Neutrino-nucleus scattering at supernova energies

Emanuel Ydrefors and Jouni Suhonen

University of Jyväskylä

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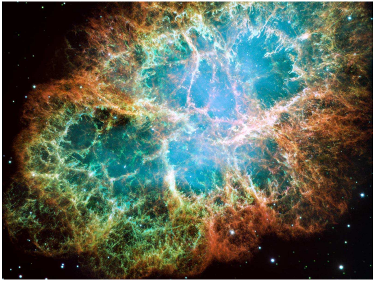
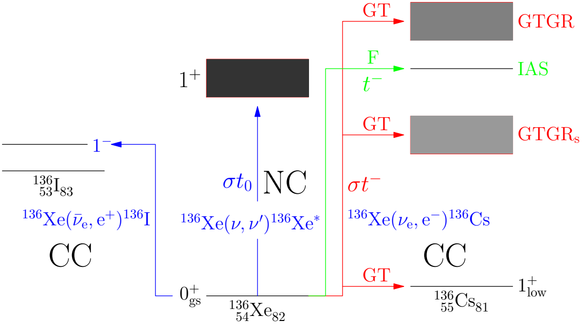
Supernova neutrinos



- 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

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 $((J_i, \pi_i) \longrightarrow (J_f, \pi_f))$:

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

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

- 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:

$$\langle \sigma_\nu \rangle = \int dE_\nu F_\nu(E_\nu)\sigma(E_\nu) \qquad (3)$$

Nuclear models

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

$$|\omega\rangle = Q^\dagger_\omega|\mathrm{QRPA}\rangle, \tag{4}$$

$$Q^\dagger_\omega = \sum_{a\leqslant a'} \sigma^{-1}_{aa'}(X^\omega_{aa'}[a^\dagger_a a^\dagger_{a'}]_{J_\omega M_\omega} + Y^\omega_{aa'}[\tilde{a}_a\tilde{a}_{a'}]_{J_\omega M_\omega}) \tag{5}$$

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

$$Q^\dagger_\omega = \sum_{pn}(X^\omega_{pn}[a^\dagger_p a^\dagger_n]_{J_\omega M_\omega} + Y^\omega_{pn}[\tilde{a}_p\tilde{a}_n]_{J_\omega M_\omega}) \tag{6}$$

- MQPM (odd nuclei)

$$\Gamma^\dagger_k(jm) = \sum_n Z^k_n a^\dagger_{njm} + \sum_{b\omega} Z^k_{b\omega}[a^\dagger_b Q^\dagger_\omega]_{jm} \tag{7}$$

Results

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

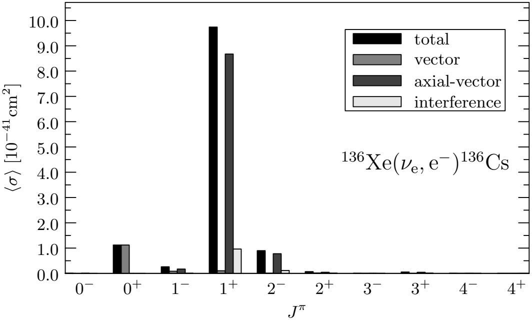
Motivation:

- ^{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

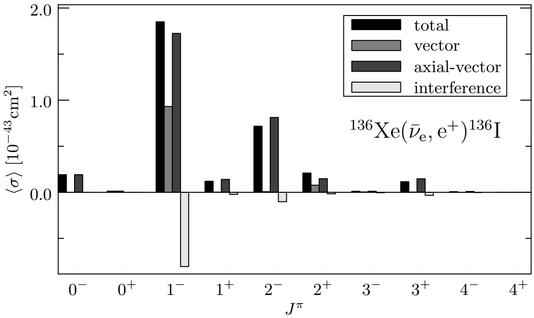
[2] E. Ydrefors et al, PRC 91 (2015) 014307

CC neutrino scattering: multipole contributions



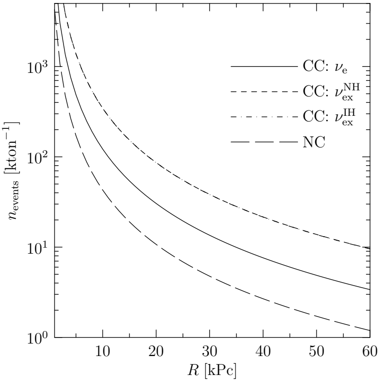
- Transitions mediated by the 0^+ (Fermi) and 1^+ (Gamow-Teller) multipoles are the most crucial ones
- Spin-dipole type of transtions also important

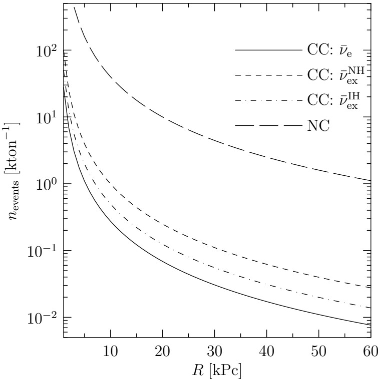
CC antineutrino scattering: multipole contributions



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

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





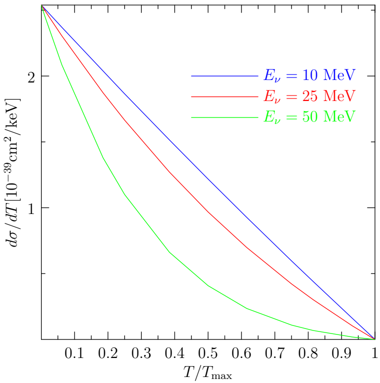
- $F_{\nu_{ex}} = p(E_\nu)F^0_{\nu_e} + (1 - p(E_\nu))F^0_{\nu_x}$
- Most of the neutrino-induced events are CC ones. However, antineutrino events mostly caused by NC scatterings.

Neutrino scattering off ^{129}Xe

Motivation:

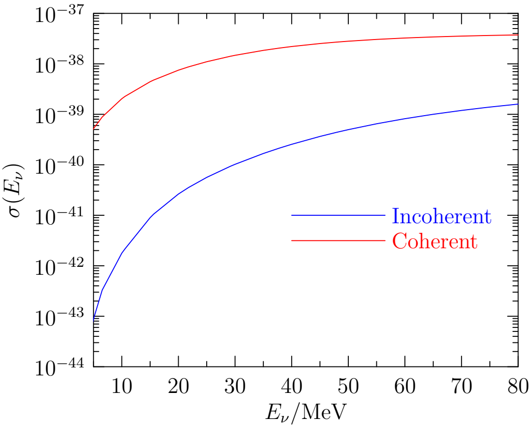
- ^{129}Xe is of interest for detection of Dark Matter (e.g. XMASS).
- Coherent neutrino-nucleus scattering has a large cross section and could be used to detect e.g. supernova neutrinos.
- It requires the detection of nuclear recoils $T \lesssim 1$ keV: $\langle T \rangle = \frac{2}{3Am_N} E_\nu^2 \approx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

Coherent neutrino scattering ^{129}Xe



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

NC ν scattering (preliminary results)



- 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.