

The Many Facets of Beta Spectral Shapes

Jouni Suhonen

Department of Physics, University of Jyväskylä

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Contents:

- **Motivation:** Double beta decay and the quenching of Gamow-Teller β transitions
- **β spectral shapes:**
- Spectrum-Shape Method (SSM)
- Rn backgrounds in rare-events experiments
- Reactor $\bar{\nu}$ s
- Precision oncology???

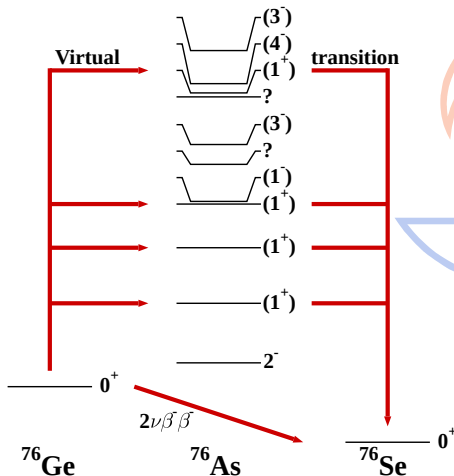
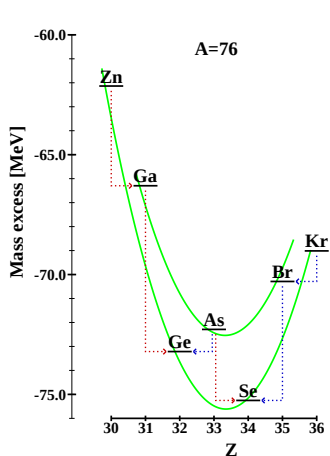
Highly-suppressed weak decays:

Nuclear decays of higher order:

Double beta decays:

Two-neutrino $\beta\beta$ decay
and
NEUTRINOLESS $\beta\beta$ decay

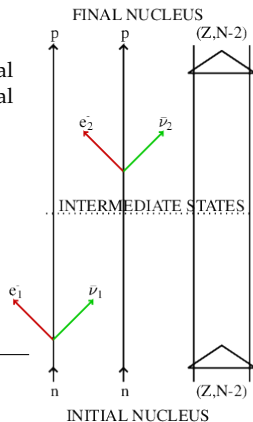
$2\nu\beta\beta$ decay from nuclear-structure point of view



Two-neutrino double beta decay

Nucleus	half-life (years)	experiments
^{48}Ca	$4.4^{+0.6}_{-0.5} \cdot 10^{19}$	laboratory
^{76}Ge	$1.60^{+0.13}_{-0.10} \cdot 10^{21}$	laboratory
^{82}Se	$(0.92 \pm 0.07) \cdot 10^{19}$	laboratory, geochemical
^{96}Zr	$(2.3 \pm 0.2) \cdot 10^{19}$	laboratory, geochemical
^{100}Mo	$(7.1 \pm 0.4) \cdot 10^{18}$	laboratory
$^{100}\text{Mo}(0_1^+)$	$6.2^{+0.7}_{-0.5} \cdot 10^{20}$	laboratory
^{116}Cd	$(2.85 \pm 0.15) \cdot 10^{19}$	laboratory
^{128}Te	$(2.0 \pm 0.3) \cdot 10^{24}$	geochemical
^{130}Te	$(6.9 \pm 1.3) \cdot 10^{20}$	geochemical
^{136}Xe	$(2.20 \pm 0.06) \cdot 10^{21}$	laboratory
^{150}Nd	$(8.2 \pm 0.9) \cdot 10^{18}$	laboratory
$^{150}\text{Nd}(0_1^+)$	$1.33^{+0.45}_{-0.26} \cdot 10^{20}$	laboratory
^{238}U	$(2.0 \pm 0.6) \cdot 10^{21}$	radio-chemical

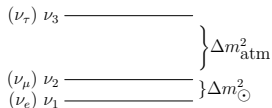
$$10^{20} \text{ years} = 10000000000 \times \text{age of the UNIVERSE} = (\text{age of the UNIVERSE})^2$$



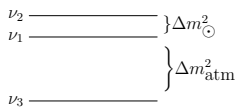
Neutrinoless double β^- decay

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

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



Normal hierarchy



Inverted hierarchy

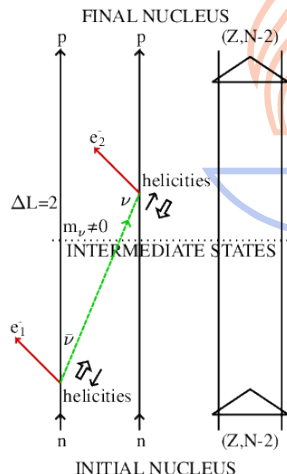
$$\Delta m_{\odot}^2 = 7.67_{-0.19}^{+0.16} \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{\text{atm}}^2 = 2.39_{-0.08}^{+0.11} \times 10^{-3} \text{ eV}^2$$

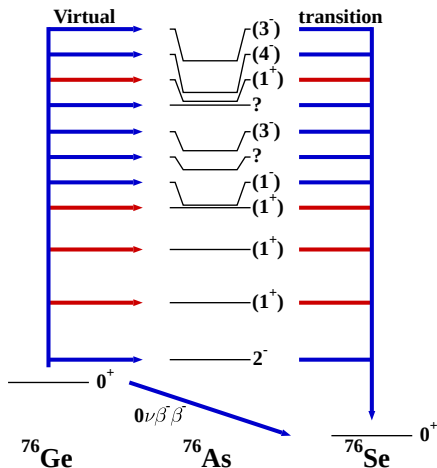
[Global 3ν oscillation analysis (2008)]

MASS MODE:

$$T_{1/2}^{-1} \propto \langle m_\nu \rangle^2$$



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



Decay rate in the mass mode:

$$\frac{\ln 2}{T_{1/2}} = (g_A)^4 g^{(0\nu)}(Q) [M^{(0\nu)}]^2 \langle m_\nu \rangle^2$$

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

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

- Light and heavy Majorana-neutrino exchange: J. Hyvärinen and J.S., Phys. Rev. C 91 (2015) 024613

Quenching of the spin-isospin operator $\sigma\tau$

$\sigma\tau \leftrightarrow g_A^{\text{eff}}$ in

Gamow-Teller β decays
and

Two-neutrino $\beta\beta$ decays

Effective value of the weak axial coupling g_A

The PCVC hypothesis $\Rightarrow g_A = 1.27$

↓↓ Non-nucleonic degrees of freedom (delta resonances)

↓↓ Nuclear many-body effects (two-body currents)

↓↓ Nuclear-model effects (valence- and configuration-space truncations, neglect of three-nucleon forces,...)

Effective value: g_A^{eff}

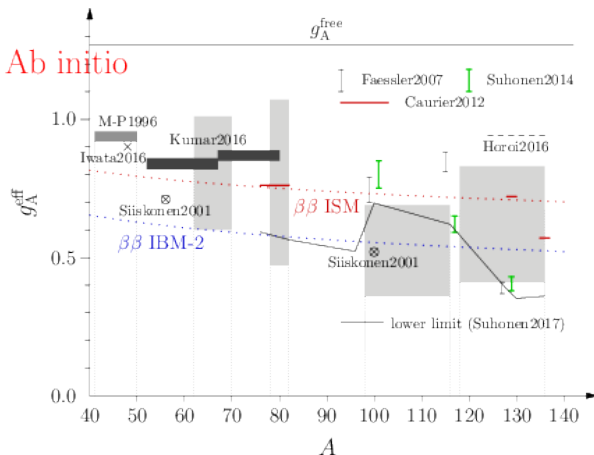
Effective value of g_A affects everything

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, reactor antineutrinos, precision oncology, ...
- Backgrounds in rare-events experiments
- 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, ...)

Collection of 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

Quenching of the higher spin-isospin operator

Higher $\sigma\tau$ operator is quenched

for 1^{st} -, 2^{nd} -, 3^{rd} - and 4^{th} -forbidden β decays:

$$\begin{aligned} [\sigma Y_L]_{L+1} \tau & \quad \text{UNIQUE} \\ [\sigma Y_L]_L \tau & \quad \text{NON-UNIQUE} \\ & \quad \beta \text{ decays for } L = 1, 2, 3, 4 \end{aligned}$$

Special case with ENHANCEMENT:

$$\begin{aligned} [\sigma \cdot \mathbf{p}_e]_0 \tau & \leftrightarrow g_A^{\text{eff}}(\gamma_5) = g_A^{\text{eff}} \times \epsilon_{\text{MEC}} \\ & \quad \text{for } 1^{st}\text{-forbidden } J^+ \leftrightarrow J^- \beta \text{ decays} \end{aligned}$$

Introducing the **SSM**: Spectrum-Shape Method

From $0\nu\beta\beta$ decay to β decay:

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

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

Effective value of $g_A(J^\pi)$

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

Spectral shape of higher-forbidden non-unique β decays

Half-life:

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

Dimensionless integrated shape function:

$$\tilde{S} = \int_1^{w_0} S(w_e) dw_e, \quad S(w_e) = C(w_e) p w_e (w_0 - w_e)^2 F_0(Z_f, w_e).$$

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

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

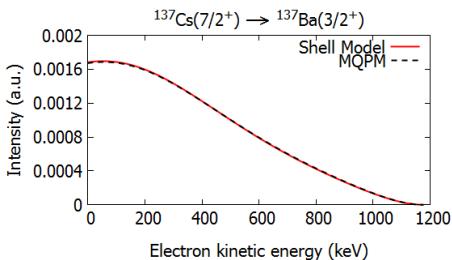
$F_{k-1}(Z, w_e)$ being the generalized Fermi function.

Decomposition of the shape factor:

$$C(w_e) = g_V^2 C_V(w_e) + g_A^2 C_A(w_e) + g_V g_A C_{VA}(w_e).$$

β spectral shapes without dependence on g_A

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

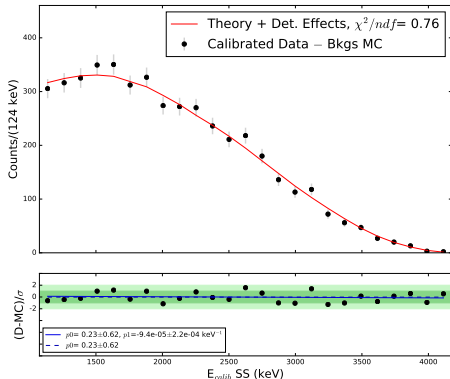


From: J. Kostensalo and J. S., Phys. Rev. C 96
(2017) 024317

Future measurement by **GAIAS**?

First-forbidden nonunique β^- decay

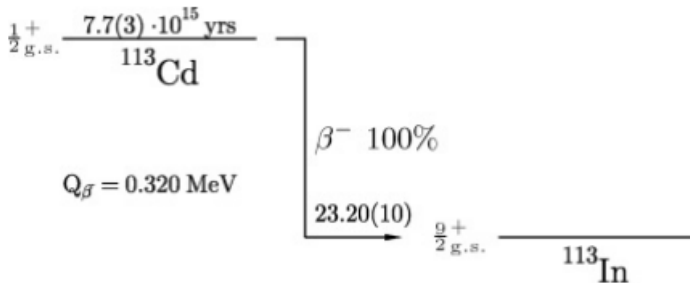
$$^{137}\text{Xe}(7/2^-) \rightarrow ^{137}\text{Cs}(7/2^+).$$



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

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

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

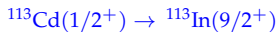


Calculated by using the **Interacting Shell Model (ISM)**, the **Microscopic Quasiparticle-Phonon Model (MQPM)** and the **microscopic Interacting Boson-Fermion Model (IBFM-2)**.

Decay of ^{113}Cd – Comparison with data

Normalized electron spectra for
the 4th-forbidden nonunique

β^- transition



($g_V = 1.0$).

Experimental data from

The COBRA collaboration:

PLB2020, SSM: L.

Bodenstein-Dresler *et al.*, Phys.

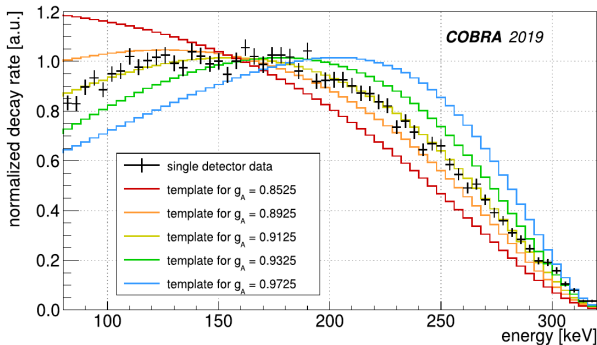
Lett. B 800 (2020) 135092.

PLB2021, ESSM: J. Kostensalo *et*

al., Phys. Lett. B 822 (2021)

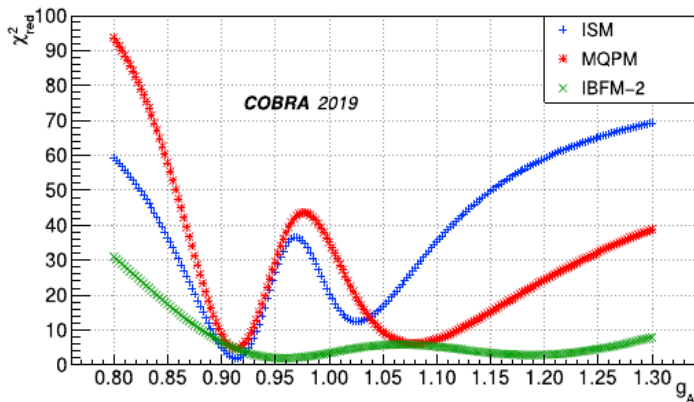
136652.

Measured spectrum by detector no. 54:



ESSM = Enhanced SSM: Adjust both the spectral shape and the (partial) half-life of the β transition by using s-NME (small relativistic vector NME)

Decay of ^{113}Cd – Comparison with data



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

Decay of $^{113}\text{Cd} - g_A^{\text{eff}}$ using ESSM

Table 1 Results of the Bayesian fit to the g_A^{eff} , s-NME and half-life of the ^{113}Cd β decay, including systematic uncertainties. The last column indicates the goodness of the fit expressed as χ^2 with 305 degrees of freedom for the reference fit

Model	g_A^{eff}	s-NME	$T_{1/2}$ [yr]	χ^2
IBFM-2 (s-NME > 0)	$1.160^{+0.019}_{-0.018}$	1.59 ± 0.04	7.50 ± 0.08	414
IBFM-2 (s-NME < 0)	$1.053^{+0.092}_{-0.088}$	-1.74 ± 0.13	$7.84^{+0.28}_{-0.26}$	473
MQPM (s-NME > 0)	1.068 ± 0.005	1.60 ± 0.04	7.43 ± 0.07	688
MQPM (s-NME < 0)	$1.050^{+0.055}_{-0.052}$	$-1.78^{+0.22}_{-0.21}$	$8.10^{+0.40}_{-0.37}$	618
NSM (s-NME > 0)	0.998 ± 0.006	1.66 ± 0.03	7.45 ± 0.08	572
NSM (s-NME < 0)	$0.987^{+0.070}_{-0.068}$	$-1.86^{+0.22}_{-0.20}$	8.07 ± 0.38	608

From: I. Bandac *et al.*, Eur. Phys. J. C (2024) 84:1158

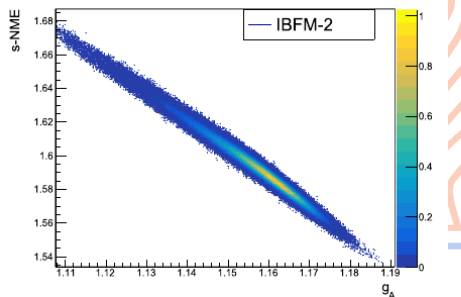


Fig. 8 Probability distribution function of the s-NME as function of g_A^{eff} for the positive case of the IBFM-2 model. The color code shows the probability in arbitrary units. We observe a clear anti-correlation between the two parameters

$$g_A^{\text{eff}}(\text{ISM}, \text{MQPM}, \text{IBFM-2}) = 1.0 - 1.2$$

Decay of $^{113}\text{Cd} - g_A^{\text{eff}}$ using spectral moments

SMM = Spectral Moments Method

$$\mu_n = \int_{w_{\text{thr}}}^{w_0} S(w_e) w_e^n dw_e,$$

$n = 0 \leftrightarrow$ area under the spectral curve $\leftrightarrow T_{1/2}$

$n = 1 \leftrightarrow$ mean energy

$n = 2 \leftrightarrow$ variance

Usually only first few moments μ are enough!

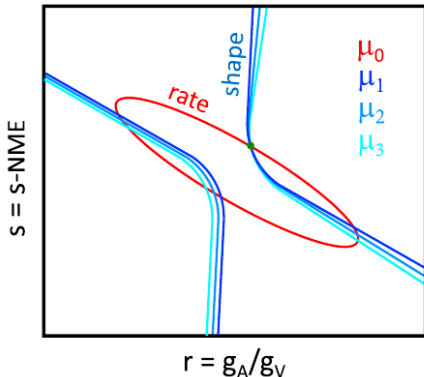
Result from

J. Kostensalo, E. Lisi, A. Marrone and J.

S., ^{113}Cd β -decay spectrum and g_A

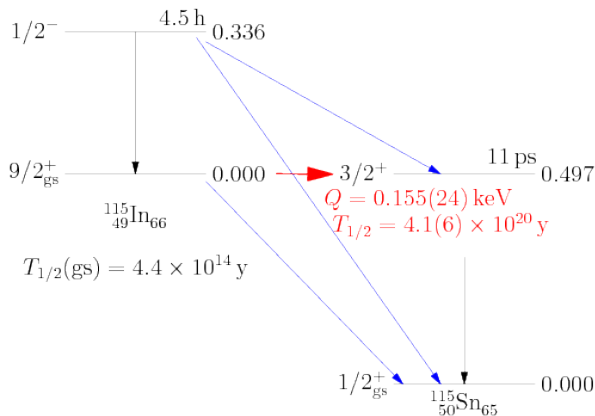
quenching using spectral moments,

Phys. Rev. C 107 (2023) 055502.



$$\begin{aligned}\bar{g}_A(\text{ISM}) &= 0.96 - 0.99 \\ \bar{g}_A(\text{IBFM-2}) &= 1.03 - 1.13 \\ \bar{g}_A(\text{MQPM}) &= 1.02 - 1.07\end{aligned}$$

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



Interesting ultra-low Q -value transition: The **2nd-forbidden unique** transition

$^{115}\text{In}(9/2^+) \rightarrow ^{115}\text{Sn}(3/2^+)$ has the **smallest known Q value of a nuclear transition**: J. S. E.

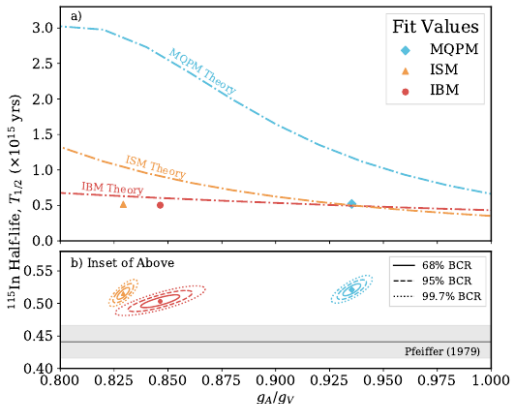
Wieslander *et al.*, Phys. Rev. Lett. 103 (2009) 122501; B. J. Mount *et al.*, Phys. Rev. Lett. 103 (2009) 122502.

Decay of ^{115}In – Comparison with data

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

Result from

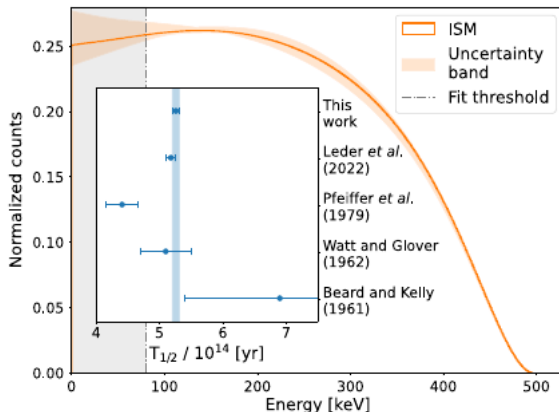
The CEA-CNRS-CSNSM-
INR-JYFL-MIT-LUKE-UCB
collaboration: A. F. Leder *et al.*, Phys. Rev. Lett. 129 (2022)
232502.



SSM:

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

Experimental vs computed spectrum for ^{115}In : The ACCESS experiment

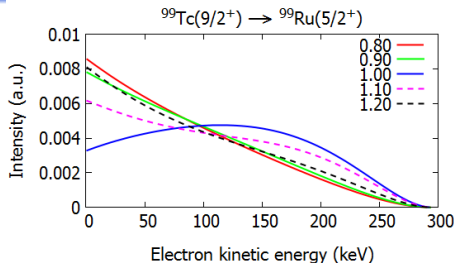


ACCESS article (L. Pagnanini *et al.*): Phys. Rev. Lett. 133 (2024) 122501: $g_A^{\text{eff}} = 0.964 - 1.172$ with NSM, MQPM and IBFM-2 by using the **ESSM**

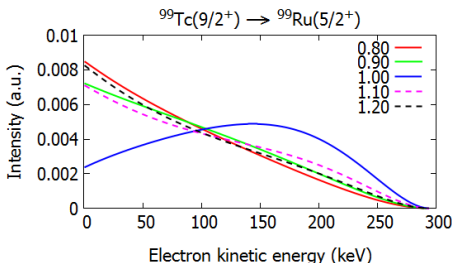
Example: ISM- and MQPM-computed electron spectra for ^{99}Tc

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

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

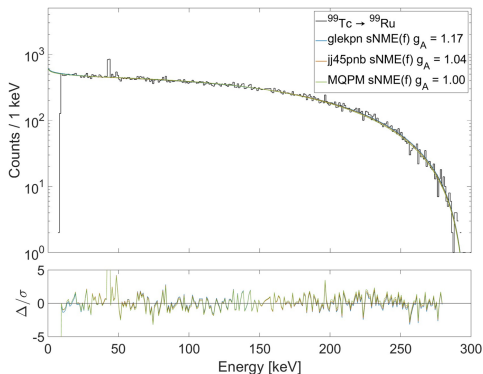


(ISM)



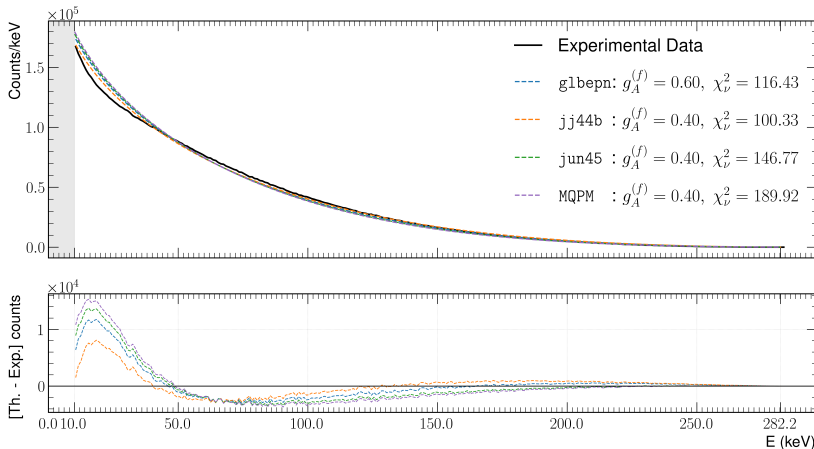
(MQPM)

Experimental vs computed spectrum for $^{99}\text{Tc}(9/2^+) \rightarrow ^{99}\text{Ru}(5/2^+)$



Conflicting results of gA-EXPERT and Paulsen *et al.* (Phys. Rev. C 110 (2024) 055503): For $g_V = 1$ Paulsen *et al.* get $g_A^{\text{eff}} = 1.526(92)$ and gA-EXPERT gets with NSM and MQPM $g_A^{\text{eff}} = 1.0 - 1.2$ using the ESSM. !

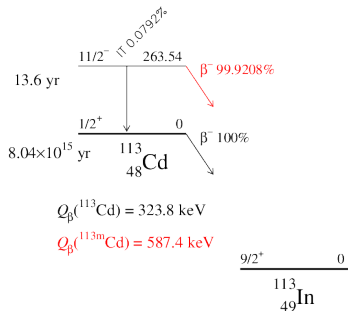
3rd-forbidden β transition $^{87}\text{Rb}(3/2^-) \rightarrow ^{87}\text{Sr}(9/2^+)$



Article (P. Belli *et al.*): Eur. Phys. J. A (2026) 62:16: $g_A^{\text{eff}} = 0.4 - 0.6$ with NSM and MQPM using the ESSM

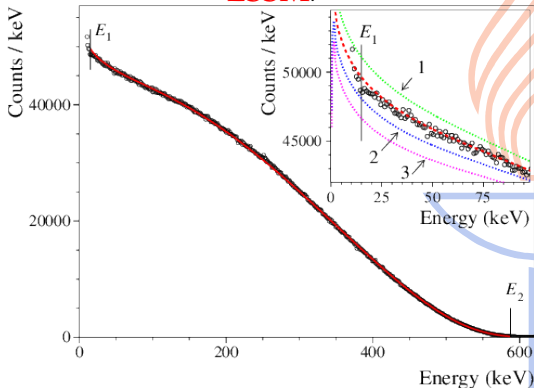
1^{st} -forbidden β decay of an **isomer** !

Decay scheme for 1^{st} -forbidden
nonunique β^- decay of ^{113m}Cd



From: P. Belli *et al.*, submitted

NSM-computed vs. **measured** β spectrum using the
ESSM:

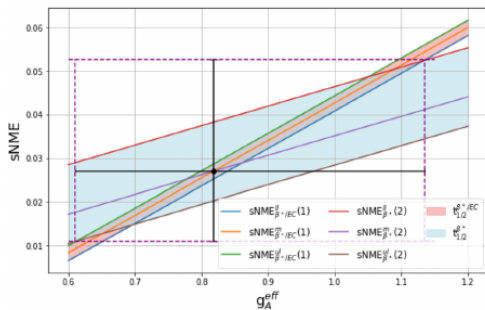


The NSM interaction $jj45pnb$ yields the result

$$g_A^{\text{eff}} = 0.59^{+0.05}_{-0.06}$$

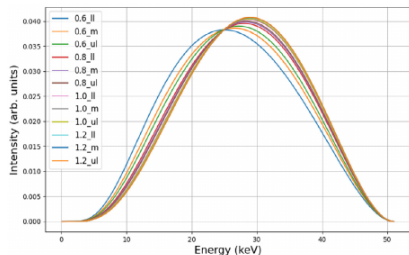
2nd-FNU β^+/EC transition $^{59}\text{Ni}(3/2^-) \rightarrow ^{59}\text{Co}(7/2^-)$

The Total β^+/EC and partial β^+ half-lives determine the values of g_A^{eff} and s-NME



Also a β^+ positron spectrum can be g_A^{eff} dependent:

(a) KB3GPN spectra for $(g_A^{\text{eff}}, s\text{NME}_{\beta^+/\text{EC}}^{\beta^+}(2))$



FROM: A. Agnihotri and J.S., Novel way of evaluating g_A quenching in β^+/EC decays: Introducing the Branching-Ratio Method (BRM), Phys. Lett. B 868 (2025) 139627.

More spectral shapes: Total β spectra for rare-events experiments

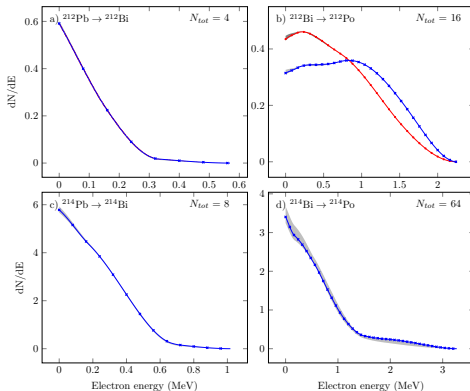
Investigating

$^{220,222}\text{Rn}$ radioactive chains:

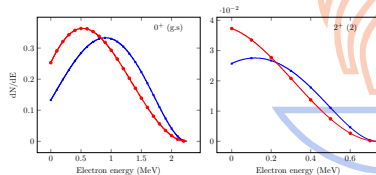
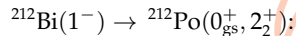


Total β spectra computed using the NSM

Total β spectra for the decays of $^{212,214}\text{Pb}$ and $^{212,214}\text{Bi}$



Strong dependence on sNME for the transitions



FROM: M. Ramalho and J.S., Computed total β -electron spectra for decays of Pb and Bi in the $^{220,222}\text{Rn}$ radioactive chains, Phys. Rev. C 109 (2024) 014326

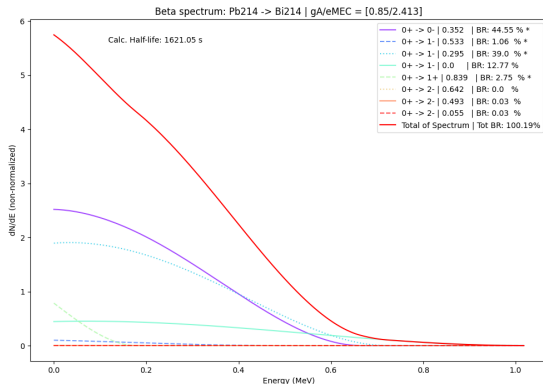
Future measurements by GAIAS?

Spectral shapes as background: Disassembling the total β spectrum of ^{214}Pb

^{85}Kr , ^{212}Pb and ^{214}Pb are backgrounds in dark-matter experiments like XENON1T, XENONnT, PandaX, etc. (see S. J. Haselschwardt et al., Phys. Rev. C 102 (2020) 065501).

Beta decay of ^{214}Pb includes several first-forbidden non-unique transitions from 0^+ to 0^- and 1^- states within the decay Q window.

Total spectrum from M. Ramalho *et al.*, in collaboration with the PandaX dark-matter experiment



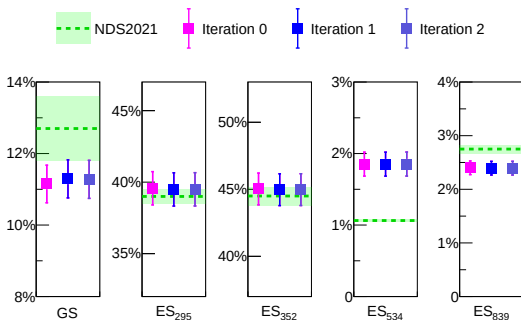
^{214}Pb : The most notorious background in future rare-events experiments

Need better knowledge about the
branching ratios of the ^{214}Pb decay:

a. branching ratio values

NDS 2021	NDS 2009	DDEP	
2.75 (8)	2.75	2.762	$^{214}\text{Pb}_{82}$ β^- (%)
1.063 (18)	1.04	1.047	839 keV
44.5 (7)	45.9	46.52	534 keV
39.0 (5)	40.2	41.09	352 keV
12.7 (9)	11.0	9.2	295 keV
			0 keV
			$^{214}\text{Bi}_{83}$

Do an iterative fitting of the experimental spectra
by the NSM:



FROM: PandaX Collaboration: Zhe Yuan *et al.* + M. Ramalho and J.S.,
Tomographic beta-gamma spectroscopy of nuclear beta decay, Submitted.

Still more spectral shapes: β spectra of fission yields

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

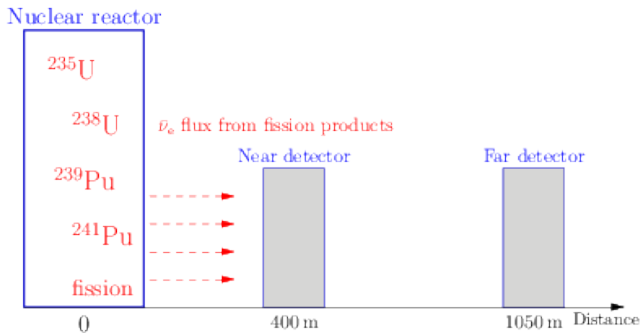
STERILE NEUTRINO

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).



¹RENO: 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

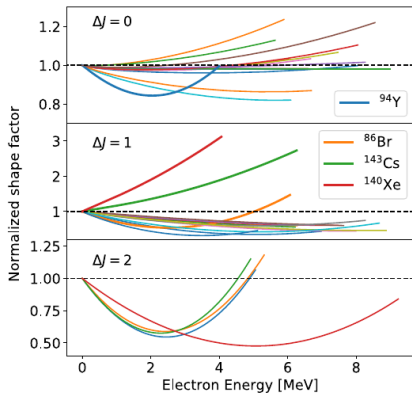
$\Rightarrow$?
 $\Rightarrow$ Oscillations to STERILE NEUTRINOS

The bump anomaly:

There is an unexpected **bump at 4 – 6 MeV (spectral shoulder)** in the measured $\bar{\nu}_e$ spectrum.

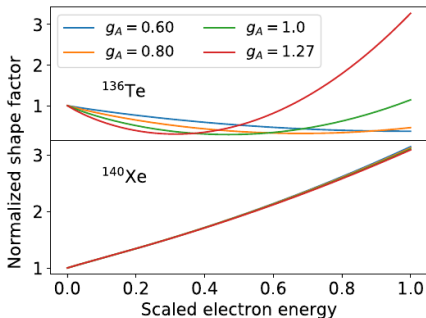
$\Rightarrow$???

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

Results from the analyses including the β spectra

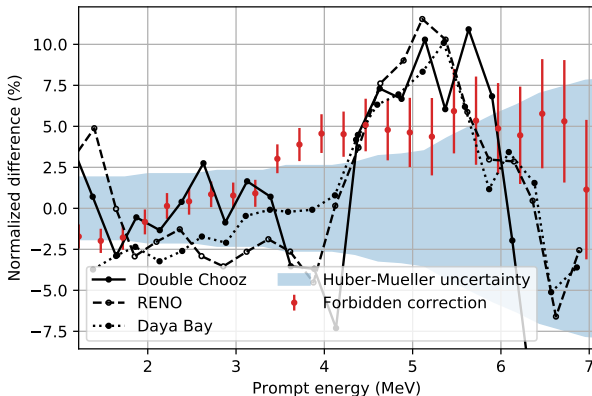
Taking into account the
(first-forbidden) decays of

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

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

HKSS flux model:

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

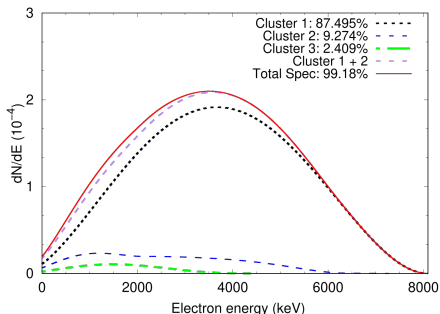


The spectral shoulder appears due to forbidden
spectral corrections !

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

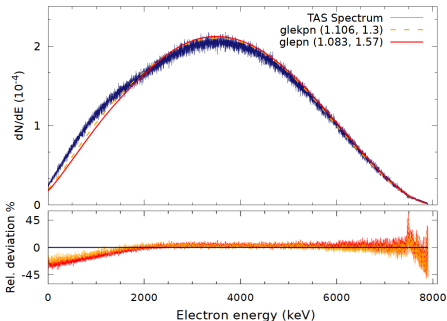
Pioneering calculation of a total β -electron spectrum of a high- Q reactor fission product: The β^- decay of ^{92}Rb with a Q value of 8.095 MeV

Computed cumulative electron spectrum



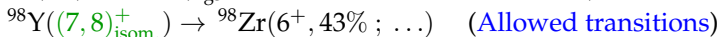
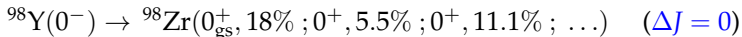
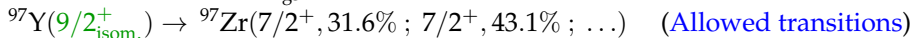
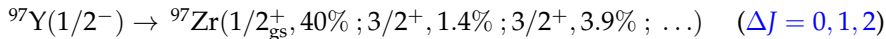
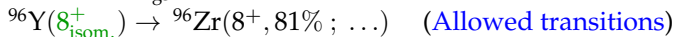
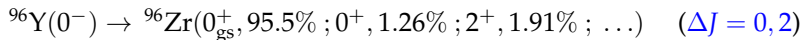
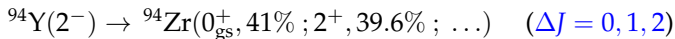
Cluster 1: gs-to-gs transition (based on TAS-measured branching), **Cluster 2:** known 1st-forbidden transitions (based on TAS-measured branchings), **Cluster 3:** unresolved higher-energy 1st-forbidden and allowed transitions

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. Algorta *et al.*) branchings assuming all transitions to be allowed.

The yttrium contribution to reactor $\bar{\nu}_e$ s and determination of ε_{MEC}



Total yield **19.3%!**

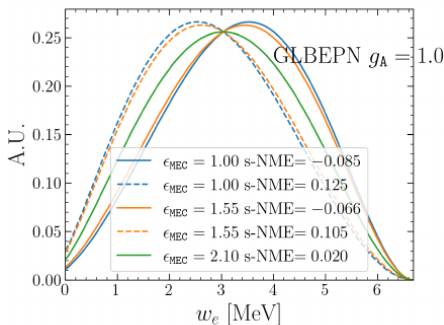
Results:

Interaction	$g_{\text{A}}^{\text{eff}}$	$g_{\text{A}}^{\text{eff}}(\gamma_5)$
GWBXG	0.706 ± 0.011	2.430 ± 0.050
GLEPN	1.039 ± 0.020	2.253 ± 0.052
GLBEPN	1.219 ± 0.030	2.392 ± 0.069

Yttrium isotopes: Spectral shapes and antineutrino spectra

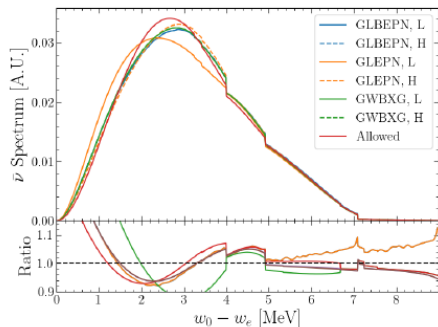
From: A. Agnihotri *et al.*, in preparation:

FIG. 2: (g_A^{eff} , ϵ_{mec} , s-NME) dependent spectra for $^{97}\text{Y}(1/2_1^-) \rightarrow ^{97}\text{Zr}(1/2_1^+)$ using GLBEPN. The free parameters are fitted to the BR of the transition.

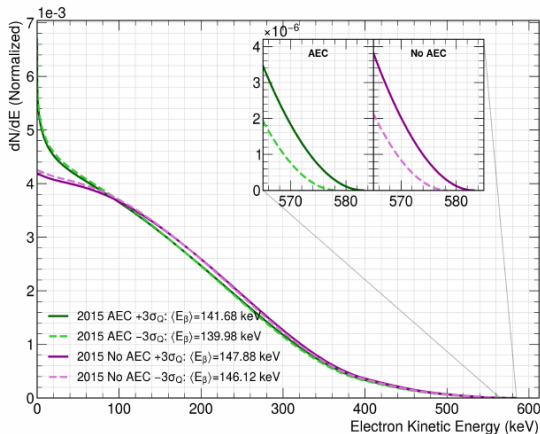


Shift of neutrino flux from low-energy to
4 – 5 MeV

FIG. 3: The total $\bar{\nu}_e$ spectra of β decays considered in this Letter for GWBXG, GLEPN, and GLBEPN interactions. The transitions have been weighted by their respective BRs and the rel. CFY of ^{235}U . Total $\bar{\nu}_e$ spectra are compared with their allowed version. The bottom panel shows the ratio between the spectra and their allowed version. Spectra labeled "L" ("H") are obtained by always choosing the low (high) s-NME solution when fitting the half-life.



Gamow-Teller β decays in precision oncology



Approved proposal to JYFLTRAP: Precise **Q-value** measurements of the radioisotopes ^{47}Sc , ^{67}Cu (in the figure) and ^{161}Tb for **precision oncology** (radiation of tumors and cancers).

Note the effects of the **Q-value** and **AEC = Atomic Exchange Correction** for **allowed** β decays.

Precision oncology with allowed transitions

$$^{32}\text{P}(1^+) \rightarrow ^{32}\text{S}(0_{\text{gs}}^+, 100\%), T_{1/2} = 14.28 \text{ d}, Q = 1.7104 \text{ MeV}$$

$$^{47}\text{Sc}(7/2^-) \rightarrow ^{47}\text{Ti}(5/2_{\text{gs}}^-, 31.5\% ; 7/2^-, 68.5\%), \\ T_{1/2} = 3.42 \text{ d}, Q = 0.6005 \text{ MeV}$$

$$^{67}\text{Cu}(3/2^-) \rightarrow ^{67}\text{Zn}(5/2_{\text{gs}}^-, 20\% ; 1/2^-, 23\% ; 3/2^-, 56\% ; 3/2^-, 1\%), \\ T_{1/2} = 61.9 \text{ h}, Q = 0.575 \text{ MeV}$$

$$^{131}\text{I}(7/2^+) \rightarrow ^{131}\text{Xe}(5/2^+, 89\% ; 7/2^+, 7.6\% ; 5/2^+, 2.17\%), \\ T_{1/2} = 8.040 \text{ d}, Q = 0.9708 \text{ MeV}$$

$$^{153}\text{Sm}(3/2^+) \rightarrow ^{153}\text{Eu}(5/2_{\text{gs}}^+, 21\% ; 3/2^+, 44\% ; 5/2^+, 34\%), \\ T_{1/2} = 46.8 \text{ h}, Q = 0.8052 \text{ MeV}$$

Precision oncology with first-forbidden transitions

$$^{38}\text{Cl}(2^-) \rightarrow ^{38}\text{Ar}(0_{\text{gs}}^+, 58\% ; 2^+, 11\% ; 3^-, 31\%),$$
$$T_{1/2} = 37.3 \text{ min}, Q = 4.9170 \text{ MeV} \quad (\Delta J = 0, 1, 2)$$

$$^{88}\text{Rb}(2^-) \rightarrow ^{88}\text{Sr}(0_{\text{gs}}^+, 77\% ; 2^+, 4.3\%, ; 3^-, 14\%, ; 2^+, 1.0\%, ; 2^-, 2.2\%)$$
$$T_{1/2} = 17.8 \text{ min}, Q = 5.309 \text{ MeV} \quad (\Delta J = 0, 1, 2)$$

$$^{89}\text{Sr}(5/2^+) \rightarrow ^{89}\text{Y}(1/2_{\text{gs}}^-, 100\%),$$
$$T_{1/2} = 50.5 \text{ d}, Q = 1.4921 \text{ MeV} \quad (\Delta J = 2)$$

$$^{90}\text{Y}(2^-) \rightarrow ^{90}\text{Zr}(0_{\text{gs}}^+, 100\%),$$
$$T_{1/2} = 64.1 \text{ h}, Q = 2.2839 \text{ MeV} \quad (\Delta J = 2)$$

$$^{161}\text{Tb}(3/2^+) \rightarrow ^{161}\text{Dy}(5/2_{\text{gs}}^+, 10\% ; 3/2^-, 66\%, ; 5/2^-, 23\%)$$
$$T_{1/2} = 6.90 \text{ d}, Q = 0.590 \text{ MeV} \quad (\Delta J = 0, 1, 2)$$

First-forbidden transitions (continued)

$$^{166}\text{Ho}(0^-) \rightarrow ^{166}\text{Er}(0_{\text{gs}}^+, 51\% ; 2^+, 48\%),$$
$$T_{1/2} = 26.80 \text{ min}, Q = 1.8543 \text{ MeV} \quad (\Delta J = 0, 2)$$

$$^{177}\text{Lu}(7/2^+) \rightarrow ^{177}\text{Hf}(7/2^-, 78\% ; 9/2^-, 9.7\%, ; 9/2^+, 12\%)$$
$$T_{1/2} = 6.71 \text{ d}, Q = 0.4971 \text{ MeV} \quad (\Delta J = 0, 1, 2)$$

$$^{186}\text{Re}(1^-) \rightarrow ^{186}\text{Os}(0_{\text{gs}}^+, 71\% ; 2^+, 21\%, ; \text{EC} : 7.9\%)$$
$$T_{1/2} = 90.6 \text{ h}, Q = 1.0766 \text{ MeV} \quad (\Delta J = 1, 2)$$

$$^{188}\text{Re}(1^-) \rightarrow ^{188}\text{Os}(0_{\text{gs}}^+, 70\% ; 2^+, 27\%, ; 2^+, 1.7\%)$$
$$T_{1/2} = 16.9 \text{ h}, Q = 2.1197 \text{ MeV} \quad (\Delta J = 1, 2)$$

$$^{199}\text{Au}(3/2^+) \rightarrow ^{199}\text{Hg}(1/2_{\text{gs}}^-, 6\% ; 5/2^-, 72\%, ; 3/2^-, 22\%)$$
$$T_{1/2} = 3.14 \text{ d}, Q = 0.4530 \text{ MeV} \quad (\Delta J = 0, 1, 2)$$

The (hopefully happy) end

THANKS FOR PATIENCE!