Nucleosynthesis in neutrino-heated matter

Gabriel Martínez Pinedo

GSI

June 30, 2006
1. Proton-rich ejecta
   - Are light p-nuclei synthesized in neutrino heated ejecta?

2. Neutron-rich ejecta: The role of fission
   - Nuclear physics input and models
   - Results

3. Conclusions
Outline

1. Proton-rich ejecta
   - Are light p-nuclei synthesized in neutrino heated ejecta?

2. Neutron-rich ejecta: The role of fission
   - Nuclear physics input and models
   - Results

3. Conclusions
1. Proton-rich ejecta
   - Are light p-nuclei synthesized in neutrino heated ejecta?

2. Neutron-rich ejecta: The role of fission
   - Nuclear physics input and models
   - Results

3. Conclusions
Proton-rich ejecta could be the major contributor of $^{45}$Sc, $^{49}$Ti and $^{64}$Zn (Pruet et al. 2005, Fröhlich et al. 2006)

Can proton-rich ejecta be the site of a kind of rp-process in supernovae?

Problem with the short time scales for explosive nucleosynthesis in supernovae ($\sim$ seconds).

Antineutrino absorption can speed up matter flow.

$\bar{\nu}_e + p \rightarrow e^+ + n$ (time $\sim$ seconds)
Proton-rich ejecta: The $\nu p$-process

- Proton-rich ejecta could be the major contributor of $^{45}$Sc, $^{49}$Ti and $^{64}$Zn (Pruet et al. 2005, Fröhlich et al. 2006)

- Can proton-rich ejecta be the site of a kind of rp-process in supernovae?

- Problem with the short time scales for explosive nucleosynthesis in supernovae ($\sim$ seconds).

- Antineutrino absorption can speed up matter flow.

$$\bar{\nu}_e + p \rightarrow e^+ + n \text{ (time } \sim \text{ seconds)}$$

The $\nu p$-process

Physical Review Focus (April 21).
CERN-COURIER (June Issue)
Nucleosynthesis variability

Trajectories from Garching group

Sensitivity entropy, $Y_e$, radius.  

Masses, $(p, \gamma)$, $(n, p)$, $(n, \gamma)$,
Production of $^{92}$Mo is sensitive to the masses (and proton capture rates) in the region of $^{92}$Pd.
Composition in neutrino heated ejecta

- Early ejecta proton-rich: $\nu p$-process
- Later ejecta neutron rich: $r$-process.
- Nucleosynthesis sensitive to proton to seed ratio ($\nu p$-process) and neutron to seed ratio ($r$-process).
92\textsuperscript{Mo} is produced in slightly neutron rich ejecta, $Y_e \approx 0.47–0.49$ (Fuller & Meyer 1995, Hoffman \textit{et al.} 1996).

The rest is produced in proton-rich ejecta.
**r-process and metal poor stars**

**r-process sites:**

- Low entropy, low $Y_e$ ejecta:
  - Prompt explosion of ONeMg white dwarfs. Seems to be ruled out by recent calculations (Kitaura, Janka and W. Hillebrandt 2006, Adam Burrows talk).
  - Neutron stars mergers (Freiburghaus, Rosswog, and Thielemann 1999).

J. Cowan, NIC-IX talk

Our calculations

- Adiabatic expansions (Freiburghaus et al. 1999). Expansion velocity 4500 km/s ($\tau = 50$ ms), $Y_e = 0.45$. We want to achieve large enough neutron to seed ratio to study the effect of fission in the r-process.
- Full nuclear network (p,n...Eu) before alpha-rich freeze-out.
- R-process code (D. Mocelj), $Z \leq 110, A \leq 340$.
- Neutron-capture and neutron fission cross sections (I. Panov, T. Rauscher, F.-K. Thielemann).
- Beta-decay rates and beta-delayed fission (P. Möller, B. Pfeiffer, and K.-L. Kratz).
- Neutrino absorption and neutrino induced fission (N. Zinner & K. Langanke).
Where does fission occur?

Myers & Swiatecki Barriers

[Graph showing Myers & Swiatecki Barriers with different contour lines and labels for FRDM, Duflo Zuker, and ETFSI.]
Heavier nuclei tend to produce lighter fragments.
Proton-rich ejecta

Neutron-rich ejecta: The role of fission

Conclusions

Nuclear physics input and models

Results

Snapshot

\[ T_g = 0.35, \quad n_n = 4.146 \times 10^{22}, \quad t = 0.9531 \text{ s} \]
Comparison of abundances

FRDM
- $s = 300, n/s = 67$
- $s = 350, n/s = 116$
- $s = 400, n/s = 186$
- $s = 500, n/s = 417$

ETFSI–Q
- $s = 300, n/s = 67$
- $s = 350, n/s = 116$
- $s = 400, n/s = 186$
- $s = 500, n/s = 417$

Duflo–Zuker
- $s = 300, n/s = 67$
- $s = 350, n/s = 116$
- $s = 400, n/s = 186$
- $s = 500, n/s = 417$

Differences are due to different shell structure at $N = 82$
### Some quantitative results

Percent of final abundance that has undergone fission.

<table>
<thead>
<tr>
<th>$n/s$</th>
<th>$(n_{\text{fission}})$</th>
<th>$\beta$-fission</th>
<th>$\nu$-fission</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>116</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>ETFSI-Q</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FRDM</td>
<td>10</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Duflo-Zuker</td>
<td>10</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>186</td>
<td>33</td>
<td>5</td>
<td>0</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>ETFSI-Q</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FRDM</td>
<td>36</td>
<td>3</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>Duflo-Zuker</td>
<td>36</td>
<td>3</td>
<td>39</td>
</tr>
<tr>
<td>417</td>
<td>56</td>
<td>4</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>ETFSI-Q</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FRDM</td>
<td>58</td>
<td>5</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>Duflo-Zuker</td>
<td>58</td>
<td>5</td>
<td>63</td>
</tr>
</tbody>
</table>
Abundances at freeze-out

R-process path and abundances at freeze out for $n/s = 116$.

$T_9 = 0.6, N_n = 6.4 \times 10^{23} \text{ cm}^{-3}$
Matter accumulated at $N = 184 (A \sim 270)$ will fission in the decay to “stability”.

During the decay will reach a region with large fission probabilities and fission will take place. Mainly neutron induced (chain reaction in atomic bomb).

The released neutrons can produce major shifts in the $A \sim 195$ peak if the beta decay half-lives are too long. They are responsible for a kind of weak r (strong s) process with $N_n \sim 10^{16} \text{ cm}^{-3}$. Sensitive to $(n, \gamma)$ cross sections.
Coulomb dissociation measurements by the LAND Collaboration (GSI) show an increase in $E1$ strength at low energies in neutron rich Sn isotopes. [P. Adrich et al., PRL 95, 132501 (2005)]
If we increase neutrino fluence there is no production of heavy r-process nuclei (α-effect, Fuller & Meyer 1995).
Elemental abundances

-3
-4
-5
-6
-7
-8

30 40 50 60 70 80 90

Z

s=300
s=350
s=400
s=500
CS 22892–052

NIC-IX
Nucleosynthesis in neutrino-heated matter
Neutron stars mergers

Trajectory from Freiburghaus, Rosswog, and Thielemann 1999
\( (Y_e = 0.1, n/s = 238) \).

\( Y_e = 0.1, n/s = 238 \).

\begin{align*}
\text{FRDM} & \quad \text{Duflo Zuker} \\
\text{ETFSI-Q} & \quad \text{NIC-IX}
\end{align*}
Conclusions

- A combination of proton-rich material ($\nu p$-process) and slightly neutron-rich material ($Y_e \sim 0.48$) could explain the solar abundances of light p-nuclei ($^{92,94}_{\text{Mo}},^{96,98}_{\text{Ru}}$).

- Fission plays a very important role in determining the final abundances and dynamics of the r-process.

- The strength of the $N = 82$ plays a very important role in determining the role of fission.

- Mass models with strong shell effects are able to produce a consistent and robust r-process patterns as soon as the neutron to seed ratio is large enough to induce fissions.

- Neutrino-induced fission is irrelevant for the determination of the r-process abundances. Neutron-induced fission is the dominating channel.
Proton-rich ejecta.

C. Fröhlich (Basel)  F.-K. Thielemann (Basel)  M. Liebendörfer (Basel)
K. Langanke (GSI)  N. T. Zinner (Århus)  R. Hix (Oak Ridge)
E. Bravo (Barcelona)

r-process nucleosynthesis.

D. Mocelj (Basel)  F.-K. Thielemann (Basel)  T. Rauscher (Basel)
K. Langanke (GSI)  A. Kelić (GSI)  K.-H. Schmidt (GSI)
N. T. Zinner (Århus)  I. Panov (Moscow)  P. Möller (Los Alamos)
B. Pfeiffer (Mainz)  K.-L. Kratz (Mainz)

Collaborators
N=82 and N=126 Two-Neutron separation energies

- Duflo–Zuker
- ETFSI–Q
- HFB–9
- FRDM

Nucleosynthesis in neutrino-heated matter