Effective Value of Weak Axial Coupling: A Review

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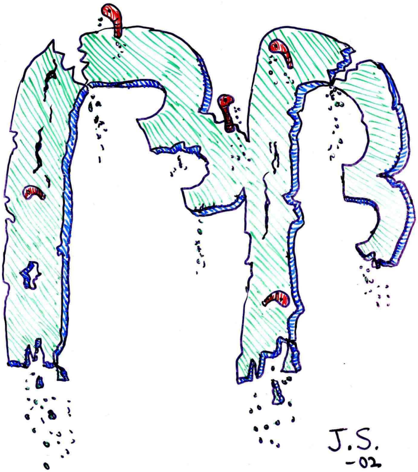
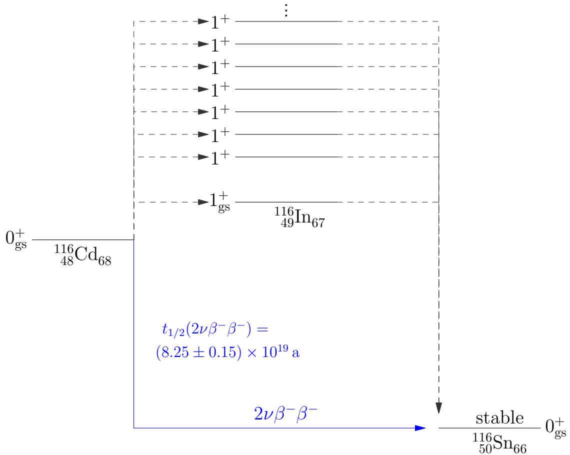
Contents:

- Double-beta-decay rates
- Effective value of g_{A}:
- from allowed β Decays
- from forbidden β Decays
- Effects on $0\nu\beta\beta$ NMEs
- Is there any reactor-$\bar{\nu}$ anomaly?

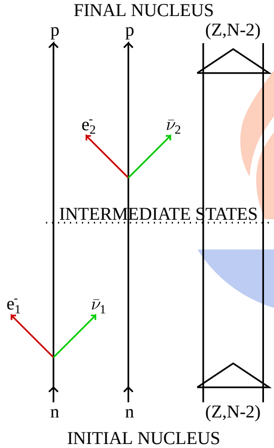
Motivation for the Work: Double Beta Decay



Two-Neutrino Double Beta Decay of ^{116}Cd

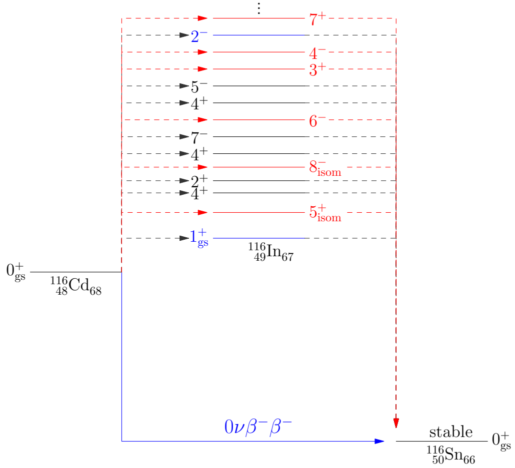


$t_{1/2}(2\nu\beta^-\beta^-) =$
$(8.25 \pm 0.15) \times 10^{19}$ a

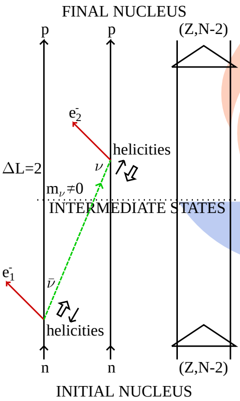


$$\boxed{2\nu\beta\beta - \text{rate} \sim \left|M^{(2\nu)}_{\rm GTGT}\right|^2 = (g_{\rm A})^4 \left|\sum_{m,n} \frac{M_{\rm L}(1^+_m)M_{\rm R}(1^+_n)}{D_m}\right|^2}$$

Neutrinoless Double Beta Decay of ^{116}Cd



MASS MODE



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

Definitions

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

Nucleon weak current in a nucleus:

$$j_{\mathrm{N}}^{\mu} = g_{\mathrm{V}}\gamma^{\mu} - g_{\mathrm{A}}\gamma^{\mu}\gamma^{5}$$

Quenching:

$$q = g_{\mathrm{A}}/g_{\mathrm{A}}^{\mathrm{free}}$$

Free value of g_{A} (Particle Data Group 2016) from the decay of free neutron:

$$g_{\mathrm{A}}^{\mathrm{free}} = 1.2723(23)$$

Effective value of g_{A}:

$$g_{\mathrm{A}}^{\mathrm{eff}} = q g_{\mathrm{A}}^{\mathrm{free}}$$

Gamow-Teller β decays

There are data on:

Gamow-Teller β

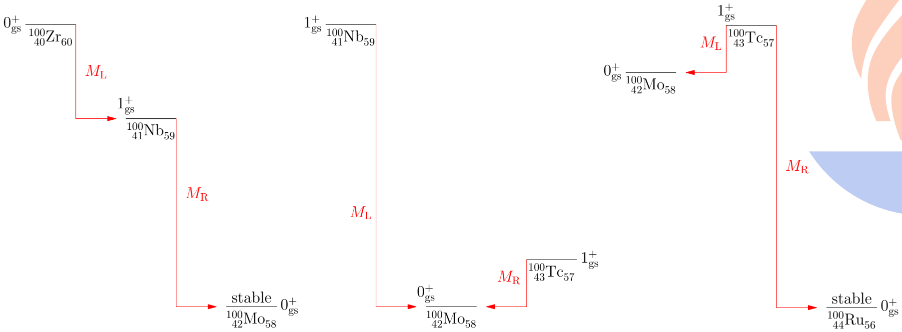
TRANSITIONS

Theoretical approaches:

ISM (Interacting Shell Model)

pnQRPA (proton-neutron QRPA)

Typical Gamow-Teller β transitions



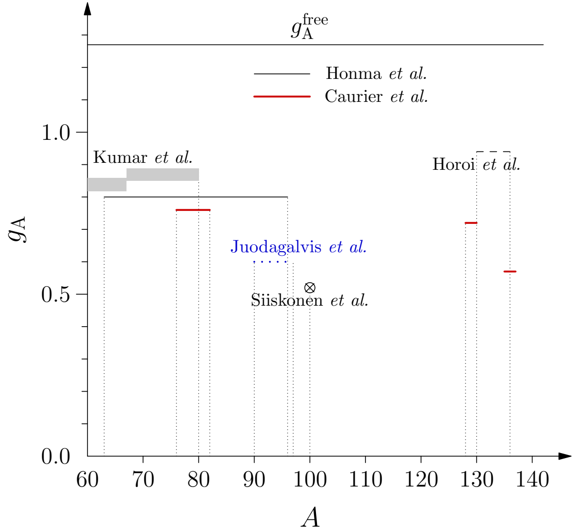
Interacting Shell Model (ISM)

Results from:

Quenching of $g_{\rm A}$

in the ISM calculations

Results from the ISM



- Kumar *et al.*: J. Phys. G 43 (2016) 105104
- Honma *et al.*: J. Phys. Conf. Ser. 49 (2006) 45
- Caurier *et al.*: Phys. Lett. B 711 (2012) 62
- Horoi *et al.*: Phys. Rev. C 93 (2016) 024308
- Juodagalvis *et al.*: Phys. Rev. C 72 (2005) 024306
- Siiskonen *et al.*: Phys. Rev. C 63 (2001) 055501

Proton-neutron Quasiparticle Random-Phase Approximation (pnQRPA)

Results from:

Quenching of g_{A}

in the pnQRPA calculations

Results from the pnQRPA analyses

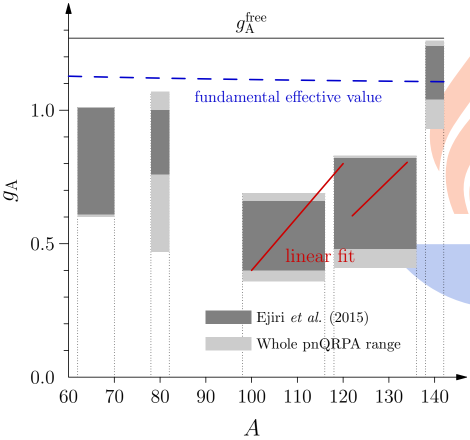
A	pn Conf.	$\bar{g}_{\mathrm{A}}^{\mathrm{eff}}$ [1]
$62-70$	$1p_{3/2}-1p_{1/2}$	0.81 ± 0.20
$78-82$	$0g_{9/2}-0g_{9/2}$	0.88 ± 0.12
$98-116$	$0g_{9/2}-0g_{7/2}$	0.53 ± 0.13
$118-136$	$1d_{5/2}-1d_{5/2}$	0.65 ± 0.17
$138-142$	$1d_{5/2}-1d_{3/2}$	1.14 ± 0.10

[1] H. Ejiri, J. S., J. Phys. G 42 (2015) 055201

Other analyses in the whole range:

[2] P. Pirinen, J. S., Phys. Rev. C 91 (2015) 054309

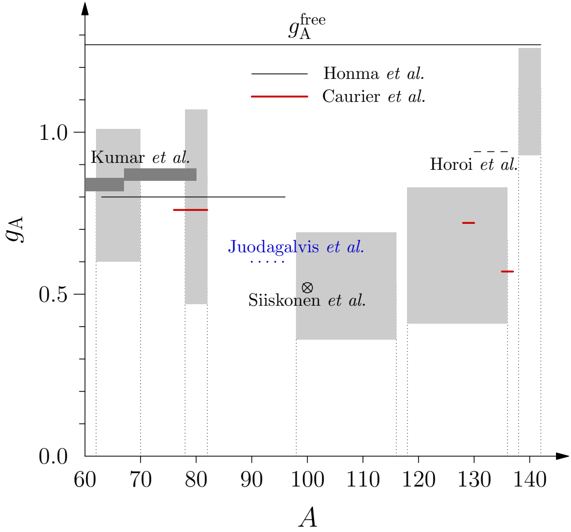
[3] F. Deppisch, J. S., Phys. Rev. C 94 (2016) 055501



Fundamental quenching: M. Ericson (1971); M. Ericson *et al.* (1973); M. Rho (1974); D. H. Wilkinson (1974)

(Meson-exchange currents → effective two-body operators)

Results from the ISM on top of the pnQRPA ranges



- Kumar *et al.*: J. Phys. G 43 (2016) 105104
- Honma *et al.*: J. Phys. Conf. Ser. 49 (2006) 45
- Caurier *et al.*: Phys. Lett. B 711 (2012) 62
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- Juodagalvis *et al.*: Phys. Rev. C 72 (2005) 024306
- Siiskonen *et al.*: Phys. Rev. C 63 (2001) 055501

Calculations for the β decays and $\beta\beta$ decays

Results from:

Quenching of g_{A}

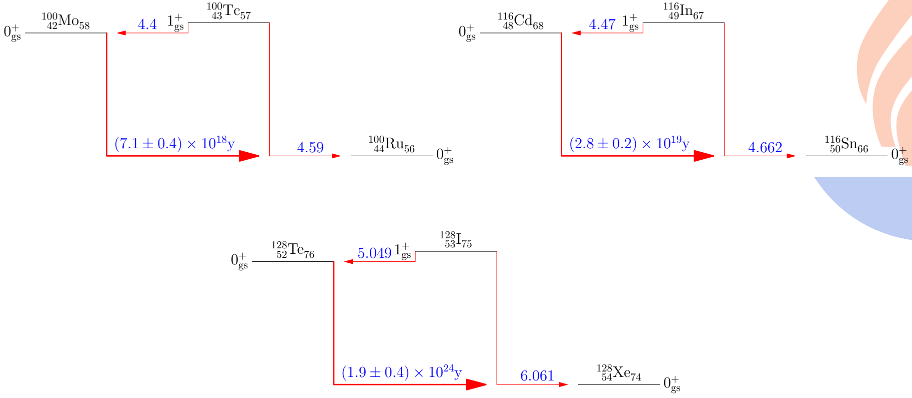
in the pnQRPA-based,

ISM-based and

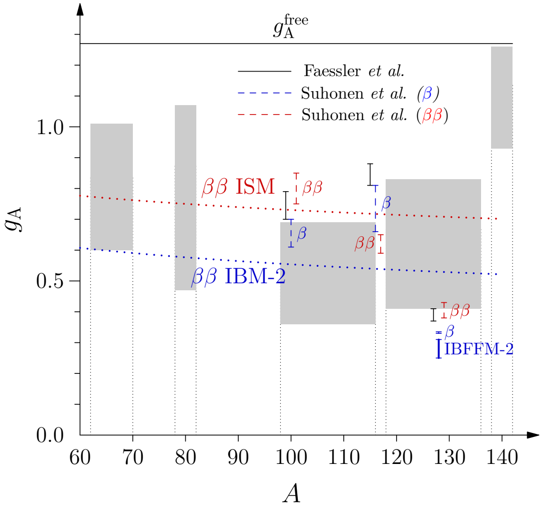
IBM-based calculations

of β decays and $\beta\beta$ decays

The studied cases



Results from the β+$\beta\beta$ calculations against the pnQRPA ranges from Gamow-Teller β decays



- pnQRPA: Faessler *et al.*, A. Faessler, G. L. Fogli, E. Lisi, V. Rodin, A. M. Rotunno, F. Šimkovic, arXiv 0711.3996v1 [Nucl-th]
- pnQRPA: Suhonen *et al.*, J. Suhonen, O. Civitarese, Nucl. Phys. A 924 (2014) 1
- $\beta\beta$ ISM and IBM-2: J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 87 (2013) 014315
- IBFFM-2: N. Yoshida, F. Iachello, Prog. Theor. Exp. Phys. 2013 (2013) 043D01

Forbidden β decays and the value of g_{A}

Results from:

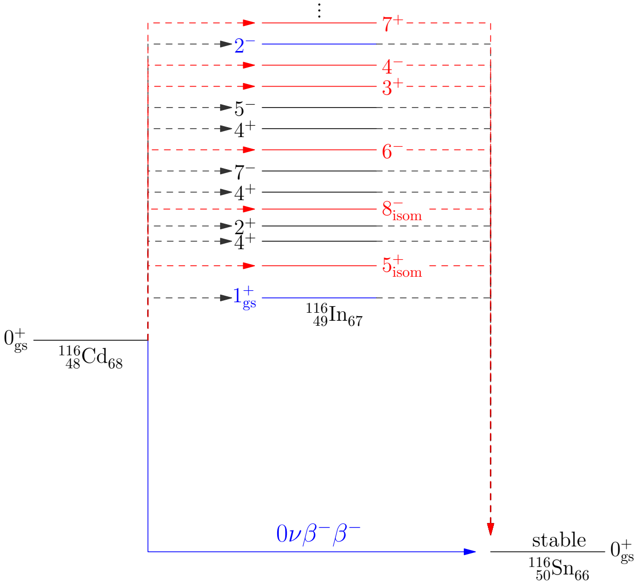
Quenching of g_{A}

as derived from

β decays

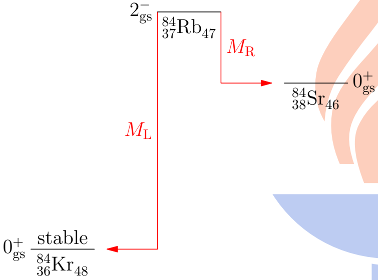
of forbiddenness F

INCENTIVE: $0\nu\beta\beta$ decay through the higher angular-momentum states



Global study for the first-forbidden ($F = 1$) $2^-_{\mathrm{gs}} \to 0^+_{\mathrm{gs}}$ decays

H. Ejiri, N. Soukouti and J. S., Spin-dipole nuclear matrix elements for double beta decays and astro-neutrinos, Phys. Lett. B 729 (2014) 27



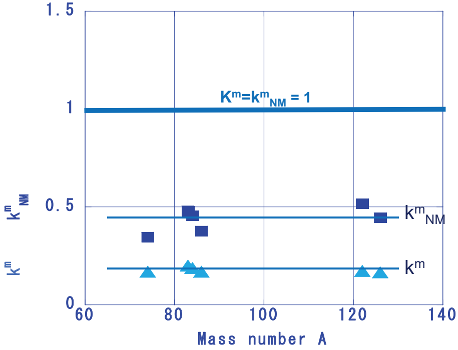
2^-_{gs} $^{84}_{37}\mathrm{Rb}_{47}$

M_{R}

0^+_{gs} $^{84}_{38}\mathrm{Sr}_{46}$

M_{L}

0^+_{gs} stable $^{84}_{36}\mathrm{Kr}_{48}$



$$\bar{M}(\mathrm{SD2}^-) = \sqrt{M_{\mathrm{L}} M_{\mathrm{R}}}$$

$$\langle k \rangle = \left\langle \frac{\bar{M}_{\mathrm{exp}}(\mathrm{SD2}^-)}{\bar{M}_{\mathrm{qp}}(\mathrm{SD2}^-)} \right\rangle \approx 0.18$$

$$\langle k_{\mathrm{NM}} \rangle = \left\langle \frac{\bar{M}_{\mathrm{exp}}(\mathrm{SD2}^-)}{\bar{M}_{\mathrm{pnQRPA}}(\mathrm{SD2}^-)} \right\rangle \approx 0.45$$

$$\Rightarrow \bar{g}_{\mathrm{A}}^{\mathrm{eff}} \approx 0.57$$

Extrapolation to β decays of higher forbiddenness ($F \geq 2$)

Based on the global studies in

H. Ejiri, J. S., J. Phys. G: Nucl. Part. Phys. 42 (2015) 055201

H. Ejiri, N. Soukouti, J. S., Phys. Lett. B 729 (2014) 27

J. Kostensalo, J.S., Phys. Rev. C 95 (2017) 014322 conclude that all unique-forbidden β transitions roughly evenly quenched)

Then: Low-energy quenching of g_{A} derivable from the hatched regions of the Gamow-Teller studies in the pnQRPA framework:

Mass range	$A = 76 - 82$	$A = 100 - 116$	$A = 122 - 136$
$g_{\mathrm{A},0\nu}^{\mathrm{eff}}$	$0.5 - 1.0$	$0.4 - 0.7$	$0.5 - 0.8$

Assumption: Also the forbidden non-unique virtual transitions behave like the forbidden unique virtual transitions. BUT: How to study the forbidden non-unique decays?

Caveat: $0\nu\beta\beta$ decay is a high-momentum transfer process ($q \sim 100$ MeV) $\Rightarrow$ less quenching (J. Menéndez, D. Gazit, A. Schwenk, PRL 107 (2011) 062501)

Spectrum-shape method (SSM)

Results from:

Effective value of g_{A}

as derived from

electron spectra of

forbidden non-unique β decays

Spectrum shape of higher-forbidden non-unique β decays

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

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

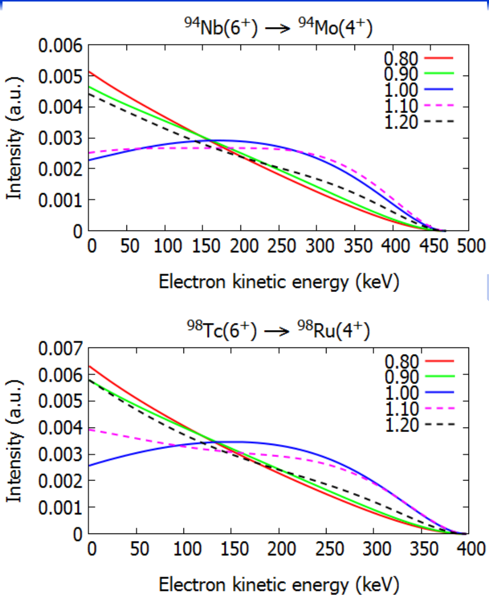
$F_{k-1}(Z,w_e)$ being the generalized Fermi function.

Decomposition of the shape factor:

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

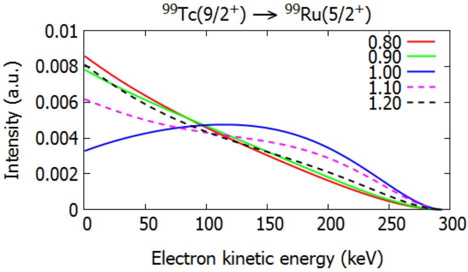
ISM-computed β spectra for different values of g_A

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

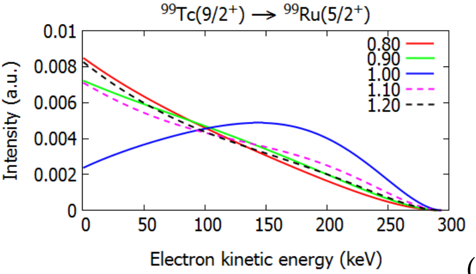


Example: ISM- and MQPM-computed electron spectra

Normalized ISM- and MQPM-computed electron spectra for the $2nd$-forbidden nonunique β^- decay of ^{99}Tc ($g_{\rm V} = 1.0$) using different values of $g_{\rm A}$.



(ISM)



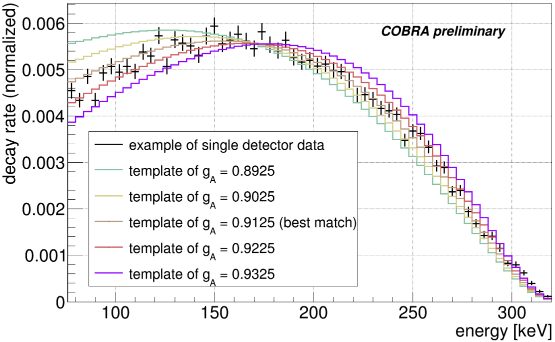
(MQPM)

Example: Decay of ^{113}Cd – Comparison with data

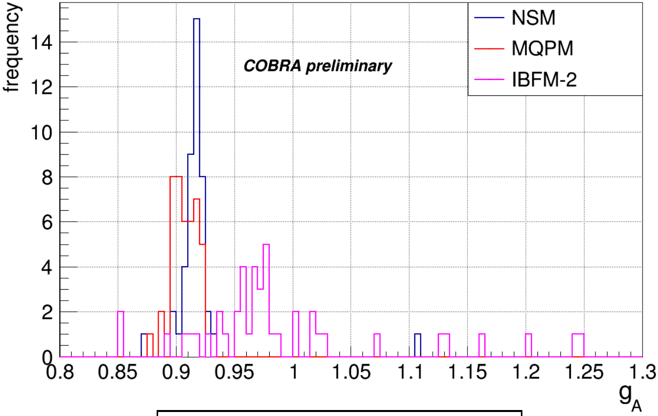
Normalized electron spectra for the 4*th*-forbidden nonunique β^- decay $^{113}\mathrm{Cd}(1/2^+) \rightarrow {}^{113}\mathrm{In}(9/2^+)$ ($g_V = 1.0$).

Experimental data from:

The COBRA collaboration, L. Bodenstein-Dresler *et al.*, arXiv:1806.02254 [nucl-ex] 6 Jun 2018



Distribution of the best-match g_A values from 44 detector units



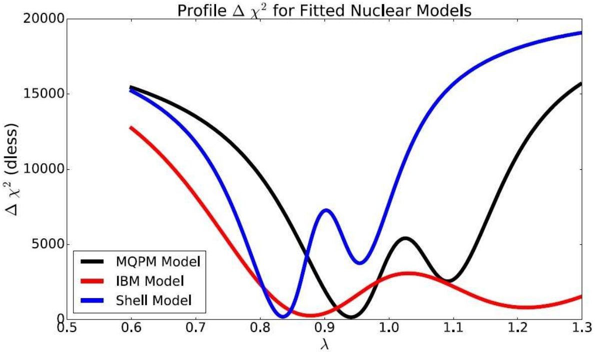
$$\bar{g}_A(\text{ISM}) = 0.92 \pm 0.02$$
$$\bar{g}_A(\text{MQPM}) = 0.91 \pm 0.01$$
$$\bar{g}_A(\text{IBFM-2}) = 0.94 \pm 0.09$$

Example: Decay of ^{115}In – Comparison with data

Normalized electron spectra for the $4th$-forbidden nonunique β^- decay $^{115}\mathrm{In}(9/2^+) \to {}^{115}\mathrm{Sn}(1/2^+)$ ($g_\mathrm{V} = 1.0$).

Result from:

The MIT-CSNSM-Jyväskylä collaboration, A. Leder *et al.*, to be submitted.



$$\bar{g}_\mathrm{A}(\mathrm{ISM}) = 0.83 \pm 0.03$$
$$\bar{g}_\mathrm{A}(\mathrm{IBFM\text{-}2}) = 0.88 \pm 0.06$$
$$\bar{g}_\mathrm{A}(\mathrm{MQPM}) = 0.94^{+0.03}_{-0.04}$$

Summary of the exploratory work on β spectra

Transition	$J_i^{\pi_i}$ (gs)	$J_f^{\pi_f}$ (n_f)	Branching	K	Sensitivity	Nucl. model
$^{36}\text{Cl} \rightarrow {}^{36}\text{Ar}$	2^+	0^+ (gs)	**98%**	2	None	ISM
$^{48}\text{Ca} \rightarrow {}^{48}\text{Sc}$	0^+	4^+ (2)	$\sim$0%	4	None	ISM
$^{48}\text{Ca} \rightarrow {}^{48}\text{Sc}$	0^+	6^+ (gs)	$\sim$0%	6	None	ISM
$^{50}\text{V} \rightarrow {}^{50}\text{Cr}$	6^+	2^+ (1)	$\sim$0%	4	Weak	ISM
$^{60}\text{Fe} \rightarrow {}^{60}\text{Co}$	0^+	2^+ (1)	**100%**	2	None	ISM
$^{85}\text{Br} \rightarrow {}^{85}\text{Kr}$	$3/2^-$	$9/2^+$ (gs)	$\sim$0%	3	Moderate	MQPM
$^{87}\text{Rb} \rightarrow {}^{87}\text{Sr}$	$3/2^-$	$9/2^+$ (gs)	**100%**	3	Moderate	MQPM, ISM
$^{92}\text{Rb} \rightarrow {}^{92}\text{Sr}$	0^-	0^+ (gs)	**95%**	1	Weak	ISM
$^{93}\text{Zr} \rightarrow {}^{93}\text{Nb}$	$5/2^+$	$9/2^+$ (gs)	$5 \leq$%	2	Weak	MQPM
$^{93}\text{Y} \rightarrow {}^{93}\text{Zr}$	$1/2^-$	$1/2^+$ (1)	2%	1	Moderate	ISM
$^{94}\text{Nb} \rightarrow {}^{94}\text{Mo}$	6^+	4^+ (2)	**100%**	2	**Strong**	NSM
$^{95}\text{Sr} \rightarrow {}^{95}\text{Y}$	$1/2^+$	$1/2^-$ (gs)	**56%**	1	Weak	ISM
$^{96}\text{Zr} \rightarrow {}^{96}\text{Nb}$	0^+	4^+ (2)	$\sim$0%	4	None	ISM
$^{96}\text{Zr} \rightarrow {}^{96}\text{Nb}$	0^+	6^+ (gs)	$\sim$0%	6	**Strong**	ISM
$^{96}\text{Y} \rightarrow {}^{96}\text{Zr}$	0^-	0^+ (gs)	**96%**	1	weak	ISM
$^{97}\text{Zr} \rightarrow {}^{97}\text{Nb}$	$1/2^+$	$9/2^+$ (gs)	$\sim$0%	4	**Strong**	MQPM
$^{97}\text{Y} \rightarrow {}^{97}\text{Zr}$	$1/2^+$	$1/2^-$ (gs)	**40%**	1	Weak	ISM
$^{98}\text{Tc} \rightarrow {}^{98}\text{Ru}$	6^+	4^+ (3)	**100%**	2	**Strong**	ISM
$^{99}\text{Tc} \rightarrow {}^{99}\text{Ru}$	$9/2^+$	$5/2^+$ (gs)	**100%**	2	**Strong**	MQPM, ISM

Summary on β spectra continues . . .

Transition	$J_i^{\pi_i}$ (gs)	$J_f^{\pi_f}$ (n_f)	Branching	K	Sensitivity	Nucl. model
^{101}Mo → ^{101}Tc	$1/2^+$	$9/2^+$ (gs)	∼0%	4	**Strong**	MQPM
^{113}Cd → ^{113}In	$1/2^+$	$9/2^+$ (gs)	**100%**	4	**Strong**	MQPM, ISM, IBFM-2
^{115}Cd → ^{115}In	$1/2^+$	$9/2^+$ (gs)	∼0%	4	**Strong**	MQPM
^{115}In → ^{115}Sn	$9/2^+$	$1/2^+$ (gs)	**100%**	4	**Strong**	MQPM, ISM, IBFM-2
^{117}Cd → ^{117}In	$1/2^+$	$9/2^+$ (gs)	∼0%	4	**Strong**	MQPM
^{119}In → ^{119}Sn	$9/2^+$	$1/2^+$ (gs)	∼0%	4	**Strong**	MQPM
^{123}Sn → ^{123}Sb	$11/2^-$	$1/2^+$ (4)	∼0%	5	Weak	MQPM
^{125}Sb → ^{125}Te	$7/2^+$	$9/2^-$ (3)	7.2%	1	None	MQPM
^{126}Sn → ^{126}Sb	0^+	2^+ (5)	**100%**	2	None	ISM
^{133}Sn → ^{133}Sb	$7/2^-$	$7/2^+$ (gs)	**85%**	1	Weak	ISM
^{134}Sb → ^{134}Te	0^-	0^+ (gs)	**98%**	1	Weak	ISM
^{135}Cs → ^{135}Ba	$7/2^+$	$3/2^+$ (gs)	**100%**	2	None	MQPM
^{135}Te → ^{135}I	$7/2^-$	$7/2^+$ (gs)	**62%**	1	Weak	ISM
^{137}Cs → ^{137}Ba	$7/2^+$	$3/2^+$ (gs)	5.4%	2	None	MQPM, ISM
^{137}Xe → ^{137}Cs	$7/2^-$	$7/2^+$ (gs)	**67%**	1	Weak	ISM
^{138}Cs → ^{138}Ba	3^-	3^+ (1)	**44%**	1	**Strong**	ISM
^{139}Ba → ^{139}La	$7/2^-$	$7/2^+$ (gs)	**70%**	1	Weak	ISM
^{139}Cs → ^{139}Ba	$7/2^+$	$7/2^-$ (gs)	**85%**	1	Weak	ISM

Summary on β spectra continues . . .

Transition	$J_i^{\pi_i}$ (gs)	$J_f^{\pi_f}$ (n_f)	Branching	K	Sensitivity	Nucl. model
$^{141}\mathrm{Ce} \to {}^{141}\mathrm{Pr}$	$7/2^-$	$5/2^+$ (gs)	31%	1	Weak	MQPM
$^{142}\mathrm{Pr} \to {}^{142}\mathrm{Nb}$	2^-	2^+ (1)	3.7%	1	Weak	ISM
$^{143}\mathrm{Pr} \to {}^{143}\mathrm{Nb}$	$7/2^+$	$7/2^-$ (gs)	**100%**	1	Weak	ISM
$^{159}\mathrm{Gd} \to {}^{159}\mathrm{Tb}$	$3/2^-$	$5/2^+$ (1)	26%	1	None	MQPM
$^{161}\mathrm{Tb} \to {}^{161}\mathrm{Dy}$	$3/2^+$	$5/2^-$ (1)	∼0%	1	None	MQPM
$^{169}\mathrm{Er} \to {}^{169}\mathrm{Tm}$	$1/2^-$	$3/2^+$ (1)	**45%**	1	None	MQPM
$^{210}\mathrm{Bi} \to {}^{210}\mathrm{Po}$	1^-	0^+ (gs)	**100%**	1	**Strong**	ISM
$^{211}\mathrm{Pb} \to {}^{211}\mathrm{Bi}$	$9/2^+$	$9/2^-$ (gs)	**91%**	1	Weak	ISM
$^{213}\mathrm{Bi} \to {}^{213}\mathrm{Po}$	$9/2^-$	$9/2^+$ (gs)	**66%**	1	Weak	ISM

Effects of quenched values of g_{A}

Results from:

Effects of a quenched g_{A}

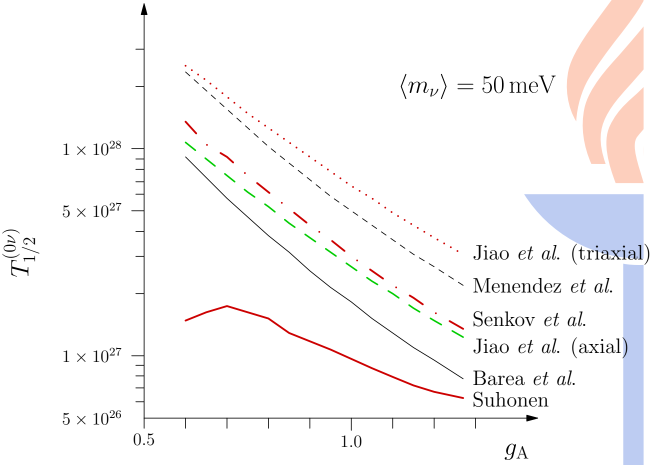
on NMEs of $0\nu\beta\beta$ decays:

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

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

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 + isospin restoration + data on $2\nu\beta\beta$)



Novel application of electron spectra of forbidden decays

Try to investigate:

Reactor-$\bar{\nu}$ anomaly

and

the spectral shoulder

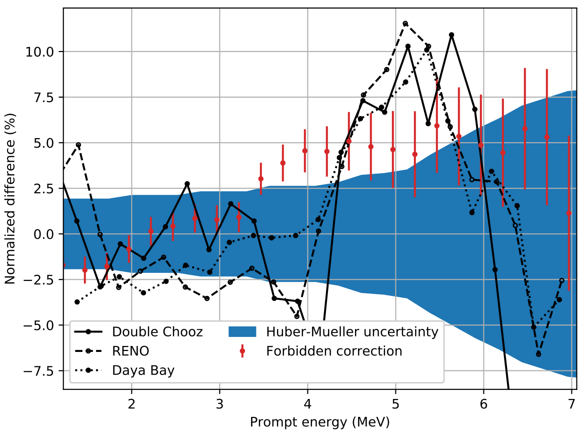
See: L. Heyen, J. Kostensalo, N. Severijns, J.S., First forbidden transitions in the reactor anomaly, arXiv:1805.12259 [nucl-th] 30 May 2018

Results from the analyses (see the parallel talk of Joel Kostensalo on Tuesday evening!)

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

decreases the $\bar{\nu}$ flux by 5% !



The spectral sholder appears due to forbidden spectral corrections !

Conclusions and Outlook

Conclusions:

- The long chain of ISM calculations and the recent pnQRPA and IBM-2 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}
- Studies on GT 1^+ and SD 2^- β decays shed light on the suppression chain: quasiparticle NME → pnQRPA NME → experimental NME
- Studies of high-forbidden unique β decays ($F \geq 2$) → uniform quenching → speculations about modifications in the $0\nu\beta\beta$-decay half-lives
- The spectrum-shape method (SSM) for forbidden non-unique β decays is a robust tool (largely independent of the nuclear model, the assumed Hamiltonian and mean field) to seach for the effective value of g_{A} and to try to solve other problems, like those related to the reactor-$\bar{\nu}$ spectra.

Outlook:

- Urge measurements of the β spectra for the interesting decays amenable to the SSM
- The effective value of g_{A} is involved in all weak processes, and thus has impact on studies of rare β decays, neutrino physics and astrophysics