$r$-process nucleosynthesis and radioactivity in merger ejecta

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KITP Program GW170817:
The First Double Neutron Star Merger
5-8 December 2017
r-process nucleosynthesis

Burbidge, Burbidge, Fowler, and Hoyle 1957

solar system abundances

\[ \beta \]

\[ (n,\gamma) \]

\[ (\gamma,n) \]
$r$-process elements in metal-poor stars

Arnould+2007

elemental abundances from $r$-process-enhanced metal-poor stars

Cowan+2011

solar system $r$-process residuals
**r-process simulations**

Network calculation by E. Holmbeck, T. Sprouse
NSM trajectory from Just+15

![Graph showing r-process simulation results]

- Time: $4.6889 \times 10^{-2}$ s
- $T_9 = 2.00172 \times 10^0$
r-process simulations

Beun, McLaughlin, Surman, Hix 2008

fission recycling

network calculation by E. Holmbeck, T. Sprouse
NSM trajectory from Just+15
integrated nucleosynthesis with neutrinos

with $e^\pm$-captures and $\nu$-interactions (Case 2)

Mass fraction

Te, Cs

gold, platinum UNDERPRODUCED

lanthanides

Goriely+2015
GW170817 and the $r$ process: open questions

Are neutron star mergers responsible for the production of all $r$-process elements, or do multiple distinct sites contribute?

Can we understand neutron star merger nucleosynthesis from first principles?
merger outflow nucleosynthesis: required nuclear data

- masses
- beta-decay rates
- beta-delayed neutron emission probabilities
- neutron capture rates
- fission rates
- fission product distributions
- neutrino interaction rates

Mumpower, Surman, McLaughlin, Aprahamian
Progress in Particle and Nuclear Physics 86 (2016) 86
required nuclear data: masses

masses from AME2016

masses
beta-decay rates
beta-delayed neutron emission probabilities
neutron capture rates
fission rates
fission product distributions
neutrino interaction rates
required nuclear data: beta decay

beta decay rates from NUBASE 2016

masses
beta-decay rates
beta-delayed neutron emission probabilities
neutron capture rates
fission rates
fission product distributions
neutrino interaction rates
required nuclear data: neutron capture

neutron capture rates from KADONIS

masses
beta-decay rates
beta-delayed neutron emission probabilities
neutron capture rates
fission rates
fission product distributions
neutrino interaction rates
required nuclear data: fission properties

FIRE: Fission In R-process Elements
US DOE/NNSA Topical Collaboration
required nuclear data: masses

masses from AME2016

- masses
- beta-decay rates
- beta-delayed neutron emission probabilities
- neutron capture rates
- fission rates
- fission product distributions
- neutrino interaction rates
mass uncertainties

Mumpower, Surman, McLaughlin, Aprahamian 2016
impact of random uncorrelated mass uncertainties

Surman, Mumpower, McLaughlin 2016

FRDM masses + Monte Carlo variations within mass model rms (~0.5 MeV)
impact of random correlated mass uncertainties

50 mass tables generated using the UNEDF1 functional with uncertainties

Surman, Navarro Perez, Mumpower, McLaughlin, Schunck, in preparation
impact of systematic mass uncertainties

Côté, Fryer, Belczynski, Korobkin, Chruślińska, Vassh, Mumpower, Lippuner, Sprouse, Surman, Wollaeger, submitted
impact of systematic mass uncertainties

Footnote: the role of $\beta$-decay Luminosity (especially at late times) could indicate the importance of $\beta$-decay (or of fission!).

Barnes+2016
GRB170817A/SSS17a + galactic chemical evolution

Côté, Fryer, Belczynski, Korobkin, Chruścińska, Vassh, Mumpower, Lippuner, Sprouse, Surman, Wollaeger, submitted

Lookback time [Gyr]

$0.0 \quad 5.0 \quad 7.5 \quad 10.0$

NS-NS merger rate [Gpc$^{-3}$ yr$^{-1}$]

$10^1 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5$

LIGO/Virgo (GW170817)

Galactic chemical evolution

$M_{\text{Eu}} = 3.0 \times 10^{-6} M_\odot$

$M_{\text{Eu}} = 1.5 \times 10^{-5} M_\odot$

Population synthesis
can we use $r$-process astrophysical conditions to learn about nuclear physics?
impact of random correlated mass uncertainties

50 mass tables generated using the UNEDF1 functional with uncertainties

Surman, Navarro Perez, Mumpower, McLaughlin, Schunck, in preparation
correlations between UNEDF1 parameters and r-process pattern features

TABLE II: Optimized parameter set unedf1. Listed are bounds used in the optimization, final optimized parameter values, standard deviations, and 95% confidence intervals.

<table>
<thead>
<tr>
<th>x</th>
<th>Bounds</th>
<th>x(ﬁnal)</th>
<th>σ</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρc</td>
<td>[0.15, 0.17]</td>
<td>0.15871</td>
<td>0.00042</td>
<td>[0.158, 0.159]</td>
</tr>
<tr>
<td>KNM</td>
<td>[220, 260]</td>
<td>220.000</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>a_{NM}</td>
<td>[28, 36]</td>
<td>28.987</td>
<td>0.604</td>
<td>[28.152, 29.822]</td>
</tr>
<tr>
<td>L_{sym}</td>
<td>[40, 100]</td>
<td>40.005</td>
<td>13.136</td>
<td>[21.841, 58.168]</td>
</tr>
<tr>
<td>1/M_{s}</td>
<td>[0.9, 1.5]</td>
<td>0.992</td>
<td>0.123</td>
<td>[0.823, 1.162]</td>
</tr>
<tr>
<td>C_{αA}</td>
<td>[−∞, +∞]</td>
<td>-45.135</td>
<td>5.361</td>
<td>[−52.548, -37.722]</td>
</tr>
<tr>
<td>C_{βA}</td>
<td>[−∞, +∞]</td>
<td>-145.382</td>
<td>52.169</td>
<td>[-217.515, -73.250]</td>
</tr>
<tr>
<td>V_{α'}</td>
<td>[−∞, +∞]</td>
<td>186.065</td>
<td>18.516</td>
<td>[211.666, 160.464]</td>
</tr>
<tr>
<td>V_{β'}</td>
<td>[−∞, +∞]</td>
<td>-206.580</td>
<td>13.049</td>
<td>[-224.622, -188.538]</td>
</tr>
<tr>
<td>C_{0\alpha c}</td>
<td>[−∞, +∞]</td>
<td>-74.026</td>
<td>5.048</td>
<td>[-81.006, -67.046]</td>
</tr>
<tr>
<td>C_{0\beta c}</td>
<td>[−∞, +∞]</td>
<td>-35.658</td>
<td>23.147</td>
<td>[-67.663, -3.654]</td>
</tr>
</tbody>
</table>

Surman, Navarro Perez, Mumpower, McLaughlin, Schunck, in preparation
experimental prospects at FRIB

AME 2016
FRIB Day 1 reach
FRIB design goal

Facility for Rare Isotope Beams at Michigan State University
experimental prospects at FRIB

AME 2016
FRIB Day 1 reach
FRIB design goal
can we use nuclear physics to learn about r-process astrophysical conditions?
deducing $r$-process conditions from abundance pattern details: the rare earth peak

Its formation mechanism is sensitive to both the astrophysical conditions of the late phase of the $r$-process and the nuclear physics of the nuclei populated at this time.

Surman+1998
deducing r-process conditions from abundance pattern details: the rare earth peak

mass modification parameterization:

\[ M(Z, N) = M_{DZ}(Z, N) + a_N e^{-(Z-C)^2/f} \]
deducing r-process conditions from abundance pattern details: the rare earth peak

mass modification parameterization:

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

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hot, (n,γ)-(γ,n) equilibrium

cold, very neutron-rich

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Mumpower, McLaughlin, Surman, Steiner, 2016
deducing r-process conditions from abundance pattern details: the rare earth peak

mass modification parameterization:

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

hot, \((n,\gamma)-(\gamma,n)\) equilibrium

cold, very neutron-rich

predicted mass trends for the Neodymium \((Z = 60)\) isotopic chain

Mumpower, McLaughlin, Surman, Steiner, 2016
updated reverse engineering calculations

hot, (n,γ)-(γ,n) equilibrium example

In preparation, figure by Nicole Vassh
updated reverse engineering calculations

hot, (n,γ)-(γ,n) equilibrium example

In preparation, figure by Nicole Vassh
summary

The origin of the heaviest elements in the $r$-process of nucleosynthesis has been one of the greatest mysteries in nuclear astrophysics for decades.

Evidence from a variety of directions – including the neutron star merger discovery GW170817/GRB170817A/SSS17a – increasingly points to neutron star mergers as an important source of $r$-process elements, but more work is needed.

For the NSM electromagnetic signal to be fully understood, advances in astrophysical modeling, neutrino oscillation physics, and nuclear physics are required. On the nuclear side, the next generation of radioactive beam facilities offers great promise to reach the increasingly neutron-rich nuclei that are key for $r$-process abundance predictions.