Nuclear-Structure Studies of Neutrino-Nucleus Prosesses at Supernova Energies

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Nuclear Physics and Astrophysics of Neutron-Star Mergers and Supernovae, and the Origin of R-process Elements, Trento, Italy, September 8 – 12, 2014

Contents:

Various aspects of this work have been accomplished together with

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- K. G. Balasi (Ioannina, Greece)
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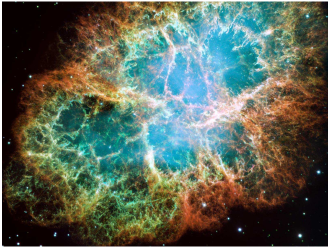
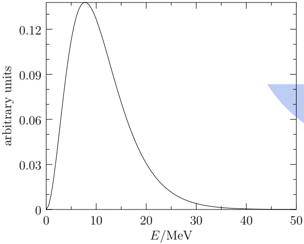
- J. Toivanen (JYFL and Monash University, Melbourne, Australia)
- B. G. Carlsson (Lund, Sweden)
- P. Vesely (Rez, Czech Republic and Charles University, Prague, Czech Republic)
- J. Dobaczewski (JYFL)

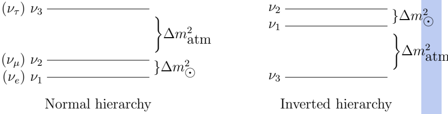
Supernova neutrinos: Theory background and motivation

Supernova neutrinos



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





Important probes of:

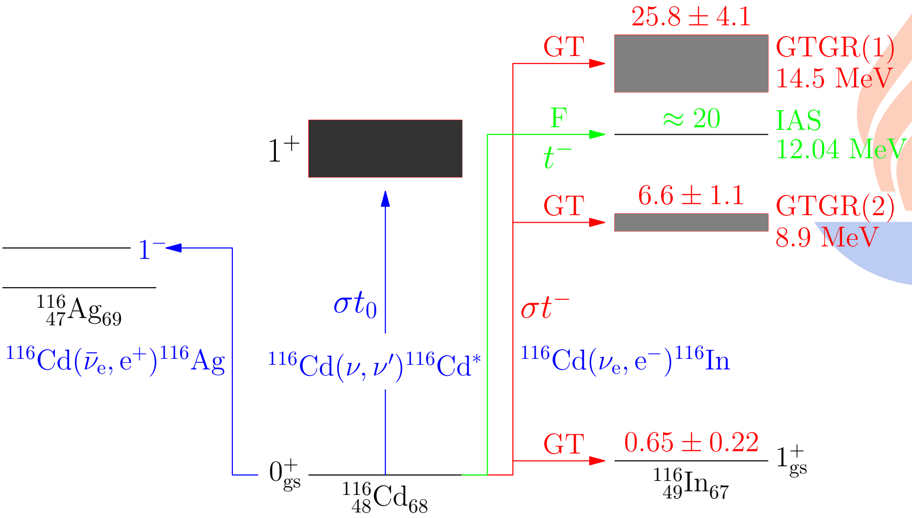
- Unknown supernova mechanisms, ν and $\bar{\nu}$ energy profiles
- Neutrino physics beyond the Standard Model, e.g. neutrino oscillations in (dense) matter and the neutrino mass hierarchy
- Only observations so far from SN1987a

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

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



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 and prospects

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)
- CC scattering on ^{204,206,208}Pb studied by the HOSPHE (future work, important for the HALO experiment)

Nuclear-structure ingredients

- Even-even nuclei: QRPA (NC), pnQRPA (CC)
- 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.

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

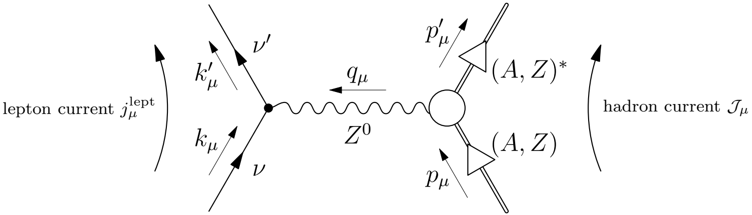
  - *Question: How large a quasiparticle-phonon basis is required to describe states with* $E_{\mathrm{exc}} \lesssim 15-20$ MeV?

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

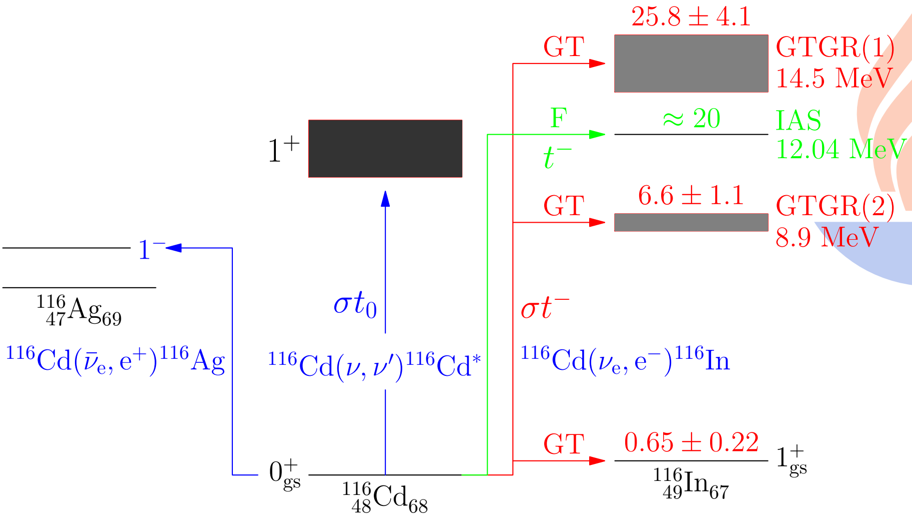
NC and CC scattering off the stable Mo isotopes

Incoherent NC scattering off the stable Mo isotopes at supernova energies

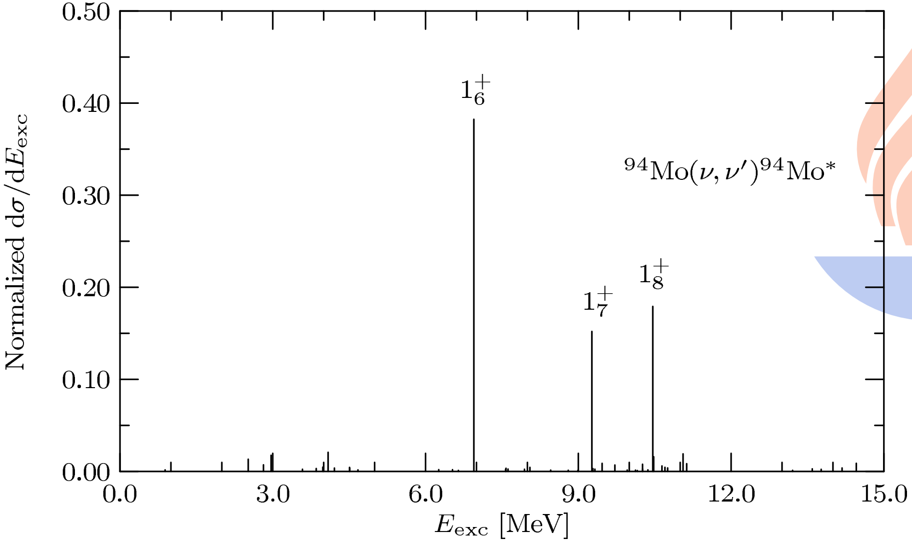
Neutral-current (NC) neutrino-nucleus scattering:



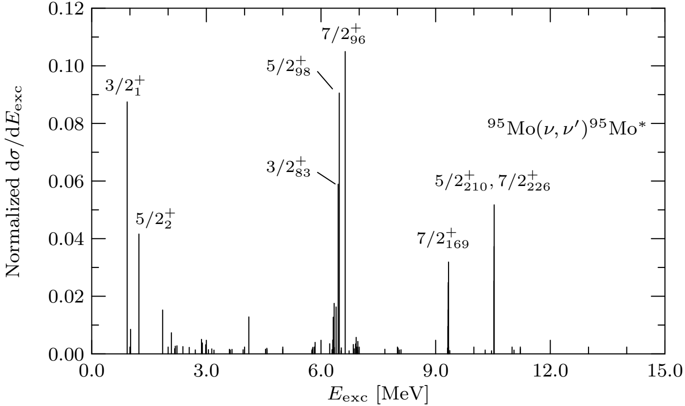
Isospin and spin-isospin properties of excitations of ^{116}Cd



NC results for ν_e scattering off ^{94}Mo (QRPA)

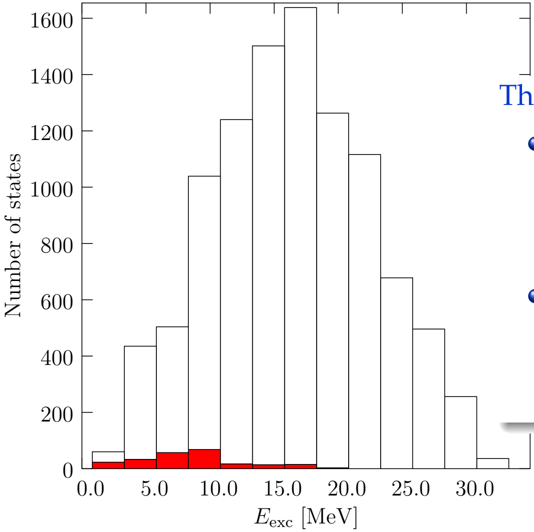


NC results for ν_e scattering off ^{95}Mo (MQPM)



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

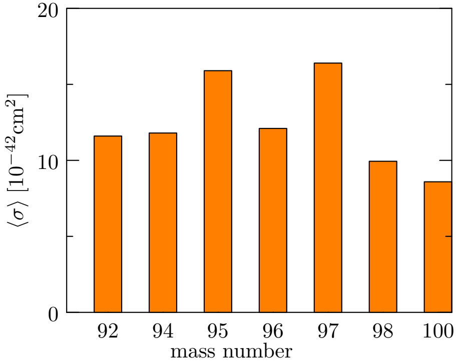
Large-scale MQPM calculations for ^{95}Mo (NC)



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

NC ν_e scattering results for the Mo isotopes



- Results similar for ^{92,94,96}Mo. Cross sections slightly smaller for ^{98,100}Mo
- The 1^+ distributions are not known experimentally for $E_{exc} > 5.0$ MeV. Future experiments?

NC scattering results for the Mo isotopes (all flavors)

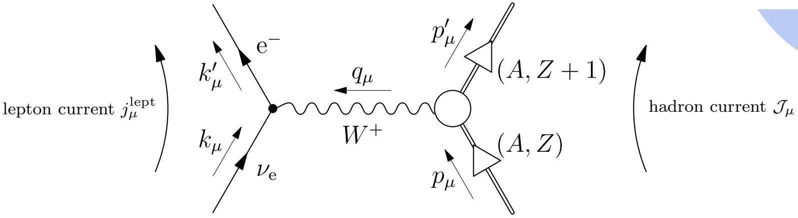
flavor	$\langle\sigma\rangle^{92}$	$\langle\sigma\rangle^{94}$	$\langle\sigma\rangle^{95}$	$\langle\sigma\rangle^{96}$	$\langle\sigma\rangle^{97}$	$\langle\sigma\rangle^{98}$	$\langle\sigma\rangle^{100}$
ν_e	11.6	11.8	15.9	12.1	16.4	9.94	8.59
$\bar{\nu}_e$	17.3	17.6	23.0	17.9	23.7	15.1	13.1
ν_μ, ν_τ	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

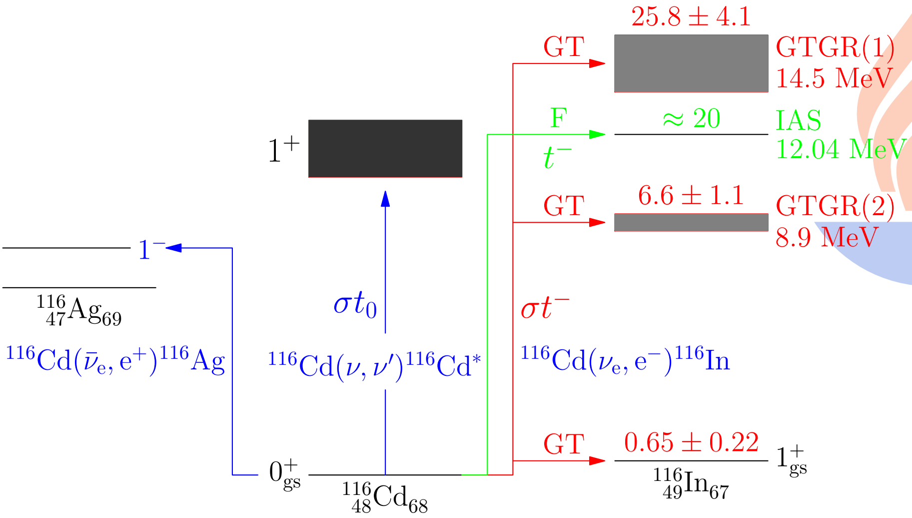
- Results qualitatively similar for all flavors.

CC scattering off the stable Mo isotopes at supernova energies

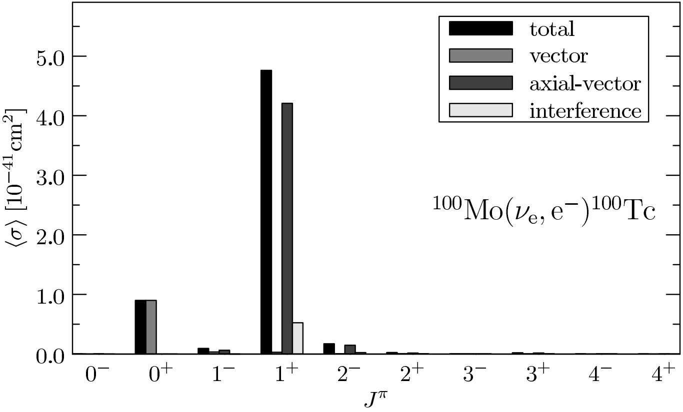
Charged-current (CC) neutrino-nucleus scattering:



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

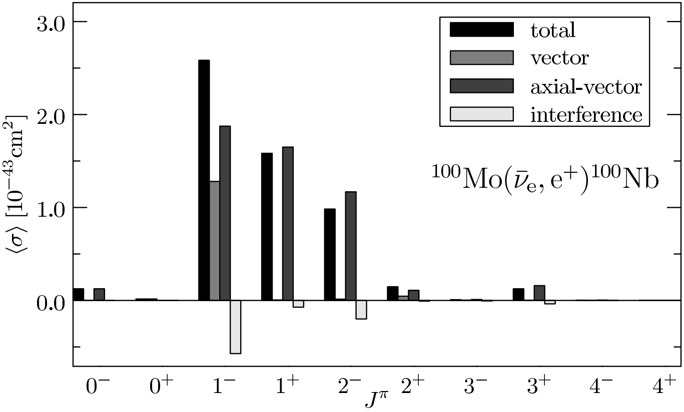


Multipole contributions: CC ν-scattering



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

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



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

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).

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

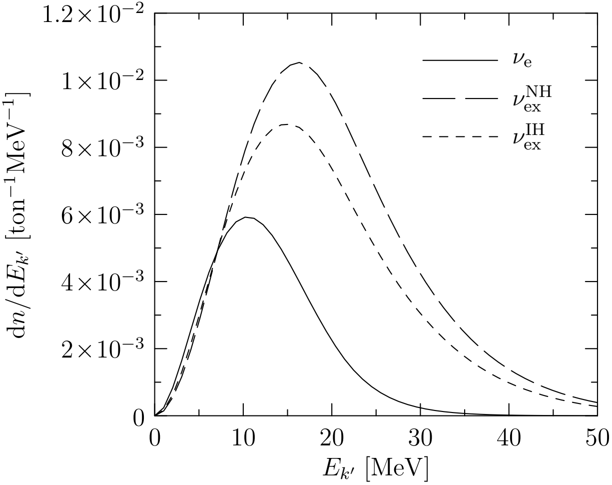
- Due to interactions with the matter of the star the energy profile for the detected neutrinos (antineutrinos) is a superposition of the initial ν_e ($\bar{\nu}_e$) and ν_x ($\bar{\nu}_x$) spectra, i.e.

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

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

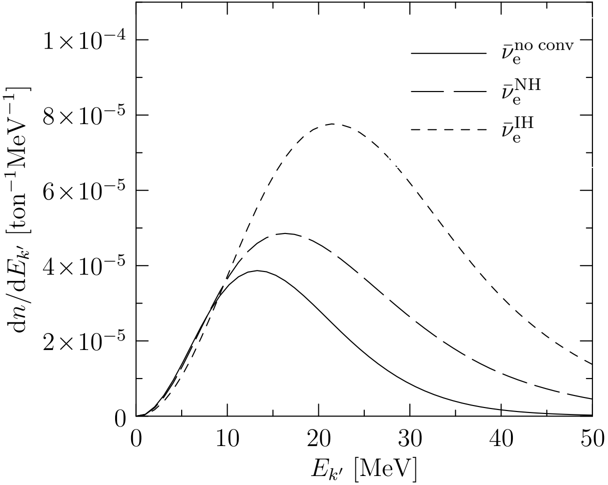
(J.Gava and C. Volpe, PRD 78 (2008) 083007 ; A.B. Balantekin and G.M. Fuller, PLB 471 (1999) 195 ; G.G. Raffelt, Prog. Part. Nucl. Phys. 64 (2010) 393 ; G. Martinez-Pinedo *et al.*, Eur. Phys. J. A 47 (2011) 98)

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



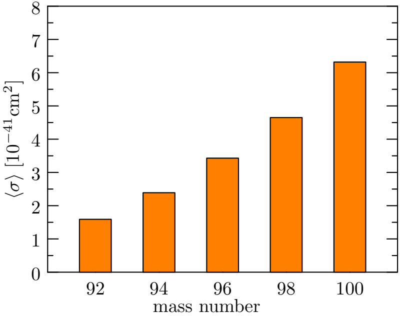
- Number of events significantly increased by flavor conversions
- The produced spectra similar for both mass hierarchies

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

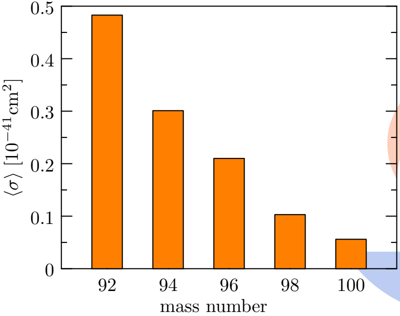


- Small number of events
- The difference between the two neutrino-mass hierarchies very clear

Variation of the CC cross section with mass number



ν_e



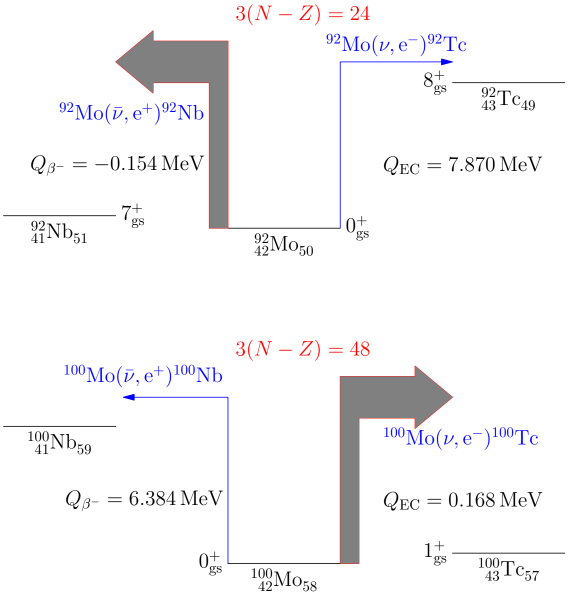
$\bar{\nu}_e$

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

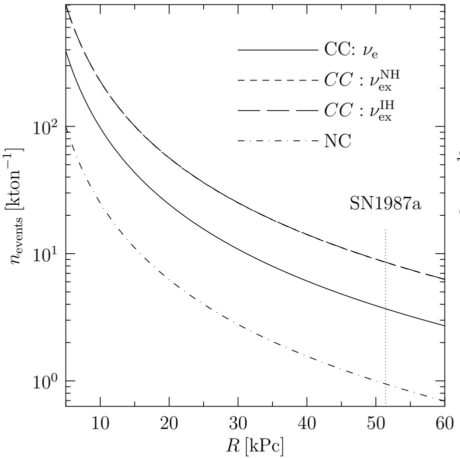
- Ikeda sum rule $S^-(1^+) - S^+(1^+) = 3(N-Z)$
- Variation of threshold energies

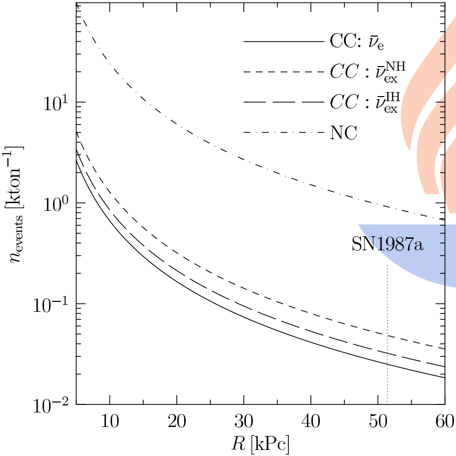
SN-ν detector based on natural Mo could detect both ν_e and $\bar{\nu}_e$!

Threshold energies and Pauli blocking in the Mo chain



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





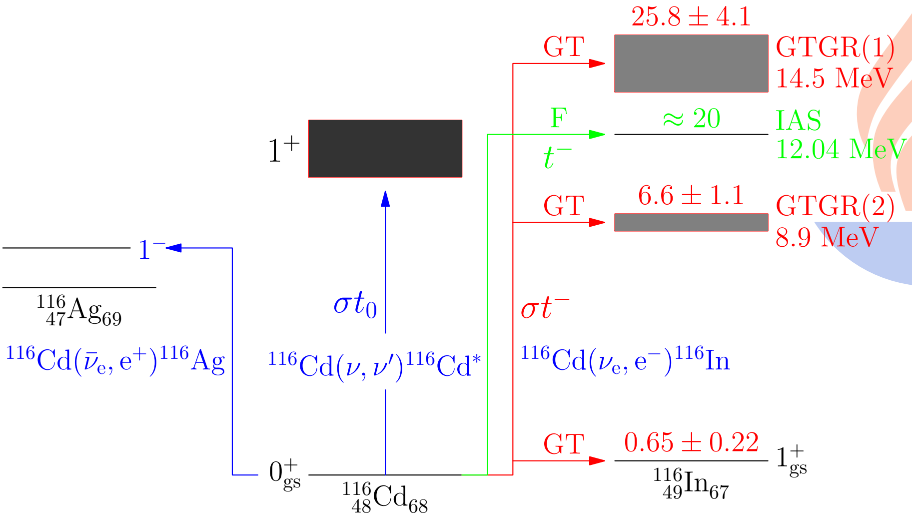
Number of events/(kiloton of ^{116}Cd) as a function of the distance to the supernova in kPc

Isospin and spin-isospin excitations of ^{116}Cd with 10 different Skyrme forces

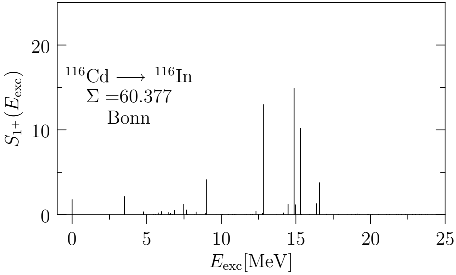
The pnQRPA code HOSPHE with full diagonalization in 15 harmonic-oscillator major shells

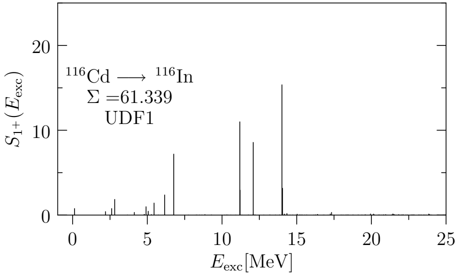
W. Almosly, B.G. Carlsson, J. Dobaczewski, J. Suhonen, J. Toivanen, P. Vesely, and E. Ydrefors, Phys. Rev. C 89 (2014) 024308

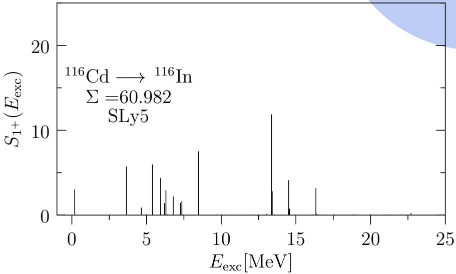
Isospin and spin-isospin properties of excitations of ^{116}Cd



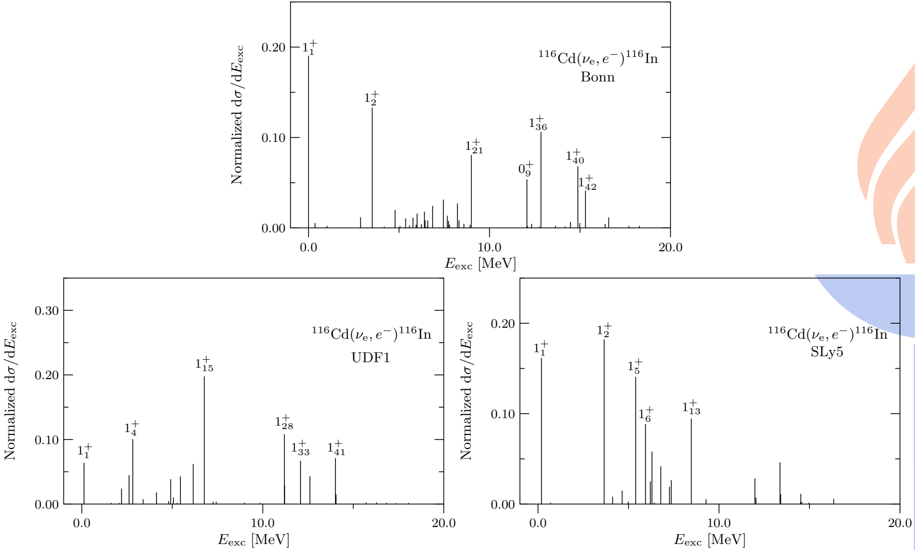
Examples of the GT strength in ^{116}In





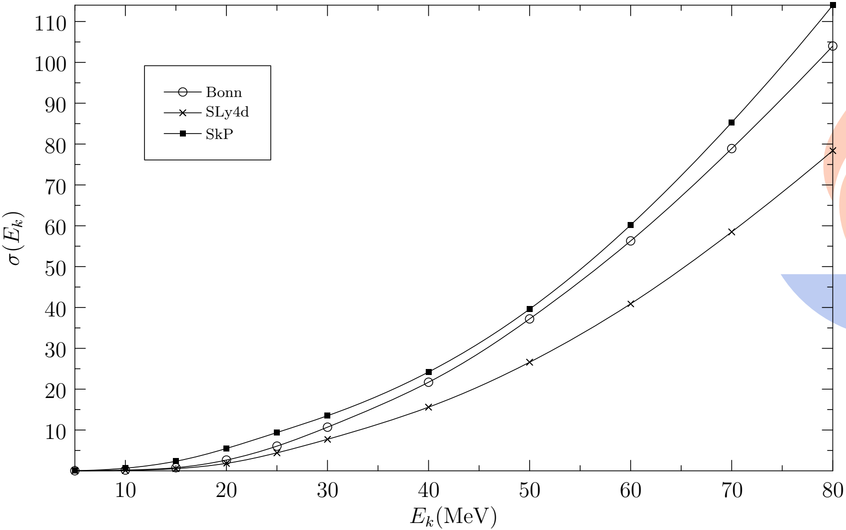


Folded cross sections normalized by the total one



The folded cross sections correlate strongly with the F and GT strength distributions!

Total cross sections in units of 10^{-40}cm^2 up to 80 MeV



E_k is the energy of the incoming neutrino

Total folded ν cross sections in units of 10^{-41}cm^2

Interaction	SN model I	SN model II
Bonn	7.45	10.1
SkX	10.1 – 11.2	12.6 – 13.8
SkM*	5.48 – 6.37	7.56 – 8.57
SkP	14.8 – 16.7	17.5 – 19.5
UDF0	8.68 – 9.43	11.2 – 12.0
UDF1	8.88 – 9.61	11.3 – 12.1
SIII	4.83 – 5.58	6.79 – 7.66
SV	2.68 – 2.77	3.95 – 4.07
SLy5	13.5 – 14.2	15.9 – 16.7
SLy4	5.51 – 5.68	7.56 – 7.75
SLy4d	4.94 – 5.09	6.82 – 7.01

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 $\bar{\nu}$ is, however, small. The use of natural molybdenum in the MOON would probably make $\bar{\nu}$ detection possible.
- 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.

Neutrinos and Dark Matter in Nuclear Physics:

NDM'15

in Jyväskylä, June 1-5, 2015

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