Neutrino-Nucleus Scattering at Astrophysical Energies

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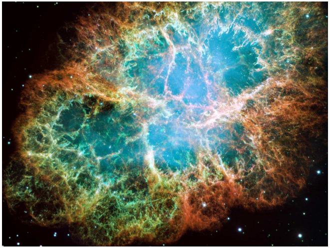
Contents:

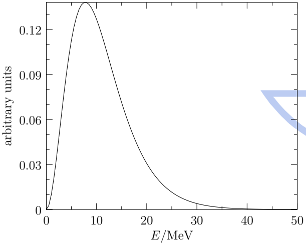
- INTRO: Motivation, Theory framework
- Results for folded cross sections
- Effects of neutrino oscillations

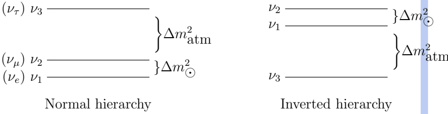
Supernova neutrinos: Motivation for studies, theory framework and nuclear-structure models

Supernova neutrinos



Neutrino-nucleus interactions are crucial in supernova explosions and for the nucleosynthesis of heavy elements





Important probes of:

- Unknown supernova mechanisms, ν and $\bar{\nu}$ energy profiles
- Neutrino physics beyond the Standard Model, e.g. neutrino oscillations in (dense) matter and the neutrino mass hierarchy
- Only observations so far from SN1987a

Supernova-neutrino-nuclear responses

Importance:

- Knowledge about supernova-ν-nuclear responses needed 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

Basic formalism for the ν-nucleus scattering

- Donnelly-Walecka method:
  - $Q^2 = -q_\mu q^\mu \ll M_W^2 \implies \langle f|H_{\rm eff}|i\rangle = \frac{G}{\sqrt{2}} \int {\rm d}^3x \langle {\rm e}|j_\mu^{\rm lept}|\nu\rangle \langle f|\mathcal{J}^\mu|i\rangle$
  - Multipole expansion of $\langle f|\mathcal{J}^\mu|i\rangle$
  - Nuclear-structure dependence contained in $(J_f\|T_J\|J_i)$, $T_J = T_J^{\rm V} - T_J^{\rm A}$ (V−A theory). T_J one-body operator

$\Rightarrow \sigma(E_\nu)$

- Need flux-averaged cross section: $\langle \sigma_\nu \rangle =$

$$\int {\rm d}E_\nu E_\nu^2 F_\nu(E_\nu)\sigma(E_\nu) = \frac{1}{T_\nu^3 F_2(\alpha_\nu)} \int \frac{{\rm d}E_\nu E_\nu^2 \sigma(E_\nu)}{1+\exp(E_\nu/T_\nu - \alpha_\nu)}$$

(Folding with the energy profile $F(E_\nu)$ of the ν and $\bar{\nu}$ flavors)

Flavor	$\nu_{\rm e}$	$\bar{\nu}_{\rm e}$	ν_μ, ν_τ	$\bar{\nu}_\mu, \bar{\nu}_\tau$
T (MeV)	$2-4$	$4-5$	$6-8$	$6-8$
α_ν	$0-3$	$0-3$	$0-3$	$0-3$

Table: Flavor Fermi-Dirac parameters (M.T. Keil and G.G. Raffelt, Astrophys. J. 590 (2003) 971)

Progress thus far

The Bonn-A interaction

- CC and NC scattering on ^{92,94,96,98,100}Mo studied by the QRPA
- CC and NC scattering on ^{95,97}Mo studied by the MQPM (Microscopic Quasiparticle-Phonon model)
- Important for the MOON (Mo Observatory Of Neutrinos) experiment

The Bonn-A interaction

- CC and NC scattering on ^{106,108,110,112,114,116}Cd studied by the QRPA
- CC and NC scattering on ^{111,113}Cd studied by the MQPM (Microscopic Quasiparticle-Phonon model)
- Interesting for the COBRA (cadmium-telluride experiment)

The Skyrme interactions

- CC scattering on ^{116}Cd studied by the HOSPHE (pnQRPA)
- NC and CC scattering on ^{204,206,208}Pb studied by the HOSPHE (important for the HALO experiment)

Nuclear-structure ingredients

- Even-even nuclei: QRPA (NC), pnQRPA (CC) in Woods-Saxon single-particle basis with Bonn-A interaction (not self-consistent) ; in 15 HO major shells with Skyrme interactions (self-consistent)
- Odd nuclei: MQPM (microscopic quasiparticle-phonon model)[1]:
  - Even-even $(A-1)$ nucleus used as reference nucleus
  - MQPM basis (neutron-odd nucleus): $|n;jm\rangle$, $|n\omega;jm\rangle$, which form a non-orthogonal and over-complete basis set for the MQPM diagonalization.
  - Schematically: $^{95}\mathrm{Mo} = {}^{94}\mathrm{Mo} \otimes n$, etc.
  - After diagonalization the states of an odd-A nucleus are linear combinations of one-quasiparticle states and quasiparticle-phonon states, i.e.

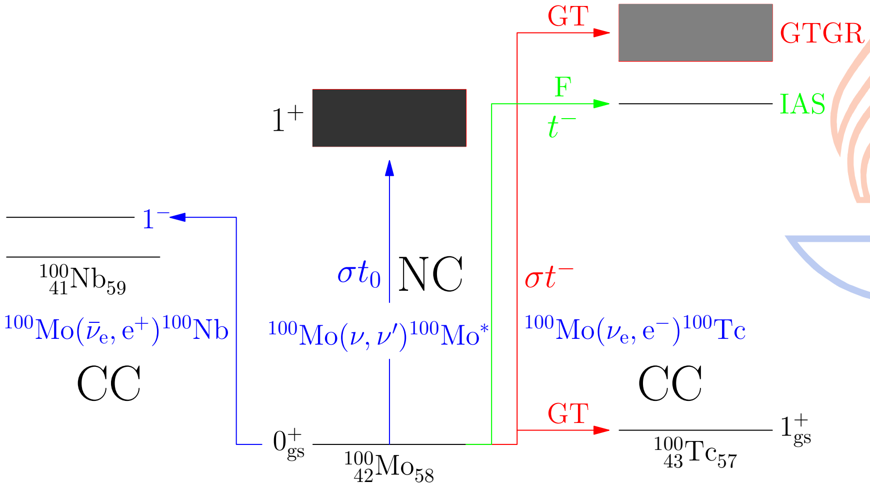
$$\Gamma_k^\dagger(jm) = \sum_n X_n^k a_{njm}^\dagger + \sum_{a\omega} X_{a\omega}^k [a_a^\dagger Q_\omega^\dagger]_{jm} \,. \quad (1)$$

  - *Question: How large a quasiparticle-phonon basis is required to describe states with $E_{\mathrm{exc}} \lesssim 15-20$ MeV?*

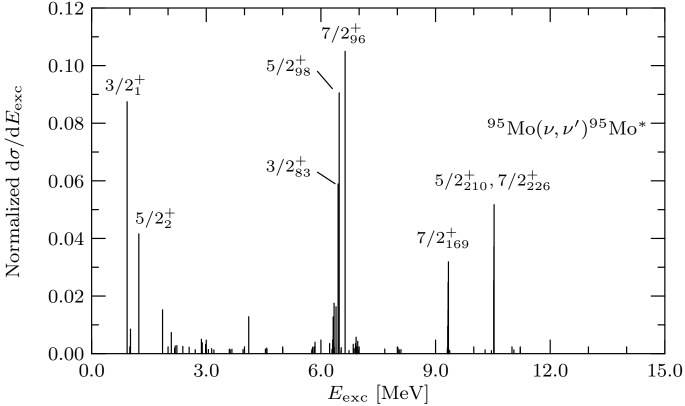
[1] J. Toivanen and J. Suhonen, Phys. Rev. C 57 (1998) 1237

Supernova-neutrinos:
Nuclear-structure aspects and results for cross sections

Isospin and spin-isospin properties of excitations of ^{100}Mo

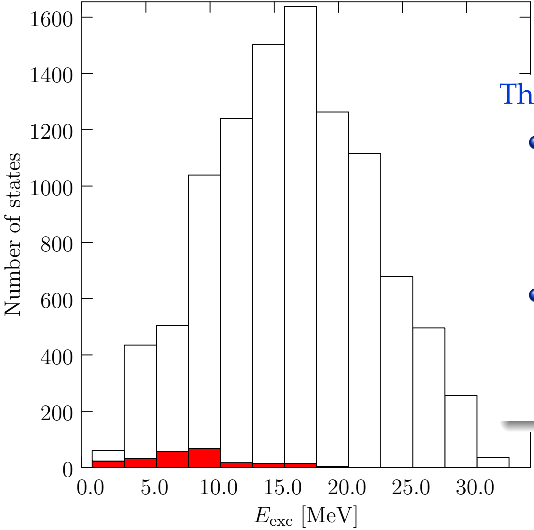


NC results for ν_e scattering off ^{95}Mo (MQPM)



- $3/2^+_1$ mainly a one-quasiparticle state ($\nu 1d_{3/2}$)
- Inclusion of high-lying QRPA excitations crucial in computations of ν-scattering off odd-A open-shell nuclei

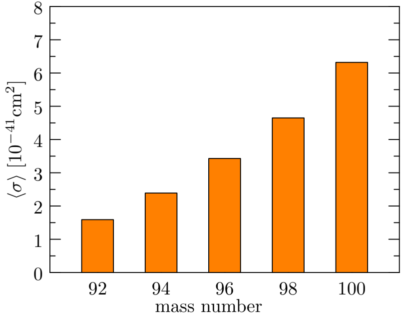
Large-scale MQPM calculations for ^{95}Mo (NC)



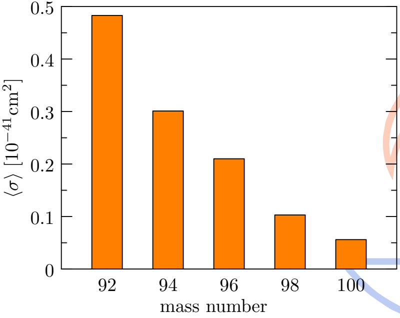
The MQPM procedure:

- A quasiparticle-phonon basis containing phonons having $E_\omega \leqslant 20$ MeV
- Only a small fraction of the final states contribute significantly to the cross sections

Folded CC cross sections for the Mo isotopes



ν_e



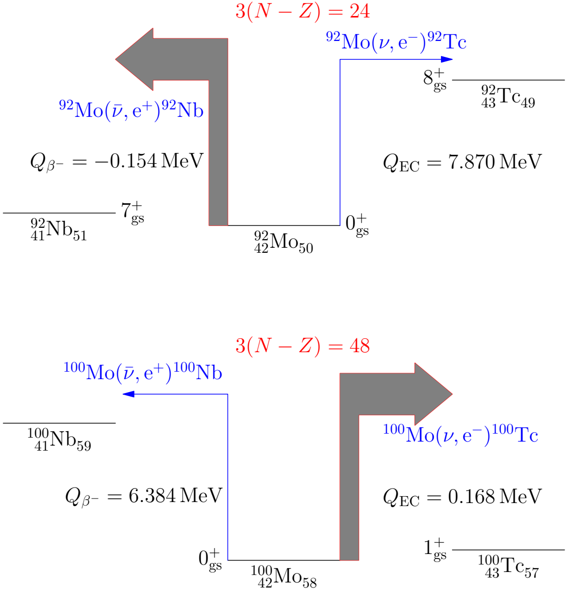
$\bar{\nu}_e$

Opposite trend for the ν and $\bar{\nu}$ cross sections because of

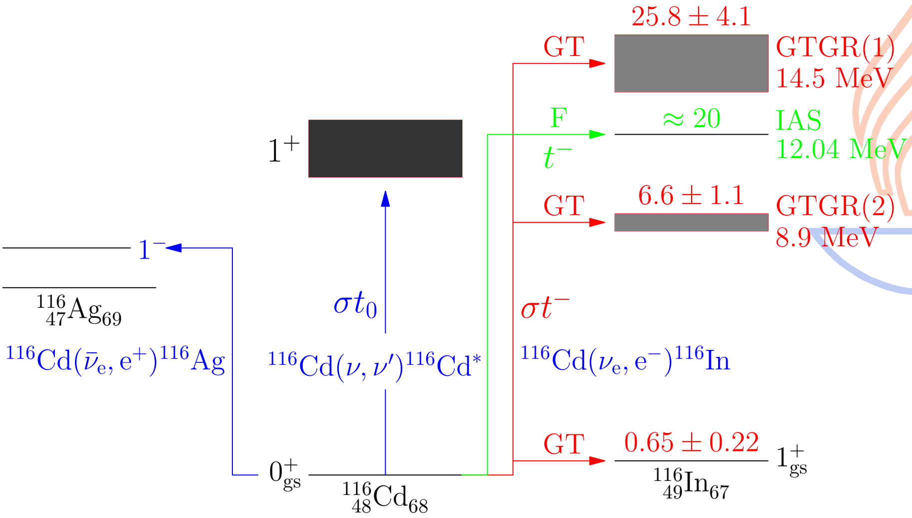
- Ikeda sum rule $S^-(1^+) - S^+(1^+) = 3(N - Z)$
- Variation of threshold energies

SN-ν detector based on natural Mo could detect both ν_e and $\bar{\nu}_e$!

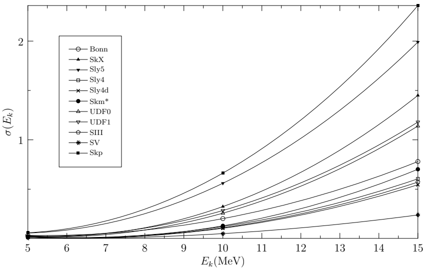
Threshold energies and Pauli blocking in the Mo chain



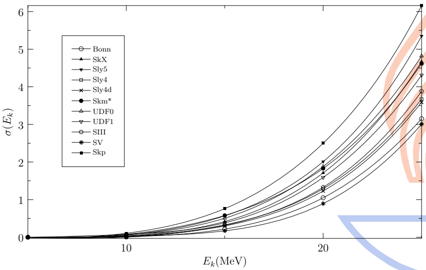
Isospin and spin-isospin properties of excitations of ^{116}Cd



Total CC cross sections for scattering off ^{116}Cd



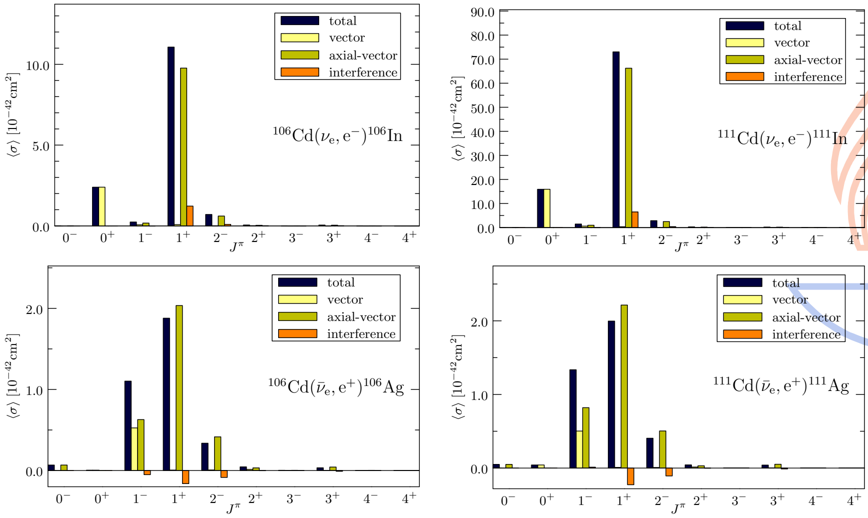
Neutrino scattering



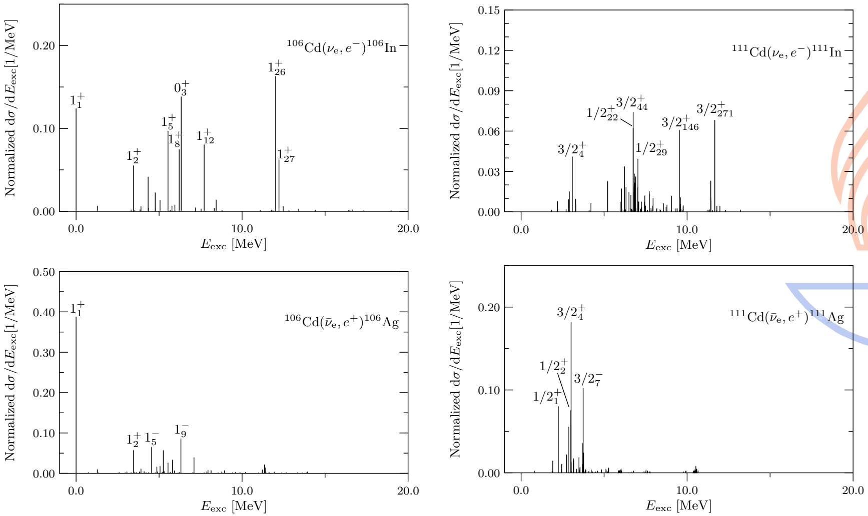
Antineutrino scattering

Comparison of calculations done with 10 Skyrme interactions and Bonn-A interaction (Phys. Rev. C 89 (2014) 024308).

Multipole decomposition of the folded ν and $\bar{\nu}$ CC cross sections for cadmiums

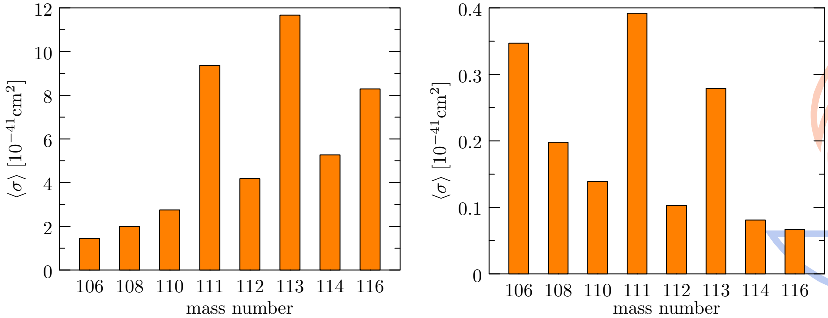


Calculations done with the Bonn-A interaction (J. Phys. G: Nucl. Part. Phys. 42 (2015) 095106).



Calculations done with the Bonn-A interaction (J. Phys. G: Nucl. Part. Phys. 42 (2015) 095106).

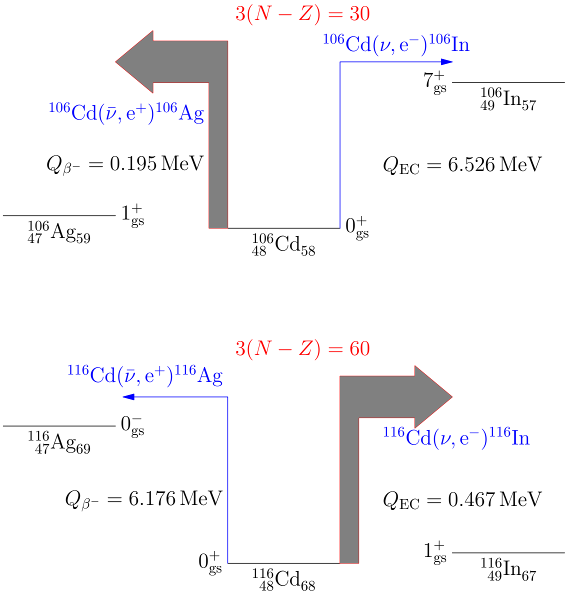
Folded CC cross sections for the cadmium isotopes



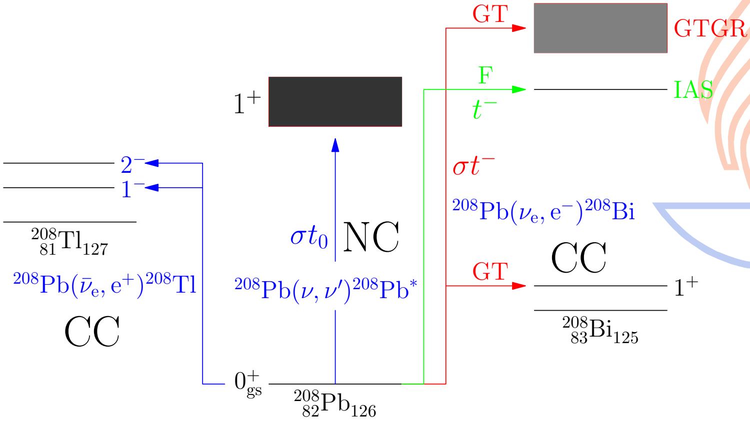
Neutrino scattering　　　Antineutrino scattering

Electron-neutrino and -antineutrino scattering calculated by the Bonn-A interaction (J. Phys. G: Nucl. Part. Phys. 42 (2015) 095106).

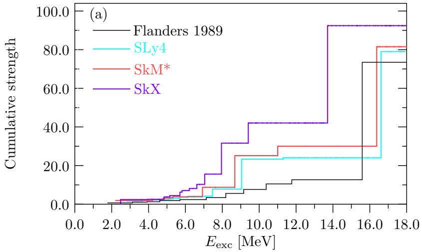
Threshold energies and Pauli blocking in the Cd chain



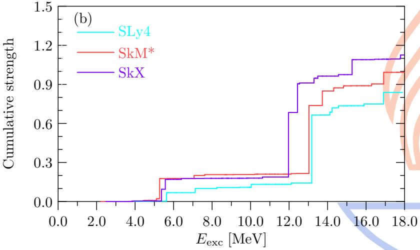
Isospin and spin-isospin properties of excitations of ^{208}Pb



Cumulative β^- and β^+ strengths for ^{208}Pb



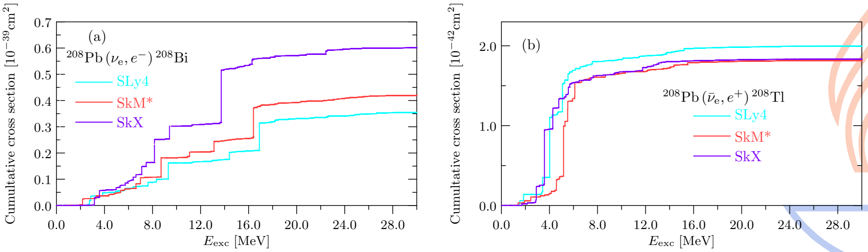
β^-strength in ^{208}Bi



β^+strength in ^{208}Tl

Calculations done with the SkX, SKM*, SLy4 Skyrme interactions (Phys. Rev. C 94 (2016) 044614).

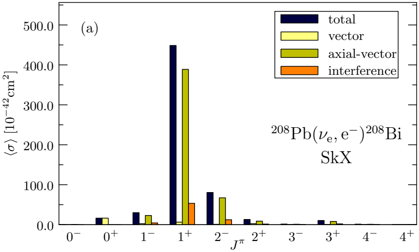
Cumulative sums of folded CC cross sections for ^{208}Pb



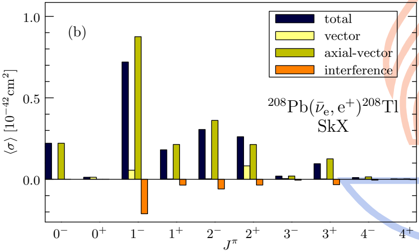
Neutrino scattering   Antineutrino scattering

Calculations done with the SkX, SKM*, SLy4 Skyrme interactions (Phys. Rev. C 94 (2016) 044614).

Multipole decomposition of the folded ν and $\bar{\nu}$ CC cross sections for lead



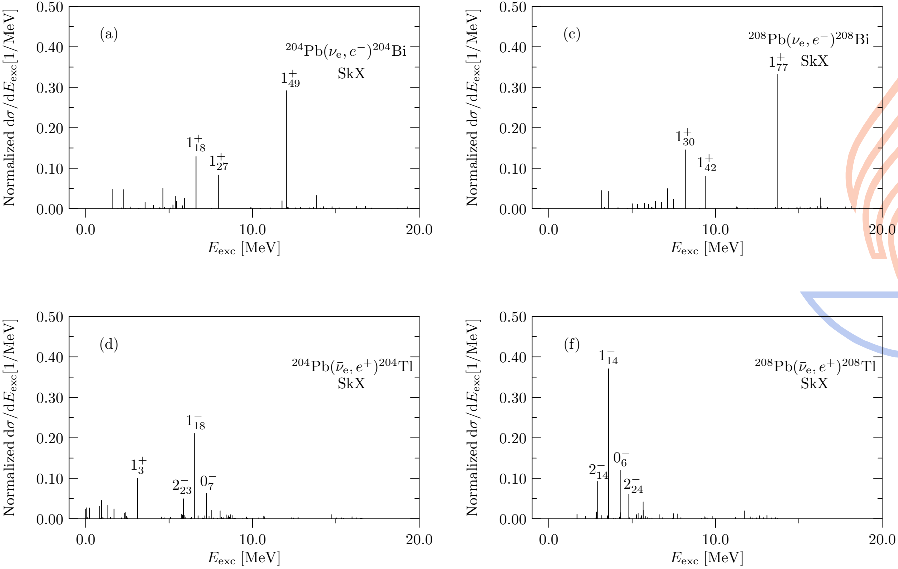
Neutrino scattering



Antineutrino scattering

Calculations done with the SkX, SKM*, SLy4 Skyrme interactions (Phys. Rev. C 94 (2016) 044614).

Folded CC cross sections of ^{204,208}Pb



SkX interaction for ^{204,206,208}Pb [only ^{204,208}Pb shown] (Phys. Rev. C 94 (2016) 044614).

CC cross sections including neutrino-flavor oscillations

Inclusion of neutrino-flavor conversion effects

- SN-neutrino detectors based on CC ν-nucleus scattering detect only ν_e and $\bar{\nu}_e$ ($E_\nu \leqslant 100$ MeV).

$$\langle \sigma_{\nu_e} \rangle = \int dE_\nu E_\nu^2 F_{\nu_e}^{osc}(E_\nu) \sigma(E_\nu)$$

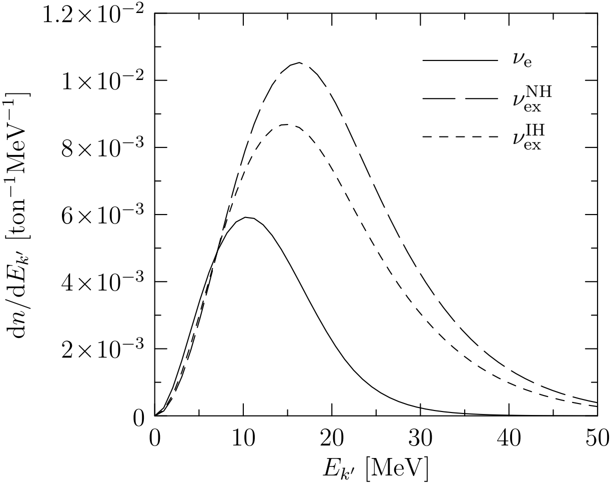
- Due to interactions with the matter of the star the energy profile for the detected neutrinos (antineutrinos) is a superposition of the initial ν_e ($\bar{\nu}_e$) and ν_x ($\bar{\nu}_x$) spectra, i.e.

$$F_{\nu_e}^{osc}(E_\nu) = pF_{\nu_e} + (1-p)F_{\nu_x} \quad ; \quad F_{\bar{\nu}_e}^{osc}(E_\nu) = \bar{p}F_{\bar{\nu}_e} + (1-\bar{p})F_{\bar{\nu}_x}$$

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

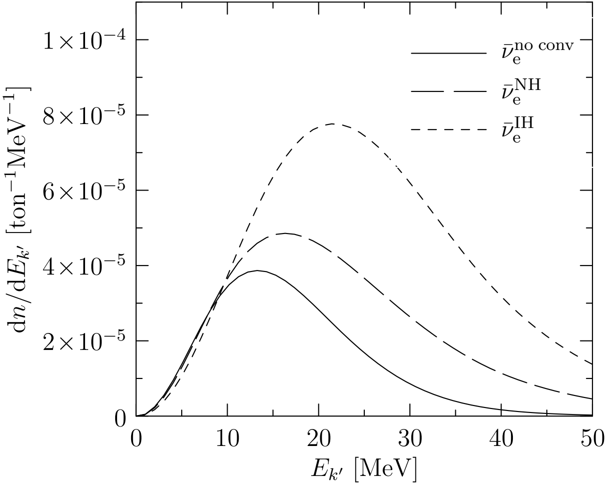
(J.Gava and C. Volpe, PRD 78 (2008) 083007 ; A.B. Balantekin and G.M. Fuller, PLB 471 (1999) 195 ; G.G. Raffelt, Prog. Part. Nucl. Phys. 64 (2010) 393 ; G. Martinez-Pinedo *et al.*, Eur. Phys. J. A 47 (2011) 98)

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

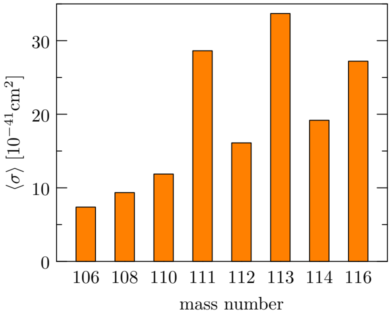


- Number of events significantly increased by flavor conversions
- The produced spectra similar for both mass hierarchies

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

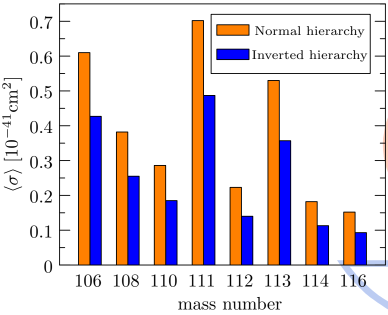


- Small number of events
- The difference between the two neutrino-mass hierarchies very clear



Neutrino scattering

Normal hierarchy

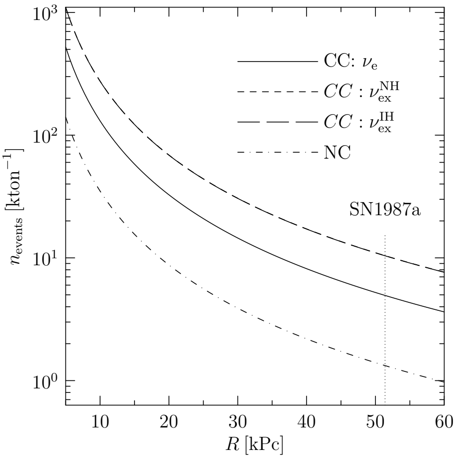


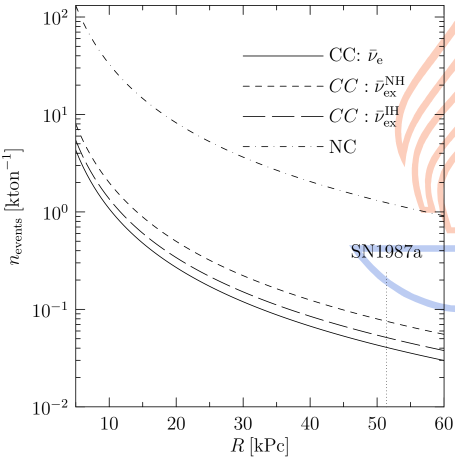
Antineutrino scattering

Normal and inverted hierarchies

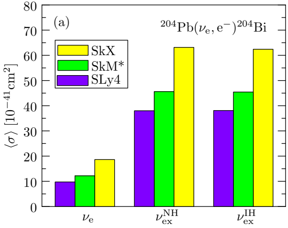
Electron-neutrino and -antineutrino scattering calculated by the Bonn-A interaction including the flavor oscillations (J. Phys. G: Nucl. Part. Phys. 42 (2015) 095106).

Number of expected events in a ^{116}Cd detector in a supernova explosion

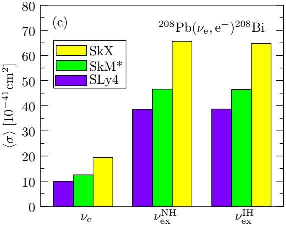




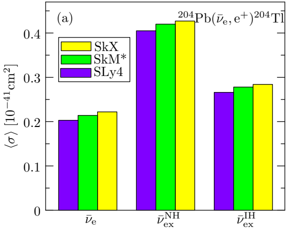
Number of events/(kiloton of ^{116}Cd) as a function of the distance to the supernova in kPc



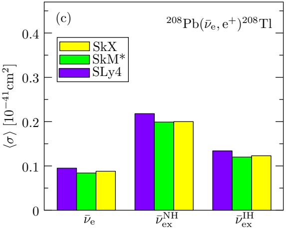
ν scattering off ^{204}Pb



ν scattering off ^{208}Pb



$\bar{\nu}$ scattering off ^{204}Pb



$\bar{\nu}$ scattering off ^{208}Pb

Skyrme interactions for ^{204,206,208}Pb [only ^{204,208}Pb shown] (Phys. Rev. C 94 (2016) 044614).

Conclusions and Outlook

- 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-A) open-shell target nuclei.
- High-lying QRPA excitations essential for the NC ν-scattering off odd-A nuclei.
- Locally adjusted Bonn-A potential reproduces the spin-isospin properties better than the globally adjusted Skyrme forces in the case of ^{116}Cd $\rightarrow$ ^{116}In excitations.
- In the future apply the available theory framework to the coherent and incoherent scattering of neutrinos from stable Xe isotopes (^{124,126,128,129,130,131,132,134,136}Xe) to explore the implications for the neutrino floor of the direct dark-matter experiments