r-Process nucleosynthesis in neutron star mergers and GW170817

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FRIB and the GW170817 Kilonova
FRIB/NSCL/MSU, East Lansing MI
1. r-Process nucleosynthesis overview
2. r-Process in neutron star mergers
3. Observational signature and first detection
Solar system abundances

Data sources:
Solar system abundances

- Hydrogen
- Helium
- Oxygen
- Silicon
- Iron
- Lithium
- Big Bang
- Supernovae
- Stars

Total abundances in the solar system

Data sources:
The s-process

slow neutron capture

$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr

closed neutron shell
The s-process

slow neutron capture

$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr

closed neutron shell
The r-process

rapid neutron capture

$\tau_n \ll \tau_{\beta^-} \sim 10 \text{ ms} - 10 \text{ s}$
The r-process

rapid neutron capture

\[ \tau_n \ll \tau_{\beta^-} \sim 10 \text{ ms} - 10 \text{ s} \]
### Double peaks due to closed neutron shells

**s-process:** \( \tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5 \text{ yr} \)

**r-process:** \( \tau_n \ll \tau_{\beta^-} \sim 10 \text{ ms} - 10 \text{ s} \)

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<table>
<thead>
<tr>
<th>Element</th>
<th>Mass Number</th>
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<tbody>
<tr>
<td>Cu</td>
<td>65</td>
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<tr>
<td>Zn</td>
<td>66, 67, 68</td>
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<td>Ge</td>
<td>70, 72, 73, 74, 76</td>
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<td>As</td>
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<td>Se</td>
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<tr>
<td>Br</td>
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<td>Kr</td>
<td>78, 80, 82, 83, 84, 86</td>
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<tr>
<td>Sr</td>
<td>84, 86, 87, 88</td>
</tr>
<tr>
<td>Y</td>
<td>89</td>
</tr>
<tr>
<td>Zr</td>
<td>90, 91, 92</td>
</tr>
</tbody>
</table>

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**Neutron drip line**

**Closed neutron shell**
Double peaks due to closed neutron shells

s-process: $\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr

r-process: $\tau_n \ll \tau_{\beta^-} \sim 10$ ms – 10 s

| 65Cu | 66Zn | 67Zn | 68Zn | 69Ga | 70Zn | 71Ga | 72Ge | 73Ge | 74Ge | 75As | 76Ge | 77Se | 78Se | 79Br | 80Se | 81Br | 82Se | 83Kr | 84Kr | 86Kr | 87Kr | 88Sr | 85Rb | 86Sr | 87Rb | 89Y | 90Zr | 91Zr | 92Zr |
Double peaks due to closed neutron shells

s-process: \( \tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5 \text{ yr} \)

r-process: \( \tau_n \ll \tau_{\beta^-} \sim 10 \text{ ms} - 10 \text{ s} \)
Double peaks due to closed neutron shells

s-process: $\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr

r-process: $\tau_n \ll \tau_{\beta^-} \sim 10$ ms – 10 s

Los Alamos National Laboratory

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Solar system abundances

Data sources:

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SkyNet

- General-purpose nuclear reaction network
- ~8000 isotopes, ~140,000 nuclear reactions
- Evolves temperature based on nuclear reactions
- Input: $\rho(t)$, initial composition, entropy
- Open source

SkyNet features

Science

• Extended Timmes equation of state (EOS)
• Calculate nuclear statistical equilibrium (NSE)
• NSE evolution mode
• Calculate inverse rates from *detailed balance* to be consistent with NSE
• Electron screening with smooth transition between weak and strong screening (reactions and NSE)

Code

• Adaptive time stepping
• Python bindings
• Modularity
• Extendible reaction class (currently REACLIB, table, neutrino)
• Make movies
1. r-Process nucleosynthesis overview
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Merger ejecta: Dynamical

Tidal tails or collision interface

NS–NS: $M_{ej} \sim 10^{-4} - \text{few} \times 10^{-2} \, M_{\odot}$, $Y_e \sim 0.05 - 0.45$

NS–BH: $M_{ej} \sim 0 - 10^{-1} \, M_{\odot}$, $Y_e \lesssim 0.2$

Bauswein+13, Hotokezaka+13, Foucart+14, Sekiguchi+15, Kyutoku+15, Radice+16

From Price+06

From Bauswein+13
Merger ejecta: Disk outflow

Neutrino driven wind or outflow due to viscous heating and \( \alpha \) recombination

\[
M_{\text{ej}} \sim \text{few} \times 10^{-3} \, M_\odot, \quad Y_e \sim 0.2 - 0.45
\]

Surman+08, Wanajo+11, Fernández+13, Perego+14, Just+15, Foucart+15

From Perego+14

From Fernández+13
http://jonaslippuner.com/skynet/SkyNet_Ye_0.010_s_010.000_tau_007.100.mp4
http://jonaslippuner.com/skynet/SkyNet_Ye_0.250_s_010.000_tau_007.100.mp4

Temperature = 3.65E+08 K
Density = 3.13E+01 g / cm³
Heating rate = 8.74E+18 erg / s / g
Entropy = 1.94E+02 kB / baryon
Ye = 0.316

Made with SkyNet by Jonas Lippuner
r-Process abundances vs. electron fraction

Observed solar r-process

$Y_e = 0.01$
$Y_e = 0.19$
$Y_e = 0.25$
$Y_e = 0.50$

Full binary neutron star merger simulations

From Wanajo+14

See also Goriely+15
Nucleosynthesis in HMNS disk outflow

- $3 M_\odot$ central HMNS or BH, $0.03 M_\odot$ accretion disk
- Variable HMNS lifetime, neutrino leakage, $\alpha$ viscosity

Figure from Metzger & Fernández (2014)
Final abundances

- Observed solar r-process

Black hole–neutron star merger


1. **Full GR simulation of BH–NS**
   Francois Foucart (UNH), Foucart *et al*.,

2. **Evolve ejecta in SPH code**
   Matt Duez (WSU)

3. **Nucleosynthesis with varying neutrino luminosity**
   JL and Luke Roberts (MSU)

Figure credit: F. Foucart
BHNS: Final abundances vs. neutrino luminosity

Relative final abundance vs. mass number $A$ for different neutrino luminosities $L_{\nu_e,52}$:

- $L_{\nu_e,52} = 0.2$ (red line)
- $L_{\nu_e,52} = 1$ (purple line)
- $L_{\nu_e,52} = 25$ (blue line)

Plot includes data points indicating the solar r-process.

Mass number $A$ ranges from 0 to 250.
Neutrino driven wind in core-collapse supernovae

- Neutrinos emitted from hot proto-neutron star can drive outflow of n and p
- Neutrino driven wind is mildly neutron-rich → r-process?
Jet in MHD-driven supernova

- Requires very high magnetic field \((B \sim 10^{12} - 10^{13} \, \text{G})\) and rapid rotation
- Maybe 0.1 – 1% of all core-collapse supernovae
Jet in MHD-driven supernova

From Moesta+17

Abundance

10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0}

mass number A

solar
B13
B12-sym
B12
Outline

1. r-Process nucleosynthesis overview
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Observational signature of r-process: Kilonova

Jet–ISM Shock (Afterglow)
Optical (hours–days)
Radio (weeks–years)

Ejecta–ISM Shock
Radio (years)

GRB
(t ~ 0.1–1 s)

Kilonova
Optical (t ~ 1 day)

Merger Ejecta
Tidal Tail & Disk Wind
v ~ 0.1–0.3 c

θ_j

θ_\text{obs}

Impact of lanthanides

The diagram shows the abundance of observed solar r-process lanthanides and actinides as a function of the mass number A. The abundance is plotted on a logarithmic scale, with different colors representing different electron fractions $Y_e$: red for $Y_e = 0.01$, purple for $Y_e = 0.19$, and blue for $Y_e = 0.25$. The observed solar r-process is indicated by black dots. The plot also highlights lanthanides in red and actinides in blue.

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Impact of lanthanides

\[ s = 10 \, k_B \text{ baryon}^{-1} \]

\[ \tau = 7.1 \, \text{ms} \]

\[ M = 0.01 \, M_\odot \]

\[ Y_e = 0.01 \]

\[ Y_e = 0.19 \]

\[ Y_e = 0.25 \]

\[ Y_e = 0.50 \]

Luminosity, heating rate [erg s\(^{-1}\)]

Time [day]
First neutron star merger observation: GW170817

GW170817: Hunt for electromagnetic counterpart

- LIGO/VIRGO localization: 31 deg$^2$
  $\sim$ 150 full moons
- Distance estimate: 40 ± 8 Mpc
- 49 galaxies in that volume
- Check all galaxies starting with most massive first

Kasliwal et al., 2017, Science 358, 1559
GW170817: Counterpart discovered in NGC 4993

- Discovered 10.9 hours after merger
- Host galaxy: NGC 4993, elliptical galaxy, constellation Hydra, 40 Mpc\(\sim 130\) Mly

Credit: 1M2H Team / UC Santa Cruz & Carnegie Observatories / Ryan Foley
GW170817: Rapid color evolution

Credit: ESO / N.R. Tanvir, A.J. Levan and the VIN-ROUGE collaboration
GW170817: Huge observing campaign

GW170817: Combined light curve

GW170817: One-component kilonova models fail

GW170817: Two-component models do better

\[ \theta_v \approx 28^\circ \]

Troja et al., 2017, Nature 551, 71

GW170817: Three-component model needed?

GW170817: Featureless optical spectrum

Nicholl et al., 2017, ApJL 848, L18
GW170817: Infrared spectrum

GW170817: What we learned

• Confirmed neutron star mergers make short GRBs (but this was a weird GRB)
• Total ejecta mass larger than expected: $\sim 5 \times 10^{-2} M_\odot$
• Neutron star mergers can easily make all r-process material in the galaxy
• Blue (lanthanide-free) component larger than expected, maybe large disk wind or blue dynamical component
• Lanthanide-rich component is evidence for full r-process, tens of Earth masses of gold and platinum
• “Purple” kilonova component with $X_{La} \sim 10^{-3} - 10^{-2}$, $\kappa \sim 3 \text{ cm}^2 \text{ g}^{-1}$?
• Gravity propagates at the speed of light, rules out many alternative theories of gravity besides Einstein’s General Relativity
Summary

- s- and r-process create heavy elements beyond the iron peak
- r-process happens in dynamical and disk ejecta in a neutron star merger
- Dynamical ejecta (NS-NS and BH-NS) is generally neutron-rich enough for full r-process
- Neutron star mergers are probably the dominant site of the r-process, core-collapse supernovae may contribute weakly
- GW170817: First LIGO detection of neutron star merger accompanied by GRB and kilonova
  - Kilonova followed pretty well what we expected
  - Yet more work is needed to understand light curve in detail, purple component?
Solar system abundances

Data sources:
Letters to the Editor

Publication of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. Alpher*
Applied Physics Laboratory, The Johns Hopkins University,
Silver Spring, Maryland

And

H. Bethe
Cornell University, Ithaca, New York

And

G. Gamow
The George Washington University, Washington, D. C.
February 18, 1948

As pointed out by one of us,1 various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,2 the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances3 it is necessary to assume the integral of \( \rho_m dt \) during the building-up period is equal to \( 5 \times 10^4 \) g sec./cm³.

On the other hand, according to the relativistic theory of the expanding universe4 the density dependence on time is given by \( \rho = 10^6 \rho_0 \). Since the integral of this expression diverges at \( t = 0 \), it is necessary to assume that the building-up process began at a certain time \( t_0 \), satisfying the relation:

\[
\int_{t_0}^{\infty} (10^6 / \rho) dt = 5 \times 10^4, \tag{2}
\]

which gives us \( t_0 \approx 20 \) sec. and \( \rho_0 \approx 2.5 \times 10^6 \) g sec./cm³. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value \( 2.5 \times 10^4 \) g sec./cm³ which can possibly be understood if we
Synthesis of the Elements in Stars*

E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

“It is the stars, The stars above us, govern our conditions”;  
(King Lear, Act IV, Scene 3)

but perhaps

“The fault, dear Brutus, is not in our stars, But in ourselves,”  
(Julius Caesar, Act I, Scene 2)

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<td>B. Four Theories of the Origin of the Elements</td>
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</table>
Define abundance

\[ Y_i = \frac{n_i}{n_B}. \]  \hspace{1cm} (1)

Consider reaction

\[ p + ^7\text{Li} \rightarrow 2^4\text{He} \]  \hspace{1cm} (2)

with rate \( \lambda = \lambda(T, \rho) \). Then

\[ \dot{Y}_{^4\text{He}} = 2\lambda Y_p Y_{^7\text{Li}} + \cdots, \]
\[ \dot{Y}_p = -\lambda Y_p Y_{^7\text{Li}} + \cdots, \]
\[ \dot{Y}_{^7\text{Li}} = -\lambda Y_p Y_{^7\text{Li}} + \cdots \]  \hspace{1cm} (3)

Need to solve big, stiff, non-linear system of ODEs
NS–NS ejecta sources: Tidal tails

$$Y_e \sim 0.05 - 0.45$$

Credit: D. J. Price et al. (2006)
NS–NS ejecta sources: Collision interface

\[ Y_e \sim 0.05 \text{ -- } 0.45 \]

Credit: D. Berry, SkyWorks Digital, Inc.
NS–NS ejecta sources: Disk outflow

\[ Y_e \sim 0.2 - 0.45 \]

Credit: A. Bauswein et al. (2013)
**Parametrized r-process**


**Parameters**

\[ 0.01 \leq Y_e \leq 0.50 \quad \text{initial electron fraction} \]
\[ 1 \, k_B \text{ baryon}^{-1} \leq s \leq 100 \, k_B \text{ baryon}^{-1} \quad \text{initial specific entropy} \]
\[ 0.1 \, \text{ms} \leq \tau \leq 500 \, \text{ms} \quad \text{expansion time scale} \]

**Density profile**

\[
\rho(t, \tau) = \begin{cases} 
\rho_0 e^{-t/\tau} & t \leq 3\tau \\
\rho_0 \left( \frac{3\tau}{te} \right)^3 & t \geq 3\tau 
\end{cases}
\]

**Initial conditions**

- Choose initial temperature \( T_0 = 6 \, \text{GK} \)
- Find \( \rho_0 \) by solving for NSE at \( T_0 \) and \( Y_e \) that produces specified \( s \)
Final abundances vs. entropy

Electron fraction distribution

Electron fraction $Y_e$

$\tau = 0 \text{ ms}$
$\tau = 10 \text{ ms}$
$\tau = 30 \text{ ms}$
$\tau = 100 \text{ ms}$
$\tau = 300 \text{ ms}$
$\tau = \infty$

Mass [$10^{-3} M_\odot$]

Electron fraction $Y_e$
Ejected mass

\[ \text{Ejected mass} = [10^{-3} M_\odot] \]

HMNS lifetime [ms]

\[ Y_e \leq 0.25 \]

\[ Y_e > 0.25 \]
BHNS: Electron fraction distribution

\[ L_{\nu_e,52} = 0.2 \]
\[ L_{\nu_e,52} = 1 \]
\[ L_{\nu_e,52} = 25 \]
Light curves vs. electron fraction

Lanthanide and actinide mass fraction $X_{\text{La+Ac}}$

Peak time $t_p$ [day]

Peak effective temperature $T_{\text{eff}}$ [K]

Peak Luminosity [erg s$^{-1}$]

$s = 10 k_B \text{ baryon}^{-1}$

$\tau = 1 \text{ ms}$

6000 K

1600 K

6 days

1 day
Recent evidence for rare r-process

- Reticulum II: 1 in 10 highly r-process enhanced ultra-faint dwarf galaxy
- Recently discovered second UFD with r-process star: Tucana III


Ji et al., 2016, Nature 531, 610
Recent evidence for rare r-process

- $^{244}\text{Pu}$ is actinide (r-process only) with $\tau_{1/2} \sim 80$ Myr ($< \tau_{\text{mix}} \sim 300$ Myr)
- Interstellar material is swept up and deposited in deep-sea crust
- Measure abundance of $^{244}\text{Pu}$ in 25 Myr old deep-sea crust $\rightarrow ^{244}\text{Pu}$ abundance in ISM

From Wallner+15

From Hotokezaka+15