Theoretical calculations for weak transitions: $2\nu\beta\beta$, competing decays, and the gallium anomaly

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OUTLINE

- Motivation
- Case studies
  - **^{76}Ge:** competing $2\nu\beta\beta$-decays
  - **^{48}Ca and ^{96}Zr:** $2\nu\beta\beta$ vs. β-decays
  - **^{71}Ga:** evidence for sterile neutrinos?
- Summary
- What am I currently working on?

MOTIVATION: WHY TO STUDY $2\nu\beta\beta$ AND β-DECAYS?

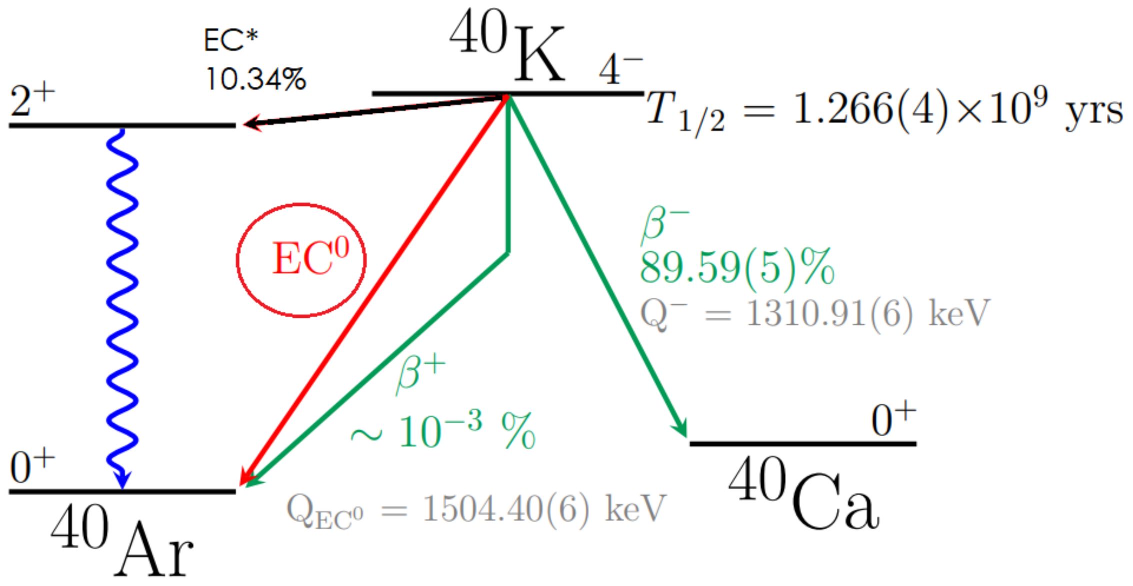
- Allowed by the standard model, so they definitely exist.
- A lot of unmeasured decays to be discovered.
- Many interesting cases with competing decays which can be used to test nuclear structure models.
- Advances in computing power: large-scale shell-model calculations → optimizing experiments based on theoretical half-life estimates.
- Background characterization: $2\nu\beta\beta$-decays are background in $0\nu\beta\beta$-decay experiments, rare β-decays in various rare-event experiments.
- Interpreting results from neutrino experiments: are we missing neutrino flux?

Are branching ratios, cross sections, and half-lives based on effective Hamiltonians useful?

Uncertain uncertainties?
Systematic underestimation of half-lives?

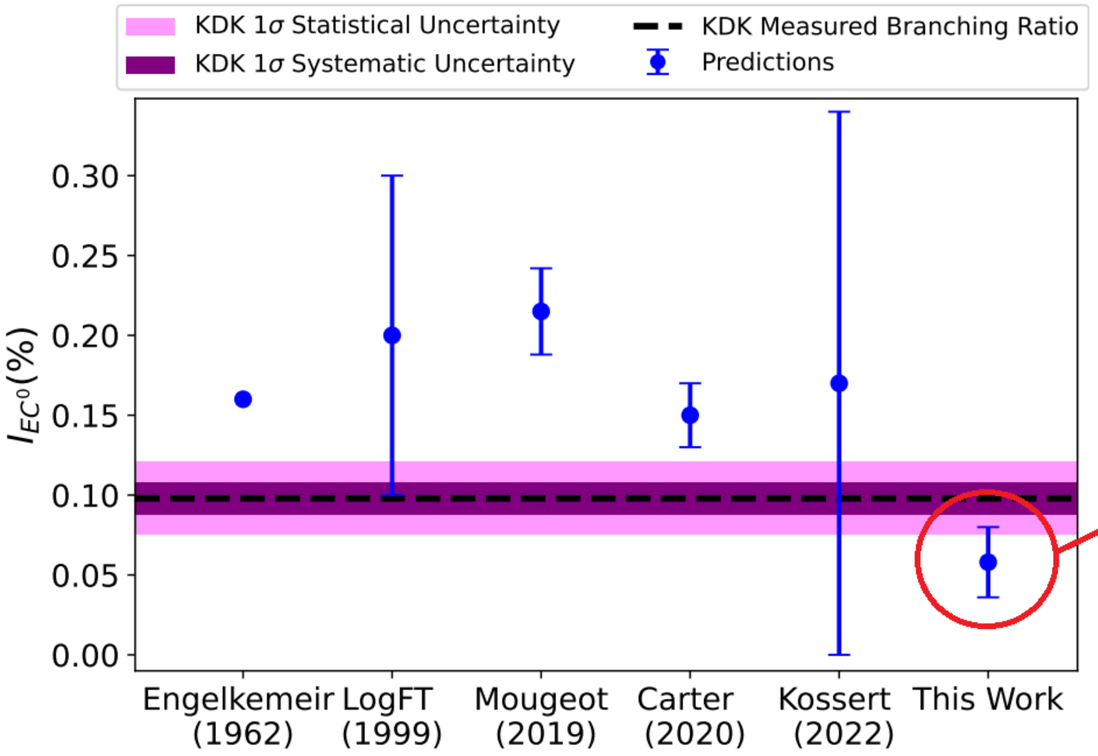
RECENT SUCCESS STORY: ^{40}K

- KDK Collaboration measurement of a rare ^{40}K decay branch using a low-threshold x-ray detector surrounded by a tonne-scale, high-efficiency γ-ray tagger at Oak Ridge National Laboratory.
- Prior to conducting the experiment, the branching ratio was estimated to be ~(0.06 ± 0.03)% → multiple effective Hamiltonians tested, one chosen based on its ability to produce the total half-life and EC* branching.

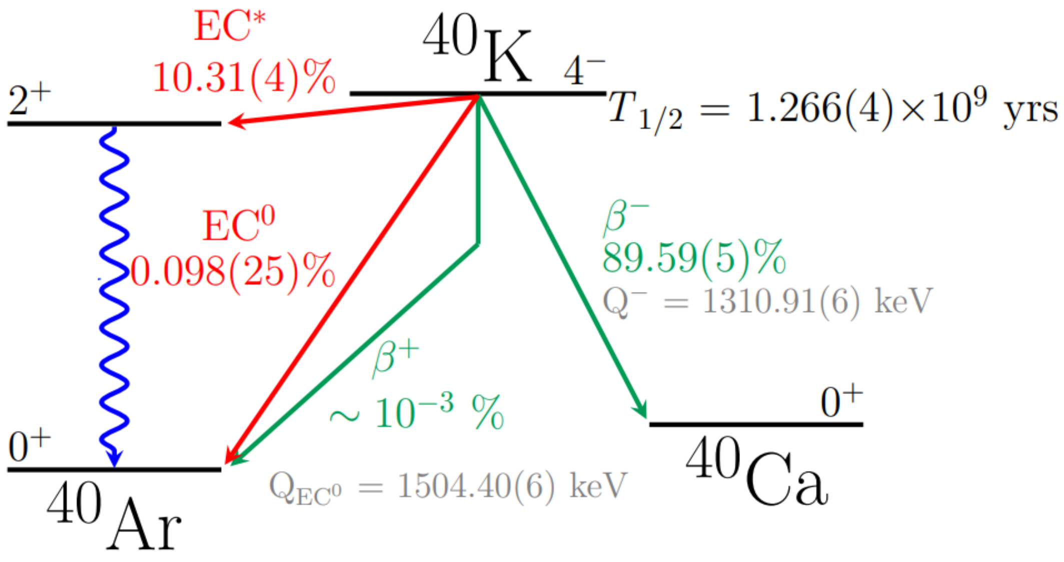


L. Hariasz *et al.* (KDK Collaboration) Phys. Rev. C **108**, 014327 – Published 31 July 2023

RECENT SUCCESS STORY: ^{40}K



Shell-model predicion using an effective Hamiltonian prior to the experiment



Shell-model based branching ratios work!

50% errors can be expected, but getting the magnitude right can be enough.

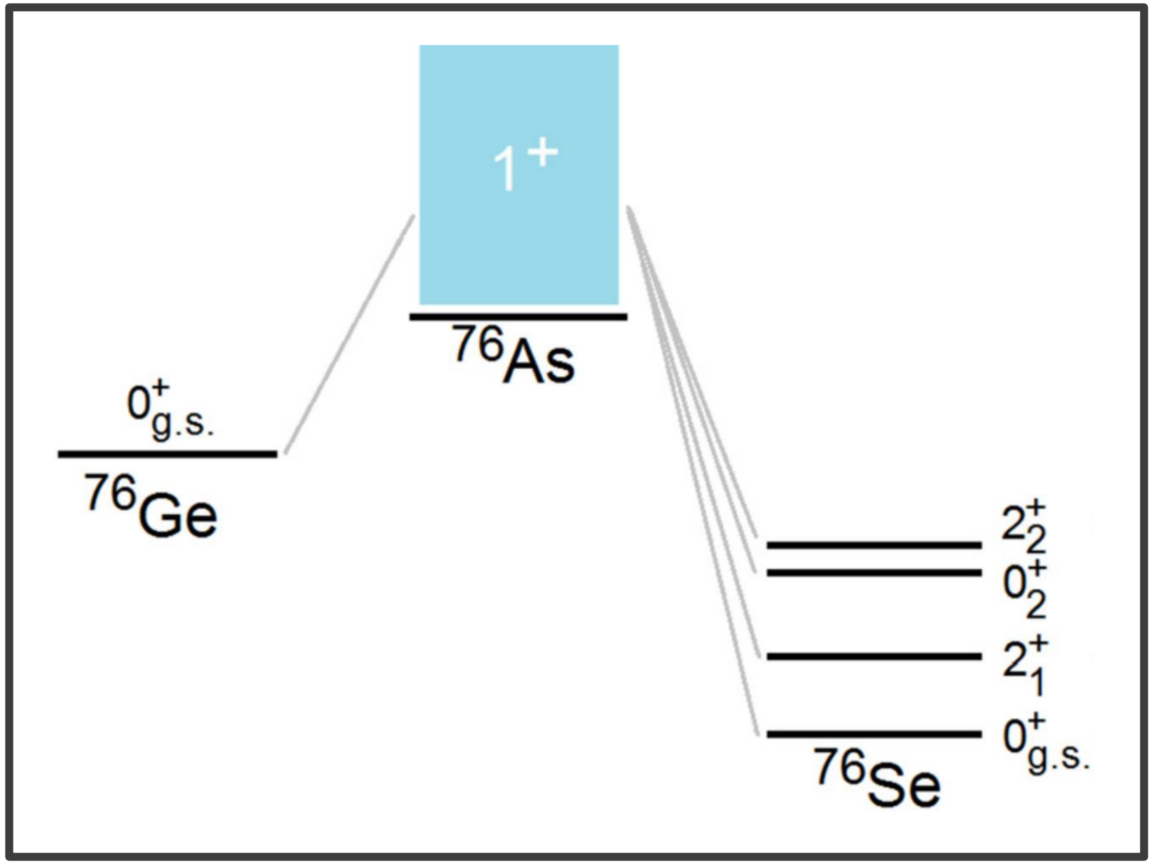
L. Hariasz *et al.* (KDK Collaboration) Phys. Rev. C **108**, 014327 – Published 31 July 2023

^{76}Ge

COMPETING $2\nu\beta\beta$-DECAYS

Kostensalo, J., Suhonen, J., & Zuber, K. (2022). The first large-scale shell-model calculation of the two-neutrino double beta decay of 76Ge to the excited states in 76Se. *Physics Letters B*, *831*, Article 137170. https://doi.org/10.1016/j.physletb.2022.137170

COMPETING $2\nu\beta\beta$



- 76Ge has four energetically allowed $2\nu\beta\beta$-branches.
- The ground state is measured to high accuracy by GERDA: $(2.022 \pm 0.018_{stat} \pm 0.038_{syst})\times 10^{21}$ yr [2023]
- Decays to excited states have not yet been detected. Only lower limits for half-lives exist.

SUPPRESSION OF 2^+ STATES

$$M_{2\nu} = \sum_m \frac{(J^+||\sigma\tau^-||1_m^+)(1_m^+||\sigma\tau^-||0_{g.s.}^+)}{\sqrt{J+1}([\frac{1}{2}Q_{\beta\beta} + E(1_m^+) - M_i]/m_e + 1)^k}$$

Final state 0^+ → k = 1
Final state 2^+ → k = 3

Experimental interest is on the first excited 0^+ state.

DESCRIPTION OF THE SHELL-MODEL CALCULATIONS

- Three stage calculation with a computer cluster using the effective interaction JUN45.

1. Calculation in the full $0f_{5/2}$-$1p$-$0g_{9/2}$ model space (250 intermediate 1^+ states, 4.7 MeV in excitation energy)
2. Calculation with neutron $0f_{5/2}$ filled (500 intermediate 1^+ states, include only states above the 4.7 MeV)
3. Calculation with neutron $0f_{5/2}$ filled and proton $0g_{9/2\ \mathrm{empty}}$ (9999 intermediate 1^+ states, include all states above the excitation energy reached in step 2)

We end up with 10,266 states in total reaching 30.6 MeV.

CUMULATIVE NME

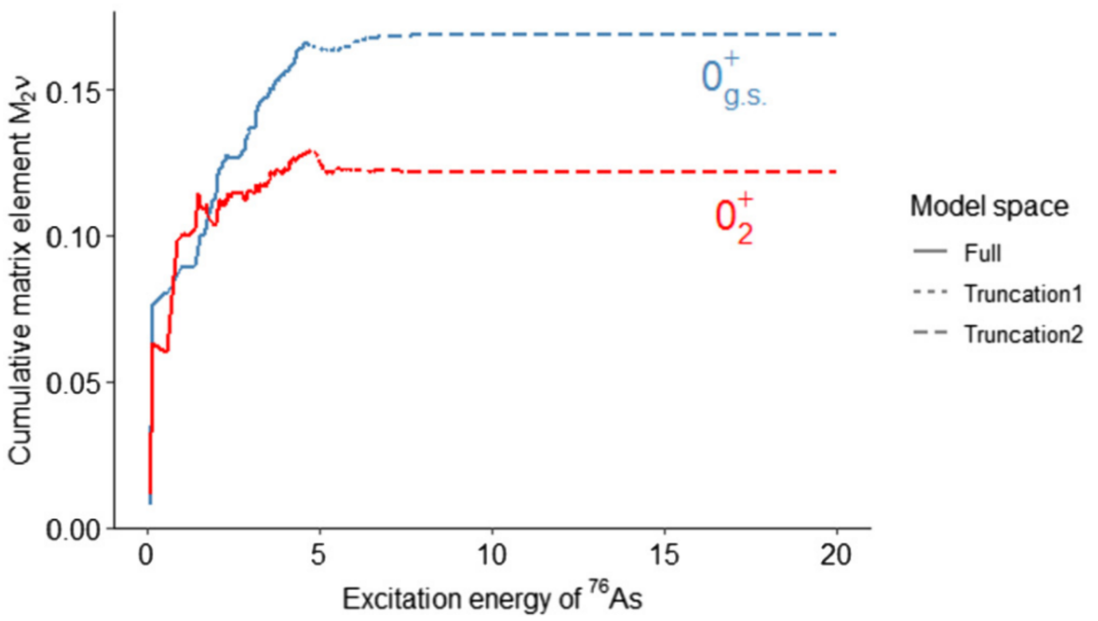


Fig. 1. Cumulative $2\nu\beta\beta$ NMEs $M_{2\nu}$ for the decay of ^{76}Ge to the $0^+_{g.s.}$ and 0^+_2 states in ^{76}Se as functions of the excitation energy of the intermediate states in ^{76}As. The full calculation (solid line) has been carried out in the $0f_{5/2} - 1p - 0g_{9/2}$ model space, for truncation 1 (dotted line) the neutron orbital $0g_{5/2}$ was kept full and for Truncation 2 (dashed line), additionally, the proton orbital $0g_{9/2}$ was kept empty.

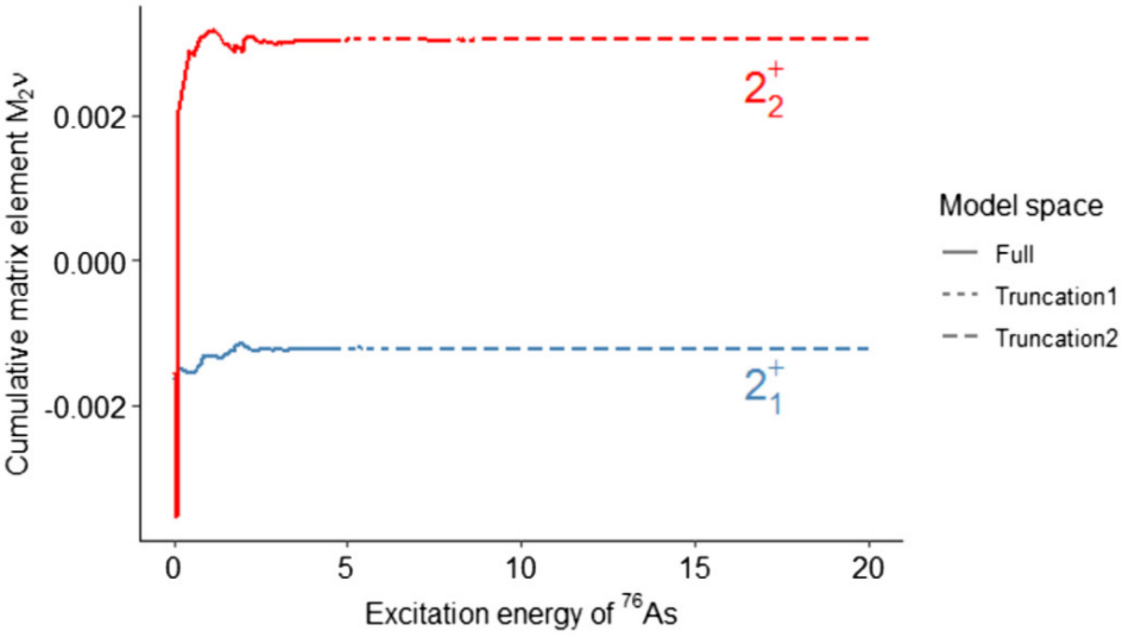


Fig. 2. The same as in Fig. 1 for cumulative $2\nu\beta\beta$ NMEs $M_{2\nu}$ of the decay of ^{76}Ge to the 2^+_1 and 2^+_2 states in ^{76}Se.

COMPARISON WITH PREVIOUS THEORETICAL ESTIMATES

Table 2
Comparison of the presently computed $2\nu\beta\beta$ NMEs (last line) with earlier calculations for the $0^+_{\text{g.s.}}$, 2^+_1, 0^+_2 and 2^+_2 states (columns 1-4). Column 5 indicates the used theory, with MCM=Multiple Commutator Model, HQRPA=Higher QRPA, RQRPA=Renormalized QRPA, SM=shell model. The last column gives the reference to the calculation.

$\lvert M_{2\nu}(0^+_{\text{g.s.}})\rvert$	$\lvert M_{2\nu}(2^+_1)\rvert$	$\lvert M_{2\nu}(0^+_2)\rvert$	$\lvert M_{2\nu}(2^+_2)\rvert$	Theory	Ref.
0.074	1×10^{-3}	0.363	3×10^{-3}	MCM	[13]
-	2×10^{-3}	-	-	HQRPA	[15]
0.100	3×10^{-3}	0.838	3×10^{-3}	MCM	[14]
0.083	0.013	0.056	-	HQRPA	[16]
0.074	3×10^{-3}	$0.130 - 0.229$	$(7 - 12) \times 10^{-3}$	RQRPA	[19]
-	$(0.48 - 0.65) \times 10^{-3}$	-	-	RQRPA	[20]
0.113	0.74×10^{-3}	-	-	HRPA	[17]
0.168	1.2×10^{-3}	0.121	3.1×10^{-3}	SM	This work

COMPARISON WITH THEORETICAL LOWER LIMITS FOR HALF-LIFE

Table 1

Shell-model calculated $2\nu\beta\beta$ NMEs, phase-space integrals and half-lives (columns 3-5) for the decay of ^{76}Ge to the ground state and lowest three excited states (column 1) of ^{76}Se. The phase-space integrals for the lowest three states are taken from [21] and the fourth one has been calculated using the formulas of this reference. Experimental Q values (column 2) are used in the calculations. The half-life for the ground-state transition matches the measured one [9] and the rest of the half-lives are based on the shell model calculations using $g_A = 0.80 \pm 0.01$, derived from the comparison of the computed half-life with the experimental one for the ground-state transition. The uncertainties include only the uncertainty related to the value of the experimental half-life of the ground-state transition. In the sixth column we list the measured lower limits for the half-lives, including the corresponding reference in the last column.

J^π_f	$Q_{\beta\beta}$ (keV)	$\lvert M_{2\nu}\rvert$	G (yr^{-1})	$T^{\beta\beta}_{1/2}$(th.) (yr)	$T^{\beta\beta}_{1/2}$(exp.) (yr)	Ref.
0^+_{gs}	2039	0.168	4.51×10^{-20}	$(1.926 \pm 0.094) \times 10^{21}$	$(1.926 \pm 0.094) \times 10^{21}$	[9]
2^+_1	1480	1.2×10^{-3}	4.0×10^{-22}	$(4.37 \pm 0.20) \times 10^{27}$	$> 1.1 \times 10^{21}$	[32]
0^+_2	917	0.121	6.4×10^{-23}	$(2.60 \pm 0.13) \times 10^{24}$	$> 6.2 \times 10^{21}$	[31]
2^+_2	823	3.1×10^{-3}	3.33×10^{-25}	$(7.57 \pm 0.37) \times 10^{29}$	$> 1.4 \times 10^{21}$	[32]

[31] A.A. Klimenko, et al., Czechoslov. J. Phys. 52 (2002) 589.

[32] A.S. Barabash, A.V. Derbin, L.A. Popeko, V.I. Umatov, Z. Phys. A 352 (1995) 231.

Up-to-date limits:

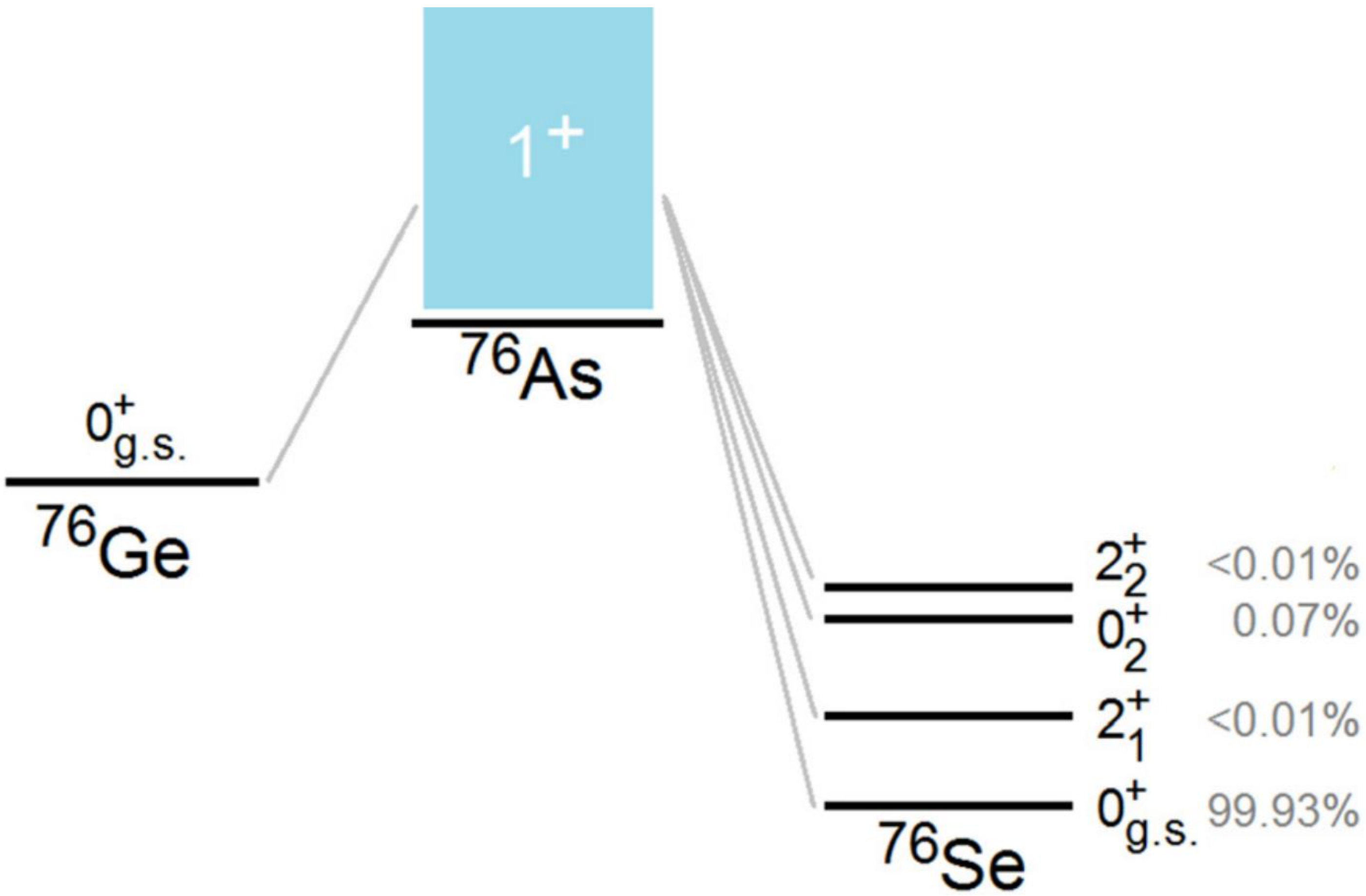
$>7.7 \times 10^{23}$ (2^+_1)

$>7.5 \times 10^{23}$ (0^+_2)

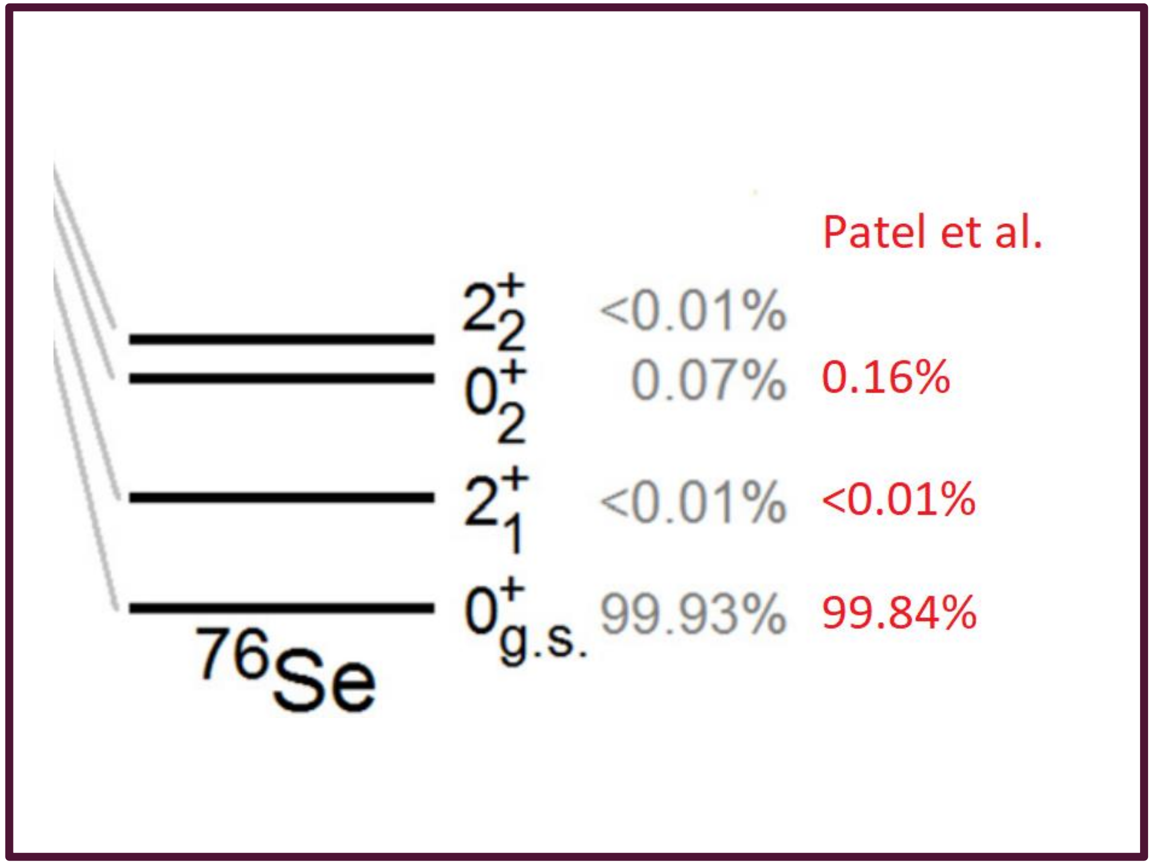
$>12.8 \times 10^{23}$ (2^+_2)

*I. J. Arnquist et al. (MAJORANA Collaboration) Phys. Rev. C **103**, 015501 – Published 6 January 2021 (90% C.L.).*

PREDICTED BRANCHINGS



RECENT DEVELOPMENTS (SINCE PUBLICATION)



- GERDA updated the gs-to-gs half-life (Oct. 2023) to $(2.022 \pm 0.018_{stat} \pm 0.038_{syst})\times10^{21}$ yr from $(1.926 \pm 0.095)\times10^{21}$ → 5% longer, twice as accurate.
- Patel et al. (2024) [pre-print] carried out another large-scale shell-model calculation using the Hamiltonian GWBXG.
- The experimental half-life limit $>7.5\times10^{23}$ yr $(0^+{}_2)$ is getting close to the theoretical estimates $1 - 3\times10^{24}$ yr.

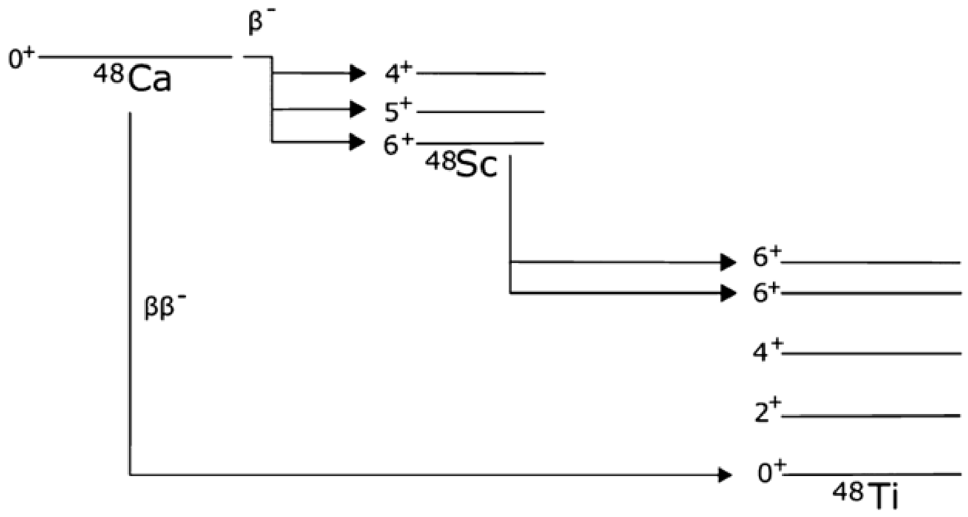
^{48}Ca and ^{96}Zr

$2\nu\beta\beta$ vs. β-decays

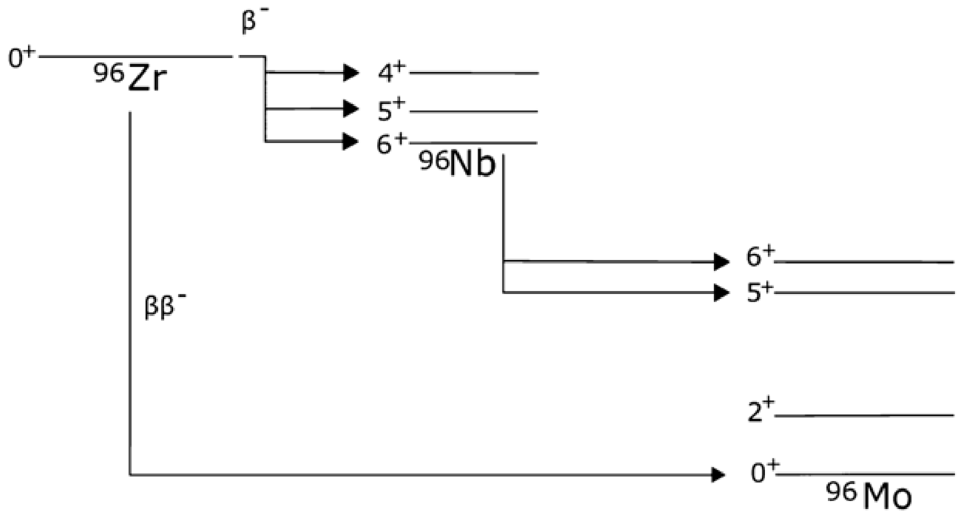
Kostensalo, J., & Suhonen, J. (2020). Consistent large-scale shell-model analysis of the two-neutrino ββ and single β branchings in 48Ca and 96Zr. *Physics Letters B*, *802*, Article 135192. https://doi.org/10.1016/j.physletb.2019.135192

DOUBLE BETA AND BETA DECAYS

$Q_{\beta\beta}$= 4268 keV
Q_{β}= 279/146/27 keV (6+/5+/4+)
$T_{1/2\beta\beta}$=~ 5.6 ×10^{19} yr
$T_{1/2\beta}$= ???



$Q_{\beta\beta}$= 3356 keV
Q_{β}= 164/120/18 keV (6+/5+/4+)
$T_{1/2\beta\beta}$=~ 2.3 ×10^{19} yr
$T_{1/2\beta}$= ???



SINGLE BETA DECAYS: LIMITS

Best experimental limits for single beta decays according to *Tretyak, AIP Conf. Proc. 1894, 020026 (2017):*

^{48}Ca: $>2.5 \times 10^{20}$ yr *A. Bakalyarov et al., JETP Lett. 76, 545 (2002).*

^{96}Zr: $>3.8 \times 10^{19}$ yr *M. Arpesella et al., Europhys. Lett. 27, 29 (1994).*

DESCRIPTION OF THE SHELL-MODEL CALCULATIONS

- 48Ca: calculation in the full *fp* model space with *GFPX1A*. Effective g_A fixed by two-beta decay half-life (same value used for single and double beta decay). 9470 intermediate 1^+ states (60 MeV).

- 96Zr: Full model space with proton orbitals $0f_{5/2}$-1p-$0g_{9/2}$ and neutron orbitals $0g_{7/2}$-1d-$2s_{1/2}$ with *glekpn*. 5894 intermediate 1^+ states (18 MeV).

CUMULATIVE NME

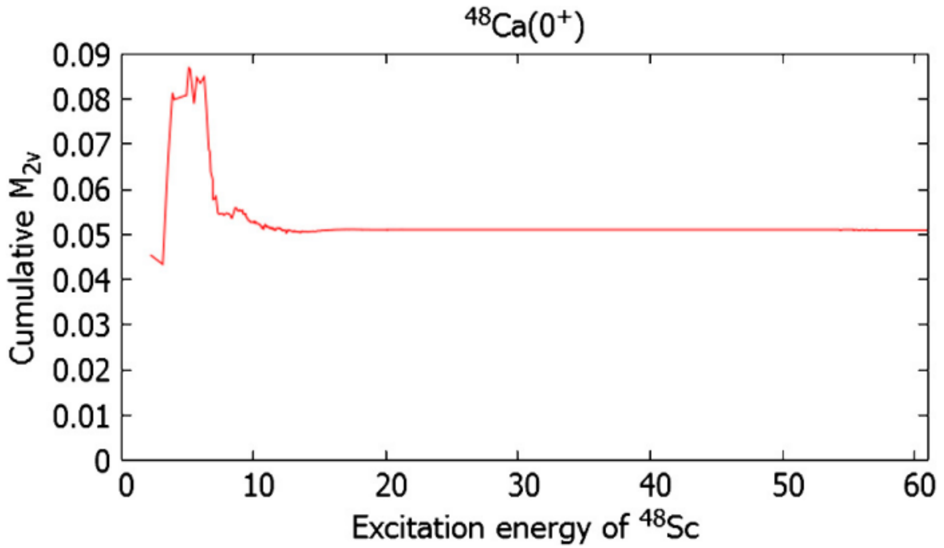


Fig. 1. Cumulative $2\nu\beta\beta$ NME $M_{2\nu}$ for ^{48}Ca as a function of excitation energy of the intermediate state in ^{48}Sc.

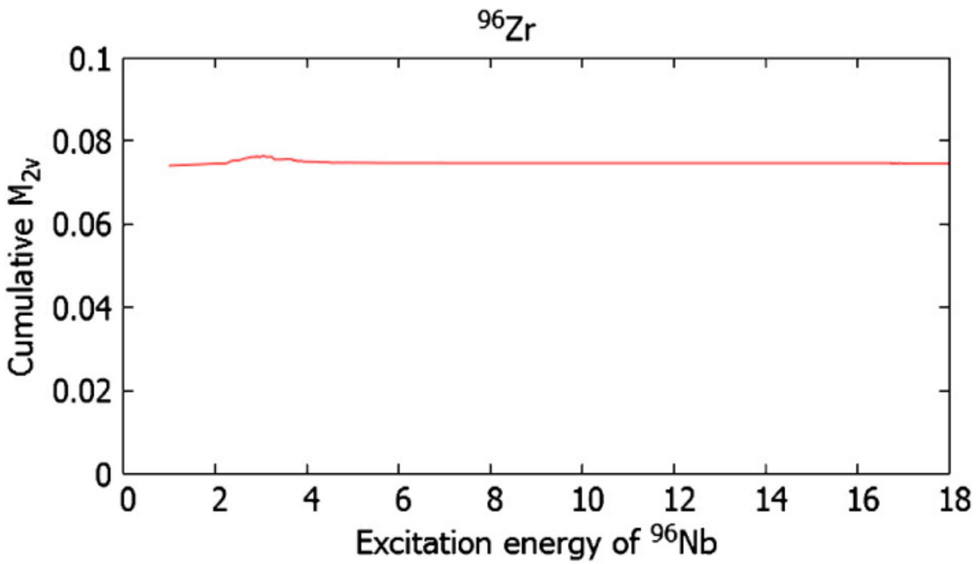


Fig. 2. Cumulative $2\nu\beta\beta$ NME $M_{2\nu}$ for ^{96}Zr as a function of excitation energy of the intermediate state in ^{96}Nb.

BRANCHING RATIO AND AXIAL-VECTOR COUPLING

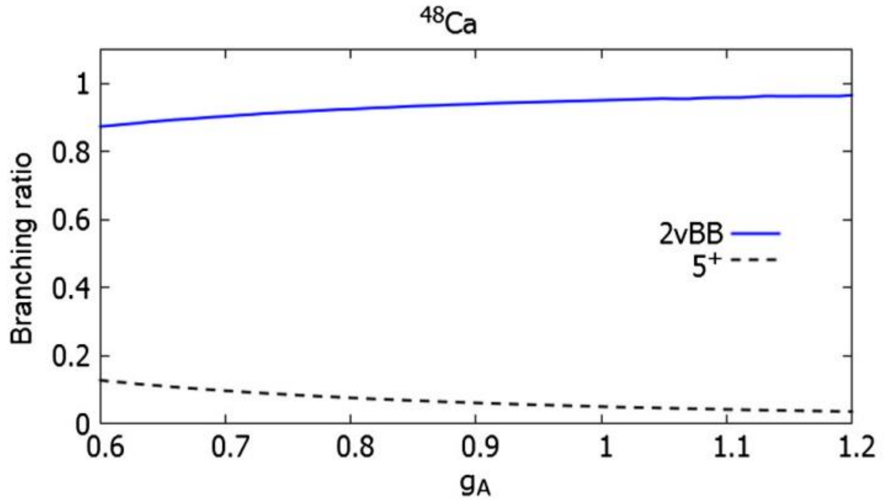


Fig. 5. Branching ratios of the two dominant branches of ^{48}Ca as functions of g_A.

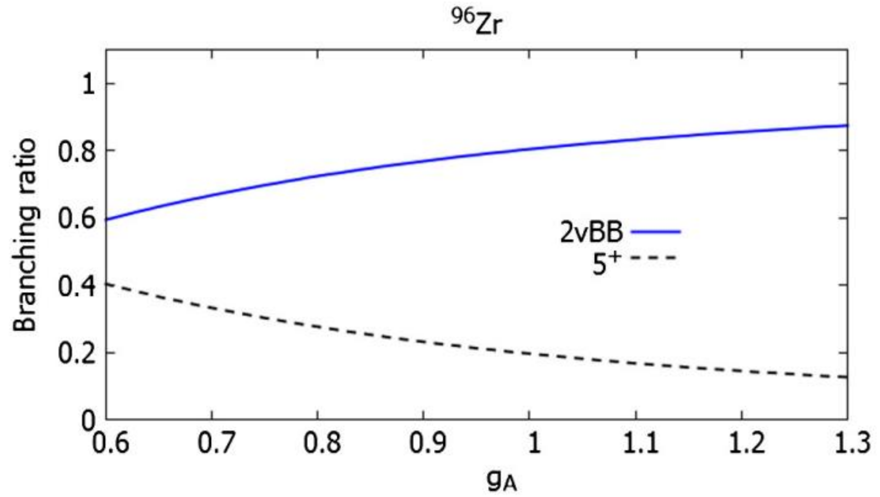


Fig. 8. Branching ratios of the two dominant branches of ^{96}Zr as functions of g_A.

Table 1
Shell-model calculated $2\nu\beta\beta$ NMEs and the extracted effective value g_A^{eff} of the axial-vector coupling.

Nucleus	$\lvert M_{2\nu}\rvert$	G (10^{-18} yr^{-1}) [25]	$T_{1/2}^{\beta\beta}$ (10^{19} yr)	g_A^{eff}
^{48}Ca	0.0511	14.805	$6.4^{+1.4}_{-1.1}$ [9]	0.80 ± 0.04
^{96}Zr	0.0747	6.420	2.35 ± 0.21 [10]	$1.04^{+0.03}_{-0.02}$

[9] R. Arnold, C. Augier, A.M. Bakalyarov, J.D. Baker, A.S. Barabash, et al., NEMO-3 Collaboration, Phys. Rev. D 93 (2016) 112008.
[10] J. Argyriades, R. Arnold, C. Augier, J. Baker, A. Barabash, et al., Nucl. Phys. A 847 (2010) 168.

PREDICTED BRANCHING RATIOS

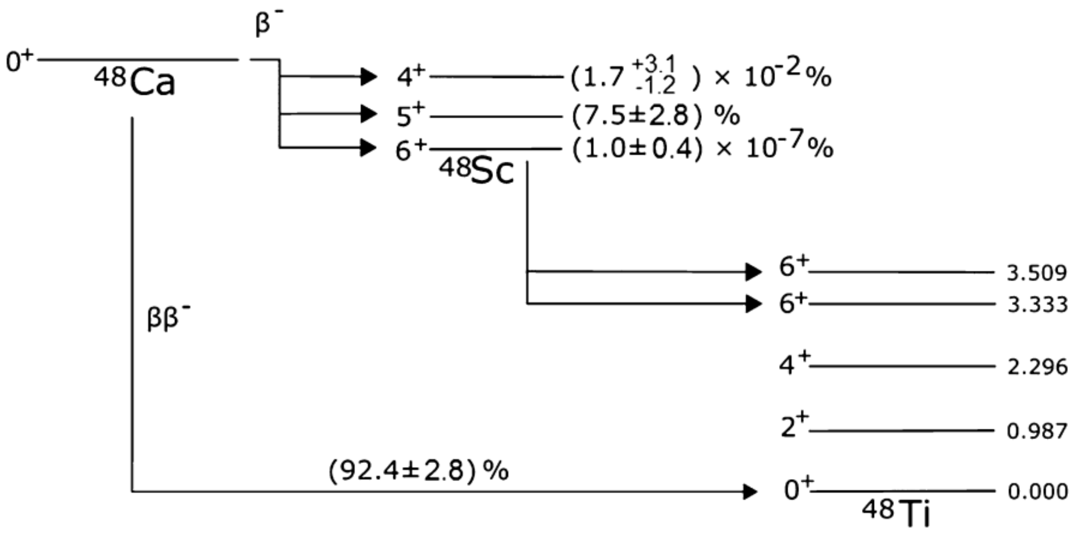


Fig. 3. Decay scheme of ^{48}Ca. Also indicated are our shell-model computed β-decay and $2\nu\beta\beta$-decay branching ratios.

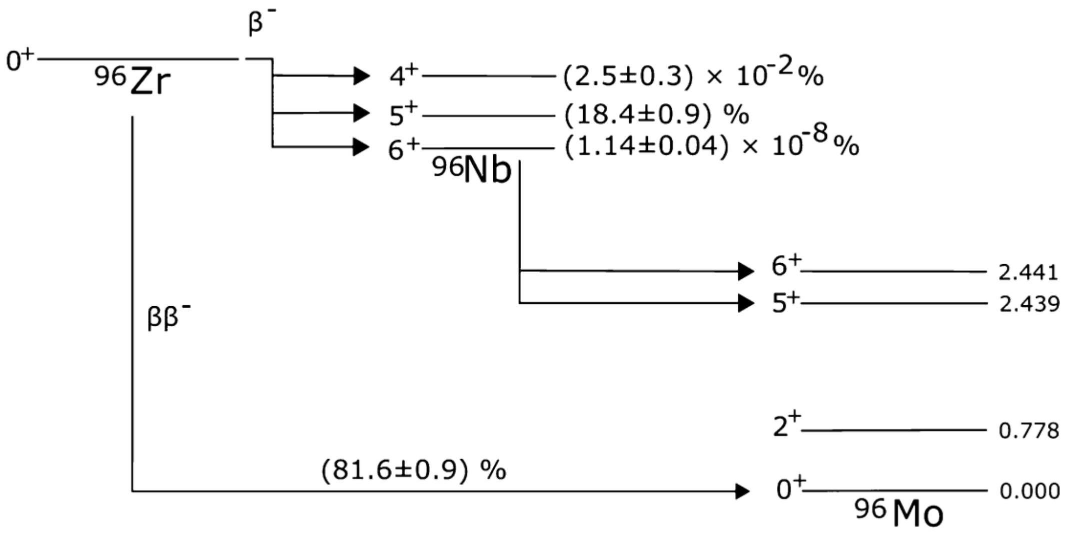


Fig. 6. Decay scheme of ^{96}Zr. Also indicated are our shell-model computed β-decay and $2\nu\beta\beta$-decay branching ratios.

HOW CLOSE ARE THE EXPERIMENTAL LIMITS?

^{48}Ca:

~ 8 ×10^{20} yr (shell model)

~ 3.4 ×10^{20} yr (shell model, Haaranen et al., 2014)

*>2.5 ×10^{20} yr * (exp. limit)*

^{96}Zr:

~ 1 ×10^{20} yr (shell model)

~ 2.4 ×10^{20} yr (pnQRPA – Heiskanen et al., 2007)

*>3.8 ×10^{19} yr ** (exp. limit)*

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Shell-model calculated $2\nu\beta\beta$ NMEs and the extracted effective value g_A^{eff} of the axial-vector coupling.

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** A. Bakalyarov et al., JETP Lett. 76, 545 (2002).*

*** M. Arpesella et al., Europhys. Lett. 27, 29 (1994).*

^{71}Ga

Evidence for sterile neutrinos?

Kostensalo, J., Suhonen, J., Giunti, C., & Srivastava, P. C. (2019). The gallium anomaly revisited. *Physics Letters B*, *795*, 542-547. https://doi.org/10.1016/j.physletb.2019.06.057

Corrigendum to “The gallium anomaly revisited” [Phys. Lett. B 795 (2019) 542–547]
Physics Letters B, *846*, 138190 (2023).

THE GALLIUM ANOMALY

- GALLEX and SAGE experiments were designed to detect neutrinos utilizing the transition

$$\nu_e + {}^{71}\mathrm{Ga}(3/2^-)_{\mathrm{g.s.}} \rightarrow {}^{71}\mathrm{Ge}(J^\pi) + e^-$$

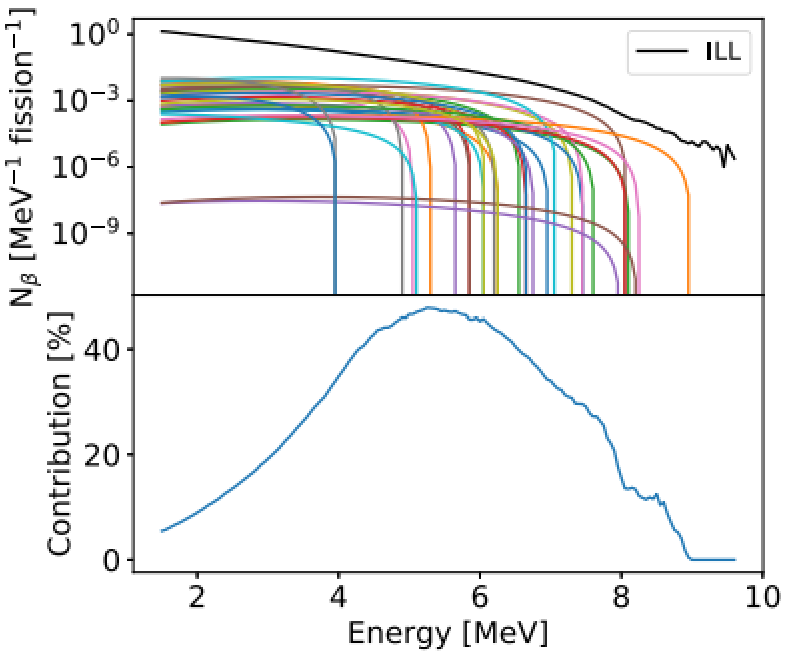
- Source experiments with ^{51}Cr and ^{37}Ar neutrinos showed slightly lower fluxes than predicted by Bahcall based on (p,n)-reaction cross sections.
- Haxton (1998) showed that charge-exchange reactions may be unreliable in this case due to tensor contributions because the transition to the $5/2^-$ state is *L-forbidden*.
- Missing neutrino flux could potentially be an indication of *sterile neutrinos*.
- Reactor antineutrino anomaly could potentially also be explained by sterile neutrinos.

EXCURSION: REACTOR ANTINEUTRINO ANOMALY

Hayen, L., Kostensalo, J., Severijns, N., & Suhonen, J. (2019). First-forbidden transitions in the reactor anomaly. *Physical Review C*, *100*(5), Article 054323. https://doi.org/10.1103/PhysRevC.100.054323

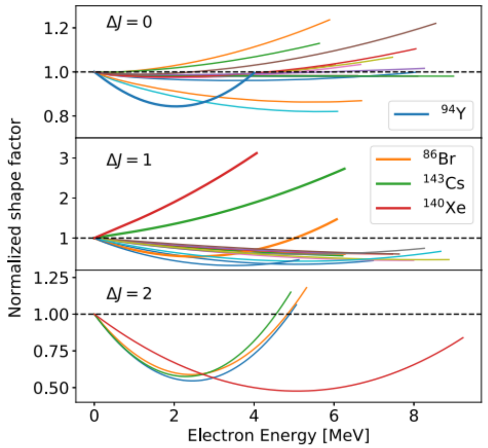
- Missing neutrino flux from reactors (~5%)
- Spectral shoulder (“bump”) at ~5 MeV
- Previous theoretical calculations missing forbidden transitions

Nuclide	Q_β (MeV)	E_{ex} (MeV)	BR (%)	$J_i^\pi \rightarrow J_f^\pi$	FY (%)	ΔJ
^{89}Br	8.3	0	16	$3/2^- \rightarrow 3/2^+$	1.1	0
^{90}Rb	6.6	0	33	$0^- \rightarrow 0^+$	4.5	0
^{91}Kr	6.8	0.11	18	$5/2^+ \rightarrow 5/2^-$	3.5	0
^{92}Rb	8.1	0	95.2	$0^- \rightarrow 0^+$	4.8	0
^{93}Rb	7.5	0	35	$5/2^- \rightarrow 5/2^+$	3.5	0
^{94}Y	4.9	0.92	39.6	$2^- \rightarrow 2^+$	6.5	0
^{95}Rb[a]	9.3	0.68	5.9	$5/2^- \rightarrow 5/2^+$	1.7	0
^{95}Sr	6.1	0	56	$1/2^+ \rightarrow 1/2^-$	5.3	0
^{96}Y	7.1	0	95.5	$0^- \rightarrow 0^+$	6.0	0
^{97}Y	6.8	0	40	$1/2^- \rightarrow 1/2^+$	4.9	0
^{98}Y	9.0	0	18	$0^- \rightarrow 0^+$	1.9	0
^{133}Sn	8.0	0	85	$7/2^- \rightarrow 7/2^+$	0.1	0
^{135}Te	5.9	0	62	$(7/2-) \rightarrow 7/2^+$	3.3	0
^{135}Sb	8.1	0	47	$(7/2+) \rightarrow (7/2^-)$	0.1	0
^{136m}I	7.5	1.89	71	$(6^-) \rightarrow 6^+$	1.3	0
^{136m}I	7.5	2.26	13.4	$(6^-) \rightarrow 6^+$	1.3	0
^{137}I	6.0	0	45.2	$7/2^+ \rightarrow 7/2^-$	3.1	0
^{142}Cs	7.3	0	56	$0^- \rightarrow 0^+$	2.7	0
^{86}Br	7.3	0	15	$(1^-) \rightarrow 0^+$	1.6	1
^{86}Br	7.3	1.6	13	$(1^-) \rightarrow 2^+$	1.6	1
^{87}Se	7.5	0	32	$3/2^+ \rightarrow 5/2^-$	0.8	1
^{89}Br	8.3	0.03	16	$3/2^- \rightarrow 5/2^+$	1.1	1
^{91}Kr	6.8	0	9	$5/2^+ \rightarrow 3/2^-$	3.4	1
^{95}Rb[a]	9.3	0.56	6.0	$5/2^- \rightarrow (7/2^+)$	1.7	1
^{95}Rb	9.3	0.68	5.9	$5/2^- \rightarrow 3/2^+$	1.7	1
^{134m}Sb	8.5	1.69	42	$(7-) \rightarrow 6^+$	0.8	1
^{134m}Sb	8.5	2.40	54	$(7^-) \rightarrow (6^+)$	0.8	1
^{136}Te	5.1	0	8.7	$0^+ \rightarrow (1^-)$	3.7	1
^{138}I	8.0	0	26	$(1-) \rightarrow 0^+$	1.5	1
^{140}Xe	4.0	0.08	8.7	$0^+ \rightarrow 1^-$	4.9	1
^{140}Cs	6.2	0	36	$1^- \rightarrow 0^+$	5.7	1
^{143}Cs	6.3	0	25	$3/2^+ \rightarrow 5/2^-$	1.5	1
^{88}Rb	5.3	0	76.5	$2^- \rightarrow 0^+$	3.6	2
^{94}Y	4.9	0	41	$2^- \rightarrow 0^+$	6.5	2
^{95}Rb	9.3	0	0.1	$5/2^- \rightarrow 1/2^+$	1.7	2
^{139}Xe	5.1	0	15	$3/2^- \rightarrow 7/2^+$	5.0	2



EXCURSION: REACTOR ANTINEUTRINO ANOMALY

HAYEN, L., KOSTENSALO, J., SEVERIJNS, N., & SUHONEN, J. (2019). FIRST-FORBIDDEN TRANSITIONS IN THE REACTOR ANOMALY. *PHYSICAL REVIEW C, 100*(5), ARTICLE 054323. HTTPS://DOI.ORG/10.1103/PHYSREVC.100.054323



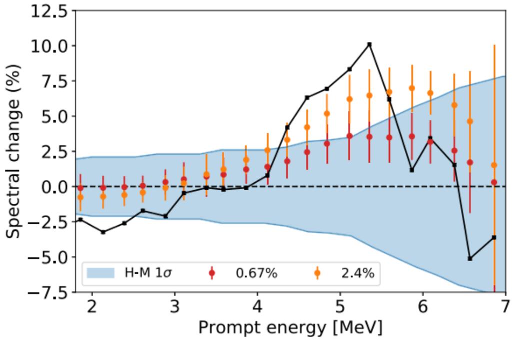


FIG. 18. Comparison of the Daya Bay shape discrepancy with the change due to the forbidden shape factors of Sec. IV when compared to two different slopes of the allowed approximation: 0.67% and 2.4%, as discussed in Secs. II D and VII B 1.

- Some flux still missing
- Spectral shoulder mitigated
- Uncertainties increase significantly

DESCRIPTION OF THE SHELL-MODEL CALCULATIONS

- Calculation in the full $0f_{5/2}$-$1p$-$0g_{9/2}$ model space without truncations.
- Effective interaction JUN45.
- Good agreement with known electric and magnetic moments.

ENERGY SPECTRA

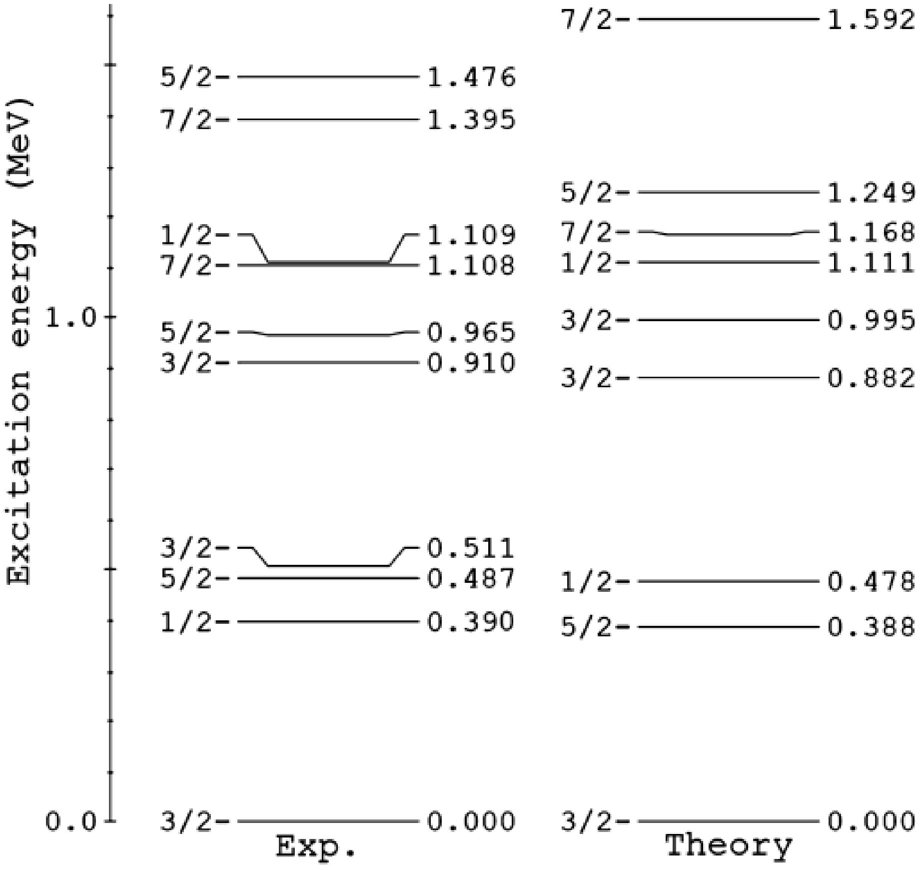


Fig. 1. Experimental and theoretical low-lying energy spectra of ^{71}Ga.

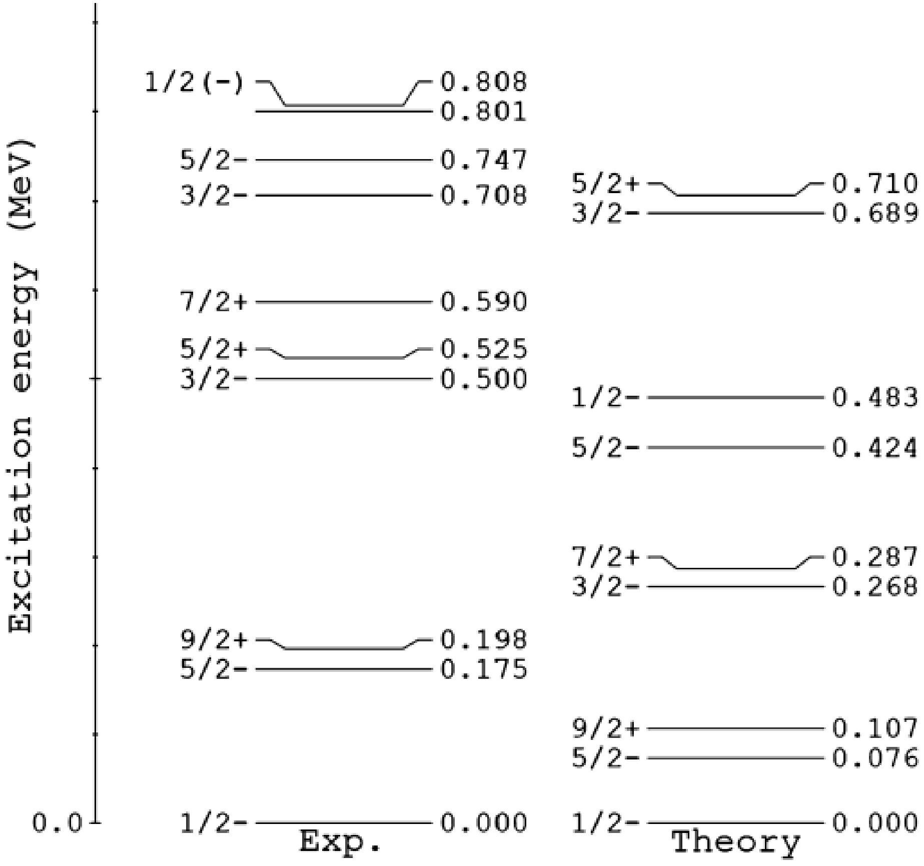


Fig. 2. Experimental and theoretical low-lying energy spectra of ^{71}Ge.

HOW TO EVALUATE THE CROSS SECTION?

$$\sigma = \sigma_{gs}\left(1 + \xi_{5/2-}\frac{\mathrm{BGT}_{5/2-}}{\mathrm{BGT}_{gs}} + \xi_{3/2-}\frac{\mathrm{BGT}_{3/2-}}{\mathrm{BGT}_{gs}}\right)$$

$$\xi_{5/2-}(^{51}\mathrm{Cr}) = 0.663 \qquad \xi_{3/2-}(^{51}\mathrm{Cr}) = 0.221$$

$$\xi_{5/2-}(^{37}\mathrm{Ar}) = 0.691 \qquad \xi_{3/2-}(^{37}\mathrm{Ar}) = 0.262$$

$$\sigma_{gs}(^{51}\mathrm{Cr}) = (5.53 \pm 0.01) \times 10^{-45}\ \mathrm{cm}^2\,,$$

$$\sigma_{gs}(^{37}\mathrm{Ar}) = (6.62 \pm 0.01) \times 10^{-45}\ \mathrm{cm}^2\,.$$

- GS-cross sections from half-life of ^{71}Ge.
- Phase-space factors from kinematics.
- BGT-ratios are non-trivial:
  - Charge-exchange reaction
  - Theoretical calculation

CROSS SECTIONS FROM CHARGE EXCHANGE REACTIONS

- Haxton (1998): Cross sections based on charge-exchange reactions can be described well with the effective operator:

$$\langle f||O_{(p,n)}||i\rangle = \langle f||O_{\mathrm{GT}}||i\rangle + \delta\langle f||O_{L=2}||i\rangle$$

- Based on (p,n)-reaction data, the mixing parameter δ is about ~0.1.
- The transition to $5/2^-$ would be predominantly between the orbitals 0f5/2 and 1p3/2 → single-particle GT identically zero, i.e., *L-forbidden!* Tensor contribution becomes important.
- Kostensalo et al. (2019): BGT for ground state underestimated, BGT for $3/2^-$ overestimated → systematic overestimation.

SYSTEMATIC PROBLEMS WITH CHARGE-EXCHANGE CROSS SECTIONS

Table 1. Results for ^{71}Ga with $\delta = 0.097$ and corrected tensor matrix elements.

State	$\langle f \| O_{GT} \| i \rangle$	$\langle f \| O_{L=2} \| i \rangle$	$BGT^{SM}{}_{\beta}$	$BGT^{SM}{}_{(p,n)}$
$1/2^-_{g.s.}$	−0.795	0.521	0.158	0.139
$5/2^-_1$	0.144	−0.763	0.0052	0.0012
$3/2^-_1$	0.100	0.0687	0.0025	0.0028

Underestimation

Extermely sensitive

Overestimation

CONTRIBUTIONS FOR THE EXCITED STATES ARE LOWER

Table 6
Values of the Gamow-Teller strengths of the transitions from the ground state of ^{71}Ga to the relevant excited states of ^{71}Ge relative to the Gamow-Teller strength of the transitions to the ground state of ^{71}Ge obtained by Krofcheck et al. [36,37], Haxton [8], Frekers et al. [5], and with the JUN45 calculation presented in this paper.

	Method	$\frac{BGT_{5/2-}}{BGT_{gs}}$	$\frac{BGT_{3/2-}}{BGT_{gs}}$	$\frac{BGT_{5/2+}}{BGT_{gs}}$
Krofcheck	$^{71}Ga(p,n)^{71}Ge$	< 0.057	0.126 ± 0.023	
Haxton	Shell Model	0.19 ± 0.18		
Frekers	$^{71}Ga(^{3}He,{}^{3}H)^{71}Ge$	0.040 ± 0.031	0.207 ± 0.016	
JUN45	Shell Model	$(3.30 \pm 1.66) \times 10^{-2}$	$(1.59 \pm 0.79) \times 10^{-2}$	$(4.46 \pm 2.24) \times 10^{-6}$

GALLIUM ANOMALY IS SMALLER, BUT DOES NOT DISAPPEAR

Table 7
Ratios of measured and expected ^{71}Ge event rates in the four radioactive source experiments, their correlated average, and the statistical significance of the gallium anomaly obtained with the cross sections in Table 5.

	GALLEX-1	GALLEX-2	SAGE-1	SAGE-2	Average	Anomaly
R_{Bahcall}	0.95 ± 0.11	0.81 ± 0.11	0.95 ± 0.12	0.79 ± 0.08	0.85 ± 0.06	2.6σ
R_{Haxton}	0.86 ± 0.13	0.74 ± 0.12	0.86 ± 0.14	0.72 ± 0.10	0.76 ± 0.10	2.5σ
R_{Frekers}	0.93 ± 0.11	0.79 ± 0.11	0.93 ± 0.12	0.77 ± 0.08	0.84 ± 0.05	3.0σ
R_{JUN45}	0.97 ± 0.11	0.83 ± 0.11	0.97 ± 0.12	0.81 ± 0.08	0.88 ± 0.05	2.3σ

AGREEMENT WITH REACTOR DATA IS SIGNIFICANTLY IMPROVED

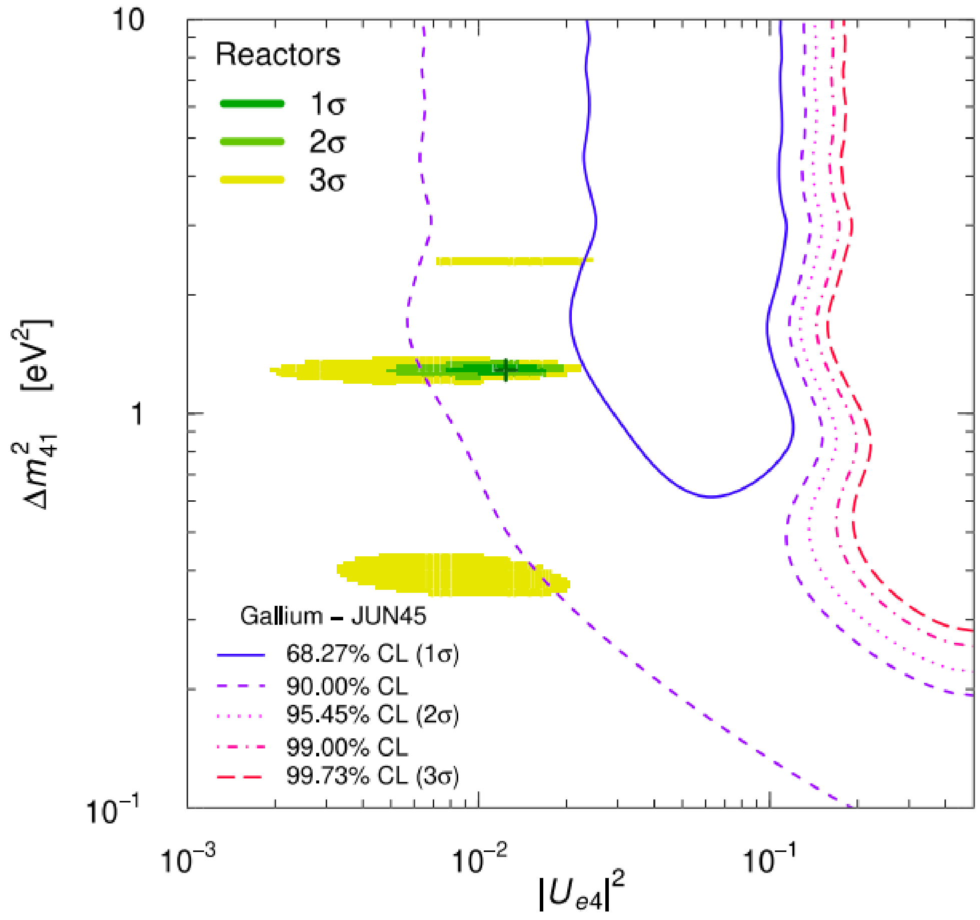


Fig. 4. Comparison of the allowed regions in the $|U_{e4}|^2$–Δm^2_{41} plane obtained from the Gallium data with the JUN45 cross sections and the allowed regions obtained from the analysis of the data of the NEOS, DANSS and PROSPECT reactor experiments.

Fig. 4 shows the comparison of the allowed regions in the $|U_{e4}|^2$–Δm^2_{41} plane obtained with our JUN45 shell model for different confidence levels with the regions obtained from the combined analysis of the data of the NEOS and DANNS reactor experiments, to which we have added the more recent data of the PROSPECT [48] reactor experiment that excludes large values of $|U_{e4}|^2$ for $0.7 \lesssim \Delta m^2_{41} \lesssim 7\,\mathrm{eV}^2$. One can see that there is an overlap of the 90% CL allowed regions, indicating a reasonable agreement between the gallium anomaly and the reactor data. The corresponding parameter goodness of fit is a favorable 16% ($\Delta\chi^2/\mathrm{NDF} = 3.6/2$).

SUMMARY

- Experimental limits of three transitions are closing in on theoretical half-lives.
- Good test cases for nuclear models.
- Shell-model calculations can give insights regarding charge-exchange reactions.
- Conflict between reactor antineutrino anomaly and the gallium anomaly is mitigated by the new calculations.

SUMMARY

Decays soon to be discovered:

^{76}Ge:

$\sim 2.6 \times 10^{24}$ yr (shell model)

*$> 7.5 \times 10^{23}$ yr ** (exp. limit)*

^{48}Ca:

$\sim 8 \times 10^{20}$ yr (shell model)

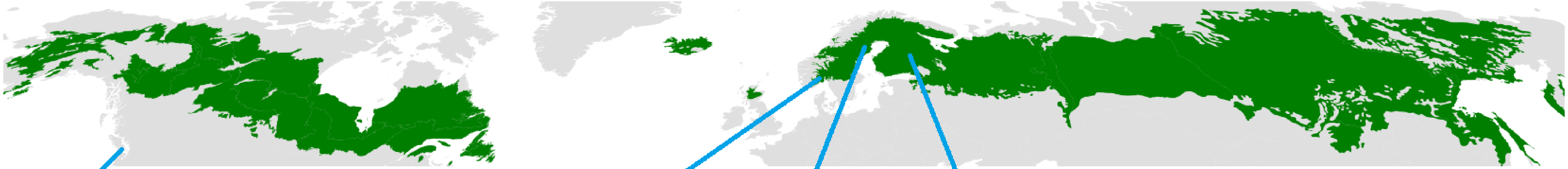
*$> 2.5 \times 10^{20}$ yr * (exp. limit)*

^{96}Zr:

$\sim 1 \times 10^{20}$ yr (shell model)

*$> 3.8 \times 10^{19}$ yr ** (exp. limit)*

WHAT AM I WORKING ON CURRENTLY?



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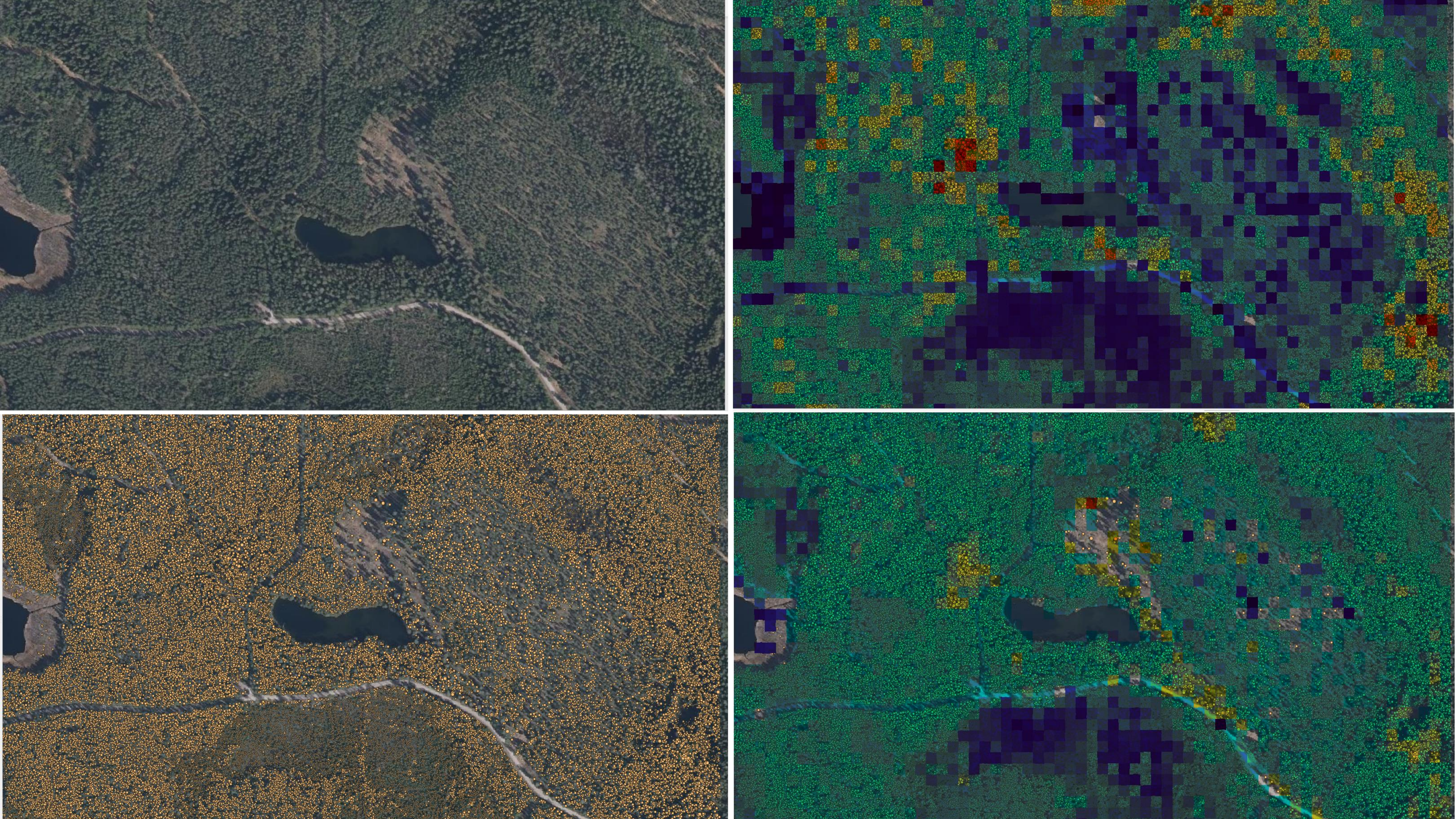
DigiTForest-project

- Four year project to create a digital twin of Boreal zone biodiversity
- > 1 000 000 € budget
- 2 postdoc positions

Research Council of Finland



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Joel Kostensalo [a], Riitta Lemola [b], Tapio Salo [b], Liisa Ukonmaanaho [c], Eila Turtola [b],

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Research article

Methodological choices in size and density fractionation of soil carbon reserves – A case study on wood fiber sludge amended soils

Riikka Keskinen [a,*], Johanna Nikama [a], Joel Kostensalo [b], Mari Räty [c], Kimmo Rasa [a], Helena Soinne [d]

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THANK YOU!