Nuclear Processes and Effective Weak Couplings

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Contents:

- INTRO: Rare weak decays
- Effective value of g_A and its impact on $0\nu\beta\beta$ NMEs
- Pinning down the value of g_A^{eff}
- ν mass from low-Q β/EC decays
- Competition of β and $2\nu\beta\beta$ decays
- OMC vs $0\nu\beta\beta$
- About reactor-$\bar{\nu}$ anomaly

INTRO: Rare weak decays

What causes the rare weak decays to be so rare?

- Very low Q values
- 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 review:
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

Effective value of the weak 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,. . .)

Effective value of g_A:

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

$$\Downarrow$$

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

$$\Downarrow$$

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

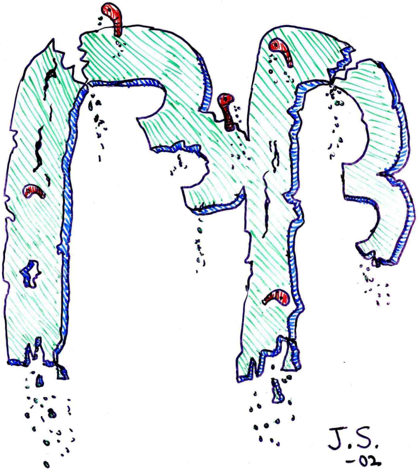
$$j_N^\mu = g_V \gamma^\mu - g_A^{\text{eff}} \gamma^\mu \gamma^5$$

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

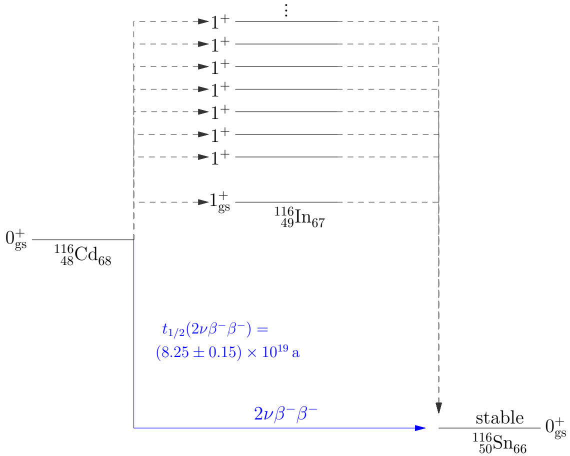
- Non-nucleonic degrees of freedom (e.g. Δ resonances)
- Effects beyond the impulse approximation (e.g. two-body meson-exchange currents)
- Deficiencies in nuclear many-body approaches (e.g. restricted valence spaces, lacking many-body configurations, omission of three-body nuclear forces)

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

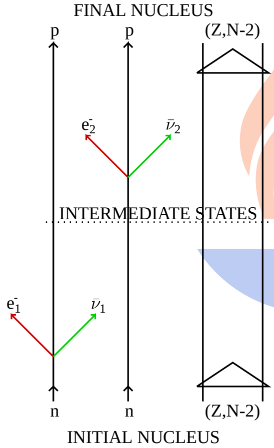
Rates of $\beta\beta$ decay and the weak axial coupling g_A



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

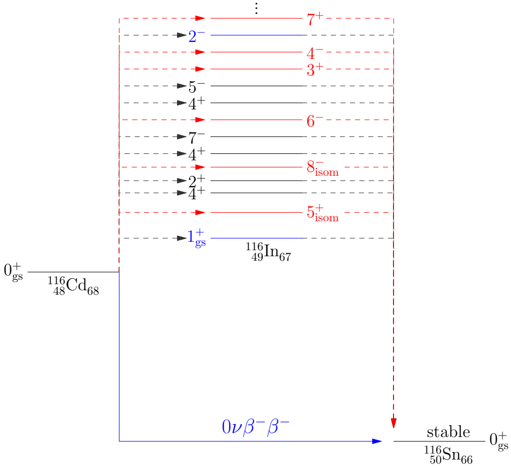


$t_{1/2}(2\nu\beta^-\beta^-) =$
$(8.25 \pm 0.15) \times 10^{19}$ a

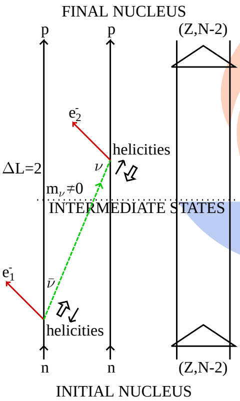


$$\boxed{2\nu\beta\beta - \text{rate} \sim \left|M^{(2\nu)}_{\mathrm{GTGT}}\right|^2 = (g_{\mathrm{A}}^{\mathrm{eff}})^4 \left|\sum_{m,n} \frac{M_{\mathrm{L}}(1^+_m)M_{\mathrm{R}}(1^+_n)}{D_m}\right|^2}$$

Neutrinoless $\beta\beta$ decay of ^{116}Cd



MASS MODE



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

Effects of quenched values of g_{A}

Results from:

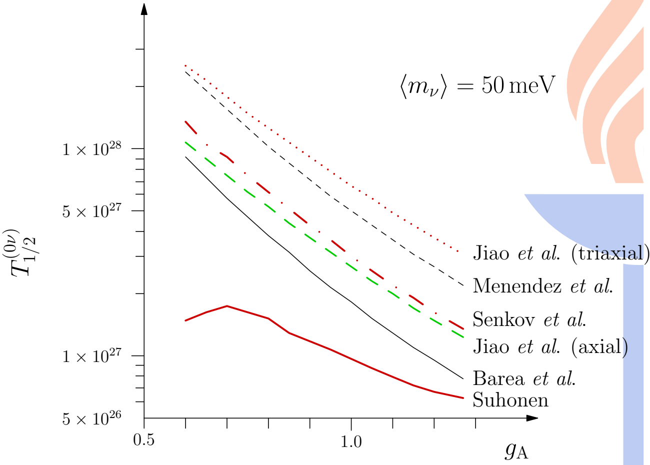
Effects of a quenched g_{A} on NMEs of $0\nu\beta\beta$ decays:

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

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

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



Gamow-Teller β and $2\nu\beta\beta$ decays: $g_\mathrm{A}(1^+)$

There are data on:

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

For these we have the low-momentum-exchange limit

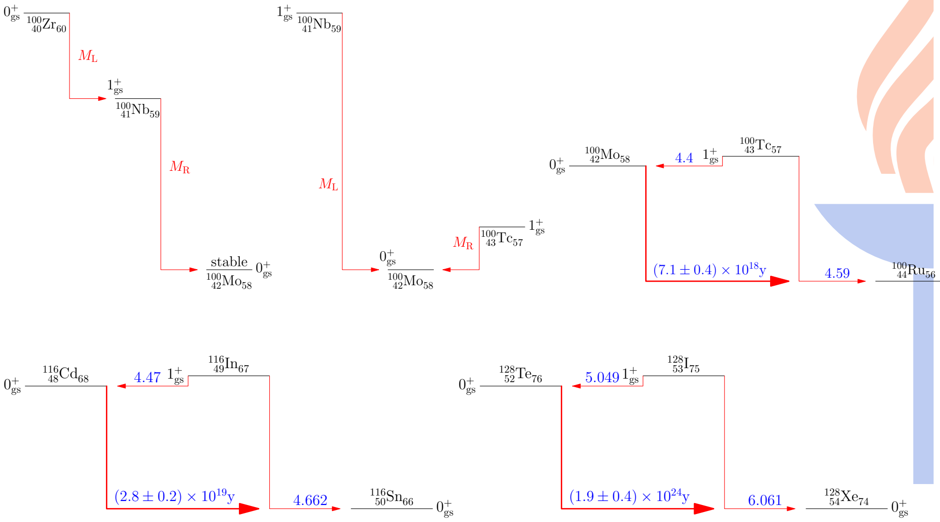
$$g_{\mathrm{A},0\nu}(J^\pi) \xrightarrow{q\to 0} g_\mathrm{A}(J^\pi),$$

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)

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



$0^+_{\rm gs}$ ${}^{100}_{40}\mathrm{Zr}_{60}$

$M_{\rm L}$

$1^+_{\rm gs}$ ${}^{100}_{41}\mathrm{Nb}_{59}$

$M_{\rm R}$

stable $0^+_{\rm gs}$ ${}^{100}_{42}\mathrm{Mo}_{58}$

$1^+_{\rm gs}$ ${}^{100}_{41}\mathrm{Nb}_{59}$

$M_{\rm L}$

$0^+_{\rm gs}$ ${}^{100}_{42}\mathrm{Mo}_{58}$

$M_{\rm R}$

${}^{100}_{43}\mathrm{Tc}_{57}$ $1^+_{\rm gs}$

$0^+_{\rm gs}$ ${}^{100}_{42}\mathrm{Mo}_{58}$

4.4 $1^+_{\rm gs}$ ${}^{100}_{43}\mathrm{Tc}_{57}$

$(7.1 \pm 0.4) \times 10^{18}$y

4.59

${}^{100}_{44}\mathrm{Ru}_{56}$

$0^+_{\rm gs}$ ${}^{116}_{48}\mathrm{Cd}_{68}$

4.47 $1^+_{\rm gs}$ ${}^{116}_{49}\mathrm{In}_{67}$

$(2.8 \pm 0.2) \times 10^{19}$y

4.662

${}^{116}_{50}\mathrm{Sn}_{66}$ $0^+_{\rm gs}$

$0^+_{\rm gs}$ ${}^{128}_{52}\mathrm{Te}_{76}$

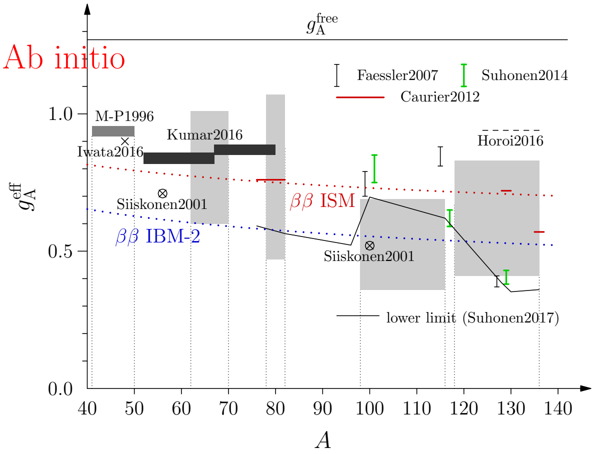
5.049 $1^+_{\rm gs}$ ${}^{128}_{53}\mathrm{I}_{75}$

$(1.9 \pm 0.4) \times 10^{24}$y

6.061

${}^{128}_{54}\mathrm{Xe}_{74}$ $0^+_{\rm gs}$

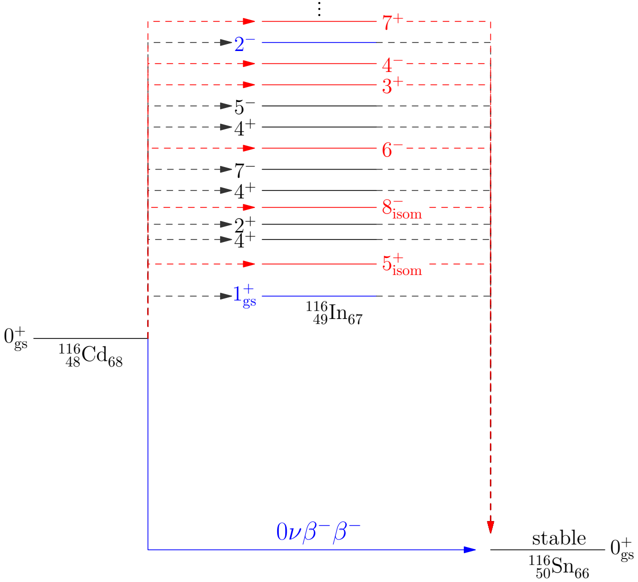
Results extracted from the GT β+$2\nu\beta\beta$ calculations



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

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



Forbidden non-unique β decays and $g_{\rm A}(J^\pi)$

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

Results for higher-multipole transitions: the Spectrum Shape Method (SSM):

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

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.

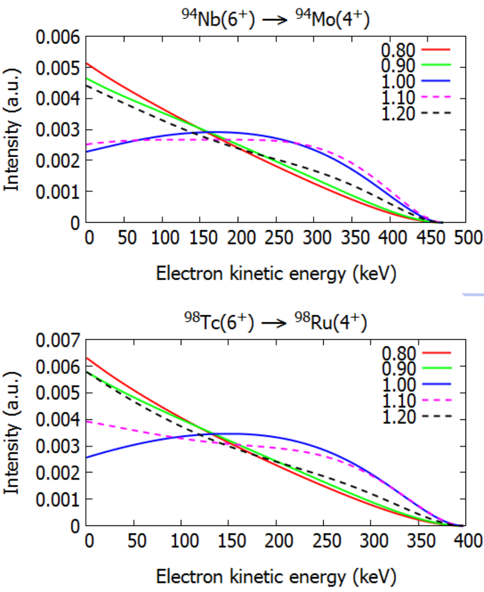
Decomposition of the shape factor:

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

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 ($g_V = 1.0$).

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



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	**Strong**	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) and ^{210}Bi (in preparation) measured by the COBRA collaboration (Kai Zuber's talk!).
- Electron spectrum of ^{115}In measured by the MIT-CSNSM-Jyväskylä collaboration (work ongoing).
- The g_A-independent spectral shape of the transition ^{137}Xe$(7/2^-) \rightarrow {}^{137}Cs(7/2^+)$ has been measured by the EXO-200 collaboration (see arXiv:2002.00108 [nucl-ex])

Low Q values

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

Neutrino Mass Measurements with low Q values

The KArlsruhe TRItium Neutrino experiment = KATRIN

$Q_{\beta^-} = 18.6\,\mathrm{keV}$, Allowed
$^3\mathrm{H}(1/2^+) \rightarrow {}^3\mathrm{He}(1/2^+)$ β^- decay, $T_{1/2} = 12.33\,\mathrm{y}$
Sensitivity to neutrino mass: $m_\nu \sim 0.1\,\mathrm{eV}$

$\Downarrow$

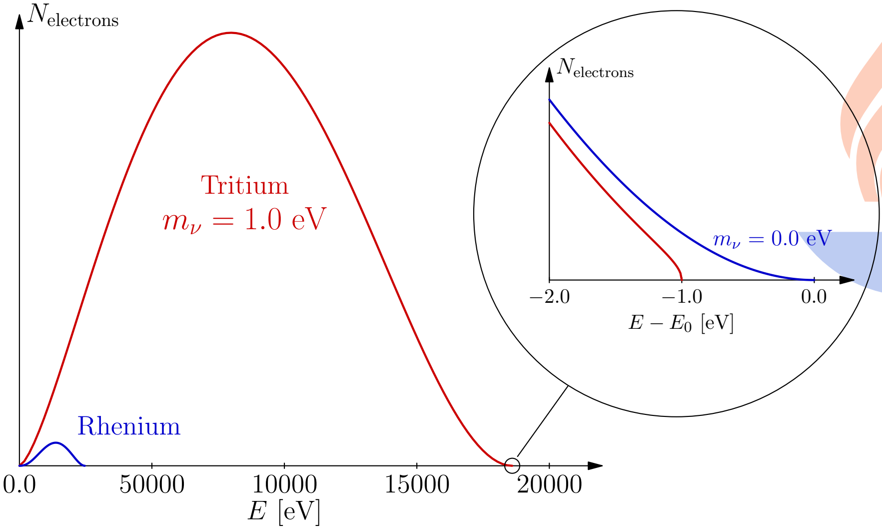
The Microcalorimetric Array for a Rhenium Experiment = MARE

$Q_{\beta^-} = 2.469(4)\,\mathrm{keV}$, First-forbidden unique
$^{187}\mathrm{Re}(5/2^+) \rightarrow {}^{187}\mathrm{Os}(1/2^-)$ β^- decay, $T_{1/2} = 4 \times 10^{10}\,\mathrm{y}$
Sensitivity to neutrino mass: $m_\nu \sim ?$

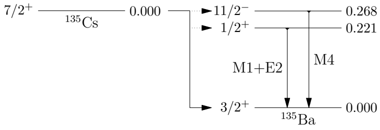
$\Downarrow$

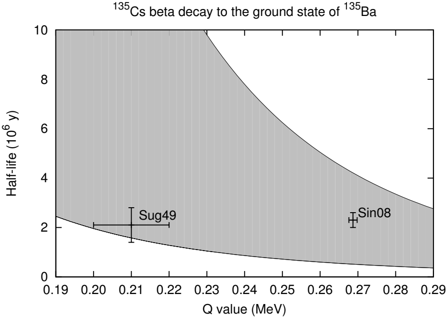
?

Extraction of the neutrino mass



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



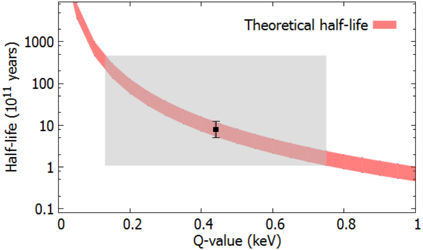


M.T. Mustonen and J. S., PLB 703 (2011) 370:

Important to revisit the Q-value msrmt!

Recent measurement of the Q value by the JYFLTRAP gives $Q = 210(10)$ keV, leading to $Q_{\mathrm{exc}} = 0.44(31)$ keV for the first-forbidden unique transition $^{135}\mathrm{Cs}(7/2^+) \rightarrow {}^{135}\mathrm{Ba}(11/2^-)$.

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



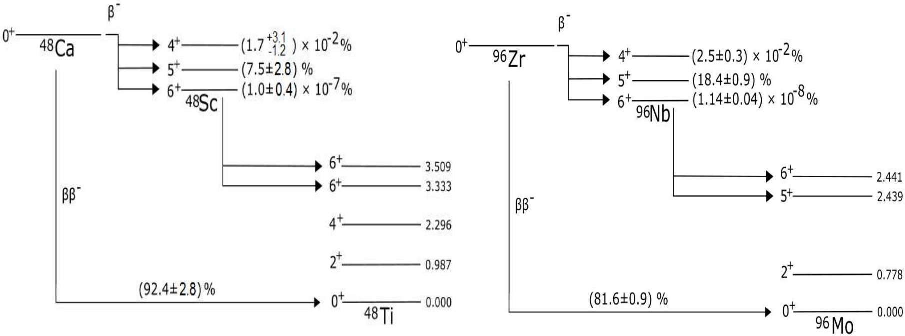
A. de Roubin *et al.*, arXiv:2002.08282 [nucl-ex]

See Tommi Eronen's talk on Tuesday after lunch!

Slow β decays compete with $2\nu\beta\beta$ decay

Competition between
β and $2\nu\beta\beta$ decays

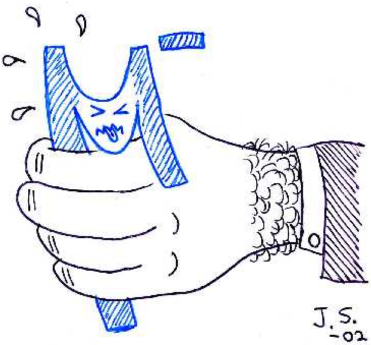
Competition between β and $2\nu\beta\beta$ decays of ^{48}Ca and ^{96}Zr: Branchings to different channels



The fourth-forbidden unique β-decay branch to the 5^+ state dominates the rest of the β decays (4^+, fourth-forbidden non-unique ; 6^+, sixth-forbidden non-unique)

J. Kostensalo and J.S., Consistent large-scale shell-model analysis of the two-neutrino $\beta\beta$ and single β branchings in ^{48}Ca and ^{96}Zr, Phys. Lett. B 802 (2020) 135192

OMC as a probe of $0\nu\beta\beta$ NMEs



There are and will be more data on:

PARTIAL CAPTURE RATES

OF

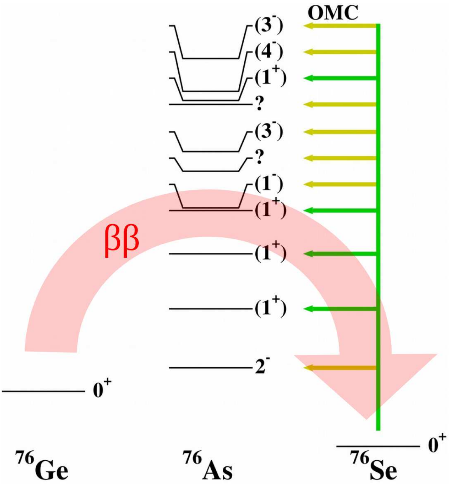
ORDINARY MUON CAPTURE (OMC)

In particular:

OMC STRENGTH DISTRIBUTIONS

Ordinary Muon Capture on ^{76}Se

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



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

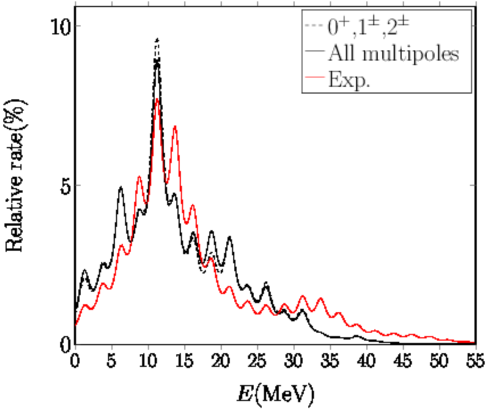
$\Downarrow$

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

Experiments:

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

Experimental and computed rates of OMC on ^{100}Mo



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

OMC giant resonances and comparison with $0\nu\beta\beta$ NMEs:

See Lotta Jokiniemi's talk on Friday!

Novel application of electron spectra of forbidden decays

Investigating

Reactor-$\bar{\nu}$ anomaly

and

the spectral bump

Neutrino-related anomalies could imply oscillations to sterile neutrinos

Sterile neutrinos:

The gallium anomaly

(See Joel Kostensalo's talk on Friday!)

The reactor antineutrino anomaly

imply oscillations of the "ordinary" neutrinos (ν_{e}, ν_μ, ν_τ) to

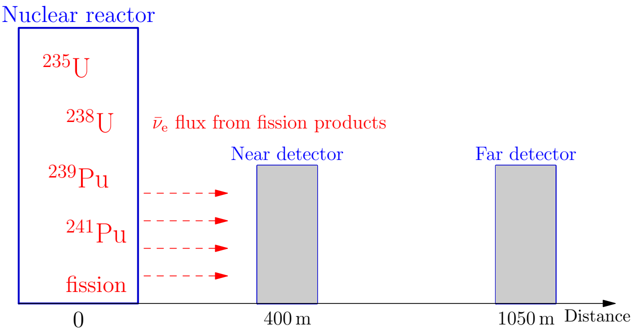
STERILE NEUTRINO

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).



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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 $\bar{\nu}_e$ 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 $\bar{\nu}_e$ spectrum.

$\Longrightarrow$??? See Leendert Hayen's talk on Wednesday!

Conclusions and outlook

Conclusions:

- 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
- 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}
- The spectrum-shape method (SSM) for forbidden non-unique β decays is a robust tool to seach for the effective value of g_{A}.
- Proper account of the spectral shapes of forbidden β decays is instrumental for the theoretical construction of the reactor-$\bar{\nu}$ spectra:
- There are interesting unexplored low Q-value β/EC transitions for ν-mass measurements
- The OMC can test the weak axial couplings at the momentum-exchange region relevant for the $0\nu\beta\beta$ decay

Outlook:

- Urge 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 will yield important information on the (induced) axial couplings relevant for $0\nu\beta\beta$ decay

The (hopefully happy) end

THANKS FOR PATIENCE!