



R Process for the Nucleosynthesis of Heavy Elements

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Abundances of Heavy Elements

r-Process

- Definitions and Quantities

- What is the r-Process?

- Classical r-Process Model

- Calculation of Abundances

- Other effects

SN II as a Possible Site for the r-Process

- Core Collapse Supernova Explosions

- Why SN-II as a possible Site?

- Influences of Neutrinos on the r-Process

References



Solarsystem Abundances

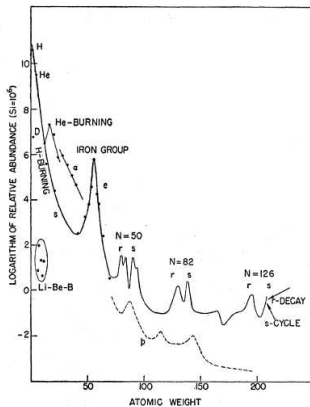


Figure: Atomic abundances relative to $Si = 10^6$, taken from Fowler [3]



- ▶ $\tau_{n\gamma}$ time between neutron captures
- ▶ τ_{β} timescale of a beta decay
- ▶ N_n neutron density
- ▶ $N(A, Z)$ density of species with mass A and charge Z



What is the r-Process?

Short Definition

- ▶ Element synthesis for elements heavier than iron
- ▶ Basic mechanism: neutron captures
- ▶ $\tau_{n\gamma} \ll \tau_{\beta}$



Outline

- ▶ Seed nuclei captures neutrons until reaching a waiting point
- ▶ At least one β decay
- ▶ Switches to new isotopic chain
- ▶ Takes up neutron capture again as a new seed nuclei



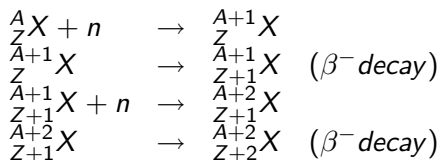
Waiting Points

- ▶ Even-N nuclei have smaller (n, γ) Q-values.
- ▶ β decay to new isotopic chain
- ▶ Nucleus takes up neutron captures again
- ▶ Higher abundance



Magic Numbers

When a nucleus (A,Z) reaches a magic neutron number, Q is small

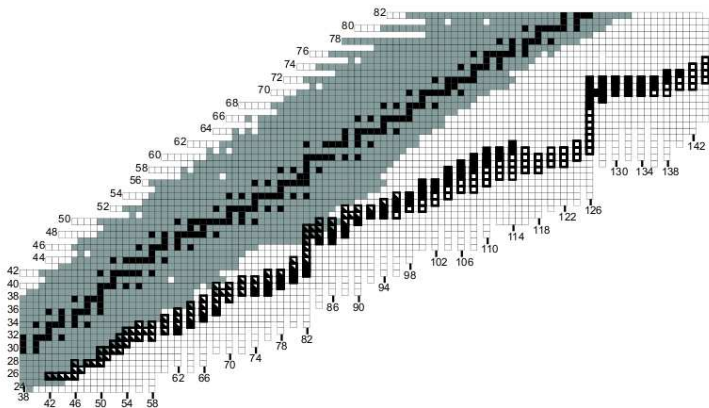


Until the nucleus is close to the valley of β stability. Then $(A+k, Z+k)$ takes up fast neutron capture again.



Classical r-Process Model

r-Process Path





Expected Features of Abundance Spectrum

- ▶ Peaks around magic neutron numbers $A_m + Z(N)$
- ▶ Peaks at smaller mass numbers than s-process



Solarsystem Abundances

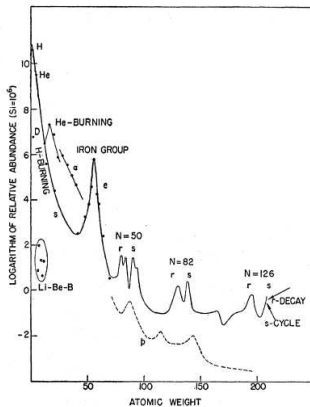


Figure: Atomic abundances relative to $Si = 10^6$, taken from Fowler [3]



When does the Process stop?

- ▶ Bypasses α emitters
- ▶ Stops with spontaneous fission/ β delayed fission
- ▶ Feeds back into the process



Assumptions

- ▶ (n, γ) and (γ, n) reactions in equilibrium for $Z=\text{constant}$
- ▶ $\tau_{n\gamma} \ll \tau_{\beta}$ and $\tau_{\gamma n} \ll \tau_{\beta}$
- ▶ After τ , neutron flux and temperature fall immediately to 0
- ▶ Temperature and neutron flux constant during r-process



Saha equation

For $T \approx 10^9 K$, $N_n > 10^{20} \frac{\text{cm}^3}{\text{cm}^3}$

$$\frac{N(Z, A+1)}{N(Z, A)} = N_n \left(\frac{h^2}{2\pi m_{An} kT} \right)^{3/2} \frac{2j_{Z,A+1} + 1}{(2j_{Z,A} + 1)(2j_n + 1)} \frac{G_{Z,A+1}^{norm}}{G_{Z,A}^{norm}} e^{Q_{n\gamma}/kT}$$

Where

$G_{Z,A}^{norm}$ Normalized partition function for excited states of (Z,A)

m_{ij} Reduced mass of particles i and j

$Q_{n\gamma}$ Q value of neutron capture

j_i Spin of particle i



$$\dot{N}(Z) = N(Z-1) \sum_A P(Z-1, A) \lambda_{\beta}^{Z-1, A} - N(Z) \sum_A P(Z, A) \lambda_{\beta}^{Z, A}$$

$$P(Z, A) = N(Z, A) / N(Z)$$

$$N(Z, A) \text{ from equilibrium condition}$$

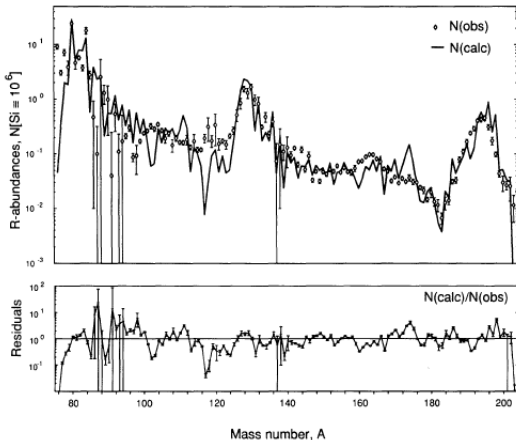


Simulation of Classical r-process Model

- ▶ Classical r-process model
- ▶ Superposition of 3 conditions
- ▶ 3 paths
- ▶ β^- decay rates predicted theoretically



Results from Classical r-Process Model





Neglected so far...

- ▶ Time dependence
- ▶ Other reactions
- ▶ ν 's
- ▶ General relativistic effects

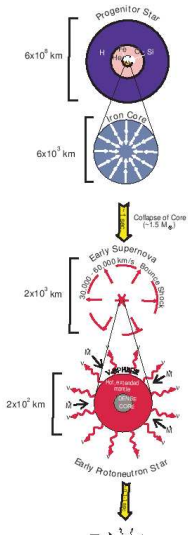


When a Star Dies

- ▶ Star in hydrostatic equilibrium
- ▶ Electron degeneracy pressure prevents collapse
- ▶ Mass limit for a star or core supported by degeneracy pressure:
 $1.43M_{\odot}$ (Chandrasekhar limit)
- ▶ Implosion
- ▶ When $\rho \approx 10^{14} \frac{\text{g}}{\text{cm}^3}$, material becomes incompressible
- ▶ Bounce $70000 \frac{\text{km}}{\text{s}}$



Core Collapse Supernova Explosions





A little bit more Details...

- ▶ $p + e^{-} \rightarrow n + \nu_e$
- ▶ Huge amount of neutrons and neutrinos



Arguments in Favor of SN- Type II as a r-Process site

- ▶ Amount of material
- ▶ Frequency
- ▶ Conditions



Why not clear yet?

- ▶ Underproduction of heavy elements
- ▶ ν influence?
- ▶ Many uncertainties about the data
- ▶ SN-II not perfectly understood



During the r-Process

- ▶ ν_e capture on free n hinder r-process
- ▶ ν_e capture on nucleus speed it up
- ▶ $\bar{\nu}_e + p \rightarrow n + e^+$ produce n
- ▶ ν do not interact with all nuclei








Spallation

(ν_e, e^-) Charged current reaction, $(Z, A) \rightarrow (Z + 1, A)$
 $(\nu_e, \nu_{e'})$ Neutral current reaction

- ▶ Both can leave the nucleus well above B_n .
- ▶ Can account for underproduction in $A=124-126$ region



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