How Nature makes Gold

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Each heavy atom in our body was built and processed through ~100-1000 star generations since the initial Big Bang event!

We are made of star stuff

Carl Sagan
Abundances of the elements

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen mass fraction</td>
<td>X = 0.71</td>
</tr>
<tr>
<td>Helium mass fraction</td>
<td>Y = 0.28</td>
</tr>
<tr>
<td>Metallicity (mass fraction of everything else)</td>
<td>Z = 0.019</td>
</tr>
<tr>
<td>Heavy Elements (beyond Nickel) mass fraction</td>
<td>4E-6</td>
</tr>
</tbody>
</table>

Diagram showing:
- Gap B, Be, Li
- α-nuclei $^{12}\text{C},^{16}\text{O},^{20}\text{Ne},^{24}\text{Mg}, \ldots,^{40}\text{Ca}$
- r-process peaks (nuclear shell closures)
- s-process peaks (nuclear shell closures)
- Fe peak (width !)
- Fe
- U, Th
Where were the elements made?

- The lightest elements (hydrogen, helium, lithium) were created in the first 3 minutes of the Universe.
- The heavier elements up to uranium are and have been made in stars.
- Elements with Z>92 have been artificially produced in labs; the elements with Z=107-112 at GSI.
Nuclear fusion generates energy
Solar hydrogen burning

• When a star is born, temperature and density increase in its interior
• matter consists of charged nuclei (and electrons); no free neutrons
• nuclei move fast; nuclei with small charges have the chance to overcome the Coulomb repulsion (tunnel effect)
• fusion of hydrogen (protons) is the first nuclear energy source
Helium burning

- At the end of hydrogen burning the star has a helium core. This core contracts under its own gravity and gets hotter.
- Hydrogen continues burning in a shell around the helium core and produces more helium. The core grows and gets denser and hotter.
- The radiation pressure grows. Hereby the outer regions of the star extend. It turns into a Red Giant. Our sun reaches this phase in about 3 billion years. Its radius reaches then up to the earth orbit.
- In the interior it is finally hot enough (100 Millionen Kelvin) that also helium nuclei can fuse.
Stellar helium burning

- Helium burning decides the ratio of carbon (C) and oxygen (O) in the Universe.
- These are the building blocks of life!
### Nuclear burning stages
(e.g., 20 solar mass star)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Main Product</th>
<th>Secondary Product</th>
<th>T (10^9 K)</th>
<th>Time (yr)</th>
<th>Main Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>He</td>
<td>$^{14}$N</td>
<td>0.02</td>
<td>10^7</td>
<td>$^4\text{H} \rightarrow ^4\text{He}$</td>
</tr>
<tr>
<td>He</td>
<td>O, C</td>
<td>$^{18}$O, $^{22}$Ne s-process</td>
<td>0.2</td>
<td>10^6</td>
<td>$3\text{He}^4 \rightarrow ^{12}\text{C}$ $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$</td>
</tr>
<tr>
<td>C</td>
<td>Ne, Mg</td>
<td>Na</td>
<td>0.8</td>
<td>10^3</td>
<td>$^{12}\text{C} + ^{12}\text{C}$</td>
</tr>
<tr>
<td>Ne</td>
<td>O, Mg</td>
<td>Al, P</td>
<td>1.5</td>
<td>3</td>
<td>$^{20}\text{Ne}(\gamma,\alpha)^{16}\text{O}$ $^{20}\text{Ne}(\alpha,\gamma)^{24}\text{Mg}$</td>
</tr>
<tr>
<td>O</td>
<td>Si, S</td>
<td>Cl, Ar, K, Ca, Ti, V, Cr, Mn, Co, Ni</td>
<td>2.0</td>
<td>0.8</td>
<td>$^{16}\text{O} + ^{16}\text{O}$</td>
</tr>
<tr>
<td>Si</td>
<td>Fe</td>
<td></td>
<td>3.5</td>
<td>0.02</td>
<td>$^{28}\text{Si}(\gamma,\alpha)...$</td>
</tr>
</tbody>
</table>

Courtesy: A. Heger and S. Woosley
Final fate of a massive star

- Star has an onion structure
- Iron is the final product of hydrostatic burning
- The inner iron core grows, gets unstable against its own gravity and collapses
- SUPERNOVA!
Collapse and explosion of a star

- Stability by pressure-gravity balance
- Pressure produced by nuclear reactions
- Balance cannot be kept when iron core grows
- In about 1 second the core radius reduces from 6000 km to 20 km
- Collapse stops, when the core corresponds to a gigantic atomic nucleus. A large portion of the gravitational energy is set free. This energy corresponds to the energy production of 100 suns during its life of about 10 billion years.
- The majority of energy is carried away by neutrinos.
Making Gold: The R-Process

National Research Council: one of the 11 greatest unanswered questions in physics

- Heavy elements produced in neutron capture processes
- R-process operates at early Galactic history
Making heavy elements in Nature

Assume a reservoir of free neutrons and a competition of neutron capture and beta decay:

Consider the two cases:

1. If $\tau_\beta < \tau_n$, then an unstable nucleus, reached on the path, will beta-decay before it captures another neutron. The path runs through the valley of stability. This is the s-process.

2. If $\tau_\beta >> \tau_n$, several neutron captures will occur, before a nucleus is reached which beta-decays. The path runs through very neutron rich nuclei. This is the r-process. To achieve the short neutron capture times one needs very high neutron densities.
S-process nucleosynthesis
Astrophysical S-process

Main component. Produces most of the nuclei in the mass range $90 < A < 204$. It occurs in AGB (Asymptotic Giant Branch) stars. The main neutron source is $^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$. The temperature is of order $3 \times 10^8$ K, the neutron number density of order $10^8$/cm$^3$.

Weak component. This component contributes significantly to the production of s-nuclides in the $A \sim 90$ mass range. It operates in core-helium burning in more massive stars. The main neutron source is $^{22}\text{Ne}(\alpha,\text{n})^{25}\text{Mg}$.

The s-process stops at Pb and Bi, where the s-process path hits the region of alpha instability.
Making Gold! – The \( r \)-process

very fast nuclear reactions in environment with extreme densities of free neutrons Nuclei involved very neutron-rich and short-lived.

Nature vs Humans

Johann Friedrich Böttger, Alchemist Inventor of European White China
In Meissen, Germany
# Astrophysical sites

<table>
<thead>
<tr>
<th></th>
<th>Supernova</th>
<th>Mergers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal conditions</td>
<td>😞</td>
<td>☺</td>
</tr>
<tr>
<td>Yield / Frequency</td>
<td>😞</td>
<td>☺</td>
</tr>
<tr>
<td>Direct signature</td>
<td>😞</td>
<td>☺</td>
</tr>
</tbody>
</table>
Neutron Star merger confirmed as astrophysical site of heavy element production

Electromagnetic "Kilonova" signal due to "r process" in a NS merger has recently been verified by astronomical observations (August 2017)
R-Process in NS merger

$T = 3.50 \text{ GK}, \quad n_p = 2.937 \times 10^3 \text{ cm}^{-3}, \quad R = 623.3, \quad s = 0.621 \text{ kgs}^{-1}\text{nuc}^{-1}, \quad t = 0.0131 \text{ s}$

G. Martinez-Pinedo, M.R. Wu
Nuclear physics needs

- Masses
- Half lives
- neutron capture rates
- fission yields and fragment distributions
- alpha decays

- of nuclei with extreme neutron excess. Most have never been produced yet.
- But this will change -> **Radioactive ion Beam Facility**
Facility for Antiproton and Ion Research in Europe
International Participation in FAIR

- FAIR governed by international convention
- 9 shareholders + 1 assoc. partner (orange)
- Scientists from all over the world are engaged
- More than 200 institutions from 53 countries are involved with their scientists (orange + blue)
Accelerator complex

- APPA ions, antiprotons
- UNILAC
- SIS18
- p-Linac
- HESR
- CR & RESR
- NESR
- CryRing
- C.B.M. relativistic nuclear collisions
- NUSTAR radioactive ion beams
- PANDA antiproton beams
- Antiproton beams
- SIS100/300
- 100 m
How to create artificial nuclei

Billions of collisions per second -> how to fish the exact nucleus one likes to study out of this debris
FAIR: rings and instrumentation

**Parameters:**
- all elements (H through U)
- intensity > $10^{11}$ ions/sec (before target)
- rigidity 20 Tm
- fast ($\mu$s) and slow extraction
frequency measurement

4 particles with different m/q
Frequency measurement

\[ \sin(\omega_1) \]

\[ \sin(\omega_2) \]

\[ \sin(\omega_3) \]

\[ \sin(\omega_4) \]

Fast Fourier Transformation

\( \omega_1 \), \( \omega_2 \), \( \omega_3 \), \( \omega_4 \)
Measured mass spectrum

\[ 143^m \text{Sm}^{62+} \quad \text{754 keV} \quad 143^g \text{Sm}^{62+} \]

(1 particle)  

\[ m/\Delta m \approx 700000 \]
Precision of mass measurement

$M \sim 160\,000\,\text{kg}$

$M \sim 5\,\text{g}$
Neutron star mergers ...
... and FAIR – the Universe in the Laboratory

**Neutron Star Mergers**

**FAIR Research Pillars**

- **Equation of State (Hades, CBM)**
  - Gravitational wave signal
  - Amount of ejecta
- **Lambda-nucleon interactions (PANDA)**
- **Exotic neutron-rich nuclei (NUSTAR)**
  - r-process nucleosynthesis and abundancies of the heaviest elements gold, platinum and beyond
- **Plasma and atomic opacities (APPA)**
  - Kilonova electromagnetic transient

**FAIR offers unique opportunities for studying these fundamental questions related to the STRUCTURE OF MATTER and EVOLUTION OF THE UNIVERSE!**
Sensitivity to nuclear data

- **Masses**: 
  - $N=126$ half-lives \( \rightarrow \) FAIR range

- **Lightcurve**
  - Lightcurve sensitive to $N=126$ half-lives \( \rightarrow \) FAIR range

- **Half lives**
  - $r$-process abundances
FAIR: nuclear masses
important progress:
halflives from RIKEN
Future of society:

SKILLS and TECHNOLOGY
Educating the next generation

students learn in interplay of universities and large-scale labs:

- exciting science
- solving of complex problems
- forefront technology and IT
- mobility
- social skills (working in groups)
- internationality, languages
HGS-HIRe Graduate Days 2013

5th Anniversary of HGS-HIRe
The FAIR Chance: New Horizons
The FAIR Chance: New Horizons