Theoretical calculations of neutrino-nucleus scattering for supernova neutrinos

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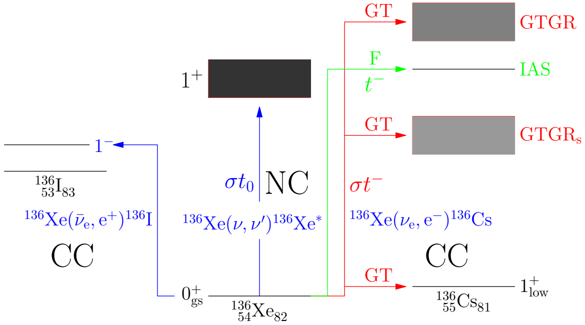
Motivation

- 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.

Neutrino-nucleus scattering (supernova neutrinos)

Schematic view of the NC and CC neutrino reactions:



Basic formalism for the ν-nucleus scattering (CC case)

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

$$\frac{d^2\sigma_{i\longrightarrow f}}{d\Omega dE_{\text{exc}}} = \frac{G^2 F(\pm Z_f, E_{\mathbf{k}'})|\mathbf{k}'|E_{\mathbf{k}'}}{\pi(2J_i+1)} \left(\sum_J \sigma_{\text{CL}}^J + \sum_{J\geqslant 1} \sigma_T^J \right), \tag{1}$$

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

- Nuclear-structure dependence contained in $(J_f \| T_J \| J_i)$, T_J one-body operator. E.g. $j_0(qr)\mathbf{1}$, $j_0(qr)\boldsymbol{\sigma}$, $j_1(qr)[\mathbf{Y}_1\boldsymbol{\sigma}]_{2^-}$
- Flux-averaged cross section:

$$\langle \sigma_\nu \rangle = \int dE_\nu F_\nu(E_\nu)\sigma(E_\nu) \tag{3}$$

Nuclear models

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

$$|\omega\rangle = Q_\omega^\dagger |\text{QRPA}\rangle, \tag{4}$$

$$Q_\omega^\dagger = \sum_{a \leqslant a'} \sigma_{aa'}^{-1} (X_{aa'}^\omega [a_a^\dagger a_{a'}^\dagger]_{J_\omega M_\omega} + Y_{aa'}^\omega [\tilde{a}_a \tilde{a}_{a'}]_{J_\omega M_\omega}) \tag{5}$$

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

$$Q_\omega^\dagger = \sum_{pn} (X_{pn}^\omega [a_p^\dagger a_n^\dagger]_{J_\omega M_\omega} + Y_{pn}^\omega [\tilde{a}_p \tilde{a}_n]_{J_\omega M_\omega}) \tag{6}$$

- MQPM (odd nuclei)

$$\Gamma_k^\dagger(jm) = \sum_n Z_n^k a_{njm}^\dagger + \sum_{b\omega} Z_{b\omega}^k [a_b^\dagger Q_\omega^\dagger]_{jm} \tag{7}$$

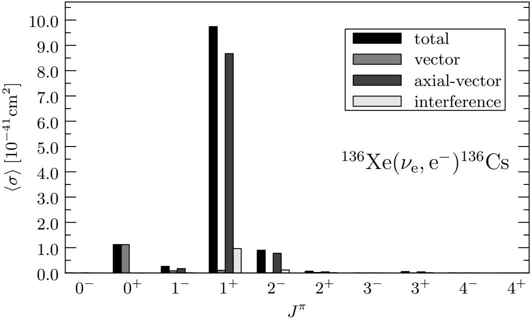
CC and NC neutrino-nucleus scattering off ^{136}Xe [2]

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].

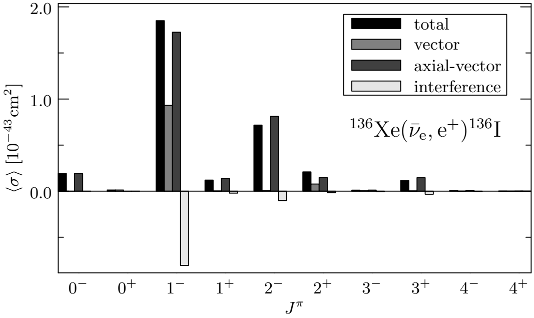
[1] H. Ejiri and S. R. Elliot, arXiv: 1309.7957v1
[2] E. Ydrefors et al, PRC 91 (2015) 014307

CC neutrino scattering: multipole contributions



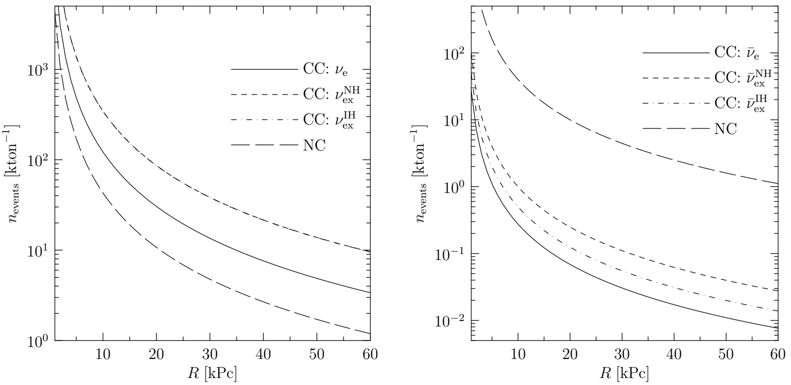
- Transitions mediated by the 0^+ (Fermi) and 1^+ (Gamow-Teller) multipoles are the most crucial ones
- Spin-dipole type of transtions also important

CC antineutrino scattering: multipole contributions



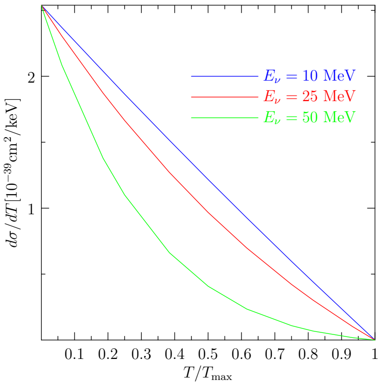
- "Allowed" transitions suppressed because $N - Z$ is large.
- Spin-dipole type of transitions more important

Number of events in a ^{136}Xe-based detector



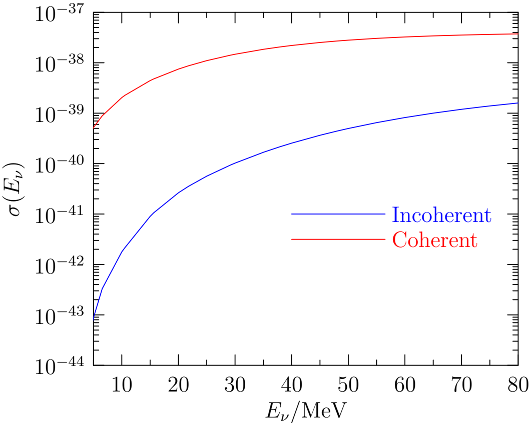
- $F_{\nu_{ex}} = p(E_\nu)F^0_{\nu_e} + (1 - p(E_\nu))F^0_{\nu_x}$
- Most of the neutrino-induced events are CC ones. However, antineutrino events mostly caused by NC scatterings.

Coherent neutrino scattering ^{129}Xe



- In the figure $T_{\mathrm{max}}(10) = 1.65$ keV, $T_{\mathrm{max}}(25) = 10.3$ keV and $T_{\mathrm{max}}(50) = 41.2$ keV
- Future detectors could probably be used to study SN neutrinos via this reaction.
- Astrophysical neutrinos could cause events in DM detectors.

NC ν scattering



- Incoherent mode: Large-scale calculations, roughly 30000 final states.

CC (anti)neutrino scattering for the Xe isotopes [3]

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

Table: Averaged cross sections in units of 10^{-42} 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 initital state)
- The cross sections are quite sensitive to the adopted neutrino mixing scenario, and if normal/inverted hierarchy is assumed.

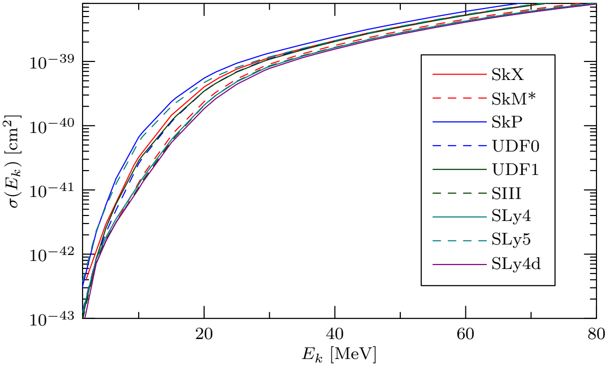
[3] P. Pirinen, E. Ydrefors and J. Suhonen, in preparation.

CC ν-nucleus scattering off ^{116}Cd with Skyrme forces[4]

- 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)

[4] W. Almosly, PRC 89 (2014) 024308

Results I



- Rather large discrepancies for $E_k \leqslant 30$ 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.

Results II

- 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, $E_{\mathrm{GGT}} = 11.41 - 16.47$ MeV. Experimental value is $E_{\mathrm{GGT}} = 14.5$ 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.