Element Synthesis: Exploration of Chemical Fundamentals

**Thematic Questions about Chemical Elements**
- Nature of the chemical elements
  - What distinguishes elements from one another?
- Occurrence of the range of elements
  - Which elements occur in the universe and why?
- Origin of specific elements
  - How, why and when were the various elements formed?
- Stability of individual elements
  - Why are some elements unstable?
  - What happens to them?

Element Building: Nucleosynthesis

**Element Synthesis and Isotopes**
- Elemental Abundance and Isotopes
  - distribution of elements in the universe
  - factors that define elemental differences
- Forms of Radioactivity
  - types of decay and processes
- Formation of Elements and their Stability
  - sequence of element formation in stars
  - role of binding in stabilizing atomic nuclei
- Elemental Composition of the Universe
  - products of formation and nuclear fusion
**Cosmic Abundance of Elements**

**Relative Abundance in the Sun**
- non-uniform trend
- general decrease as atomic number increases; even > odd
- higher relative abundance of iron and lead
- production or preservation?

**Elements and Isotopes**

**Elemental Characteristics**
- Major components: protons, neutrons, electrons
- Atomic Number = number of protons in nucleus
- Name: Helium; Symbol: $^3\text{He}_2$
  - $2 =$ atomic number, which determines name
  - $3 =$ sum of protons and neutrons
- Elements may have variable numbers of neutrons: $^3\text{He}_2$ or $^4\text{He}_2$; these are isotopes
- Individual isotopes may be stable or unstable
  - unstable = radioactive, decay to other elements
  - elements without stable isotopes don’t occur naturally
Examples of Characteristics

• Names, symbols, isotopes (radioactive)
• Most elements occur as a number of isotopes

<table>
<thead>
<tr>
<th>Name</th>
<th>Hydrogen</th>
<th>Helium</th>
<th>Lithium</th>
<th>Beryllium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>H</td>
<td>He</td>
<td>Li</td>
<td>Be</td>
</tr>
<tr>
<td>Atomic No.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Isotopes</td>
<td>1, 2, 3</td>
<td>3, 4</td>
<td>6, 7</td>
<td>9, 10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Boron</th>
<th>Carbon</th>
<th>Nitrogen</th>
<th>Oxygen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>B</td>
<td>C</td>
<td>N</td>
<td>O</td>
</tr>
<tr>
<td>Atomic No.</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Isotopes</td>
<td>10, 11</td>
<td>12, 13, 14</td>
<td>14, 15</td>
<td>16, 17, 18</td>
</tr>
</tbody>
</table>

Chart of the Nuclides

Range of natural nuclei: stable and unstable

Nuclear Landscape

G302 Development of the Global Environment
Natural Distribution of Isotopes

Equal numbers of protons and neutrons

Natural trend of elements, more neutrons than protons

Radioactivity

Three Common Forms of Radioactive Decay

- Nucleons constant, but changed in alpha decay

Beta decay

\[ ^{14}\text{C} \rightarrow e^- + ^{14}\text{N} \]
\[ (n^0 \rightarrow e^- + p^+) \]

Electron capture

\[ ^{40}\text{K} + e^- \rightarrow ^{40}\text{Ar} \]
\[ (p^- + e^- \rightarrow n^0) \]

Alpha decay

\[ ^{238}\text{U} \rightarrow ^{234}\text{Th} + ^4\text{He} \]
Radioactive Decay

**Alpha Decay - Loss of He Atom**

- Decay of Uranium-238 to Thorium-234

\[ ^{238}\text{U} \rightarrow ^{234}\text{Th} + ^{4}\text{He} \]

- Enriched Uranium
  - Uranium-235 as target
  - Producing fission products and neutrons to continue chain reaction

---

G302 Development of the Global Environment
Nuclear Fission versus Fusion

Processes of Splitting and Building Atoms
• Both involve energy release

Fission: splitting atoms

Fusion: building atoms

Formation of Elements

Fusion Processes
• Formation of Deuterium (\(^2\text{H}_1\))
• subsequent focus on protons and neutrons

Formation of Elements

Fusion Processes
• Formation of Deuterium (\(^2\text{H}_1\))
• subsequent focus on protons and neutrons

\[ ^1\text{H}_1 \rightarrow \text{nucleons} \]
\[ ^2\text{H}_1 \rightarrow \text{nucleons} \]

\[ ^1\text{H}_1 \rightarrow \text{positron} \]
\[ ^1\text{H}_1 \rightarrow \text{neutrino} \]

\[ ^2\text{H}_1 \rightarrow \text{proton} \]
\[ ^2\text{H}_1 \rightarrow \text{neutron} \]
Formation of Elements

**Initial Stages of Fusion**

1. hydrogen burning to helium (to $6 \times 10^7\text{K}$)

   
   
   
   

2. successive burning of He, C, O, and Ne (to $1.5 \times 10^8\text{K}$)

   
   
   
   

**Subsequent Stages of Fusion**

3. Capture of $^4\text{He}$ ($\alpha$-particles; $T = 10^9\text{K}$)
Formation of Elements

Later Stages of Nucleosynthesis

4. An equilibrium process that accounts for the high abundance of iron group elements ($T = 4 \times 10^9$K)

5. Neutron capture by the slow (s) process with long time ($10^2 - 10^5$ years) intervals between successive captures allowing for intervening $\beta$ decay

6. Neutron capture by the rapid (r) process in supernova with short (0.01s - 1s) intervals between successive captures, enabling formation of elements beyond bismuth

Formation of Elements

Comparison of Neutron Capture Processes

- Slow process with the cores of stars (nuclear reactor)
- Rapid process occurs during supernova (atomic bomb)
Formation of Elements

**Final Process of Nucleosynthesis**

7. Proton capture (p-process) yielding rare light isotopes of heavy elements in an H-rich medium (T = 3 x 10^9K)

**Controls on Nucleosynthesis**

- Relationship to stability of nuclei
- Binding energies of nucleons vs. atomic number
- Even numbers of nucleons more tightly bound

**Occurrence of Nucleosynthesis**

- Nuclear fusion within stars, supernova
- Related to star size

---

Stability of the Elements

**Most Stable Nuclei**

- Isotopes with low binding energies
- Matches cosmic abundance of major elements (9/top 10)

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>He</th>
<th>C</th>
<th>(N)</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>77</td>
<td>21</td>
<td>0.3</td>
<td>(0.5)</td>
<td>0.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Ne</th>
<th>Mg</th>
<th>Si</th>
<th>S</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>0.2</td>
<td>0.06</td>
<td>0.07</td>
<td>0.04</td>
<td>0.1</td>
</tr>
</tbody>
</table>
**Binding Energy of Atomic Nuclei**

**Stability**
- Low binding energies are more stable
- A function of packing of nucleons within nucleus

---

**Nucleon Number Systematics**

**Odd vs. Even**
- Smaller nuclear mass is more stable
- Even numbers of nucleons pack tighter within nucleus
- Even numbered nuclei are more stable
Element Formation within Stars

Dependent on Size and Temperature
- Element burning from interior outward
- Series of layers

H-burning

unburned H

The Sun

unburned He

Late Sun

Large star as Red Giant

H-burning

He-burning

C-burning

Ne-burning

O-burning

Si-burning

Abundance of Elements

Summary of Processes
- Big bang formation of atomic matter (H, He)
- Sequential series of nucleosynthetic processes within stars and supernova
- Resulting cosmic occurrence of elements
  - function of synthesis and stability

G302 Development of the Global Environment
Origins of Stars

Formation from Atomic Remnants

- Region of star formation
- Material from supernova: birthplace for stars
- Supernova

G302 Development of the Global Environment