Origin of the Nuclides  (Week 8, Seminar)

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06.11. 2017
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- Summary
(Nuclear) Astrophysics

- Is the offspring of the marriage of (nuclear) physics and astronomy.

- Topics in Astrophysics are: Astronomy (radio, infrared, optical, ultraviolet, X-ray, γ-ray), stellar dynamics and evolution, galaxy formation, large-scale structure of matter in the universe, origin of cosmic rays, black holes, gravitational waves (general relativity), physical cosmology, astroparticle physics.

- Nuclear Astrophysics strives to answer the following questions:
  - How did the chemical elements we have on Earth come into existence?
  - Where in space were they formed?
  - How does stellar energy production work (How does the sun shine?)

- Diagram shows the abundances of the elements in the solar system (mass-%).
Astrophysics: Explain abundances of the elements and isotope variations.

Abundance of the elements on the surface of the earth (lithosphere, hydrosphere and atmosphere).
The universe is thought to have begun with a cataclysmic explosion. Pieces of evidence for this “Big Bang” are:

- Astronomical observations show that the universe is isotropically expanding (red shift).
- There is a 2.7 K universal microwave background radiation, the thermal remnant of the Big Bang EM-radiation.
After about 200 s and at a temperature of about $10^9$ K primordial nucleosynthesis (or BBN) began with the reaction: $n + p \rightarrow d + \gamma$

At this time the reverse reaction $d + \gamma \rightarrow n + p$ declined, such that the deuteron lived long enough to allow for the reactions:
- $p + d \rightarrow ^3\text{He} + \gamma$
- $n + d \rightarrow ^3\text{H} + \gamma$

As $^3\text{He}$ and $^3\text{H}$ are more strongly bound, further reactions leading to the very stable $\alpha$-particle can occur:
- $^3\text{H} + p \rightarrow ^4\text{He} + \gamma$
- $^3\text{He} + n \rightarrow ^4\text{He} + \gamma$
- $^3\text{H} + d \rightarrow ^4\text{He} + n$
- $d + d \rightarrow ^4\text{He} + \gamma$

As stable nuclei with $A=5$ and $A=8$ do NOT exist, further ($A=1$ step) reactions cannot take place. Just some $^7\text{Li}$ is produced by:
- $^4\text{He} + ^3\text{H} \rightarrow ^7\text{Li} + \gamma$
- $^4\text{He} + ^3\text{He} \rightarrow ^7\text{Be} + \gamma$ and $^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e$

$^7\text{Li}$ is very weakly bound and rapidly destroyed. Thus the synthesis of larger nuclei was blocked. Further nucleosynthesis goes on in stars.
The main nuclear reaction chains for BBN

Radiation Biology, Protection and Applications

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A well defined correlation between luminosity and surface temperature of stars was observed by Hertzsprung and Russell. Most stars (like our sun) fall in a narrow band called the main sequence.
Stellar Evolution: Hertzsprung-Russell diagram (2)
Stellar Evolution: Hertzsprung-Russell diagram (3)

There are 3 main regions (or evolutionary stages):

**The main sequence stars:**
- spend about 90% of their lives burning hydrogen into helium in their core

**Red giant and supergiant stars:**
- occupy the region above the main sequence
- have low surface temperatures and high luminosities which, according to the Stefan-Boltzmann law, means they also have large radii
- enter this evolutionary stage once they have exhausted the hydrogen fuel in their cores and have started to burn helium and other heavier elements.

**White dwarf stars:**
- are the final evolutionary stage of low to intermediate mass stars
- are found in the bottom left of the HR diagram
- are very hot but have low luminosities due to their small size.

The **Sun** is found on the main sequence with a luminosity of 1 and a temperature of around 5,400 Kelvin.
Stellar Evolution: Hertzsprung-Russell diagram (4)

Surface temperature

Luminosity (Sun=1)

Spectral class

30 M☉

10 M☉

Supergiant

Red giant

1 solar mass

White dwarfs
Nuclear Fusion in Stars

- The proton-proton chain dominates in stars the size of the Sun or smaller.

- The CNO cycle dominates in stars heavier than the Sun.
Three chains of nuclear reactions that constitute hydrogen burning and convert protons into \(^4\text{He}\). The rate-limiting step in all reactions is the first reaction to create the deuterium.

Chain I

\[
p (p, e^+ \nu) d \rightarrow d (p, \gamma) ^3\text{He} \quad 86\% \\
^3\text{He} (p, 2p) ^4\text{He} \\
\]

\(Q_{\text{effective}} = 26.20\, \text{MeV}\)

Chain II

\[
^3\text{He} (\alpha, \gamma) ^7\text{Be} \quad 14\% \\
^7\text{Be} (\beta^-) ^7\text{Li} \\
^7\text{Li} (p, \alpha) ^4\text{He} \\
\]

\(Q_{\text{effective}} = 25.66\, \text{MeV}\)

Chain III

\[
^7\text{Be} (p, \gamma) ^8\text{B} \quad 0.02\% \\
^8\text{B} (\beta^+) ^8\text{Be}^* \\
^8\text{Be}^* (\alpha) \alpha \\
\]

\(Q_{\text{effective}} = 19.17\, \text{MeV}\)

The electrostatic force between the +charged nuclei is repulsive, but when the separation is small enough, the QE will tunnel through the wall.
Helium Burning and Higher Burning Stages

- When the hydrogen fuel of a star is exhausted a further gravitational collapse will occur leading to temperatures up to $1-2 \times 10^8$ K. In this red giant helium burning will start by the triple-$\alpha$-process:
  - $3 \, ^4\text{He} \rightarrow ^{12}\text{C} + \gamma$ (through a resonance in $^{12}\text{C}$)

- After some amount of $^{12}\text{C}$ has been formed the following reactions can take place:
  - $^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{O} + \gamma$
  - $^4\text{He} + ^{16}\text{O} \rightarrow ^{20}\text{Ne} + \gamma$

- And nucleosynthesis may continue with neon-burning:
  - $^4\text{He} + ^{20}\text{Ne} \rightarrow ^{24}\text{Mg} + \gamma$

- ... and carbon and oxygen burning:
  - $^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + ^4\text{He} ; ^{23}\text{Na} + p ; ^{23}\text{Mg} + n ; ^{24}\text{Mg} + \gamma$
  - $^{16}\text{O} + ^{16}\text{O} \rightarrow ^{24}\text{Mg} + 2^4\text{He} ; ^{28}\text{Si} + ^4\text{He} ; ^{31}\text{P} + p ; ^{31}\text{S} + n ; ^{32}\text{S} + \gamma$

- ... and silicon burning up to nuclei with $A \sim 60$:
  - $^{28}\text{Si} + ^4\text{He} \leftrightarrow ^{32}\text{S} + \gamma$
  - $^{32}\text{S} + ^4\text{He} \leftrightarrow ^{36}\text{Ar} + \gamma$
  - ...
  - $^{52}\text{Fe} + ^4\text{He} \leftrightarrow ^{56}\text{Ni} + \gamma$

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>H burning</td>
<td>$6 \times 10^9$ y</td>
</tr>
<tr>
<td>He burning</td>
<td>$0.5 \times 10^6$ y</td>
</tr>
<tr>
<td>C burning</td>
<td>200 y</td>
</tr>
<tr>
<td>Ne burning</td>
<td>1 y</td>
</tr>
<tr>
<td>O burning</td>
<td>Few months</td>
</tr>
<tr>
<td>Si burning</td>
<td>Days</td>
</tr>
</tbody>
</table>
How the life of a star ends depends to a large extent on the mass of the star:

- Stars with masses $\sim M_{\odot}$ do not reach the temperatures in their center to complete all burning stages. They extinguish and end as white dwarfs.
- Stars with masses $> 8 M_{\odot}$ complete all stellar burning stages and can have an explosive end (supernova). The brightness of the star increases by a factor of $10^6 - 10^9$ releasing $\sim 10^{51}$ ergs on a time scale of seconds. During the stellar explosion a lot of neutrons can be released leading to $(n, \gamma)$-reactions on iron-seed nuclei in the core.
s-process: Buildup of A>60 nuclei by slow n-capture

- $^{56}\text{Fe} + n \rightarrow ^{57}\text{Fe} (\text{stable}) + \gamma$; $^{57}\text{Fe} + n \rightarrow ^{58}\text{Fe} (\text{stable}) + \gamma$; $^{58}\text{Fe} + n \rightarrow ^{59}\text{Fe} (t_{1/2} = 44.5\text{d}) + \gamma$; $^{59}\text{Fe} (\beta^-) ^{59}\text{Co} (\text{stable})$

- The s-process terminates at $^{209}\text{Bi}$: $^{209}\text{Bi} (n, \gamma)^{210}\text{Bi} (\beta^-)^{210}\text{Po} (\alpha)^{206}\text{Pb} (n, \gamma)(n, \gamma)^{209}\text{Pb} (\beta^-)^{209}\text{Bi}$
r-process: Buildup of A>60 nuclei by rapid n-capture

Neutron-capture paths for the s-process and the r-process are shown in the (N, Z)-plane. Both paths start with the iron-peak nuclei as seeds (mainly $^{56}$Fe). The s-process follows a path along the stability line and terminates finally above $^{209}$Bi via $\alpha$-decay (Cla67). The r-process drives the nuclear matter far to the neutron-rich side of the stability line, and the neutron capture flows upward in the (N, Z)-plane until $\beta$-delayed fission and neutron-induced fission occur (Thi83). The r-process path shown was computed (See65) for the conditions $T_9 = 1.0$ and $N_n = 10^{24}$ neutrons cm$^{-3}$. 

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Other Processes that can synthesize Elements

- **p-process:**
  - Consists of a series of photonuclear reactions ($\gamma$,p), ($\gamma$,α), ($\gamma$,n) on seed nuclei from the s- or r-process.
  - Leads to the synthesis of some proton-rich nuclei with $70 < A < 200$.
  - Contribution to the abundances of most elements is very small, but there are some nuclei ($^{190}$Pt, $^{168}$Yb) that seem to have been exclusively made by it.

- **rp-process:**
  - Rapid proton capture process that makes proton-rich nuclei with $7 < Z < 27$ by (p, $\gamma$)-reactions and $\beta^+$-decays.
  - Creates p-rich nuclei like $^{21}$Na, $^{19}$Ne, and a small number of nuclei with $A < 100$.

- **$\nu$-nucleosynthesis:**
  - In a type II supernova the intense neutrino flux of all flavors that passes through the onion layers of the PNS can cause a transmutation of nuclei via ($\nu$, $\nu'$)- and ($\nu_e$,e$^-$)-, ($\bar{\nu}_e$,e$^+$)-reactions on nuclei.
  - Some rare isotopes that could be due to this process are $^7$Li, $^{11}$B, $^{19}$F, $^{138}$La, and $^{180}$Ta.

- **$\nu$-p-process:**
  - Occurs in supernovae when strong neutrino fluxes create proton-rich ejecta.
  - In this process antineutrino absorptions produce neutrons that are immediately captured by proton rich nuclei.
  - Nuclei with $A > 64$ can be produced, e.g., $^{92,94}$Mo and $^{96,98}$Ru.
Radionuclides in the Environment (1)

Stages of the evolution of the Earth

<table>
<thead>
<tr>
<th>Time before present</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0 \times 10^9 y</td>
<td>Solar nebula</td>
</tr>
<tr>
<td>4.6 \times 10^9 y</td>
<td>Formation of the solar system</td>
</tr>
<tr>
<td>4.5 \times 10^9 y</td>
<td>Formation of the earth, the moon and of meteorites</td>
</tr>
<tr>
<td>4.3 \times 10^9 y</td>
<td>First stages of the earth’s crust, formation of the oldest minerals found on the earth, formation of hydrosphere and atmosphere</td>
</tr>
<tr>
<td>3.9 \times 10^9 y</td>
<td>End of major meteoritic impacts</td>
</tr>
<tr>
<td>3.8 \times 10^9 y</td>
<td>Beginning of formation of rocks</td>
</tr>
<tr>
<td>(3.8 - 3.5) \times 10^9 y</td>
<td>Formation of oldest rocks</td>
</tr>
<tr>
<td>3.5 \times 10^9 y</td>
<td>First traces of life (stromatolites)</td>
</tr>
</tbody>
</table>

Ratio of the activities of some long-lived radionuclides at the time of the birth of the Earth to those present.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Activity Ratio $A/A_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}\text{K}$</td>
<td>11.40</td>
</tr>
<tr>
<td>$^{87}\text{Rb}$</td>
<td>1.07</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>1.02</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>84.10</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>2.01</td>
</tr>
</tbody>
</table>
### Radionuclides from natural decay series

<table>
<thead>
<tr>
<th>Decay series</th>
<th>Decay mode of the mother nuclide</th>
<th>Half-life of the mother nuclide [y]</th>
<th>Range of dating [y]</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{238}\text{U}\ldots^{226}\text{Ra}\ldots^{206}\text{Pb})</td>
<td>(\alpha)</td>
<td>(4.468 \cdot 10^9)</td>
<td>(10^6-10^{10})</td>
<td>Minerals, geology, geochemistry</td>
</tr>
<tr>
<td>(^{235}\text{U}\ldots^{207}\text{Pb})</td>
<td>(\alpha) (sf: (3.7 \cdot 10^{-7}%))</td>
<td>(7.038 \cdot 10^8)</td>
<td>(10^6-10^{10})</td>
<td>Minerals, geology, geochemistry</td>
</tr>
<tr>
<td>(^{232}\text{Th}\ldots^{208}\text{Pb})</td>
<td>(\alpha)</td>
<td>(1.405 \cdot 10^{10})</td>
<td>(10^6-10^{10})</td>
<td>Minerals, geology, geochemistry</td>
</tr>
<tr>
<td>(^{210}\text{Pb}\ldots^{206}\text{Pb})</td>
<td>(\beta^-)</td>
<td>(22.3)</td>
<td>(20-150)</td>
<td>Ice, exchange with the atmosphere</td>
</tr>
</tbody>
</table>
## Terrestrial radionuclides

<table>
<thead>
<tr>
<th>Nuclide pair</th>
<th>Decay mode of the mother nuclide</th>
<th>Half-life of the mother nuclide [y]</th>
<th>Range of dating [y]</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$K/$^{40}$Ar</td>
<td>$\beta^-$ (89%) $\varepsilon + \beta^+$ (11%)</td>
<td>$1.28 \cdot 10^9$</td>
<td>$10^3$–$10^{10}$</td>
<td>Minerals</td>
</tr>
<tr>
<td>$^{87}$Rb/$^{87}$Sr</td>
<td>$\beta^-$</td>
<td>$4.8 \cdot 10^{10}$</td>
<td>$8 \cdot 10^6$–$3 \cdot 10^9$</td>
<td>Minerals, geochronology, geochemistry</td>
</tr>
<tr>
<td>$^{147}$Sm/$^{143}$Nd</td>
<td>$\alpha$</td>
<td>$1.06 \cdot 10^{11}$</td>
<td>$10^8$–$10^{10}$</td>
<td>Minerals, geochronology, geochemistry</td>
</tr>
<tr>
<td>$^{176}$Lu/$^{176}$Hf</td>
<td>$\beta^-$ (97%) $\varepsilon$ (3%)</td>
<td>$3.8 \cdot 10^{10}$</td>
<td>$10^7$–$10^9$</td>
<td>Geochemistry</td>
</tr>
<tr>
<td>$^{187}$Re/$^{187}$Os</td>
<td>$\beta^-$</td>
<td>$5 \cdot 10^{10}$</td>
<td>$10^6$–$10^{10}$</td>
<td>Minerals</td>
</tr>
</tbody>
</table>
## Cosmogenic radionuclides

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Production</th>
<th>Decay mode and half-life [y]</th>
<th>Production rate [atoms per m² per y]</th>
<th>Range of dating [y]</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$H (T)</td>
<td>$^{14}$N(n, t) $^{12}$C</td>
<td>$\beta^-$, 12.323</td>
<td>$\approx 1.3 \cdot 10^{11}$</td>
<td>0.5–80</td>
<td>Water, ice</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>$^{14}$N(n, p) $^{14}$C</td>
<td>$\beta^-$, 5730</td>
<td>$\approx 7 \cdot 10^{11}$</td>
<td>2.5 $\cdot$ 10²–4 $\cdot$ 10⁴</td>
<td>Archaeology, climatology, geology (carbon, wood, tissue, bones, carbonates)</td>
</tr>
<tr>
<td>$^{10}$Be</td>
<td>Interaction of p and n with $^{14}$N and $^{16}$O</td>
<td>$\beta^-$, 1.6 $\cdot$ 10⁶</td>
<td>$\approx 1.3 \cdot 10^{10}$</td>
<td>7 $\cdot$ 10⁴–10⁷</td>
<td>Sediments, glacial ice, meteorites</td>
</tr>
<tr>
<td>$^{26}$Al</td>
<td>Interaction of cosmic rays with $^{40}$Ar</td>
<td>$\beta^+$, 7.16 $\cdot$ 10⁵</td>
<td>$\approx 4.8 \cdot 10^7$</td>
<td>5 $\cdot$ 10⁴–5 $\cdot$ 10⁶</td>
<td>Sediments, meteorites</td>
</tr>
<tr>
<td>$^{32}$Si</td>
<td>Interaction of cosmic rays with $^{40}$Ar</td>
<td>$\beta^-$, 172</td>
<td>$\approx 5.10^7$</td>
<td>10$^{10}$–10³</td>
<td>Hydrology, ice</td>
</tr>
<tr>
<td>$^{36}$Cl</td>
<td>Interaction of cosmic rays with $^{40}$Ar</td>
<td>$\beta^-$, 3.0 $\cdot$ 10⁵</td>
<td>$(4.5–6.5) \cdot 10^8$</td>
<td>3 $\cdot$ 10⁴–2 $\cdot$ 10⁶</td>
<td>Hydrology, water, glacial ice</td>
</tr>
<tr>
<td>$^{39}$Ar</td>
<td>Interaction of cosmic rays with $^{40}$Ar</td>
<td>$\beta^-$, 269</td>
<td>$\approx 4.2 \cdot 10^{11}$</td>
<td>10²–10⁴</td>
<td>–</td>
</tr>
</tbody>
</table>
Stars are Cauldrons in the Cosmos.

The atomic abundances of the elements/isotopes in the solar system can largely be explained by astrophysical processes:

- Big Bang Nucleosynthesis
- Stellar burning phases
- Explosive burning (s- and p-process)

The radionuclides found in the lithosphere, hydrosphere and atmosphere are largely leftovers (decay-products) from supernova explosions.

We consist of “star-dust”.

Radionuclides are a part of nature!
