Theoretical calculations of neutrino-nucleus scattering for supernova neutrinos

Emanuel Ydrefors, P. Pirinen, W. Almosly and J. Suhonen

Instituto Tecnológico de Aeronáutica

Sixth International ICTP-SAIFR/CLAF Workshop for the Design of the ANDES Underground Laboratory
São Paulo, Finland
August 4-6, 2018
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-matter interactions and collective neutrino oscillations

Neutrino-nucleus interactions with neutrinos from astrophysical origins (e.g. the sun) could cause background events in future Dark Matter detectors.

Neutrino-nucleus scatterings with neutrinos from e.g. beta beams could also be used to study some of the intermediate states involved in double beta decays.
Schematic view of the NC and CC neutrino reactions:

\[ ^{136}_{53}\text{I}^{83}
\]
\[ ^{136}_{55}\text{Cs}^{81}
\]
\[ ^{136}_{54}\text{Xe}^{82}
\]
\[ ^{136}_{55}\text{Cs}^{81}_{\text{low}}
\]

\[ ^{136}_{54}\text{Xe}(\bar{\nu}_e, e^+)^{136}\text{I}
\]
\[ ^{136}_{55}\text{Xe}(\nu, \nu')^{136}\text{Xe}^*
\]
\[ ^{136}_{54}\text{Xe}(\nu_e, e^-)^{136}\text{Cs}
\]
Basic formalism for the $\nu$-nucleus scattering (CC case)

- State-by-state calculations with double-differential cross section $((J_i, \pi_i) \rightarrow (J_f, \pi_f))$:

$$
\frac{d^2\sigma_{i\rightarrow f}}{d\Omega dE_{\text{exc}}} = \frac{G^2 F(\pm Z_f, E_{k'}) |k'|E_{k'}}{\pi(2J_i + 1)} \left( \sum_J \sigma^J_{\text{CL}} + \sum_{J\geq 1} \sigma^J_{\text{T}} \right),
$$

(1)

$$
\sigma(E_\nu) = \sum_f \int d\Omega \frac{d^2\sigma_{i\rightarrow f}}{d\Omega dE_{\text{exc}}}
$$

(2)

- Nuclear-structure dependence contained in $(J_f \parallel T_J \parallel J_i)$, $T_J$ one-body operator. E.g. $j_0(qr)1$, $j_0(qr)\sigma$, $j_1(qr)[Y_1 \sigma]_2^-$

- Flux-averaged cross section:

$$
\langle \sigma_\nu \rangle = \int dE_\nu F_\nu(E_\nu) \sigma(E_\nu)
$$

(3)
Nuclear models

- QRPA (used for the NC scattering off an even-even nucleus):
  \[
  |\omega\rangle = Q^\dagger_\omega |\text{QRPA}\rangle, \tag{4}
  \]
  \[
  Q^\dagger_\omega = \sum_{a \leq a'} \sigma_{aa'}^{-1} (X^\omega_{aa'} [a^+_a a^+_a] J\omega M\omega + Y^\omega_{aa'} [\tilde{a}_a \tilde{a}_a] J\omega M\omega) \tag{5}
  \]

- pnQRPA (used for the CC scattering off an even-even nucleus)
  \[
  Q^\dagger_\omega = \sum_{pn} (X^\omega_{pn} [a^+_p a^+_n] J\omega M\omega + Y^\omega_{pn} [\tilde{a}_p \tilde{a}_n] J\omega M\omega) \tag{6}
  \]

- MQPM (odd nuclei)
  \[
  \Gamma^+_k (jm) = \sum_n Z^k_n a^+_n j m + \sum_{b\omega} Z^k_{b\omega} [a^+_b Q^\dagger_\omega] j m \tag{7}
  \]
Motivation:

- $^{136}$Xe is used by the EXO experiment in the search for neutrinoless double-beta decay.
- The proposed nEXO would contain 1-10 tonnes of $^{136}$Xe. Such a detector could also be used for studies of astrophysical neutrinos (from supernovae or the Sun).
- The $^{136}$Xe has a low Q-value for the CC neutrino scattering and a rather large low-energy nuclear response\(^1\).

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\(^1\) H. Ejiri and S. R. Elliot, arXiv: 1309.7957v1
\(^2\) E. Ydrefors et al, PRC 91 (2015) 014307
Transitions mediated by the $0^+$ (Fermi) and $1^+$ (Gamow-Teller) multipoles are the most crucial ones.

Spin-dipole type of transitions also important.
CC antineutrino scattering: multipole contributions

- "Allowed" transitions suppressed because $N - Z$ is large.
- Spin-dipole type of transitions more important
Number of events in a $^{136}$Xe-based detector

Most of the neutrino-induced events are CC ones. However, antineutrino events mostly caused by NC scatterings.

$$F_{\nu_{\text{ex}}} = p(E_{\nu}) F_{\nu_{\text{e}}}^0 + (1 - p(E_{\nu})) F_{\nu_{\text{x}}}^0$$
In the figure $T_{\text{max}}(10) = 1.65 \text{ keV}$, $T_{\text{max}}(25) = 10.3 \text{ keV}$ and $T_{\text{max}}(50) = 41.2 \text{ keV}$

Future detectors could probably be used to study SN neutrinos via this reaction.

Astrophysical neutrinos could cause events in DM detectors.
Incoherent mode: Large-scale calculations, roughly 30000 final states.
CC (anti)neutrino scattering for the Xe isotopes

<table>
<thead>
<tr>
<th>Target</th>
<th>$\nu_\text{e}$</th>
<th>$\nu^{\text{NH}}_{\text{ex}}$</th>
<th>$\nu^{\text{IH}}_{\text{ex}}$</th>
<th>$\bar{\nu}_\text{e}$</th>
<th>$\bar{\nu}^{\text{NH}}_{\text{ex}}$</th>
<th>$\bar{\nu}^{\text{IH}}_{\text{ex}}$</th>
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<tbody>
<tr>
<td>$^{128}\text{Xe}$</td>
<td>35.6</td>
<td>228</td>
<td>230</td>
<td>0.772</td>
<td>2.58</td>
<td>1.33</td>
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<tr>
<td>$^{129}\text{Xe}$</td>
<td>195</td>
<td>567</td>
<td>568</td>
<td>2.00</td>
<td>5.48</td>
<td>3.07</td>
</tr>
<tr>
<td>$^{130}\text{Xe}$</td>
<td>45.2</td>
<td>267</td>
<td>269</td>
<td>0.631</td>
<td>2.21</td>
<td>1.12</td>
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<tr>
<td>$^{131}\text{Xe}$</td>
<td>229</td>
<td>611</td>
<td>612</td>
<td>1.50</td>
<td>4.24</td>
<td>2.34</td>
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<tr>
<td>$^{132}\text{Xe}$</td>
<td>57.1</td>
<td>312</td>
<td>313</td>
<td>0.529</td>
<td>1.93</td>
<td>0.962</td>
</tr>
<tr>
<td>$^{134}\text{Xe}$</td>
<td>71.2</td>
<td>362</td>
<td>362</td>
<td>0.429</td>
<td>1.64</td>
<td>0.805</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>116</td>
<td>482</td>
<td>480</td>
<td>0.289</td>
<td>1.29</td>
<td>0.599</td>
</tr>
</tbody>
</table>

Table: Averaged cross sections in units of $10^{-42} \text{ cm}^2$.

- The neutrino cross sections increases with increasing $N - Z$. Opposite trend for antineutrinos.
- Larger cross sections for the odd-mass isotopes (different Q-values, richer low-lying spectra, non-zero spin of initial state)
- The cross sections are quite sensitive to the adopted neutrino mixing scenario, and if normal/inverted hierarchy is assumed.

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$^3$P. Pirinen, E. Ydrefors and J. Suhonen, in preparation.
Global properties of the neutrino-nucleus cross sections are of interest for astrophysical applications (supernova simulations, etc)

HFB+pnQRPA performed self-consistently in a HO basis containing 16 major HO shells

Computations with 9 different modern energy density functionals (Skyrme forces)

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4W. Almosly, PRC 89 (2014) 024308
Rather large discrepancies for $E_k \leq 30$ MeV. Three groups:

1. SkP and SLy5 (largest cross sections)
2. SkX, UDF0 and UDF1 (moderate cross sections)
3. the rest (smallest cross sections)

For the Bonn-A interaction (renormalized realistic interaction) the results are between 2 and 3.
Averaged cross sections $\langle \sigma \rangle = (4.83 - 16.70) \times 10^{-41}$ cm$^2$

The discrepancies mainly due to different predictions for the Gamow-Teller strength. For example, $E_{\text{GGT}} = 11.41 - 16.47$ MeV. Experimental value is $E_{\text{GGT}} = 14.5$ MeV$^5$.

No "simple" relation between the parameters of the EDF’s and the produced Gamow-Teller distributions. How can they be improved in order to better describe collective excited states?

$^5$H. Akimune et al, PLB 394 (1997) 23
Conclusions

- Knowledge about nuclear responses for neutrinos from supernovae and other astrophysical essential for neutrino detection and applications in astrophysics.
- A detector based on $^{136}$Xe or natural xenon (e.g. a large-scale EXO) provide an interesting alternative for studies of astrophysical neutrinos.
- Coherent neutrino scattering could be used to study supernova neutrinos if the small recoils can be detected.
- Next-generation DM detectors might reach a sensitivity where background events caused by coherent neutrino scatterings off nuclei could limit the discovery potential of the detector. It is thus important to get more precise understanding of that reactions.