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)

Periodic Table of Elements

1896 Becquerel discovers radioactivity

⇒ 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)

The Nobel Prize in Physics 1903

A. H. Becquerel Pierre Curie Marie Curie

Modern “Alchemy”: radioactivity
A chemical element is uniquely identified by the atomic number $Z$:

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 disassemble 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!

- in atoms: $BE \sim eV$
- in nuclei: $BE \sim MeV$

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

enormous energy stored in nuclei!
Thanks to $E=mc^2$, tiny amounts of mass convert into huge energy release...

He-4
(2 protons + 2 neutrons)

Radium-226
(88 protons + 138 neutrons)

Radon-222
(86 protons + 136 neutrons)

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 x $(3 \times 10^8)^2 = 2.07 \times 10^{12}$ joules.

Equivalent to the energy from over 400 tonnes of TNT!!!

1 kg Ra (nuclear) $\leftrightarrow 4 \times 10^5$ kg TNT (chemical)

• Nuclear Reactions

- origin of chemical elements
- origin of stellar energies

$X + Y \rightarrow A + B$

Conservation laws:

\[
\begin{align*}
A_1 + A_2 &= A_3 + A_4 \quad &\text{(mass numbers)} \\
Z_1 + Z_2 &= Z_3 + Z_4 \quad &\text{(atomic numbers)}
\end{align*}
\]

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

\[
Q_{val} = [(m_1 + m_2) - (m_3 + m_4)]c^2
\]

Initial \hspace{1cm} Final

$Q_{val} > 0$: exothermic process (release of energy) \hspace{1cm} \text{in stars}

$Q_{val} < 0$: endothermic process (absorption of energy)
• 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.

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**FISSION**

*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!

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**Stability and Binding Energy Curve**

The graph shows the average binding energy per nucleon for different elements.

- **Fission** (Qval > 0)
- **Fusion** (Qval < 0)

The region of greatest stability is indicated on the graph.
Origin of chemical elements

Abundance of the Elements

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

Features:
- 12 orders-of-magnitude span
- H ~ 75%
- He ~ 23%
- C \rightarrow 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)
• 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 (B²FH)
Rev. Mod. Phys. 29 (1957) 547

The Nobel Prize in Physics 1983

• Big Bang Nucleosynthesis

- 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 $^1\text{H} (75\%), ^4\text{He} (23\%), ^2\text{H} (0.003\%), ^3\text{He} (0.004\%),$ trace amounts ($10^{-10}\%$) of Li and Be, and no other heavy elements

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

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

Interstellar gas

BIRTH

gravitational contraction

DEATH

explosion

Stars

element mixing

thermonuclear reactions

Stellar nucleosynthesis

abundance distribution

energy production

stability against collapse

synthesis of “metals”
• **Hydrogen Burning**
  - almost 95% of all stars spend their lives burning the H in their core (including our Sun):

• **Helium Burning:** Carbon formation
  - BBN produced no elements heavier than Li 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

### How is Carbon synthesized in stars?

\[ T \sim 6 \times 10^8 \text{ K and } \rho \sim 2 \times 10^5 \text{ g cm}^{-3} \]

\[ ^4\text{He} + ^4\text{He} \leftrightarrow ^8\text{Be} \]

$^8\text{Be}$ unstable \((\tau \sim 10^{-16} \text{ s})\)

\[ ^8\text{Be} + ^4\text{He} \leftrightarrow ^{12}\text{C} \]
• **Helium Burning: Oxygen formation**

\[ {^{12}\text{C}} + {^4\text{He}} \rightarrow {^{16}\text{O}} + \gamma \]

**Carbon consumption!**

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

• **Oxygen production from carbon:**

• **Nucleosynthesis up to Iron**

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

- **Carbon burning** ⇒ \( T \sim 6 \times 10^8 \text{ K} \)
  \( \rho \sim 2 \times 10^5 \text{ g cm}^{-3} \)

\[ {^{12}\text{C}} + {^{12}\text{C}} \rightarrow {^{20}\text{Ne}} + {^4\text{He}} + 4.6 \text{ MeV} \]

\[ {^{23}\text{Na}} + {^1\text{H}} + 2.2 \text{ MeV} \]

- **Neon burning** ⇒ \( T \sim 1.2 \times 10^9 \text{ K} \)
  \( \rho \sim 4 \times 10^6 \text{ g cm}^{-3} \)

\[ {^{20}\text{Ne}} + \gamma \rightarrow {^{16}\text{O}} + {^4\text{He}} \]

\[ {^{20}\text{Ne}} + {^4\text{He}} \rightarrow {^{24}\text{Mg}} + \gamma \]

- **Oxygen burning** ⇒ \( T \sim 1.5 \times 10^9 \text{ K} \)
  \( \rho \sim 10^7 \text{ g cm}^{-3} \)

\[ {^{16}\text{O}} + {^{16}\text{O}} \rightarrow {^{28}\text{Si}} + {^4\text{He}} + 10 \text{ MeV} \]

\[ {^{31}\text{P}} + {^1\text{H}} + 7.7 \text{ MeV} \]

- **Silicon burning** ⇒ \( T \sim 3 \times 10^9 \text{ K} \)
  \( \rho \sim 10^8 \text{ g cm}^{-3} \)

major ash: Fe

stars can no longer convert mass into energy via nuclear fusion!
• Nucleosynthesis beyond Iron

WE BELIEVE THAT
HALF of THE ELEMENTS BEYOND IRON ARE PRODUCED
IN EXPLOSIONS of SUCH STARS

• Rapid Neutron Capture: r-process
  • 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: \(^{13}\text{C}(\alpha,n)^{16}\text{O}\) and \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}\))
• Messages to take away

**What you have learned about the abundance of elements:**

Both occur during quiescent and explosive stages of stellar evolution

- involve mainly **STABLE NUCLEI**
- involve mainly **UNSTABLE NUCLEI**
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.
Just as your parents told you, you really are star material!