Supernova Neutrino-Nucleus Physics and the r-process

- “standard” supernova neutrino properties
- oscillations: matter effects, neutrino background effects, uncertainties
- nuclear structure techniques, limitations
- nucleosynthesis: $\nu$ process effects in the r-process
Basic Supernova Neutrino Characteristics

- infall of Type II supernova, $\rho \gtrsim 10^{12}$ g/cm$^3$
  - $\tau^{\nu \text{ diffusion}} \gtrsim \tau^{\text{collapse}}$

- $3 \cdot 10^{53}$ ergs of gravitational energy trapped in protoneutron star

- after core bounce, neutrino diffuse outward
  - $\nu_e + \bar{\nu}_e \leftrightarrow \nu_\mu + \bar{\nu}_\mu$ etc. $\Rightarrow$ flavor equilibrium
  - $\Rightarrow$ rough equipartition of energy/flavor

- decoupling from matter flavor dependent
  - $\nu_x + e \leftrightarrow \nu_x + e : \sigma_{\nu_\mu} / \sigma_{\nu_e} \sim 1/6$
  - $\nu_e + n \leftrightarrow p + e^-$
  - $\bar{\nu}_e + p \leftrightarrow n + e^+$

- thus heavy flavors decouple at higher $\rho$, $T$
• resulting neutrino temperature hierarchy

\[ T_{\nu_\mu, \nu_\tau} \sim 8 \text{ MeV} \]
\[ T_{\bar{\nu}_e} \sim 4.5 \text{ MeV} \]
\[ T_{\nu_e} \sim 3.5 \text{ MeV} \]

but \( <L_{\nu_e}> \sim <L_{\nu_\mu}> \sim <L_{\nu_\tau}> \)

• details of this decoupling from the matter determines the precise temperature hierarchy

• \( \nu_e, \bar{\nu}_e \) hierarchy certainly important for the p/n chemistry of the “hot bubble” where r-process may occur

• in principle new physics (oscillations) could generate temperature inversions, affecting r-process conditions

• r-process products are ejected in an intense neutrino wind, altering nuclear distributions

• relevant parameter is the \( \nu \) fluence after r-process freezeout
• preSNO solar $\nu$ two-flavor solutions
- SNO: heavy flavor vs comprise 2/3rds of solar flux
- LMA probable solution; total flux agrees with SSM
• oscillations in matter can be strongly enhanced
• unique solution identified for SNO and other solar neutrino experiments: large mixing angle
• KamLAND $\bar{\nu}_e$ disappearance experiment confirmation of SNO results, narrowing uncertainty on $\delta m^2_{12}$
• observation of a distinct $\delta m^2_{23}$ in atmospheric neutrino oscillations
• mixing angle maximal (within errors)
• Chooz, Palo Verde searches for $\bar{\nu}_e$ disappearance on $\delta m^2_{23}$ length scales: limits on $\theta_{13}$
• net result is a determination of $\delta m_{12}^2$, $\theta_{12}$, $\delta m_{23}^2$, $\theta_{23}$

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \begin{pmatrix}
c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\
-s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta} & s_{23} c_{13} \\
s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta} & c_{23} c_{13}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
= \begin{pmatrix}
1 & c_{23} & s_{23} \\
c_{23} & s_{23} & -s_{23} \\
-s_{23} & c_{23} & 1
\end{pmatrix}
\begin{pmatrix}
c_{13} & s_{13} e^{-i\delta} \\
& & 1 \\
-s_{13} e^{i\delta} & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} \\
& & 1 \\
-s_{12} & c_{12} & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

atmospheric results: $\theta_{23} \sim 45^\circ$

$\nu_e$ disappearance results: $\sin \theta_{13} \leq 0.17$

solar results: $\theta_{12} \sim 30^\circ$
Implications for Supernovae

- have probed matter effects up to $\sim 100 \text{ g/cm}^3$ due to electrons; relevant densities in a supernovae range to $10^{12} \text{ g/cm}^3$ and involve enormous neutrino backgrounds
- do not know $\theta_{13}$, crucial supernova mixing angle
  - corresponds to deepest $\nu_e/\bar{\nu}_e$ crossing, naively at base of the carbon zone
  - transition adiabatic in a supernova to well below $10^{-3}$
  - do not know the sign of $\delta m_{13}$: ordinary hierarchy would lead to enhanced $\nu_\tau \leftrightarrow \nu_e$, inverted would lead to $\bar{\nu}_\tau \leftrightarrow \bar{\nu}_e$
- neutrino-neutrino scattering contribution of MSW potential:
  George Fuller
Nuclear Structure Issues

• Heavy flavor neutrinos have $\langle E \rangle \sim 3.1$ T $\sim 25$ MeV

• more energetic vs most effective for high-threshold nuclear reactions

• back-angle scattering (which dominates first-forbidden transitions) involve a $|\vec{q}|$ about twice $E_{eff}$
  ◯ consequently, $qR$ is not small

  ◯ generally one must evaluate both the allowed (GT) and first-forbidden (giant resonance) contributions to neutrino-nucleus scattering
Shell Model Efforts

- the shell model wave function contains only low-momentum components
- requires effective operators
- for complex nuclei, get this from experiment
- the effective GT operator (the allowed contribution) is relatively well understood phenomenologically
  
      $g_A \rightarrow g_A^{eff} \sim 1.0$ for full sd-shell calculations
- excellent progress (Lanczos, Monte Carlo SM approaches) in extending full or nearly full-shell calculations up to Fe/Ni region
• first-forbidden strengths important to neutral-current scattering more problematic

• best experimental tests comes electron scattering, but this fails to probe the important axial currents
  ◦ $qR$ vs. $qR \times \sigma$

• nothing as useful as allowed $\beta$ decay, (p,n) reactions to test theoretical estimates
  ◦ first-forbidden operators potentially more complicated because they couple components in a $0 + 1\hbar\omega$ space directly to excluded $(2\hbar\omega)$ space: no analog of the Ikeda sum rule in calculations

• techniques employed range from somewhat (QRPA) to very (Goldhaber-Teller model) schematic

• there are shell-model method-of-moments techniques under development for $F(q,\omega)$
strength in the \((p, n)\) channel. In symmetric nuclei with \(N = Z\) the Ikeda sum rule, unfortunately, does not help in fixing the Gamow-Teller strength.

To calculate the various partial neutrino-induced reaction cross sections for neutrino-induced reactions we assume a two-step process. In the first step we calculate the charged current \((\nu_l, l^-)\) and \((\bar{\nu}_l, l^+)\) cross sections (where \(l = e\) or \(\mu\)), or the neutral current cross section \((\nu, \nu')\) as a function of excitation energy in the final nucleus. These calculations are performed within the RPA or CRPA and considering all multipole operators up to a certain \(J\) and both parities. In the second step one calculates for each final state with well-defined energy the branching ratios into the various decay channels using the statistical model code SMOKER [12]. As possible final states in the residual nucleus the SMOKER code considers the experimentally known levels supplemented at higher energies by an appropriate level density formula [12]. Proton, neutron, \(\alpha\) and \(\gamma\) emission are included in the code as decay channels. If the decay leads to an excited level of the residual nucleus, the branching ratios for the decay of this state is calculated in an analogous fashion [13]. Keeping track of the energies of the ejected particles and photons during the cascade, and weighting them with appropriate branching ratios and the corresponding primary charged- or neutral-current cross sections, we determine the various partial particle emission cross sections.

II. COMPARISON OF DIFFERENT METHODS

Here we demonstrate, using the neutrino interaction with \(^{16}\text{O}\) as an illustration, how different theoretical methods can be used at different neutrino energies. We show that at certain transition energy intervals the corresponding methods give essentially identical results.

A. Shell model versus CRPA

![Graph showing comparison of CRPA and shell model cross sections for \(^{16}\text{O}(\bar{\nu}_e, e^+)X\) and \(^{16}\text{O}(\nu_e, e^-)X\) reactions.](image)

FIG. 1. Comparison of the CRPA (full lines) and shell model (dashed lines) cross sections. The upper panel is for the \(\bar{\nu}_e\) induced reaction and the lower one is for the reaction induced by \(\nu_e\).
The Neutrino Process

- Consider $\nu$ effects in the outer mantle

$$\nu + A \rightarrow \nu' + A'$$

$$\sigma \sim 3 \cdot 10^{-41} \text{ cm}^2/\text{flavor} \quad (\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau)$$

response governed by TRK sum rule

$$\sigma \propto NZ/A \sim A/4$$

- $\nu$ flux in middle of Ne shell

$$\phi \sim \frac{4 \cdot 10^{57}}{4\pi(20,000\text{km})^2} \sim 10^{38}/\text{cm}^2$$

$$\Rightarrow 1/300 \text{ of Ne nuclei excited by } (\nu, \nu')$$

- typical $\Delta E_{\text{excitation}} \sim 20 \text{ MeV}$

- $^{19}\text{F}$: only stable $\text{F}$ isotope

solar abundance $^{19}\text{F}/^{20}\text{Ne} \sim 1/3100$
• production by heavy flavor \( (\nu, \nu') \)

\[
^{20}\text{Ne}(\nu, \nu')^{20}\text{Ne}^* \rightarrow ^{19}\text{Ne} + n \rightarrow ^{19}\text{F} \quad 1/3
\]

\[
^{20}\text{Ne}(\nu, \nu')^{20}\text{Ne}^* \rightarrow ^{19}\text{F} + p \quad 2/3
\]

• Does the F survive?

\[10^{-8} \text{ sec} \Rightarrow \text{coproduced neutrons react}\]

eg, \(^{19}\text{Ne}(n, \alpha)^{16}\text{O} \quad ^{20}\text{Ne}(n, \gamma)^{21}\text{Ne} \quad ^{19}\text{Ne}(n, p)^{19}\text{F}\]

\[\uparrow\]

destroys 70% of \(^{19}\text{Ne}\)

\[10^{-6} \text{ sec} \Rightarrow \text{proton processing}\]

\(^{15}\text{N}(p, \alpha)^{12}\text{C} \quad ^{19}\text{F}(p, \alpha)^{16}\text{O} \quad ^{23}\text{Na}(p, \alpha)^{20}\text{Ne}\]

compete
shock wave $\Rightarrow$ heating destroys by $^{19}\text{F}(\gamma, \alpha)^{15}\text{N}$

$R \sim (1 - 3) \cdot 10^4 \text{ km} \Leftrightarrow T_{\text{peak}}^{\text{explosion}} \sim (2.5 - 1.0) \cdot 10^9 \text{ K}$

$^{19}\text{F}$ survives at $\lesssim 1.7 \cdot 10^9 \text{ K} \Leftrightarrow$ at large $R$

Treat all of this in a nuclear network code

$[^{19}\text{F}/^{20}\text{Ne}] \quad T_{\nu\mu/\nu\tau}^{\text{MeV}}$

<table>
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<th>$^{19}\text{F}/^{20}\text{Ne}$</th>
<th>$T_{\nu\mu/\nu\tau}^{\text{MeV}}$</th>
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Feedback: $^{19}\text{F}(p, \alpha)$ vs $^{23}\text{Na}(p, \alpha)$ (shown for solar Na)

$\Rightarrow$ crude $T_{\nu\mu}$ thermometer $T_{\nu\mu} \gtrsim 6 \text{ MeV}$

$\Rightarrow$ predicts that $^{23}\text{Na}$ is needed to produce $^{19}\text{F}$

$\Rightarrow$ $^{19}\text{F}$ production not really primary
Supernova event modeling:

- exponential $\nu$ flux, $\tau_\nu \sim 3$ sec;
- preprocessing at some fixed $r$;
- postprocessing after shock wave:
  - adiabatic expansion, $T$ declines exp.;
  - integrated into network for explosive synthesis;
  - integrated over galactic model

- introduce a neutrino cross section network
  - need cross section
  - need response as a function of $E_x$

- need spallation probabilities $P(i, E_x)$

- Significant productions: $^{19}$F, $^{11}$B, $^{10}$B, $^7$Li, $^{138}$La, $^{180}$Ta, $^{22}$Na, $^{26}$Al, $^{15}$N, $^{31}$P, $^{35}$Cl, $^{39,40}$K, $^{51}$V, $^{45}$Sc ...
Most recent work: Heger et al.

- improved treatment of progenitor star evolution (mass loss)
- reaction network extended from zinc to bismuth
- partial neutrino network, but some heavy-nucleus cross sections
- much improved treatment of spallation via SMOKER

Principal productions $^{11}\text{B}$, $^{19}\text{F}$, $^{138}\text{La}$, $^{180}\text{Ta}$

- $^{11}\text{B}$ slightly overproduced, but subject to uncertainties in $^{12}\text{C}(\alpha, \gamma)$
- $^{19}\text{F}$ slightly underproduced, but still consistent with supernova origin
- La produced from $^{138}\text{Ba}$ by charged currents: $\nu_e$ thermometer potentially
FIG. 14. Production factor of $^{11}$B, $^{19}$F, $^{138}$La and $^{180}$Ta relative to $^{16}$O in 15 $M_\odot$ (squares) and 25 $M_\odot$ (circles) stars (from [67]). The open (filled) symbols represent stellar evolution studies in which neutrino reactions on nuclei were excluded (included).

[16] The partial rates listed in Table II of Ref. [20] should be multiplied by a factor 1000.
new galactic abundance data

- Prochaska et al: solar B/O ratio in a star with 1/3 solar metallicity $\rightarrow$ primary metal-independent process
- low F/O ratio in two $\omega$ Centauri stars argues against AGB star production of F (Cunha et al.)
\( \nu \) process in the supernova “hot bubble” r-process (Qian et al.)

- favorable r-process conditions in last material (near mass cut) driven off by \( \nu \) wind
  - expanding, high entropy, n-rich gas
  - He synthesis, then \( \alpha \) process to a moderately heavy \( Z \)
  - produces an \( n/\text{seed} \) ratio \( \sim 100 \)
- resulting r-process material driven off by a neutrino wind
- produces a reasonable r-process distribution below \( A \sim 190 \)
- yield of \( 10^{-5} - 10^{-6} \) M_\( \\odot \) per event
- problems others may address: requirement of high entropies, \( \nu \) reactions scouring out needed neutrons, etc.
• characteristics of the hot-bubble r-process

  r-process T: $3 \cdot 10^9 k \rightarrow 1 \cdot 10^9 k$
  freezeout radius $\sim 600-1000$ km
  $L_\nu \sim (0.015-0.005) \cdot 10^{51}$ ergs/(100km)$^2$s
  $\tau \sim 3$ sec

• $\nu$ fluence after freezeout $\sim (0.045-0.015) \cdot 10^{51}$ ergs/(100km)$^2$

• up to an order of magnitude large fluence than encountered in Ne shell

• $\nu$-process signature distinctive because of loosely bound neutrons

  $(Z,N)(\nu, \nu')(Z,N-x) + xn$
• these isotopes generally not produced at this level by standard r-process calculations

• fit is at $1\sigma \Rightarrow$ consistent with $\nu$-process synthesis

• required fluences/flavor can be extracted

  $N = 82$ peak $0.031 \cdot 10^{51}$ ergs/(100km)$^2$
  $N = 126$ peak $0.015 \cdot 10^{51}$ ergs/(100km)$^2$

• fluences in good agreement with hot bubble fluences from Santa Cruz group’s calculations, hint of expansion of material off star

• places upper bound on $\nu$ fluence $\Rightarrow$ constraint on freezeout radius/ejection velocity
(L\nu/T^2)_0 = \left[10^{51} \text{ erg s}^{-1}/(100 \text{ km})^2\right]

\tau_{\text{dyn}} (s)

Allowed Conditions
At The Freeze-Out
Of The A \sim 130 Peak
Allowed Conditions

At The Freeze-Out

Of The $A \sim 195$ Peak
Conclusions

- potentially a lot of information on supernova environments could be derived from $\nu$ nucleosynthesis
- uncertainties include nuclear structure, basic neutrino parameters, and the $\nu - \nu$ contribution to the MSW potential
- r-process effects fascinating due to the low removal energies for the neutrons
- lots of related issues – $\beta$ and electron capture rates, $\nu$ energy deposition – depend on reliable techniques for $\nu$ cross section calculations
- any constraints we can place on the environment of the r-process will make future RIA data more valuable
- similarly, any RIA information on $\beta$ decay and strength distributions would test structure calculations in a region where we have few if any constraints