Neutrino-Nucleus Interactions at Low Energies

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Computational Challenges in Nuclear and Many-Body Physics,
Stockholm, Sweden, Sept. 15 - Oct. 10, 2014

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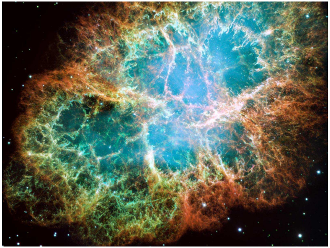
Supernova neutrinos: Theory background and motivation

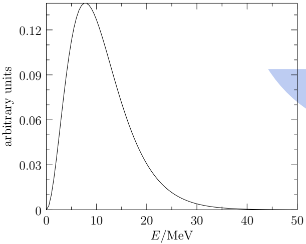
Supernova neutrinos

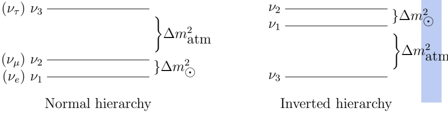


Important probes of:

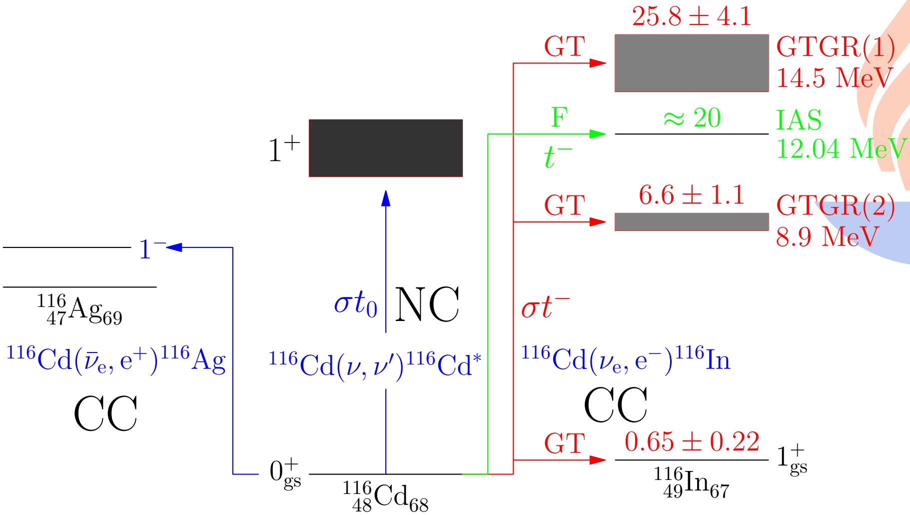
- Unknown supernova mechanisms, ν and $\bar{\nu}$ energy profiles
- Neutrino physics beyond the Standard Model, e.g. neutrino oscillations in (dense) matter and the neutrino mass hierarchy
- Only observations so far from SN1987a

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





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: $^{95}\text{Mo} = \ ^{94}\text{Mo} \otimes n$, 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 $E_{\text{exc}} \lesssim 15-20$ MeV?*

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

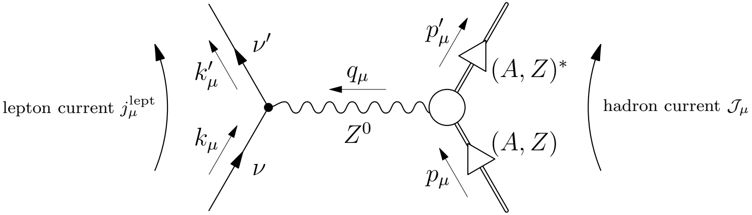
Example: NC and CC scattering off the Mo isotopes

NC and CC scattering off the stable Mo isotopes

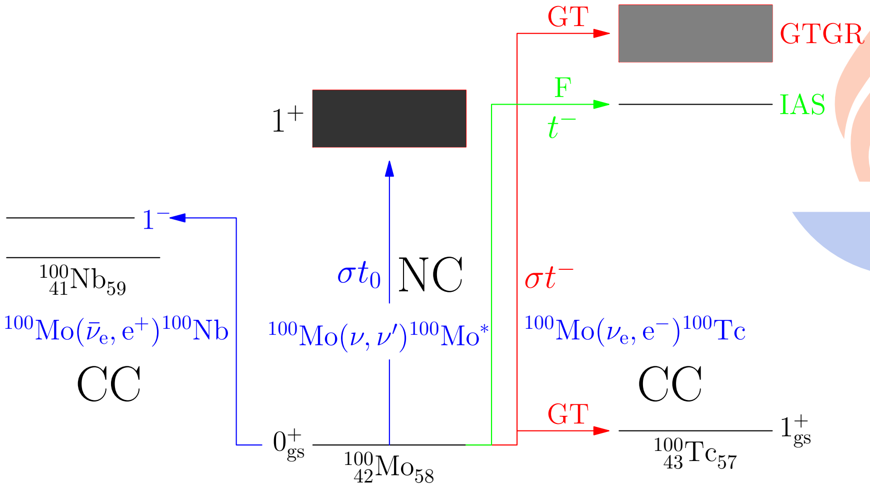
Neutral-current scattering off the Mo isotopes

Incoherent NC scattering off the stable Mo isotopes at supernova energies

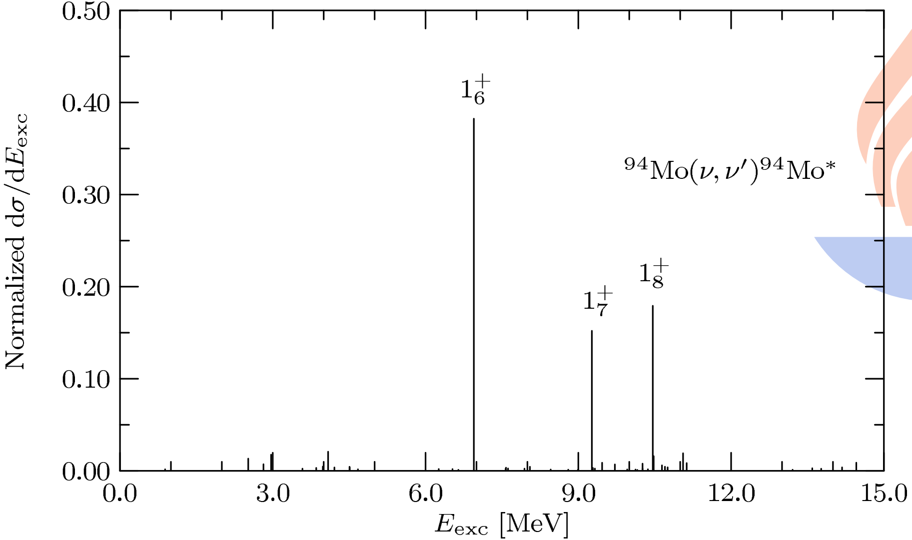
Neutral-current (NC) neutrino-nucleus scattering:



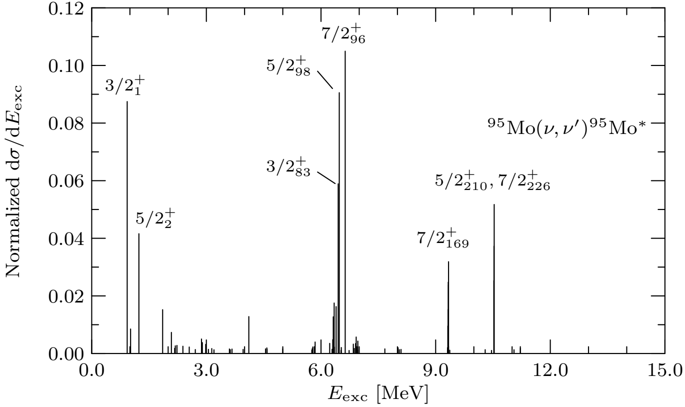
Isospin and spin-isospin properties of excitations of ^{100}Mo



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

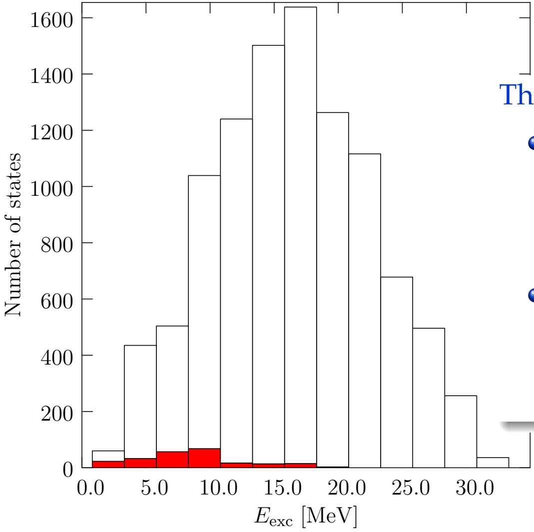


NC results for ν_e scattering off ^{95}Mo (MQPM)



- $3/2^+_1$ 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

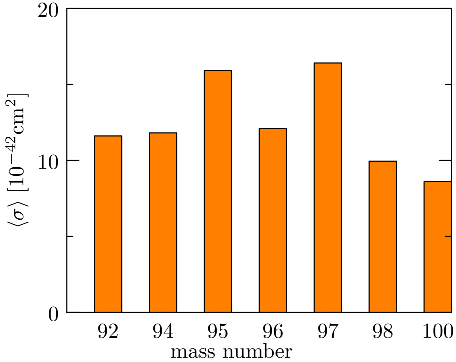
Large-scale MQPM calculations for ^{95}Mo (NC)



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
$\bar{\nu}_{\mathrm{e}}$	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

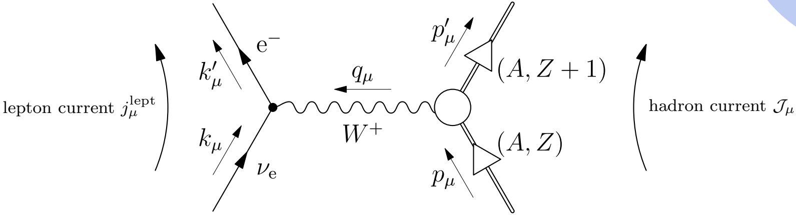
Table: Averaged incoherent cross sections for the stable molybdenum isotopes in units of 10^{-42} cm^2

- Results qualitatively similar for all flavors.

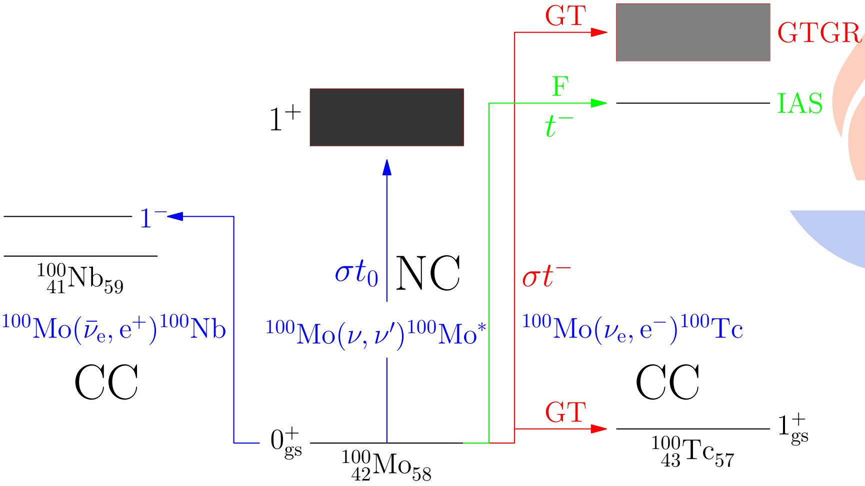
Charged-current scattering off the Mo isotopes

CC scattering off the stable Mo isotopes at supernova energies

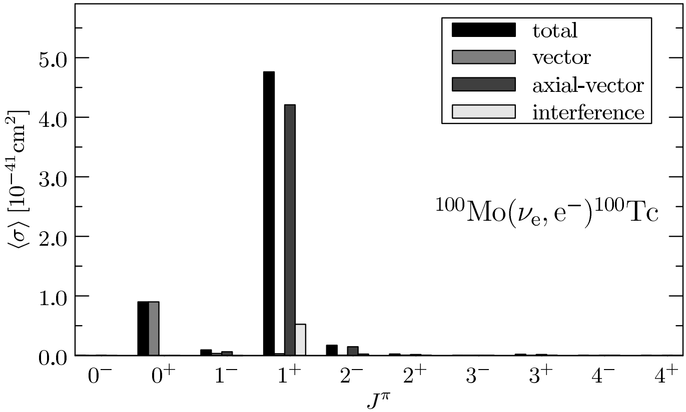
Charged-current (CC) neutrino-nucleus scattering:



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

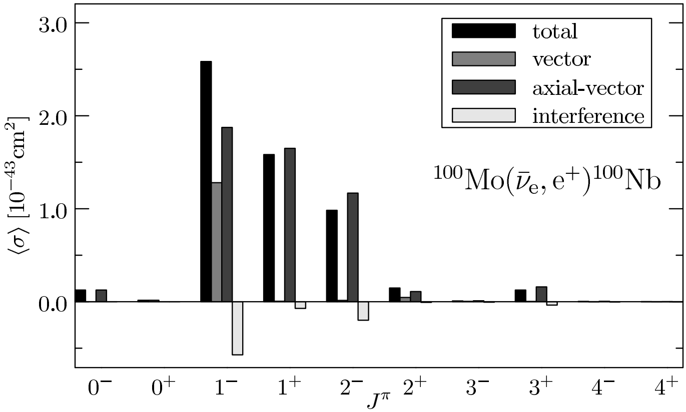


Multipole contributions: CC ν-scattering



- 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 $\bar{\nu}_e$ ($E_\nu \lesssim 100$ MeV).

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

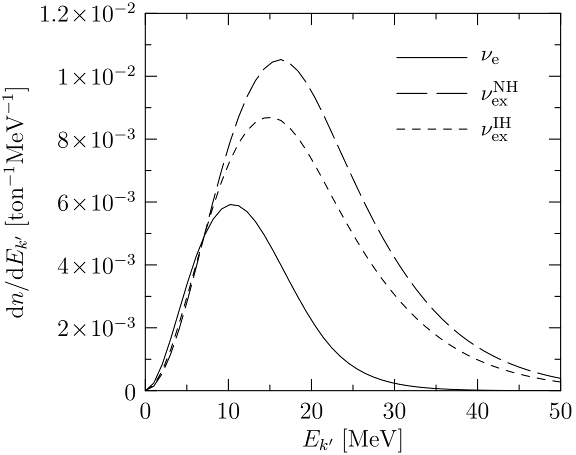
- Due to interactions with the matter of the star the energy profile for the detected neutrinos (antineutrinos) is a superposition of the initial ν_e ($\bar{\nu}_e$) and ν_x ($\bar{\nu}_x$) spectra, i.e.

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

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

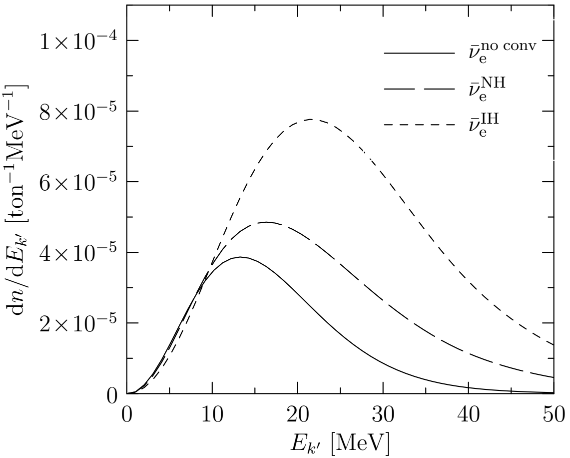
(J.Gava and C. Volpe, PRD 78 (2008) 083007 ; A.B. Balantekin and G.M. Fuller, PLB 471 (1999) 195 ; G.G. Raffelt, Prog. Part. Nucl. Phys. 64 (2010) 393 ; G. Martinez-Pinedo *et al.*, Eur. Phys. J. A 47 (2011) 98)

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



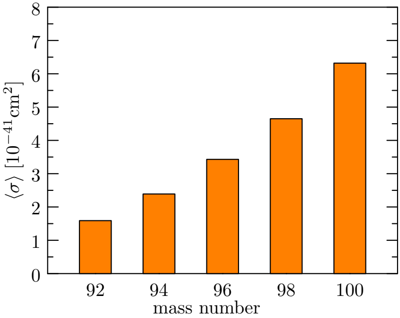
- Number of events significantly increased by flavor conversions
- The produced spectra similar for both mass hierarchies

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

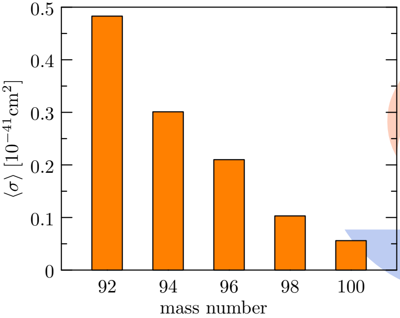


- Small number of events
- The difference between the two neutrino-mass hierarchies very clear

Variation of the CC cross section with mass number



ν_e



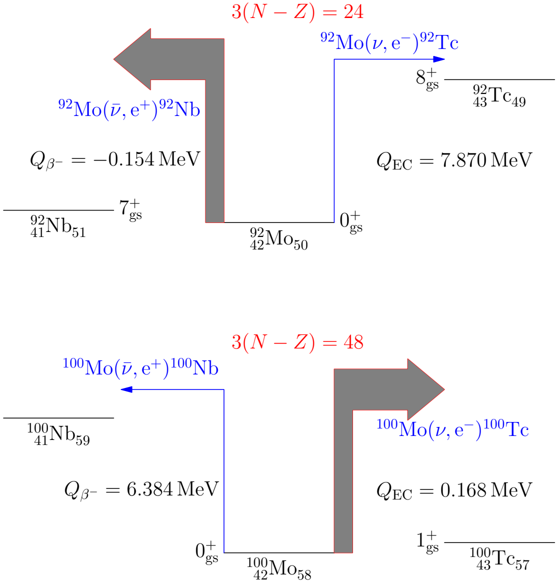
$\bar{\nu}_e$

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

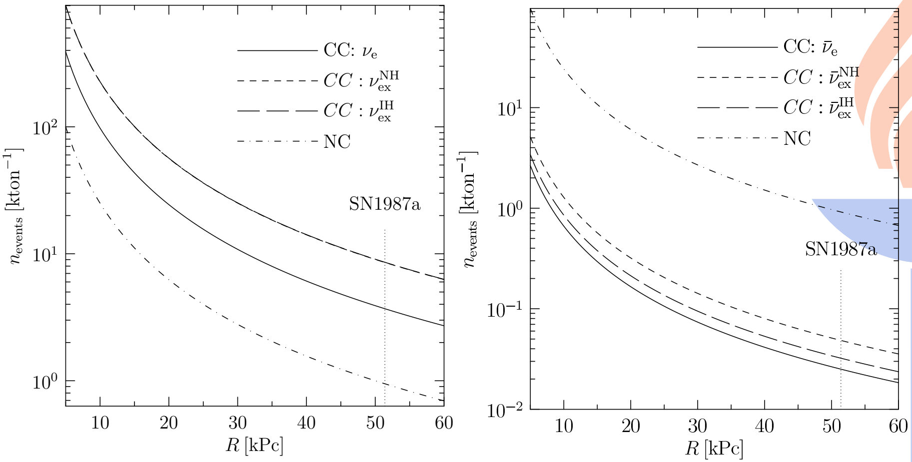
- Ikeda sum rule $S^-(1^+) - S^+(1^+) = 3(N - Z)$
- Variation of threshold energies

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

Part II: Low Q values for neutrino-mass measurements

What causes the rare weak decays to be so rare?

- Ultra-low Q values (Case I)
- Large difference in the angular momenta of the initial and final states (Case II)
- Weak-interaction processes of higher order (Case III)

Ultra-low Q values

Low Q Values for Neutrino Mass Measurements

Neutrino Mass Measurements with low Q values

The KArlsruhe TRItium Neutrino experiment = KATRIN

$Q_{\beta^-} = 18.6\,\text{keV}$, Allowed $^{3}\text{H}(1/2^+) \rightarrow {}^{3}\text{He}(1/2^+)$ β^- decay

$\Downarrow$

The Microcalorimetric Array for a Rhenium Experiment = MARE

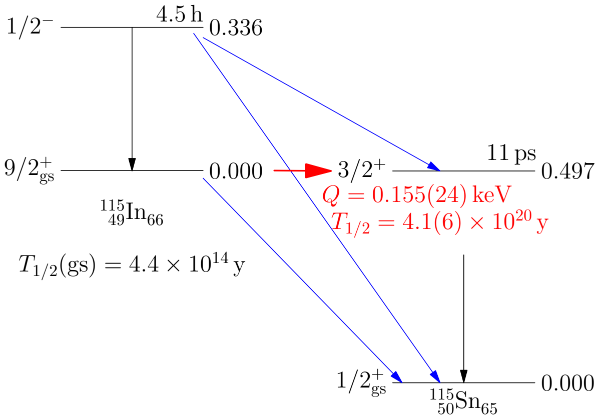
$Q_{\beta^-} = 2.469(4)\,\text{keV}$, First-forbidden unique $^{187}\text{Re}(5/2^+) \rightarrow {}^{187}\text{Os}(1/2^-)$ β^- decay

$\Downarrow$

?

^{115}In: Beta decay with an ultra-low Q value

First discovered by Cattadori et al. (Nucl. Phys. A 748 (2005) 333)



Suggested as a possible independent experiment to look for the neutrino mass

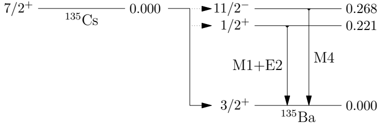
Experimental results

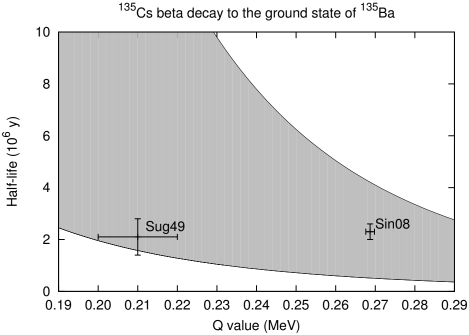
LNGS (C.M. Cattadori et al.)	first observation
	$b = 1.18(31) \times 10^{-6}$
	$T_{1/2}^{\text{partial}} = 3.73(98) \times 10^{20}$ a
HADES (J.S.E. Wieslander et *al*.)	$b = 1.07(17) \times 10^{-6}$
	$T_{1/2}^{\text{partial}} = 4.1(6) \times 10^{20}$ a
JYFLTRAP (J.S.E. Wieslander et *al*.)	$Q_{\beta^-} = 0.35(17)$ keV
Florida StU (B. J. Mount et *al*.)	$Q_{\beta^-} = 0.155(24)$ keV

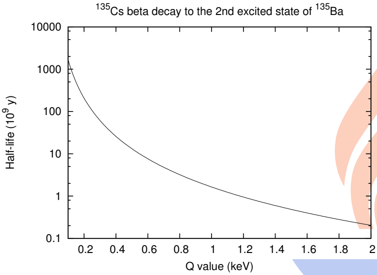
Lowest Q value recorded so far! (J.S.E. Wieslander et *al*., PRL 103 (2009) 122501)
Previous record: ^{187}Re $Q_{\beta^-} = 2.469(4)$ keV [2] (first-forbidden unique transition, used in the MARE neutrino-mass experiment)

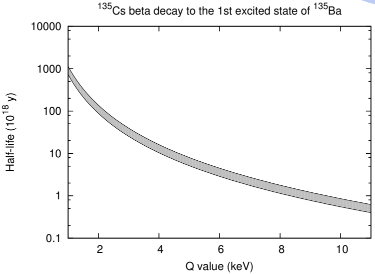
[2] M.S. Basunia, Nucl. Data Sheets 110 (2009) 999.

Decays of ^{135}Cs (1st and 2nd forbidden unique)









Important to revisit the Q-value msrmt!

M.T. Mustonen and J. Suhonen, PLB 703 (2011) 370

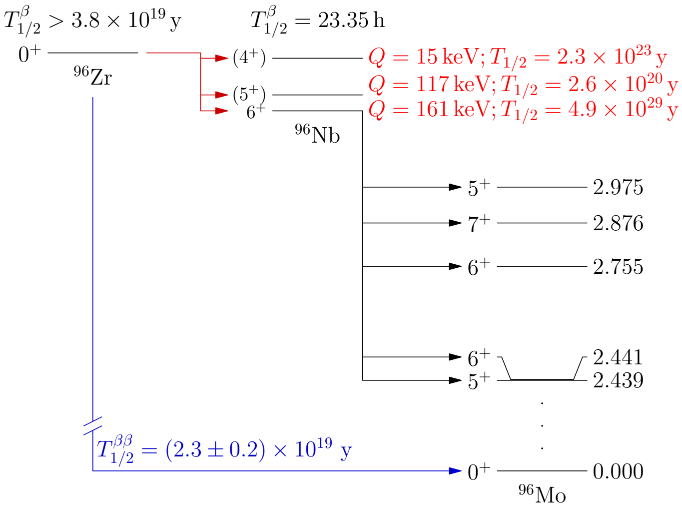
Other interesting cases

initial state	final state	E^* in keV	decay type	Q in keV
^{77}As($3/2^-$)	^{77}Se($5/2^+$)	680.1046(16)	1st non-unique β^-	2.8 ± 1.8
^{111}In($9/2^+$)	^{111}Cd($3/2^+$)	864.8(3)	2nd unique EC	-2.8 ± 5.0
	^{111}Cd($3/2^+$)	866.60(6)	2nd unique EC	-4.6 ± 5.0
^{131}I($7/2^+$)	^{131}Xe($9/2^+$)	971.22(13)	allowed β^-	-0.4 ± 0.7
^{146}Pm(3^-)	^{146}Nd(2^+)	1470.59(6)	1st non-unique EC	1.4 ± 4.0
^{149}Gd($7/2^-$)	^{149}Eu($5/2^+$)	1312(4)	1st non-unique EC	1 ± 6
^{155}Eu($5/2^+$)	^{155}Gd($9/2^-$)	251.7056(10)	1st unique β^-	1.0 ± 1.2
^{159}Dy($3/2^-$)	^{159}Tb($5/2^-$)	363.5449(14)	allowed EC	2.1 ± 1.2
^{161}Ho($7/2^-$)	^{161}Dy($7/2^-$)	857.502(7)	allowed EC	1.4 ± 2.7
	^{161}Dy($3/2^-$)	858.7919(18)	2nd non-unique EC	0.1 ± 2.7

Part III: Highly forbidden beta decays

^{96}Zr and ^{48}Ca: Competition of beta and double beta decays

^{96}Zr decay channels calculated by the QRPA



Results and conclusion for ^{96}Zr

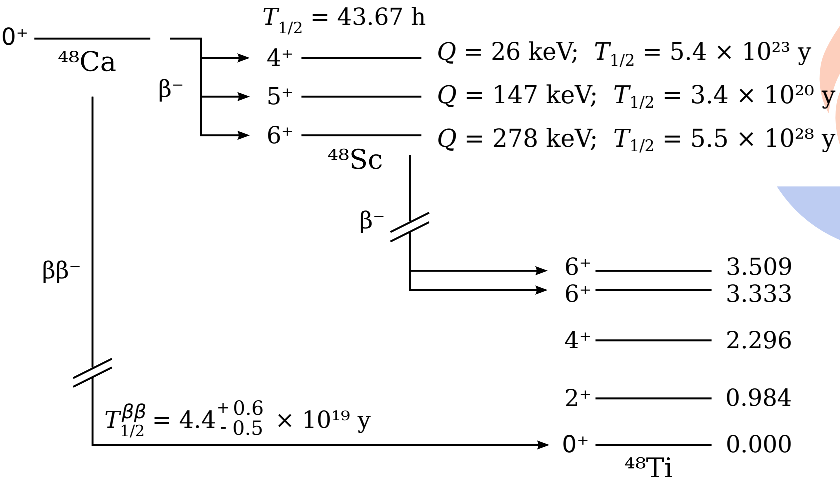
- Transitions from pnQRPA vacuum to pnQRPA excitations

J_f	Forbiddeness	Q value [keV]	$T_{1/2}$ [a]
6^+	6*th* non-unique	161	4.9×10^{29}
5^+	4*th* unique	117	2.6×10^{20}
4^+	4*th* non-unique	15	2.3×10^{23}

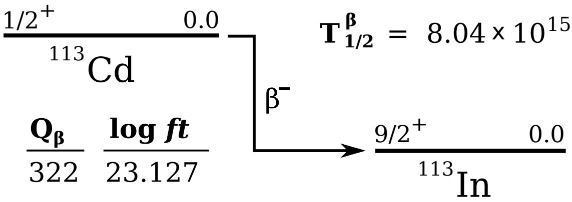
- Calculated total $T^{\beta}_{1/2} = 2.6 \times 10^{20}$ a
- Experimental $T^{\beta\beta}_{1/2} = (2.3 \pm 0.2) \times 10^{19}$ a
- Published in J. Phys. G: Nucl. Part. Phys. 34 (2007) 837.
- Conclusion: The single beta-decay rate is much slower than the double-beta-decay rate! $\longrightarrow$ single-β decay does not interfere severely with the determination of the time variation of the weak coupling constant)

^{48}Ca decay channels calculated by the SHELL MODEL

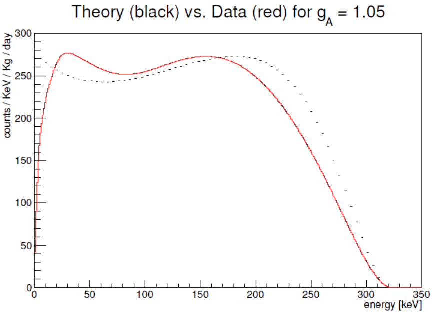
pf-shell GXPF1A interaction (PRC 69 (2004) 034335)

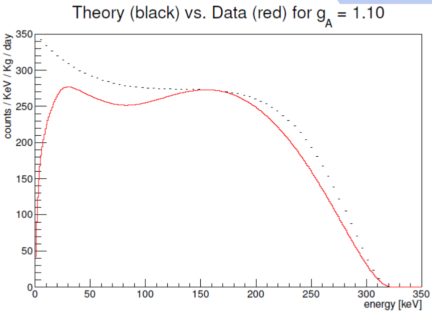


Beta spectrum shape: access the effective value of g_A



$$T^{\beta}_{1/2} = 8.04 \times 10^{15}\ \mathrm{yr}$$





Part IV: Weak processes of higher order

Double Beta Decays

Neutrino properties from experiments

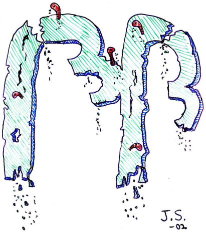
Neutrino Properties from Oscillation Experiments:

From solar, atmospheric, accelerator and reactor-neutrino data (SuperKamiokande, SNO, KamLAND, etc.):

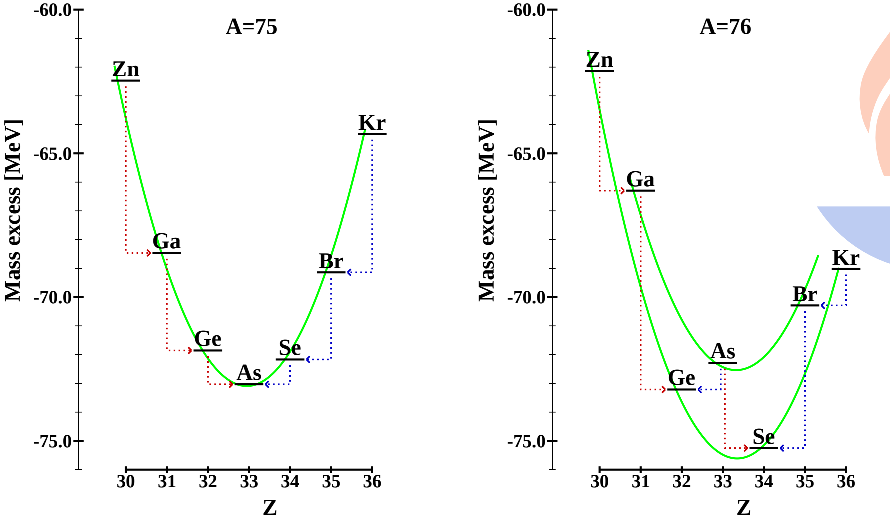
- Squared mass differences Δm^2 of neutrinos
- Matrix elements of the neutrino mixing matrix $\Leftrightarrow$ flavor eigenstates in terms of mass eigenstates: $\nu_e \rightarrow \nu_i \rightarrow \nu_\mu \rightarrow \nu_j \rightarrow \nu_e \rightarrow \nu_k \rightarrow \nu_\mu \cdots$

Complementary experiments:

- Beta decays (absolute neutrino mass): KATRIN, MARE
- **Double beta decays** (nature, absolute mass and hierarchy of neutrinos)

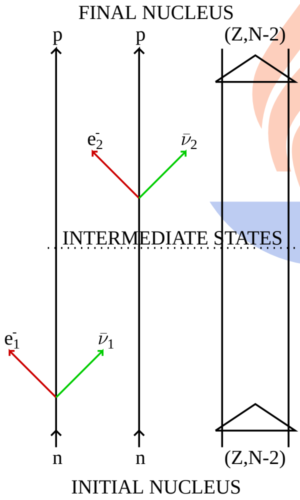


Double beta decay (Isobars $A = 76$)



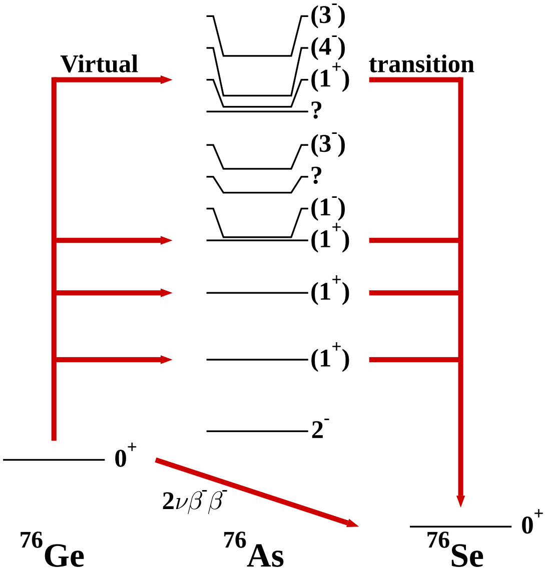
Two-neutrino double beta decay

Nucleus	half-life (years)	experiments
^{48}Ca	$4.2 \cdot 10^{19}$	laboratory
^{76}Ge	$1.4 \cdot 10^{21}$	laboratory
^{82}Se	$9 \cdot 10^{19}$	laboratory, geochemical
^{96}Zr	$2.1 \cdot 10^{19}$	laboratory, geochemical
^{100}Mo	$8.0 \cdot 10^{18}$	laboratory
^{116}Cd	$3.3 \cdot 10^{19}$	laboratory
^{128}Te	$2.5 \cdot 10^{24}$	geochemical
^{130}Te	$9 \cdot 10^{20}$	geochemical
^{136}Xe	$2.4 \cdot 10^{21}$	laboratory
^{150}Nd	$7.0 \cdot 10^{18}$	laboratory
^{238}U	$2.0 \cdot 10^{21}$	radio-chemical



10^{20} years =
10000000000 × age of the UNIVERSE

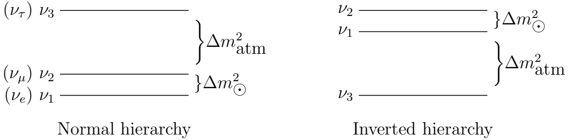
$2\nu\beta\beta$ decay from nuclear-structure point of view



Neutrinoless double β^- decay

$0\nu\beta\beta$ Decay is Able to:

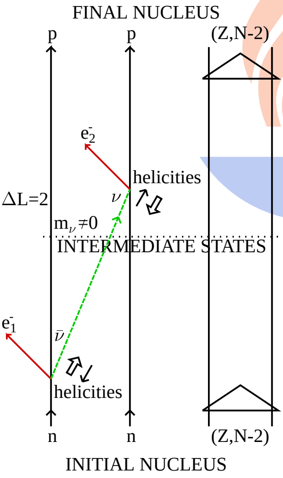
- Reveal if the neutrino is a Majorana particle
- Probe the neutrino effective mass $\langle m_\nu \rangle = \sum_{j=\text{light}} \lambda_j^{\text{CP}} |U_{\text{e}j}|^2 m_j$
- Probe the degenerate or inverted mass hierarchies (next-generation experiments!)
- Probe possibly the CP phases (nuclear matrix elements are critical!)



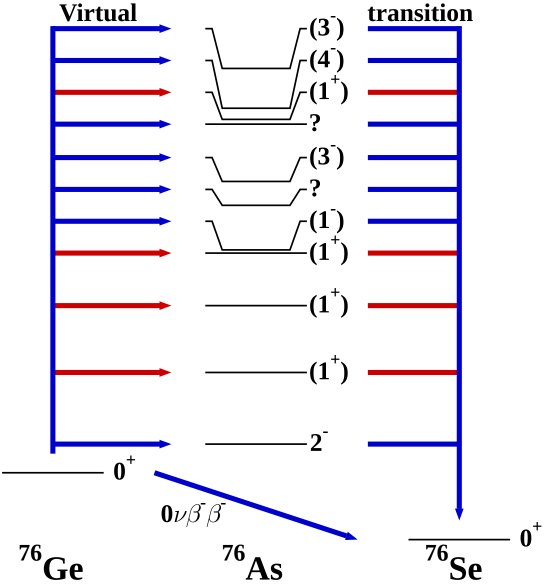
$$\Delta m^2_\odot = 7.67^{+0.16}_{-0.19} \times 10^{-5}\,\text{eV}^2$$
$$\Delta m^2_{\text{atm}} = 2.39^{+0.11}_{-0.08} \times 10^{-3}\,\text{eV}^2$$

[Global 3ν oscillation analysis (2008)]

MASS MODE:
$T_{1/2} \propto \langle m_\nu \rangle^2$



$0\nu\beta\beta$ decay from nuclear-structure point of view



Nuclear Matrix Elements and the $0\nu\beta\beta$ Decay

Decay rate:

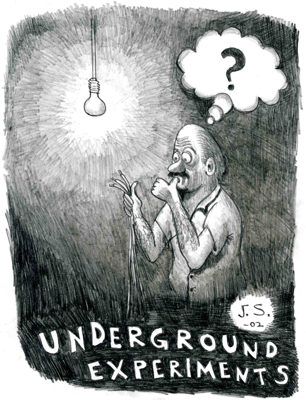
$$\frac{\ln 2}{T_{1/2}} = g^{(0\nu)}(Q)[M^{(0\nu)}]^2 \langle m_\nu \rangle^2$$

- $g^{(0\nu)}(Q) \propto Q^5$ is the phase-space factor
- $M^{(0\nu)}$ = NUCLEAR MATRIX ELEMENT
- Effective neutrino mass:

$$\langle m_\nu \rangle = \sum_{j=\text{light}} \lambda_j^{\text{CP}} |U_{\text{e}j}|^2 m_j$$

Presently computed by: QRPA (Jyväskylä-La Plata, Chapel Hill, Tübingen-Bratislava-Caltec), ISM (Strasbourg-Madrid), IBA-2 (Yale), Gogny-based EDF+GCM (Darmstadt), Projected HFB (Indian-Mexican collaboration)

About Experiments



UNDERGROUND LABORATORIES protect from **COSMIC RAYS** and their secondary particles

Canfranc (Spain)
Kamioka (Japan)
Boulby (England)
Gran Sasso (Italy)
Pyhäsalmi (Finland)
Baksan (Ukraine)
Modane (France-Italy)
Sudbury (Canada)

Experiments Searching for $0\nu\beta\beta$ Decays:

Major recent experiments:

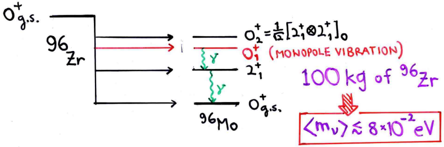
- Heidelberg–Moscow (^{76}Ge) (ceased, claim of detection by H.-V. K-Kgh, but result still **controversial**)
- NEMO3 (^{76}Ge ^{82}Se ^{96}Zr ^{100}Mo ^{116}Cd ...) (Just stopped in Modane)
- Cuoricino (^{128,130}Te) (Running in Gran Sasso)
- GERDA (^{76}Ge) (Latest result strongly **contests the H.-V. K-Kgh claim**)
- EXO-200 (^{136}Xe)
- Kamland-Zen (^{136}Xe)
- COBRA (^{70}Zn ^{106,114,116}Cd ^{128,130}Te)

Future Experiments:

SUPERNEMO (^{82}Se ^{100}Mo...), MAJORANA (^{76}Ge), CAMEOII,III (^{116}Cd), CUORE (^{128,130}Te), MOON (^{100}Mo), EXO-1000 (^{136}Xe), **ZORRO (^{96}Zr)**

These are in $100 - 1000$ kg scale and cost about 100000000 EURO/$ each!

The ZORRO Experiment

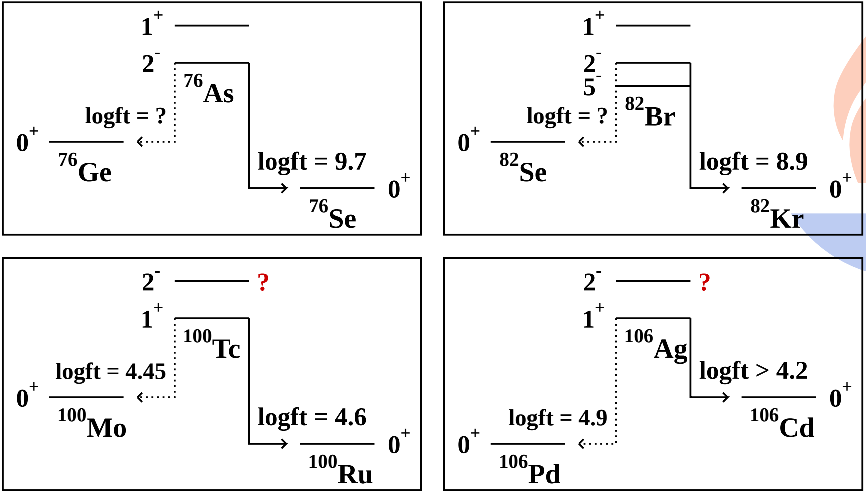


Complementary experimental probes of $0\nu\beta\beta$ NMEs

Possible Experimental Probes:

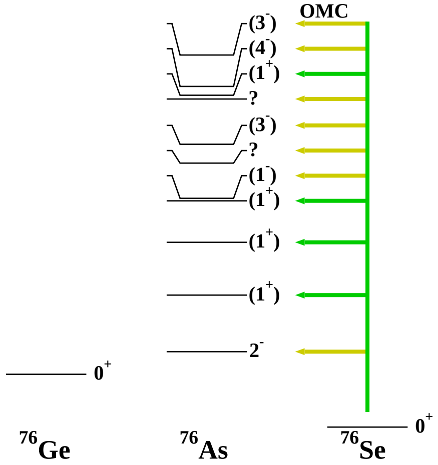
- Beta decays (Need more data!) $\leftrightarrow$ Measurements of EC branches using the TITAN ion trap facility at TRIUMF (access also the renormalization of g_A!)
- Charge-exchange reactions [β^+-type (d,^{2}He) reactions at KVI, Groningen; β^--type (^{3}He,t) reactions at RCNP, Japan]
- Measurements of occupation numbers of active neutron orbitals $\leftrightarrow$ (d,p), (α,^{3}He) [add neutron] and (p,d), (^{3}He,α) [remove neutron]
- Measurements of occupation numbers of active proton orbitals $\leftrightarrow$ (^{3}He,d) [add proton] and (d,^{3}He) [remove proton]
- Ordinary muon capture (now experimentally feasible)

Examples of available data on beta decays



Ordinary muon capture as a probe

$$^{76}\mathrm{Se} + \mu^- \rightarrow {}^{76}\mathrm{As} + \nu_\mu$$



$$m_\mu c^2 \approx 105\,\mathrm{MeV}$$

Note:

- Forbidden OMC is not forbidden in the sense of beta decay
- The induced currents are activated

Experiments:

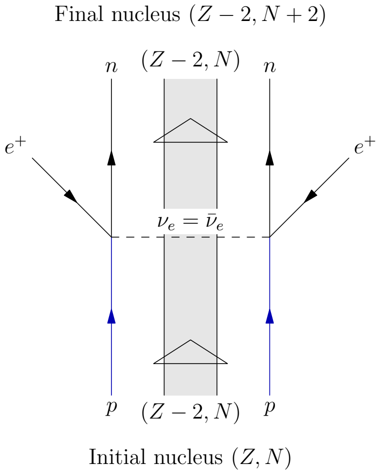
Paul Scherrer Institute (PSI)

Double β^+/EC decays

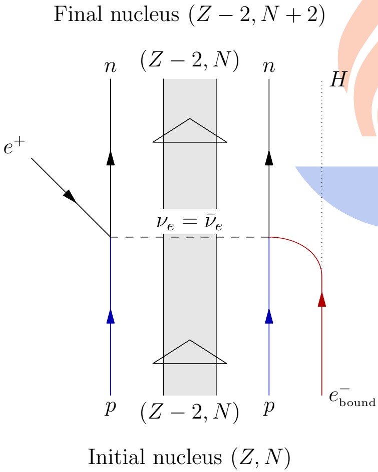
Double beta decays on the positron-emitting/electron-capture side

Double positron/EC decays

$0\nu\beta^+\beta^+$ Decay

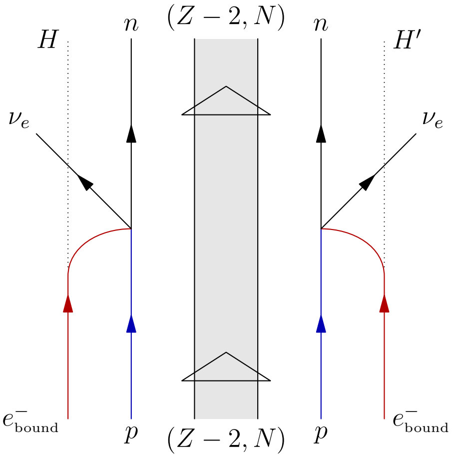


$0\nu\beta^+$EC Decay



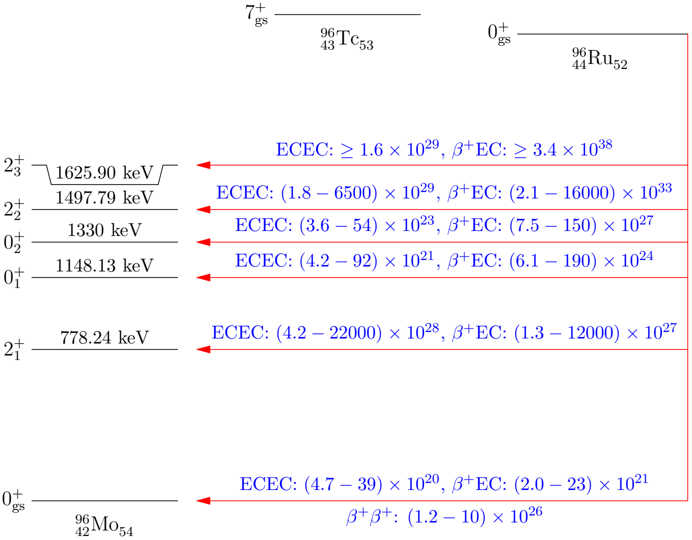
Two-neutrino double electron capture

Final nucleus $(Z-2, N+2)$

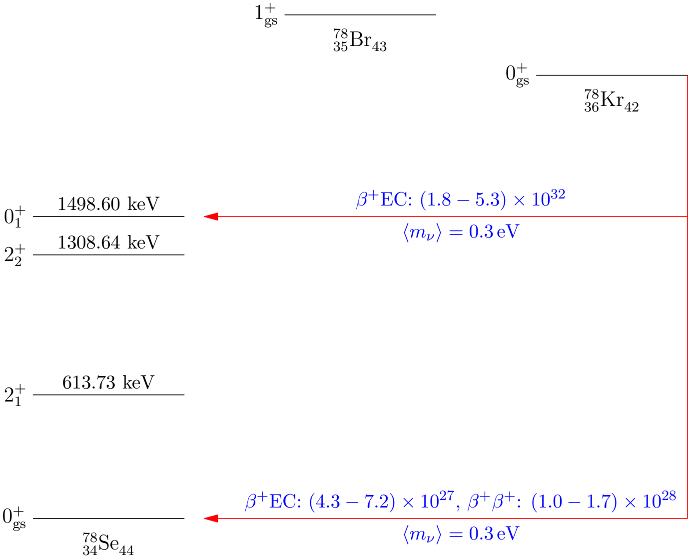


Initial nucleus (Z, N)

Example: Various $2\nu2\beta$ decay modes of ^{96}Ru



Example: Various $0\nu2\beta$ decay modes of ^{78}Kr



Conclusions

Conclusions:

- Knowledge about nuclear responses to supernova neutrinos essential for neutrino detection and applications in astrophysics.
- QRPA (MQPM) + Donnelly-Walecka formalism powerful framework for neutrino-nucleus calculations for even-even (odd) open-shell nuclei.
- Beta transitions with ultra-low Q values can potentially be used in neutrino-mass detection $\longleftrightarrow$ ATOMIC effects are important
- In the case of ^{96}Zr and ^{48}Ca decays the single beta-decay rate is much slower than the double-beta-decay rate
- Theoretical and experimental studies of the electron spectra of forbidden non-unique β transitions have potential to probe the effective value of the axial-vector coupling constant g_A
- Double β^- decays are much studied both theoretically and experimentally $\longleftrightarrow$ Nature and mass scale of the neutrino
- The double positron emitting/electron-capture modes are less studied (smaller Q values, less observational potential)