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

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 ~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}H + ^{1}H → ^{2}H + positron + neutrino + thermal energy) [timescale ~10^9 years]
2 (^{2}H + ^{1}H → ^{3}He + gamma ray + thermal energy) [timescale ~1 second]
^{3}He + ^{3}He → ^{4}He (i.e. alpha particle) + 2^{1}H +2 gamma ray + thermal energy [timescale ~10^6 years]

Net: 4^{1}H → ^{4}He + 2 positron + 2 neutrino + thermal energy

d*E*/d*t* (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}C + ^{1}H → ^{13}N + thermal energy
^{13}N → ^{13}C + positron + neutrino + thermal energy
^{13}C + ^{1}H → ^{14}N + thermal energy
^{14}N + ^{1}H → ^{15}O + thermal energy
^{15}O →^{15}N + positron + positron + thermal energy
^{15}N + ^{1}H → ^{12}C + ^{4}He

Net: 4^{1}H → 4He + 2 positron + 2 neutrino + thermal energy

Catalyzed by C, N, O.
Both the p-p chain and the CNO cycle need $T > 10^7$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 ($T > 10^8$K) and pressures sufficient for He fusion (red giant phase)

^{4}He + ^{4}He → ^{8}Be (half life of only 10^{-16} sec)
^{8}Be + ^{4}He → ^{12}C

Short half-life of ^{8}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:
^{12}C + ^{4}He → ^{16}O
^{16}O + ^{4}He → ^{20}Ne
^{20}Ne + ^{4}He → …

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

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He-addition continue up to the production of:
^{56}Ni → decays to ^{56}Co decays to → ^{56}Fe. He addition stops at ^{56}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}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} 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}He has finally consumed, $T \rightarrow 10^{9}$ K and C-burning occurs.
This generates free protons:
$^{12}C + {}^{12}C \rightarrow {}^{20}Ne + {}^{4}He$
$^{12}C + {}^{12}C \rightarrow {}^{23}Na$ + proton
$^{12}C + {}^{12}C \rightarrow {}^{23}Na$ + proton

Protons are consumed to make new elements via *P– Process*:
$^{12}C + P \rightarrow {}^{13}N$ + gamma ray
$^{13}N \rightarrow {}^{13}C$ + positron + gamma ray
$^{13}C + {}^{4}He \rightarrow {}^{16}O$ + neutron

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

$^{18}O + {}^{4}He \rightarrow {}^{21}Ne$ + neutron
$^{18}O + {}^{4}He \rightarrow {}^{22}Ne$ + gamma
$^{22}Ne + {}^{4}He \rightarrow {}^{25}Mg$ + neutron