

Inelastic Neutrino Interactions on Nuclei

Jouni Suhonen

Department of Physics
University of Jyväskylä

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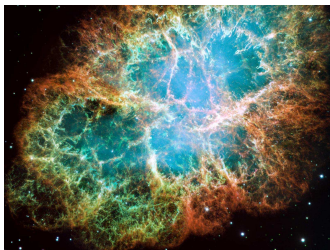


Contents:

- **Supernova neutrinos:**
- Motivation and theory framework
- Results for folded cross sections
- Effects of neutrino oscillations
- **Solar neutrinos:**
- Results for folded cross sections
- Heavy deformed nuclei and WIMPs

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

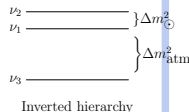
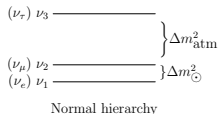
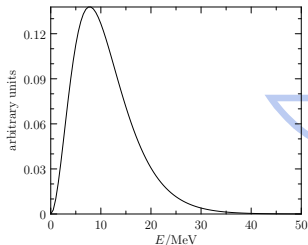
Supernova neutrinos



Important probes of:

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

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



Basic formalism: Folded cross sections

- Donnelly-Walecka method:

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

- **Need flux-averaged (folded) cross section:** $\langle \sigma_\nu \rangle =$

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

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

Flavor	ν_e	$\bar{\nu}_e$	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 and NSM interactions

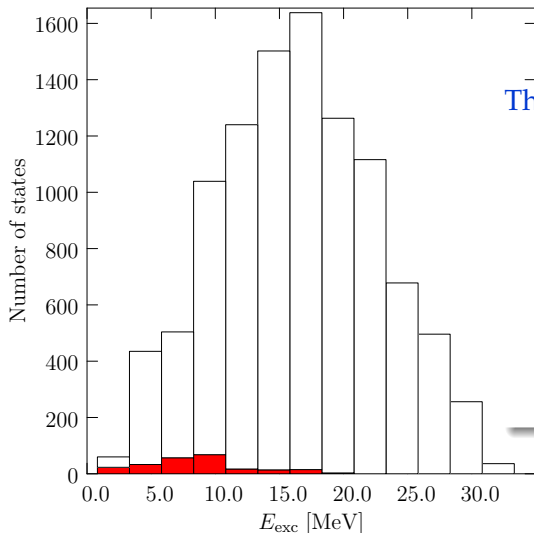
- CC scattering on ^{40}Ar studied by the **NSM** (nuclear shell model)
- CC and NC scattering on $^{92,94,96,98,100}\text{Mo}$ studied by the **QRPA** (Quasiparticle Random-Phase Approximation)
- CC and NC scattering on $^{95,97}\text{Mo}$ studied by the **MQPM** (Microscopic Quasiparticle-Phonon model)
- CC and NC scattering on $^{106,108,110,112,114,116}\text{Cd}$ studied by the **pnQRPA** (proton-neutron QRPA) and **QRPA**
- CC and NC scattering on $^{111,113}\text{Cd}$ studied by the **MQPM**
- CC and NC scattering on $^{128,129,130,132,132,134,136}\text{Xe}$ studied by the **pnQRPA** and the **QRPA**, as also the **MQPM** (odd isotopes); NC CEvNS by the **NSM**, **QRPA**, and **MQPM**

The Skyrme interactions

- CC scattering on ^{116}Cd studied by the **Skyrme-pnQRPA**
- NC and CC scattering on $^{204,206,208}\text{Pb}$ studied by the **Skyrme-QRPA** and **Skyrme-pnQRPA** (important for the **HALO** experiment)

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

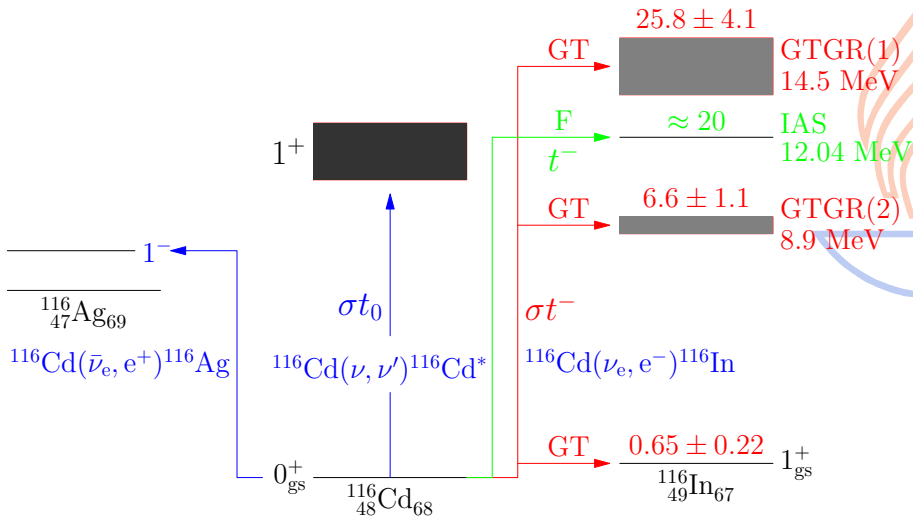
Only a small number of states contribute: ^{95}Mo (NC)



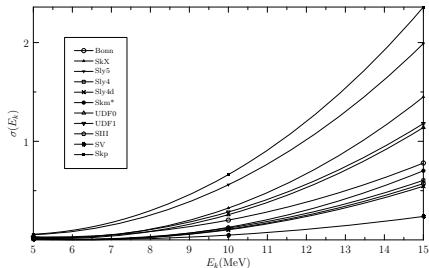
The MQPM procedure:

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

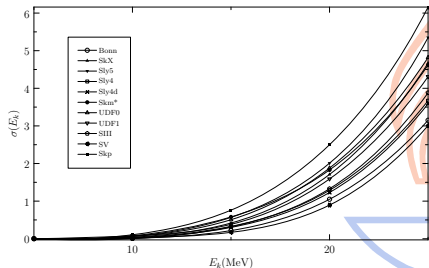
Isospin and spin-isospin properties of excitations of ^{116}Cd



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



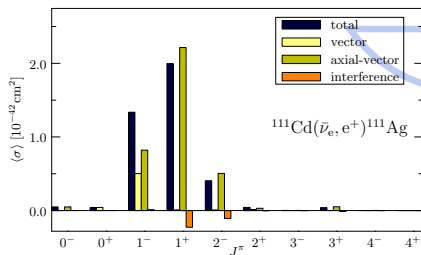
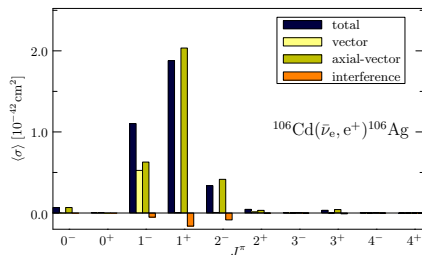
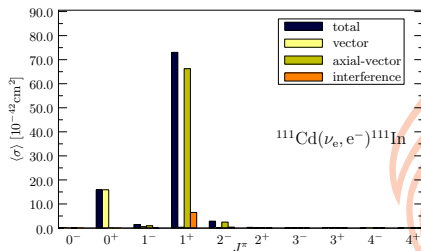
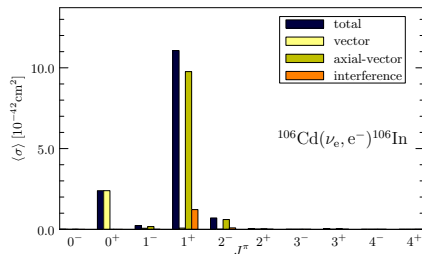
Neutrino scattering



Antineutrino scattering

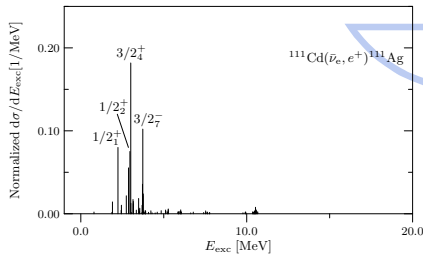
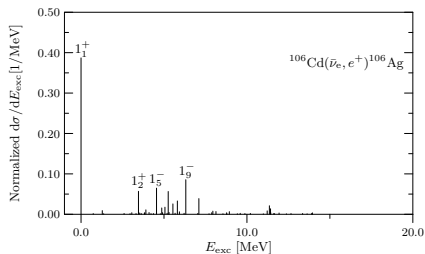
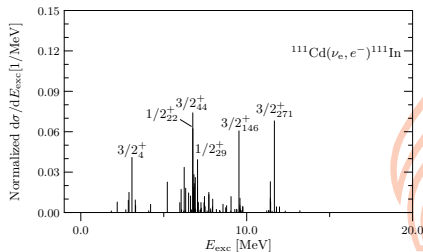
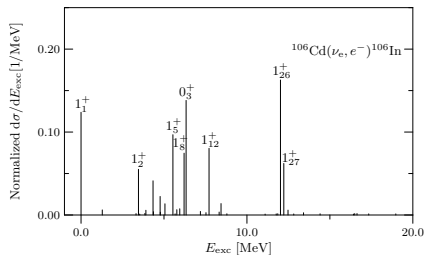
Comparison of calculations done with 10 Skyrme interactions and Bonn-A interaction (Phys. Rev. C 89 (2014) 024308).

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



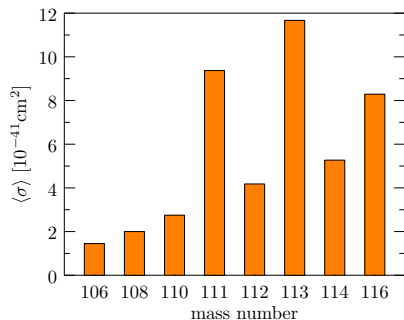
Calculations done with the Bonn-A interaction (J. Phys. G: Nucl. Part. Phys. 42 (2015) 095106).

Cadmium isotopes: Main contributions to the folded CC cross sections

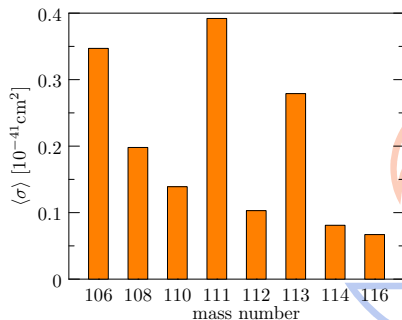


Calculations done with the Bonn-A interaction (J. Phys. G: Nucl. Part. Phys. 42 (2015) 095106).

Folded CC cross sections for the cadmium chain



Neutrino scattering



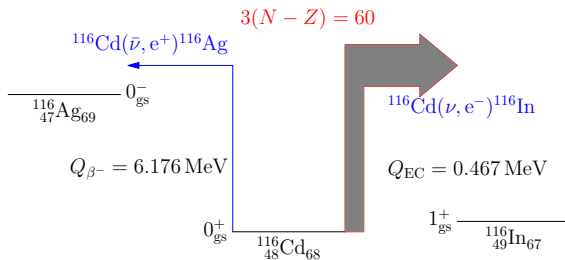
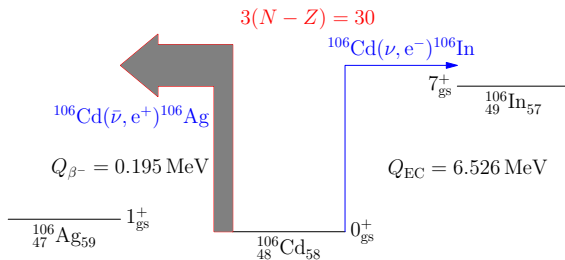
Antineutrino scattering

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

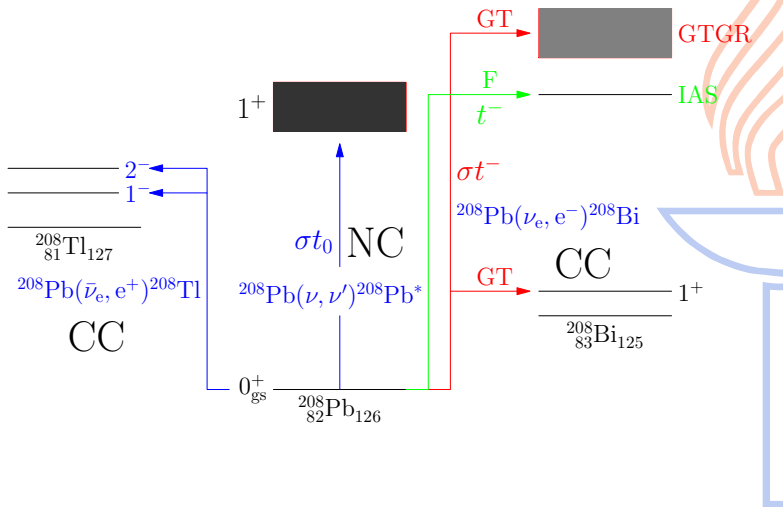
- Ikeda sum rule $S^-(1^+) - S^+(1^+) = 3(N - Z)$
- Variation of **threshold energies**

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

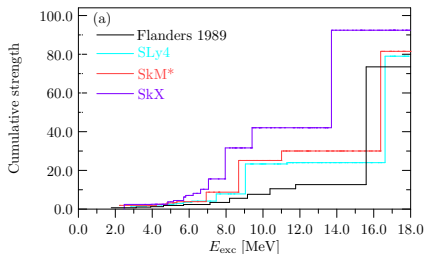
Threshold energies and Pauli blocking in the Cd chain



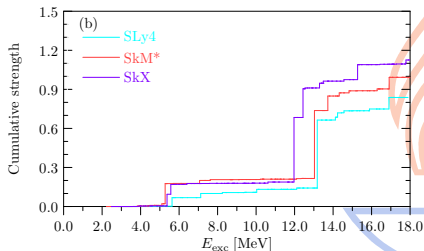
Isospin and spin-isospin properties of excitations of ^{208}Pb



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



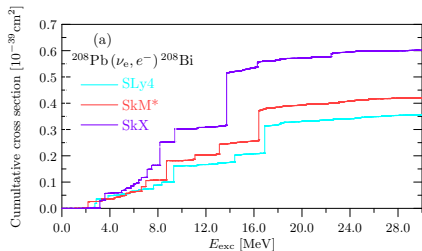
β^- strength in ^{208}Bi



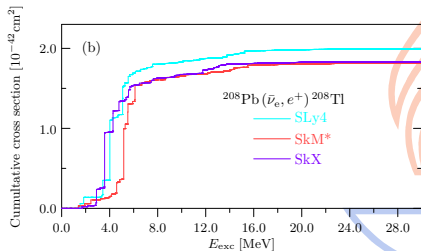
β^+ strength in ^{208}Tl

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



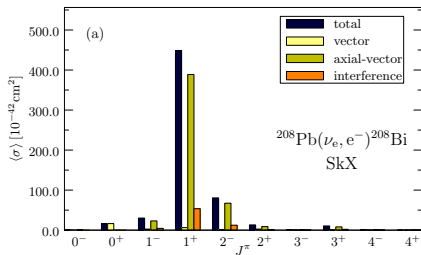
Neutrino scattering



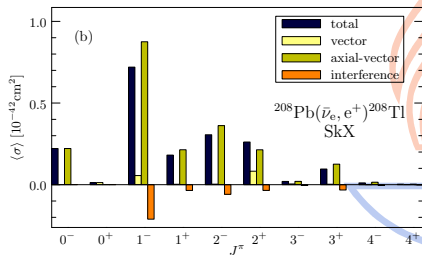
Antineutrino scattering

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



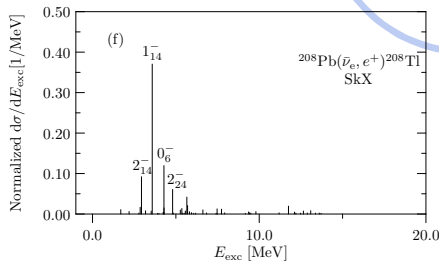
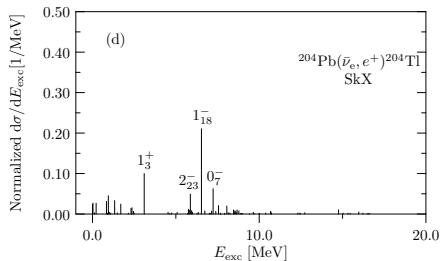
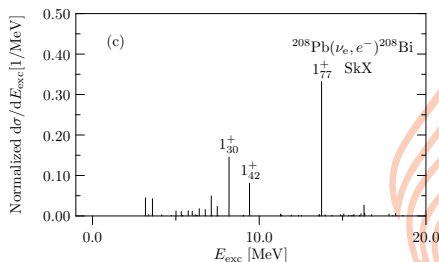
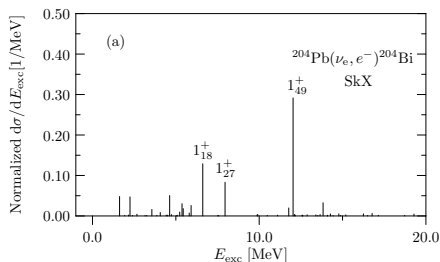
Neutrino scattering



Antineutrino scattering

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

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



SkX interaction for $^{204,206,208}\text{Pb}$ [only $^{204,208}\text{Pb}$ 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 $\bar{\nu}_e$ ($E_\nu \leq 100$ MeV).

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

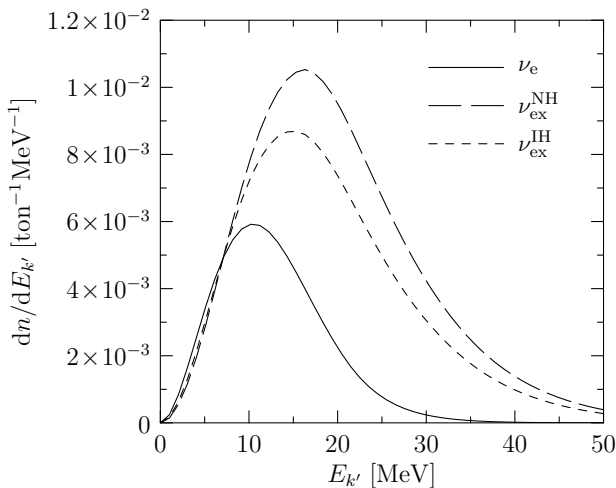
- Due to interactions with the matter of the star the energy profile for the detected neutrinos (antineutrinos) is a superposition of the initial ν_e ($\bar{\nu}_e$) and ν_x ($\bar{\nu}_x$) spectra, i.e.

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

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

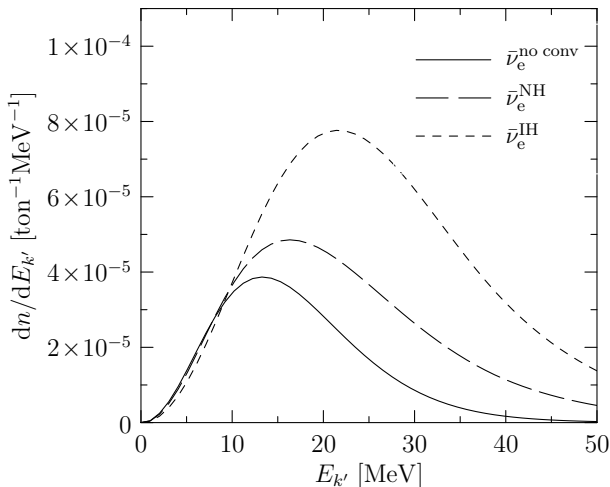
(J.Gava and C. Volpe, PRD 78 (2008) 083007 ; A.B. Balantekin and G.M. Fuller, PLB 471 (1999) 195 ; G.G. Raffelt, Prog. Part. Nucl. Phys. 64 (2010) 393 ; G. Martinez-Pinedo *et al.*, Eur. Phys. J. A 47 (2011) 98)

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



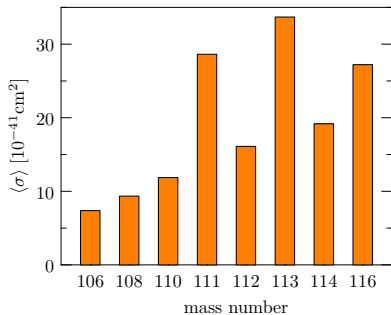
- Number of events significantly increased by **flavor conversions**
- The produced spectra similar for both mass hierarchies

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

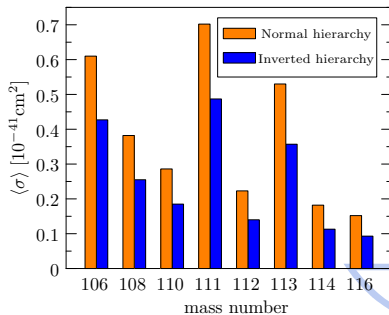


- Small number of events
- The difference between the two **neutrino-mass hierarchies** very clear

Cadmiums: Folded CC cross sections including neutrino flavor oscillations



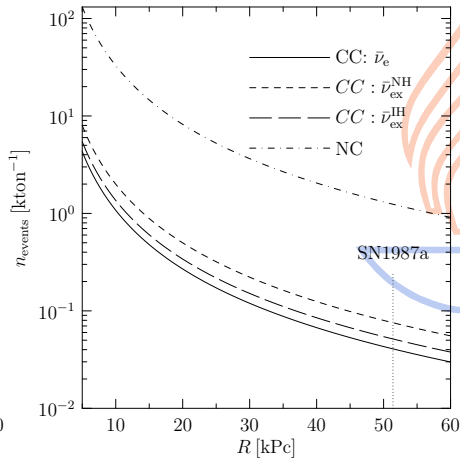
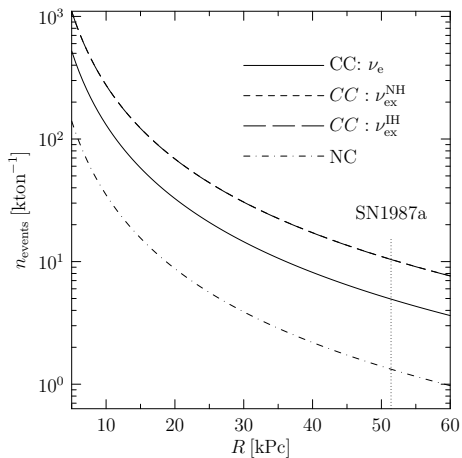
Neutrino scattering
Normal hierarchy



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).

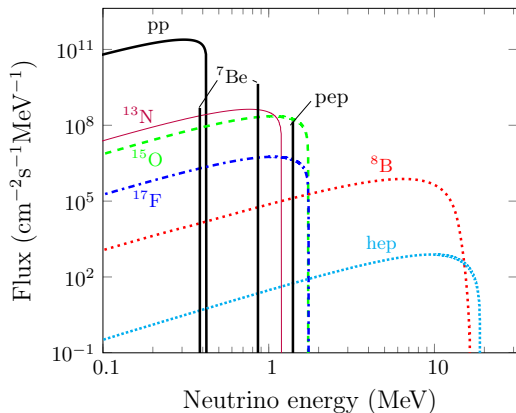
Number of expected events in a ^{116}Cd detector in a supernova explosion



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

Solar neutrinos: nuclear-structure models and results

Solar-neutrino cross sections: ^8B neutrinos are of interest

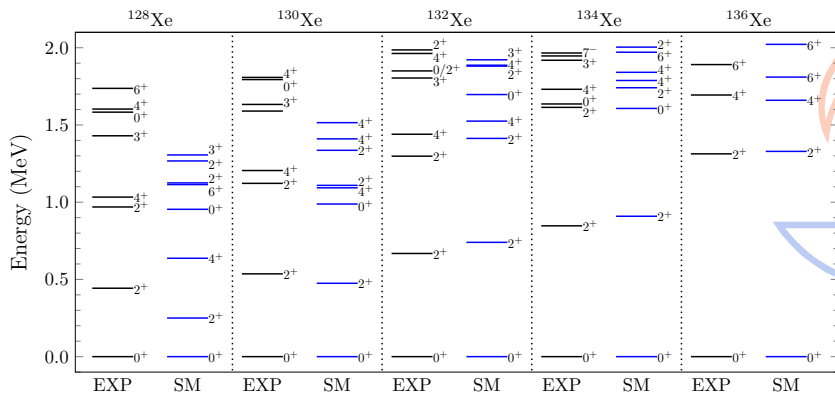


- Fold the cross sections by the ^8B neutrino flux
- Can be computed by the **nuclear shell model**, **(pn)QRPA**, and **MQPM**

The Bonn-A and NSM interactions

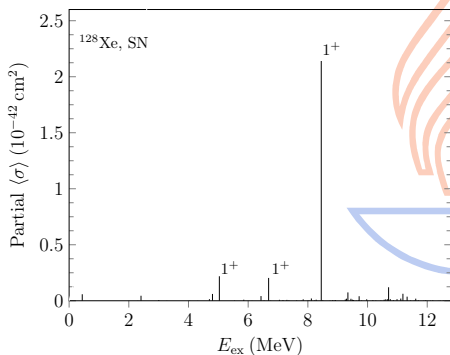
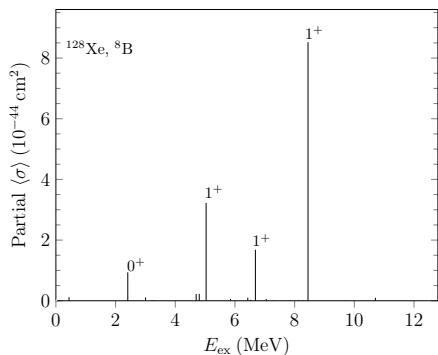
- CC scattering on ^{40}Ar studied by the **NSM** (nuclear shell model)
- CC and NC scattering on $^{128,129,130,132,132,134,136}\text{Xe}$ studied by the **pnQRPA** (proton-neutron QRPA) and the **QRPA** (Quasiparticle Random-Phase Approximation), as also the **MQPM** (Microscopic Quasiparticle Phonon Model, for odd isotopes); NC CEvNS by the **nuclear shell model**, **QRPA**, and **MQPM**

Calculations for the stable Xe isotopes: energy spectra



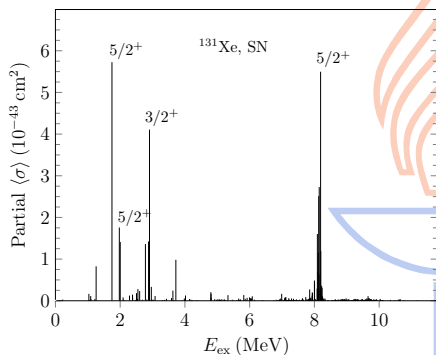
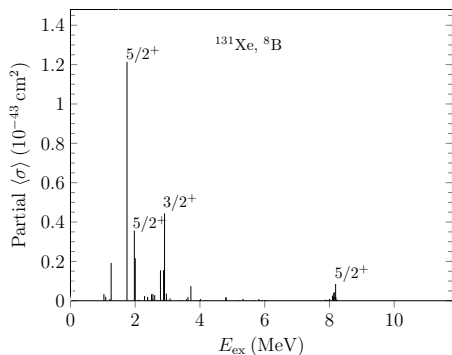
Computed spectra for the even-even Xe isotopes

NC scattering of ν_e off ^{128}Xe : Folded cross sections



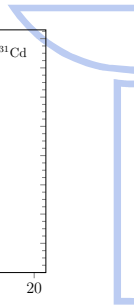
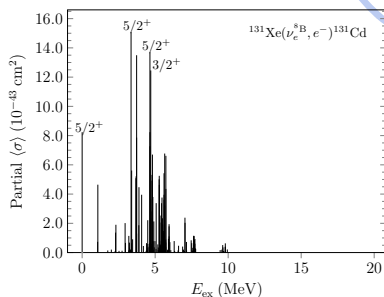
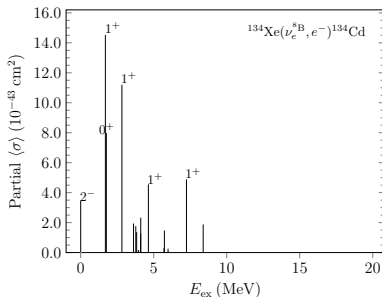
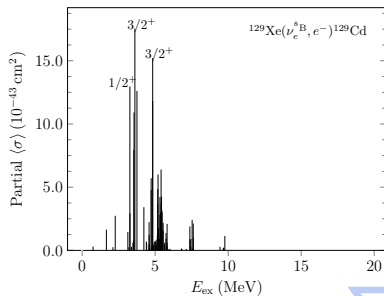
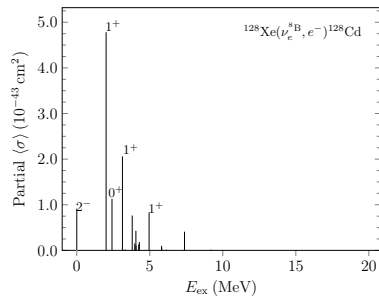
Comparison of the most important contributions to the ${}^8\text{B}$ solar and supernova (SN) electron-neutrino cross section for ^{128}Xe .

NC scattering of ν_e off ^{131}Xe : Folded cross sections



Comparison of the most important contributions to the ^8B solar and supernova (SN) electron-neutrino cross section for ^{131}Xe .

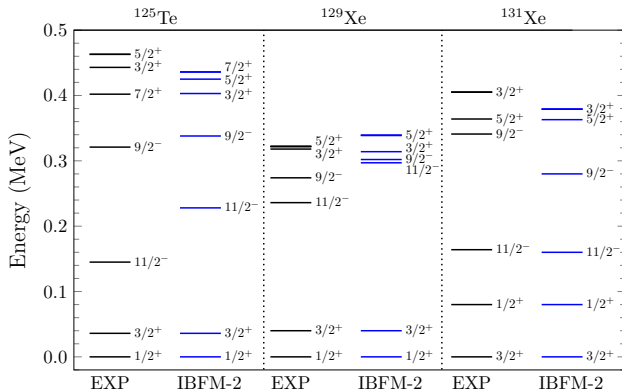
CC scattering of ^8B solar ν_e s off xenons: Folded cross sections



Inelastic WIMP and solar-neutrino NC scattering off heavy deformed nuclei

Application of the Microscopic Interacting
Boson-Fermion Model (IBFM-2)

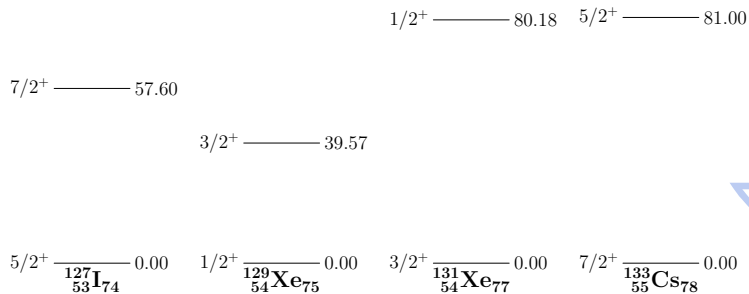
TEST of the IBFM-2 framework: Computed energy spectra



IBFM-2 computed spectra for ^{125}Te , ^{129}Xe , and ^{131}Xe .

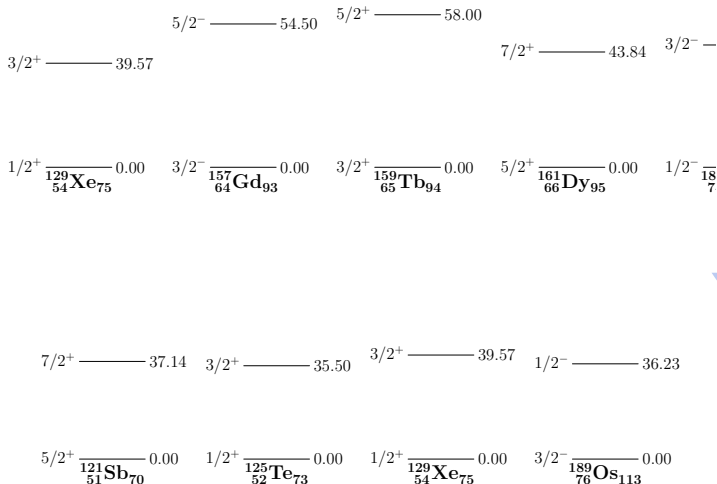
P. Pirinen, J. Kotila, J. Suhonen, Spin-dependent WIMP-nucleus scattering off ^{125}Te , ^{129}Xe , and ^{131}Xe in the microscopic interacting boson-fermion model, Nucl. Phys. A 992 (2019) 121624.

Interesting nuclei for WIMP inelastic scattering



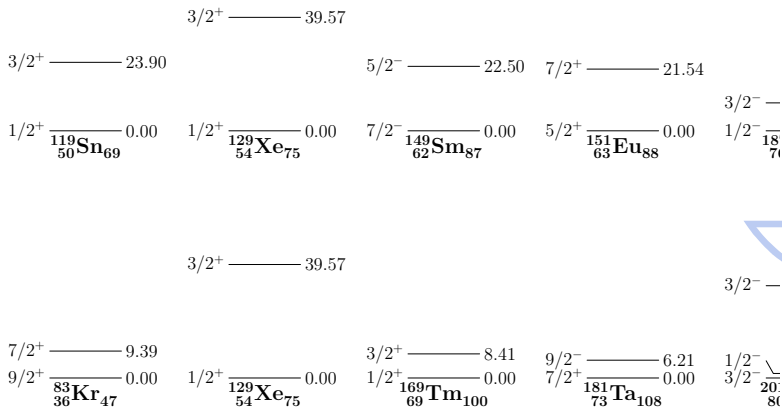
Energies in keV

Interesting nuclei (continues)



Energies in keV

Interesting nuclei (continues)



Energies in keV

Conclusions and Outlook

- Knowledge about **nuclear responses to supernova neutrinos** essential for neutrino detection and applications in astrophysics.
- (pn)QRPA/Skyrme-(pn)QRPA (MQPM) + Donnelly-Walecka formalism **powerful framework** for neutrino-nucleus NC and CC scattering calculations for even-even (**odd- A**) open-shell target nuclei.
- Potentially interesting application of the IBFM-2 nuclear-theory framework to inelastic NC scattering of solar-neutrinos and WIMPs off heavy deformed nuclei.