Neutrino Properties from Beta Decay, Double Beta Decay and Reactors

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Contents:

- INTRO: Rare weak decays and the axial coupling
- Beta-electron spectral shapes
- ν mass from low-Q β^-/EC decays
- Muon capture - background
- Muon capture as a probe of $0\nu\beta\beta$ decay
- Reactor flux anomalies

INTRO: Rare weak decays (of interest for determination of ν properties)

What causes the rare weak decays to be so rare?

- Very low decay energies (Q values) of β decays
- Weak-interaction processes of higher order ($\beta\beta$ decays)
- Large difference in the angular momenta of the initial and final states (forbidden β decays)

See the recent reviews:

H. Ejiri, J. S., K. Zuber: Neutrino-nuclear responses for astro-neutrinos, single beta decays and double beta decays, Physics Reports 797 (2019) 1–102

K. Blaum, S. Eliseev, F. A. Danevich, V. I. Tretyak, S. Kovalenko, M. I. Krivoruchenko, Yu. N. Novikov and J. S., Neutrinoless double-electron capture, Reviews of Modern Physics 92 (2020) 1–61.

Determination of the effective value of the weak axial coupling g_A

Motivation:

Effective value of the weak coupling g_A is involved in all weak processes, and thus have impact on

- studies of rare β decays
- processes in neutrino physics ($\beta\beta$ decay, low-energy (anti)neutrino-nucleus scattering, nuclear muon capture, . . .)
- processes in astrophysics (allowed and forbidden β decays, (anti)neutrino-nucleus scattering cross sections,. . .)

$$\Downarrow$$

Affects (strongly) the determination of neutrino properties!

What we know about the effective value of g_A:

At the quark level $g_A^{quark} = 1$

$\Downarrow$

At the free-nucleon level: Free-nucleon value of g_A (Particle Data Group 2016) from the decay of a free neutron: $g_A^{free} = 1.2723(23)$

$\Downarrow$

At the nuclear level: Nucleon weak current in a nucleus:

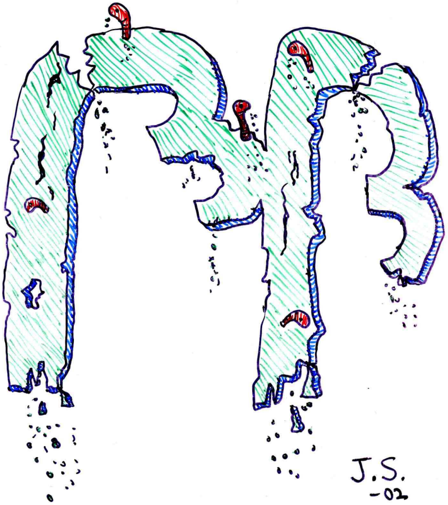
$$j_N^\mu = g_V \gamma^\mu - g_A^{eff} \gamma^\mu \gamma^5$$

The free-nucleon value of g_A is changed in nuclear-structure calculations by:

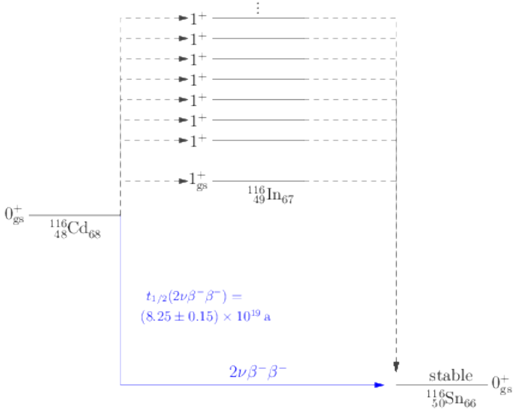
- Non-nucleonic degrees of freedom (e.g. Δ resonances)
- Effects beyond the impulse approximation (e.g. two-body meson-exchange currents)
- Deficiencies in nuclear many-body approaches (e.g. restricted valence spaces, lacking many-body configurations, omission of three-body nuclear forces)

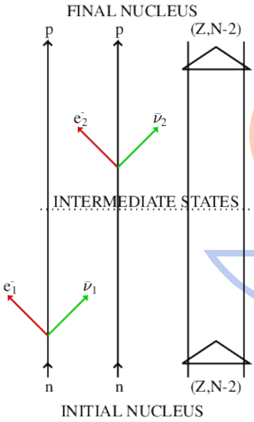
See also: "Value of the axial-vector coupling strength in β and $\beta\beta$ decays: A review" **Frontiers in Physics 5 (2017) 55**.

Rates of $\beta\beta$ decay and the weak axial coupling g_A



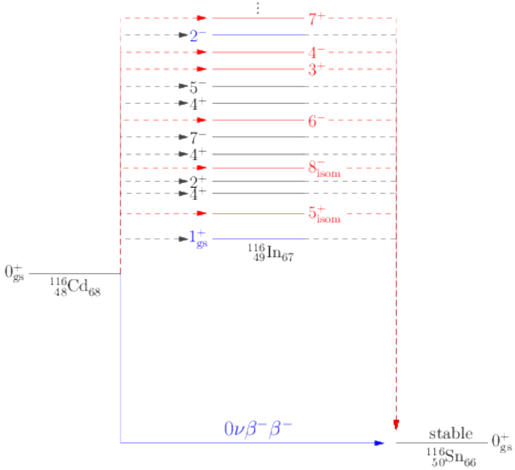
Two-neutrino $\beta\beta$ decay of ^{116}Cd

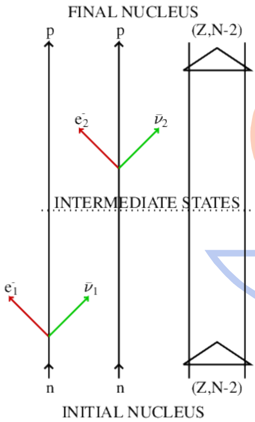




$$2\nu\beta\beta - \text{rate} \sim \left| M^{(2\nu)}_{\mathrm{GTGT}} \right|^2 = (g_{\mathrm{A}}^{\mathrm{eff}})^4 \left| \sum_{m,n} \frac{M_{\mathrm{L}}(1_m^+) M_{\mathrm{R}}(1_n^+)}{D_m} \right|^2$$

Neutrinoless $\beta\beta$ decay of ^{116}Cd (mass mode)





$$0\nu\beta\beta - \text{rate} \sim \left|M^{(0\nu)}_{\rm GTGT}\right|^2 = (g^{\rm eff}_{\rm A,0\nu})^4 \left|\sum_{J^\pi}(0^+_f||\mathcal{O}^{(0\nu)}_{\rm GTGT}(J^\pi)||0^+_i)\right|^2$$

Gamow-Teller β and $2\nu\beta\beta$ decays

There are data on:

Gamow-Teller β transitions and $2\nu\beta\beta$ transitions

For these we have the low-momentum-exchange limit of $0\nu\beta\beta$ decay

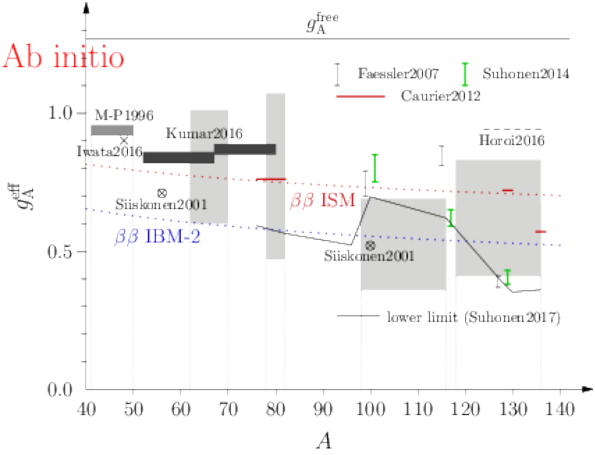
$$g_{\mathrm{A},0\nu}(J^\pi) \xrightarrow{q\to 0} g_{\mathrm{A}}(J^\pi),$$

where the usual convention is $g_{\mathrm{A}} \equiv g_{\mathrm{A}}(1^+)$

Nuclear models:

ISM (Interacting Shell Model)
pnQRPA (proton-neutron QRPA)
IBM-2 (microscopic interacting boson model)

Results extracted from the GT $\beta^{\pm}$/EC and $2\nu\beta\beta$ calculations



Ab initio: P. Gysbers *et al.*, Nature Physics 15 (2019) 428

- Faessler2007: pnQRPA A. Faessler *et al.*, arXiv 0711.3996v1 [Nucl-th]
- Suhonen2014: pnQRPA J. Suhonen *et al.*, Nucl. Phys. A 924 (2014) 1
- Suhonen2017: pnQRPA J. Suhonen, Phys. Rev. C 96 (2017) 055501
- Caurier2012: ISM E. Caurier *et al.*, Phys. Lett. B 711 (2012) 62
- Horoi2016: ISM M. Horoi *et al.*, Phys. Rev. C 93 (2016) 024308
- M-P1996: ISM G. Martínez-Pinedo *et al.*, Phys. Rev. C 53 (1996) R2602
- Iwata2016: ISM Y. Iwata *et al.*, Phys. Rev. Lett. 116 (2016) 112502
- Kumar2016: ISM V. Kumar *et al.*, J. Phys. G 43 (2016) 105104 Phys. Lett. B 711 (2012) 62
- Siiskonen2001: ISM T. Siiskonen *et al.*, Phys. Rev. C 63 (2001) 055501
- $\beta\beta$ ISM and IBM-2: J. Barea *et al.*, Phys. Rev. C 87 (2013) 014315
- Light hatched regions: pnQRPA H. Ejiri *et al.*, J. Phys. G 42 (2015) 055201 ; P. Pirinen *et al.*, Phys. Rev. C 91 (2015) 054309 ; F. Deppisch *et al.*, Phys. Rev. C 94 (2016) 055501

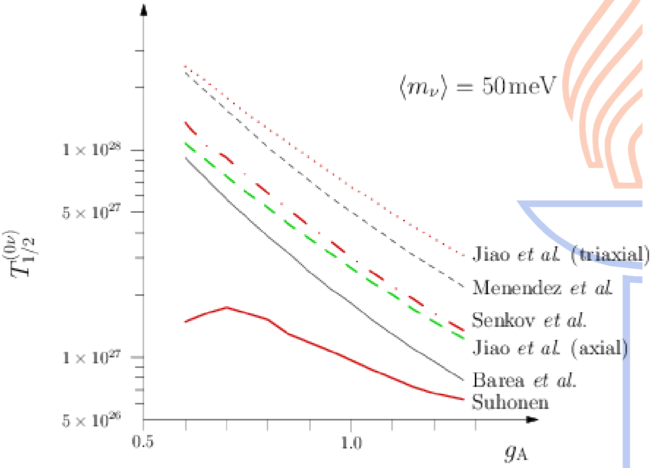
Effects of a quenched g_{A} on half-lives of $0\nu\beta\beta$ decays:

$$\left[T_{1/2}^{(0\nu)}\right]^{-1} = (g_{\mathrm{A},0\nu}^{\mathrm{eff}})^4 G^{(0\nu)} \left|M^{(0\nu)}\right|^2 \left(\frac{\langle m_\nu \rangle}{m_e}\right)^2$$

$$M^{(0\nu)} = M_{\mathrm{GT}}^{(0\nu)} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A},0\nu}^{\mathrm{eff}}}\right)^2 M_{\mathrm{F}}^{(0\nu)} + M_{\mathrm{T}}^{(0\nu)}$$

Example: $0\nu\beta\beta$ NMEs of ^{76}Ge, effect on the half-life

- Jiao *et al.*: Phys. Rev. C 96 (2017) 054310 (GCM+ISM)
- Menendez *et al.*: Nucl. Phys. A 818 (2009) 139 (ISM)
- Senkov *et al.*: Phys. Rev. C 93 (2016) 044334 (ISM)
- Barea *et al.*: Phys. Rev. C 91 (2015) 034304 (IBM-2)
- Suhonen: Phys. Rev. C 96 (2017) 055501 (pnQRPA + g_{pp} + isospin restoration + data on $2\nu\beta\beta$)



How do we extract information on the value of g_A?

These methods are now available:

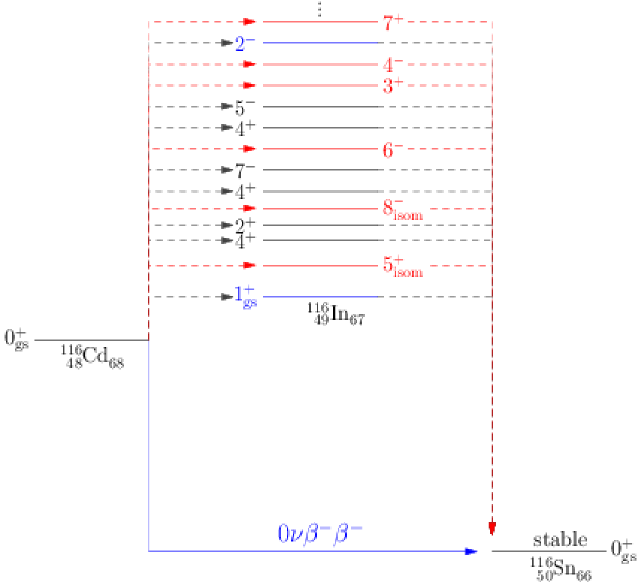
For low momentum exchanges (g_A):

- study half-lives of β decays (1^+ and 2^- states)
- study half-lives of $2\nu\beta\beta$ decays (1^+ states)
- Study electron spectral shapes of β decays (J^π states)

For high momentum exchanges like $0\nu\beta\beta$ decay ($g_{A,0\nu}$):

- Study nuclear muon capture (J^π states)

BUT: $0\nu\beta\beta$ decay goes also through higher angular-momentum states!



Introducing the SSM: Spectrum-Shape Method

$$g_{\mathrm{A},0\nu}(J^\pi) \xrightarrow{q\to 0} g_{\mathrm{A}}(J^\pi)$$

Higher-multipole transitions: Spectrum-Shape Method (SSM)*:

Effective value of $g_{\mathrm{A}}(J^\pi)$

as derived from

electron spectra of

forbidden non-unique β decays

*First introduced in: M. Haaranen, P. C. Srivastava and J. S., Forbidden nonunique β decays and effective values of weak coupling constants, Phys. Rev. C 93 (2016) 034308

Half-life:

$$t_{1/2} = \kappa/\tilde{C} \,.$$

Dimensionless integrated shape function:

$$\tilde{C} = \int_1^{w_0} C(w_e) p w_\mathrm{e} (w_0 - w_e)^2 F_0(Z_f, w_e) \mathrm{d}w_e \,.$$

Shape factor:

$$C(w_e) = \sum_{k_e, k_\nu, K} \lambda_{k_e} \left[M_K(k_e, k_\nu)^2 + m_K(k_e, k_\nu)^2 - \frac{2\gamma_{k_e}}{k_e w_e} M_K(k_e, k_\nu) m_K(k_e, k_\nu) \right] \,,$$

where

$$\lambda_{k_e} = \frac{F_{k_e - 1}(Z, w_e)}{F_0(Z, w_e)} \;; \quad \gamma_{k_e} = \sqrt{k_e^2 - (\alpha Z_f)^2} \,,$$

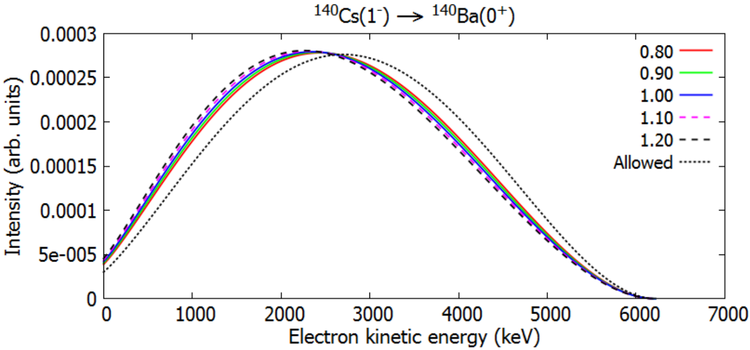
$F_{k-1}(Z, w_e)$ being the generalized Fermi function.

Decomposition of the shape factor:

$$C(w_e) = g_\mathrm{V}{}^2 C_\mathrm{V}(w_e) + g_\mathrm{A}{}^2 C_\mathrm{A}(w_e) + g_\mathrm{V} g_\mathrm{A} C_\mathrm{VA}(w_e).$$

EXAMPLE: 1*st*-forbidden nonunique decay of ^{140}Cs

First-forbidden nonunique β^- transition $^{140}\mathrm{Cs}(1^-) \rightarrow {}^{140}\mathrm{Ba}(0^+)$: a high-yield fission product$\longrightarrow$ Contributes to the reactor-flux anomalies!

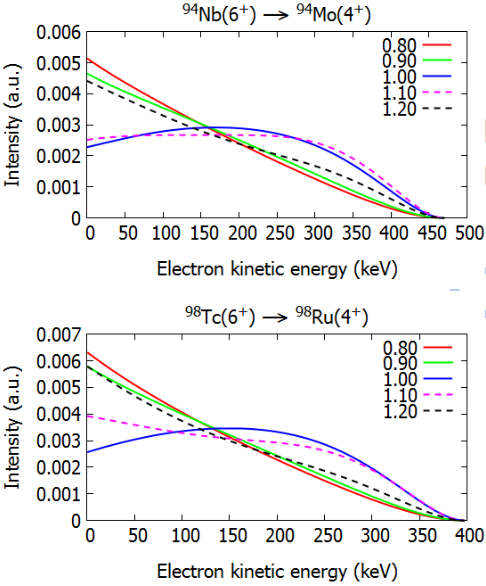


For the allowed approximation we have just a multiplicative factor and a universal spectral shape (independent of $g_{\rm A}$): $C(w_e)_{\rm allowed} = \frac{1}{2J_i+1}\left(g_{\rm A}{}^2 M_{\rm GT}^2 + g_{\rm V}{}^2 M_{\rm F}^2\right) \neq$ function of w_e

ISM-computed β spectra for different values of g_A

Normalized ISM-computed electron spectra for the 2*nd*-forbidden nonunique β^- decays of ^{94}Nb and ^{98}Tc ($g_V = 1.0$).

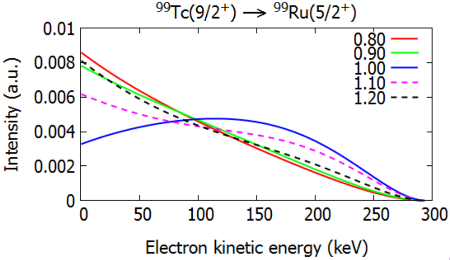
From: J. Kostensalo and J. S., g_A-driven shapes of electron spectra of forbidden β decays in the nuclear shell model, Phys. Rev. C 96 (2017) 024317



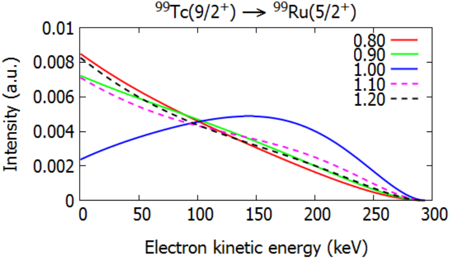
Example: ISM- and MQPM-computed electron spectra

Normalized electron spectra for the 2*nd*-forbidden nonunique β^- decay of ^{99}Tc ($g_V = 1.0$) using different values of g_A.

Going to be treated by the IBS-KNU-KRISS-LUKE-JYFL group: gA EXPERiment and Theory collaboration = gA-EXPERT and the GSSI-INFN-LNGS-LUKE-JYFL Collaboration: Array of Cryogenic Calorimeters to Evaluate Spectral Shapes = ACCESS



(ISM)

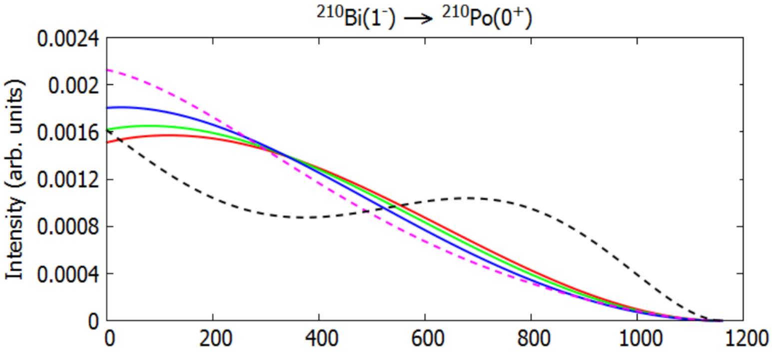


(MQPM)

EXAMPLE: 1*st*-forbidden nonunique decay of ^{210}Bi

First-forbidden nonunique β^- transition $^{210}\mathrm{Bi}(1^-) \rightarrow {}^{210}\mathrm{Po}(0^+)$

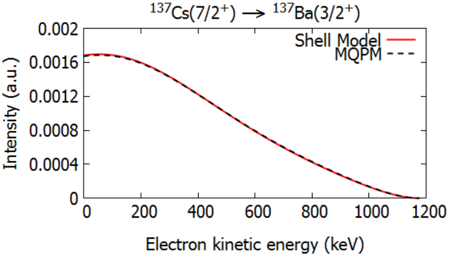
Spectral shapes for different values of $g_{\mathrm{A}} = 0.80$(solid red), 0.90, 1.00, 1.10, 1.20(dashed black)



Measured and currently analyzed by the gA-EXPERT.

β spectral shapes without dependence on g_A

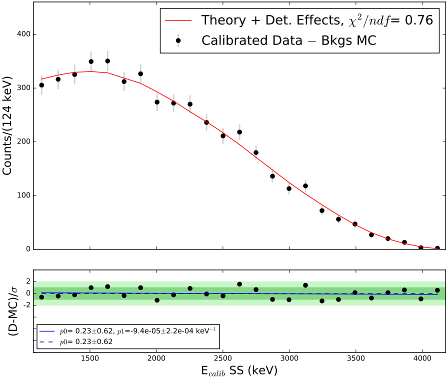
Normalized computed electron spectrum for the 2*nd*-forbidden nonunique β^- decay of ^{137}Cs



From: J. Kostensalo and J. S., Phys. Rev. C 96 (2017) 024317

First-forbidden nonunique β^- decay

$^{137}\mathrm{Xe}(7/2^-) \rightarrow {}^{137}\mathrm{Cs}(7/2^+)$.



From: S. Al Kharusi *et al.* (EXO-200 Collaboration), Phys. Rev. Lett. 124 (2020) 232502.

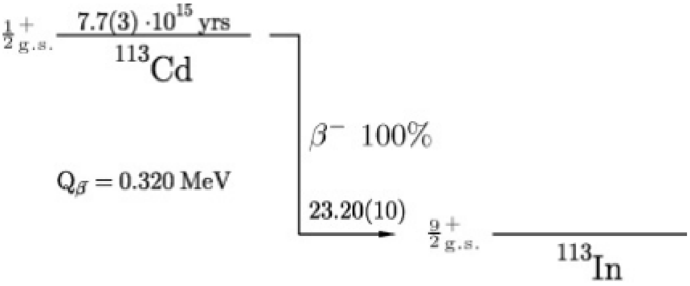
Current list of g_A-dependent β-spectrum shapes

Transition	$J_i^{\pi_i}$ (gs)	$J_f^{\pi_f}$ (n_f)	Branching	K	Sensitivity	Nuclear model
^{59}Fe → ^{59}Co	$3/2^-$	$7/2^-$ (gs)	0.18%	2	Moderate	ISM
^{60}Fe → ^{60}Co	0^+	2^+ (gs)	**100%**	2	Moderate	ISM
^{87}Rb → ^{87}Sr	$3/2^-$	$9/2^+$ (gs)	**100%**	3	Moderate	MQPM, ISM
^{94}Nb → ^{94}Mo	6^+	4^+ (2)	**100%**	2	**Strong**	ISM
^{98}Tc → ^{98}Ru	6^+	4^+ (3)	**100%**	2	**Strong**	ISM
^{99}Tc → ^{99}Ru	$9/2^+$	$5/2^+$ (gs)	**100%**	2	**Strong**	MQPM, ISM
^{113}Cd → ^{113}In	$1/2^+$	$9/2^+$ (gs)	**100%**	4	**Strong**	MQPM, ISM, IBFM-2
^{115}In → ^{115}Sn	$9/2^+$	$1/2^+$ (gs)	**100%**	4	**Strong**	MQPM, ISM, IBFM-2
^{136}Te → ^{136}I	0^+	(1^-) (gs)	**8.7%**	1	**Strong**	ISM
^{137}Xe → ^{137}Cs	$7/2^-$	$5/2^+$ (1)	**30%**	1	**Strong**	ISM
^{138}Cs → ^{138}Ba	3^-	3^+ (1)	**44%**	1	**Strong**	ISM
^{210}Bi → ^{210}Po	1^-	0^+ (gs)	**100%**	1	**Strong**	ISM

- Electron spectra of ^{113}Cd (L. Bodenstein-Dresler *et al.*, Phys. Lett. B 800 (2020) 135092) measured by the COBRA collaboration.
- Electron spectrum of ^{115}In measured by using LiInSe$_2$ bolometers (Experimentalists-Jyväskylä collaboration).

EXAMPLE: 4*th*-forbidden nonunique decay of ^{113}Cd

4*th*-forbidden nonunique β^- transition $^{113}\mathrm{Cd}(1/2^+) \rightarrow {}^{113}\mathrm{In}(9/2^+)$



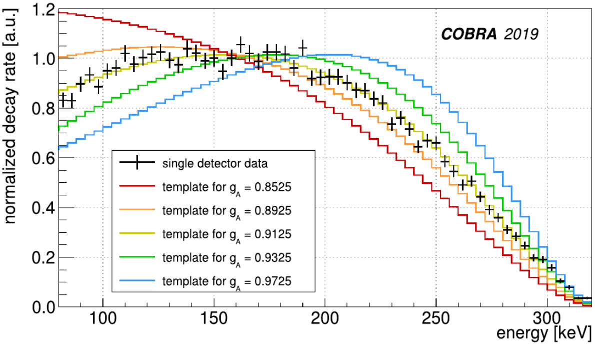
Calculated by using the Interacting Shell Model (ISM), the Microscopic Quasiparticle-Phonon Model (MQPM) and the microscopic Interacting Boson-Fermion Model (IBFM-2).

Decay of ^{113}Cd – Comparison with data

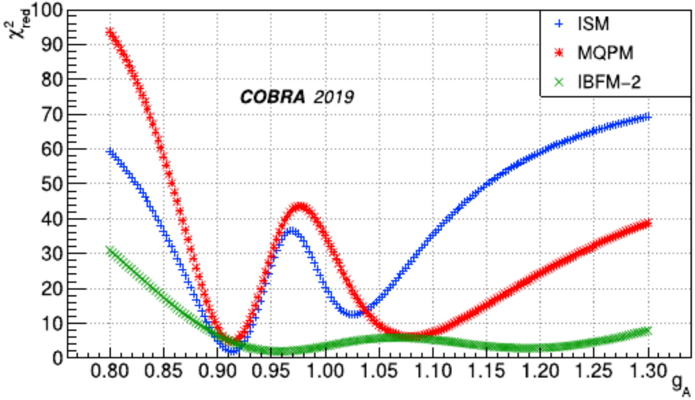
Normalized electron spectra for the *4th*-forbidden nonunique β^- transition $^{113}\mathrm{Cd}(1/2^+) \rightarrow {}^{113}\mathrm{In}(9/2^+)$ $(g_V = 1.0)$.

Experimental data from The COBRA collaboration: PLB2020: L. Bodenstein-Dresler *et al.*, Phys. Lett. B 800 (2020) 135092.

Measured spectrum by detector no. 54:

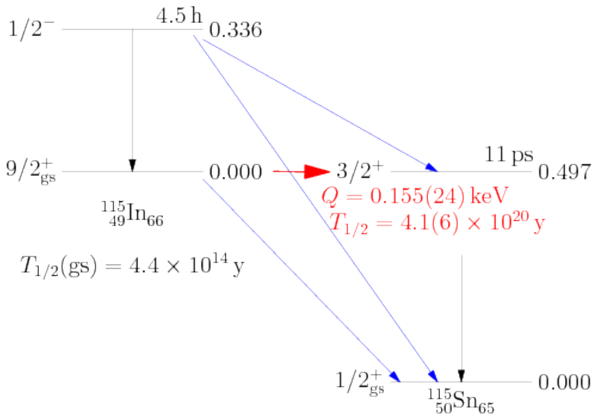


Decay of ^{113}Cd – Comparison with data



PLB2020 : $\bar{g}_A$(ISM) $= 0.914 \pm 0.008$; PLB2021 $:= 0.907 \pm 0.064$
PLB2020 : $\bar{g}_A$(MQPM) $= 0.910 \pm 0.013$; PLB2021 $:= 0.993 \pm 0.063$
PLB2020 : $\bar{g}_A$(IBFM-2) $= 0.955 \pm 0.035$; PLB2021 $:= 0.828 \pm 0.140$

EXAMPLE: 4*th*-forbidden nonunique transition $^{115}\mathrm{In}(9/2^+) \rightarrow {}^{115}\mathrm{Sn}(1/2^+)$



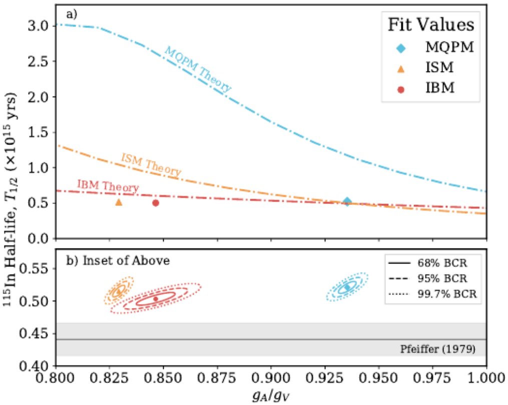
Interesting ultra-low Q-value transition: The 2*nd*-forbidden unique transition $^{115}\mathrm{In}(9/2^+) \rightarrow {}^{115}\mathrm{Sn}(3/2^+)$ has the smallest known Q value of a nuclear transition: J. S. E. Wieslander *et al.*, Phys. Rev. Lett. 103 (2009) 122501; B. J. Mount *et al.*, Phys. Rev. Lett. 103 (2009) 122502.

Decay of ^{115}In – Comparison with data

Normalized electron spectra for the 4*th*-forbidden nonunique β^- decay $^{115}\text{In}(9/2^+) \rightarrow {}^{115}\text{Sn}(1/2^+)$ ($g_V = 1.0$).

Result from

The CEA-CNRS-CSNSM-INR-JYFL-MIT-LUKE-UCB collaboration: A. F. Leder *et al.*, work submitted.



$$\bar{g}_A(\text{ISM}) = 0.830 \pm 0.002$$
$$\bar{g}_A(\text{IBFM-2}) = 0.845 \pm 0.006$$
$$\bar{g}_A(\text{MQPM}) = 0.936 \pm 0.003$$

Low Q-value β^-/EC decays for neutrino-mass measurements

$$\beta^- : (A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e$$

$$\text{EC} : (A,Z) + e^- \to (A,Z-1) + \nu_e$$

Neutrino Mass Measurements with low Q values

The KArlsruhe TRItium Neutrino experiment = KATRIN

$Q_{\beta^-} = 18.6\,\text{keV}$, Allowed

$^{3}\text{H}(1/2^+) \rightarrow {}^{3}\text{He}(1/2^+)\ \beta^-$ decay, $T_{1/2} = 12.33\,\text{y}$

Sensitivity to neutrino mass: $m_\nu \sim 0.2\,\text{eV}$

$\Downarrow$

(The Microcalorimetric Array for a Rhenium Experiment = MARE

$Q_{\beta^-} = 2.469(4)\,\text{keV}$, First-forbidden unique $^{187}\text{Re}(5/2^+) \rightarrow {}^{187}\text{Os}(1/2^-)\ \beta^-$ decay, $T_{1/2} = 4 \times 10^{10}\,\text{y}$)

The Electron Capture in Holmium experiment = ECHo

$Q_{\text{EC}} = 2.833(34)\,\text{keV}$ (Penning trap), Allowed $^{163}\text{Ho}(7/2^-) \rightarrow {}^{163}\text{Dy}(5/2^-)$ EC decay,

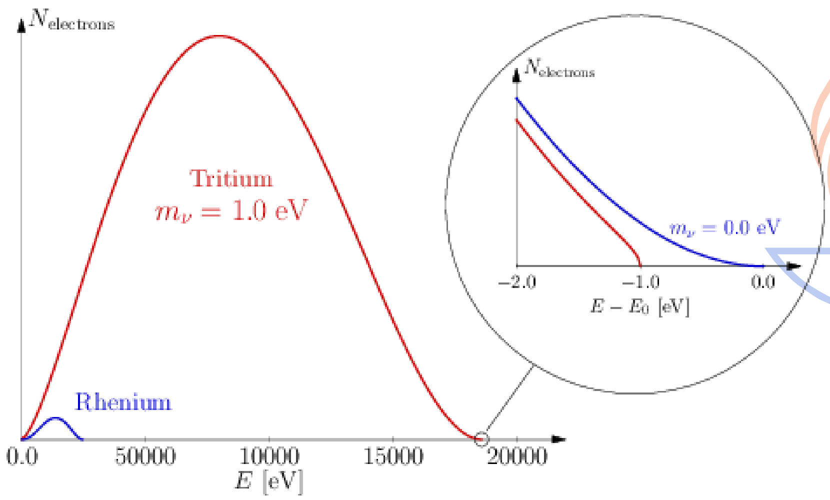
$T_{1/2} = 4570\,\text{y}$

Sensitivity to neutrino mass: $m_\nu \sim ?$

$\Downarrow$

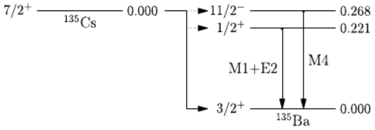
?

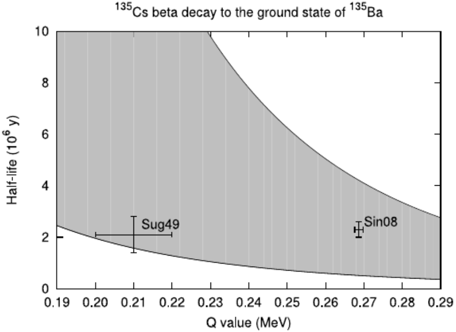
Extraction of the neutrino mass



The fraction of decays in an energy interval ΔE near the endpoint goes as $(\Delta E/Q)^3$

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



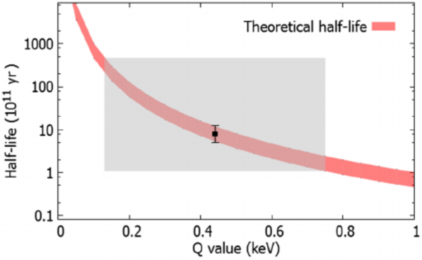


M.T. Mustonen and J. S., PLB 703 (2011) 370:

Important to revisit the Q-value msrmt!

Recent measurement of the Q value by the JYFLTRAP gives $Q = 268.66(30)$ keV, leading to $Q_{exc} = 0.44(31)$ keV for the first-forbidden unique transition ^{135}Cs$(7/2^+) \rightarrow$ ^{135}Ba$(11/2^-)$.

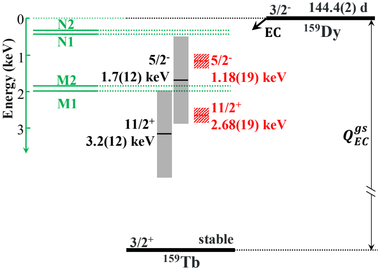
Adopting $g_A^{eff} = 0.8 - 1.2$ leads to half-life prediction:



A. de Roubin *et al.*, Phys. Rev. Lett. 124 (2020) 222503

Allowed electron-capture decay of ^{159}Dy to an excited state

gs-gs Q value improved over the AME2020 mass evaluation:

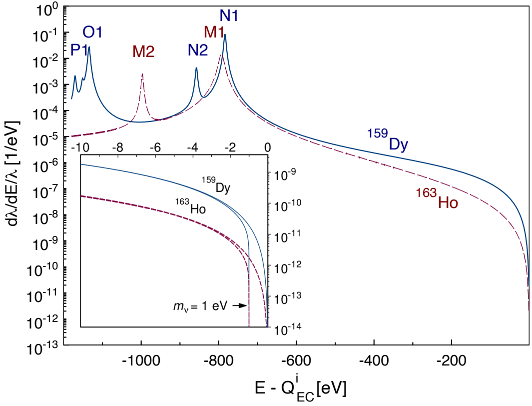


A new candidate for neutrino-mass determination!

Z. Ge *et al.*, Phys. Rev. Lett. 127 (2021) 272301

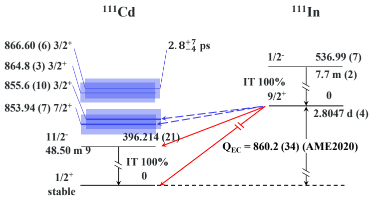
Recent measurement of the Q value by the JYFLTRAP gives $Q = 364.73(19)$ keV, leading to $Q_{\text{exc}} = 1.18(19)$ keV for the allowed β transition $^{159}\text{Dy}(3/2^-) \rightarrow {}^{159}\text{Tb}(5/2^-)$.

One has the N1, N2, O1, O2 and P1 (and M1 and M2 Breit-Wigner tails!) atomic-shell contributions at the endpoint:



Allowed electron-capture decay of ^{111}In to an excited state

gs-gs Q value improved over the AME2020 mass evaluation:

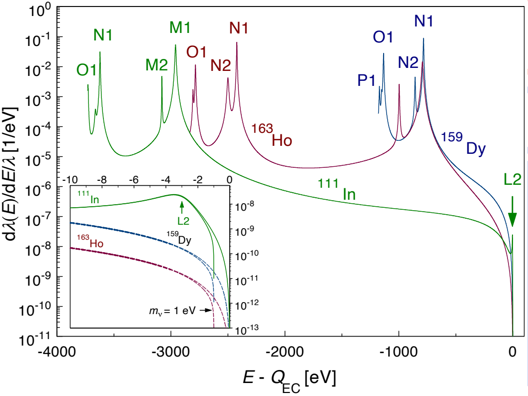


A new candidate for neutrino-mass determination!

Z. Ge *et al.*, Phys. Lett. B 832 (2022) 137226

Recent measurement of the Q value by the JYFLTRAP gives $Q = 857.63(17)$ keV, leading to $Q_{\text{exc}} = 3.69(19)$ keV for the allowed β transition $^{111}\text{In}(9/2^+) \rightarrow {}^{111}\text{Cd}(7/2^+)$.

One has the M1, M2, N1, N2, O1 and O2 (and possibly L2!) atomic-shell contributions at the endpoint:



Still extracting information on the value of g_A

These methods are now available:

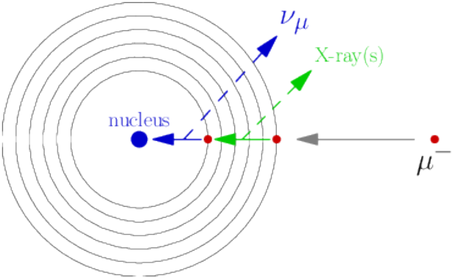
For low momentum exchanges (g_A):

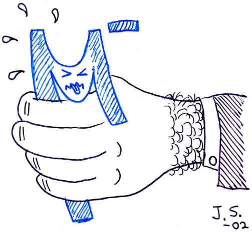
- study half-lives of β decays (1^+ and 2^- states)
- study half-lives of $2\nu\beta\beta$ decays (1^+ states)
- Study electron spectral shapes of β decays (J^π states)

For high momentum exchanges like $0\nu\beta\beta$ decay ($g_{A,0\nu}$):

- Study nuclear muon capture (J^π states)

Ordinary Muon Capture (OMC)





Nuclear muon capture:

OMC: ${}^{A}_{Z}\mathrm{X} + \mu^- \rightarrow {}_{Z-1}{}^{A}\mathrm{Y} + \nu_\mu$

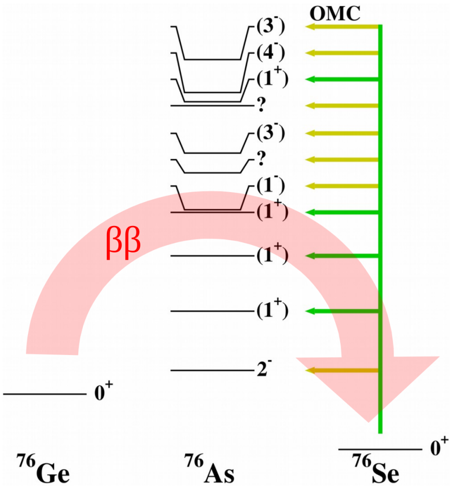
Also:

Muon decay: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \ (\tau = 2.2\mu\mathrm{s})$

OMC probability $\sim Z^4$
(in Fe 91% are captured,
breakeven at $Z \sim 11$)

Ordinary muon capture (OMC) on ^{76}Se

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



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

- OMC and $0\nu\beta\beta$ operate in the $q \approx 100\,\text{MeV}$ momentum-exchange region $\Rightarrow g_{\text{A},0\nu}(J^\pi)$
- Induced currents (g_P!) are activated

Experiments:

RCNP, Osaka ; J-PARC MLF, Japan ; PSI, Villigen, Switzerland

The capture rate of OMC

The muon-capture rate (in units of 1/s) can be written as:

$$W = 2P\frac{2J_f+1}{2J_i+1}\left(1-\frac{q}{m_\mu + AM_N}\right)q^2 ,$$

where q is OMC Q-value (essentially the magnitude of the muon-neutrino momentum) and M_N the (average) nucleon mass. Here

$$P = \frac{1}{2}\sum_{\kappa u}\Big| g_{\rm V}(q^2)P^{(1)}_{\kappa u} + g_{\rm A}(q^2)P^{(2)}_{\kappa u} - \frac{g_{\rm V}(q^2)}{M_N}P^{(3)}_{\kappa u} + \sqrt{3}\frac{q}{2M_N}g_{\rm V}(q^2)P^{(4)}_{\kappa u}$$

$$+ \sqrt{6}\frac{q}{2M_N}\left(g_{\rm V}(q^2) - g_{\rm M}(q^2)\right)P^{(5)}_{\kappa u} - \frac{g_{\rm A}(q^2)}{M_N}P^{(6)}_{\kappa u} + \sqrt{\frac{1}{3}}\frac{q}{2M_N}\left(g_{\rm P}(q^2) - g_{\rm A}(q^2)\right)P^{(7)}_{\kappa u}\Big|^2$$

Compare with the inverse half-life of the $0\nu\beta\beta$ decay:

$$\left(T^{(0\nu)}_{1/2}\right)^{-1} = G_{0\nu}\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2\Big|[g_{\rm V}(q^2)]^2M^{(0\nu)}_{\rm F} + [g_{\rm A}(q^2)]^2M^{(\rm AA)}_{\rm GT} - \frac{q^2}{3M_N}g_{\rm A}(q^2)g_{\rm P}(q^2)M^{(\rm AP)}_{\rm GT}$$

$$+ \frac{q^4}{12M_N^2}[g_{\rm P}(q^2)]^2M^{(\rm PP)}_{\rm GT} + \frac{q^2}{6M_N^2}[g_{\rm M}(q^2)]^2M^{(\rm MM)}_{\rm GT} - [g_{\rm A}(q^2)]^2M^{(0\nu)}_{\rm T}\Big|^2$$

OMC first suggested as an experimental probe for $0\nu\beta\beta$ matrix elements in:

Pioneering works:

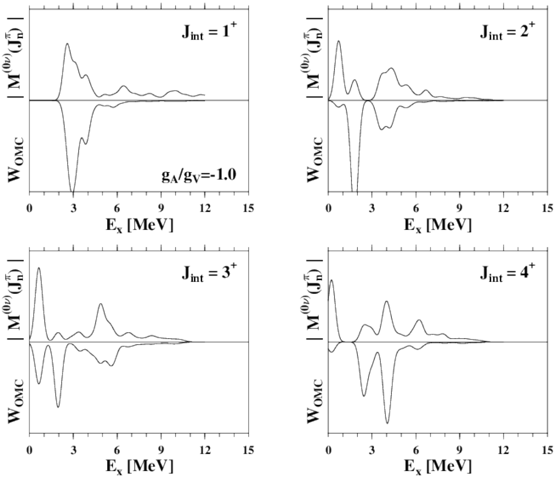
M. Kortelainen and J. S., Ordinary muon capture as a probe of virtual transitions of $\beta\beta$ decay, *Europhysics Letters* **58** (2002) 666-672

M. Kortelainen and J. S., Microscopic study of muon-capture transitions in nuclei involved in double-beta-decay processes, *Nuclear Physics* **A 713** (2003) 501-521

M. Kortelainen and J. S., Nuclear muon capture as a powerful probe of double-beta decays in light nuclei, *Journal of Physics G: Nucl. Part. Phys.* **30** (2004) 2003-2018

Original theory from: M. Morita and A. Fujii, Theory of allowed and forbidden transitions in muon capture reactions, Phys. Rev. 118 (1960) 606.

OMC as a tool to probe the $0\nu\beta\beta$ decay (Case of ^{48}Ca)



M. Kortelainen and J. S., J. Physics G: Nucl. Part. Phys. 30 (2004) 2003-2018: ISM calculation

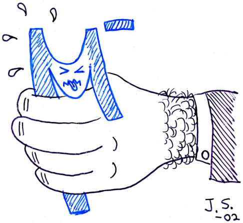
Recently: OMC in medium-heavy and heavy nuclei

There are and will be more data on:

PARTIAL CAPTURE RATES of OMC

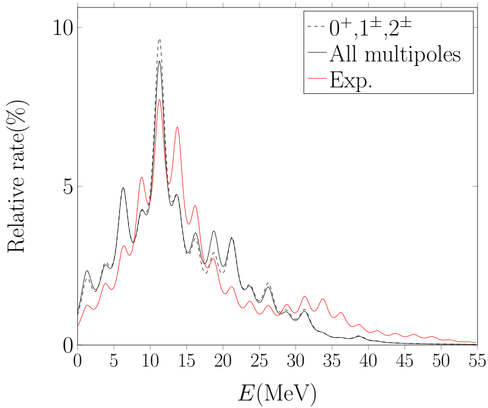
and in particular:

OMC STRENGTH DISTRIBUTIONS



Now we need:

Large-basis (with Wood-Saxon single-particle energies) no-core pnQRPA calculations with realistic effective two-nucleon interactions.



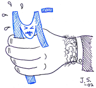
First evidence on OMC giant resonance:

L. Jokiniemi, J. S., H. Ejiri, I.H. Hashim, Pinning down the strength function for ordinary muon capture on ^{100}Mo, Phys. Lett. B 794 (2019) 143.

Experiments: MuSIC beam channel at RCNP (Research Center for Nuclear Physics), Osaka, Japan

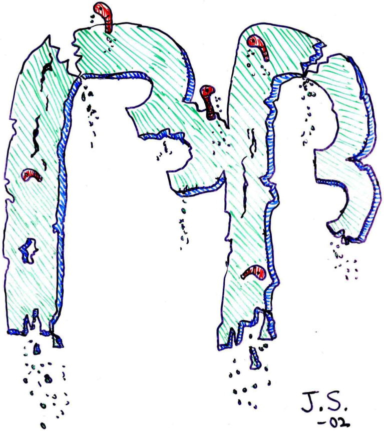
D2 beam channel in J-PARC (Japan Proton Accelerator Research Complex) MLF, Ibaraki, Japan

Ongoing work: experiments at the μE4 beamline at PSI by The MONUMENT Collaboration

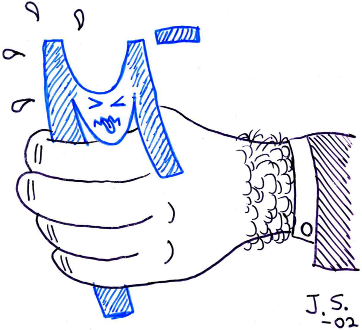


Recent work: OMC vs. $0\nu\beta\beta$ decay

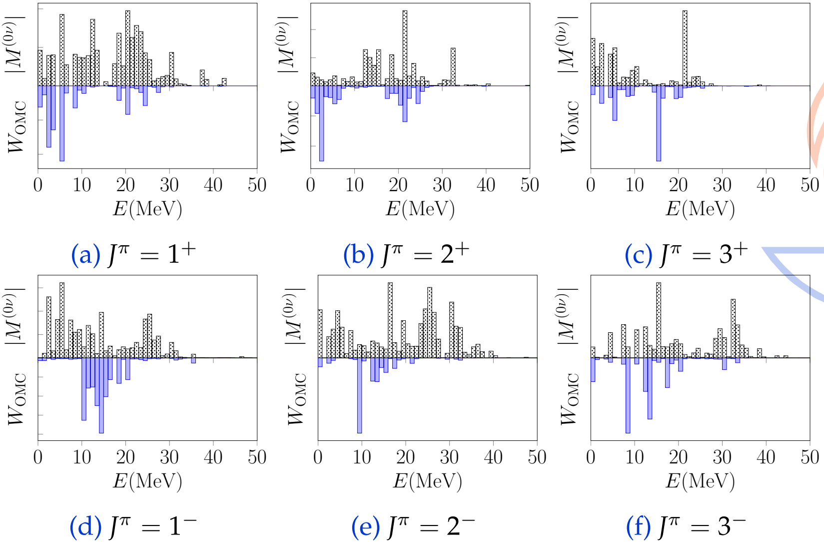
Studied in: L. Jokiniemi and J. S., Comparative analysis of muon-capture and $0\nu\beta\beta$-decay matrix elements, Phys. Rev. C 102 (2020) 024303



VS.



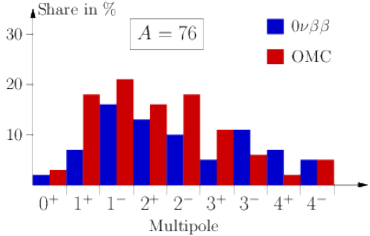
Comparative analysis between OMC rates and $0\nu\beta\beta$ NME for ^{76}Ge



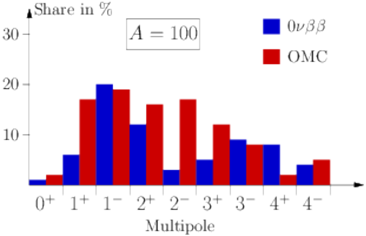
(a) $J^\pi = 1^+$ (b) $J^\pi = 2^+$ (c) $J^\pi = 3^+$

(d) $J^\pi = 1^-$ (e) $J^\pi = 2^-$ (f) $J^\pi = 3^-$

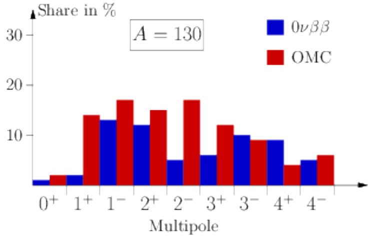
Comparison of the OMC and $0\nu\beta\beta$ multipole decompositions



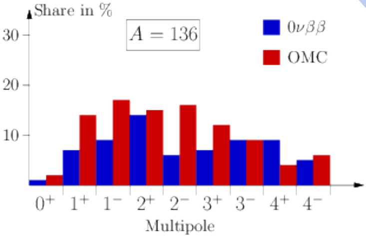
(a) OMC: 100%, $0\nu\beta\beta$: 76%



(b) OMC: 98%, $0\nu\beta\beta$: 68%



(c) OMC: 96%, $0\nu\beta\beta$: 63%



(d) OMC: 95%, $0\nu\beta\beta$: 67%

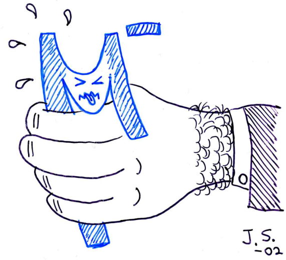
Recent and very recent work: OMC partial capture rates to individual final states

There are and will be more data on:

OMC CAPTURE RATES

to

INDIVIDUAL FINAL STATES

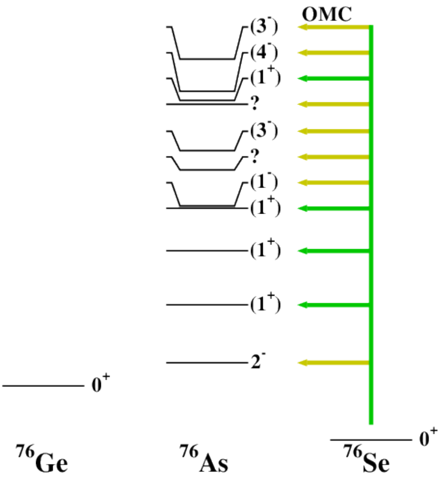


Now we can use:

pnQRPA theory, the nuclear shell model and ab initio methods

OMC to individual J^π states

OMC on ^{76}Se:



OMC on ^{76}Se: Rates to states J^π in ^{76}As below some 1 MeV: no-core large-basis pnQRPA calculation

$(g_V(0) = 1.0, g_A(0) = 0.8, g_P(0) = 7.0)$

J^π	Exp. (1/s)	Th. (1/s)
0^+	5120	414
1^+	218 240	236 595
1^-	31 360	28 991
2^+	120 960	114 016
2^-	145 920 + g.s.	177 802
3^+	60 160	55 355
3^-	53 120	34 836
4^+	-	2797
4^-	30 080	23 897

Data from: D. Zinatulina *et al.*, Phys. Rev. C 99 (2019) 024327

Calculation from: L. Jokiniemi and J.S., Phys. Rev. C 100 (2019) 014619

OMC on ^{12}C to individual J^π states in ^{12}B: 2BCs added

In addition to the one-body (weak nucleon) current (1BC) one can take into account the *meson exchanges* by adding (normal-ordered one-body part of) the two-body current (2BC) through the replacements:

$$g_A(q^2) \to \left(1 + \delta_a(q^2)\right) g_A(q^2) \; ; \quad g_P(q^2) \to \left(1 - \frac{q^2 + m_\pi^2}{q^2} \delta_a^P(q^2)\right) g_P(q^2)$$

See: M. Hoferichter *et al.*, Phys. Rev. D 102 (2020) 074018

Shell-model calculated capture rates in units of 10^3 1/s, with $g_V(0) = 1.0$, $g_A(0) = 1.27$, $g_P(0)/g_A(0) = 6.8$ (PCAC, Goldberger-Treiman):

J^π	Exp.	Th.: 1BC	Th.: 1BC+2BC*
1^+_{gs}	$5.68^{+0.14}_{-0.23}$	6.48	$3.98 - 4.45$
2^+_1	$0.31^{+0.09}_{-0.07}$	0.42	$0.30 - 0.32$
2^+_2	$0.026^{+0.015}_{-0.011}$	0.011	$0.008 - 0.009$

* The spread comes from the spread in the assumed values of the EFT low-energy constants

Data from: Y. Abe *et al.*, Phys. Rev. C 93 (2016) 054608

Nuclear shell-model calculation from: L. Jokiniemi, T. Miyagi, S. R. Stroberg, J. D. Holt, J. Kotila and J.S., submitted for publication

Very recent work: OMC and double positron decays

NEW:

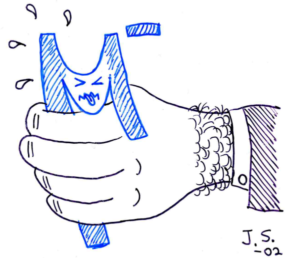
OMC

probing the

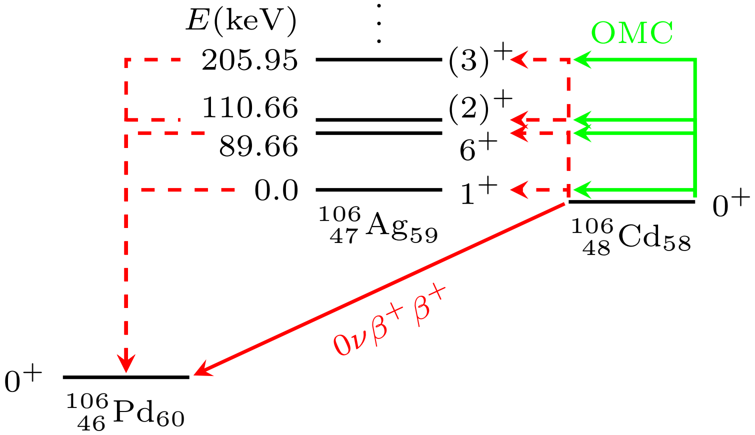
INITIAL BRANCH

of

DOUBLE BETA DECAY

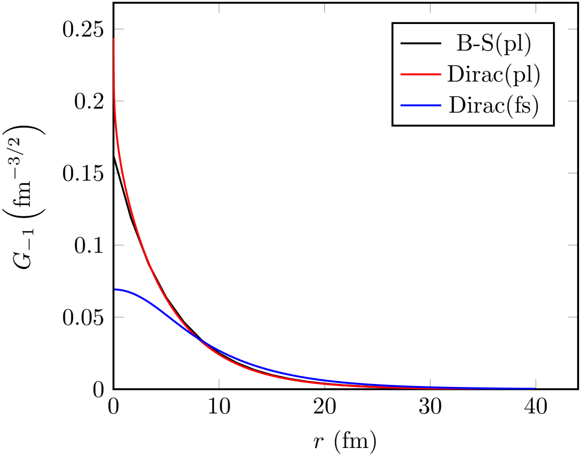


OMC and $0\nu\beta^+\beta^+$ decay of ^{106}Cd



L. Jokiniemi, J.S. and J. Kotila, Comparative Analysis of nuclear matrix elements of $0\nu\beta^+\beta^+$ decay and muon capture in ^{106}Cd, Front. Phys. 9 (2021) 652536

OMC on ^{106}Cd: Muon orbital wave function



B-S: Bethe-Salpeter point-like nucleus approximation;

Dirac: Numerical solution of the Dirac equation;

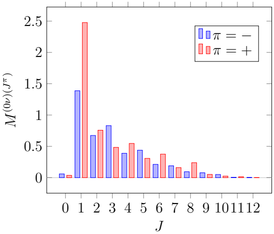
pl: point-like nucleus;

fs: finite-size nucleus.

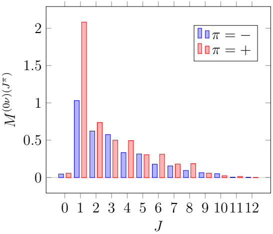
$$\mathrm{B-S}: \psi_\mu(\mathbf{r}) = \begin{pmatrix} -\mathrm{i}F_{-1}\chi_\mu \\ G_{-1}\chi_\mu \end{pmatrix} ; \quad F_{-1} = -\sqrt{\frac{1-\gamma}{1+\gamma}}G_{-1} ; \quad G_{-1} = \left(\frac{2Z}{a_0}\right)^{3/2}\sqrt{\frac{1+\gamma}{2\Gamma(2\gamma+1)}}\left(\frac{2Zr}{a_0}\right)^{\gamma-1}e^{-Zr/a_0}$$

^{106}Cd: OMC and $0\nu\beta^+\beta^+$ multipole decompositions

$0\nu\beta\beta$ decay

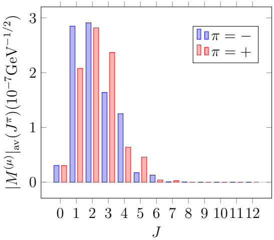


(a) Basis: 'Adj.'

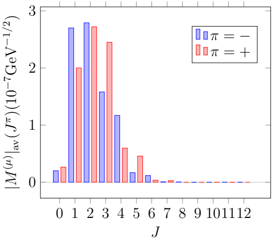


(b) Basis: 'WS'

OMC



(a) Basis: 'Adj.'



(b) Basis: 'WS'

Novel application of electron spectra of forbidden beta decays

Investigating

Reactor-$\bar{\nu}$ anomaly

and

the spectral bump

Neutrino-related anomalies and sterile neutrinos

Sterile neutrinos:

The gallium anomaly

(J. Kostensalo, J. S., C. Giunti and P. C. Srivastava,

The gallium anomaly revisited, Phys. Lett. B 795 (2019) 542)

The reactor antineutrino anomaly

imply oscillations of the "ordinary" neutrinos (ν_e, ν_μ, ν_τ) to

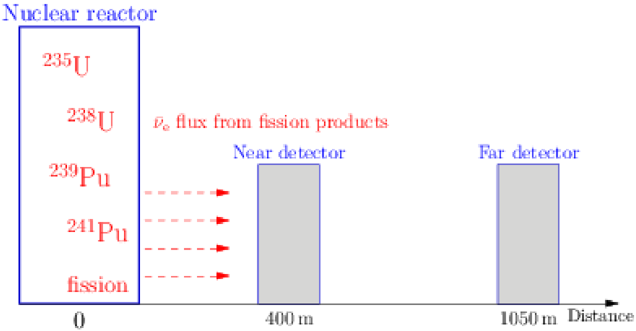
STERILE NEUTRINO

in the mass range of a few eV

But what is the reactor antineutrino anomaly?

The reactor antineutrino anomaly

The $\bar{\nu}_e$ flux from reactors has been measured in short-baseline neutrino-oscillation experiments[1]: Daya Bay (in Daya Bay, China; 6 reactors, 8 detectors), RENO (South Korea; 2 detectors 294m and 1383 m from 6 reactors) and Double Chooz (Chooz, France, 2 detectors 400m and 1050 m from 2 reactors, schematic figure below).



[1] RENO: Phys. Rev. Lett. 108 (2012) 191802; Double Chooz: J. High Energy Phys. 2014 (2014) 86; Daya Bay: Phys. Rev. Lett. 116 (2016) 061801.

The neutrino-flux measurements find:

The reactor $\bar{\nu}_{\rm e}$ anomaly:

The measured flux is some 5% smaller than that predicted from the β decays of the fission yields of the reactor fuel

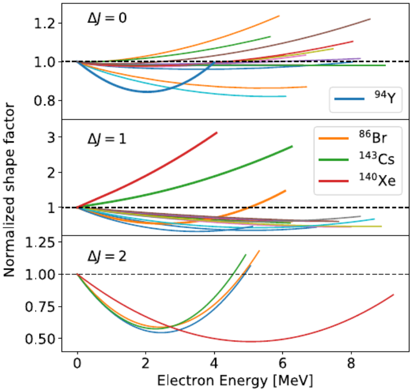
$\overset{?}{\Longrightarrow}$ Oscillations to STERILE NEUTRINOS

The bump anomaly:

There is an unexpected bump at $4 - 6$ MeV (spectral shoulder) in the measured $\bar{\nu}_{\rm e}$ spectrum.

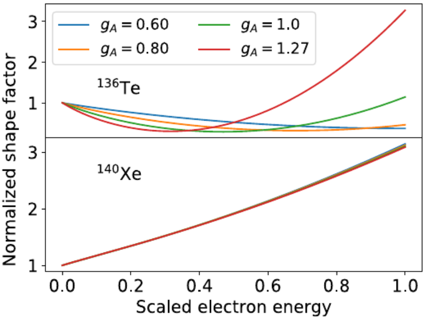
$\Longrightarrow$???

Important contributions from first-forbidden β decays to the reactor antineutrino spectra (deviations from the allowed spectral shape)



pseudoscalar ($\Delta J = 0$, non-unique),
pseudovector ($\Delta J = 1$, non-unique) and
pseudotensor ($\Delta J = 2$, unique) transitions

Pseudovector transitions with (^{136}Te) and without (^{140}Xe) g_A dependence



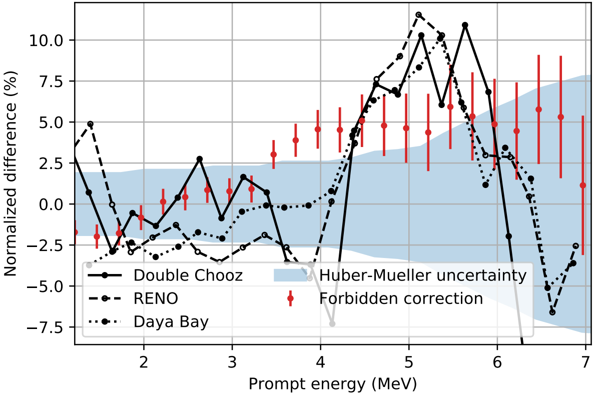
The transitions $^{137}Xe(7/2^-) \rightarrow {}^{137}Cs(7/2^+_{gs}, 5/2^+_1)$ are highly interesting: Measurement of the spectral shapes by EXO-200

Results from the analyses including the β spectra

Taking into account the (first-forbidden) decays of

^{86}Br(0^+), ^{86}Br(2^+), ^{87}Se, ^{88}Rb, ^{89}Br($3/2^+$), ^{89}Br($5/2^+$), ^{90}Rb, ^{91}Kr($5/2^-$), ^{91}Kr($3/2^-$), ^{92}Rb, ^{92}Y, ^{93}Rb, ^{94}Y(0^+), ^{94}Y(0^+), ^{95}Rb($7/2^+$), ^{95}Rb($3/2^+$), ^{95}Sr, ^{96}Y, ^{97}Y, ^{98}Y, ^{133}Sn, ^{134m}Sb(6^+), ^{134m}Sb(6^+?), ^{135}Te, ^{136m}I, ^{137}I, ^{138}I, ^{139}Xe, ^{140}Cs, ^{142}Cs

changes the $\bar{\nu}$ flux by a few % !



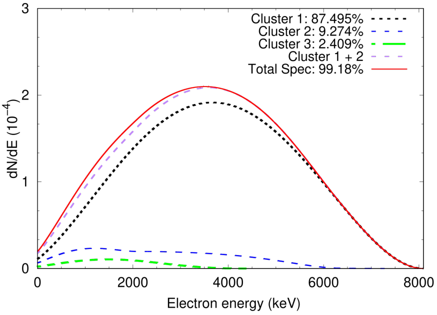
The spectral shoulder appears due to forbidden spectral corrections !

See: L. Hayen, J. Kostensalo, N. Severijns, J.S., First-forbidden transitions in reactor antineutrino spectra/in the reactor anomaly, Phys. Rev. C 99 (2019) 031301(R) ; Phys. Rev. C 100 (2019) 054323

Clear evidence of a contribution to the spectral "bump": The case of ^{92}Rb

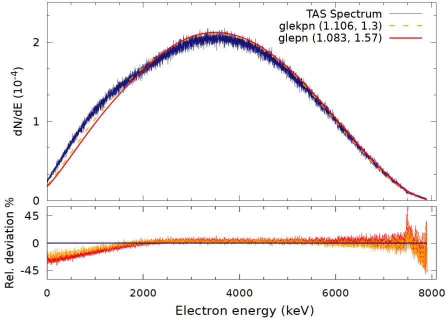
Pioneering calculation of a total β-electron spectrum of a high-Q reactor fission product: The β^- decay of ^{92}Rb with a Q value of 8.095 MeV

Computed cumulative electron spectrum



Cluster 1: gs-to-gs transition (based on TAS-measured branching), Cluster 2: known 1*st*-forbidden transitions (based on TAS-measured branchings), Cluster 3: unresolved higher-energy 1*st*-forbidden and allowed transitions

Comparison of the computed total spectrum with the TAS spectrum. Computations done by using two available shell-model interactions.



TAS spectrum obtained from the TAS-measured (A. Algora *et co.*) branchings assuming all transitions to be allowed.

Conclusions and outlook

Conclusions:

- The effective value of g_A is involved in all weak processes, and thus has impact on studies of rare weak decays, neutrino physics and astrophysics
- The large amount of calculations of Gamow-Teller β decays and $2\nu\beta\beta$ decays are (surprisingly!) consistent with each other and clearly point to a A-dependent quenched g_A
- The spectrum-shape method (SSM) for forbidden non-unique β decays is a robust tool to seach for the effective value of g_A
- There are interesting new low Q-value β/EC transitions for $\nu/\bar{\nu}$-mass measurements
- The OMC can test the weak axial couplings (g_A and g_P) at the momentum-exchange region relevant for the $0\nu\beta\beta$ decay; it is also a sensitive probe of nuclear wave functions
- Proper account of the total spectral shapes of fission products is instrumental for the theoretical construction of the reactor-$\bar{\nu}$ spectra: TAS branchings & TAGS β spectra!

Outlook:

- Boom of measurements of the β spectra for the interesting decays amenable to the SSM
- Measurements of the OMC rates for the $0\nu\beta^-\beta^-$-decay daughters ($0\nu\beta^+\beta^+$-decay mothers) will yield important information on the (induced) axial couplings relevant for $0\nu\beta\beta$ decay (There are ongoing experiments, like the MONUMENT)

The (hopefully happy) end

THANKS FOR PATIENCE!