Neutrino-nucleus scattering at supernova energies

Emanuel Ydrefors and Jouni Suhonen

University of Jyväskylä

NDM’15
Jyväskylä, Finland
June 1-5, 2015
Supernova neutrinos

- 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
- The only observations so far are the ones from SN1987a
Schematic view of the NC and CC neutrino reactions:
Basic formalism for the $\nu$-nucleus scattering (CC case)

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

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

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

- Nuclear-structure dependence contained in $(J_f || T_J || J_i)$, $T_J$ one-body operator. E.g. $j_0(qr)|1, j_0(qr)\sigma, j_1(qr)[\mathbf{Y}_1\sigma]_2$–

- Flux-averaged cross section:

$$\langle \sigma_\nu \rangle = \int dE_\nu F_\nu(E_\nu) \sigma(E_\nu) \quad (3)$$
Nuclear models

- QRPA (used for the NC scattering off an even-even nucleus):

\[ |\omega\rangle = Q^\dagger_\omega |\text{QRPA}\rangle, \]

\[ Q^\dagger_\omega = \sum_{a \leq a'} \sigma^{-1}_{aa'} (X^\omega_{aa'} [a^+_a a^+_a] J_{\omega M_{\omega}} + Y^\omega_{aa'} [\bar{a}_a \bar{a}_a'] J_{\omega M_{\omega}} ) \]  \hspace{1cm} (5)

- pnQRPA (used for the CC scattering off an even-even nucleus)

\[ Q^\dagger_\omega = \sum_{pn} (X^\omega_{pn} [a^+_p a^+_n] J_{\omega M_{\omega}} + Y^\omega_{pn} [\bar{a}_p \bar{a}_n] J_{\omega M_{\omega}} ) \]  \hspace{1cm} (6)

- MQPM (odd nuclei)

\[ \Gamma^+_k (jm) = \sum_n Z^k_{n} a^+_n j m + \sum_{b\omega} Z^k_{b\omega} [a^+_b Q^+_\omega] j m \]  \hspace{1cm} (7)
Results
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$^1$.

---

$^1$H. Ejiri and S. R. Elliot, arXiv: 1309.7957v1
$^2$E. Ydrefors et al, PRC 91 (2015) 014307
CC neutrino scattering: multipole contributions

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

\[ F_{\nu_{ex}} = p(E_{\nu})F_{\nu_{e}}^0 + (1 - p(E_{\nu}))F_{\nu_{x}}^0 \]
Motivation:

- $^{129}$Xe is of interest for detection of Dark Matter (e.g. XMASS).
- Coherent neutrino-nucleus scattering has a large cross section and could be used to detect e.g. supernova neutrinos.
- It requires the detection of nuclear recoils $T \lesssim 1$ keV:
  $$\langle T \rangle = \frac{2}{3 A m_N} E_{\nu}^2 \approx 0.55 - 14 \text{ keV} \text{ for } E_{\nu} = 10 - 50 \text{ MeV}.$$ But, this could be possible with future DM detectors.
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.
Incoherent mode: Large-scale calculations, roughly 30000 final states.

CC reactions in progress
Conclusions

- Knowledge about nuclear responses to supernova neutrinos 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.