Neutrino Nucleosynthesis in the outer layers of supernovae

A. Sieverding, L. Huther, G. Martínez-Pinedo, K. Langanke

International Workshop XLIII on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria
14 January 2015
Outline

1 Introduction
   - Neutrino nucleosynthesis
   - Supernova model

2 Results
   - Production of $^7$Li, $^{11}$B, $^{19}$F, $^{138}$La, $^{180}$Ta
   - Radioactive nuclei

3 Summary and Outlook
Neutrinos and Supernovae

- The core of a massive star collapses after the nuclear burning phases.
- Collapse stops when nuclear densities are reached.
- Hydrodynamic shock triggers explosive nucleosynthesis.
- Cooling core emits neutrinos.
- Neutrinos can influence the nucleosynthesis in outer layers of SNe.
Neutrino nucleosynthesis

- Emission of $10^{59}$ Neutrinos from the collapsing core
- $\langle E_\nu \rangle \approx 7 - 13$ MeV
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_{\mu,\tau}} \rangle$
- Charged-current and neutral-current interactions
- Particle evaporation

Neutral current (NC)

\[
\begin{align*}
\frac{A}{Z}N + \nu_x &\rightarrow \frac{A}{Z}N^* + \nu'_x \\
&\rightarrow \frac{A}{Z-1}N + n \\
&\rightarrow \frac{A}{Z-1}N + p \\
&\rightarrow \frac{A}{Z-2}N + \alpha \\
&\rightarrow \ldots
\end{align*}
\]

Charged current (CC)

\[
\begin{align*}
\frac{A}{Z}N + \nu_e &\rightarrow \frac{A}{Z+1}N^* + e^- \\
\frac{A}{Z}N + \bar{\nu}_e &\rightarrow \frac{A}{Z-1}N^* + e^+
\end{align*}
\]
Neutrino nucleosynthesis

- The supernova shock triggers photodissociation and subsequent particle capture reactions
- Regions with sufficient neutrino fluxes but still moderate post-shock temperatures are most promising for $\nu$ nucleosynthesis
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- Main candidates for neutrino nucleosynthesis: $^7\text{Li}$ and $^{11}\text{B}$ via $^4\text{He}(\nu_x,\nu'_x \ p/n)$ and $^{12}\text{C}(\nu_x,\nu'_x \ p)$ ...
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  - $^{19}\text{F}$ via $^{20}\text{Ne}(\nu_x,\nu_x' \ p/n)$
  - $^{138}\text{La}$ and $^{180}\text{Ta}$ via $^{138}\text{Ba}(\nu_e,e^-)$ and $^{180}\text{Hf}(\nu_e,e^-)$
- **Neutrino-nucleus cross-sections** have been calculated for almost the whole nuclear chart (L. Huther 2014, PhD. Thesis)
- Simulations including detailed neutrino transport give new estimates for typical neutrino energies: $\langle E_\nu \rangle = 8$-13 MeV compared to 13-25 MeV
- Results from various stellar evolution calculations are available (e.g. Heger et al. 2002)
Supernova model

- Parametrization of temperature and density evolution during the explosion (Woosley et al. 1990)

\[ T_{\text{Peak}} = 2.4 \times 10^9 \, \text{K} \times \left( \frac{E_{\text{expl}}}{10^{51} \, \text{erg}} \right)^{1/4} \times \left( \frac{R}{10^9 \, \text{cm}} \right)^{-3/4} \]

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Neutrino nucleosynthesis

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Supernova model

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- Neutrino flux
  - Exponentially decreasing neutrino luminosity
  - Thermal Fermi-Dirac spectrum
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3 Summary and Outlook
Production factors normalized to $^{16}$O

- 25 M$_{\odot}$ progenitor with solar metallicity

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<tbody>
<tr>
<td>$^7$Li</td>
<td>0.0004</td>
<td>0.11</td>
<td>-</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>0.003</td>
<td>0.8</td>
<td>1.18</td>
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<tr>
<td>$^{19}$F</td>
<td>0.06</td>
<td>0.24</td>
<td>0.32</td>
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<tr>
<td>$^{138}$La</td>
<td>0.03</td>
<td>0.63</td>
<td>0.90</td>
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<td>0.14</td>
<td>1.80</td>
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Production factors normalized to $^{16}\text{O}$

- $15\ M_{\odot}$ progenitor with solar metallicity

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Production of $^7\text{Li}$, $^{11}\text{B}$, $^{19}\text{F}$, $^{138}\text{La}$, $^{180}\text{Ta}$

Radioactive nuclei

Production factor of $^{19}\text{F}$ normalized to $^{16}\text{O}$

- without neutrinos
- $\langle E_{\nu_e}\rangle = 8.8 \text{ MeV}, T_{\nu_x} = 12.6 \text{ MeV}$
- $\langle E_{\nu_e,\bar{\nu}_e}\rangle = 12.6 \text{ MeV}, T_{\nu_x} = 18.8 \text{ MeV}$
Production of $^{19}$F

Without neutrinos:
- H- and He-shell burning create regions enriched in $^{18}$O and $^{15}$N

**Production of** $^{7}$Li, $^{11}$B, $^{19}$F, $^{138}$La, $^{180}$Ta

Radioactive nuclei

**Introduction**

**Results**

**Summary and Outlook**

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Neutrino Nucleosynthesis

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Production of $^{19}$F

Without neutrinos:
- H- and He-shell burning create regions enriched in $^{18}$O and $^{15}$N
- High shock temperatures enhance $^{15}$N($\alpha, \gamma$) and $^{18}$O($p, \gamma$)

$T_{\text{max}} = 0.3\text{--}0.8\text{ GK}$

$^{15}$N($\alpha, \gamma$)$\sim T^{9.25}$

$^{15}$N

$^{14}$N

$^{17}$O

$^{18}$O

$^{20}$Ne

$^{19}$F

$^{16}$O

$^{18}$F

$^{15}$N($\alpha, \gamma$)
Production of $^{19}$F

Without neutrinos:
- H- and He-shell burning create regions enriched in $^{18}$O and $^{15}$N
- High shock temperatures enhance $^{15}$N$(\alpha, \gamma)$ and $^{18}$O$(p, \gamma)$
- Very sensitive to temperature
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Neutral-current neutrino reactions on $^{20}$Ne
Production factor of $^{19}$F normalized to $^{16}$O

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Neutrino Nucleosynthesis

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Stellar composition

Production of $^7\text{Li}$, $^{11}\text{B}$, $^{19}\text{F}$, $^{138}\text{La}$, $^{180}\text{Ta}$ radioactive nuclei

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Neutrino Nucleosynthesis

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Stellar composition

Production of $^7\text{Li}$, $^{11}\text{B}$, $^{19}\text{F}$, $^{138}\text{La}$, $^{180}\text{Ta}$ radioactive nuclei

Stellar composition

Enclosed mass /$M_\odot$

Mass fraction

$^{4}\text{He}$ $^{12}\text{C}$ $^{16}\text{O}$ $^{20}\text{Ne}$ $^{28}\text{Si}$ 'Fe'

O/Ne C/O He

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Neutrino Nucleosynthesis

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Stellar composition

![Graph showing mass fraction vs. enclosed mass for different elements in stellar composition.]

- Production of $^7\text{Li}$, $^{11}\text{B}$, $^{19}\text{F}$, $^{138}\text{La}$, $^{180}\text{Ta}$
- Radioactive nuclei

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Neutrino Nucleosynthesis

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Production of $^{19}$F for a 15 $M_{\odot}$ progenitor

- Initial conditions

![Graph showing mass fraction enriched in $^{18}$O and $^{19}$F as a function of enclosed mass (in $M_{\odot}$).]
Production of $^{19}$F for a 15 $M_\odot$ progenitor

- Explosive nucleosynthesis without neutrinos

![Graph showing mass fraction of $^{18}$O pre-SN and without neutrinos versus enclosed mass/M$_\odot$.]
Production of $^{19}$F for a 15 M$_\odot$ progenitor

- Including neutrino interactions

![Graph showing the production of $^{19}$F with and without neutrinos](image)
Production of $^{19}$F for a 15 M⊙ progenitor

- 20% uncertainty in $T_{\text{peak}}$ or 18% uncertainty in radius
Production of $^{19}$F for a $25\,M_{\odot}$ progenitor

- With the $25\,M_{\odot}$ progenitor the neutrino-induced production dominates

\[ T_{\text{Peak}} = 0.43 \text{ GK} \]

Enclosed mass/$M_{\odot}$

Mass fraction

- pre-SN $^{18}$O
- without neutrinos
- including neutrinos
Production of $^7$Li, $^{11}$B, $^{19}$F, $^{138}$La, $^{180}$Ta
Radioactive nuclei

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3. **Summary and Outlook**
### γ-ray astronomy

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<th>Decaytime</th>
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<tr>
<td>(^{7}\text{Be})</td>
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<tr>
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Summary and Outlook

Radioactive nuclei

Sensitivity to the progenitor mass

![Graph showing sensitivity to the progenitor mass](image)

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Neutrino Nucleosynthesis

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Production of $^{22}$Na

Different mechanisms:
- indirect enhancement of p-captures
- direct charged-current channel

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Neutrino Nucleosynthesis

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Production of $^{22}\text{Na}$

Different mechanisms:
- indirect enhancement of p-captures
- direct charged-current channel
- direct neutral-current channels

Balance of the different channels is sensitive to stellar structure and neutrino spectra.
**Production of $^{22}$Na**

Different mechanisms:
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- direct charged-current channel
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Balance of the different channels is sensitive to stellar structure and neutrino spectra.
Production of $^{22}\text{Na}$

For a $15 \, M_\odot$ progenitor

![Graph showing the production of $^{22}\text{Na}$ as a function of enclosed mass.](image-url)
Production of $^{22}\text{Na}$

For a 15 $M_\odot$ progenitor
Production of $^{22}$Na

- For a 15 M$_\odot$ progenitor

**Indirect effect:** $^{20}$Ne($\nu,\nu'\ p$) enhances $^{21}$Ne($p,\gamma$)$^{22}$Na

**Diagram:**
- $^{22}$Na
- Charged-current only
- Neutral-current only

**Axes:**
- Enclosed mass / M$_\odot$
- Mass fraction

**Legend:**
- Neutral current dominated
- O/Ne layer
- Charged-current only
- Neutral-current only

**Equations:**
- $^{20}$Ne($\nu,\nu'\ p$)
- $^{21}$Ne($p,\gamma$)$^{22}$Na

**Note:**
- Hirschegg 2015
- Neutrino Nucleosynthesis
- Andre Sieverding
Production of $^{22}\text{Na}$

For a 15 $M_\odot$ progenitor

- Neutral current dominated
- Charged current dominated

Neutral current dominated:
- O/Ne layer
- C/O layer enriched in $^{22}\text{Ne}$, $^{22}\text{Ne}(\nu_e,e^-)^{22}\text{Na}$

Charged current dominated:
- Charged-current only
- Neutral-current only

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Neutrino Nucleosynthesis

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Summary

- Nuclear reaction network calculations including an extended set of neutrino-nucleus reactions
- Calculations with updated neutrino spectra
- Explore the sensitivity to stellar structure and composition
- Study the effect on nuclei that are relevant for $\gamma$-ray astronomy, like $^{22}$Na and $^{26}$Al
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- Study the effect on nuclei that are relevant for γ-ray astronomy, like $^{22}$Na and $^{26}$Al

Outlook

- Study a larger range of progenitor models, especially lower mass
- Explore effects of metallicity
- Improve thermodynamic description
- Improve neutrino spectra
- Effects of neutrino oscillations
Thank you, for your attention
Neutrino cross sections

- Two step process: Excitation and decay
  \[ \sigma_{X \rightarrow Y}^{k}(E_{\nu}) = \sum_{i} \sigma_{i}^{RPA}(X) \times P_{k}(Y) \]

- Excitation spectra from RPA
- Decay rates from Hauser-Feshbach statistical models
- Including evaporation of up to 4 particles
Stellar composition

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Neutrino Nucleosynthesis

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Supernova model

- Simple thermodynamic parametrization
- Temperature and density constant until the passage of the shock at $t_0$
- **Peak temperature** in the shock: $T_P = E_{\text{expl}}^{1/4} \times R^{-3/4}$
- Exponential decrease of temperature with time scale $\tau_{\text{dyn}} \propto \frac{1}{\sqrt{\rho_{\text{initial}}}}$
- Expansion with **constant velocity** of 5000 km/s
- Explosion energy of $10^{51}$ ergs
Parametrization of the supernova event

Example for thermodynamic trajectory
Description of $\nu$ emission

- Decreasing Luminosity
  \[ L_\nu \propto \exp \left( -\frac{t}{\tau_\nu} \right) \]
- Isotropic emission
- Emission of $10^{53}$ ergs for each flavour
- Fermi-Dirac distributed energies,
  \[ \langle E_\nu \rangle = 3.15 \times T_\nu \]
  - $T_{\nu_e} = 4$ MeV
  - $T_{\bar{\nu}_e} = 4$ MeV
  - $T_{\nu_{\mu,\tau}} = 8$ MeV