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12.002 Physics and Chemistry of the Earth and Terrestrial Planets
Fall 2008

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Origin of the Elements

Abundance of the elements of the Solar System. Six key observations to be explained:

1. H and He are by far the most abundant.
2. Elemental abundances generally drop with increasing atomic number.
3. Even Z (atomic number) elements are more abundant than odd Z elements.
4. Li, Be, B are anomalously rare.
5. Fe is anomalously abundant.
6. Tc, Pm, are elements $Z > 83$ (Bi) [except for Th, U] are extremely scarce or nonexistent.

Nearly all of the elements beyond H and He are products of nucleosynthesis (synthesis of nuclides in stars)

Big Bang

100 seconds after T cooled to 10^9 K and then elements can form.

H originated from coulomb attraction of protons and electrons.

Strong forces hold He nuclei together. (Strong force dominates within range of $\sim 10^{-15}$ m)

Big Bang epoch results in: H (72%) He (28%)

All $Z > 2$ are made via nucleosynthesis. In stars (mass $> 0.072 M_{sun}$)

Explains observation #1.

Proton – Proton Chain H-burning

$2 ({}^1\text{H} + {}^1\text{H} \rightarrow {}^2\text{H} + \text{positron} + \text{neutrino} + \text{thermal energy})$ [timescale $\sim 10^9$ years]

$2 ({}^2\text{H} + {}^1\text{H} \rightarrow {}^3\text{He} + \text{gamma ray} + \text{thermal energy})$ [timescale ~ 1 second]

${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He}$ (i.e. alpha particle) + $2{}^1\text{H}$ + 2 gamma ray + thermal energy [timescale $\sim 10^6$ years]

Net: $4{}^1\text{H} \rightarrow {}^4\text{He} + 2 \text{ positron} + 2 \text{ neutrino} + \text{thermal energy}$

dE/dt (energy production rate) is proportional to T^4 (T = temperature)

However, our sun is an evolved star: composed of elements synthesized by previous dead stars. Evolved stars primarily use the **CNO cycle** instead to synthesize He:

${}^{12}\text{C} + {}^1\text{H} \rightarrow {}^{13}\text{N} + \text{thermal energy}$

${}^{13}\text{N} \rightarrow {}^{13}\text{C} + \text{positron} + \text{neutrino} + \text{thermal energy}$

${}^{13}\text{C} + {}^1\text{H} \rightarrow {}^{14}\text{N} + \text{thermal energy}$

${}^{14}\text{N} + {}^1\text{H} \rightarrow {}^{15}\text{O} + \text{thermal energy}$

${}^{15}\text{O} \rightarrow {}^{15}\text{N} + \text{positron} + \text{neutrino} + \text{thermal energy}$

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

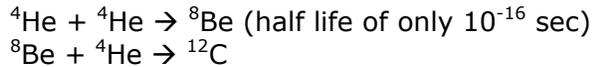
Net: $4{}^1\text{H} \rightarrow 4\text{He} + 2 \text{ positron} + 2 \text{ neutrino} + \text{thermal energy}$

Catalyzed by C, N, O.

Both the p-p chain and the CNO cycle need $T > 10^7\text{K}$

Triple Alpha Process – Helium Addition

Radiation pressure (from fusion energy) balanced with self gravity determines the size of the star's core. When a star's core has consumed most of its hydrogen, it will collapse since it is no longer pressure supported by radiative energy produced by H-fusion. For stars with $M > 0.8 M_{sun}$ core pressure will reach temperatures ($T > 10^8\text{K}$) and pressures sufficient for He fusion (red giant phase)

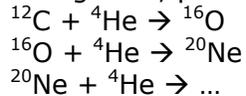


Short half-life of ${}^8\text{Be}$ explains why you need high T, P

Skips Li, B, which explains observations #4.

Carbon is the first stable element made beyond hydrogen and helium.

At higher T, pressure, further He-addition occurs:



Increasingly difficult due to increasing Coulomb repulsion with increasing Z.
Explains observation #2

He-addition continue up to the production of:

${}^{56}\text{Ni} \rightarrow$ decays to ${}^{56}\text{Co}$ decays to ${}^{56}\text{Fe}$. He addition stops at ${}^{56}\text{Fe}$ due to Coulomb repulsion.
This explains observation #5.

He-addition also explains observation #3 (even Z element preference in saw tooth pattern)
Ultimately this favorability for even Z is determined by quantum mechanical laws.

Also partly explains observation #6: Tc, Pm have odd Z. Main reason for lack of Tc and Pm is that they form no stable isotopes.

Rest masses of individual nucleons in elemental nuclei up to ${}^{56}\text{Fe}$ are slightly higher than nucleus itself. This is the mass deficit Δm . Lower energy state in the nucleus rather than free.

Binding energy = $-\Delta mc^2$

Cannot fuse anything higher than iron. Anything outside the range of the strong force ($= 10^{-15} \text{ m}$) will not fuse.

Beyond iron:

Fusion of elements with $Z < 26$ releases energy
 $Z > 26$ absorbs energy

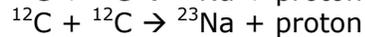
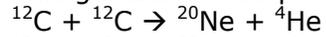
due to enormous Coulomb repulsion.

The way to build higher Z elements is to add uncharged nucleons: neutrons!

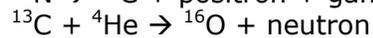
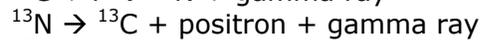
Beta – Decay and Chart of the Nuclides

Once ${}^4\text{He}$ has finally consumed, $T \rightarrow 10^9$ K and C-burning occurs.

This generates free protons:



Protons are consumed to make new elements via *P-Process*:



S-Process – Slow neutron addition. Occurs in late stage red giants. It occurs by addition of one or a few neutrons to a nuclide in the valley of stability followed by β^- decay back to the valley. Usually just one neutron addition. β^+ decay does not play a role in the s-process. This is “slow” because elements in valley of stability absorb neutrons only every 10^4 sec.

Sources of neutrons for s-process

