Rare nuclear single beta decays

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Contents:

- Introduction
- How to use studies on single beta decay – 2 applications

Few remarks:

Most of the beta decay transitions observed in nature are of allowed type, or in few cases transitions of low level of forbiddenness

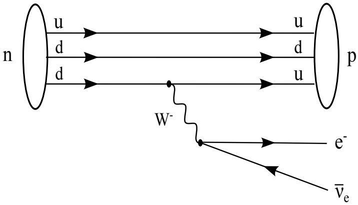
Rare beta decays:

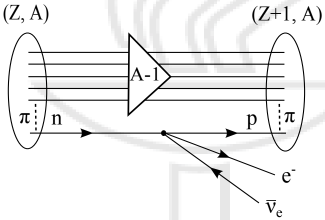
- Beta decay (β^- or β^+/EC) transitions suppressed by low Q value and/or high level of forbiddenness
- I.e. transitions with long half-lives

Introduction (1/2)

General description of beta decays – the decay process

Nuclear beta decay – *weak interaction* process inside the nucleus



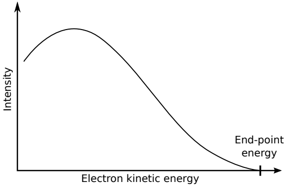


Massive $W^{\pm}$ boson ($\sim$ 80 GeV/ c^2) vs. small decay energy ($\sim$ 1 MeV)

$\rightarrow$ a point-like interaction vertex (effective decay strength G_F)

$$\mathfrak{M} = 4 \underbrace{\left[\frac{1}{2}\bar{u}_p\gamma_\mu(1-(\tfrac{g_A}{g_V})\gamma_5)u_n\right]}_{\text{Hadronic current (renorm.)}} \frac{G_F}{\sqrt{2}} \underbrace{\left[\frac{1}{2}\bar{u}_e\gamma^\mu(1-\gamma^5)u_{\bar{\nu}_e}\right]}_{\text{Leptonic current}}$$

Beta spectrum



Beta spectrum ($m_\nu = 0$)

$$P(W_e)\mathrm{dW_e} = \frac{\mathrm{G_F^2}}{(\hbar \mathrm{c})^6}\frac{1}{2\pi^3\hbar}\mathrm{C(W_e)} \times p_e c W_e (W_0 - W_e)^2 F_0(Z, W_e) dW_e$$

Characteristics of the decay are contained in the shape factor $C(W_e)$:

- Allowed decays ($L = 0$) $\leftrightarrow$ $C(W_e) =$ constant
- Forbidden decays ($L \neq 0$) $\leftrightarrow$ $C(W_e) =$ complicated (*)

(*) The expression for $C(W_e)$ depends on the level of forbiddenness and on the approximations made. The number of NMEs for non-unique decays:

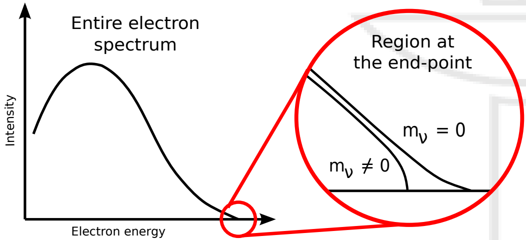
Forbiddenness	1st order	1st + 2nd order
1	6	18
2	8	27
3	10	36
4	12	45

Application #1: Determination of neutrino mass

The shape of the beta spectrum at the end-point

Current candidates are ^{3}H (18.594(8) keV), ^{187}Re (2.469(4) keV):

- direct and *model-indenpendent* approach
- relativistic energy-momentum relation, energy conservation



Which nuclei/transitions are the most suitable?

- Q-value: as low as possible (relative magnitude of the effect is larger)
- Allowed/Forb.: Allowed, but 1st (2nd, ...) forb. could be manageable

Application #1: Determination of neutrino mass

Interesting candidates for neutrino measurements

M. Mustonen:

initial state	final state	E^* in keV	decay type	Q in keV
$^{77}\mathrm{As}(3/2^-)$	$^{77}\mathrm{Se}(5/2^+)$	680.1046(16)	1^{st} non-unique β^-	2.8 ± 1.8
$^{111}\mathrm{In}(9/2^+)$	$^{111}\mathrm{Cd}(3/2^+)$	864.8(3)	2^{nd} unique EC	-2.8 ± 5.0
	$^{111}\mathrm{Cd}(3/2^+)$	866.60(6)	2^{nd} unique EC	-4.6 ± 5.0
$^{131}\mathrm{I}(7/2^+)$	$^{131}\mathrm{Xe}(9/2^+)$	971.22(13)	allowed β^-	-0.4 ± 0.7
$^{146}\mathrm{Pm}(3^-)$	$^{146}\mathrm{Nd}(2^+)$	1470.59(6)	1^{st} non-unique EC	1.4 ± 4.0
$^{149}\mathrm{Gd}(7/2^-)$	$^{149}\mathrm{Eu}(5/2^+)$	1312(4)	1^{st} non-unique EC	1 ± 6
$^{155}\mathrm{Eu}(5/2^+)$	$^{155}\mathrm{Gd}(9/2^-)$	251.7056(10)	1^{st} unique β^-	1.0 ± 1.2
$^{159}\mathrm{Dy}(3/2^-)$	$^{159}\mathrm{Tb}(5/2^-)$	363.5449(14)	allowed EC	2.1 ± 1.2
$^{161}\mathrm{Ho}(7/2^-)$	$^{161}\mathrm{Dy}(7/2^-)$	857.502(7)	allowed EC	1.4 ± 2.7
	$^{161}\mathrm{Dy}(3/2^-)$	858.7919(18)	2^{nd} non-unique EC	0.1 ± 2.7

Accurate Q value measurements are essential!

NEW idea: The role of axial-vector coupling $g_{\rm A}$

Motivation:

- The value $g_A = 1.26$ extracted from PCVC hypothesis is strictly speaking for bare nucleons only
- $\beta\beta$ decay rate $\lambda \propto (g_{\rm A})^4$

NMEs come in a combinations of $g_{\rm V}\ {}^V\mathcal{M}_{KLS}^{(N)}$ or $g_{\rm A}\ {}^A\mathcal{M}_{KLS}^{(N)}$:

$\rightarrow$ $C(w_e)$ depends also on $g_{\rm A}$:

- Unique decays $(\Delta J = K+1)$ $\leftrightarrow$ $C(g_{\rm A}) \propto g_{\rm A}^2$ (1st order)
- Non-unique decays $(\Delta J = K)$ $\leftrightarrow$ $C(g_{\rm A})$ = complicated (*)

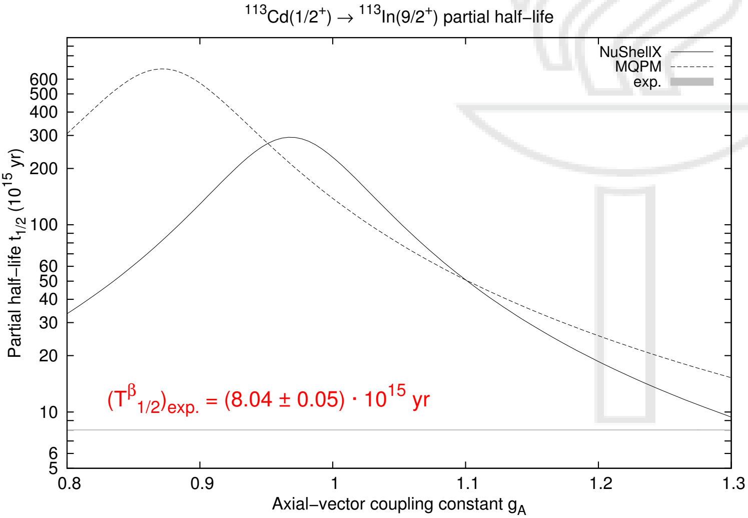
(*) The number of NMEs with $g_{\rm A}$:

Forbiddenness	1st order	1st + 2nd order
1	3	7
2	4	10
3	5	13
4	6	16

Application #2: A probe for the value of g_A (?)

Partial half-life vs. g_A: ^{113}Cd $(1/2^+_{gs}) \rightarrow$ ^{113}In $(9/2^+_{gs})$

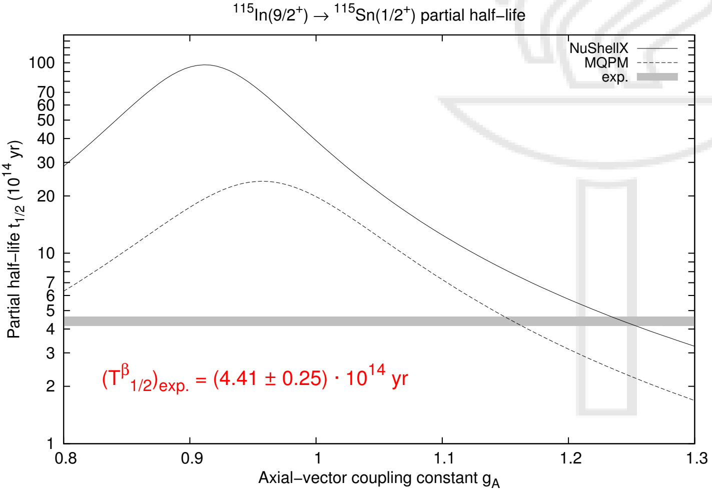
4th forbidden non-unique, $Q = (322 \pm 1)$ keV



Application #2: A probe for the value of g_A (?)

Partial half-life vs. g_A: ^{115}In $(9/2^+_{gs}) \rightarrow$ ^{115}Sn $(1/2^+_{gs})$

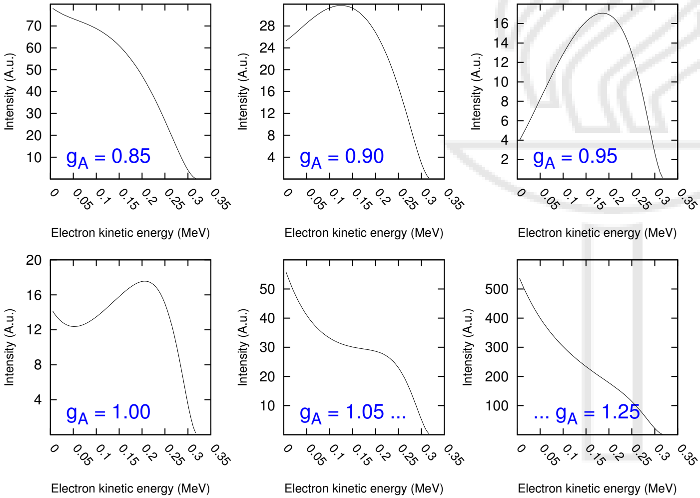
4th forbidden non-unique, $Q = (497.489 \pm 0.010)$ keV



How about the shape of the beta spectrum itself?

Application #2: A probe for the value of g_A (?)

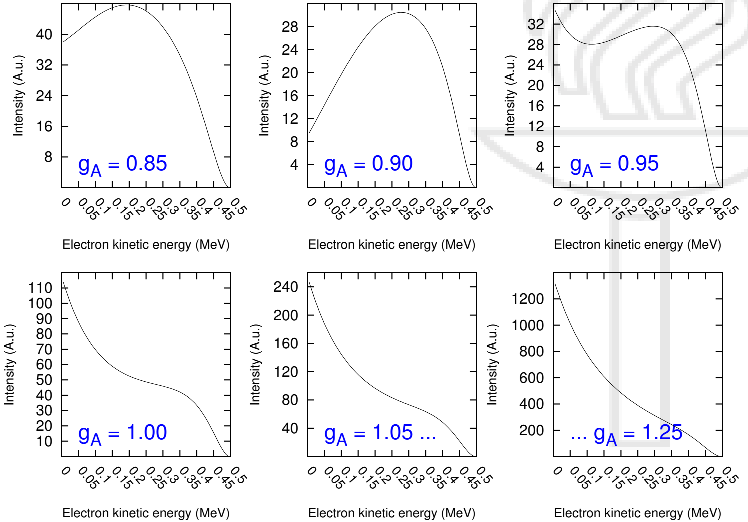
Beta spectrum shape vs. g_A: ^{113}Cd $(1/2^+_{gs})$ $\rightarrow$ ^{113}In $(9/2^+_{gs})$



Strong dependence on g_A!

Application #2: A probe for the value of g_A (?)

Beta spectrum shape vs. g_A: ^{115}In $(9/2^+_{gs})$ $\rightarrow$ ^{115}Sn $(1/2^+_{gs})$

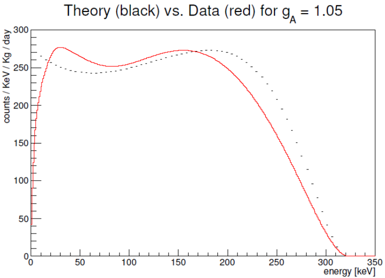


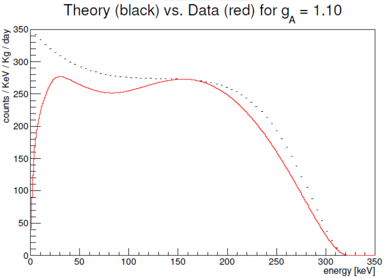
Application #2: A probe for the value of g_A (?)

Theory vs. Experiment: ^{113}Cd $(1/2^+_{gs})$ $\rightarrow$ ^{113}In $(9/2^+_{gs})$

Can we extract the value of g_A?

- Comparison with experiment $\rightarrow$ In principle, the answer is YES
- Preliminary results in collaboration with K. Zuber (work in progress)





Will something usable come out?

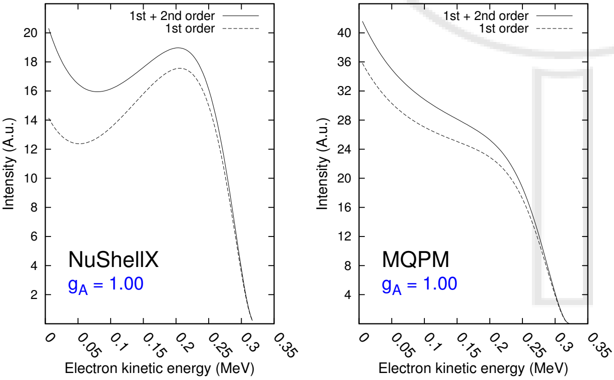
The values extracted from $t_{1/2}$ and from the spectrum seem to be in contradiction. Why?

Application #2: A probe for the value of g_A (?)

Interesting finding: The strong dependence on g_A

M. Haaranen, J. Suhonen, P. Srivastava (to be published):

- single β decays of ^{113}Cd ^{115}In, (^{135}Cs, ^{137}Cs)
- Dependence on the nuclear model (NuShellX, MQPM)
- 2nd order terms seem to be important – Now implemented!



Summary

2 applications for studies on single beta decay

Determination of the neutrino mass

- The end-point behaviour of the beta spectrum
- Accurate Q values essential

A probe for the value of g_A

- Partial half-lives & The shape of the beta spectrum
- At this point more studies needs be carried out

Thank you!