Supernova-neutrino nuclear responses for the stable Mo isotopes

Emanuel Ydrefors and Jouni Suhonen

Department of Physics
University of Jyväskylä, Finland

Neutrinos and Dark Matter in Nuclear Physics
Nara, Japan
June 14th, 2012
Neutrino-nucleus interactions crucial in supernova explosions and for the nucleosynthesis of heavy elements

Supernova neutrinos are important probes of
- Unknown supernova mechanisms
- Neutrino physics beyond the Standard Model, e.g. neutrino oscillations

Only observations so far from SN1987a
Knowledge about supernova-$\nu$ nuclear responses important both for the interpretation of future measurements and for supernova simulations.

Experimental data currently available only for $^{12}\text{C}$, $^{56}\text{Fe}$ and the deuteron.

Theoretical predictions of nuclear responses to neutrinos are thus indispensable.
The stable Mo isotopes

- $^{100}\text{Mo}$ is one of the proposed candidates for neutrinoless double-beta decay and has been used by e.g. the NEMO 3.
- MOON (Mo Observatory Of Neutrinos) experiment:
  - Double-beta decay studies using $^{100}\text{Mo}$
  - Detection of astrophysical neutrinos (supernova, solar)
  - The detector will either consist of enriched $^{100}\text{Mo}$ or (partly) of natural molybdenum
Neutrino-nucleus scattering

Neutral-current (NC) neutrino-nucleus scattering:

\[
\begin{align*}
&\text{lepton current } j_{\mu}^{\text{lept}} \\
&\quad \begin{array}{c}
k_{\mu}' \\
\nu' \\
\nu \\
k_{\mu} \\
p_{\mu} \\
p_{\mu}' \\
p_{\mu} \\
(A, Z)^* \\
(A, Z) \\
Z^0 \\
\end{array} \\
&\quad \begin{array}{c}
q_{\mu} \\
J_{\mu} \\
\end{array}
\end{align*}
\]

Charged-current (CC) neutrino-nucleus scattering:

\[
\begin{align*}
&\text{lepton current } j_{\mu}^{\text{lept}} \\
&\quad \begin{array}{c}
k_{\mu}' \\
\nu_{e}' \\
\nu_{e} \\
k_{\mu} \\
p_{\mu} \\
p_{\mu}' \\
p_{\mu} \\
(A, Z + 1) \\
(A, Z) \\
W^+ \\
\end{array} \\
&\quad \begin{array}{c}
q_{\mu} \\
J_{\mu} \\
\end{array}
\end{align*}
\]
Basic formalism for the $\nu$-nucleus scattering (CC case)

Donnelly-Walecka method:
- $Q^2 = -q_\mu q^\mu \ll M_W^2 \implies \langle f|H_{\text{eff}}|i\rangle = \frac{G}{\sqrt{2}} \int d^3x \langle e|j_{\mu}^{\text{lept}}|\nu\rangle \langle f|J^\mu|i\rangle$
- Multipole expansion of $\langle f|J^\mu|i\rangle$
- Nuclear-structure dependence contained in $(J_f || T_J || J_i)$,
  \[ T_J = T_J^V - T_J^A \] (V–A theory). $T_J$ one-body operator
- Flux-averaged cross section: $\langle \sigma_V \rangle = \frac{1}{T_v^3F_2(\alpha_V)} \int \frac{dE_V E_V^2 \sigma(E_V)}{1+\exp(E_V/T_v-\alpha)}$
Efficient algorithm for the calculation of NME’s

- $T_J(q)$ vary slowly with $q$ in the case of supernova neutrinos.
- Speed up calculations by use of barycentric Lagrange interpolation:

$$
(J_f \parallel T_J(q) \parallel J_i) = \frac{\sum_{k=0}^{n} \frac{w_k}{q-q_k} T_{ji}^f(q_k)}{\sum_{k=0}^{n} \frac{w_k}{q-q_k}}
$$

(1)

- For each final state $f$ the nuclear matrix elements only computed for $n$ values of $q$. Typically $n = 10 – 20$.
- Convenient choice of $q_k$: Chebyshev nodes
Inclusion of neutrino-flavor-conversion effects

- SN-neutrino detectors based on CC $\nu$-nucleus scattering only detect $\nu_e$ and $\bar{\nu}_e$ ($E_\nu \leq 100$ MeV).

- Due to interactions with the matter of the star the energy profile for the detected neutrinos (antineutrinos) is a superposition of the initial $\nu_e$ ($\bar{\nu}_e$) and $\nu_x$ ($\bar{\nu}_x$) spectra, i.e.

$$ F_{\nu_e} = pF^0_{\nu_e} + (1 - p)F^0_{\nu_x}, \quad F_{\bar{\nu}_e} = \bar{p}F^0_{\bar{\nu}_e} + (1 - \bar{p})F^0_{\bar{\nu}_x} $$ (2)

$$ p = \begin{cases} \sin^2 \theta_{13} & \text{Normal hierarchy,} \\ \sin^2 \theta_{12} & \text{Inverted hierarchy,} \end{cases} $$ (3)

and

$$ \bar{p} = \begin{cases} \cos^2 \theta_{12} & \text{Normal hierarchy,} \\ \sin^2 \theta_{13} & \text{Inverted hierarchy.} \end{cases} $$ (4)
Nuclear structure

- even-even isotopes: QRPA (NC), pnQRPA (CC)
- odd isotopes: MQPM (microscopic quasiparticle-phonon model)\textsuperscript{1}:
  - even-even ($A - 1$) nucleus used as reference nucleus
  - MQPM basis (neutron-odd nucleus): $|n; jm\rangle$, $|n\omega; jm\rangle$
  - Question: How large quasiparticle-phonon basis required to describe states with $E_{\text{exc}} \lesssim 15 - 20$ MeV?

\textsuperscript{1}J. Toivanen and J. Suhonen, Phys. Rev. C 57 (1998) 1237
Large scale calculations for $^{95,97}$Mo: Motivation

- Presumably these strong $1^+$ states in the even-even $A-1$ nucleus also are important for the (NC) $\nu$ scattering off the odd nucleus.
- This motivates MQPM calculations with a quasiparticle-phonon basis containing phonons having $E_\omega \leq 20$ MeV.
Calculations performed for $j \leq 9/2$, $J_\omega \leq 6$ and $E_\omega \leq 20$ MeV

Only small fraction of the final states contribute significantly to the cross sections
Results for $^{95}\text{Mo}$

- $3/2^+_1$ mainly a one-quasiparticle state ($\nu1d_{3/2}$)
- $\nu1d_{5/2} \rightarrow \nu1d_{5/2} \otimes \omega$ transitions where $\omega = 1^+_6, 1^+_7, 1^+_8$ play a crucial role for the transitions to high-lying states
- Similar conclusions for $^{97}\text{Mo}$
- Inclusion of high-lying QRPA excitations crucial in computations of $\nu$-scattering off odd open-shell nuclei
Neutral-current results for the Mo isotopes

<table>
<thead>
<tr>
<th>flavor</th>
<th>$\langle \sigma \rangle^{92}$</th>
<th>$\langle \sigma \rangle^{94}$</th>
<th>$\langle \sigma \rangle^{95}$</th>
<th>$\langle \sigma \rangle^{96}$</th>
<th>$\langle \sigma \rangle^{97}$</th>
<th>$\langle \sigma \rangle^{98}$</th>
<th>$\langle \sigma \rangle^{100}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>11.6</td>
<td>11.8</td>
<td>15.9</td>
<td>12.1</td>
<td>16.4</td>
<td>9.94</td>
<td>8.59</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>17.3</td>
<td>17.6</td>
<td>23.0</td>
<td>17.9</td>
<td>23.7</td>
<td>15.1</td>
<td>13.1</td>
</tr>
<tr>
<td>$\nu_\mu, \nu_\tau$</td>
<td>25.5</td>
<td>25.3</td>
<td>31.5</td>
<td>25.6</td>
<td>32.3</td>
<td>22.1</td>
<td>19.9</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu, \bar{\nu}</em>\tau$</td>
<td>22.7</td>
<td>22.7</td>
<td>28.6</td>
<td>23.0</td>
<td>29.4</td>
<td>20.0</td>
<td>17.7</td>
</tr>
</tbody>
</table>

**Table:** Averaged incoherent cross sections for the stable molybdenum isotopes in units of $10^{-42}$ cm$^2$

- Results similarly for $^{92,94,96}$Mo. Cross sections slightly smaller for $^{98,100}$Mo.
- The $1^+$ distributions experimentally not known for $E_{exc} > 5.0$ MeV. Calculations could thus be improved by future experiments ($\gamma$- or $p$ probes).
Charged-current $\nu$-nucleus scattering off $^{100}\text{Mo}$

<table>
<thead>
<tr>
<th></th>
<th>$\nu_e$</th>
<th>$\nu_{\text{ex}}^{\text{NH}}$</th>
<th>$\nu_{\text{ex}}^{\text{IH}}$</th>
<th>$\bar{\nu}_e$</th>
<th>$\bar{\nu}_{\text{ex}}^{\text{NH}}$</th>
<th>$\bar{\nu}_{\text{ex}}^{\text{IH}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXPWS</td>
<td>6.32</td>
<td>24.4</td>
<td>19.0</td>
<td>0.056</td>
<td>0.095</td>
<td>0.180</td>
</tr>
<tr>
<td>WS</td>
<td>7.27</td>
<td>25.4</td>
<td>20.0</td>
<td>0.066</td>
<td>0.111</td>
<td>0.210</td>
</tr>
</tbody>
</table>

**Table**: Computed averaged cross sections for the charged-current neutrino and antineutrino scatterings off $^{100}\text{Mo}$ in units of $10^{-41}$ cm$^2$.

- The $\nu$-cross section significantly increased by flavor conversions. Typically $\langle E_{\nu_e} \rangle = 11.5$ MeV and $\langle E_{\nu_x} \rangle = 16.3$ MeV.
- The cross sections notably smaller for the adjusted s.p. energies.
- The results however sensitive to the adopted supernova model (a factor of at least 2 – 3 depending on the chosen scenario).
Electron spectra from SN-ν scattering off $^{100}$Mo

- Number of events significantly increased by flavor conversions
- The produced spectra similar for both mass hierarchies
Small number of events

The difference between the two neutrino-mass scenarios more pronounced
Multipole contributions: $\nu$-scattering

- SN-$\nu$ cross sections dominated by allowed transitions ($0^+$ and $1^+$).
- Axial-vector transitions most important
Multipole contributions: \( \bar{\nu} \)-scattering

- \( 0^+ \) and \( 1^+ \) transitions suppressed (Pauli blocking). Note \( N - Z = 16 \) for \(^{100}\text{Mo}\)!
- \( 1^- \) and \( 2^- \) transitions important
The $\nu$ cross section increases with $A$. Opposite trend for the $\bar{\nu}$ cross section.

- Ikeda sum rule $S^-(1^+) - S^+(1^+) = 3(N - Z)$
- $Q_{EC}$: 0.168 MeV ($^{100}$Mo), 7.870 MeV ($^{92}$Mo)
- $Q_{\beta^-}$: 6.384 MeV ($^{100}$Mo), $-0.154$ MeV ($^{92}$Mo)
- SN-$\nu$ detector based on natural Mo could detect both $\nu_e$ and $\bar{\nu}_e$
Conclusions

- Knowledge about nuclear responses to supernova neutrinos essential for neutrino detection and applications in astrophysics.
- QRPA (MQPM) + DW formalism powerful framework for neutrino-nucleus calculations for even-even (odd) open-shell nuclei.
- High-lying QRPA excitations essential for the NC $\nu$-scattering off odd nuclei.
- $^{100}$Mo has a large CC cross section for neutrino scattering. The cross section for $\bar{\nu}$ however small. The use of natural molybdenum in the MOON would probably make $\bar{\nu}$ detection possible.

Outlook

- CC neutrino-nucleus scattering off $^{95,97}$Mo.
- Extension of calculations for odd nuclei to larger valence spaces (4 HO shells).
E. Ydrefors, K. G. Balasi, T. S. Kosmas and J. Suhonen, Submitted to NPA

