Role of neutrinos for the nucleosynthesis of heavy elements beyond iron in explosions of massive stars

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Cosmic fingerprints from heavy-element formation

- Robust enrichment of heavy $r$-process elements ($Z > 52$) and poor in iron ($r$-II stars, $[\text{Eu/Fe}] > 1.0$)
- Consistent with solar $r$-process abundance
- Main astrophysical site at low metallicity still unclear
  - ★ magnetically-driven massive star explosions  
    (models are still highly speculative)
  - ✴ neutron-star mergers  
    (still under debate as main site)

<table>
<thead>
<tr>
<th>Neutron-capture-rich stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$ - I 0.3 $\leq [\text{Eu/Fe}] \leq +1.0$</td>
</tr>
<tr>
<td>$r$ - II $[\text{Eu/Fe}] &gt; +1.0$</td>
</tr>
<tr>
<td>$r/s$ $[\text{Eu/Fe}] &gt; +1.0$</td>
</tr>
<tr>
<td>$s$ $[\text{Ba/Fe}] &gt; +1.0$</td>
</tr>
</tbody>
</table>

(Cowan & Sneden 2006)

single heavy elements as $r$-process “tracers” (e.g. Ba or Eu)
Cosmic fingerprints from heavy-element formation

There’s another type of metal-poor star observations. . .

- Poor in heavy neutron-capture elements (Z>47) but large abundances of light neutron-capture elements (38<Z<47, Sr, Y, Zr, . . .)
- Production of light and heavy neutron-capture elements seem intrinsically decoupled: 2 different sites (?)
- Astrophysical scenario: neutrino-driven winds from massive-star explosions/(proto)neutron stars (PNS)

see other talks by, e.g.,

S. Goriely, C. Fröhlich, A. Lohs, M. Ugliano, . . .
Cosmic fingerprints from heavy-element formation

There’s another type of metal-poor star observations. . .

- Poor in heavy neutron-capture elements (Z>47) but large abundances of light neutron-capture elements (38<Z<47, Sr, Y, Zr, . . .)
- Production of light and heavy neutron-capture elements seem intrinsically decoupled: 2 different sites (?)
- Astrophysical scenario: neutrino-driven winds from massive-star explosions/ (proto)neutron stars (PNS)
  - Which processes determine the nucleosynthesis relevant conditions ($Y_e$, entropy, . . .) in the $\nu$-driven wind (?)

(Focus of research for the past 3 decades !)
Outline

• Introduction: concept of protoneutron star (PNS) deleptonization

• “Historic excursion”

• Current understanding and challenges

• Summary
The deleptonization phase of ProtoNeutron Star (PNS) – concept

PNS are born in a core-collapse supernova event. . .
• **Supernova problem**: energy liberation from the protoneutron star (PNS) to the standing bounce shock

• Mass accretion provides continuously ‘fresh’ material which settles at PNS surface; thick low-density layer – subject of neutrino heating and cooling

• Timescale for explosion onset ~0.1–0.5 seconds *(for details, see talk by R. Hix)*
After the onset of the supernova explosion...

- **Supernova problem**: energy liberation from the protoneutron star (PNS) to the standing bounce shock
- Mass accretion provides continuously ‘fresh’ material which settles at PNS surface; thick low-density layer – subject of neutrino heating and cooling
- Timescale for explosion onset \( \sim 0.1 \text{–} 0.5 \text{ seconds} \) (for details, see talk by R. Hix)

- **Supernova explosion onset**: shock propagates to increasingly larger radii; central PNS settles into quasi-stationary state
- Mass accretion vanishes: region of net heating establishes
- Independent from details of the explosion mechanism
Development of neutrino-driven ejecta

\[ T = 5 - 30 \text{ MeV} \quad (E_{\nu} \sim 10^{53} \text{ erg}) \]

\[ \rho \left[ \text{g} \cdot \text{cm}^{-3} \right] \]

\[ \nu_e + n \longrightarrow p + e^- \]
\[ \bar{\nu}_e + p \longrightarrow n + e^+ \]

\[ Y_e \approx 0.05 - 0.2 \]

\( Y_e \) set!

Low-mass outflow: “\( \nu\) - driven wind”

Neutrino heating

(PNS)
Schematic picture of “late”– time mass ejection

**Nucleosynthesis:**
- **proton rich** ($Y_e > 0.5$) 
  - *vp process*
- **neutron rich** ($Y_e < 0.5$) 
  - *neutron-capture process*

**Deleptonization timescale:** 
$t = 10 - 30$ s

**Schematic picture of “late”– time mass ejection**

- **$\rho$ [g · cm$^{-3}$]**
  - $10^{14}$
  - $10^{10}$
  - $10^{6}$
  - $< 10$

- **$T$ ≈ 0.25 MeV**
  - $(> 10^4$ km$)$
- **$T$ ≈ 0.5 MeV**
  - $(\sim 100$ km$)$
- **$T$ ≈ 1 MeV**
  - $(\alpha$-rich freeze out$)$

- **$\nu_e + n \rightarrow p + e^-$**
- **$\bar{\nu}_e + p \rightarrow n + e^+$**

**$\rho$ [g · cm$^{-3}$]**

- **formation of heavy nuclei (?)**

**seed nuclei**

- **low-mass outflow:**
  - “$\nu$-driven wind”
  - $Y_e$ set !

**neutrino heating**

- **$\nu$-driven wind**

- **$T = 5 - 30$ MeV (\(E_\nu \sim 10^{53}$ erg$)$**

- **Nucleosynthesis:**
  - determined at neutrino decoupling from matter

- **proton rich** ($Y_e > 0.5$) 
  - *vp process*
- **neutron rich** ($Y_e < 0.5$) 
  - *neutron-capture process*
“Historic excursion”
—
Selection of results
Neutrinos from SN1987A

Insights from SN1987A (large Magellanic Cloud):

- Progenitor star $18 \, M_\odot$
- Confirmation of the basic model
- Stellar collapse to a (proto) neutron star $\sim 3 \times 10^{53}$ erg
- 99% emitted in neutrinos over $\sim 10$ seconds
- Explosion energy (kinetic energy of ejecta at stellar surface) $\sim 10^{51}$ erg

SN rates:

- $1\,\text{SN s}^{-1} \, \text{universe}^{-1}$
- $1\,\text{SN year}^{-1} \, 10^6 \, \text{pc}^{-1}$
- $1\,\text{SN 100 years}^{-1} \, \text{Milky Way}^{-1}$
Continuous model improvements over the years...

- **Fully general relativistic three-flavor neutrino radiation hydrodynamics; Boltzmann transport**
- Improved set of weak reactions:
  \[ \begin{align*}
  e^- + p & \rightleftharpoons n + \nu_e \\
  e^+ + n & \rightleftharpoons p + \nu_e \\
  \nu & + N \rightleftharpoons \nu + N \\
  \nu & + e^\pm \rightleftharpoons \nu + e^\pm \\
  e^- + e^+ & \rightleftharpoons \nu + \bar{\nu} \\
  N + N & \rightleftharpoons \nu + \bar{\nu} + N + N \\
  \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau} & \rightleftharpoons \nu_e + \bar{\nu}_e
  \end{align*} \]
  \[ \text{charged-current (elastic approximation)} \]
  \[ \text{elastic scattering} \]
  \[ \text{inelastic scattering} \]
  \[ \text{thermal pair production} \]
  \[ \text{Bremsstrahlung} \]
  \[ \text{flavor mixing} \]
- Consistent simulations through all supernova phases; low-mass star with O-Ne-Mg-core
- Enhanced neutrino heating to trigger explosion onset; more massive stars with Fe-core
- Qualitative agreement between different research groups (!)

Hüdepohl, et al., (2010), PRL 104, 251101
Relevance for the nucleosynthesis of heavy elements


- Analytic treatment of the neutrino-driven wind based on only integrated neutrino properties; luminosities and average energies

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

\[ \frac{\partial Y_e}{\partial t} = - \left( \lambda_{e-p} + \lambda_{\bar{\nu}_e p} \right) Y_p + \left( \lambda_{e+n} + \lambda_{\nu_e n} \right) Y_n \]

(freeze-out electron fraction; based on asymptotic neutrino values only)

\[ Y_e \simeq \frac{\lambda_{\nu_e n}}{\lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p}} \simeq \left( 1 + \frac{L_{\bar{\nu}_e} \varepsilon_{\bar{\nu}_e} - 2Q + 1.2Q^2/\varepsilon_{\bar{\nu}_e}}{L_{\nu_e} \varepsilon_{\nu_e} + 2Q + 1.2Q^2/\varepsilon_{\nu_e}} \right)^{-1} \]

\( \varepsilon_{\nu} = \langle E_{\nu}^2 \rangle / \langle E_{\nu} \rangle , \quad \lambda_{ij} \ldots \text{reaction rates} , \quad Q = m_n - m_p = 1.2935 \text{ MeV} \)

- In simulations is typically realized: \( L_{\nu_e} \simeq L_{\bar{\nu}_e} \)

\[ \varepsilon_{\bar{\nu}_e} - \varepsilon_{\nu_e} \]
\[ \begin{cases} \geq 5 \text{ MeV} & (Y_e < 0.5) \\ \text{neutron rich} & \end{cases} \]
\[ \begin{cases} < 5 \text{ MeV} & (Y_e > 0.5) \\ \text{proton rich} & \end{cases} \]

In summary:

large(small) spectral differences favor neutron(proton) excess of the material ejected in the neutrino-driven wind
Conditions required reaching the 3rd $r$-process peak

- Electron fraction: $Y_e := Y_{e^-} - Y_{e^+} = \frac{N_e}{N_B}$
- Dynamical timescale: $\tau_{\text{dyn}} \propto \frac{r}{v}$
- Entropy per Baryon

\[ \frac{Y_n}{Y_{\text{seed}}} \simeq 100 - 200 \]


\[ \tau_{\text{dyn}} = 0.0039 \text{ s} \]

0.039 s

0.195 s


**Parametrized/Steady-state studies:**
(assumed asymptotic neutrino properties)


**(radiation-)hydrodynamics models:**


**Role/presence of reverse shock:**
(entropy rise; parametrized dynamic studies)

Nucleosynthesis results under $p$–rich conditions

- Generally small spectral differences result in always $p$–rich conditions; increasing proton excess at later times
  \[ Y_e = 0.51 - 0.56 , \quad s/n_B = 50 - 150 \ k_B \]

- Site for the $vp$–process;
  - Mass-flow along proton-rich side; Overcome waiting-point nuclei (long half-lives; e.g. $^{64}$Ge)
  - Production up to $A \sim 100$
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- Site for the $vp$–process;
  - Mass-flow along proton-rich side; Overcome waiting-point nuclei (long half-lives; e.g. $^{64}\text{Ge}$)
  - Production up to $A \sim 100$

- However: neutrino transport was based on inconsistent implementation of weak rates and nuclear equation of state!
Current understanding and challenges

weak rates and nuclear physics
Charged-current weak rates in simulations

- Neutrino opacity/reaction rate (charged-current weak processes): $\nu_e + n \rightarrow e^- + p$

\[
1/\lambda(E_{\nu_e}) = \frac{G_F^2 V_{ud}^2}{\pi (\hbar c)^7} (g_V^2 + 3g_A^2) \int \frac{d^3p_e}{(2\pi)^3} (1 - F_e(E_e)) S(q_0, q)
\]

\[
q_0 = E_\nu - E_e, \quad q = |p_\nu - p_e|
\]

\[
1/\lambda_\nu(E_\nu) \simeq \frac{G_F^2 V_{ud}^2}{\pi (\hbar c)^7} (g_V^2 + 3g_A^2) p_e E_e (1 - F_e(E_e)) \frac{n_n - n_p}{1 - e^{\beta(\mu_p^0 - \mu_n^0)}}
\]

(nuclear response)

(zero-momentum transfer approximation; commonly used in simulations)
Charged-current weak rates in simulations

- Neutrino opacity/reaction rate (charged-current weak processes): \( \nu_e + n \rightarrow e^- + p \)

\[
1/\lambda(E_{\nu_e}) = \frac{G_F^2 V_{ud}^2}{\pi(\hbar c)^7} (g_V^2 + 3g_A^2) \int \frac{d^3p_e}{(2\pi)^3} (1 - F_e(E_e)) S(q_0, q)
\]

\[
q_0 = E_{\nu} - E_e, \quad q = |p_{\nu} - p_e|
\]

\[
1/\lambda_\nu(E_{\nu}) \approx \frac{G_F^2 V_{ud}^2}{\pi(\hbar c)^7} (g_V^2 + 3g_A^2) p_e E_e (1 - F_e(E_e)) \frac{n_n - n_p}{1 - e^{\beta(\mu^0_p - \mu^0_n)}}
\]

(zero-momentum transfer approximation; commonly used in simulations)

- Description of weak processes must be consistent with **nuclear equation of state**

- Supernova equations of state (EOS) threat nucleons as quasi-particles that move in a potential, \( U_N (!) \)

\[
\mu^0_n = \mu_n - U_n - m_n
\]

\[
\mu^0_p = \mu_p - U_p - m_p
\]

\( (U_n, U_p) \) (nucleon self energies)
Weak rates consistent with the equation of state

- Similar situation as in heavy neutron rich nucleus: $\nu_e + n \rightarrow e^- + p$

\[
\nu_e (E_{\nu_e}) \quad E_n = \frac{p^2}{2m_n^*} + m_n^* + U_n
\]

\[
Q = (m_n - m_p) + (U_n - U_p) = Q_0 + (U_n - U_p)
\]

\[
E_{\nu_e} \gtrsim \mu_e - (m_n - m_p) - (U_n - U_p)
\]

Note: $U_n(\rho, T, Y_e) - U_p(\rho, T, Y_e) \propto (1 - 2Y_e) S_B^F(\rho, T)$

(Figure: G. Martinez-Pinedo)
Constraints from neutron matter equation of state

- Selection of neutron-matter EOS; energy per baryon $E/N$
- Large EOS variations for supernova relevant density range
- Constraint from Chiral EFT; Krüger, et al., (2013) PRC 88, 025802
- Density-dependence of nucleon self-energies for two examples:

![Graph showing neutron matter equation of state](image)

- $\rho \left[10^{14} \text{ g cm}^{-3}\right]$
- $E/N - m_n [\text{MeV}]$
- $n_B [\text{fm}^{-3}]$
- $U_n - U_p [\text{MeV}]$


$Q_0 = 1.2935 \text{ MeV}$

$Y_e = 0.1, 0.4$
Vary only symmetry energy within current astro.- and nuclear-physics constraints:

- **HS.DD2** (reference EOS)
- **HS.DD2**⁻ (low symmetry energy at low density)
- **HS.DD2**⁺ (high symmetry energy at high density)

Spectral difference depends on nuclear symmetry energy (at low density)
Neutrinos from PNS deleptonization

- Consistent treatment of weak charged-current processes and nuclear EOS
- EOS HS(DD2) that agrees best with most current nuclear (e.g. chiral EFT) and astro. constraints (e.g. massive neutron stars)
- Neutrino signal has direct nuclear EOS dependence
- Largest spectral differences at early times; reduce at later times

11.2 M⊙ progenitor

\[ L_{\nu_{\mu/\tau}} > L_{\nu_e} \approx L_{\bar{\nu}_e} \]

continuously decreasing fluxes of all flavors

\[ \epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} \approx 4.6 \text{ MeV} \]

Initial energy hierarchy broken

\[ \langle E_{\nu_{\mu/\tau}} \rangle \approx \langle E_{\bar{\nu}_e} \rangle > \langle E_{\bar{\nu}_e} \rangle \]

\[ \epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} \approx 2 \text{ MeV} \]

\[ ( \epsilon_{\nu} = \langle E_{\nu}^2 \rangle / \langle E_{\nu} \rangle ) \]
Opacity during deleptonization

Neutrino energy integration:

\[
\frac{1}{\lambda_i^i(\rho)} \propto \frac{1}{n_\nu(\rho)} \int E^2 dE \frac{1}{\lambda_i^i(E, \rho)} f_\nu(E, \rho)
\]

(\(\nu\) ... neutrino flavor index)

(\(i\) ... weak process index)

Largest opacity: scattering on nucleons
(elastic process)

Largest energy exchange: scattering on \(e^\pm\)

(Note: no charged-current processes for \(\mu\)-neutrinos)
Opacity during deleptonization

Largest elastic opacity: scattering on nucleons

\((\bar{\nu}_e)\)

Largest energy exchange: scattering on \(e^\pm\) \(\sim\) absorption on protons

\((\nu_e)\)

Largest energy exchange: scattering on \(e^\pm\) \(<\) absorption on neutrons

Fischer et al., (2012) PRD 85, 083003
Late phase: ejecta become proton rich

Early $\nu$-driven wind phase: neutron-rich ejecta

- For the tested EOS, we find
  early phase: $Y_e \approx 0.48$ ($0.44 - 0.54$)
  late phase: $Y_e > 0.50$ ($0.49 - 0.62$)

- Moderate entropy per baryon
  early phase: $S \sim 20 - 65 \text{ k}B$
  late phase: $S \sim 65 - 120 \text{ k}B$

- Model uncertainties ($\pm 10\%$):
  weak rates, nuclear symmetry energy, weak magnetism, inelastic processes,
  reverse shock, $\nu$-oscillations . . .
  luminosity/energy enhancement from late-phase fall back
Integrated nucleosynthesis analysis

Elemental abundances:

- Robust production of light neutron-capture elements (nucleosynthesis path close to stability; nuclear physics well under control)

- Consistent with obs.: (Honda-type stars: poor in heavy neutron-capture elements (Z>45) but large abundances of light neutron-capture elements 38<Z<45, Sr, Y, Zr)

- Proton-rich ejecta: \( \nu p \) process

Mass-flow along proton-rich side draw back: weak neutrino fluxes at late times
Summary
• Nucleosynthesis-relevant conditions are given by only neutrino properties, which are determined at decoupling from matter (spectral- and angle-dependent transport/diffusion problem)

• Medium modifications for weak processes must be included
  ✴ Neutrino fluxes and spectra depend directly on nuclear-matter properties, e.g., the nuclear symmetry energy and its density dependence
  ✴ Level of sophistication (e.g. mean field, correlations,...) still under debate

• \( Y_e \) and/or entropy – not free parameters to ‘play with’
  (independent varying is meaningless; \( \nu \)-driven wind is no site for the main \( r \)-process component)

• Current models can explain robustly the production of light neutron-capture elements; one main site discovered (?)
  All massive star explosions have a \( \nu \)-driven wind component (!)
• Current supernova models have still large uncertainties; systematic understanding still lacking
• What could be missing: novel weak processes/opacity sources
• Current supernova models have still large uncertainties; systematic understanding still lacking

• What could be missing: novel weak processes/opacity sources
  * inelastic contributions
  * neutron decay channel

\[
\begin{align*}
\bar{\nu}_e + e^- + p & \longrightarrow n \\
E_{\bar{\nu}_e} &= -E_{e^-} + Q_0 + (U_n - U_p) \\
\nu_e + n & \longrightarrow p + e^- \\
E_{\nu_e} &= E_{e^-} - Q_0 - (U_n - U_p) \\
\bar{\nu}_e + p & \longrightarrow n + e^+ \\
E_{\bar{\nu}_e} &= E_{e^+} + Q_0 + (U_n - U_p)
\end{align*}
\]

(see talk by A. Lohs)
• Current supernova models have still large uncertainties; systematic understanding still lacking

• What could be missing: novel weak processes/opacity sources
  * inelastic contributions
  * neutron decay channel
  * muons (see talk by A. Lohs)
  * neutrino oscillations

\[
(\nu_\mu, \tau, \bar{\nu}_\mu, \bar{\nu}_\tau) \leftrightarrow (\nu_e, \bar{\nu}_e)
\]

(enhanced $\nu p$ process under proton-rich conditions)

Duan, et al., (2011), JPhG 38, 035201
(neutron rich environment)

Role of sterile neutrinos (?)
(see poster P-39 by Meng-Ru Wu)
• Current supernova models have still large uncertainties; systematic understanding still lacking
• What could be missing: novel weak processes/opacity sources
  ✤ inelastic contributions
  ✤ neutron decay channel
  ✤ muons
  ✤ neutrino oscillations
  ✤ light nuclear clusters

Light nuclear clusters, $^2H(d)$ and $^3H$, can be as/more abundant as free protons

\[
\begin{align*}
\nu_e + d &\leftrightarrow p + p + e^- \\
\bar\nu_e + d &\leftrightarrow n + n + e^+ \\
\nu + d &\leftrightarrow p + n + \nu
\end{align*}
\]
Thanks for your attention