Studying lanthanide production in $r$-process nucleosynthesis

Nicole Vassh
University of Notre Dame

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Observed Solar \( r \)-process Residuals

Depending on the conditions, the \( r \)-process can produce:

- Poor metals (Sn, ...)
- Lanthanides (Nd, Eu, ...)
- Transition metals (Ag, Pt, Au, ...)
- Actinides (U, Th, ...)

Arnould, Goriely and Takahashi (2007)
GW170817 and $r$-process uncertainties from nuclear physics

From GCE using Solar Data

When nuclear physics uncertainties are considered

Côté, Fryer, Belczynski, Korobkin, Chruślińska, Vassh, Mumpower, Lippuner, Sprouse, Surman and Wollaeger

r-process Sensitivity to Mass Model and Fission Yields

- 10 mass models: DZ33, FRDM95, FRDM12, WS3, KTUY, HFB17, HFB21, HFB24, SLY4, UNEDF0
- N-rich dynamical ejecta conditions: Cold (Just 2015), Reheating (Mendoza-Temis 2015)
Z=95, Z=96, Z=97, Z=98, Z=99, Z=100, Z=101, Z=102 (dotted lines – larger Z)

Rare-earth peak can be populated by fission daughter products of n-rich nuclei

Goriely (2015)
β-delayed fission in r-process nucleosynthesis

Mumpower, Kawano, Sprouse, Vassh, Holmbeck, Surman, and Möller (2018)
arXiv:1802.04398

Black outline – probability of multi-chance βdf > 10%

Andreyev, Nishio, and Schmidt (2018)

Mumpower, Kawano, and Möller (2016)
Superheavy island blocked by $\beta$-delayed fission

**Right:** Example - $\beta$df alone can prevent the population of the superheavy island of stability (purple outline – probability of $\beta$df $>$ 90%)

**Below:** previous calculations with $Z<100$ identified possibility to circumvent region with $\beta$df probability ~100%

Petermann, Langanke, Martínez-Pinedo, Panov, Reinhard, and Thielemann (2012)

See also: Thielemann, Metzinger, and Klapdor (1983)

Mumpower et al (submitted 2018)
Right: keeping a symmetric (50/50) split for neutron-induced fission yields while exchanging βdf yields from Kodama et al to a symmetric split.
Shaping the $r$-process second peak: fission barriers and shell closures

Left: impact of fission barrier heights on the $r$-process path

Below: dripline mass model comparison and effect on the abundances near $N=82$ ($A\sim130$ peak)
Masses: Model Divergence and FRIB Reach

**Experimental Mass Measurements:**

- **AME 2016**
- **FRIB - Day 1**
- **FRIB - Designed Beam Intensity**

Mumpower, Surman, McLaughlin, and Aprahamian (2016)
Studying Rare-Earth Nuclei to Understand $r$-process Lanthanide Production

**Experimental** Mass Measurements:

AME 2016
Jyväskylä
CPT at CARIBU
Studying Rare-Earth Nuclei to Understand $r$-process Lanthanide Production

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**Theory** (ND, NCSU, LANL):
Markov Chain Monte Carlo Mass Corrections to the Duflo-Zuker Model which reproduce the observed rare-earth abundance peak

(right: result with $s/k=30$, $\tau=70$ ms, $Y_e=0.2$)

N. Vassh et al (in preparation)
Standard \( r \)-process calculation

Astrophysical conditions
Fission Yields
Rates (n capture, \( \beta \)-decay, fission….)
Nuclear masses

Nucleosynthesis code (PRISM)

Abundance prediction
Reverse Engineering $r$-process calculation

Astrophysical conditions
Fission Yields
Rates (n capture, $\beta$-decay, fission....)

Nucleosynthesis code (PRISM)

Nuclear masses
Markov Chain Monte Carlo (MCMC)
Likelihood function

Abundance prediction
MCMC procedure

- Monte Carlo mass corrections
  \[ M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C)^2/2} \]

- Check: \( \sigma_{\text{rms}}^2(M_{\text{AME}12}, M) \leq \sigma_{\text{rms}}^2(M_{\text{AME}12}, M_{DZ}) \)

- Check:
  \[ D_n(Z,A) = (-1)^{A-Z+1}(S_n(Z,A+1) - S_n(Z,A)) > 0 \]

- Update nuclear quantities and rates

- Perform nucleosynthesis calculation

- Calculate \( \chi^2 = \sum_{A=150}^{180} \frac{(Y_{\odot}(A) - Y(A))^2}{\Delta Y(A)^2} \)

- Update parameters OR revert to last success
  \[ \mathcal{L}(m) = \exp\left( -\frac{\chi^2(m)}{2} \right) \quad \alpha(m) = \frac{\mathcal{L}(m)}{\mathcal{L}(m-1)} \]
Dynamic Mechanism of Rare-Earth Peak Formation

Detailed balance implies

\[(\gamma, n) \propto e^{\frac{-S_n}{kT}}\]

\[r\text{-process path tends to lie along contours of constant separation energy}\]

Pile-up of material at kinks
Results

- Astrophysical trajectory: hot, low entropy wind as from a NSM accretion disk 
  \(s/k=30, \tau=70\) ms, \(Y_e=0.2\)

- 50 parallel, independent MCMC runs; 
  Average run \(\chi^2\sim23\)

Orford, Vassh, Clark, McLaughlin, Mumpower, Savard, Surman, Aprahamian, Buchinger, Burkey, Gorelov, Hirsh, Klimes, Morgan, Nystrom, and Sharma 
(accepted to PRL)
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Rare-Earth Peak with MCMC solutions

Orford, Vassh, et al (accepted to PRL)
Nucleosynthesis in Neutron Star Mergers: Many Open Questions

- Can mergers account for most of the $r$-process material observed in the galaxy?
- Are precious metals such as gold produced in sufficient amounts? Are actinides produced?
- Where within the merger environment does nucleosynthesis occur and under what specific conditions?
- Does fission of the heaviest nuclei shape the observed second $r$-process peak?
- How does the rare-earth peak form?
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Mumpower et al (arXiv:1802.04398)  
Vassh et al (in preparation)  
Orford, Vassh, et al (accepted to PRL)
Back-up Slides
$r$-process sites within a Neutron Star Merger

Very n-rich cold, tidal outflows

Hot, shocked material

Accretion disk winds – exact driving mechanism and neutron richness varies

Foucart et al (2016)

Owen and Blondin
Lanthanide production in GW170817: “red” kilonova

Lanthanide mass fraction ↑, opacity ↑, longer duration light curve shifted toward infrared


Kasen et al (Nature 2017)
Observed Elemental Abundances

Solar System

Lodders (2010)

10 r-process rich halo stars

Cowan, Roederer, Sneden and Lawler (2011)
Côté, Fryer, Belczynski, Korobkin, Chruścińska, Vassh, Mumpower, Lippuner, Sprouse, Surman and Wollaeger (2017) - *r*-process Calculations for NSM Ejecta

Arnould et al. (2007) - Wind ejecta (s/k=10, $Y_e=0.27$)

Very n-rich dynamical ejecta

Abundance vs. mass number ($A$) for different models and scenarios.
Sneden, Cowan, and Gallino (2008)

<table>
<thead>
<tr>
<th>Element</th>
<th>N = 82</th>
<th>Elemental Breakdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd</td>
<td>142(\text{s}r)</td>
<td>42% 58%</td>
</tr>
<tr>
<td>Pr</td>
<td>141(\text{s}r)</td>
<td>100%</td>
</tr>
<tr>
<td>Ce</td>
<td>140(\text{s}r)</td>
<td>88.0% 11.2%</td>
</tr>
<tr>
<td>La</td>
<td>139(\text{s}r)</td>
<td>99.0% 25% 75%</td>
</tr>
<tr>
<td>Ba</td>
<td>134(\text{s}r)</td>
<td>2.4% 6.6% 7.9% 11.2% 71.7%</td>
</tr>
<tr>
<td>Cs</td>
<td>133(\text{s}r)</td>
<td>85% 15%</td>
</tr>
<tr>
<td>Xe</td>
<td>128(\text{s}r)</td>
<td>1.9% 28.4% 4.1% 21.2% 28.9% 10.4% 8.9%</td>
</tr>
</tbody>
</table>
Peak Formation with an MCMC Mass Solution
Peak Formation with an MCMC Mass Solution
(Abundance pattern range using the mass values found by our MCMC given disk wind conditions $s/k=30$, $\tau=70 \text{ ms}$, $Y_e=0.2$)

Vassh et al (in preparation)
Preliminary Results

- Astrophysical trajectory: n-rich NSM **dynamical** ejecta with nuclear reheating
- Simple fission prescription:
  - spontaneous fission for all A>250 nuclei
  - 57%, 43% fission fragment splits
- 50 independent MCMC runs complete

Vassh et al (in preparation)