The impact of prompt neutron emission from fission fragments on the final abundance pattern of the astrophysical r-process

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Overview

- Research performed with mentor Matthew Mumpower at Los Alamos National Laboratory
  - Eight weeks
  - NSSC LANL Summer Program
- Astrophysical r-process
- Nuclear fission
  - Prompt neutron emission
- r-process network calculation
  - Impact on the final abundance pattern of the r-process
Astrophysical r-process

\[ t = 0.00424066 \text{ s, } T_\text{e} = 2.0, \rho = 88550000.0 \text{ g/cm}^3 \]
Fission

(Z, A)

Time Evolution
Fission

(Z, A)

Time Evolution
Fission

Time Evolution

\((Z, A)\)

\((Z_L, A_L)\) \(\rightarrow\) \((Z_L, A'_L)\)

\((Z_H, A_H)\) \(\rightarrow\) \((Z_H, A'_H)\)
Fission

Time Evolution

(Z, A)

(Z_L, A_L)

(Z_H, A'_L)

γ

n

(Z_H, A_H)

(Z_H, A'_H)

(Z'_L, A'_L)

β

ν

(Z'_H, A'_H)
Fission Yield
(Fission Fragment Mass Distribution)

Fission Yield
(Fission Fragment Mass Distribution)

T. Kodama, and K. Takahashi,
Nucl. Phys. A 239 (1975) 489

\[
Z_{\text{fission}} = \sum_{Z} \sum_{A} Y(Z, A) \cdot Z
\]

\[
A_{\text{fission}} = \sum_{Z} \sum_{A} Y(Z, A) \cdot A
\]
Fission Yield
(Fission Fragment Mass Distribution)
Prompt Neutron Emission

Modifying the Yields

\[ n, \text{ Number of Prompt Neutrons from a Single Fragment} \]
Modifying the Yields

\[ Y(Z, A) \]

\[ n, \text{ Number of Prompt Neutrons from a Single Fragment} \]

\[ P(n) \]
Modifying the Yields

\[ Y(Z, A) = Y(Z, A - 1) + Y(Z, A) \times P(1) \]

\[ Y'(Z, A) = Y(Z, A) \times [1 - P(1)] \]

\[ n, \text{ Number of Prompt Neutrons from a Single Fragment} \]

\[ \frac{\nu_{\text{total}}}{2} \]
Modifying the Yields

\[ Y(Z, A) = Y(Z, A - 1) + Y(Z, A - 2) + Y(Z, A) \times P(2) \]

\[ Y'(Z, A) = Y(Z, A) [1 - P(1) - P(2)] \]

\( n \), Number of Prompt Neutrons from a Single Fragment
Modifying the Yields

\[ Y(Z, A) = Y(Z, A - 1) + Y(Z, A) \cdot P(n) \]

\[ Y'(Z, A) = Y(Z, A) \left[ 1 - \sum_{n>0} P(n) \right] \]

\[ Y'(Z, A - n) = Y(Z, A - n) + Y(Z, A) \cdot P(n) \]
Modifying the Yields

\[
\begin{align*}
Z_{\text{fission}} &= \sum_Z \sum_A Y(Z, A) \cdot Z \\
A_{\text{fission}} &= \sum_Z \sum_A Y(Z, A) \cdot A
\end{align*}
\]
Modifying the Yields

\[
Z_{\text{fission}} = \sum_Z \sum_{A'} Y(Z, A') \cdot Z
\]

\[
A_{\text{fission}} = \sum_Z \sum_{A'} Y(Z, A') \cdot A' + \bar{\nu}_{\text{total}}
\]
Modifying the Yields

\[ Z = 100, \; N = 180, \; A = 280 \]

Graph 1: Y(Z) (%) vs. Atomic Number, Z
- Original
- Conservation of Energy (\( \bar{\nu}_{\text{total}} = 4.90 \))
- Howerton Systematics (\( \bar{\nu}_{\text{total}} = 3.72 \))

Graph 2: Y(A) (%) vs. Mass Number, A
- Original
- Conservation of Energy (\( \bar{\nu}_{\text{total}} = 4.90 \))
- Howerton Systematics (\( \bar{\nu}_{\text{total}} = 3.72 \))
Modifying the Yields

$Z = 100, \ N = 180, \ A = 280$

- **Original**
- **Conservation of Energy ($\tilde{\nu}_{\text{total}} = 4.90$)**
- **Howerton Systematics ($\tilde{\nu}_{\text{total}} = 3.72$)**

**Atomic Number, $Z$**

**Mass Number, $A$**
- Use the modified yields in an r-process network calculation, and investigate the impact on the final abundance pattern
- Portable routines for integrated nucleosynthesis modeling
- Developed by mentor Matthew Mumpower at Los Alamos National Laboratory
Neutron-induced and β-delayed Fission

![Graph showing the weighted timescale of various nuclear processes over time](image)
Neutron-induced and $\beta$-delayed Fission
Neutron-induced and β-delayed Fission
Neutron-induced and $\beta$-delayed Fission

![Graph showing abundance vs. mass number for different fission types and solar system r-process residuals.]

- Baseline
- Prompt neutron emission
- Solar system r-process residuals
Neutron-induced and $\beta$-delayed Fission

Global impact – impacts the entire final abundance pattern
Neutron-induced and $\beta$-delayed Fission

Nonlinear – certain regions are impacted while others are not
Neutron-induced and β-delayed Fission

Peaks shift in mass number
Neutron-induced and $\beta$-delayed Fission

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“Fine details”
Conclusions

- Prompt neutron emission from fission fragments impacts the fine details of final abundance pattern of the r-process.
- This project will be continued and expanded upon by the FIRE (fission in r-process elements) collaboration, which uses state-of-the-art theory to explore the role of fission in the r-process, and includes scientists from the University of Notre Dame, North Carolina State University, Los Alamos National Laboratory, Brookhaven National Laboratory, and Lawrence Livermore National Laboratory.
Disclaimer

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- Main focus to present your research to NSSC partners, sponsor, and the advisory board.
- Keep in mind this will be a 15 minute presentation, with an additional 5 minutes for questions.
- Please include mention of the NSSC Focus Areas and any Crosscutting Focus Areas you are working under.
- Highlight any lab collaborations involved in your research, with specific mention of lab and lab mentor.
Modifying the Yields

\[
\bar{\nu}_{total} = \sum_{Z} \sum_{A} Y(Z, A) \cdot \bar{\nu}(A)
\]
Abundance Weighted Timescale

\[
\tau_{n,\gamma} = \frac{\sum_{Z,A} Y(Z, A)}{\sum_{Z,A} N_n \langle \sigma \nu \rangle_{Z,A} Y(Z, A)}
\]

\[
\tau_{\gamma,n} = \frac{\sum_{Z,A} Y(Z, A)}{\sum_{Z,A} \lambda_{\gamma,n}(Z, A) Y(Z, A)}
\]

\[
\tau_{\beta} = \frac{\sum_{Z,A} Y(Z, A)}{\sum_{Z,A} \lambda_{\beta}(Z, A) Y(Z, A)}
\]
Conservation of Energy

\[ E_r = M(Z, A) - M_L(Z_L, A_L) - M_H(Z_H, A_H) \]
\[ = T_L(Z_L, A_L) + T_H(Z_H, A_H) + E^*_L(Z_L, A_L) + E^*_H(Z_H, A_H) - (E_n + S_n) \]
\[ = T_f^{total} + E_n^{total} - (E_n + S_n) \]
\[ = \langle T_f^{total} \rangle + \langle E_n^{total} \rangle - (E_n + S_n) \]
\[ = \langle T_f^{total} \rangle + \langle E_n^{total} \rangle + \langle E^*_\gamma \rangle - (E_n + S_n) \]
\[ = \langle T_f^{total} \rangle + \bar{\nu} [\langle S_n \rangle + \langle \epsilon \rangle] + \langle E^*_\gamma \rangle - (E_n + S_n) \]

- Eqn. 17 in *Nuclear Physics A 772 (2006) 113–137* by D.G. Madland
- \( E_r \) = Q value = total energy release in binary fission
- \( \langle T_f^{total} \rangle \) = average total fragment kinetic energy
- \( \langle E_n^{total} \rangle \) = average total fragment excitation energy
- \( \langle E_n^{total} \rangle \) = average total fragment neutron emission energy
- \( \langle E^*_\gamma \rangle \) = average total fragment gamma-ray emission energy
- \( \langle S_n \rangle \) = average fragment neutron separation energy
- \( \langle \epsilon \rangle \) = average center-of-mass energy of emitted neutrons
- \( E_n \) = kinetic energy of incident neutron
- \( S_n \) = neutron separation energy of compound nucleus
Conservation of Energy

- \( E_r = Q \) value = total energy release in binary fission
  - Binding energies from FRDM 2012
  - \( E_r = M(Z, A) - M_{L}(Z_L, A_L) - M_{H}(Z_H, A_H) \)
    \[ = \sum_{Z,A} BE(Z, A) \cdot Y(Z, A) - BE(Z_c, A_c) \]

- \( \langle T_f^{total} \rangle = \) average total fragment kinetic energy
    - \( \langle T_f^{total} \rangle = 0.1189 \frac{Z_c^2}{A_c^{1/3}} + 7.3 \)

- \( \langle E_{\gamma}^{total} \rangle = \) average total fragment gamma-ray emission energy
    - \( \langle E_{\gamma}^{total} \rangle = 0.02772 \cdot A_c + 0.0891 \)
Conservation of Energy

- \( <S_n> \) = average fragment neutron separation energy
  - Binding energies from FRDM 2012
    \[ \langle S_n \rangle = \sum_{Z,A} S_n(Z,A) \cdot Y(Z,A) \]
- \( \langle \varepsilon \rangle \) = average center-of-mass energy of emitted neutrons
    - \( \langle \varepsilon \rangle \approx 2.34 \text{ MeV} \)
- \( E_n \) = kinetic energy of incident neutron
  - Assume thermal energies in r-process
    - \( \langle E_n \rangle \approx 0 \)
- \( S_n \) = neutron separation energy of compound nucleus
  - Binding energies from FRDM 2012
Howerton Systematics

- Based on a Taylor expansion about $^{235}\text{U}(n,f)$ at the threshold energy for fission $E_{th}$
- Tested against $\langle \nu \rangle$ for isotopes from $^{229}\text{Th}$ to $^{249}\text{Cf}$ in 1977
- Threshold energies calculated using binding energies from FRDM 2012

$$\bar{\nu}(Z, A, E_n) = 2.33 + 0.06 \cdot (2 - (-1)^{A+1-Z} - (-1)^Z)$$
$$+ 0.15 \cdot (Z - 92) + 0.02 \cdot (A - 235)$$
$$+ (0.130 + 0.006 \cdot (A - 235)) \cdot (E_n - E_{th})$$

$$E_{th}(Z, A) = 18.6 - 0.36 \cdot Z^2/(A + 1)$$
$$+ 0.2 \cdot (2 - (-1)^{A+1-Z} - (-1)^Z) - S_n(Z, A + 1)$$
Neutron-induced Fission

![Graph showing time (s) vs. abundance weighted timescale (s) with different decay processes labeled: neutron capture \((n, \gamma)\), photodisintegration \((\gamma, n)\), \(\beta\) decay, \(\alpha\) decay, \((n, 2n)\), and neutron-induced fission.]}
Neutron-induced Fission

![Graph showing time (s) vs. abundance weighted timescale (s) with legend for neutron capture (n, γ), photodisintegration (γ, n), β decay, α decay, (n, 2n), and neutron-induced fission.]
Neutron-induced Fission

Baseline
Prompt neutron emission
Solar system r-process residuals

Abundance ($\text{Si} = 10^6$)

Mass Number, A
Neutron-induced Fission

Global impact – impacts the entire final abundance pattern
Neutron-induced Fission

Nonlinear – certain regions are impacted while others are not
Neutron-induced Fission

“Fine details”
β-delayed Fission

![Graph showing τ, the abundance weighted timescale, vs. time (s) for different processes: neutron capture (n, γ), photodisintegration (γ, n), β decay, α decay, (n, 2n), and β-delayed fission.](image)
β-d delayed Fission
β-delayed Fission

![Graph showing abundance vs mass number with different lines representing baseline, prompt neutron emission, and solar system r-process residuals.](image-url)
β-delayed Fission

Peaks shift in mass number