The Role of Fission on Neutron Star Merger Nucleosynthesis and its Impact on the r-Process Peaks

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r-Process Abundance Pattern(s)

Sneden et al. (2008)

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HD 115444: Westin et al. (2000)
BD+17°324817: Cowan et al. (2002)
CS 31082-001: Hill et al. (2002)
HD 221170: Ivans et al. (2006)
HE 1523-0901: Frebel et al. (2007)

Individual stellar abundance offsets with respect to Simmerer et al. (2004)

Average abundance offsets with respect to Arlandini et al. (1999) "stellar model"
Fission Cycling

masses measured at the ESR

stable nuclei

nuclides with known masses

will be measured with CR at FAIR

graphic courtesy of Y. Litvinov
Fission Cycling

Number of fission cycles $N$:

$$N \approx \log_2 \left( \frac{\langle A \rangle_f + Y_n / Y_{seed}}{\langle A \rangle_f} \right)$$
Neutron Star Mergers

Rosswog, Piran, and Nakar (2013)
Heating Rates for Kilonovae

Barnes et al. 2016

![Heating Rates for Kilonovae diagram](image)

Hotokezaka et al. 2016

![Heating Rates for Kilonovae diagram](image)
Fission Fragment Distribution Models

Fission Fragments of $^{274}$Pu

Panov et al. 2001
Kodama & Takahashi 1975
Panov et al. 2008
ABLA07 (Kelic et al. 2008)

Neutron multiplicity: 0*
Neutron multiplicity: 19
Neutron multiplicity: 7
r-Process in Neutron Star Mergers

- trajectories from a neutron star merger with two 1.4 $M_\odot$ neutron stars (Korobkin et al. 2012)
- FRDM
- difference between fission fragment distribution models mainly around and after 2$^{nd}$ peak
- 3$^{rd}$ peak shifted to the right for all models

solar r-abundances: Sneden et al. 2008
The Position of the Third Peak at Freeze-Out

FRDM (1992) (Möller et al., 1995)

HFB-14 (Goriely et al., 2008)

Eichler et al. (2015)

→ see also Surman & Engel (2001)
What Happens After Freeze-Out?

- Aim: Identify the reactions responsible for certain features of the final abundance distribution
- Procedure: Switch off certain types of reactions after freeze-out
  - FRDM: $140 < A < 160$ region depleted by neutron captures
What Happens After Freeze-Out?

- HFB: 2\textsuperscript{nd} and 3\textsuperscript{rd} peak shifted, but not nuclei with $140 < A < 160$
Two possible sources for free neutrons at freeze-out: fission and β-decays

β-decays enhanced after last fission cycle because very neutron rich fission fragments are produced
The Position of the 3\textsuperscript{rd} Peak

- $\beta$-decays of $Z > 80$ nuclei accelerated by factors of 2.5 and 6
- FRDM (1992)

- Fission neutrons from the last fission cycle enforce neutron captures
- Affects mainly third peak and rare earths
The Position of the 3\textsuperscript{rd} Peak

- $\beta$-decays of $Z > 80$ nuclei accelerated by factors of 2.5 and 6
- HFB-14
New Sets of Beta-Decay Rates: Marketin et al. 2015

\[ \lambda_{Marketin} > 2 \lambda_{Moeller} \]
\[ 0.5 \lambda_{Moeller} < \lambda_{Marketin} < 2 \lambda_{Moeller} \]
\[ \lambda_{Marketin} < 0.5 \lambda_{Moeller} \]
New Sets of Beta-Decay Rates: Panov et al. 2015

- $\lambda_{Panov} > 2\lambda_{Moeller}$
- $0.5\lambda_{Moeller} < \lambda_{Panov} < 2\lambda_{Moeller}$
- $\lambda_{Panov} < 0.5\lambda_{Moeller}$

Proton number, Z

Neutron number, N

Pb (Z=82)
New Sets of Beta-Decay Rates

FRDM

HFB-14

original: Möller et al. 2003
Summary

- after freeze-out, the abundance features can still be changed by several processes (e.g., neutron captures, fission)
- in our NSM calculations, the third peak is shifted towards heavier nuclei due to neutron captures after the r-process freeze-out
  - fission neutrons from last fission cycle
- β-decays have a large influence on the global abundance distribution (also indirectly, i.e., by influencing the timing of the release of fission neutrons)

Fission reactions are fundamental in shaping the r-process abundance pattern from the second peak onwards
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