Nuclear Structure Solving Problems of Fundamental Physics

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Contents:

- The g_A problem of weak decays:
- allowed β decays
- forbidden β decays
- Are there sterile neutrinos?
  The Ga and reactor-$\bar{\nu}$ anomalies

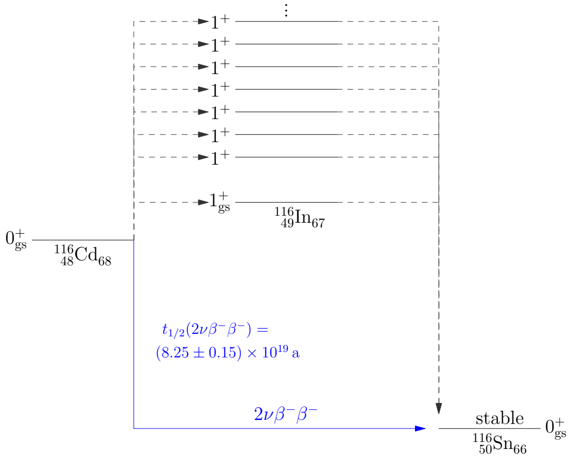
PART 1: Study of the effective value of the weak axial coupling

Motivation:

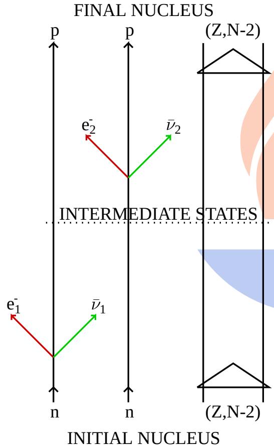
The effective value of g_{A} is involved in all weak processes, and thus has impact on

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

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

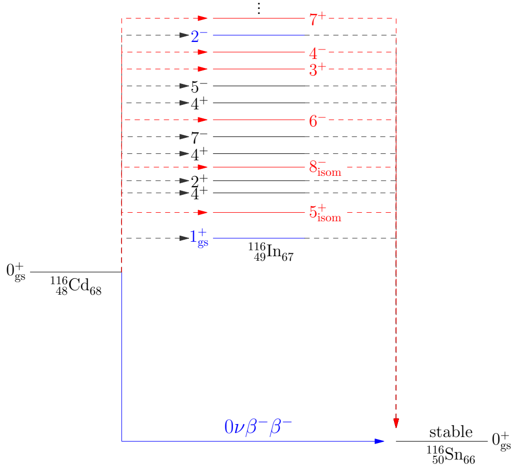


$t_{1/2}(2\nu\beta^-\beta^-) =$
$(8.25 \pm 0.15) \times 10^{19}$ a

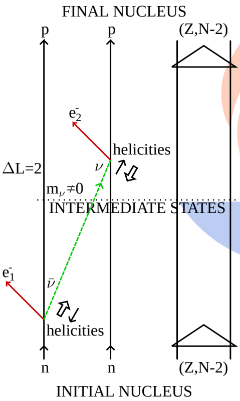


$$\boxed{2\nu\beta\beta - \text{rate} \sim \left|M^{(2\nu)}_{\text{GTGT}}\right|^2 = (g_{\text{A}})^4 \left|\sum\nolimits_{m,n} \frac{M_{\text{L}}(1^+_m)M_{\text{R}}(1^+_n)}{D_m}\right|^2}$$

Example: Neutrinoless Double Beta Decay of ^{116}Cd



MASS MODE



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

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:

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

Quenching:

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

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

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

Effective value of $g_{\rm A}$:

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

Gamow-Teller β decays

There are data on:

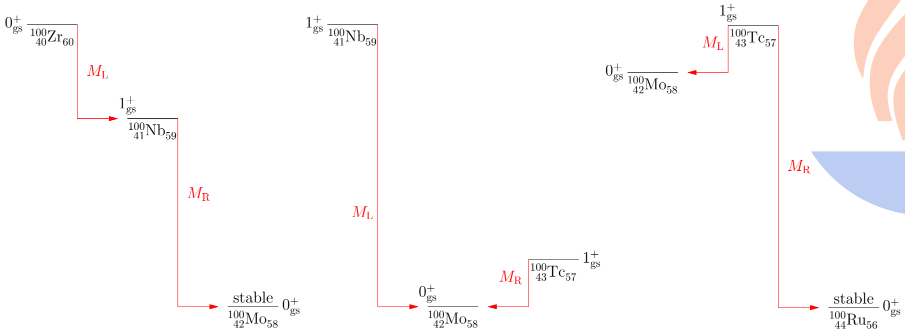
Gamow-Teller β

TRANSITIONS

Theoretical approaches:

ISM (Interacting Shell Model)
pnQRPA (proton-neutron QRPA)

Typical Gamow-Teller β transitions

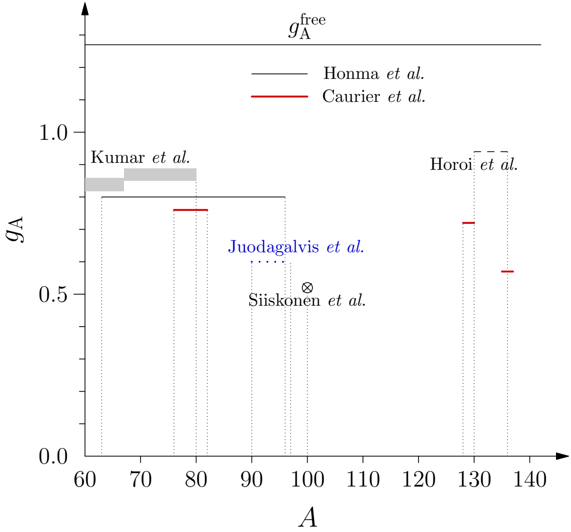


Interacting Shell Model (ISM)

Results from:

Quenching of g_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

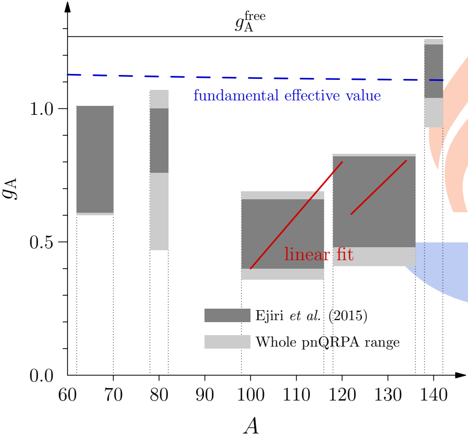
A	pn Conf.	$\bar{g}_{\rm A}^{\rm eff}$ [1]
$62-70$	$1p_{3/2}-1p_{1/2}$	0.81 ± 0.20
$78-82$	$0g_{9/2}-0g_{9/2}$	0.88 ± 0.12
$98-116$	$0g_{9/2}-0g_{7/2}$	0.53 ± 0.13
$118-136$	$1d_{5/2}-1d_{5/2}$	0.65 ± 0.17
$138-142$	$1d_{5/2}-1d_{3/2}$	1.14 ± 0.10

[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

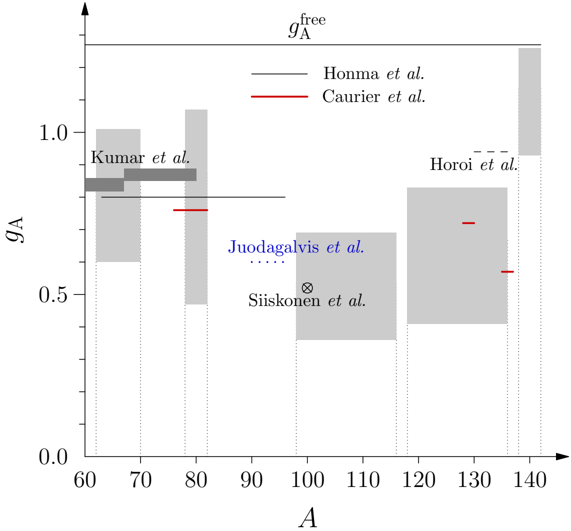
[3] F. Deppisch, J. S., Phys. Rev. C 94 (2016) 055501



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



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- Caurier *et al.*: Phys. Lett. B 711 (2012) 62
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Calculations for the β decays and $\beta\beta$ decays

Results from:

Quenching of g_A

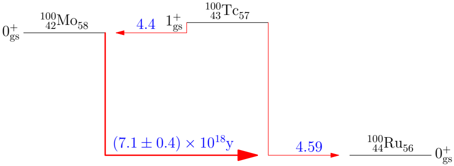
in the pnQRPA-based,

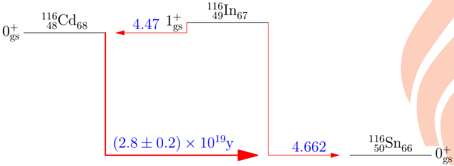
ISM-based and

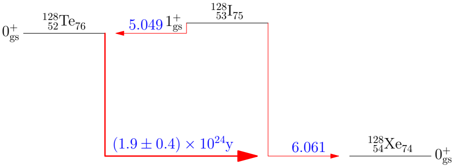
IBM-based calculations

of β decays and $\beta\beta$ decays

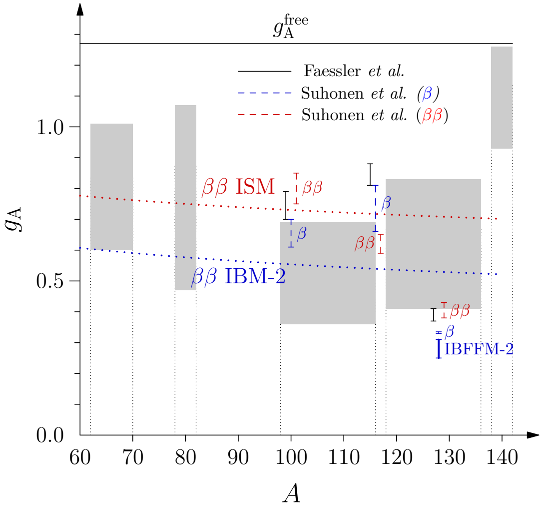
The studied cases







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

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

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

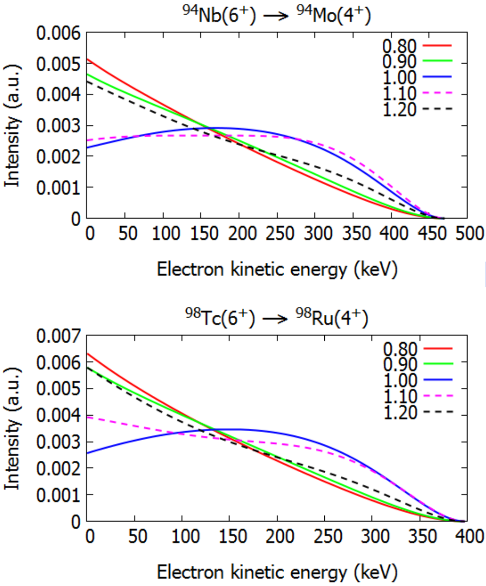
$F_{k-1}(Z, w_e)$ being the generalized Fermi function.

Decomposition of the shape factor:

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

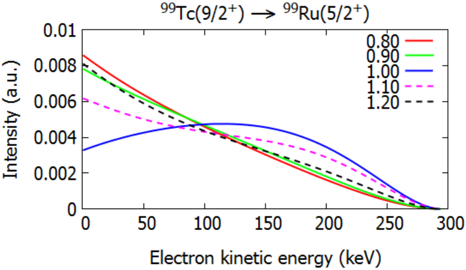
ISM-computed β spectra for different values of g_A

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

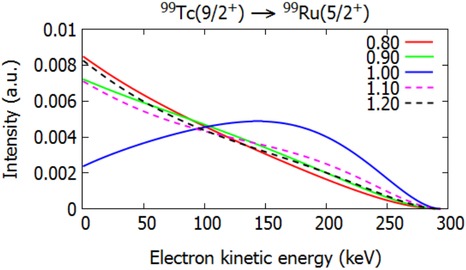


Example: ISM- and MQPM-computed electron spectra

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



(ISM)



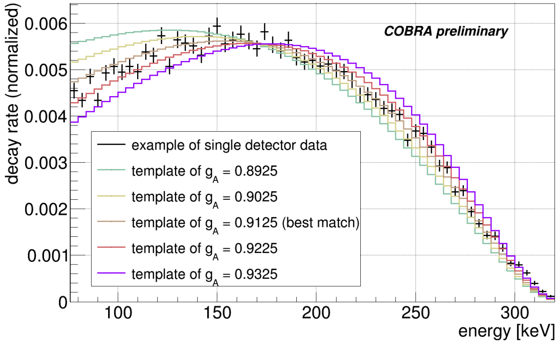
(MQPM)

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

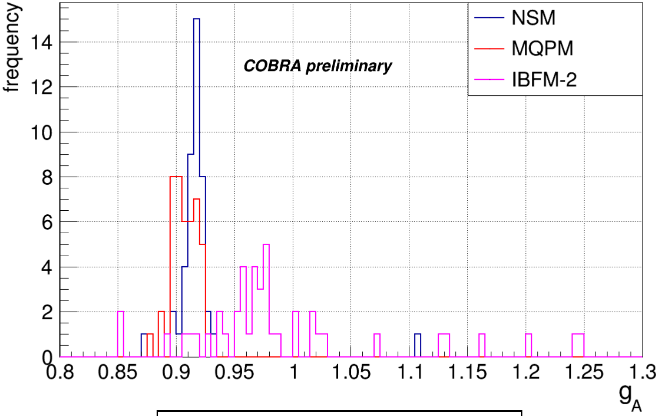
Normalized electron spectra for the $4th$-forbidden nonunique β^- decay $^{113}\mathrm{Cd}(1/2^+) \rightarrow {}^{113}\mathrm{In}(9/2^+)$ ($g_{\mathrm{V}} = 1.0$).

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



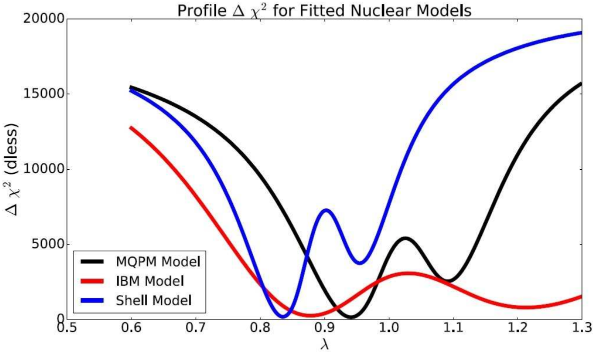
$$\bar{g}_A(\text{ISM}) = 0.92 \pm 0.02$$
$$\bar{g}_A(\text{MQPM}) = 0.91 \pm 0.01$$
$$\bar{g}_A(\text{IBFM-2}) = 0.94 \pm 0.09$$

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

Normalized electron spectra for the 4*th*-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
$^{36}\mathrm{Cl} \rightarrow {}^{36}\mathrm{Ar}$	2^+	0^+ (gs)	**98%**	2	None	ISM
$^{48}\mathrm{Ca} \rightarrow {}^{48}\mathrm{Sc}$	0^+	4^+ (2)	$\sim$0%	4	None	ISM
$^{48}\mathrm{Ca} \rightarrow {}^{48}\mathrm{Sc}$	0^+	6^+ (gs)	$\sim$0%	6	None	ISM
$^{50}\mathrm{V} \rightarrow {}^{50}\mathrm{Cr}$	6^+	2^+ (1)	$\sim$0%	4	Weak	ISM
$^{60}\mathrm{Fe} \rightarrow {}^{60}\mathrm{Co}$	0^+	2^+ (1)	**100%**	2	None	ISM
$^{85}\mathrm{Br} \rightarrow {}^{85}\mathrm{Kr}$	$3/2^-$	$9/2^+$ (gs)	$\sim$0%	3	Moderate	MQPM
$^{87}\mathrm{Rb} \rightarrow {}^{87}\mathrm{Sr}$	$3/2^-$	$9/2^+$ (gs)	**100%**	3	Moderate	MQPM, ISM
$^{92}\mathrm{Rb} \rightarrow {}^{92}\mathrm{Sr}$	0^-	0^+ (gs)	**95%**	1	Weak	ISM
$^{93}\mathrm{Zr} \rightarrow {}^{93}\mathrm{Nb}$	$5/2^+$	$9/2^+$ (gs)	$5 \leq$%	2	Weak	MQPM
$^{93}\mathrm{Y} \rightarrow {}^{93}\mathrm{Zr}$	$1/2^-$	$1/2^+$ (1)	2%	1	Moderate	ISM
$^{94}\mathrm{Nb} \rightarrow {}^{94}\mathrm{Mo}$	6^+	4^+ (2)	**100%**	2	**Strong**	NSM
$^{95}\mathrm{Sr} \rightarrow {}^{95}\mathrm{Y}$	$1/2^+$	$1/2^-$ (gs)	**56%**	1	Weak	ISM
$^{96}\mathrm{Zr} \rightarrow {}^{96}\mathrm{Nb}$	0^+	4^+ (2)	$\sim$0%	4	None	ISM
$^{96}\mathrm{Zr} \rightarrow {}^{96}\mathrm{Nb}$	0^+	6^+ (gs)	$\sim$0%	6	**Strong**	ISM
$^{96}\mathrm{Y} \rightarrow {}^{96}\mathrm{Zr}$	0^-	0^+ (gs)	**96%**	1	weak	ISM
$^{97}\mathrm{Zr} \rightarrow {}^{97}\mathrm{Nb}$	$1/2^+$	$9/2^+$ (gs)	$\sim$0%	4	**Strong**	MQPM
$^{97}\mathrm{Y} \rightarrow {}^{97}\mathrm{Zr}$	$1/2^+$	$1/2^-$ (gs)	**40%**	1	Weak	ISM
$^{98}\mathrm{Tc} \rightarrow {}^{98}\mathrm{Ru}$	6^+	4^+ (3)	**100%**	2	**Strong**	ISM
$^{99}\mathrm{Tc} \rightarrow {}^{99}\mathrm{Ru}$	$9/2^+$	$5/2^+$ (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 $\rightarrow$ ^{101}Tc	$1/2^+$	$9/2^+$ (gs)	$\sim$0%	4	**Strong**	MQPM
^{113}Cd $\rightarrow$ ^{113}In	$1/2^+$	$9/2^+$ (gs)	**100%**	4	**Strong**	MQPM, ISM, IBFM-2
^{115}Cd $\rightarrow$ ^{115}In	$1/2^+$	$9/2^+$ (gs)	$\sim$0%	4	**Strong**	MQPM
^{115}In $\rightarrow$ ^{115}Sn	$9/2^+$	$1/2^+$ (gs)	**100%**	4	**Strong**	MQPM, ISM, IBFM-2
^{117}Cd $\rightarrow$ ^{117}In	$1/2^+$	$9/2^+$ (gs)	$\sim$0%	4	**Strong**	MQPM
^{119}In $\rightarrow$ ^{119}Sn	$9/2^+$	$1/2^+$ (gs)	$\sim$0%	4	**Strong**	MQPM
^{123}Sn $\rightarrow$ ^{123}Sb	$11/2^-$	$1/2^+$ (4)	$\sim$0%	5	Weak	MQPM
^{125}Sb $\rightarrow$ ^{125}Te	$7/2^+$	$9/2^-$ (3)	7.2%	1	None	MQPM
^{126}Sn $\rightarrow$ ^{126}Sb	0^+	2^+ (5)	**100%**	2	None	ISM
^{133}Sn $\rightarrow$ ^{133}Sb	$7/2^-$	$7/2^+$ (gs)	**85%**	1	Weak	ISM
^{134}Sb $\rightarrow$ ^{134}Te	0^-	0^+ (gs)	**98%**	1	Weak	ISM
^{135}Cs $\rightarrow$ ^{135}Ba	$7/2^+$	$3/2^+$ (gs)	**100%**	2	None	MQPM
^{135}Te $\rightarrow$ ^{135}I	$7/2^-$	$7/2^+$ (gs)	**62%**	1	Weak	ISM
^{137}Cs $\rightarrow$ ^{137}Ba	$7/2^+$	$3/2^+$ (gs)	5.4%	2	None	MQPM, ISM
^{137}Xe $\rightarrow$ ^{137}Cs	$7/2^-$	$7/2^+$ (gs)	**67%**	1	Weak	ISM
^{138}Cs $\rightarrow$ ^{138}Ba	3^-	3^+ (1)	**44%**	1	**Strong**	ISM
^{139}Ba $\rightarrow$ ^{139}La	$7/2^-$	$7/2^+$ (gs)	**70%**	1	Weak	ISM
^{139}Cs $\rightarrow$ ^{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)	$\sim$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

Conclusions about the effective g_A

Conclusion 1:

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

Conclusion 2:

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-$\bar{\nu}_e$ spectra

PART 2: Neutrino-related anomalies imply oscillations to sterile neutrinos

Sterile neutrinos:

The gallium anomaly

The reactor antineutrino anomaly

imply oscillations of the “ordinary” neutrinos (ν_{e}, ν_{μ}, ν_{τ}) to

STERILE NEUTRINO

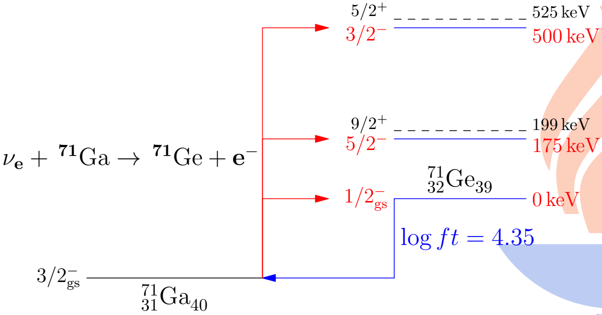
in the mass range of a few eV

But what are these anomalies?

The ^{71}Ga anomaly (has pestered us for some 20 years!)

Charged-current neutrino-^{71}Ga scattering via Gamow-Teller type of transitions.

Monoenergetic ν_e from artificial neutrino sources via Electron captures:



$$\boxed{{}^{37}\mathrm{Ar} + e^- \rightarrow {}^{37}\mathrm{Cl} + \nu_e \ (E_\nu = 814\,\mathrm{keV})\ ; \quad {}^{51}\mathrm{Cr} + e^- \rightarrow {}^{51}\mathrm{V} + \nu_e \ (E_\nu = 751\,\mathrm{keV})}$$

The scattering cross sections σ have been measured by the GALLEX experiment [Phys. Lett. B 342 (1995) 440 ; ibid B 420 (1998) 114 ; ibid B 685 (2010) 47] and the SAGE experiment [Phys. Rev. Lett. 77 (1996) 4708 ; Phys. Rev. C 59 (1999) 2246 ; ibid C 73 (2006) 045805 ; ibid C 80 (2009) 015807]

Estimation of the scattering cross section

The cross sections can be deduced from neutrino kinematics, as first done by J. N. Bahcall, Phys. Rev. C 56 (1997) 3391 (verified by our more complete calculations)

$$\sigma(^{37}\mathrm{Ar}) = 6.62 \times 10^{-45}\ \mathrm{cm}^2 \left(1 + 0.695\frac{\mathrm{BGT}_{175}}{\mathrm{BGT}_{\mathrm{gs}}} + 0.263\frac{\mathrm{BGT}_{500}}{\mathrm{BGT}_{\mathrm{gs}}}\right) .$$

$$\sigma(^{51}\mathrm{Cr}) = 5.53 \times 10^{-45}\ \mathrm{cm}^2 \left(1 + 0.667\frac{\mathrm{BGT}_{175}}{\mathrm{BGT}_{\mathrm{gs}}} + 0.218\frac{\mathrm{BGT}_{500}}{\mathrm{BGT}_{\mathrm{gs}}}\right) ,$$

where $\mathrm{BGT}_{\mathrm{gs}}$ can be normalized by the $\log ft$ of the Gamow-Teller EC transition $^{71}\mathrm{Ge}(1/2^-_{\mathrm{gs}}) \rightarrow {}^{71}\ \mathrm{Ga}(3/2^-_{\mathrm{gs}})$, and $\mathrm{BGT} = (g_{\mathrm{A}})^2 (f||\mathcal{O}_{\mathrm{GT}}||i)^2/(2J_i + 1)$, J_i being the angular momentum of the initial state.

BGT ratios can be taken from D. Frekers *et al.*, The $^{71}\mathrm{Ga}(^3\mathrm{He}, t)$ reaction and the low-energy neutrino response, Phys. Lett B 706 (2011) 134:

$$\frac{\mathrm{BGT}_{175}}{\mathrm{BGT}_{\mathrm{gs}}} = 0.039 \pm 0.030\ ; \quad \frac{\mathrm{BGT}_{500}}{\mathrm{BGT}_{\mathrm{gs}}} = 0.202 \pm 0.016\, ,$$

or from our shell-model calculations with the JUN45 interaction:

$$\frac{\mathrm{BGT}_{175}}{\mathrm{BGT}_{\mathrm{gs}}} = 0.033\ ; \quad \frac{\mathrm{BGT}_{500}}{\mathrm{BGT}_{\mathrm{gs}}} = 0.016\, ,$$

Quantitative statement of the gallium anomaly

$$\boxed{R = \frac{\sigma_{\text{measured}}(\text{GALLEX,SAGE})}{\sigma_{\text{estimated}}}.}$$

It seems that experiments measure a reduced neutrino flux:

Estimate	GALLEX 1	GALLEX 2	SAGE 1	SAGE 2
R(Frekers *et al.*)	0.93 ± 0.11	0.79 ± 0.11	0.93 ± 0.11	0.77 ± 0.08
R(SM, JUN45)	0.98 ± 0.11	0.83 ± 0.11	0.97 ± 0.12	0.81 ± 0.09

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

Questions raised:

- Are there problems with the cross-section measurements (GALLEX 1 vs. GALLEX 2, SAGE 2)?
- Why the BGT of Frekers *et al.* deviate from the shell-model computed BGTs?

Problems with the analysis of the $^{71}\mathrm{Ga}(^{3}\mathrm{He}, t)$ reaction?

$$\boxed{\mathrm{BGT}_{\mathrm{reaction}} = \frac{(g_{\mathrm{A}})^2}{2J_i+1}\left[(f\|\mathcal{O}_{\mathrm{GT}}\|i) + \delta(f\|\mathcal{O}_{\mathrm{T}}\|i)\right]^2,}$$

where $\mathcal{O}_{\mathrm{T}} \sim [\sigma Y_2]_1$ is the tensor part entering the reaction analysis and $\delta = 0.097$ is the mixing strength (From the analysis of Gamow-Teller transitions in the sd shell: W.C. Haxton, Phys. Lett. B 431 (1998) 110.).

We find interference of the GT and tensor terms:

Transition	$(f\|\mathcal{O}_{\mathrm{GT}}\|i)$	$(f\|\mathcal{O}_{\mathrm{T}}\|i)$	BGT_{β}(SM)	$\mathrm{BGT}_{\mathrm{reaction}}$(SM)
$3/2^-(\mathrm{Ga}) \rightarrow 1/2^-(\mathrm{Ge, gs})$	-0.795	0.465	0.158	0.141
$3/2^-(\mathrm{Ga}) \rightarrow 5/2^-(\mathrm{Ge}, 175\,\mathrm{keV})$	0.144	-1.902	0.0052	0.0004
$3/2^-(\mathrm{Ga}) \rightarrow 3/2^-(\mathrm{Ge}, 500\,\mathrm{keV})$	0.100	0.048	0.0025	0.0027

The charge-exchange reactions assume always a constructive interference of the GT and tensor terms!

Conclusions about the ^{71}Ga anomaly

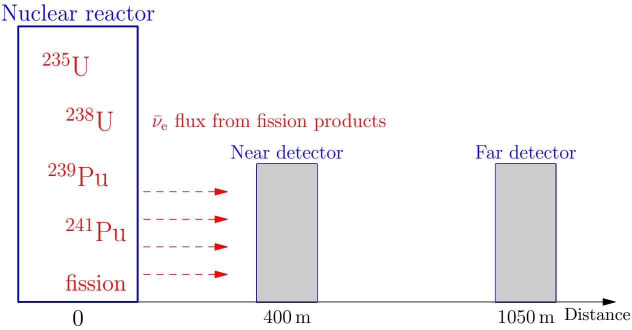
Conclusions:

NONE YET!

The work continues. . .

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).



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[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 $\bar{\nu}_{\mathrm{e}}$ 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 $\bar{\nu}_{\mathrm{e}}$ spectrum.

$\Longrightarrow$???

Novel application of calculated electron spectra

Implement:

machinery to compute

the spectral shapes of

key first-forbidden transitions

making up some 50% of the total flux

and even more at the spectral bump

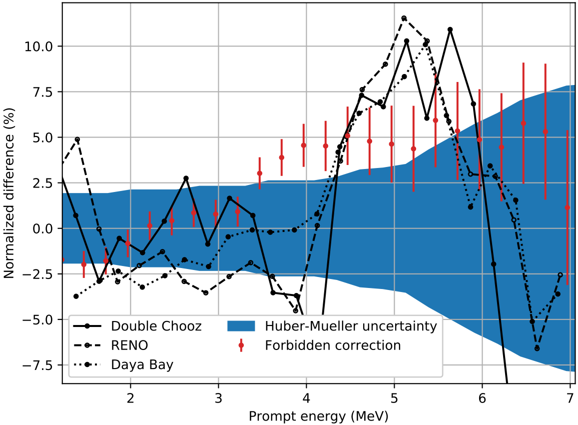
See: L. Heyen, J. Kostensalo, N. Severijns, J.S., First forbidden transitions in the reactor anomaly, arXiv:1805.12259 [nucl-th] 30 May 2018

Results from the analysis

Taking into account the first-forbidden (non-unique) decays of

^{86}Br(0^+), ^{86}Br(2^+), ^{87}Se,
^{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^+), ^{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, ^{140}Cs,
^{142}Cs

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



The spectral sholder appears due to forbidden spectral corrections !

Conclusions about the reactor $\bar{\nu}_e$ anomaly

Conclusions:

Proper account of the spectral shapes of

(first) forbidden β decays

is instrumental in the quest of the solution

to the anomaly

The work still continues. . .

The end

THANKS FOR PATIENCE!