Suppression of the pnQRPA NMEs for Highly-Forbidden Unique Beta Transitions

Jouni Suhonen

Department of Physics, University of Jyväskylä

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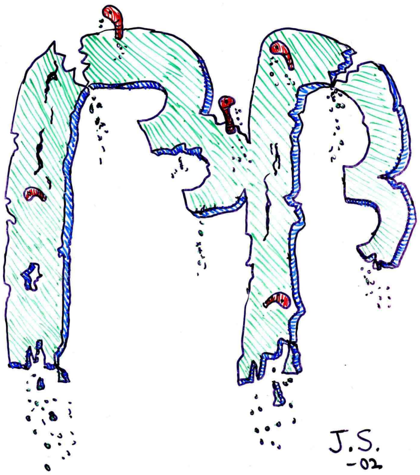
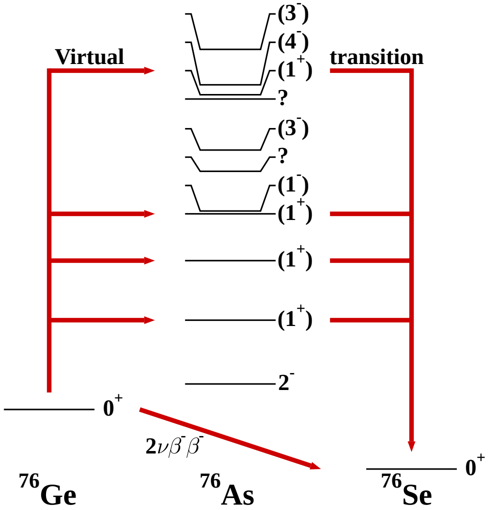
Contents:

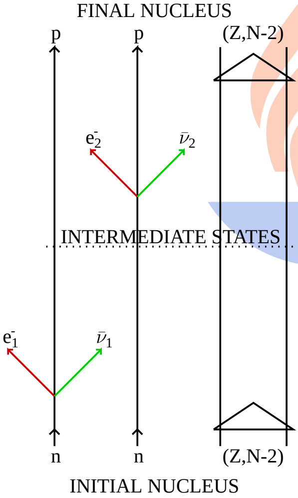
- Incentive: $0\nu\beta\beta$ Decays
- Earlier studies: GT and SD Decays
- Unique Spin-Multipole Decays
- Examples

Motivation for the Work: Double Beta Decay

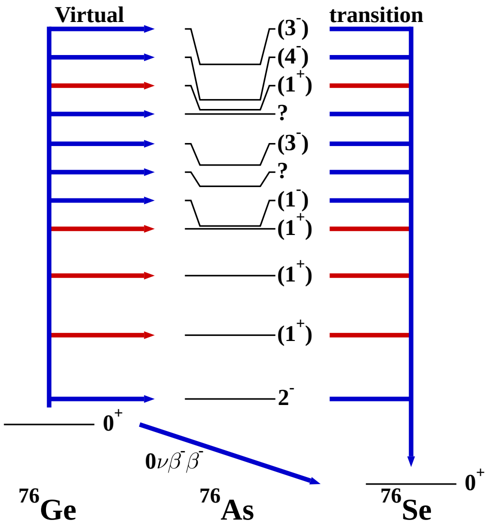


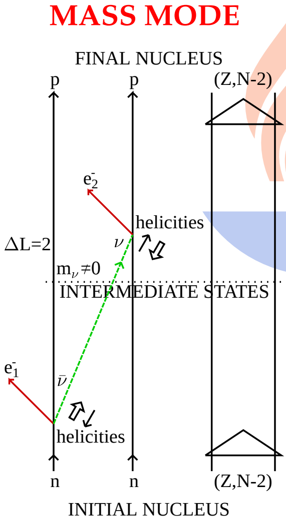
Two-Neutrino Double Beta Decay of ^{76}Ge





Neutrinoless Double Beta Decay of ^{76}Ge





The **POWER** of Neutrinoless $\beta\beta$ Decay

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

- Reveal if the neutrino is a Majorana particle
- Probe the absolute mass scale of the neutrino
- Probe the mass hierarchies and CP phases

Problem: **NUCLEAR MATRIX ELEMENTS!**

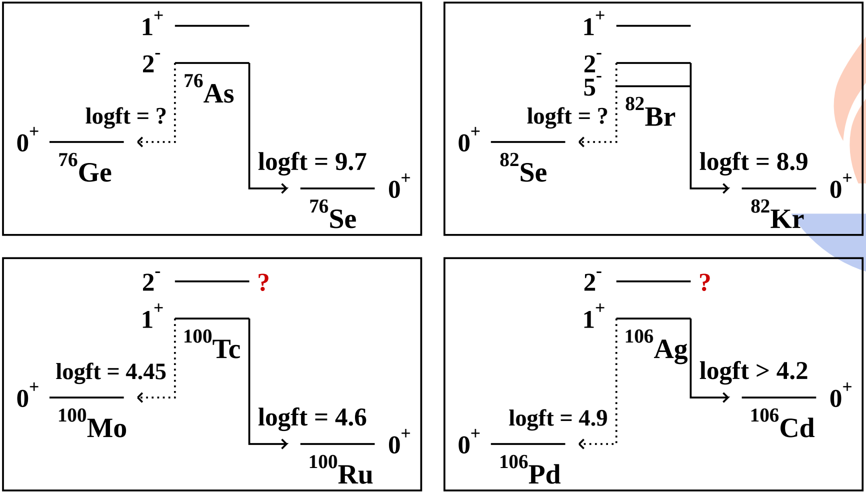
Question:

HOW CAN WE PROBE THE VIRTUAL TRANSITIONS?

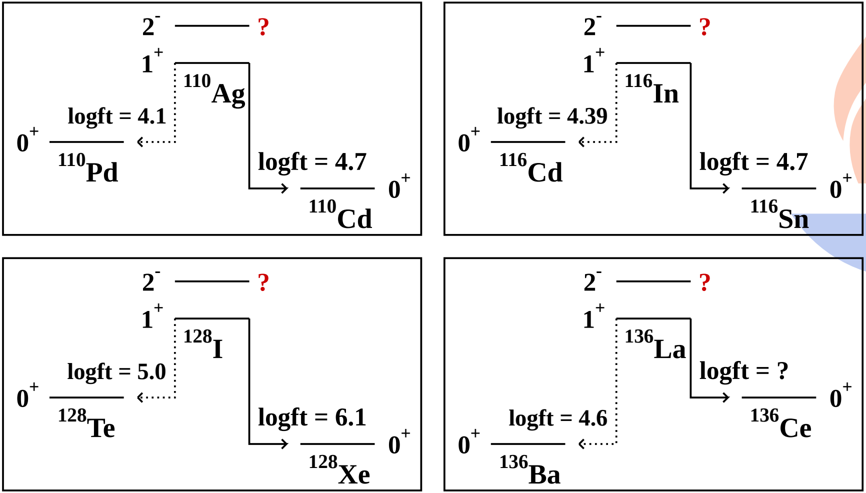
Answer:

BY e.g. BETA-DECAY DATA

Available Data on Beta Decays I



Available Data on Beta Decays II



Spin-Multipole (SM) Nuclear Matrix Elements

General half-life formula for the allowed and unique-forbidden beta decays

$$t_{1/2}^{K}(0_{\rm gs}^{+} \leftrightarrow J^{\pi}) = \frac{\rm Constant}{\frac{g_{\rm A}^{2}}{2J_i+1}\left(M^{K}(\mathrm{SM}J^{\pi})\right)^{2} f_K} ,$$

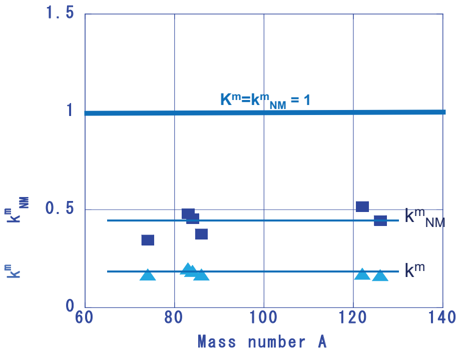
where

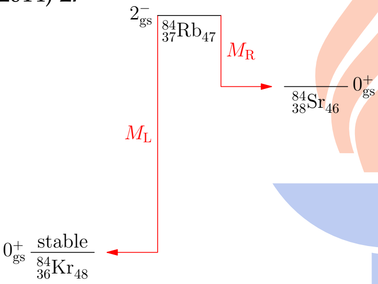
- f_K is the phase-space factor for the K^{th} forbidden (allowed $\equiv 0^{th}$ forbidden) β-decay transition,
- $g_{\rm A}$ is the axial-vector coupling constant,
- $J_i = J$ or $J_i = 0$ ($J = K + 1$) is the angular momentum of the decaying state, and
- $M^{K}(\mathrm{SM}J^{\pi})$ is the spin-multipole NME for the K^{th} forbidden transition.

The unique decays are classified as:

K	0 (allowed)	1	2	3	4	5	6	7
J^{π}	1^{+}	2^{-}	3^{+}	4^{-}	5^{+}	6^{-}	7^{+}	8^{-}

H. Ejiri, N. Soukouti and J. Suhonen, Spin-dipole nuclear matrix elements for double beta decays and astro-neutrinos, Phys. Lett. B 729 (2014) 27





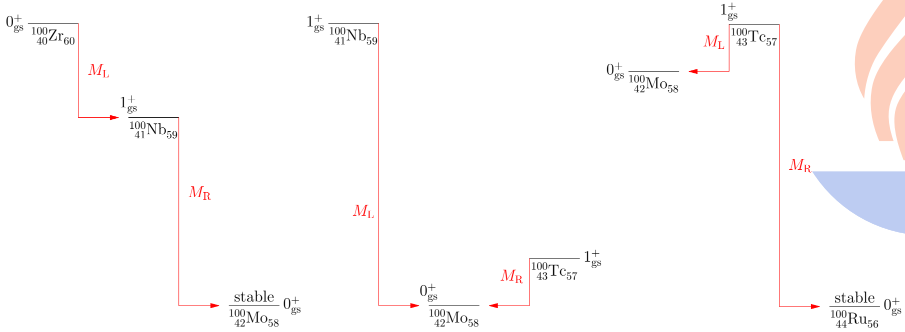
$$M(\mathrm{SD2}^-) = \sqrt{M_L M_R}$$

$$k = \frac{M_{\mathrm{exp}}(\mathrm{SD2}^-)}{M_{\mathrm{qp}}(\mathrm{SD2}^-)} \approx 0.18$$

$$k_{\mathrm{NM}} = \frac{M_{\mathrm{exp}}(\mathrm{SD2}^-)}{M_{\mathrm{pnQRPA}}(\mathrm{SD2}^-)} \approx 0.45$$

Global Study for the Allowed GT $1^+_{gs} \leftrightarrow 0^+_{gs}$ Decays

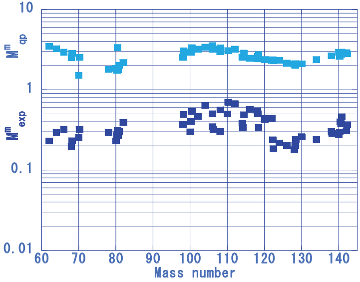
H. Ejiri and J. Suhonen, GT neutrino-nuclear responses for double beta decays and astro-neutrinos, J. Phys. G: Nucl. Part. Phys. 42 (2015) 055201

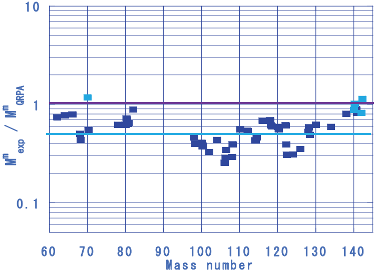


$$M(\mathrm{GT}1^+) = \sqrt{M_L M_R} \quad ; \quad k = \frac{M_{\rm exp}(\mathrm{GT}1^+)}{M_{\rm qp}(\mathrm{GT}1^+)} \quad ; \quad k_{\rm NM} = \frac{M_{\rm exp}(\mathrm{GT}1^+)}{M_{\rm pnQRPA}(\mathrm{GT}1^+)}$$

$M_{\rm qp}(\mathrm{SM}J^\pi) = P_{uv} M_{\rm sp}(\mathrm{SM}J^\pi)$, P_{uv} is the BCS occupation factor and $M_{\rm sp}$ the single-particle matrix element of the spin-miltipole (SM) operator.

Allowed GT $1^+_{gs} \leftrightarrow 0^+_{gs}$ Decays Continue . . .





A	$p-n$ conf.	$\bar{M}^{m}_{exp}$	M_{qp}	$\bar{M}^{m}_{pnQRPA}$	$\bar{k}$	$\bar{k}_{NM}$
62 – 70	$1p_{3/2}-1p_{1/2}$	0.265	0.99	0.401	0.268	0.660
78 – 82	$0g_{9/2}-0g_{9/2}$	0.297	1.50	0.431	0.198	0.689
98 – 116	$0g_{9/2}-0g_{7/2}$	0.467	1.82	1.015	0.257	0.459
118 – 136	$1d_{5/2}-1d_{5/2}$	0.231	1.03	0.505	0.224	0.467
138 – 142	$1d_{5/2}-1d_{3/2}$	0.345	1.33	0.420	0.259	0.821

Decays Through Higher Spin-Multipole ($K \geq 2$) Operators

Question:

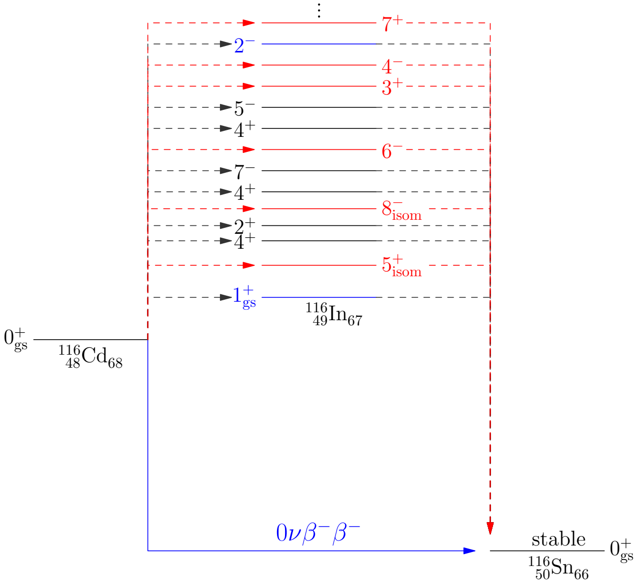
WHAT CAN WE LEARN

FROM THE UNIQUE HIGHER-FORBIDDEN

β DECAYS?

Answer:

A LOT!



7^+
2^-
4^-
3^+
5^-
4^+
6^-
7^-
4^+
$8^-_{\rm isom}$
2^+
4^+
$5^+_{\rm isom}$
$1^+_{\rm gs}$
$^{116}_{49}\mathrm{In}_{67}$
$0^+_{\rm gs}$
$^{116}_{48}\mathrm{Cd}_{68}$
$0\nu\beta^-\beta^-$
stable
$0^+_{\rm gs}$
$^{116}_{50}\mathrm{Sn}_{66}$

Decays Through Higher Spin-Multipole ($K \geq 2$) Operators

Task:

STUDY 148 UNIQUE HIGHER-FORBIDDEN

β DECAYS IN ISOTOPIC CHAINS

Problem:

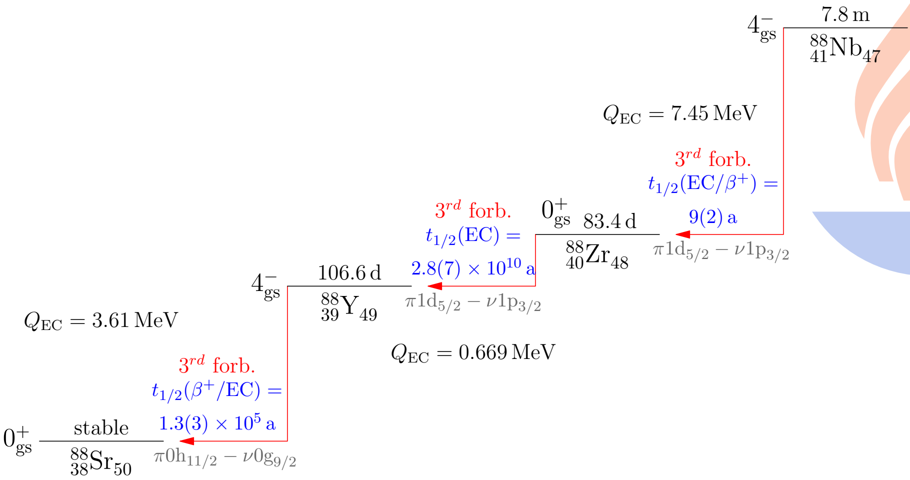
NO EXP. DATA AVAILABLE

Study:

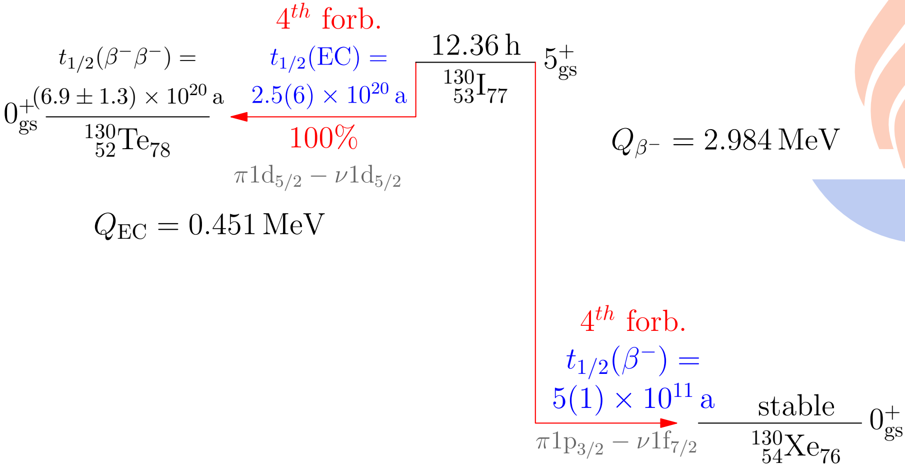
$$k = \frac{M^K_{\mathrm{pnQRPA}}(\mathrm{SM}J^\pi)}{M^K_{\mathrm{qp}}(\mathrm{SM}J^\pi)} = ?$$

Dependence on K and mass number A?

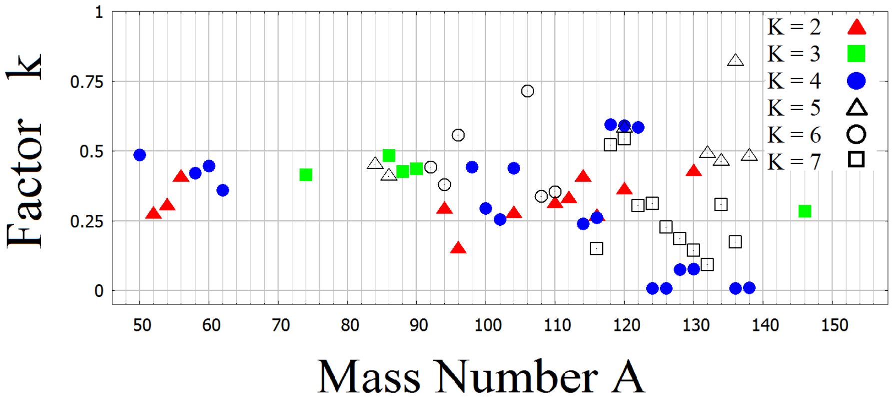
Example: Decays in the $A = 88$ Chain



Example: Decays in the $A = 130$ Chain (Including a $\beta\beta$ Decay)

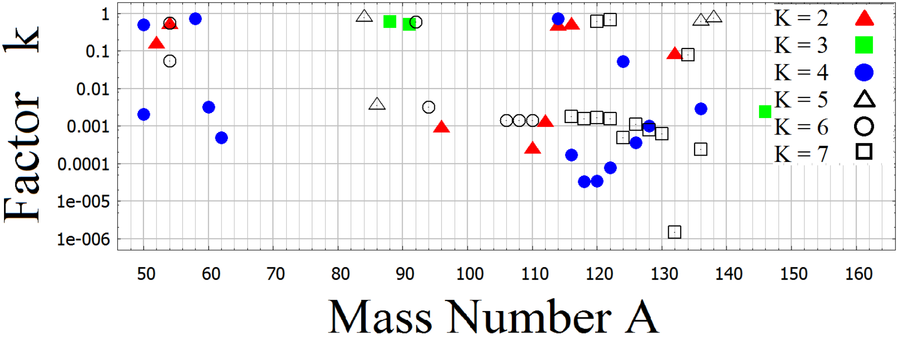


Ratio k for β Decays Involving Non-magic Nuclei



k extracted using the geometric mean of the full set of K^{th} ($K = 2 - 7$) forbidden β-decay transitions in an isobaric chain.

Ratio k for β Decays Involving (Semi-)Magic Nuclei



k extracted without using the geometric mean for the K^{th} ($K = 2 - 7$) forbidden β-decay transitions

Note the logarithmic scale!

Two Distinct Groups Appear

The transitions can be divided in two groups:

GROUP 1

with $k > 0.005$ and the mean

$$k = \frac{M^K_{\mathrm{pnQRPA}}(\mathrm{SM}J^\pi)}{M^K_{\mathrm{qp}}(\mathrm{SM}J^\pi)} = 0.38 \pm 0.20$$

All non-magic cases and part of the magic cases belong to this group.
GROUP 1 covers some 80% of all studied cases!

GROUP 2

with $k \leq 0.005$ and the mean

$$k = \frac{M^K_{\mathrm{pnQRPA}}(\mathrm{SM}J^\pi)}{M^K_{\mathrm{qp}}(\mathrm{SM}J^\pi)} = (1.3 \pm 1.0) \times 10^{-3}$$

Part of the magic cases belong to this group.

Results for the Ratio $k = M^K_{\rm pnQRPA}({\rm SM}J^\pi)/M^K_{\rm qp}({\rm SM}J^\pi)$

For $K \geq 2$ only the nuclei of GROUP 1 are considered

A	$K = 0^*$	$K = 1^{**}$	$K = 2$	$K = 3$	$K = 4$	$K = 5$	$K = 6$	$K = 7$	Avg.
$50 - 88$	0.35	0.40	0.33	0.48	0.49	0.55	0.31	-	0.42
$90 - 122$	0.52	0.40	0.33	0.48	0.43	0.58	0.48	0.46	0.46
$122 - 146$	0.40	0.40	0.25	0.28	0.10	0.61	-	0.27	0.33

* H. Ejiri, N. Soukouti, J.S., Phys. Lett. B 729 (2014) 27

** H. Ejiri, J.S., J. Phys. G: Nucl. Part. Phys. 42 (2015) 055201

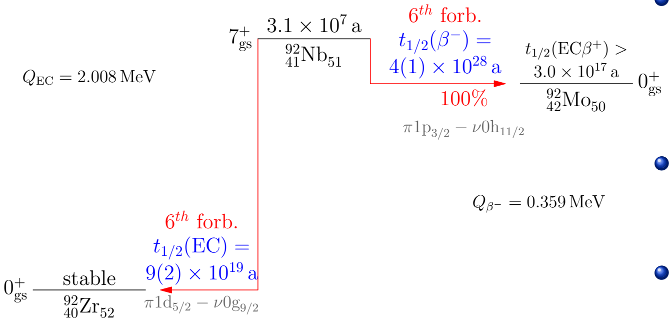
From ** we get:

A	$k_{\rm NM}$	ξ
$50 - 96$	0.67	2.2
$98 - 136$	0.46	4.7
$138 - 146$	0.82	1.5

Conjecture:

$\xi = (k_{\rm NM})^{-2} = t_{1/2}({\rm exp})/t_{1/2}({\rm pnQRPA}) \Rightarrow$ Correct the pnQRPA computed half-lives $\Rightarrow$ Expected half-lives

Error Estimates for the Expected Half-lives



- $\Delta M^K_{\mathrm{pnQRPA}}(\mathrm{SM}J^\pi) \Leftarrow$ Vary g_{ph} and g_{pp} by 10% from their default values (pure G matrix interaction) $g_{\mathrm{ph}} = g_{\mathrm{pp}} = 1.0$
- $\Delta f_K(Q_\beta)$ for the phase-space factor from the experimental error ΔQ of the Q value
- $\Delta k_{\mathrm{NM}} = 10\%$ (ad hoc)

Speculate by the $0\nu\beta\beta$ Decay

Conjecture:

$$M_{0\nu\beta\beta}^{J^\pi}(\text{true}) = k_{\rm NM}^2 M_{0\nu\beta\beta}^{J^\pi}(\text{pnQRPA})$$

From

J. Hyvärinen and J. S., Analysis of the Intermediate-State Contributions to Neutrinoless Double β^- Decays, AHEP 2016 (2016) 4714829

One obtains

J_1^π	Nucleus	% of $M_{0\nu\beta\beta}$	$k_{\rm NM}^2$	New % of $M_{0\nu\beta\beta}$
1_1^+	^{124}Sn	8.2	0.21	1.7
2_1^-	^{76}Ge	8.7	0.45	4.1
	^{82}Se	8.9	0.45	4.2
	^{96}Zr	11	0.45	5.2
3_1^+	^{100}Mo	2.1	0.21	0.4
	^{116}Cd	2.6	0.21	0.5
	^{128}Te	0.5	0.21	0.1

Examples of Decay Chains

EXAMPLES OF

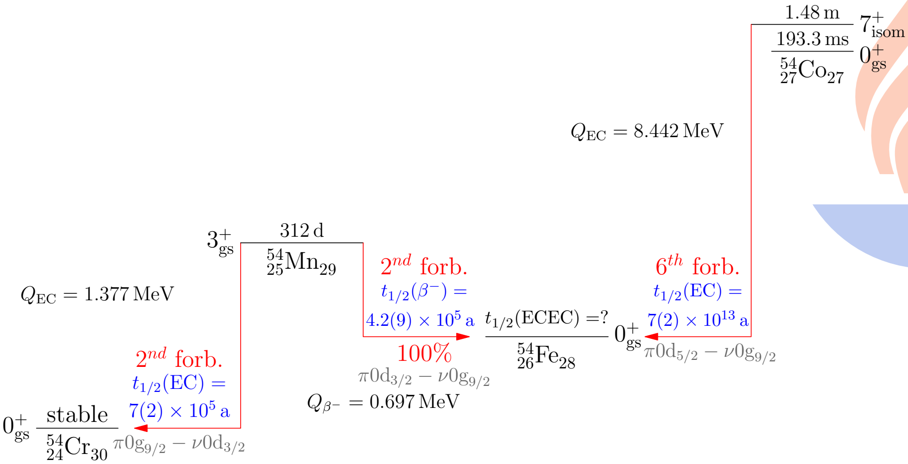
PREDICTED β-DECAY HALF-LIVES

IN VARIOUS ISOTOPIC CHAINS

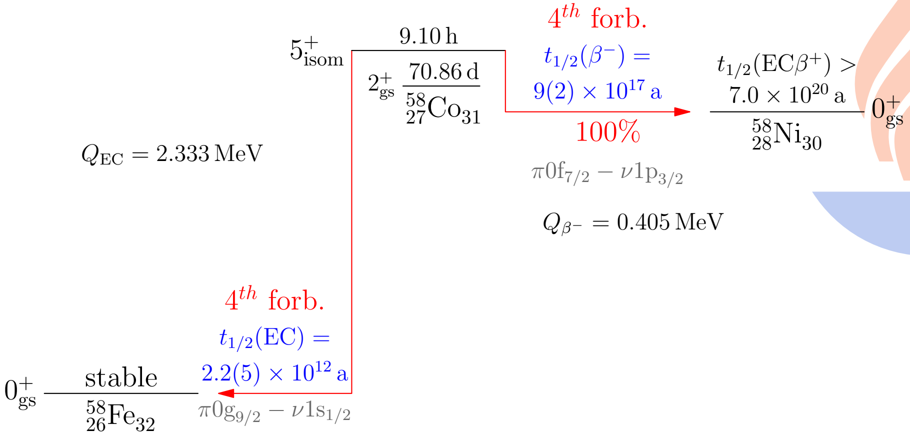
CONTAINING

DOUBLE-BETA-DECAYING NUCLEI

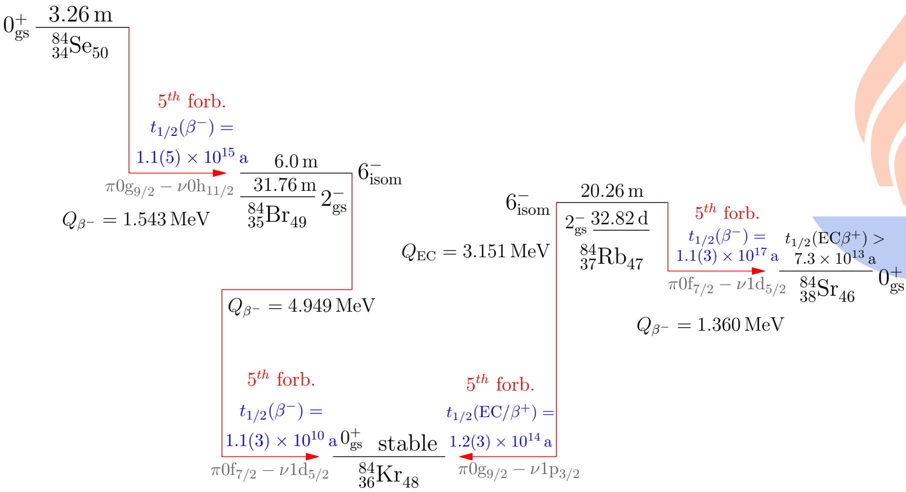
Decays in the $A = 54$ Chain



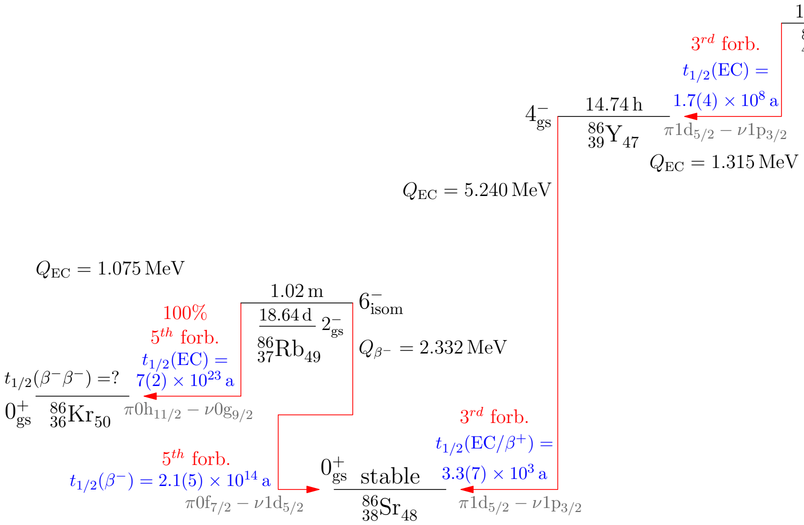
Decays in the $A = 58$ Chain



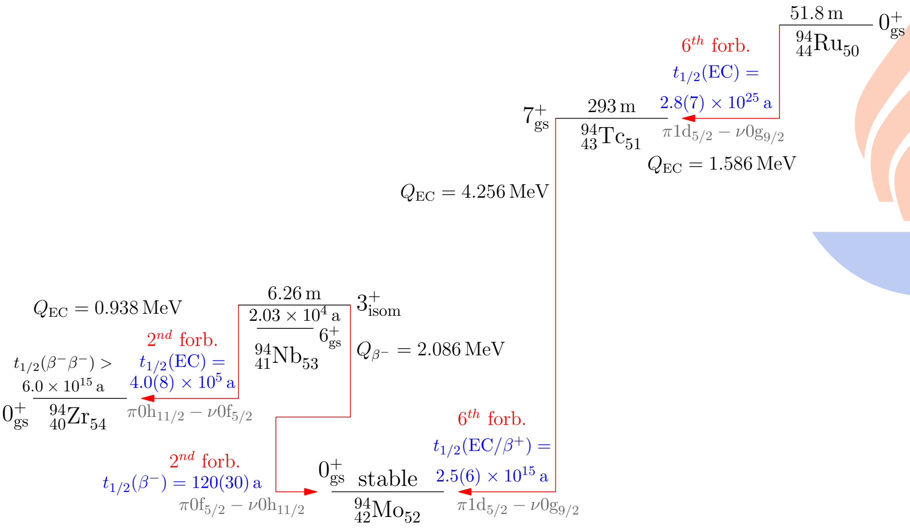
Decays in the $A = 84$ Chain



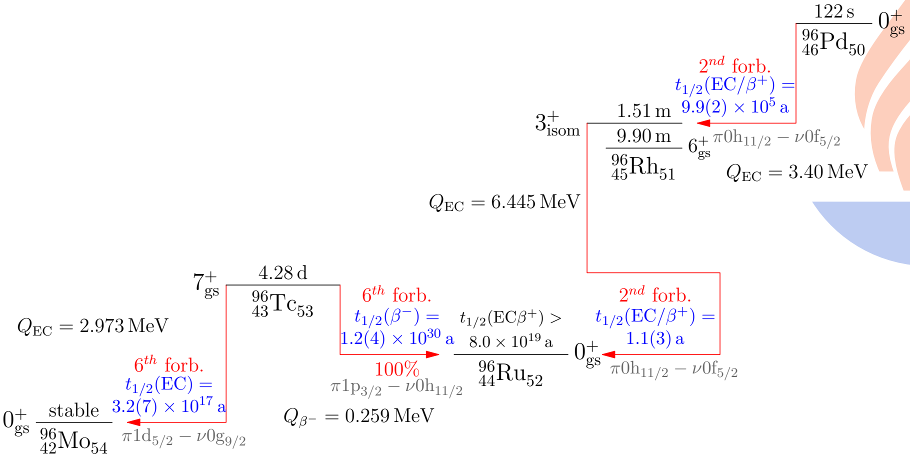
Decays in the $A = 86$ Chain



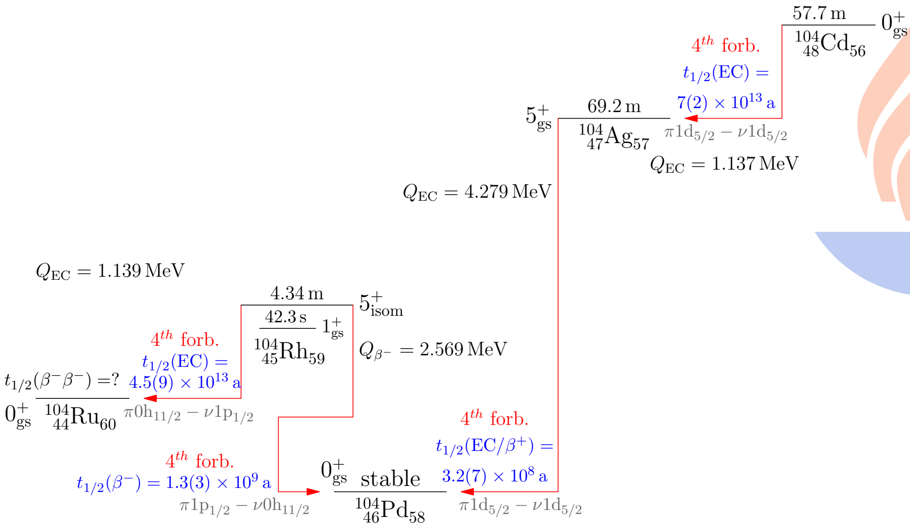
Decays in the $A = 92$ Chain



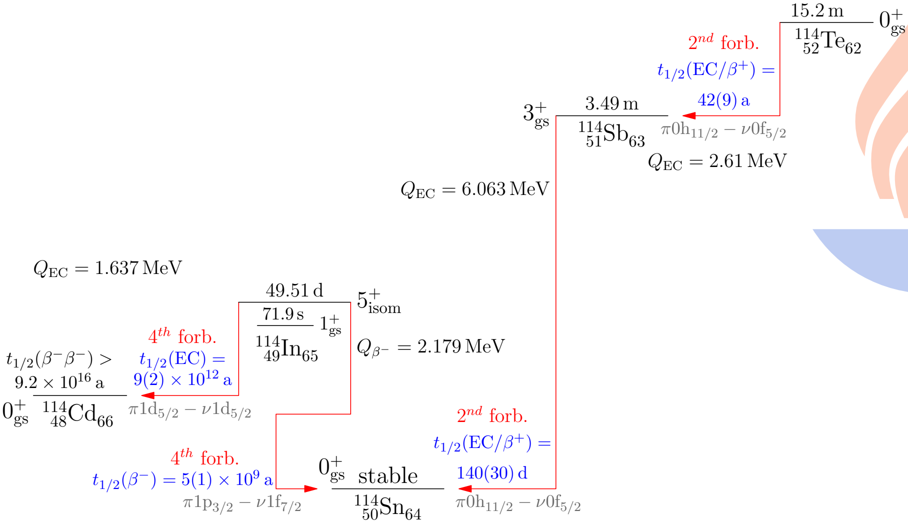
Decays in the $A = 96$ Chain



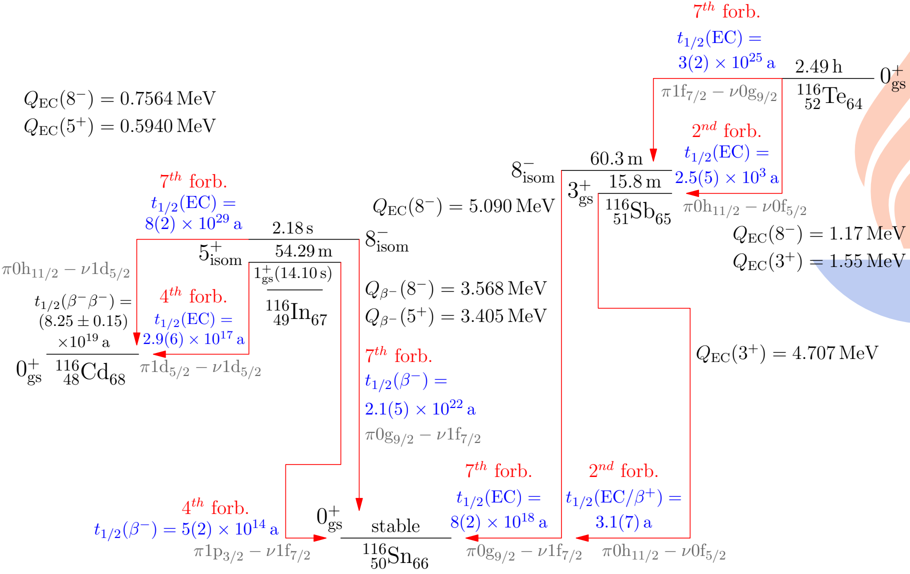
Decays in the $A = 104$ Chain



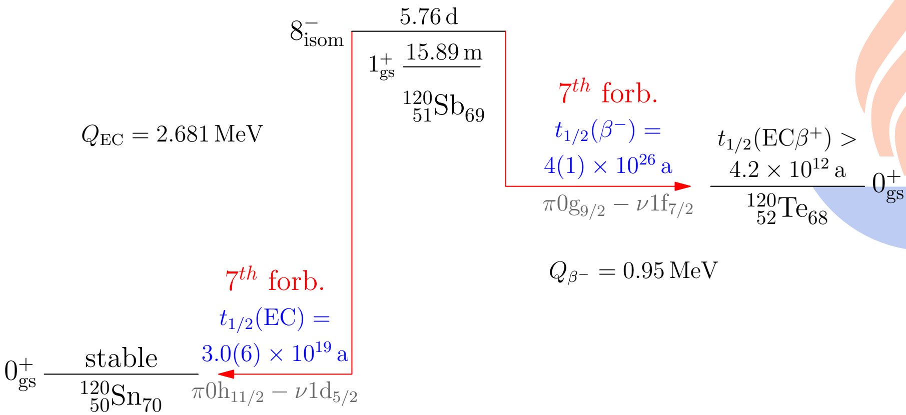
Decays in the $A = 114$ Chain



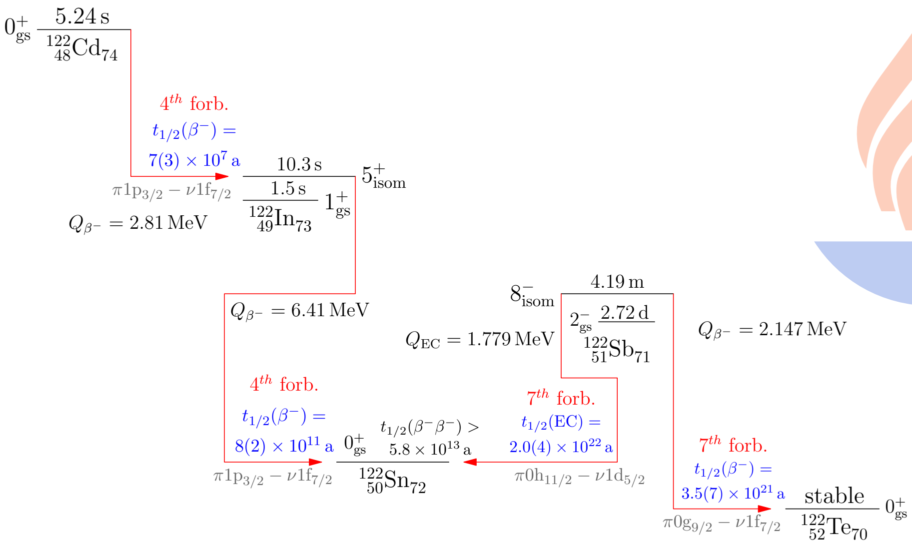
Decays in the $A = 116$ Chain



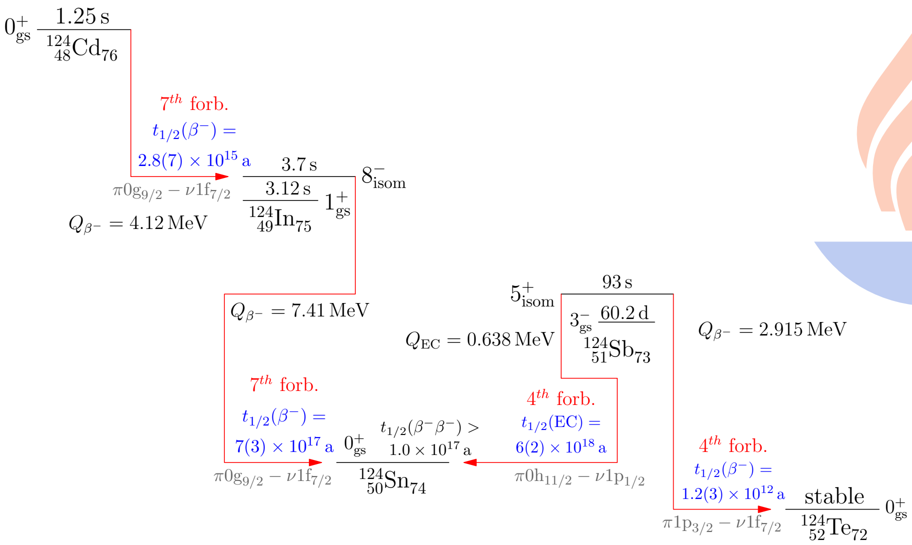
Decays in the $A = 120$ Chain



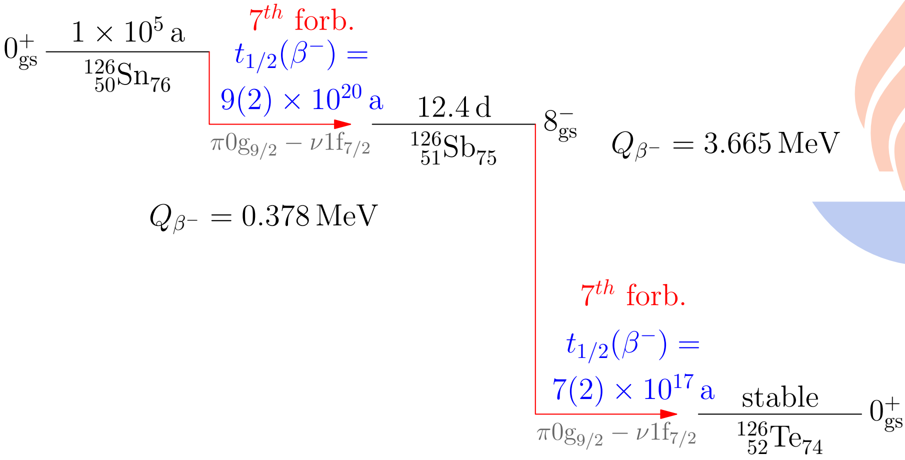
Decays in the $A = 122$ Chain



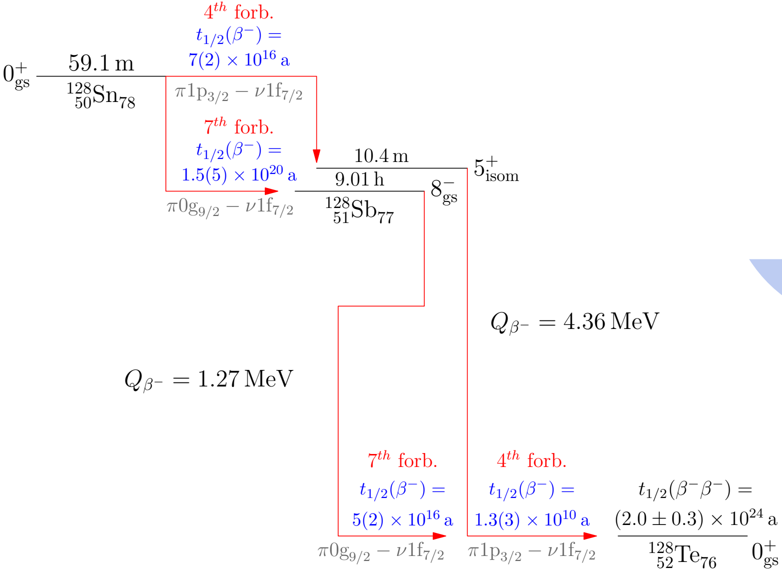
Decays in the $A = 124$ Chain



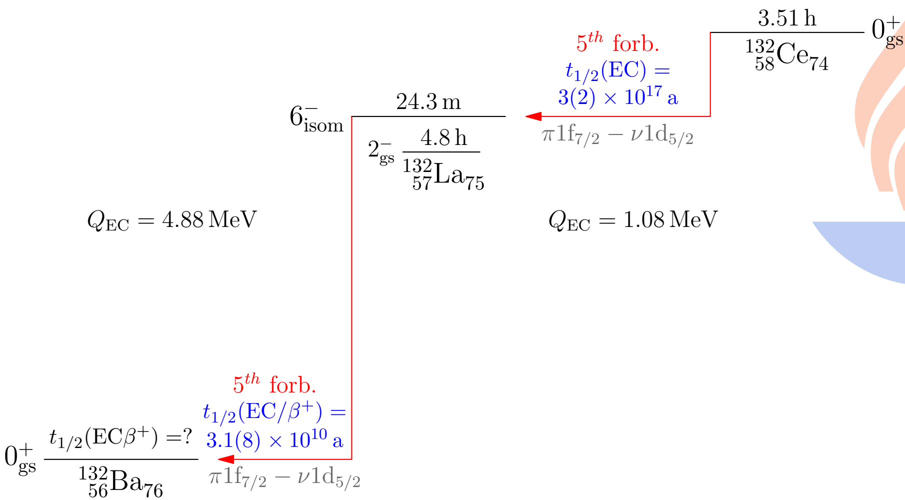
Decays in the $A = 126$ Chain



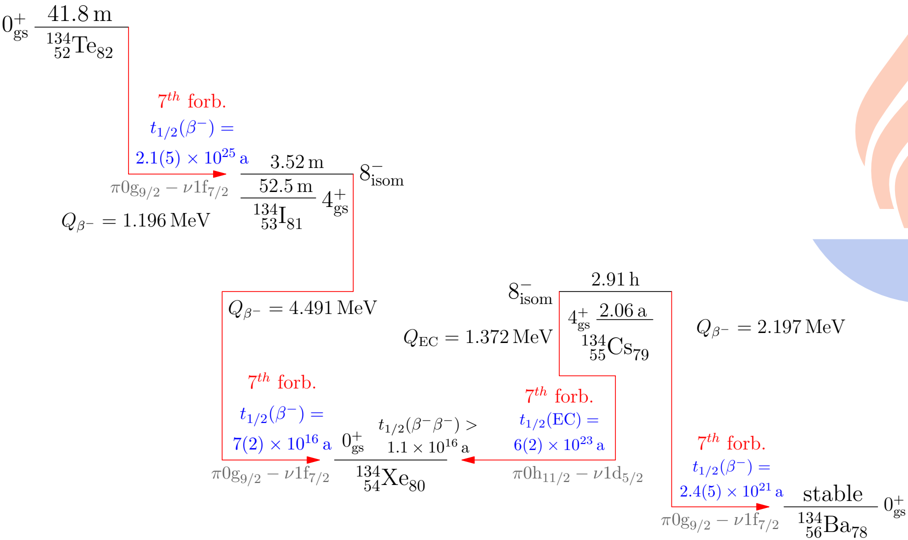
Decays in the $A = 128$ Chain



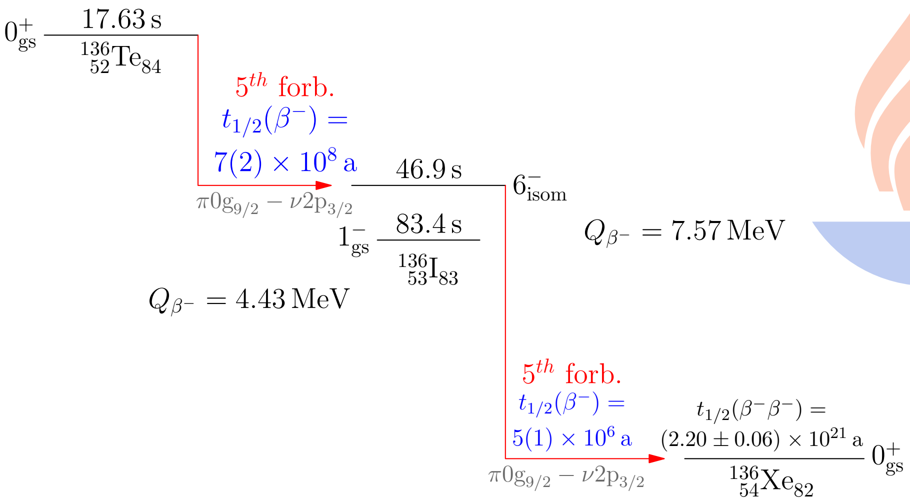
Decays in the $A = 132$ Chain



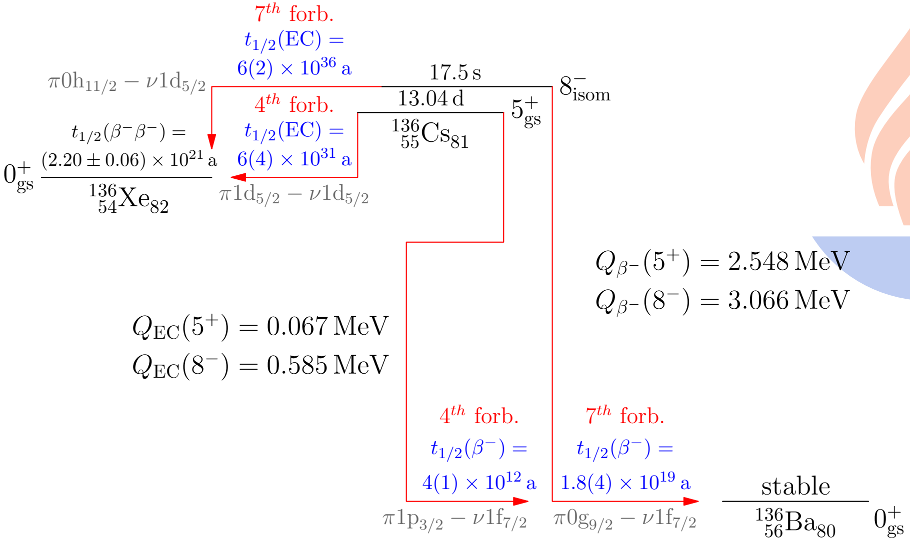
Decays in the $A = 134$ Chain



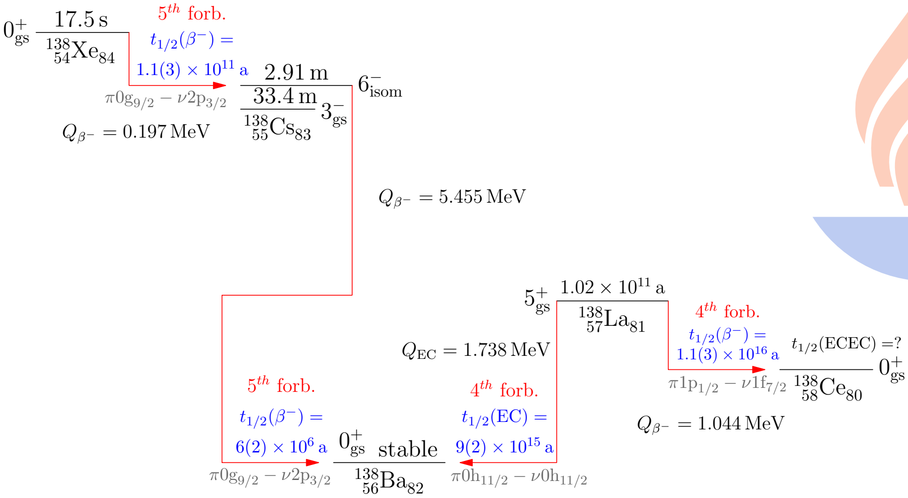
Decays in the $A = 136$ Chain



Decays in the $A = 136$ Chain



Decays in the $A = 138$ Chain



Conclusions and Outlook

Conclusions:

- Previous studies on GT 1^+ and SD 2^- β decays shed light on the suppression chain: quasiparticle NME $\rightarrow$ pnQRPA NME $\rightarrow$ experimental NME
- From the above studies $k_{\rm NM}$ can be extracted
- From studies of unique high-forbidden β decays ($K \geq 2$) the suppression chain: quasiparticle NME $\rightarrow$ pnQRPA NME can be extracted
- Using $k_{\rm NM}$ one can extract the expected half-lives for the 148 studied unique high-forbidden β decays
- Using $k_{\rm NM}$ one can speculate about modifications in the pnQRPA computed $0\nu\beta\beta$-decay half-lives

Outlook:

- Find ways to use the present studies in a more reliable prediction of the pnQRPA-based $0\nu\beta\beta$ NMEs
- Urge measurements of the studied decays to see how accurate is the $k_{\rm NM}$ conjecture