Supernova-neutrino nuclear responses for the stable Mo isotopes

Emanuel Ydrefors and Jouni Suhonen

Department of Physics
University of Jyväskylä, Finland

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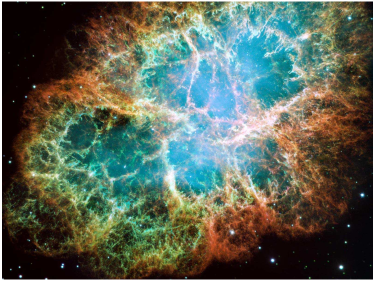
Supernova neutrinos



- 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 oscillations
- Only observations so far from SN1987a

Supernova-neutrino nuclear responses

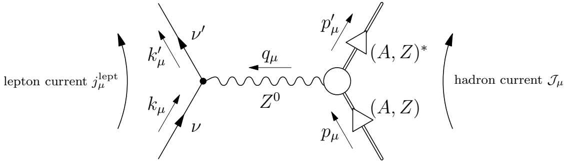
- Knowledge about supernova-ν nuclear responses important both for for the interpretation of future measurements and for supernova simulations
- Experimental data currently available only for ^{12}C, ^{56}Fe and the deuteron
- Theoretical predictions of nuclear responses to neutrinos are thus indispensable

The stable Mo isotopes

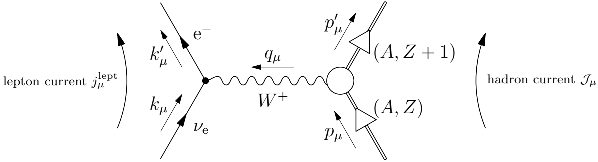
- ^{100}Mo is one of the proposed candidates for neutrinoless double-beta decay and has been used by e.g. the NEMO 3.
- MOON (Mo Observatory Of Neutrinos) experiment:
  - Double-beta decay studies using ^{100}Mo
  - Detection of astrophysical neutrinos (supernova, solar)
  - The detector will either consist of enriched ^{100}Mo or (partly) of natural molybdenum

Neutrino-nucleus scattering

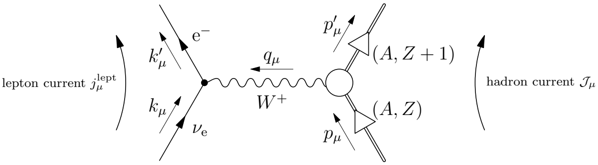
Neutral-current (NC) neutrino-nucleus scattering:



Charged-current (CC) neutrino-nucleus scattering:



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



- Donnelly-Walecka method:
  - $Q^2 = -q_\mu q^\mu \ll M_W^2 \implies \langle f|H_{\text{eff}}|i\rangle = \frac{G}{\sqrt{2}} \int \mathrm{d}^3x \langle \mathrm{e}|j_\mu^{\text{lept}}|\nu\rangle \langle f|\mathcal{J}^\mu|i\rangle$
  - Multipole expansion of $\langle f|\mathcal{J}^\mu|i\rangle$
  - Nuclear-structure dependence contained in $(J_f \| T_J \| J_i)$, $T_J = T_J^{\text{V}} - T_J^{\text{A}}$ (V$-$A theory). T_J one-body operator
- Flux-averaged cross section: $\langle \sigma_\nu \rangle = \frac{1}{T_\nu^3 F_2(\alpha_\nu)} \int \frac{\mathrm{d}E_\nu E_\nu^2 \sigma(E_\nu)}{1+\exp(E_\nu/T_\nu - \alpha)}$

Efficient algorithm for the calculation of NME's

- $T_J(q)$ vary slowly with q in the case of supernova neutrinos.
- Speed up calculations by use of barycentric Lagrange interpolation:

$$(J_f \| T_J(q) \| J_i) = \frac{\sum_{k=0}^{n} \frac{w_k}{q-q_k} T_J^{fi}(q_k)}{\sum_{k=0}^{n} \frac{w_k}{q-q_k}} \tag{1}$$

- 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

Inclusion of neutrino-flavor-conversion effects

- SN-neutrino detectors based on CC ν-nucleus scattering only detect ν_e and $\bar{\nu}_e$ ($E_\nu \leqslant 100$ MeV).
- Due to interactions with the matter of the star the energy profile for the detected neutrinos (antineutrinos) is a superposition of the initial ν_e ($\bar{\nu}_e$) and ν_x ($\bar{\nu}_x$) spectra, i.e.

$$F_{\nu_e} = pF^0_{\nu_e} + (1-p)F^0_{\nu_x},\ F_{\bar{\nu}_e} = \bar{p}F^0_{\bar{\nu}_e} + (1-\bar{p})F^0_{\bar{\nu}_x} \tag{2}$$

$$p = \begin{cases} \sin^2\theta_{13} & \text{Normal hierarchy,} \\ \sin^2\theta_{12} & \text{Inverted hierarchy,} \end{cases} \tag{3}$$

and

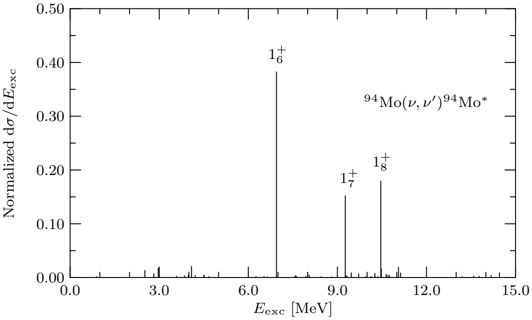
$$\bar{p} = \begin{cases} \cos^2\theta_{12} & \text{Normal hierarchy,} \\ \sin^2\theta_{13} & \text{Inverted hierarchy.} \end{cases} \tag{4}$$

Nuclear structure

- even-even isotopes: QRPA (NC), pnQRPA (CC)
- odd isotopes: MQPM (microscopic quaisparticle-phonon model)[1]:
  - even-even $(A-1)$ nucleus used as reference nucleus
  - MQPM basis (neutron-odd nucleus): $|n;jm\rangle$, $|n\omega;jm\rangle$
  - *Question: How large quasiparticle-phonon basis required to describe states with* $E_{exc} \lesssim 15-20$ *MeV?*

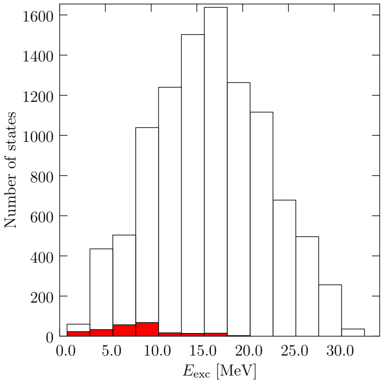
[1] J. Toivanen and J. Suhonen, Phys. Rev. C 57 (1998) 1237

Large scale calculations for ^{95,97}Mo: Motivation



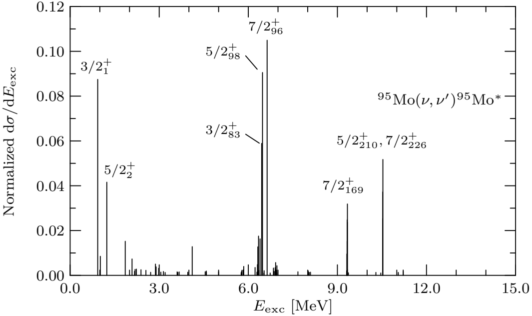
- Presumably these strong 1^+ states in the even-even $A-1$ nucleus also are important for the (NC) ν scattering off the odd nucleus
- This motivates MQPM calculations with a quasiparticle-phonon basis containing phonons having $E_\omega \leqslant 20$ MeV

Large scale calculations for ^{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



- $3/2^+_1$ 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

Neutral-current results for the Mo isotopes

flavor	$\langle\sigma\rangle^{92}$	$\langle\sigma\rangle^{94}$	$\langle\sigma\rangle^{95}$	$\langle\sigma\rangle^{96}$	$\langle\sigma\rangle^{97}$	$\langle\sigma\rangle^{98}$	$\langle\sigma\rangle^{100}$
ν_e	11.6	11.8	15.9	12.1	16.4	9.94	8.59
$\bar{\nu}_e$	17.3	17.6	23.0	17.9	23.7	15.1	13.1
ν_μ, ν_τ	25.5	25.3	31.5	25.6	32.3	22.1	19.9
$\bar{\nu}_\mu, \bar{\nu}_\tau$	22.7	22.7	28.6	23.0	29.4	20.0	17.7

Table: Averaged incoherent cross sections for the stable molybdenum isotopes in units of 10^{-42} cm^2

- Results similarly for ^{92,94,96}Mo. Cross sections slightly smaller for ^{98,100}Mo
- The 1^+ distributions experimentally not known for $E_{exc} > 5.0$ MeV. Calculations could thus be improved by future experiments ($\gamma-$ or p probes).

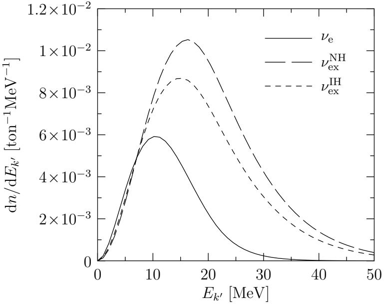
Charged-current ν-nucleus scattering off ^{100}Mo

	ν_e	ν_{ex}^{NH}	ν_{ex}^{IH}	$\bar{\nu}_e$	$\bar{\nu}_{ex}^{NH}$	$\bar{\nu}_{ex}^{IH}$
EXPWS	6.32	24.4	19.0	0.056	0.095	0.180
WS	7.27	25.4	20.0	0.066	0.111	0.210

Table: Computed averaged cross sections for the charged-current neutrino and antineutrino scatterings off ^{100}Mo in units of 10^{-41} cm^2.

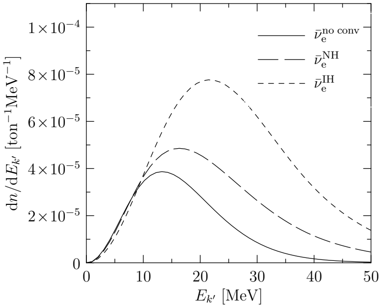
- The ν-cross section significantly increased by flavor conversions. Typically $\langle E_{\nu_e} \rangle = 11.5$ MeV and $\langle E_{\nu_x} \rangle = 16.3$ MeV
- The cross sections notably smaller for the adjusted s.p. energies.
- The results however sensitive to the adopted supernova model (a factor of at least $2 - 3$ depending on the chosen scenario).

Electron spectra from SN-ν scattering off ^{100}Mo



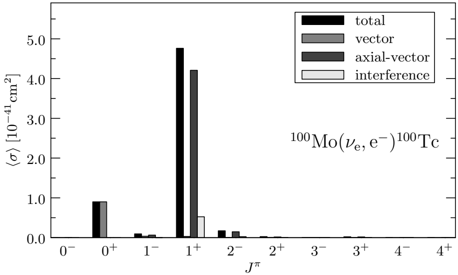
- Number of events significantly increased by flavor conversions
- The produced spectra similar for both mass hierarchies

Positron spectra from SN-$\bar{\nu}$ scattering off ^{100}Mo



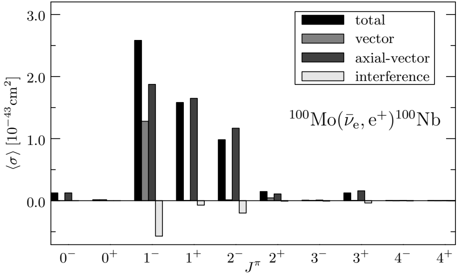
- Small number of events
- The difference between the two neutrino-mass scenarios more pronounced

Multipole contributions: ν-scattering



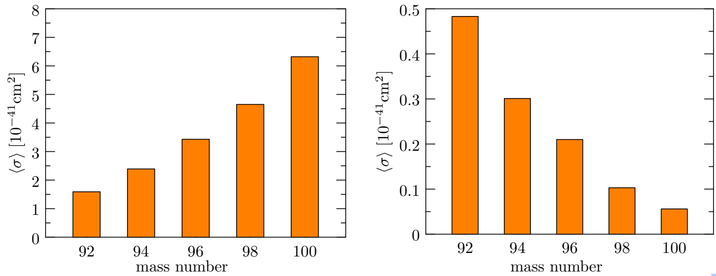
- SN-ν cross sections dominated by allowed transitions (0^+ and 1^+).
- Axial-vector transitions most important

Multipole contributions: $\bar{\nu}$-scattering



- 0^+ and 1^+ transitions suppressed (Pauli blocking). Note $N - Z = 16$ for ^{100}Mo!
- 1^- and 2^- transitions important

Variation with mass number



ν_e $\bar{\nu}_e$

- The ν cross section increases with A. Opposite trend for the $\bar{\nu}$ cross section
- Ikeda sum rule $S^-(1^+) - S^+(1^+) = 3(N - Z)$
- Q_{EC}: 0.168 MeV (^{100}Mo), 7.870 MeV (^{92}Mo)
- Q_{β^-}: 6.384 MeV (^{100}Mo), -0.154 MeV (^{92}Mo)
- SN-ν detector based on natural Mo could detect both ν_e and $\bar{\nu}_e$

Conclusions

- Knowledge about nuclear responses to supernova neutrinos essential for neutrino detection and applications in astrophysics
- QRPA (MQPM) + DW formalism powerful framework for neutrino-nucleus calculations for even-even (odd) open-shell nuclei
- High-lying QRPA excitations essential for the NC ν-scattering off odd nuclei
- ^{100}Mo has a large CC cross section for neutrino scattering. The cross section for $\bar{\nu}$ however small. The use of natural molybdenum in the MOON would probably make $\bar{\nu}$ detection possible.
- Outlook
  - CC neutrino-nucleus scattering off ^{95,97}Mo
  - Extension of calculations for odd nuclei to larger valence spaces (4 HO shells)

Related publications

- E. Ydrefors, K. G. Balasi , T. S. Kosmas and J. Suhonen, Submitted to NPA
- E. Ydrefors, "Supernova-neutrino induced reaction on molybdenum using neutral currents", Ph.D thesis, 2012
- E. Ydrefors, K. G. Balasi, T. S. Kosmas and J. Suhonen, NPA 866 (2011) 67
- K. G. Balasi, E. Ydrefors and T. S. Kosmas, NPA 868-869 (2011) 82