Neutrinos and Nucleosynthesis

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the astrophysical formation of the elements

solar system abundances

http://nedwww.ipac.caltech.edu/level5/Pagel/Figures/figure1_4.jpeg
heavy element synthesis

M. Arnould, S. Goriely / Physics Reports 384 (2003) 1–84

Abundances (Si=10^6)

80 100 120 140 160 180 200
A

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v-rich environments for heavy element synthesis

core-collapse supernova

black hole accretion disk

PNS

jet (?)

outflow

accretion disk

ν

ν

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\(\nu\)-rich environments for heavy element synthesis

- Shock
- Nucleosynthesis
- Nuclear physics of core
- Neutrino scattering and emission
- Jet (?)
- Nucleosynthesis
- Outflow
- Accretion disk
- Nuclear physics of disk
stages of heavy element synthesis

1. free neutrons and protons
   
   \[ p + e^- \leftrightarrow n + \nu_e \]
   \[ n + e^+ \leftrightarrow p + \overline{\nu}_e \]

2. assembly of alpha particles
   
   \[ p, n \rightarrow \alpha's + \text{excess } p \text{ or } n \]

3. assembly of seed nuclei
   
   \[ \alpha's + \text{excess } p \text{ or } n \rightarrow \text{iron peak nuclei } + \text{ remaining } p \text{ or } n \]

4. free nucleon capture on seeds
   
   \[ \text{iron peak nuclei } + \text{ remaining } p \text{ or } n \rightarrow \text{heavy nuclei} \]
(1) free neutrons and protons
\[ p + e^- \leftrightarrow n + \nu_e \quad \text{\(\nu\) can set the neutron to proton ratio, \(n/p\)}
\[ n + e^+ \leftrightarrow p + \bar{\nu}_e \quad \text{\(n/p\) determines the subsequent nucleosynthesis}\n
(2) assembly of alpha particles
\[ p, n \rightarrow \alpha'\text{s} + \text{excess } p \text{ or } n\n
(3) assembly of seed nuclei
\[ \alpha'\text{s} + \text{excess } p \text{ or } n \rightarrow \text{iron peak nuclei} + \text{remaining } p \text{ or } n\n
(4) free nucleon capture on seeds
\[ \text{iron peak nuclei} + \text{remaining } p \text{ or } n \rightarrow \text{heavy nuclei} \]
(1) free neutrons and protons

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

(2) assembly of alpha particles

\[ p, n \rightarrow \alpha's + \text{excess } p \text{ or } n \]

\( \nu \) can continue to convert the excess \( p \) or \( n \)

this alters the free nucleons available for capture onto seeds
e.g., ‘alpha effect’

(3) assembly of seed nuclei

\[ \alpha's + \text{excess } p \text{ or } n \rightarrow \text{iron peak nuclei} + \text{remaining } p \text{ or } n \]

(4) free nucleon capture on seeds

\[ \text{iron peak nuclei} + \text{remaining } p \text{ or } n \rightarrow \text{heavy nuclei} \]
the supernova neutrino-driven wind

\[ \langle E_{\nu_x} \rangle \geq \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle \]

late-time $\nu$ fluxes from Keil et al (2003)

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

\[ n + \nu_e \leftrightarrow p + e^- \]

\[ p, n \rightarrow \alpha, n \rightarrow \text{seed nuclei} + n \rightarrow r \text{ process} \]
the supernova neutrino-driven wind

Hydrodynamic conditions required to build the heaviest nuclei are difficult to achieve, in part due to the neutrino-induced alpha effect.

In the standard SNe energy hierarchy, neutrino oscillations only enhance the role of neutrinos.

\[ \langle E_{\nu_x} \rangle \geq \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle \]

\[ p, n \rightarrow \alpha, \ n \rightarrow \text{seed nuclei} + \ n \rightarrow \text{r process} \]
No $\nu$ for $T < 9 \times 10^9$ K

No oscillations

Test swap at seed assembly

Test swap at alpha assembly

$f_{\nu_e}(E)$ replaced by $f_{\nu_\mu}(E)$
where does each nucleosynthesis stage take place?

\[ n, p \]
\[ \alpha \]
\[ \text{seeds} \]
\[ r\text{-process} \]

\[ T_9 \]
\[ r \text{ (km)} \]
\[ P(e) \]

Duan, Friedland, McLaughlin, & Surman, in preparation (2010)

ν oscillation calculation by Huaiyu Duan and Alex Friedland (as in hep-ph/10062359)
a full neutrino oscillation + $r$-process calculation

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$s/k = 200$

$\tau = 18 \text{ ms}$

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_Duan, Friedland, McLaughlin, & Surman, in preparation (2010)_.

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mass hierarchy

\[ s/k = 300 \]
\[ \tau = 35 \text{ ms} \]

Duan, Friedland, McLaughlin, & Surman, in preparation (2010)
Neutrino interactions on nucleons play an important role in heavy element synthesis in extreme environments.

Supernova nucleosynthesis calculations cannot (safely) ignore neutrino oscillations:

⇒ act only increase the importance of neutrino interactions
⇒ the influence is the greatest at the earliest stages of nucleosynthesis
⇒ correctly predicting the radius at which the flavor transformations occur is of key importance for the nucleosynthesis - this requires a multiangle ν oscillation calculation.