Neutrino-nucleus scattering and supernova neutrinos

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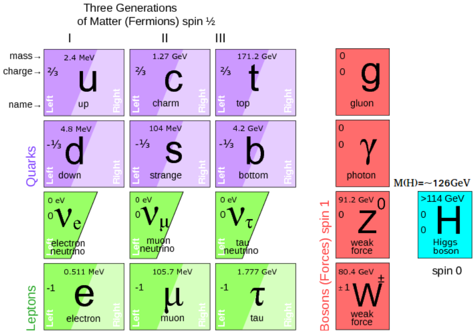
Outline

The Standard Model of particle physics

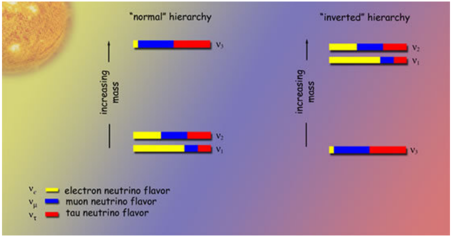
- The Standard Model has been proved to be extremely successful in describing the interactions between the fundamental particles.



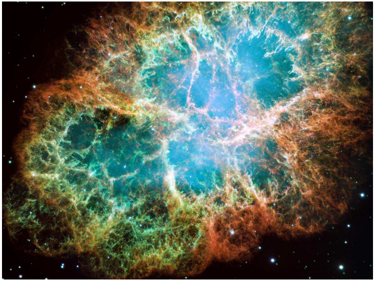
- However, observations of neutrino oscillations show that at least two of the neutrino masses are non-zero. Consequently, the theory is incomplete.

Neutrino oscillations

- As has been confirmed by observations the neutrinos "oscillate". Consequently, one has a mass basis (ν_1, ν_2 and ν_3) and a flavor basis ($\nu_l = \nu_{\mathrm{e}}, \nu_\mu, \nu_\tau$) connected by unitary transformation.
- However, the type of mass hierarchy (normal or inverted) is still an open question.



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

Supernova-neutrino nuclear responses

- Knowledge about supernova-ν nuclear responses important both for for the interpretation of future measurements and for supernova simulations
- Experimental data currently available only for ^{12}C, ^{56}Fe and the deuteron
- Theoretical predictions of nuclear responses to neutrinos are thus crucial

Neutrino-nucleus scattering I

- Charged-current reactions (inversed beta decays):

$$(A, Z) + \nu_{\mathrm{e}} \longrightarrow (A, Z+1) + \mathrm{e}^{-} \tag{1}$$

$$(A, Z) + \bar{\nu}_{\mathrm{e}} \longrightarrow (A, Z-1) + \mathrm{e}^{+} \tag{2}$$

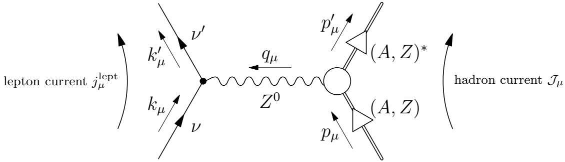
- Neutral-current reactions:

$$(A, Z) + \nu \longrightarrow (A, Z)^{*} + \nu \tag{3}$$

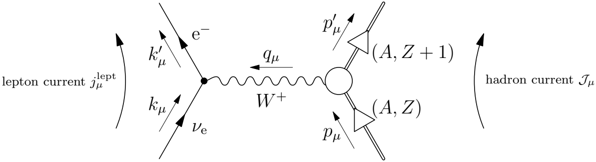
$$(A, Z) + \bar{\nu} \longrightarrow (A, Z)^{*} + \bar{\nu} \tag{4}$$

Neutrino-nucleus scattering II

Neutral-current (NC) neutrino-nucleus scattering:



Charged-current (CC) neutrino-nucleus scattering:



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

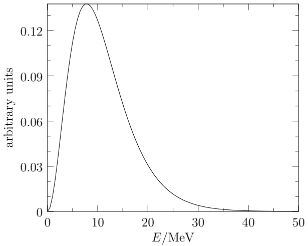
- $Q^2 = -q_\mu q^\mu \ll M_W^2$ means that the neutrino-nucleus scattering is described by point-like interaction and that the matrix element is separable into leptonic and hadronic parts.
- State-by-state calculations with double-differential cross section $((J_i, \pi_i) \longrightarrow (J_f, \pi_f))$:

$$\frac{\mathrm{d}^2\sigma_{i\longrightarrow f}}{\mathrm{d}\Omega \mathrm{d}E_{\mathrm{exc}}} = \frac{G^2 F(\pm Z_f, E_{\mathbf{k}'})|\mathbf{k}'|E_{\mathbf{k}'}}{\pi(2J_i + 1)} \left(\sum_J \sigma_{\mathrm{CL}}^J + \sum_{J\geqslant 1} \sigma_T^J \right) \quad (5)$$

- Nuclear-structure dependence contained in $(J_f \| T_J \| J_i)$, T_J one-body operator
- Flux-averaged cross section:

$$\langle \sigma_\nu \rangle = \int \mathrm{d}E_\nu F_\nu(E_\nu) \sigma(E_\nu) \quad (6)$$

Challenges in calculations of supernova-ν cross sections



- Transitions to final nuclear states with excitation energies $E \approx 10 - 20$ MeV or even more can contribute significantly to the cross sections.
- Consequently, both good nuclear models and efficient computer codes are required
- One further difficulty is that the involved states may not be very well-known experimentally.

Efficient algorithm for the calculation of NME's

- A very large amount of q-dependent nuclear matrix elements are required. Therefore, important to compute these NME's as fast as possible.
- $T_J(q)$ vary slowly with q in the case of supernova neutrinos.
- Barycentric Lagrange interpolation:

$$(J_f \| T_J(q) \| J_i) = \frac{\sum_{k=0}^{n} \frac{w_k}{q-q_k} T_J^{fi}(q_k)}{\sum_{k=0}^{n} \frac{w_k}{q-q_k}} \tag{7}$$

- 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

Nuclear structure: QRPA, pnQRPA and MQPM

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

$$|\omega\rangle = Q_\omega^\dagger |\mathrm{QRPA}\rangle, \tag{8}$$

$$Q_\omega^\dagger = \sum_{a\leqslant a'} \sigma_{aa'}^{-1} \left(X_{aa'}^\omega [a_a^\dagger a_{a'}^\dagger]_{J_\omega M_\omega} + Y_{aa'}^\omega [\tilde{a}_a \tilde{a}_{a'}]_{J_\omega M_\omega} \right) \tag{9}$$

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

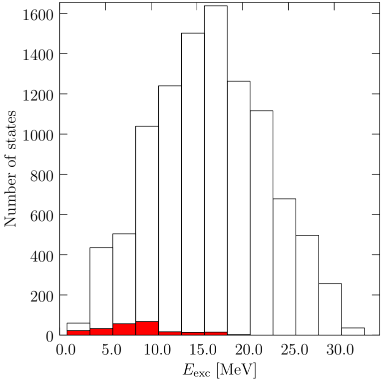
$$Q_\omega^\dagger = \sum_{pn} \left(X_{pn}^\omega [a_p^\dagger a_n^\dagger]_{J_\omega M_\omega} + Y_{pn}^\omega [\tilde{a}_p \tilde{a}_n]_{J_\omega M_\omega} \right) \tag{10}$$

- MQPM (microscopic quasiparticle-phonon model)[1]

$$\Gamma_k^\dagger(jm) = \sum_n X_n^k a_{njm}^\dagger + \sum_{a\omega} X_{a\omega}^k [a_a^\dagger Q_\omega^\dagger]_{jm} \tag{11}$$

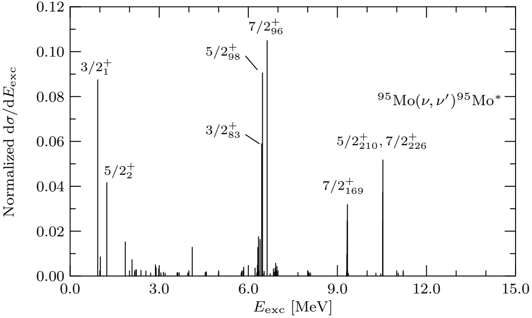
[1] J. Toivanen and J. Suhonen, Phys. Rev. C 57 (1998) 1237

NC scattering off ^{95,97}Mo: Calculations



- Calculations performed for $j \leqslant 9/2$, $J_\omega \leqslant 6$ and $E_\omega \leqslant 20$ MeV
- Only small fraction of the final states contribute significantly to the cross sections

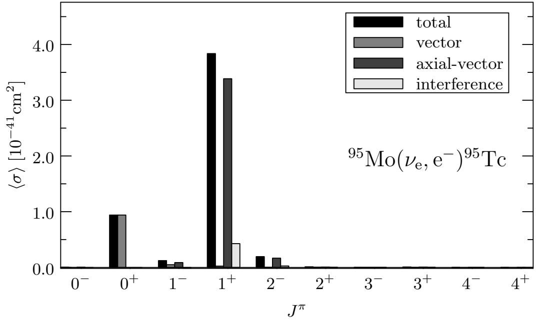
Results for ^{95}Mo[2]



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

[2]E. Ydrefors et al, NPA 896 (2012) 1

CC neutrino-nucleus scattering off ^{95,97}Mo[3]



- The charged-current neutrino-nucleus scattering dominated by Fermi-like $(j_0(qr)\tau_-)$ and Gamow-Teller-like $(j_0(qr)\sigma\tau_-)$ transitions
- Generally, the cross sections are very small: $10^{-41}\text{cm}^2 = 10^{-17}\ b$

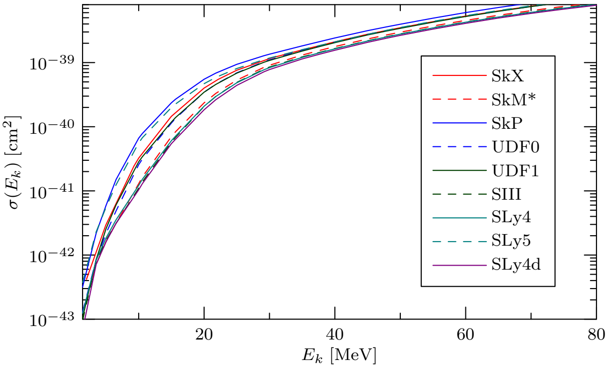
[3]E. Ydrefors and J. Suhonen, PRC 97 (2013) 034314

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)
- Large-scale calculations (15 HO shells) performed for modern energy density functionals.
- Collaboration with W. Almosly and the FIDIPRO group in Jyväskylä (J. Dobaczwski et al)

[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

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

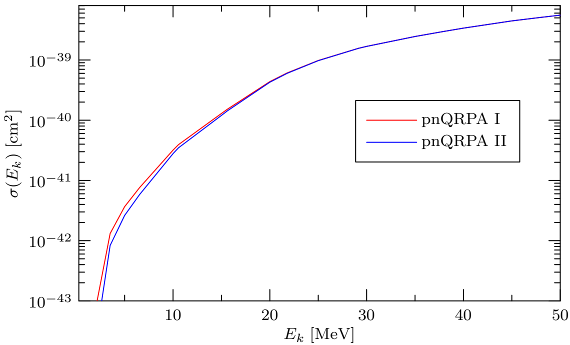
Motivation:

- ^{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.
- Furthermore, natural xenon is rather easy (and cheap) to purify into ^{136}Xe.

Calculations (CC scattering)

- Two-body matrix elements (Bonn-A interaction) scaled by two parameters: $g_{\rm pp}$ (particle-particle strength) and $g_{\rm ph}$ (particle-hole strength)
- For the supernova neutrinos 1^+ channel most important
- Typically, in the pnQRPA $g_{\rm ph}(1^+)$ determined from the energy of the giant Gamow-Teller resonance.
- The value of $g_{\rm pp}(1^+)$ is more difficult to determine. Sometimes single-beta decay half-lives or matrix elements related to two-neutrino double-beta decay are used.
- For ^{136}Xe is even more difficult since the beta-decay partners (^{136}Cs and ^{136}I) have non-1^+ ground states
- Therefore, it is relevant to study how sensitive the cross sections are to the value of $g_{\rm pp}$
- Calculations performed for $g_{\rm pp} = 1.0$ and $g_{\rm pp} = 0.6$.

Results: CC cross section



- The results for the two calculations differ for $E_k \leqslant 15$ MeV. However, the cross sections are almost independent of $g_{\rm pp}$ for $E_k > 15$ MeV.
- Knowledge about the value of $g_{\rm pp}$ is important for the nuclear response to low-energy neutrinos such as solar neutrinos, etc.

Results: Nuclear responses to supernova neutrinos

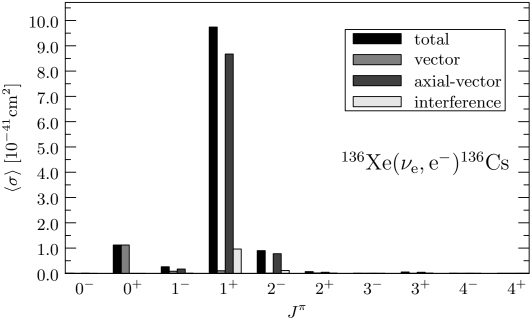
Neutral-current (10^{-42} cm^2):

ν_e	$\bar{\nu}_e$	ν_x	$\bar{\nu}_x$
5.31	9.30	26.5	22.6

Charged-current (10^{-40} cm^2):

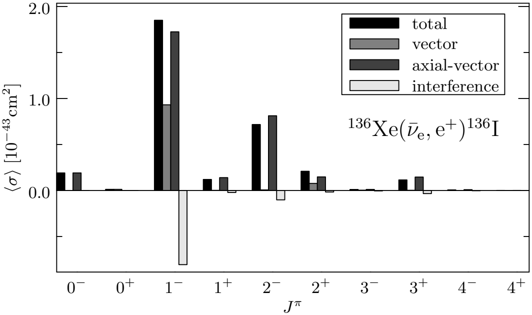
	ν_e	ν_{ey}^{NH}	ν_{ey}^{IH}	$\bar{\nu}_e$	$\bar{\nu}_{ey}^{NH}$	$\bar{\nu}_{ey}^{IH}$
pnQRPA I	1.21	4.87	4.86	3.24×10^{-3}	1.40×10^{-2}	6.57×10^{-3}
pnQRPA II	1.16	4.82	4.80	3.41×10^{-3}	1.43×10^{-2}	6.80×10^{-3}

CC antineutrino scattering: multipole contributions



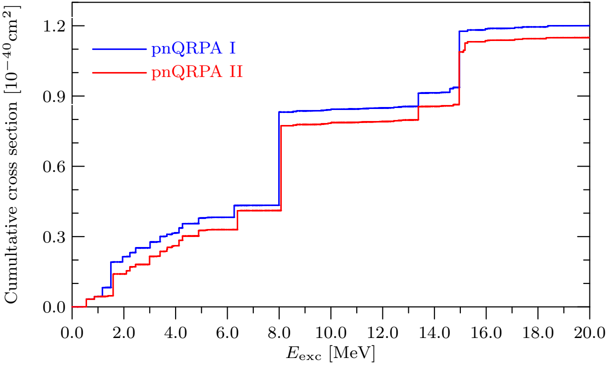
- Transitions mediated by the 0^+ (Fermi) and 1^+ (Gamow-Teller) multipoles are the most crucial ones
- Spin-dipole type of transtions also important

CC neutrino scattering: multipole contributions



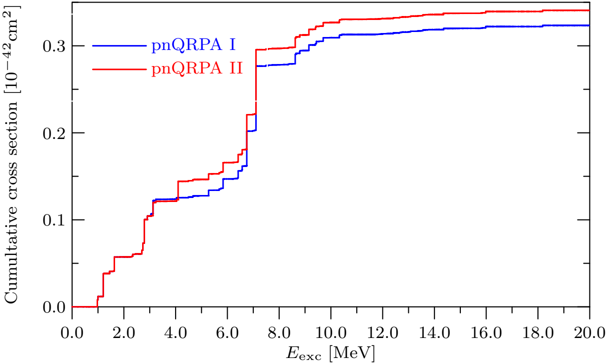
- "Allowed" transitions suppressed because $N - Z$ is large.
- Spin-dipole type of transitions more important

Final-state contributions to the CC ν cross sections



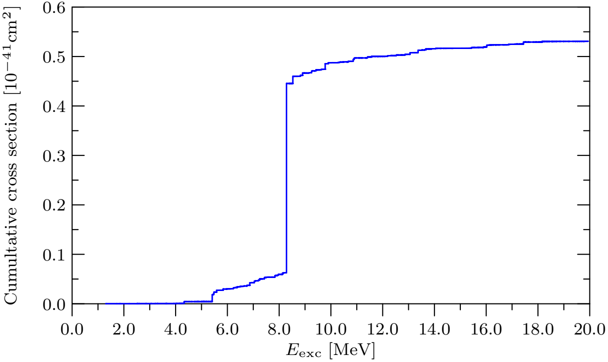
- Large contributions from the main peak of the GGT at $E_{\mathrm{exc}} \approx 15$ MeV and the smaller satellite at $E_{\mathrm{exc}} \approx 8$ MeV.
- Largest discrepancies for $E_{\mathrm{exc}} \leqslant 5$ MeV.

Final-state contributions to the CC $\bar{\nu}$ cross sections



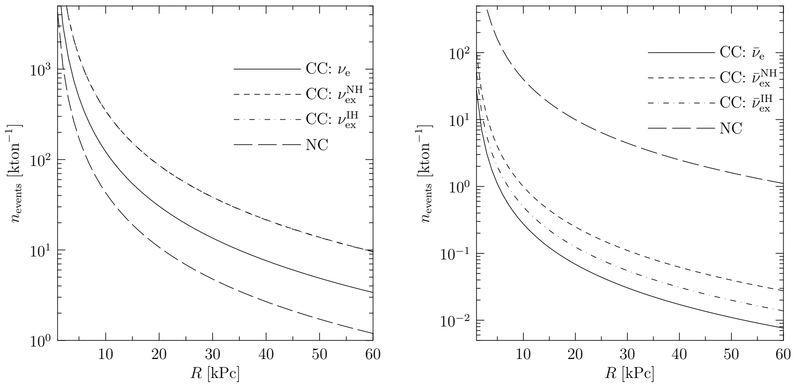
- Transitions to states with $E_{\text{exc}} \leqslant 10$ MeV.

Final-state contributions to the NC ν cross sections



- Neutral-current cross section is dominated by excitation of the M1 resonance at $E_{\text{exc}} = 8.3$ MeV.
- Unfortunately, no experimental data exist concerning the energy of this state.

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



- $n_{\text{events}} \sim 1/R^2$, R = distance to supernova
- Most of the neutrino-induced events are CC ones. However, antineutrino events mostly caused by NC scatterings.

Open questions related to neutrino-nucleus scattering

- How can the EDF's be improved in order to better describe Gamow-Teller distributions?
- What is the impact of positive energy s.p. states (resonanses and continuum)?
- What is the influence of deformation?
- Are higher-order components beyond the QRPA important?
- Many nuclear models (e.g. MQPM, shell-model) lead to many states which have small contributions to the cross sections. Are there better truncation schemes?

Conclusions

- Knowledge about nuclear responses to supernova neutrinos essential for neutrino detection and applications in astrophysics
- "Good" nuclear model + DW formalism powerful framework for neutrino-nucleus calculations for even-even (odd) open-shell nuclei
- High-lying QRPA excitations essential for the CC and NC ν-scatterings off odd nuclei
- ^{136}Xe has quite many advantageous properties which are relevant for studies of supernova neutrinos. For example, rather larger nuclear response for low-energy neutrinos, easy and cheap to purify, etc.