Neutrinos and Neutrons in the r-process

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Neutrino Astrophysics

- What are the fundamental properties of neutrinos?
- What do they do in astrophysical environments?
- What do neutrinos in a core collapse supernova do?
- What do neutrinos in a black hole accretion disk do?

Nuclear Astrophysics

- What is the origin of the elements?
- Where are the heaviest elements made?
- What elements are made in compact object mergers/ stellar explosions?
Where is uranium made?

Uranium is an r-process element . . .
From where do the heaviest elements come?

- Elements beyond the iron peak in three main categories
  - r-process
  - s-process
  - p-process

- Examples of r-process elements
  - Europium
  - Platinum
  - Uranium
  - Thorium
Solar Abundances

![Scaled Solar Data](graph.png)
The \(r\)-process elements

e. g. Uranium-238 \(Z=92, N=146\) → need lots of neutrons

\[
A(Z, N) + n \leftrightarrow A + 1(Z, N + 1) + \gamma
\]

\[
A(Z, N) \rightarrow A(Z + 1, N - 1) + e^- + \bar{\nu}_e
\]

rapid neutron capture as compared with beta decay

At what temperatures does this happen?
\((n, \gamma) (\gamma, n)\) equilibrium at \(T \approx 10^9\)K
What astrophysical sites have a lot of neutrons and eject material?

- neutron star mergers/ neutron star - black hole mergers
- “wind” close to the center of a core-collapse supernova
Two kinds of r-process data: Observational and Meteoritic

Meteoritic: Isotopic measurements of \( r \)-process nuclei:

- two \( r \)-process sites?

Wasserburg, Busso and Gallino (1996)

Observational Halo Stars:

- two \( r \)-process sites?

Figure from Cowan and Sneden (2004)

What do the data suggest?

Supernovae are favored over neutron star mergers

Argast et al 2004
Core Collapse Supernovae

end of the life of a massive star

$M_{\text{core}} \sim 1.5M_{\odot}$

- core unstable
- collapse to nuclear density
- core bounce
- shock produced
- shock stalls
- neutrinos diffuse out of core, may energize shock
Supernova Explosion!

Figure from John Blondin
Explosions of Massive Stars:
What’s happening at the Center?

Standard core core collapse SN

Long duration gamma ray burst from core collapse SN or compact object merger
Explosions of Massive Stars: Where is the nuclear-neutrino physics?

Standard core core collapse SN

Long duration gamma ray burst from core collapse SN or compact object merger
Neutrinos from Standard Supernovae

All types of neutrinos are trapped in the core. At the surface they escape and travel through the outer layers of the SN, then to earth.

The Neutrino Sphere, near the surface of the proto-neutron star is where the neutrinos decouple. This is where the neutrino energies are determined.
Measuring the Supernova Neutrino Signal

Why? Neutrinos are our window deep into the core of the Supernova

Roughly the range is

- \( \langle E_{\nu\mu} \rangle = \langle E_{\bar{\nu}\mu} \rangle = \langle E_{\nu\tau} \rangle = \langle E_{\bar{\nu}\tau} \rangle = 16 - 25 \text{ MeV} \)
- \( \langle E_{\bar{\nu}e} \rangle = 12 - 18 \text{ MeV} \)
- \( \langle E_{\nu e} \rangle = 8 - 13 \text{ MeV} \)

Predictions of the spectral shape are different, too.
Supernova Neutrinos

Most neutrinos emitted during the first $\sim 10$ sec

Galactic supernovae estimated to occur $\sim 1$ every 30 years

Supernova neutrinos detected from SN1987a:

$\sim 20$ events observed in Kamiokande and IMB.
Returning to the uranium problem

We want to examine a supernova “wind” near the core

We want to know if it has a lot of neutrons . . .
The weak interaction

The only way to convert protons to neutrons and vice-versa

- beta decay \( n \rightarrow p + e^- + \bar{\nu}_e \)
- electron (neutrino) capture \( e^- + p \leftrightarrow n + \nu_e \)
- positron (antineutrino) capture \( e^+ + n \leftrightarrow p + \bar{\nu}_e \)

A few words about neutrinos . . .

They come in three flavors: \( \nu_e, \nu_\mu, \nu_\tau \) and have associated charged leptons \( e, \mu, \tau \)

The neutrinos have 10s of MeV energies, not enough to make muons or taus, so only the electron type change charge.
The weak interaction

So does the material have more protons or neutrons?

- electron (neutrino) capture \( e^- + p \leftrightarrow n + \nu_e \)
- positron (antineutrino) capture \( e^+ + n \leftrightarrow p + \bar{\nu}_e \)

Electrons and positrons are in equilibrium with the rest of the matter, the neutrinos are not.

i.e. the electrons are positrons are cooling as material moves away from the core, but the neutrino temperatures are fixed.

At some point the neutrino and antineutrino reactions begin to dominate
The weak interaction

So does the material have more protons or neutrons?

- electron (neutrino) capture \( e^- + p \leftrightarrow n + \nu_e \)
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Let’s try a network calculation

Reaction network calculation contains \( \sim 3000 \) elements and isotopes.

Takes as input temperature, density profiles . . .

Outputs an abundance pattern . . .

Recall that we want to match the data . . .
Core Collapse Supernovae: Nucleosynthesis in the Traditional Neutrino Driven Wind

Hoped for r-process site

What happened?
Not enough entropy $E_{\bar{\nu}_e}$'s too low
Most current simulations don’t work!
Nucleosynthesis in Hot Outflows

\[ n, p \rightarrow ^4\text{He} \rightarrow \text{iron peak nuclei} \rightarrow \text{heavier nuclei} \]
Nucleosynthesis in hot outflows

What matters?

- outflow timescale, milliseconds to seconds
- entropy $s \sim 20$ to $s \sim 400$
- electron fraction, $Y_e = \frac{P}{n+p}$, $Y_e \sim 0.1$ to $0.6$,

Electron fraction is set by the weak interactions:

$\nu_e + n \leftrightarrow p + e^-$, $\bar{\nu}_e + p \leftrightarrow n + e^+$

What about $\bar{\nu}_e + p \rightarrow n + e^+$ on left over protons?
Neutrino induced processes in proton rich winds in core collapse supernova

Antineutrino capture on left over protons produces p process elements

Frohlich et al 2011
But what about the r-process?
Core Collapse Supernovae: Nucleosynthesis in non-Traditional Neutrino Driven Winds

Other ideas:
- magnetic fields
- 3-D calculations
- compact object mergers

Active Sterile $\nu$ oscillations

Beun et al 2007
Compact Object Mergers:
Can they make the r-process?

- two neutrons stars spiral together
- or: a black hole and a neutron star spiral together
- a disk is formed
- some material is ejected from tails
- some material is blown off in a neutrino wind

Examine: neutrino wind from the disk
Neutrino Surfaces

Black Hole Neutron Star Merger

Accretion disk in neutrinos

Side view shows neutrino surfaces

Surman et al. 2008
Do you get to the r-process stage in this environment?

Hypothetical schematic of events in outflow
Uncertainties

- Astrophysical Environment
- Equation of state
- Neutrino Properties/Oscillations
- $\beta$-decay rates
- nuclear masses/capture rates
- fission rates/daughter products
Fission Cycling in the r-process

astrophysical data hints at fission cycling

fission cycling requires many neutrons

Very little data on the relevant fission rates and daughter products

Beun et al 2006, Beun et al 2008
Neutron Capture rates on the A=130 peak

Change the mass model (bottom) or vary the capture rates (top)

Nuclei in the 130 peak with neutron capture rates that effect a 5% or more change in the abundance distribution

Surman et al 2008
Neutron capture rates and the rare earth peak

Rare earth peak forms from combination of beta decay and neutron capture. Surman and Engel 1997

Neutron capture rates together with astrophysical conditions determine the rare earth peak. Entering precision era of abundance measurements → need better data and better analysis of astrophysical conditions.
Summary

- Supernova may be the site of the r-process (or not)
- Neutrinos play an important role in determining the type of elements formed in supernovae and compact object mergers
- Neutron capture as well as beta decay are important for future understanding the r-process
- Improvements in our understanding of nuclear physics will allow better constraints on the site of the r-process