Neutrino Interactions and Nucleosynthesis: Lecture 1

Sites and Conditions for heavy element synthesis

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Lecture plan

• Lecture 1
  • How to make heavy elements
  • Neutrinos set the conditions
  • Neutron-rich nucleosynthesis
  • Proton-rich nucleosynthesis

• Lecture 2
  • Thermonuclear reaction networks
  • Nuclear inputs
Origin of elements

Solar system abundances

Big Bang

Hydrogen

Helium

Stellar burning

Iron Group

$\alpha$-elements ($^{12}\text{C}, {^{16}\text{O}}, ...$)
Nuclear binding energy

Average binding energy per nucleon (MeV)

Number of nucleons $A$

Fission

Fusion

Nucleon Binding Energy

H $\rightarrow$ He $\rightarrow$ C $\rightarrow$ O $\rightarrow$ .... $\rightarrow$ Fe

Nuclear fusion in stellar cores

Need mechanisms other than charged-particle fusion:
E.g. neutrons, photons, neutrinos
Origin of elements

Hydrogen
Helium
Stellar burning
Big Bang
Solar system abundances

Iron Group

$\alpha$-elements ($^{12}C, ^{16}O, ...$)
Neutron-capture processes

Heavy elements are made by

- slow ($\tau_\beta / \tau_n < 1$)
- fast ($\tau_\beta / \tau_n > 1$)

neutron-capture events

- Sequences of $(n, \gamma)$ reactions and $\beta^-$-decays
  
  $A(Z, N) + n \leftrightarrow A + 1(Z, N + 1) + \gamma$
  
  $A(Z, N) \rightarrow A(Z + 1, N - 1) + e^- + \bar{\nu}_e$
Neutron-capture paths

\[ (n, \gamma) \text{ reactions} \]

\[ \beta^- \text{-decays} \]

Number of protons

Number of neutrons

N=82 closed neutron-shell
Neutron-capture paths

- s-process path
  - β-decay to stability at the end
  - N=82 closed neutron-shell

- r-process path

Number of protons

Number of neutrons
Neutron-capture processes

heavy elements are made by

slow \( (\tau_\beta/\tau_n < 1) \)

and

fast \( (\tau_\beta/\tau_n > 1) \)

eutron-capture events

- Sequences of \((n,g)\) reactions and \(\beta^-\)decays

\[
A(Z,N) + n \leftrightarrow A + 1(Z, N + 1) + \gamma
\]

\[
A(Z,N) \rightarrow A(Z + 1, N - 1) + e^- + \bar{\nu}_e
\]

- Closed neutron-shells give rise to the peaks at \(\text{Te,Xe} / \text{Ba}\) and at \(\text{Os,Pt,Au} / \text{Pb}\)
The s-process

• Secondary process
  → neutron captures on pre-existing Fe-group nuclei

• Strong s-process (up to Pb)
  • He-shell flashes in AGB stars
  • Protons are mixed from H-shell; produce $^{13}\text{C}$
  • During He-burning: $^{13}\text{C} + \alpha \rightarrow ^{16}\text{O} + \text{n}$
  → strong neutron source

• Weak s-process (truncated at $Z \approx 60$)
  • Core burning in massive stars:
    • He-burning ($1-2 \times 10^8\text{K}$)
      $^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}(\alpha,\text{n})^{25}\text{Mg}$
    • C-burning ($6-8 \times 10^8\text{K}$)
      $^{12}\text{C}(p,\gamma)^{13}\text{N}(\beta^+)^{13}\text{C}$
      $^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$
      p from $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$
      $\alpha$ from $^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$
The weak s-process

Overproduction factors of 25 $M_\odot$ models with $Z = 10^{-5}$ ($[\text{Fe/H}] = -3.8$)

Seed nuclei and neutron sources are secondary, neutron poisons are primary!
The r-process

1\textsuperscript{st} peak: A\sim 80 (N=50)
2\textsuperscript{nd} peak: A\sim 130 (N=82)
3\textsuperscript{rd} peak: A\sim 195 (N=126)

Primary process!

Stable nuclei
iron
Silver
Gold

r-process path
r-process abundances
The r-process site

Most important criteria for an r-process site:
- High neutron density
- Eject material

Neutron sources:
- Neutrons in nuclei (must be liberated)
- Neutron stars
- Made through weak reactions

Conditions:
- High entropy, alpha-rich freeze-out
- Low entropy, normal freeze-out with very low Ye
The r-process site(s)

- Neutrino-driven wind in CCSNe
- He-shell of CCSNe
- Jets from CCSNe
- Accretion disks from CCSNe
- ONeMg core collapse
- Tidal ejection of matter from NS mergers
- Accretion disk outflows from compact object mergers (NSNS or NSBH)
- Shocked ejecta from compact object mergers
- Neutrino flavor oscillations in CCSNe
Origin of elements

- Hydrogen
- Helium
- Stellar burning
- Big Bang
- Solar system abundances
- r-process
- s-process
- Iron Group
- α-elements ($^{12}$C, $^{16}$O, ...)

Graph showing the distribution of atomic masses with log N (solar system) on the y-axis and Atomic Mass on the x-axis.
The neutron-capture processes

s-process

r-process

p-process

The Enrico Fermi Institute, U Chicago
The p-process (for the p-nuclei)

Suggested by Arnould (1976) and Woosley&Howard (1978)

Now understood to be several processes:

• \(\gamma\)-process: photodisintegration of pre-existing heavy nuclei

• \(\nu\)-process: \((\nu, \nu')\) or \((\nu, e^-)\)

• \(\nu p\)-process: \(p(\nu, e^+)n\) followed by \((n, p)\)
The $\gamma$-process

- Photodisintegrations of pre-existing heavy (s-process) nuclei
  - In thermal bath of supernova explosions in explosive Ne/O burning layers with peak temperatures of $2-3 \times 10^9$K
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- In thermal bath of supernova explosions in explosive Ne/O burning layers with peak temperatures of $2-3 \times 10^9$K

The $\gamma$-process

- Predicted $p$-nuclei overproduction

$\Rightarrow$ Underproduction of light $p$-nuclei

Arnould & Goriely (2003)

Origin of elements

Big Bang
Hydrogen
Helium
Stellar burning
Solar system abundances

Origin of elements

Iron Group
α-elements
(12C, 16O, …)

r-process
s-process
p-nuclei

Atomic Mass
Observations

- What old (metal-poor) stars tell us
Trends with metallicity

Significant scatter at low metallicities

r-process is rare in early Galaxy
The oldest observed stars

Figure: John Cowan (2011)

Robust r-process pattern

Larger scatter

Individual stellar abundance offsets with respect to Simmerer et al. (2004)
LEPP: Lighter Element Primary Process

- Observations of halo stars indicate two “r-process” sites:
  - Main r-process
  - Stellar LEPP / weak r-process

Stars with high enrichment in heavy r-process abundances
Stars with low enrichment in heavy r-process abundances
Observations of halo stars indicate two “r-process” sites:
- Main r-process
- Stellar LEPP / weak r-process

Solar LEPP
- Explains underproduction of “s-only” isotopes from Mo to Xe
- Contributes 20-30% of solar Sr, Y, Zr
- Solar abuns = r-process + s-process + LEPP

Stellar LEPP
- Same as solar LEPP?
LEPP: Lighter Element Primary Process

- Some amount of proton-rich ejecta from CCSN neutrino-driven winds is needed to be compatible with observations.

Observed pattern reproduced
Production of p-nuclei

Overproduction of $A=90$ ($N=50$) ➔ Only a fraction of neutron-rich ejecta (Hoffman et al 1996)
Neutrino-driven winds

- Core-collapse supernovae explode early
- Conditions of neutrino-driven wind

→ ideal site for the r-process ?!
Neutrino-driven winds in CCSNe

- T = 10-8 GK
  - NSE
  - charged-particle reactions; α-process

- T = 8 - 2 GK
  - (weak) r-process

- T < 3 GK
  - vp-process
Neutrinos from CCSNe

Effects of neutrinos

Heating:
\[ \nu_e + n \leftrightarrow p + e^- \]
\[ \bar{\nu}_e + p \leftrightarrow n + e^+ \]

Opacity:
\[ \nu_e + A' \leftrightarrow A + e^- \]
\[ \nu + N \leftrightarrow \nu + N \]
\[ \nu + A \leftrightarrow \nu + A \]

Thermalization:
\[ \nu + e^- \leftrightarrow \nu + e^- \]
\[ e^+ + e^- \leftrightarrow \nu + \bar{\nu} \]

Source terms (all flavors):
\[ e^+ + e^- \leftrightarrow \nu + \bar{\nu} \]
\[ \gamma + \gamma \leftrightarrow \nu + \bar{\nu} \]

\( \nu \)-spheres:
- where neutrinos decouple
  \( \rightarrow \) sets neutrino energies
- Deeper inside for \( \mu/\tau \) neutrinos
  \( \rightarrow \) larger energies (20-30 MeV)
  - \( \bar{\nu}_e \): 13-19 MeV
  - \( \nu_e \): 8-13 MeV
Wind conditions for r-process

- High neutron-to-seed ratio: $Y_n/Y_{seed} \sim 100$
- Short expansion timescale: $10^{-3}$ to 1 second
  → inhibits formation of nuclei through $\alpha$-process
- High entropy: $s/k_B \sim 20 – 400$
  → many free nucleons
- Moderately low electron fraction: $Ye<0.5$

**BUT**: Conditions not realized in recent simulations

Simulations find:
- $\tau \sim$ few milliseconds
- $s \sim 50-120 \text{ k_B/nuc}$
- $Ye \sim 0.4 – 0.6$

→ Additional ingredients??
• If neutrino-driven winds from CCSNe (currently) cannot produce an r-process, what can they do?
Electron fraction in neutrino-winds

- Electron fraction $Y_e$: set by weak interactions

\[ \nu_e + n \leftrightarrow e^- + p \]
\[ \bar{\nu}_e + p \leftrightarrow e^+ + n \]

- Luminosity ratio $L_{\bar{\nu}_e}/L_{\nu_e}$

- Difference in neutrino energies:

- Proton-rich if $\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} < 4(m_n c^2 - m_p c^2) \approx 5.2\text{MeV}$

- Details of nuclear physics (nuclear potentials, etc)
  - EOS treats neutrons and protons as non-interacting particles in mean field potential $\rightarrow$ need to be consistent
  - Up to 10 MeV difference in neutrino energies
Proton-rich winds

Ye > 0.5 is generic result of simulations with elaborate ν-transport

\[
\begin{align*}
\nu_e + n & \leftrightarrow e^- + p \\
\bar{\nu}_e + p & \leftrightarrow e^+ + n
\end{align*}
\]

- If the neutrino flux is sufficient (scales 1/r^2):
- High density / low temperature \( \rightarrow \) high \( E_F \) for electrons \( \rightarrow \) e-captures dominate \( \rightarrow \) n-rich
- If electron degeneracy lifted for high T \( \rightarrow \) \( \nu_e \)-captures dominate \( \rightarrow \) due to n-p mass difference, p-rich composition

Liebendörfer et al (2001)  
Rampp & Janka (2000)  
The $\nu p$-Process

- Proton-rich matter is ejected under the influence of neutrino interactions.
- True rp-process is limited by slow $\beta$ decays, e.g. $\tau(64\text{Ge})$.
- Neutron source:
  $$\bar{\nu}_e + p \rightarrow n + e^+$$

- Antineutrinos help bridging long waiting points via $(n,p)$ reactions:
  $64\text{Ge} (n,p) 64\text{Ga}$
  $64\text{Ga} (p,\gamma) 65\text{Ge}$
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  64\text{Ge} & \rightarrow (n,p) 64\text{Ga} \\
  64\text{Ga} & \rightarrow (p,\gamma) 65\text{Ge}
  \end{align*}
  \]
Heavy element synthesis inventory

- **s-process**
  - Secondary process; in AGB stars up to Pb or in massive stars as weak s-process

- **γ-process**
  - Secondary process; underproduction of light p-nuclei

- **r-process**
  - Primary process; in neutrino-driven winds from CCSNe?
  - ???

- **vp-process**
  - In proton-rich neutrino winds