon (18%)
Hydrogen (10%)
Nitrogen (3%)
Calcium (1.5%)
Phosphorus (1.0%)
Potassium (0.35%)
Sulfur (0.25%)
Sodium (0.15%)
Magnesium (0.05%)

BUT ALSO

Copper, Zinc, Selenium, Molybdenum, Fluorine, Chlorine, Iodine, Manganese, Cobalt, Iron (0.70%)
Lithium, Strontium, Aluminum, Silicon, Lead, Vanadium, Arsenic, Bromine (trace amounts)

Origin of chemical elements

• What Is the Origin of the Elements?

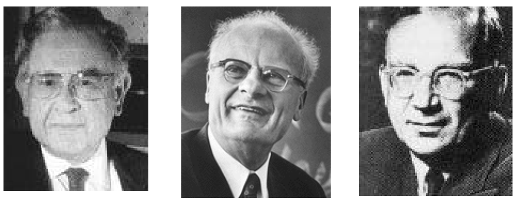
• nucleosynthesis: the making of elements through nuclear reactions

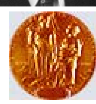
Which one is correct?

Big-Bang nucleosynthesis

all elements formed from protons and neutrons
sequence of n-captures and β decays
soon after the Big Bang

Alpher, Bethe & Gamow ("α β γ")
Phys. Rev. 73 (1948) 803



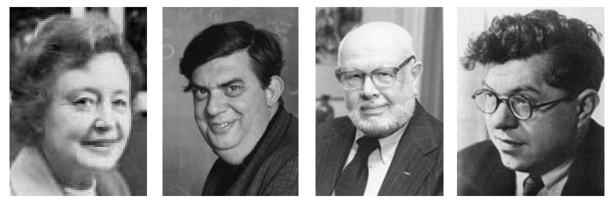


The Nobel Prize in Physics 1967

Stellar nucleosynthesis

elements synthesised inside the stars
nuclear processes
well defined stages of stellar evolution

Burbidge, Burbidge, Fowler & Hoyle (B^2FH)
Rev. Mod. Phys. 29 (1957) 547

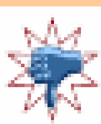


The Nobel Prize in Physics 1983

Primordial nucleosynthesis

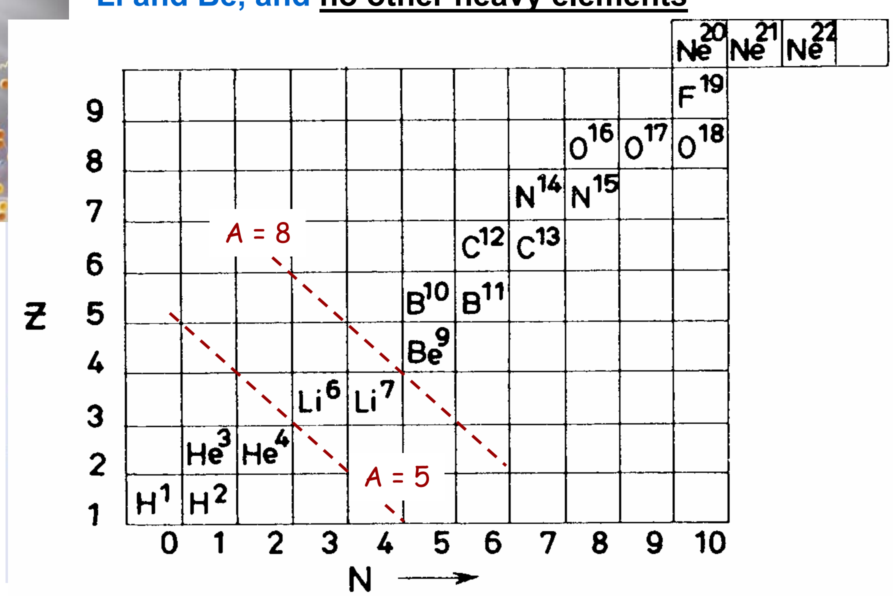
• Big Bang Nucleosynthesis

Mass stability gap at **A=5** and **A=8** !!!

BBN 

No way to bridge the gap through sequence of neutron captures…

- **occurred within the first 3 minutes of the Universe after the primordial quark-gluon plasma froze out to form neutrons and protons**
- **BBN stopped by further expansion and cooling (temperature and density fell below those required for nuclear fusion)**
- **resulted in mass abundances of ^1H (75%), ^4He (23%), ^2H (0.003%), ^3He (0.004%), trace amounts (10^{-10}%) of Li and Be, and <u>no other heavy elements</u>**



After that, very little happened in nucleosynthesis for a long time.

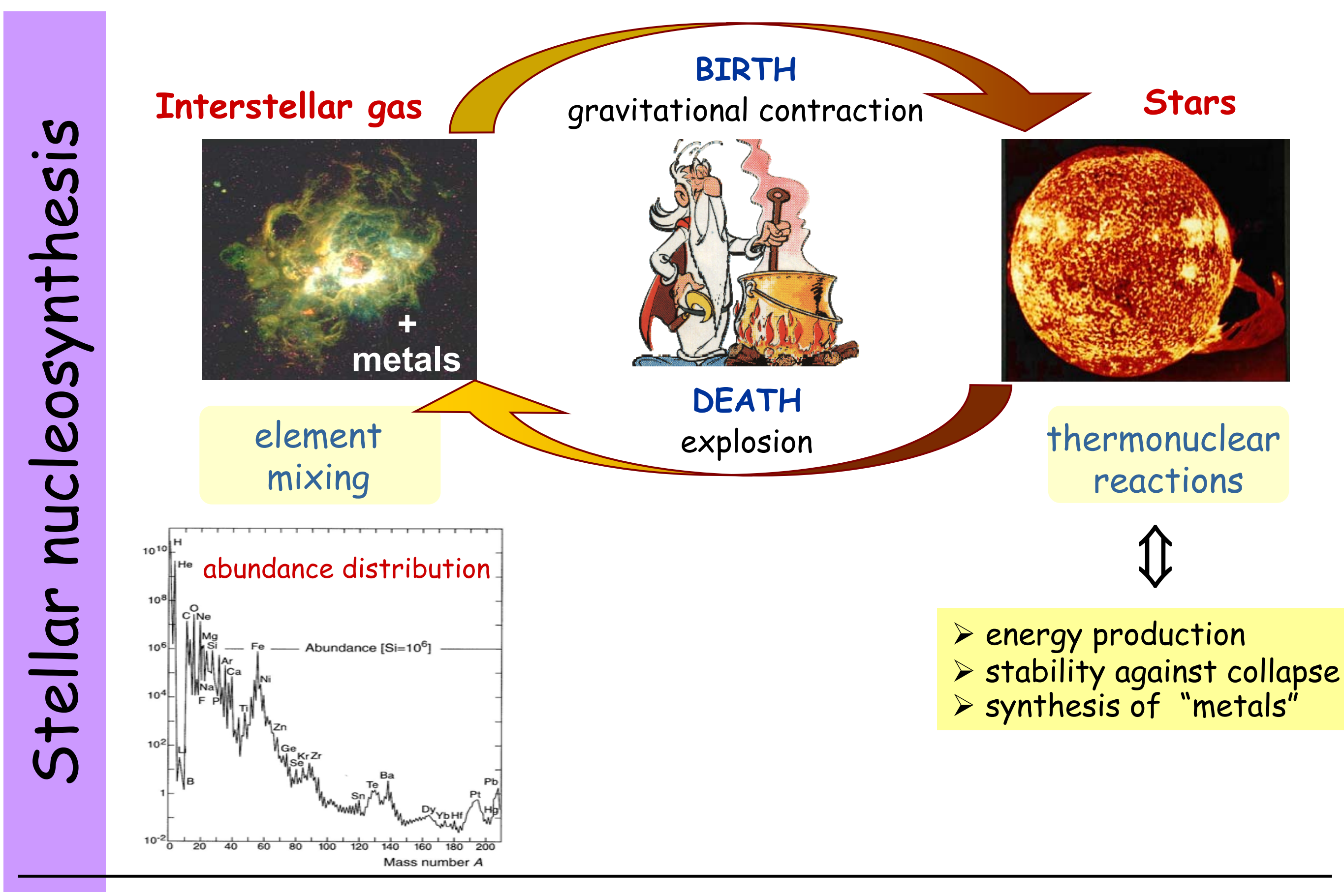
temperature and density too small !!!

It required galaxy and star formation via gravitation to advance the synthesis of heavier elements.

matter coalesces to higher temperature and density…

Because in stars the reactions involve mainly charged particles, stellar nucleosynthesis is a slow process.

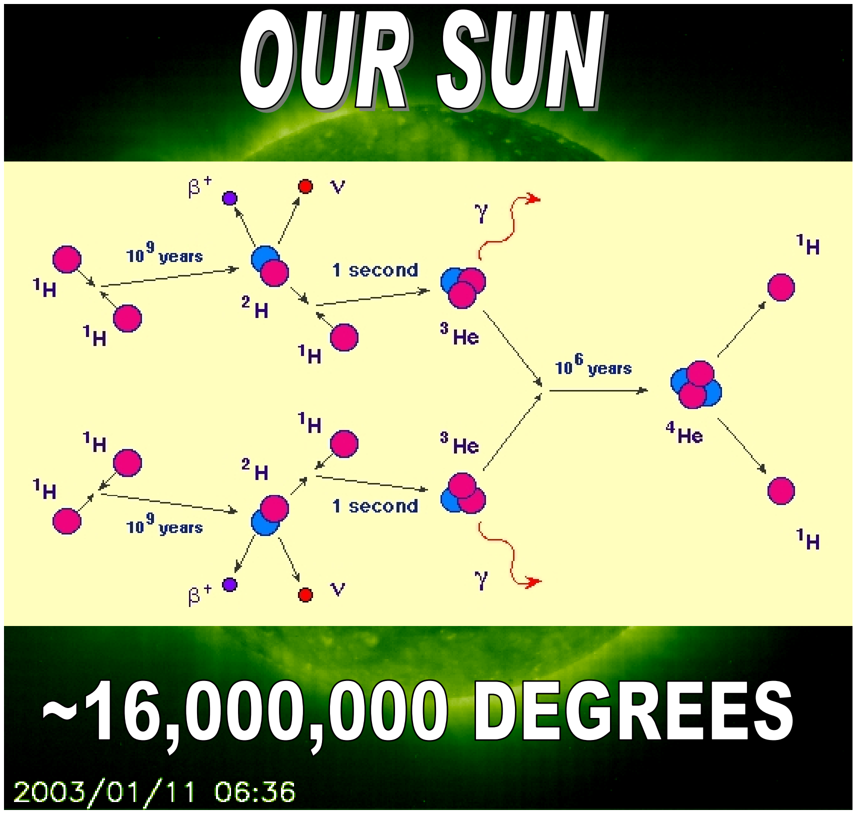
- Stellar life cycle



Stellar nucleosynthesis

- Hydrogen Burning

  - almost 95% of all stars spend their lives burning the H in their core (including our Sun):



Stellar nucleosynthesis

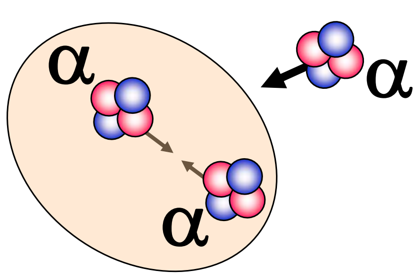
- Helium Burning: **Carbon formation**

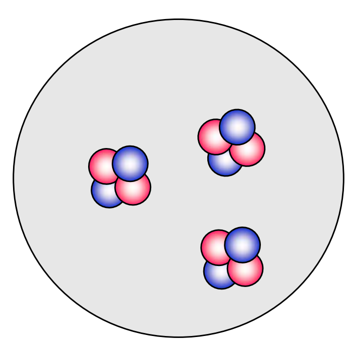
  - *BBN produced <u>no elements heavier than Li</u> due to the absence of a stable nucleus with 8 nucleons*

  - *in stars ^{12}C formation set the stage for the entire nucleosynthesis of heavy elements*

<u>How is Carbon synthesized in stars?</u>

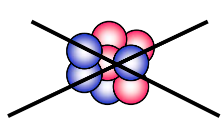
T ~ 6*10^8 K and ρ ~ 2*10^5 gcm^{-3}





^{4}He + ^{4}He ↔ ^{8}Be

^{8}Be + ^{4}He ↔ ^{12}C



^{8}Be unstable
(τ ~ 10^{-16} s)

- Helium Burning: **Oxygen formation**

Stellar nucleosynthesis

- *Oxygen production from carbon:*

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

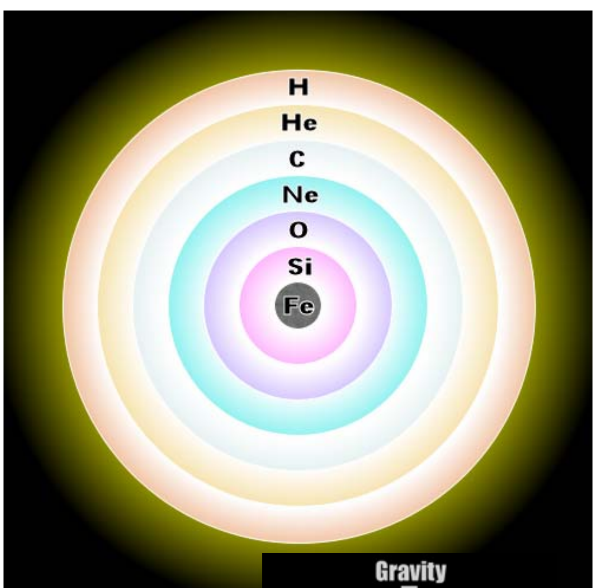
Carbon consumption !

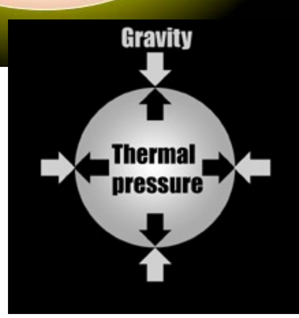
Reaction rate is very small ⇒ not all C is burned, but Oxygen production is possible and Carbon-based life became possible…

- Nucleosynthesis up to Iron

Stellar nucleosynthesis

A massive star near the end of its lifetime has "onion ring" structure





Carbon burning ⇒ *$T \sim 6*10^8$ K*, *$\rho \sim 2*10^5$ gcm^{-3}*

$^{12}C + {}^{12}C \rightarrow {}^{20}Ne + {}^{4}He + 4.6$ MeV

$\qquad\qquad\quad {}^{23}Na + {}^{1}H + 2.2$ MeV

Neon burning ⇒ *$T \sim 1.2*10^9$ K*, *$\rho \sim 4*10^6$ gcm^{-3}*

$^{20}Ne + \gamma \rightarrow {}^{16}O + {}^{4}He$

$^{20}Ne + {}^{4}He \rightarrow {}^{24}Mg + \gamma$

Oxygen burning ⇒ *$T \sim 1.5*10^9$ K*, *$\rho \sim 10^7$ gcm^{-3}*

$^{16}O + {}^{16}O \rightarrow {}^{28}Si + {}^{4}He + 10$ MeV

$\qquad\qquad\quad {}^{31}P + {}^{1}H + 7.7$ MeV

Silicon burning ⇒ *$T \sim 3*10^9$ K*, *$\rho \sim 10^8$ gcm^{-3}*

major ash: Fe

stars can no longer convert mass into energy via nuclear fusion !

- Nucleosynthesis beyond Iron

Explosive nucleosynthesis

WE BELIEVE THAT

HALF of THE ELEMENTS BEYOND IRON ARE PRODUCED

IN EXPLOSIONS of SUCH STARS

SUPERNOVAE

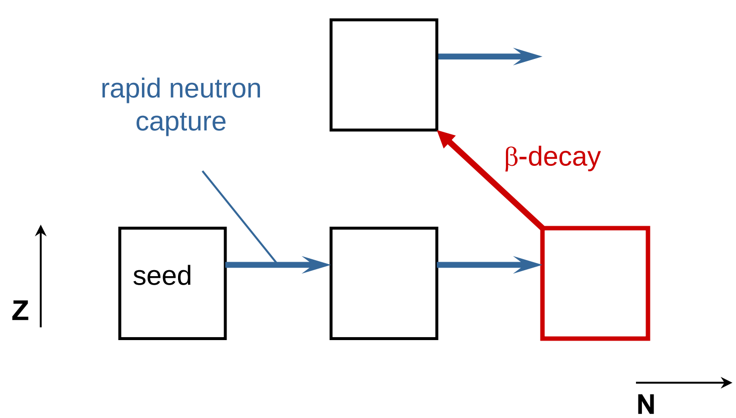
- Rapid Neutron Capture: r-process

Explosive nucleosynthesis

- nucleosynthesis occurring in core-collapse supernovae
- responsible for the creation of about half of neutron-rich nuclei heavier than Fe
- entails a succession of *rapid* neutron captures on iron seed nuclei

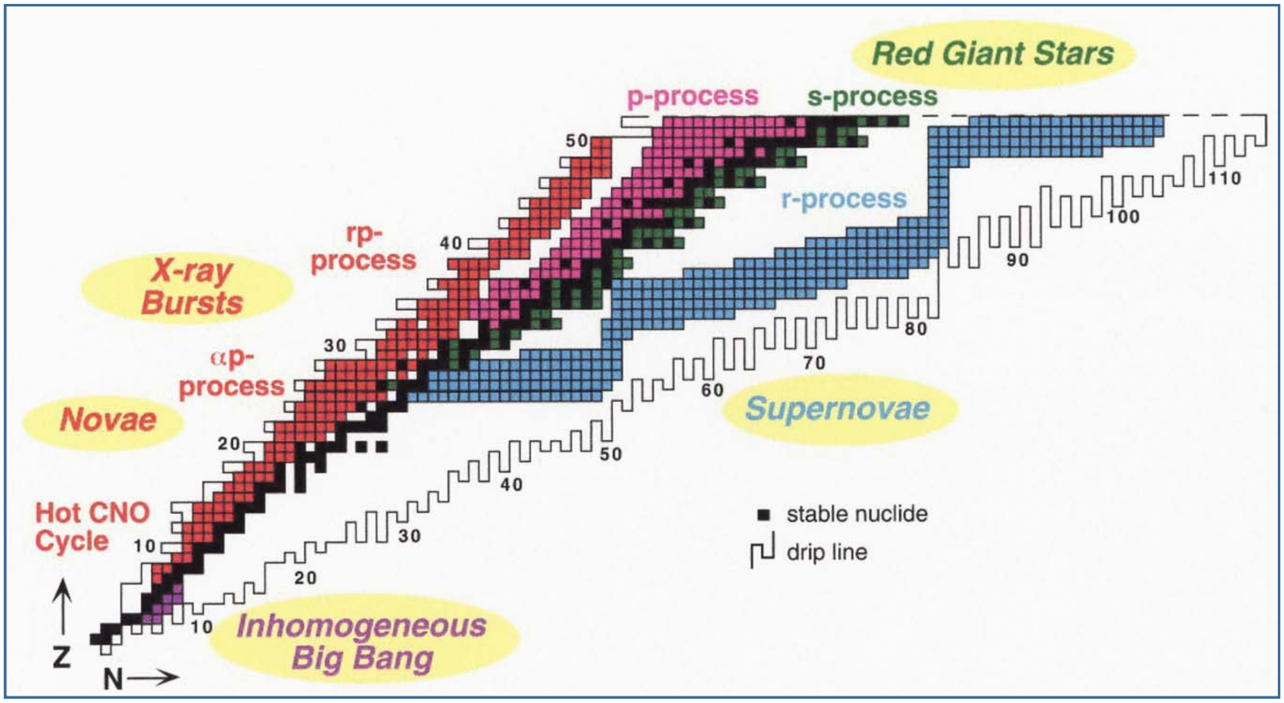
The r-process schematic

- Fast neutron capture until the nuclear force is unable to bind an extra neutron
- Then, a beta decay occurs, and in the new chain the neutron capture continues



- the other predominant mechanism for the production of heavy elements is the s-process: nucleosynthesis by means of *slow* neutron captures occurs in stars during He-burning (the source for neutrons: $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$))

Overview of main astrophysical processes

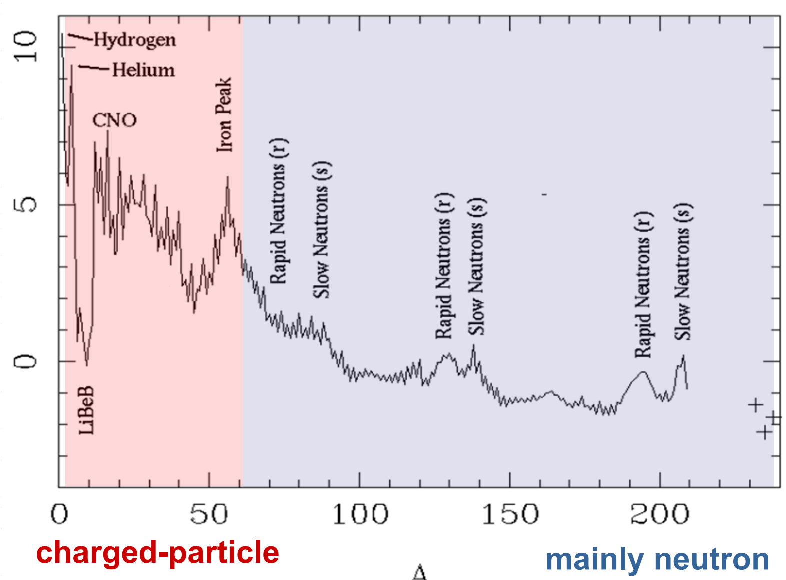


M.S. Smith and K.E. Rehm, Ann. Rev. Nucl. Part. Sci, 51 (2001) 91-130

- Messages to take away

Summary

What you have learned about the abundance of elements:



charged-particle induced reaction

mainly neutron capture reaction

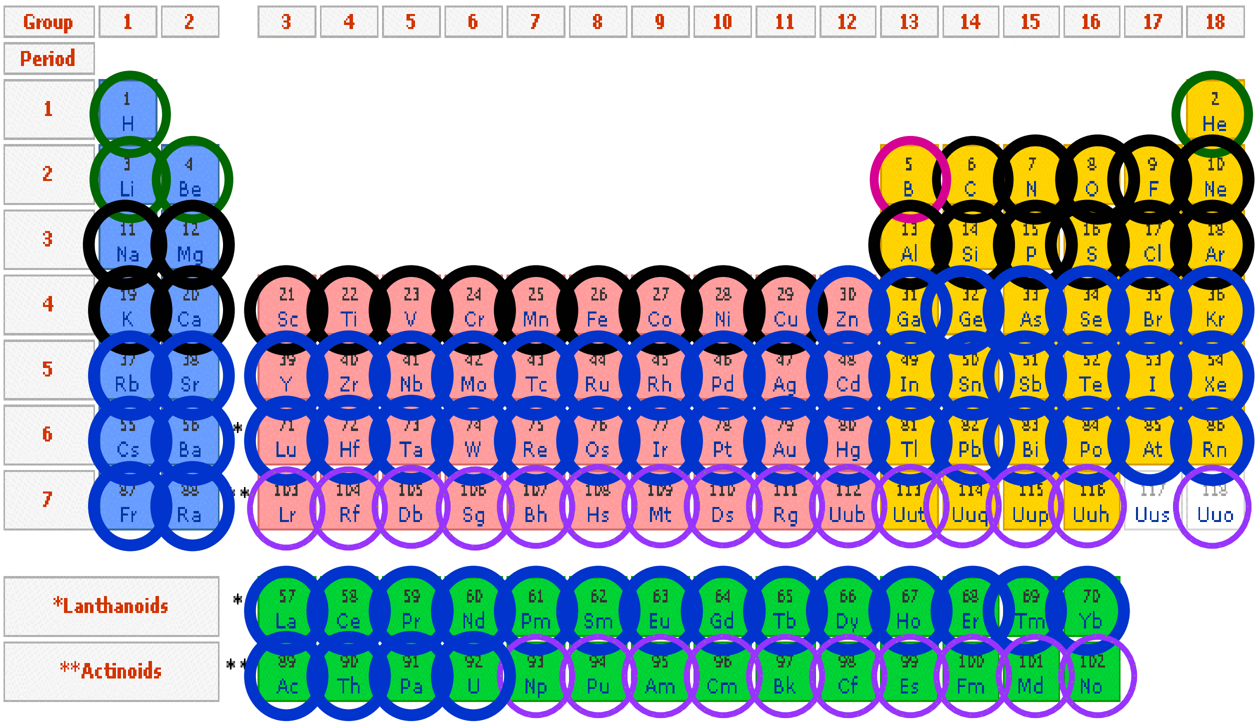
Both occur during **quiescent** and **explosive** stages of stellar evolution

involve mainly **STABLE NUCLEI**

involve mainly **UNSTABLE NUCLEI**

• Messages to take away

Summary



Instead of Conclusions:

Nuclear reactions play a crucial role in the Universe:

• they produced all the elements we depend on.

• they provide the energy in stars including that of the Sun.

There are ~270 stable nuclei in the Universe. By studying reactions between them we have produced ~3000 more (unstable) nuclei.

There are ~4000 more (unstable) nuclei which we know nothing about and which will hold many surprises and applications. Present techniques are unable to produce them in sufficient quantities.

It will be the next generation of accelerators and the next generation of scientists (*why not some of you?!*) which will complete the work of this exciting research field.

CHEMICAL GALAXY II

A NEW VISION OF THE PERIODIC SYSTEM OF THE ELEMENTS