Nuclear data and \textit{r}-process nucleosynthesis

Rebecca Surman
Union College

Workshop on Decay Spectroscopy at CARIBU: Advanced Fuel Cycle Applications, Nuclear Structure, and Astrophysics
Argonne National Laboratory
14 April 2011
rapid neutron capture nucleosynthesis

solar $r$-process abundances

as compiled by Anders and Grevesse (1988)
classic picture of the $r$ process

from Seeger et al (1965)
$r$-process nucleosynthesis: open questions

**Astrophysics**

What is the astrophysical site (or sites) of the $r$ process?

Some possibilities:

- **shocked surface layers of O-Ne-Mg cores** e.g., Wanajo et al (2003), Ning et al (2007)
- **gamma-ray bursts** e.g., Surman et al (2005)

**Nuclear Physics**

What are the nuclear properties of neutron-rich nuclei far from stability?

We need:

- masses
- beta decay rates
- neutron capture rates
- neutrino interaction rates
- fission probabilities and daughter product distributions
halo star observations of $r$-process nuclei

Main $r$ process

$\Rightarrow$ site within core-collapse supernovae?

Weak $r$ process, LEPP

a supernova neutrino-driven wind $r$ process?

Initial studies were very promising….  

*e.g., Meyer et al (1992), Woosley et al (1994)*

…but it was found to be more difficult to produce the requisite conditions than first thought


The most recent calculations of proto-neutron star evolution predict no robustly neutron-rich outflows

*Huedepohl et al (2010), Fischer et al (2010)*

\[
p + \bar{\nu}_e \leftrightarrow n + e^+  \\
\]

\[
T_{\bar{\nu}_e} > T_{\nu_e}  \\
\]

\[
n + \nu_e \leftrightarrow p + e^- \]
compact object mergers as an $r$-process site

Several environments within NS-NS or BH-NS mergers have been found to be attractive $r$-process sites


...but the timescale for mergers to develop is inconsistent with the data

Astrophysics

What is the astrophysical site (or sites) of the $r$ process?

Some possibilities:

- shocked surface layers of O-Ne-Mg cores e.g., Wanajo et al (2003), Ning et al (2007)
- gamma-ray bursts e.g., Surman et al (2005)

Nuclear Physics

What are the nuclear properties of neutron-rich nuclei far from stability?

We need:

- masses
- beta decay rates
- neutron capture rates
- neutrino interaction rates
- fission probabilities and daughter product distributions
Astrophysics

What is the astrophysical site (or sites) of the $r$ process?

Some possibilities:

- **shocked surface layers of O-Ne-Mg cores** e.g., Wanajo et al (2003), Ning et al (2007)
- **gamma-ray bursts** e.g., Surman et al (2005)

How does the $r$ process proceed?

- $(n,\gamma)$-$(\gamma,n)$ equilibrium, instantaneous freezeout (i.e., Kratz)
- no $(n,\gamma)$-$(\gamma,n)$ equilibrium, cold $r$ process (i.e., Wanajo)
Astrophysics

What is the astrophysical site (or sites) of the $r$ process?

Some possibilities:

- **shocked surface layers of O-Ne-Mg cores** e.g., Wanajo et al (2003), Ning et al (2007)
- **gamma-ray bursts** e.g., Surman et al (2005)

Nuclear Physics

What are the nuclear properties of neutron-rich nuclei far from stability?

We need:

- masses
- beta decay rates
- neutron capture rates
- neutrino interaction rates
- fission probabilities and daughter product distributions
classic picture of the $r$ process

$n, \gamma \rightleftharpoons (\gamma, n)$ equilibrium:

$$S_n(Z, A_{path}) \sim -kT \ln \left( \frac{n_n}{2} \left( \frac{2\pi \hbar^2}{m_n kT} \right)^{3/2} \right)$$

from Seeger et al (1965)
nuclear masses

FRDM
ETFSI
FRDM + experimental
steady beta flow: \[ \lambda_\beta(Z, A_{path}) Y(Z, A_{path}) \approx \text{constant} \]
beta decay rates

Moller et al (1997)
+ experimental
individual beta decay rates

Weak $r$-process trajectories with one or two beta decay rates modified
beta-delayed neutron emission

[Graphs showing log Yn vs t (s) and log Y(A) vs A with and without annotations]
beta-delayed neutron emission and a cold $r$ process
beta-delayed neutron emission

Cold $r$-process trajectory
neutron capture rates

⇒ can influence time until onset of freezeout
e.g., Goriely (1997, 8), Farouqi et al, Rauscher (2005)

⇒ can shape local details of the abundance distribution
e.g., Surman et al (1998), Surman & Engel (2001)

Surman & Engel (2001)
neutron capture rates

⇒ can influence time until onset of freezeout
e.g., Goriely (1997,8), Farouqi et al, Rauscher (2005)

⇒ can shape local details of the abundance distribution
e.g., Surman et al (1998), Surman & Engel (2001)

⇒ can influence the overall abundance pattern
e.g., Beun et al (2009), Surman et al (2009)

neutron capture rate/mass model variations

Surman, Beun, McLaughlin, and Hix, PRC, 79, 045809 (2009)

Neutron capture rate variation

Mass model variation
nonequilibrium effects of neutron capture rates

\[ \sigma_{131}^{Cd} \times 10 \]

\[ \sigma_{131}^{Sn} \times 100 \]

130 peak rare earth region + 195 peak

\[ \langle ov \rangle_{131}^{Cd} \times 10 \]

\[ \langle ov \rangle_{131}^{Sn} \times 100 \]

[Chemical Elements Chart]

Surman, Beun, McLaughlin, and Hix, PRC, 79, 045809 (2009)
Capture rates that affect a 5-20% change in the weak $r$-process abundance pattern for increases to the rate by a factor of 100.

*Surman et al, in preparation*

---

Capture rates that affect a 5-40% change in the global $r$-process abundance pattern for increases to the rate by a factor of:

- 10
- 50
- 100-1000

---

*Surman, Beun, McLaughlin, and Hix, PRC, 79, 045809 (2009)*
influential neutron capture rates: rare earth region

Mumpower et al, in preparation
fission probabilities and daughter products
fission probabilities and daughter products

How is a consistent pattern achieved?

\[
Y_e = \frac{1}{1 + n/p}
\]

\[
Y_e = 0.25 \\
Y_e = 0.26 \\
Y_e = 0.27
\]
fission cycling and a consistent $r$-process pattern

Beun, McLaughlin, Surman, & Hix, PRC 77, 035804 (2008)
We still don’t know where the $r$ process takes place

⇒ but once astrophysical uncertainties are reduced, understanding the nuclear physics of neutron-rich nuclei will be crucial to make detailed comparisons between simulations and observations

We need:

- nuclear masses
- beta decay rates
- beta-delayed neutron emission probabilities
- neutron capture rates
- fission probabilities and daughter product distributions

As discussed by F. Montes

Particularly of nuclei on the beta-decay chains of the closed shell nuclei, and of nuclei in the rare earth region