The Influence of Neutron Capture Rates in the Rare Earth Region on the R-Process Abundance Pattern

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r-process nucleosynthesis: open questions

• What is the physical site in which the r-process occurs?

• Is there more than one location which could produce a consistent r-process? (supernovae, neutron star mergers, gamma ray bursts, etc.)

• Can we understand all the physical mechanisms which occur during r-process?

• What are the nuclear properties of heavy elements far from stability?
r-process nucleosynthesis: open questions

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questions i’ve focused on:

• In the r-process, can we understand the physical mechanisms by which the rare earth sector is produced?

• By changing the neutron capture rates (NCRs) in this region, do we see a change in the r-process abundance pattern?

• Which of the nuclear species in this region are most important to the development of the r-process?
the r-process abundance pattern
the rare earth region

• Green = **Unstable** or Relatively Unstable - beta decay.

• Yellow = **Stable** or Relatively Stable - beta decay.

• Red = Region of Interest

**Basic Interactions:**

**Neutron Capture** – Sends us along the x-axis.

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

**Beta Decay** – Diagonal movement.

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

• For our simulations we assume a particular r-process site: core collapse supernovae

• We follow a spherical mass element through a reaction network propagated by a neutrino driven wind.

• Two characteristic parameters are: Temperature $T(r)$ and Density $\rho(r)$ ($r$ denotes radius from the star core).

• Our code involves three main stages:

  1. Thermodynamics
  2. Charge particle interactions
  3. R-process

• At the end of the calculation we are interested in the final abundance pattern.
astrophysical input parameters

\[ \tau \] - Outflow timescale. Values range from milliseconds to seconds

\[ s/b \] - Entropy per baryon. Values range from 50 to 400

\[ Y_e \equiv N\left(\frac{p}{n+p}\right) \] - Electron fraction. Values range from .2 to .5

• These parameters have a strong influence on our r-process distribution.
nuclear input parameters

- Nuclear mass models.
- Beta Decay Rates.
- Neutron Capture Rates.

- Nearly all of which are *theoretical* at this time.
formation of the rare earth region

• How does the model produce this region?

• In the beginning the temperature and density are very large, and thus no nuclei form. Everything is in nuclear statistical equilibrium (nse).

• Next, seed nuclei form with left over neutrons. We build up heavy elements by capturing neutrons on the seed nuclei.

• The temperature begins to drop and we start capturing neutrons which competes with very fast beta decay rates in the green region.

• Lastly, the nuclei beta decay back to more stable regions.
Temperature has started to drop.

Heavy nuclei begin to populate.
simulation: r-process path

- More heavy nuclei become populated.
- Time scale: fractions of a second.
Free neutron abundance begins to drop.
• Free neutron abundance drops rapidly.

• Time scale: ~ 1 s
when do the neutron capture rates matter?

![Graph of Free N-Abundance Vs Time](image)

- **Free N-Abundance vs Time**
- **Y-axis:** Free Neutron Abundance
  - Values range from $10^{-12}$ to $10^0$
- **X-axis:** Time (sec)
  - Values range from 1 to 9 seconds
- **Legend:**
  - Blue line: $\tau = 0.1$
  - Green line: $\tau = 0.3$

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when do the neutron capture rates matter?

Free N-Abundance Vs Time

Equilibrium

Free Neutron Abundance

Time (sec)

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**Free N-Abundance Vs Time**

- **Equilibrium**
- **Freeze Out: Rates Matter**

**Free Neutron Abundance**

- **Time (sec)**: 1, 2, 3, 4, 5, 6, 7, 8, 9

**Graph Details**

- **tau = 0.1**
- **tau = 0.3**
when do the neutron capture rates matter?

Equilibrium

Freeze Out: Rates Matter

After Freeze Out
why neutron capture rates matter

_They Matter When:_
- The time in which the free neutron abundance drastically falls off, an epoch known as freeze out.

_Rates Don’t Matter:_
- Equilibrium – abundances are determined by statistics. (High T, High Yn)
- After Freeze Out – There are very few free neutrons left to capture at this stage. (Low T, Low Yn)

- Notice this happens at different times with different astrophysical models!
now we can ask...

• Which neutron capture rates in the rare earth region are important?

• To do this we study ALL of the neutron capture rates in the rare earth sector.

• This means we have to do A LOT of calculations... (hundreds of cpu hours).

• We also need a method to keep track of the important elements.

• To quantify the importance of NCRs in this region we create a quantity called “The F measure.”
To study a **SINGLE** NCR we:

1. Set the parameters (astrophysical and nuclear), run a **baseline** simulation.
2. This produces an abundance pattern (squiggly line) which we save for later.
3. Next we pick a particular nuclear species and rerun the simulation with the specific NCR changed by a factor of 100.
4. This produces a **second** abundance pattern (another squiggly line...).
5. Measure the change in the overall abundance pattern via two methods:
   - Visually looking at the pattern.
   - Quantitatively using the F-measure.
a metric for NCR calculations

• We call our metric, the F-measure:

\[
F = 100 \sum_{A} \left| \frac{Y_{\text{baseline}}(A) - Y_{\text{ncr}}(A)}{Y_{\text{baseline}}(A)} \right|
\]

• A Large F value means there was a large effect on the abundance pattern relative to the baseline curve.

• A F-value near ZERO means there was hardly any effect at all on the abundance pattern by changing the NCR of the particular nuclear species. In other words, the baseline curve and the NCR curve are nearly identical.

• We repeat the NCR calculations for EVERY nuclear species in our grid. Exporting a F-value for each of them and then create a pretty plot...
- Yellow = important – we see change in the abundance pattern.
- Red = no change in abundance pattern.
to reiterate...

• We can clearly see which NCRs are important:

• Those in yellow have the highest effect.  (approximately F ~ 600 - 1000)

• While those in red have little to no effect.  (approximately F ~ 0)

• For nuclear species in yellow, what does the abundance pattern look like compared to the baseline calculation?
NCR vs baseline abundance curves
• We don’t know exactly the astrophysical parameters. Recall the main parameters are the outflow timescale, entropy, electron fraction.

• Nor do we have experimental measurements on the nuclear properties of the elements with such high atomic mass (mass models, beta decay rates).

• Therefore we run more simulations to attempt to take into account this uncertainty.

• We do this by varying the parameters, rates and models.

• For each of these simulations we run the conglomerate NCR calculations on the rare earth region. This produces many colorful grids as shown above.

• We reduce this massive information set down to one colorful grid by taking the **maximum** F-measure for each element across all the data sets.
<table>
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<tr>
<th>Conglomerate Grid</th>
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<td>Mumpower, NCSU INT summer school June 2009</td>
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summary

• We are able to reproduce the rare earth sector with a reasonable degree of accuracy, but still need to understand (or add) more physics to the simulations in order to fully replicate the region exactly.

• We have shown that NCRs in the rare earth region are important in determining local features of the r-process abundance pattern.

• We have identified particular elements which show significant leverage such as:

Gd167, Sm163, Nd161, Pr155, Ce155, and Ce154.