Weak r-process in the blue-kilonova of double NS mergers

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  - “weak r-process” as origin of blue-kilonovae
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  - weak r-process in post-merger evolution
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  - remaining physical uncertainty
  - beta-decay of N = 82 neutron magic nuclei

References
- Fujibayashi+NN+2018 ApJ 860 64
- NN+2018 (in prep.)
Weak r-process in metal-poor stars?

- many r-rich Galactic halo stars show the solar-like r-pattern
- r-process has happened from the early Galaxy
- astrophysical models reproduce this common pattern (Z>40; A>90)

Nishimura+2017 (poster #73)
The “kilonova/macronova” with GW

The electromagnetic counter part of GW170817 (17. Aug. 2017)

Energy source?

→ radioactive decay (e.g., $\beta$, $\alpha$ & fission etc.) of neutron-rich matter during r-process nucleosynthesis

NGC4993 (39.5Mpc)
Kilonova observation

GW170817 (SSS17a) the bolometric light curve

Light curves, based on 625 flux measurements (38 instruments)

Hydrodynamical calculations are needed to explain this feature.
- Realistic set-up
- Log-term evolution ($t = 0.1 \rightarrow 1$ s)
Kilonova prediction

Tanaka+2018

(also, Kasen+2013, Tanaka & Hotokezaka 2013)
Kilonova model (scenario)

Optical observation in several wave-lengths reveals detailed structure of the NS-NS merger remnant

Later ejecta: mild n-rich 
(0.2 < Ye < 0.4)

Early ejecta: very n-rich
(Ye < 0.2)

Shibata+2017
NS-NS merger: post-merger evolution

GR-radiation hydrodynamics (Fujibayashi+NN+2018)

the early phase of NS-NS merger (Sekiguchi+2015)

→ post-merger (in axi-symmetry) from 50 ms after the merger

Ye: electron faction (green: heavy nuclei; blue: lighter nuclei)
R-process flows

lanthanides

$Z = 57-71$

Very n-rich ($Y_e = 0.1$)

In dynamical ejecta

$\rightarrow$ lanthanide-rich
R-process flows

lanthanides

$Z = 57–71$

Less n-rich ($Ye = 0.35$)

viscous winds

Fujibayashi+2017

$\rightarrow$ lanthanide-free
NS-NS merger (post-merger)

post-merger ejecta (Fujibayashi+2017)

\[
\frac{\alpha}{t = 2.8 \text{ s}} = 0.04
\]

<table>
<thead>
<tr>
<th>Region</th>
<th>(X(Z = 57 - 71))</th>
<th>(M_{\text{ej}}/M_{\odot})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(2.1 \times 10^{-10})</td>
<td>0.0031</td>
</tr>
<tr>
<td>2</td>
<td>(2.0 \times 10^{-12})</td>
<td>0.0088</td>
</tr>
<tr>
<td>3</td>
<td>(1.2 \times 10^{-11})</td>
<td>0.0095</td>
</tr>
<tr>
<td>4</td>
<td>(7.1 \times 10^{-8})</td>
<td>0.0089</td>
</tr>
<tr>
<td>5</td>
<td>(1.0 \times 10^{-3})</td>
<td>0.0162</td>
</tr>
<tr>
<td>Total</td>
<td>(3.6 \times 10^{-4})</td>
<td>0.046</td>
</tr>
</tbody>
</table>
A set of r-process calculations

\( \tau_{\text{dyn}} \): time duration of ejecta

\( T = 9 \rightarrow 2.5 \text{ GK} \)

(seed formation)
A set of r-process calculations

\[ t_{\text{dyn}} = 0.1; \ s = 21 \ k_B \]
A set of r-process calculations

see, also Lippuner & Roberts (2015)

mass fraction of Lanthanide elements: \(X^{”La”}\)
A set of r-process calculations

r-process production condition (Hoffman+1997) for $A = 140-160$

\[
S \approx \left\{ \frac{4 \times 10^7 \bar{Z}(1 - 2Y_{e,i})}{\left[ (1/2 - \bar{Z}/A)/(Y_{e,i} - \bar{Z}/A) \right]^2 - (1/2Y_{e,i})^2 \left( \frac{\tau_{\text{dyn}}}{s} \right)} \right\}^{1/3}
\]

for $Y_{e,i} < \frac{\bar{Z}}{A}$,
A set of r-process calculations

\[ \tau_{\text{dyn}} = 0.1; \ S = 21 \ k_{\text{B}}/\text{nuc.} \]

Lanthanoids

Abundance, log_{10} Y

Mass number, A

\[ 80 \ 100 \ 120 \ 140 \ 160 \ 180 \ 200 \]

Solar-r

\[ Y_e = 0.32 \]
\[ Y_e = 0.30 \]
\[ Y_e = 0.28 \]
\[ Y_e = 0.26 \]
\[ Y_e = 0.25 \]

Solar-r

\[ Y_e = 0.25 \]
\[ Y_e = 0.24 \]
\[ Y_e = 0.23 \]
\[ Y_e = 0.20 \]
Impacts of beta-decay uncertainty

uncertainty factor: 2 and 5 on N=82 isotone

\[ \tau_{\text{dyn}} = 0.1; \ S = 21 \ \text{kB/nuc.}; \ Y_e = 0.23 \]

\[ \tau_{\text{half}} = \frac{0.1}{2} \]
\[ \tau_{\text{half}} = \frac{0.1}{5} \]
\[ \tau_{\text{half}} = \frac{0.1}{2} \times 5 \]
\[ \tau_{\text{half}} = \frac{0.1}{2} \times 10 \]

Lanthanoids

\[ Y_e = 0.23: \ X(\text{Lanthanoids}) = 6.35 \times 10^{-3} \ (\sim 10\% \ \text{uncertainty}) \]
\[ Y_e = 0.24: \ X(\text{Lanthanoids}) = 1.19 \times 10^{-5} \quad \text{lower} \quad \frac{4.81 \times 10^{-5}}{\text{standard}} \quad \frac{6.41 \times 10^{-4}}{\text{upper}} \]
Comprehensive uncertainty analysis

PizBuin MC driver (Rauscher); for details, see posters

#11 (s-process; Cescutti);  #72 (νp-process; Nishimura)
#82 (gamma-process; Rauscher)

- (n,g) factor 5
- β-decay factor 5
- no variation for mass; e.g., Q_ν

→ can be very optimistic

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Ye = 0.20

![Graph showing abundance vs. mass number, A]

Ye = 0.24

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Only (n,g)
Summary

- Weak r-process in blue-kilonova
  - GR hydrodynamics simulations indicate “lantanide-poor” component in post-merger ejecta
    —> the “blue”-kilonova component of GW170817
- Production mechanism/uncertainty
  - lanthanide poor if $Y_e > 0.25$
  - strong dependency on $Y_e$ (←post-merger models)
- Nuclear-physics uncertainty (e.g. $\beta$-decay)
  - has impacts on the weak r-process
  - possibly much more uncertainty for the n-rich r-process “path” region
  —> needs much studies to consider the both of hydro-uncertainties and nuclear-physics uncertainties