A View to Double Beta Decays of Atomic Nuclei

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Topic I

Low Q Values for Neutrino Mass Measurements

Neutrino Mass Measurements with low Q values

The KArlsruhe TRItium Neutrino experiment = KATRIN

$Q_{\beta^-} = 18.6\,\text{keV}$, Allowed $^{3}\text{H}(1/2^+) \rightarrow {}^{3}\text{He}(1/2^+)\ \beta^-$ decay

$\Downarrow$

The Microcalorimetric Array for a Rhenium Experiment = MARE

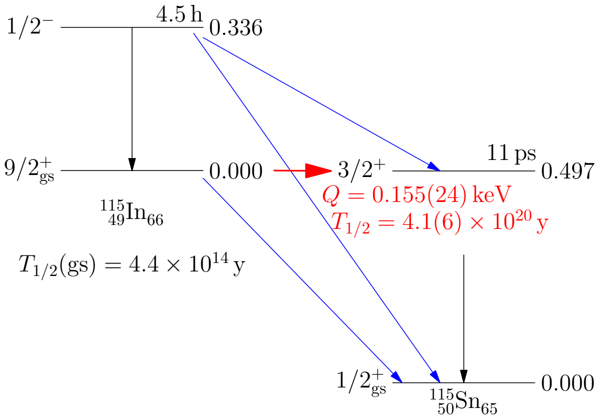
$Q_{\beta^-} = 2.469(4)\,\text{keV}$, First-forbidden unique $^{187}\text{Re}(5/2^+) \rightarrow {}^{187}\text{Os}(1/2^-)\ \beta^-$ decay

$\Downarrow$

?

^{115}In: Beta decay with an ultra-low Q value

First discovered by Cattadori et al. (Nucl. Phys. A 748 (2005) 333)



Suggested as a possible independent experiment to look for the neutrino mass

Experimental results

LNGS (C.M. Cattadori et al.)	first observation
	$b = 1.18(31) \times 10^{-6}$
	$T_{1/2}^{\text{partial}} = 3.73(98) \times 10^{20}$ a
HADES (J.S.E. Wieslander et al.)	$b = 1.07(17) \times 10^{-6}$
	$T_{1/2}^{\text{partial}} = 4.1(6) \times 10^{20}$ a
JYFLTRAP (T. Eronen et *al*.)	$Q_{\beta^-} = 0.35(17)$ keV
Florida StU (B. J. Mount et *al*.)	$Q_{\beta^-} = 0.155(24)$ keV

Lowest Q value recorded so far!
Previous record: ^{187}Re $Q_{\beta^-} = 2.469(4)$ keV [1] (first-forbidden unique transition, used in the MARE neutrino-mass experiment)

[1] M.S. Basunia, Nucl. Data Sheets 110 (2009) 999.

Theory

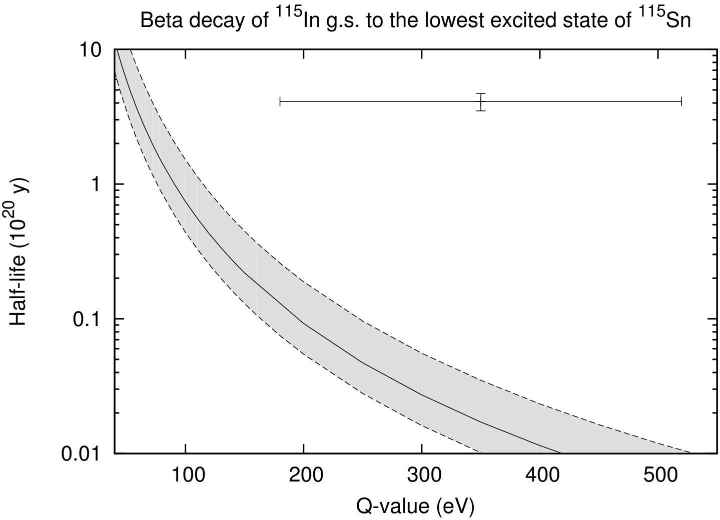
- 2nd-forbidden unique $^{115}\mathrm{In}(9/2^+) \to {}^{115}\mathrm{Sn}(3/2^+)$ decay
- dependent on only one nuclear matrix element (NME) M

$$T_{1/2} = \frac{1}{M^2 f_K(w_0, Z_f, R)}$$

- wave functions from the proton-neutron microscopic quasiparticle-phonon model (pnMQPM)
- pnMQPM was previously successfully applied to the 4th-forbidden non-unique $^{115}\mathrm{In}(9/2^+) \to {}^{115}\mathrm{Sn}(1/2^+)$ g.s.-to-g.s. decay ($\log ft$, half-life, electron spectrum) [2]

[2] M.T. Mustonen and J. Suhonen, Phys. Lett. B 657 (2007) 38.

Experiments meet theory



Possible sources of the discrepancy

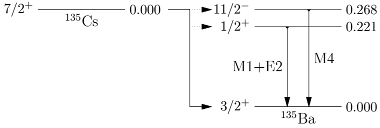
Nuclear wave functions?

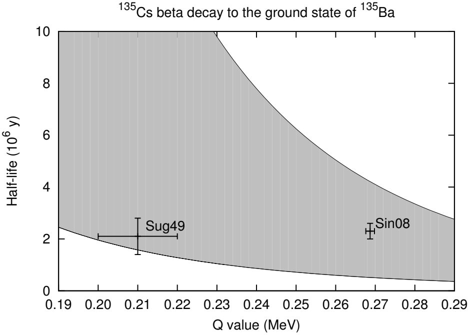
- MQPM and pnMQPM take also into account the 3-qp degrees of freedom
  $\Rightarrow$ Relevant states still dominantly 1-qp states
- To explain the discrepancy, the NME should be wrong by an order of magnitude!
- Maybe the problem lies in the *lepton* wave functions...

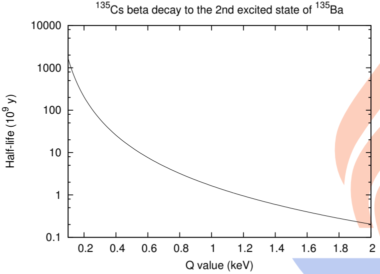
Atomic effects for ultra-low Q values

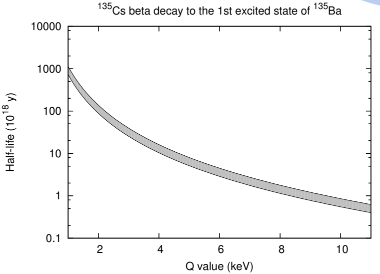
- electron screening (not estimated for forbidden decays)
- atomic overlap (previous approximations break down)
- exchange effects (contradictory results for low Q values)
- final-state interactions (estimates only for tritium beta decay)

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









Important to revisit the *Q*-value measurement !

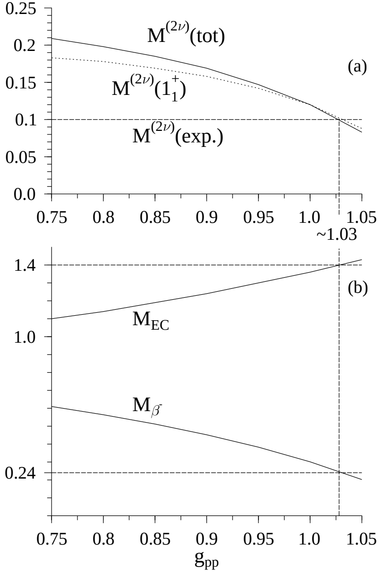
Other interesting cases

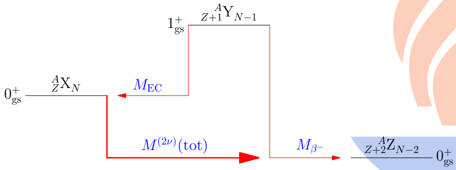
initial state	final state	E^* in keV	decay type	Q in keV
^{77}As$(3/2^-)$	^{77}Se$(5/2^+)$	680.1046(16)	1st non-unique β^-	2.8 ± 1.8
^{111}In$(9/2^+)$	^{111}Cd$(3/2^+)$	864.8(3)	2nd unique EC	-2.8 ± 5.0
	^{111}Cd$(3/2^+)$	866.60(6)	2nd unique EC	-4.6 ± 5.0
^{131}I$(7/2^+)$	^{131}Xe$(9/2^+)$	971.22(13)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

Topic II

The g_A Problem of the pnQRPA revisited

Behavior of the β and $\beta\beta$ NMEs





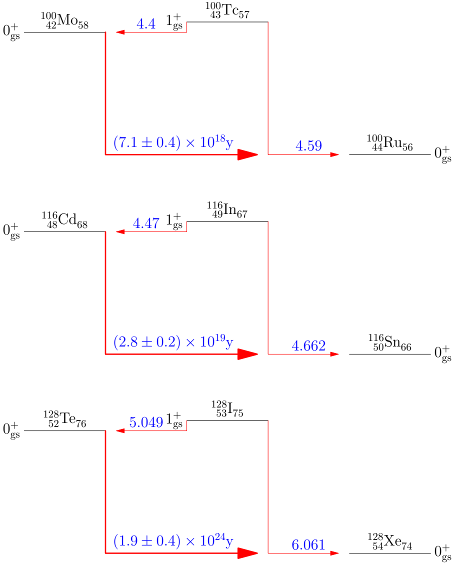
Here one cannot reproduce both the β^- and EC properties by one single g_{pp} value with fixed value of g_A

Proposal: $g_A \to g_A^{\text{eff}}$

Let the value of g_A vary freely

Work together with Osvaldo Civitarese
Phys. Lett. B 725 (2013)153-157

Beta and double beta decays of A=100,116,128 nuclei

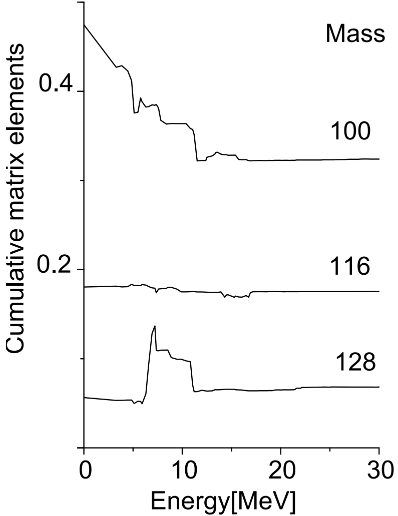


For each case $(A = 100, 116, 128)$ try to find a pair of values

$$(g_{pp}, g_A^{\rm eff})$$

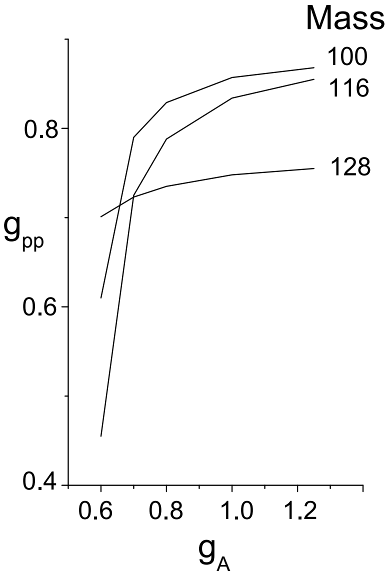
so that the $\log ft$ of the beta decays and the half-life of the $2\nu\beta\beta$ are all reproduced.

Cumulative sums of the two-neutrino $\beta\beta$ NMEs



The three studied cases display qualitatively different trends of the cumulative $\beta\beta$ NME

Dependence of g_{pp} on g_A in a pnQRPA calculation



Choose value of g_A

$\Downarrow$

$T_{1/2}^{\mathrm{exp}}(2\nu\beta\beta)$

$\Downarrow$

$M_{\beta\beta}^{\mathrm{exp}}$

$\Downarrow$

$M_{\beta\beta}^{\mathrm{th}} = M_{\beta\beta}^{\mathrm{exp}}$

$\Downarrow$

g_{pp}

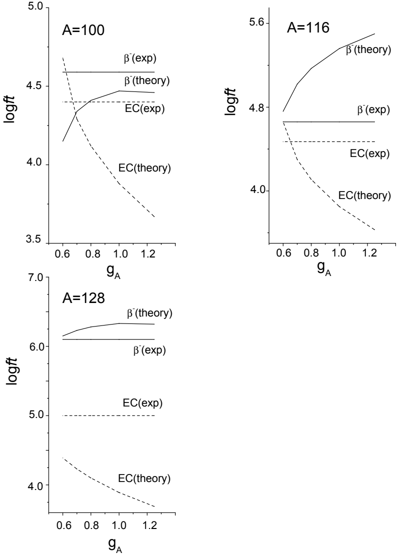
Next procedure

With the obtained pair (g_{pp},g_A^{eff}) see what you get for the log *ft* of the beta decays.

$\Downarrow$

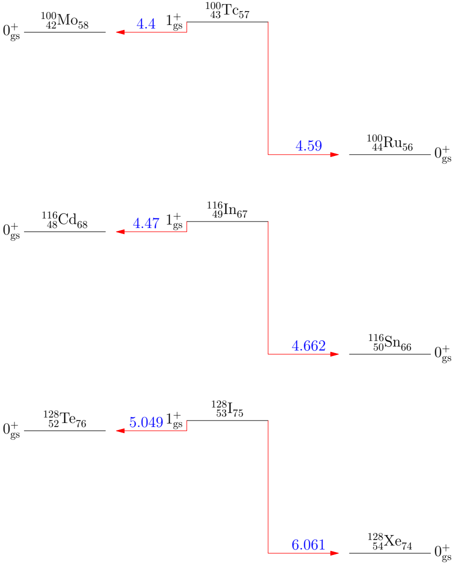
QUESTION: Can the log *ft* values be reproduced for any pair (g_{pp},g_A^{eff})?

Behavior of the computed log *ft* values



ANSWER:
not QUITE!

Next step: try to reproduce only the beta decays



For each case ($A = 100, 116, 128$) try to find a pair of values

$$(g_{pp}, g_A^{eff})$$

so that the $\log ft$ of the beta decays are reproduced.

QUESTION: Can this be done?

Answer:

ANSWER: YES IT CAN!!! $\Rightarrow g_{\mathrm{A}}^{\mathrm{eff}}(\beta)$

$$\Downarrow g_{\mathrm{pp}}$$

$$M_{\beta\beta}^{\mathrm{th}}$$

$$\Downarrow$$

$$T_{1/2}^{\beta\beta}(\mathrm{th.}) = T_{1/2}^{\beta\beta}(\mathrm{exp.})$$

$$\Downarrow$$

$$g_{\mathrm{A}}^{\mathrm{eff}}(\beta\beta)$$

We then end up with...

			$g_A(\beta\beta)$			
A	g_{pp}	$g_A(\beta)$	Present	pnQRPA [1]	ISM [2]	IBA-2 [2]
100	0.815	0.59	0.75	0.74	0.73	0.55
116	0.515	0.71	0.61	0.84	0.72	0.54
128	0.530	0.33	0.40	-	0.71	0.53

[1] A. Faessler *et al.*, JPG 35 (2008) 075104
[2] J. Barea, J. Kotila and F. Iachello, PRC 87 (2013) 014315

This is important for the $0\nu\beta\beta$ decay !!!

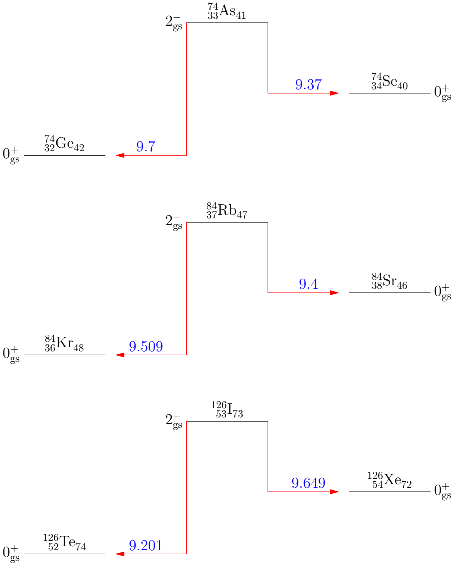
Alternative approach to g_A^{eff}

g_A^{eff} from first-forbidden unique beta decays

Work together with Hiro Ejiri and Nael Soukouti

This is again important for the $0\nu\beta\beta$ decay !!!

First-forbidden unique beta decays (examples)



Now the computed $\log ft$ values are practically independent of g_{pp}

⇓

Extract g_A^{eff} by reproducing the $\log ft$ values of the beta decays.

QUESTION: Anything sensible coming out?

ANSWER: work in progress, stay tuned

Conclusions and Outlook

Conclusions:

- ^{115}In decays by an ultra-low Q value $\longrightarrow$ ATOMIC effects important
- There are many potential candidates for ultra-low Q value neutrino-mass measurements
- Studies of β and $\beta\beta$ decays for the $A = 100, 116, 128$ nuclei point to quenched effective g_A
- Studies of effective g_A for first-forbidden unique β decays is in progress

Outlook:

- Much work needed to chart the magnitudes of the atomic effects in beta decays with ultra-low Q values
- The effective value of g_A for the contributing multipole channels of the $0\nu\beta\beta$ decay remains an important challenge