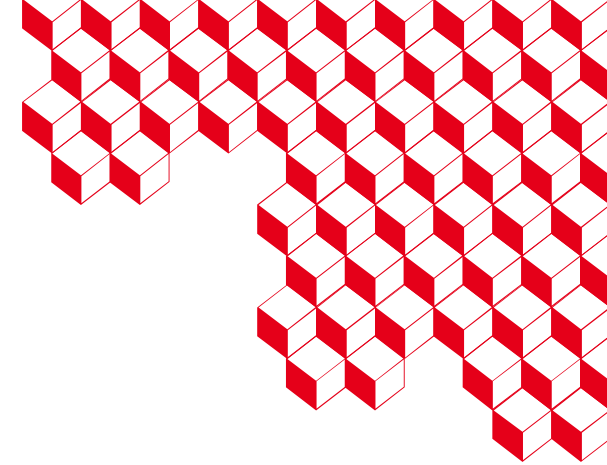




Beta decay from the nuclear data perspective

X. Mougeot, CEA-LNHB (France)

ESNT workshop 2026 – Saclay



Importance of beta decays

Metrology

Activity measurements

(Liquid scintillation,
ionization chambers)



Better knowledge → **Improvement of accuracy and uncertainties**

Fundamental research

Nuclear astrophysics (*r*-process)

Neutrino physics (reactor anomaly,
reactor monitoring, non-proliferation)

Standard Model (CKM matrix unitarity, weak
magnetism)

New physics (Fierz interference, sterile
neutrino, dark matter)



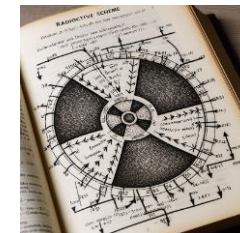
Nuclear decay data

ENSDF, DDEP, JEFF databases

Properties calculated with the
LogFT legacy code

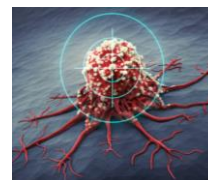
(Gove and Martin, 1971)

log-*ft* for $J\pi$ assignment, no beta spectrum



Medical applications

Micro-dosimetry, internal
radiotherapy, contamination



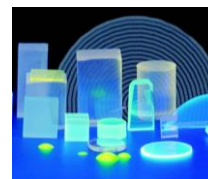
Nuclear fuel cycle

Decay heat, nuclear waste

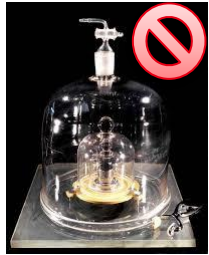


Developments

Beta-voltaic batteries, new
detectors (e.g. LaBr₃)



Radionuclide metrology



LNHB (National Laboratory Henri Becquerel) is the French Designated Institute for primary standards in ionizing radiation metrology.

→ **Definition of activity (Bq) and dose (Sv, Gy) units.**

The diversity of radioactive processes makes necessary a certain pre-knowledge to establish primary and secondary standards: decay schemes, atomic and nuclear data.

→ **Evaluation of atomic and nuclear decay data.**

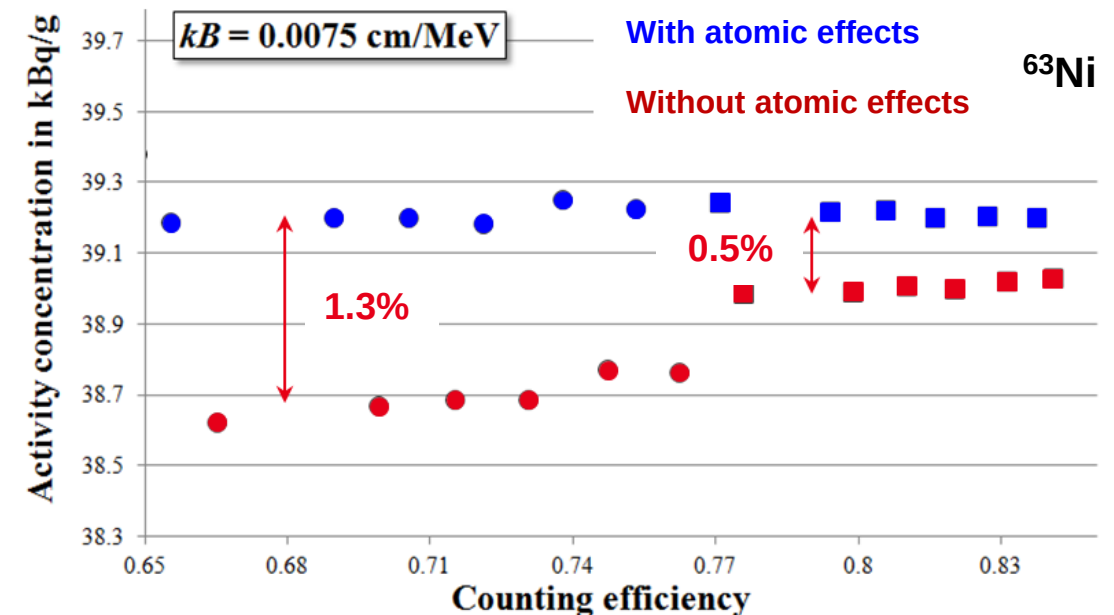
- ✓ Coordination of the DDEP (Decay Data Evaluation Project) international collaboration.
- ✓ Decay data officially recommended by the BIPM.

Extension of SIR to almost pure beta emitters

- Primary activity by liquid scintillation counting.
- Strong non-linear efficiency at low energy.
- **Sensitivity to beta spectrum shape**

Estimate of deposited dose in patient's cells

→ **Impact at DNA level**

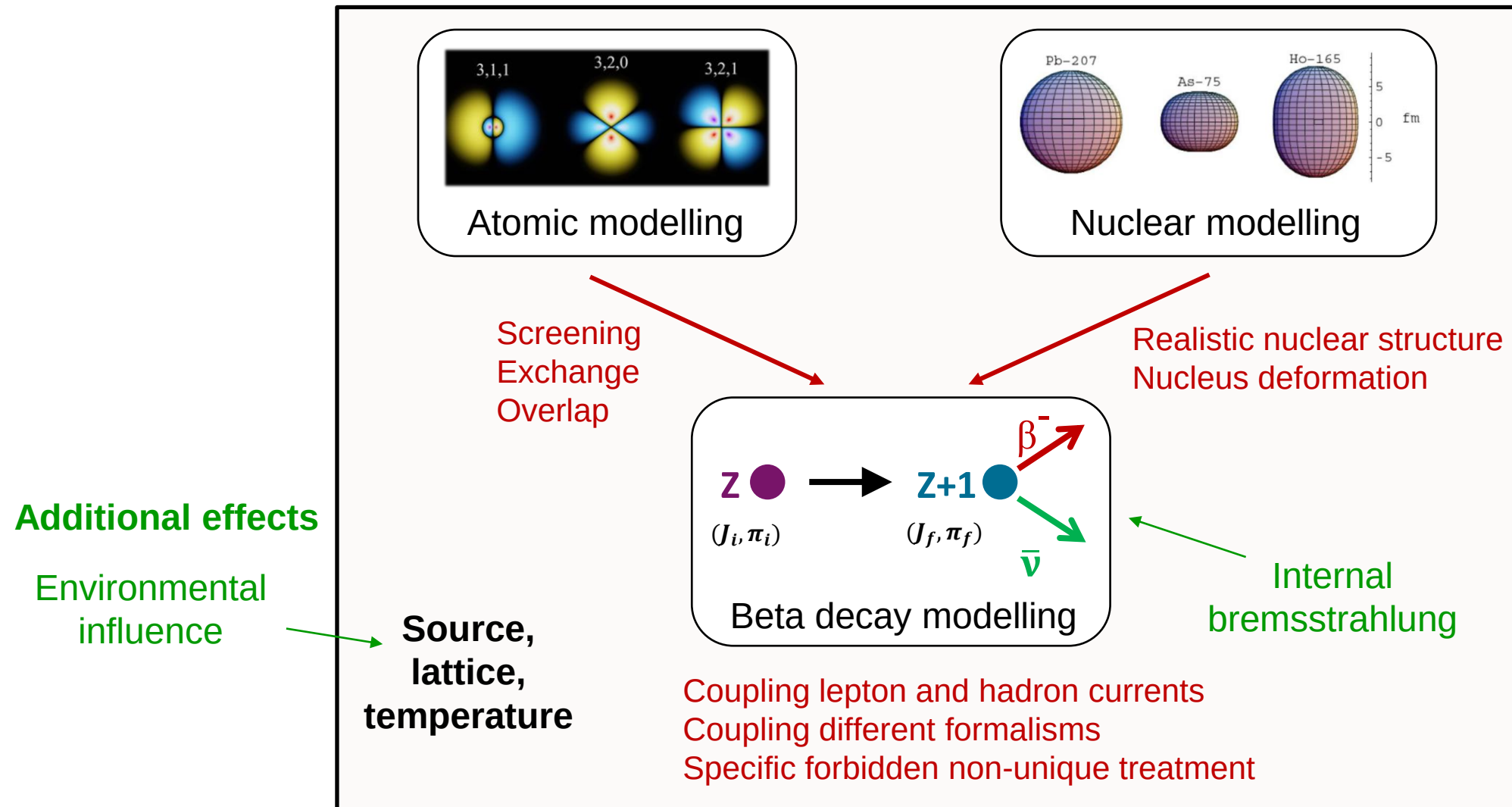


^{63}Ni K. Kossert, X. Mougeot, Appl. Radiat. Isot. 101, 40 (2015)

^{60}Co K. Kossert et al., Appl. Radiat. Isot. 134, 212 (2018)

$^{90}\text{Sr}/^{90}\text{Y}$ K. Kossert, X. Mougeot, Appl. Radiat. Isot. 168, 109478 (2021)

Overview of an ideal modelling





Radioactive decay databases

Current situation

Weak interaction properties in nuclear decay data are incomplete and come from calculation: mean energies, capture probabilities, log- ft values.

→ **Not measured values**

They have been determined for the last 50 years with the LogFT code, developed in the late 1960's.

Quite simple analytical models of beta transitions and electron captures. Limited in forbiddenness degree.



→ **ENSDF and DDEP evaluations up to 2023.**

Decay data in JEFF

CEA-LNHB is responsible for the Radioactive Decay Data Library in JEFF.

JEFF 3.3 (2017): Decay data in JEFF 3.3 resulted from several years of work of three scientists with high expertise: Olivier Bersillon (CEA/DAM), Mark A. Kellett (CEA-LNHB) and Alan L. Nichols (AIEA and University of Surrey).

EPJ Web of Conferences **146**, 02009 (2017)
ND2016

DOI: 10.1051/epjconf/201714602009

The Decay Data Evaluation Project (DDEP) and the JEFF-3.3 radioactive decay data library: Combining international collaborative efforts on evaluated decay data

Mark A. Kellett^{1,a} and Olivier Bersillon^{2,b}

The codes developed to generate the decay data for JEFF 3.3 have been permanently lost.

→ **New codes – developed from scratch – are urgently required for future JEFF releases.**

Minimal update for JEFF4.0: two nuclei (⁹⁹Tc, ²⁴²Am)

+ recently published TAGS data (⁹³Rb, ^{96gs}Y, ^{96m}Y, ⁹⁹Y, ¹⁰³Tc, ¹⁰⁸Tc, ¹³⁸I, ¹⁴²Cs).

Strict energy balance

Strict balance (intensities, energies) is needed for reactor applications

For each nucleus, ENDF-6 format requires the average energies of the decay products:

- **Either grouped:** all light particles + all electromagnetic radiations + all heavy particles.
- **Or detailed:** β^- , β^+ , Auger, conversion electrons, γ -ray, X-ray, internal Bremsstrahlung, annihilation, α , recoil, spontaneous fission, prompt/delayed neutrons, protons, and (anti)neutrinos.

Such information is not provided in the decay data evaluations

- Must be determined consistently with the decay scheme, which may not be properly normalized.
- Intensity of a global decay mode is not sufficient to accurately determine average energies.
- Accurate treatment of the β transitions is challenging.

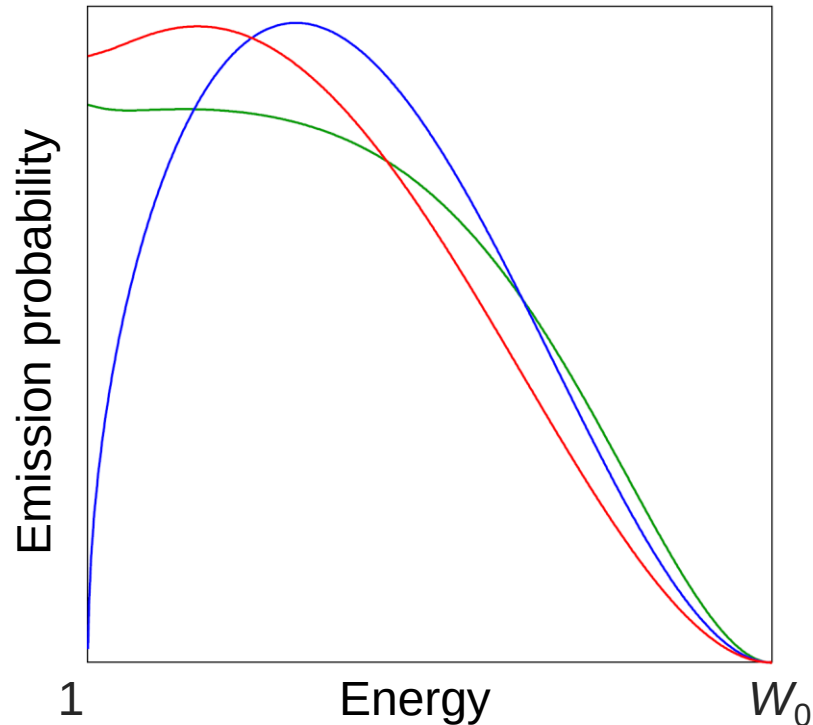


Allowed and forbidden unique transitions

Beta spectrum shape

Phase space Fermi function Shape factor

$$\frac{dP}{dW} \propto \boxed{pWq^2} \cdot \boxed{F(Z, W)} \cdot \boxed{C(W)}$$



W electron energy, W_0 transition energy

p electron momentum, q neutrino momentum

Allowed

$$C(W) = 1$$

First forbidden unique

$$C(W) = q^2 + \lambda_2 p^2$$

Second forbidden unique

$$C(W) = q^4 + \lambda_2 q^2 p^2 + \lambda_3 p^4$$

Third forbidden unique

$$C(W) = q^6 + \lambda_2 q^4 p^2 + \lambda_3 q^2 p^4 + \lambda_4 p^6$$

Etc.

- ✓ The BetaShape program (version 2.4) now replaces the LogFT code for the new ENSDF evaluations. Electron captures also treated.
→ Available on IAEA-NSDD GitHub: <https://github.com/IAEA-NSDDNetwork>
- ✓ $F(Z, W)$ and λ_k parameters determined from the relativistic electron wave functions, obtained by numerical solving of the Dirac equation.
- ✓ Included: extended nucleus; atomic exchange, overlap and screening; radiative corrections; database of experimental shape factors.

For forbidden non-unique transitions, coupling with nuclear structure is necessary.

→ ξ -approximation possible but accuracy is questionable.

New review of log-*ft* values

Former review of log-*ft* values, calculated with the LogFT code:
B. Singh et al., Nuclear Data Sheets 84, 487 (1998)

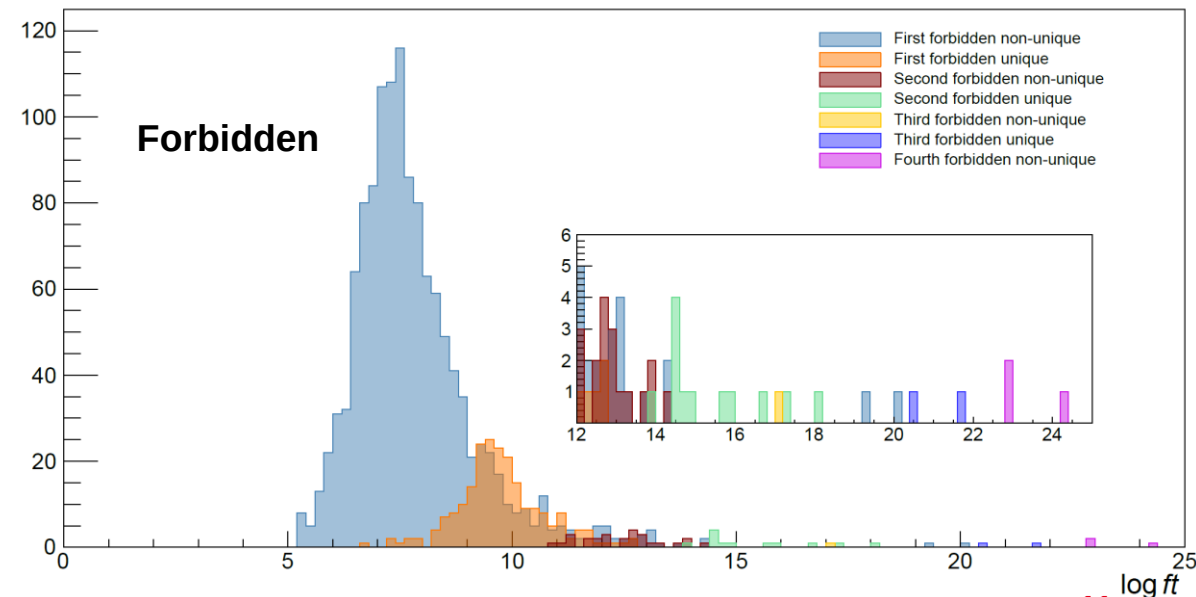
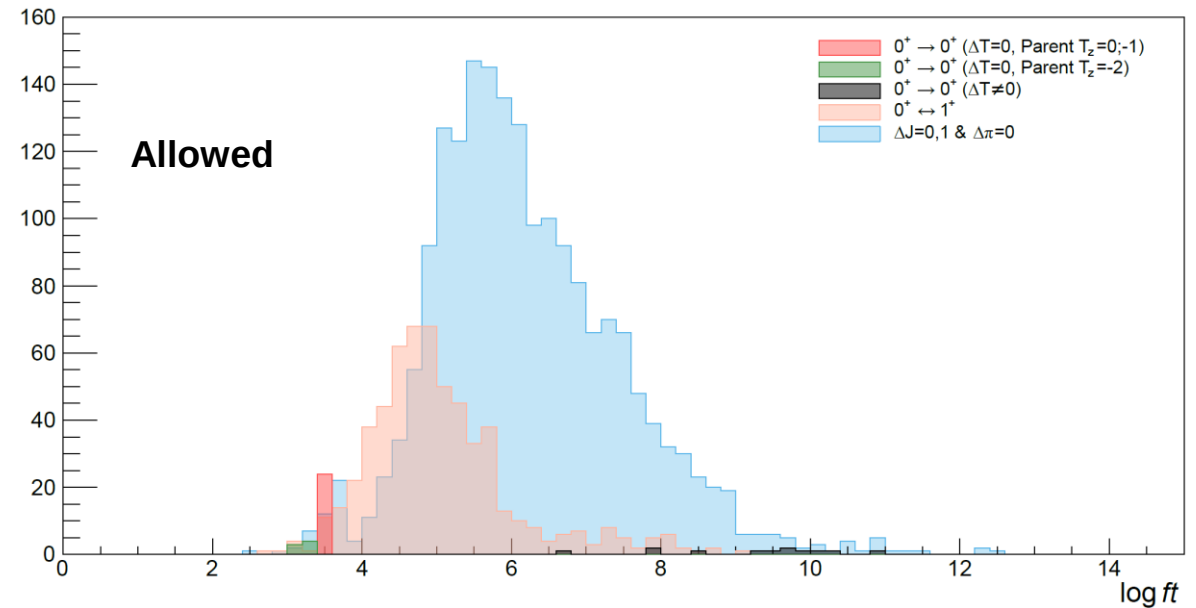
These values are used in nuclear structure studies, e.g. to assign spin and parity to a level.

Collaborative work: B. Singh[†] (McMaster University), S. Turkat and K. Zuber (TU Dresden), X. Mougeot (CEA-LNHB)

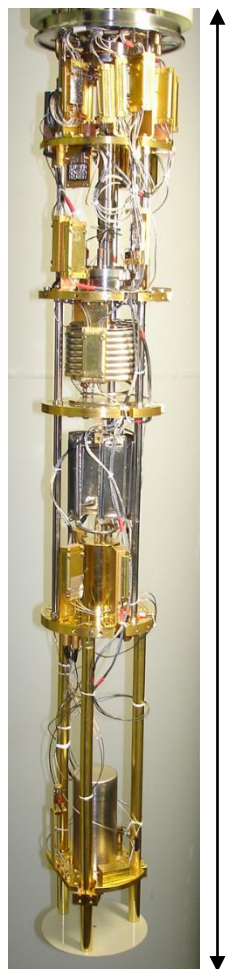
- ✓ Update of B and EC decays present in ENSDF database (as of mid-April 2023).
- ✓ Use of BetaShape to calculate the log-*ft* values.
- ✓ In total, 26 318 transitions calculated. Selection of well-defined transitions. Possible pandemonium nuclei flagged.
- ✓ 4 038 transitions survived this filtering. All distributions re-established. Specific transitions are discussed.

S. Turkat et al., Atomic Data and Nuclear Data Tables 152, 101584 (2023)

[†] Deceased

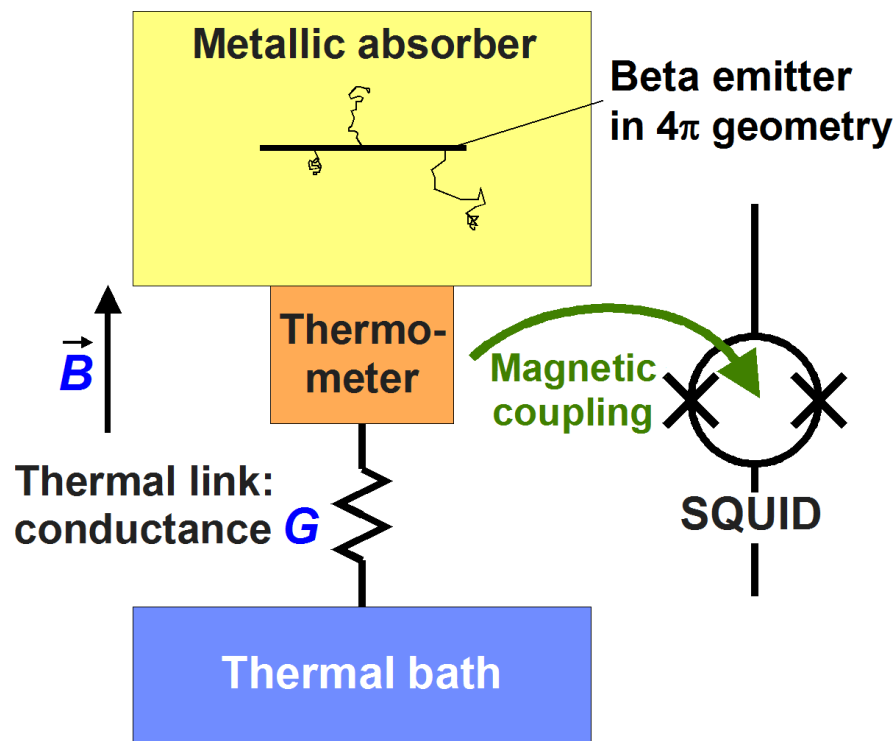


Metallic magnetic calorimetry (MMC)



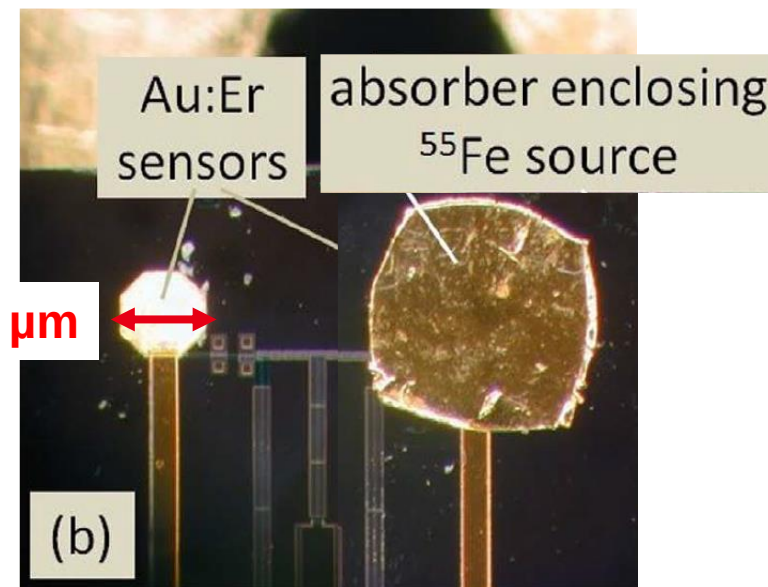
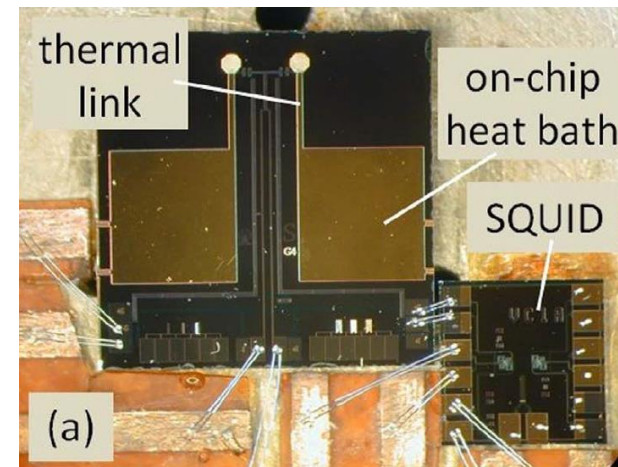
80 cm

Dilution refrigerator
(10 mK)

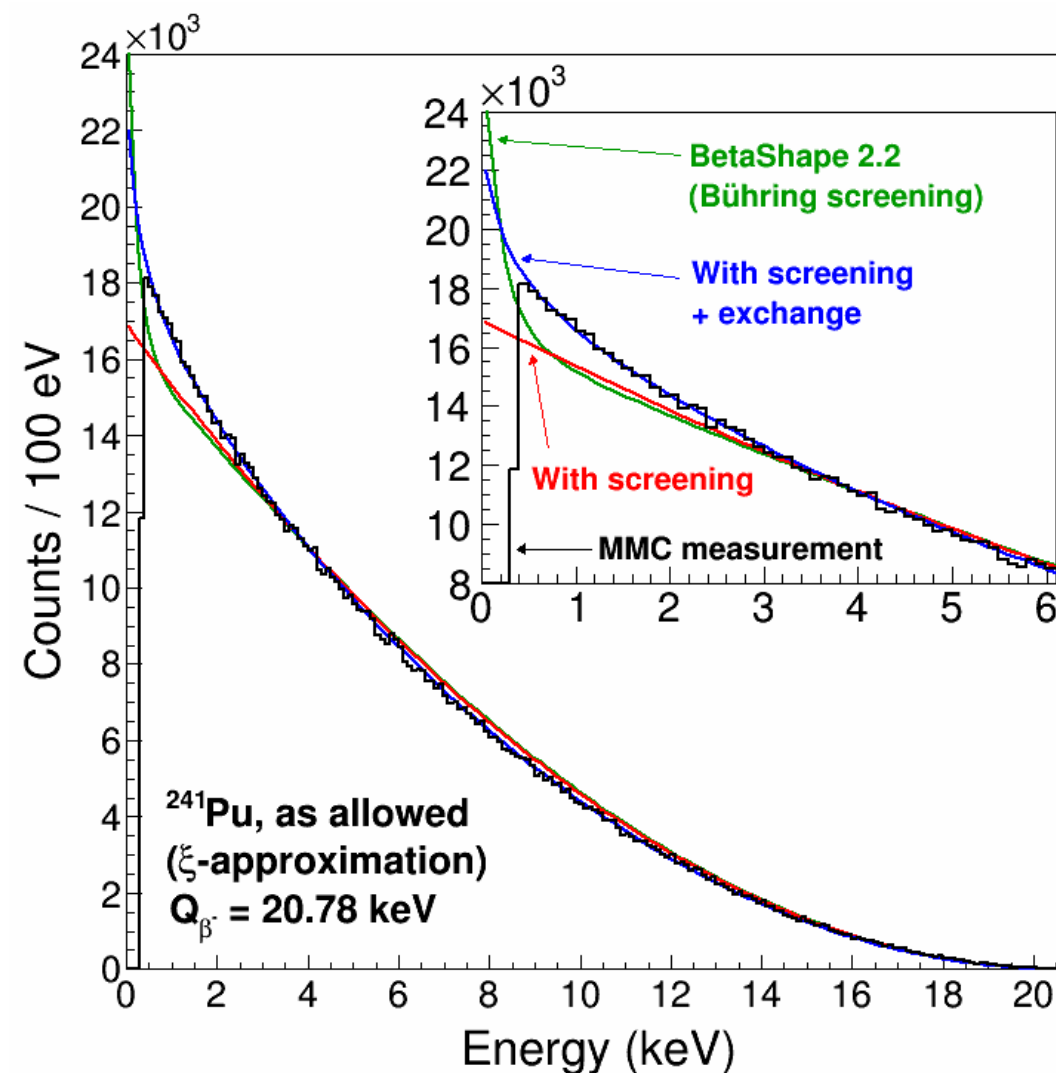
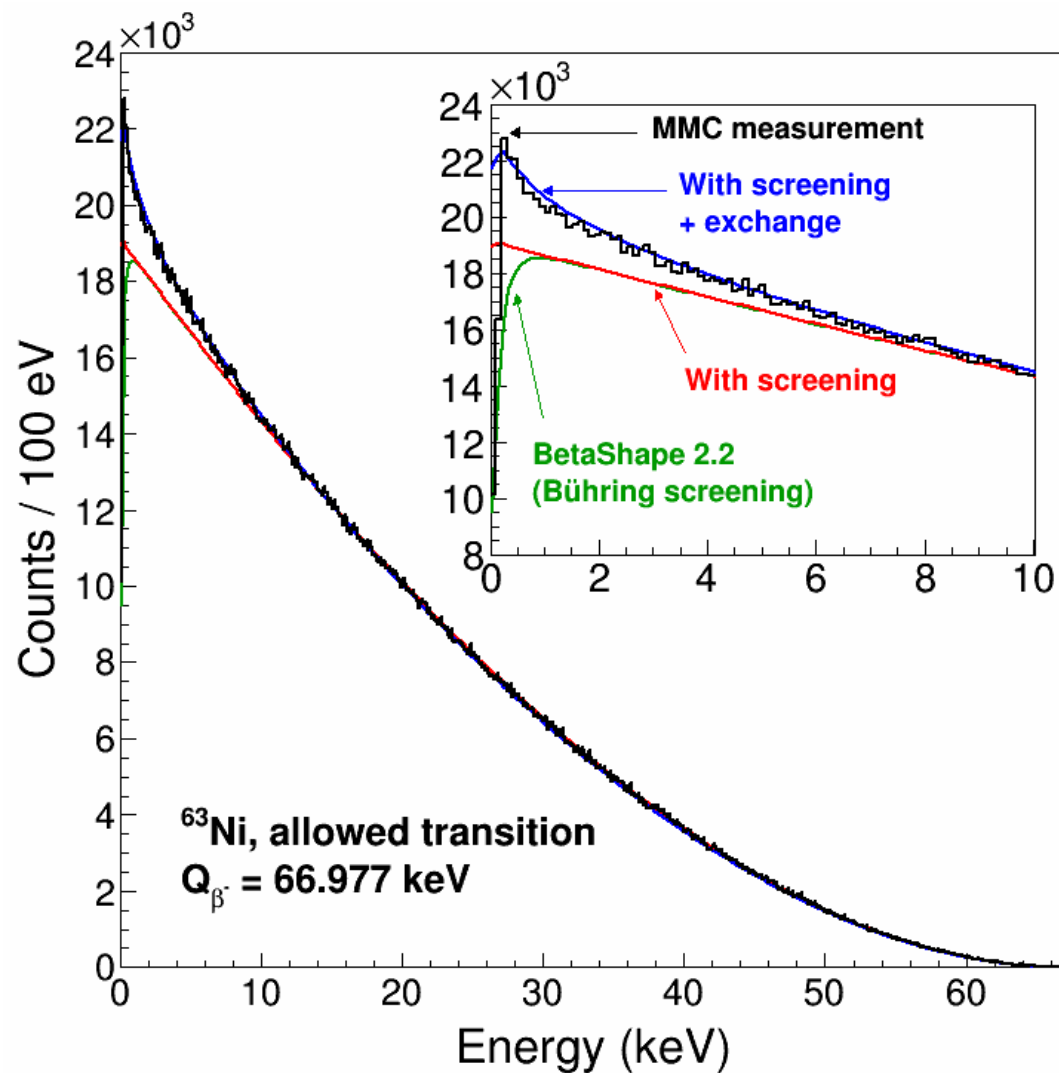


M. Loidl *et al.*, App. Radiat. Isot. 134, 395 (2018)

→ See Matias Rodrigues' talk on Tuesday



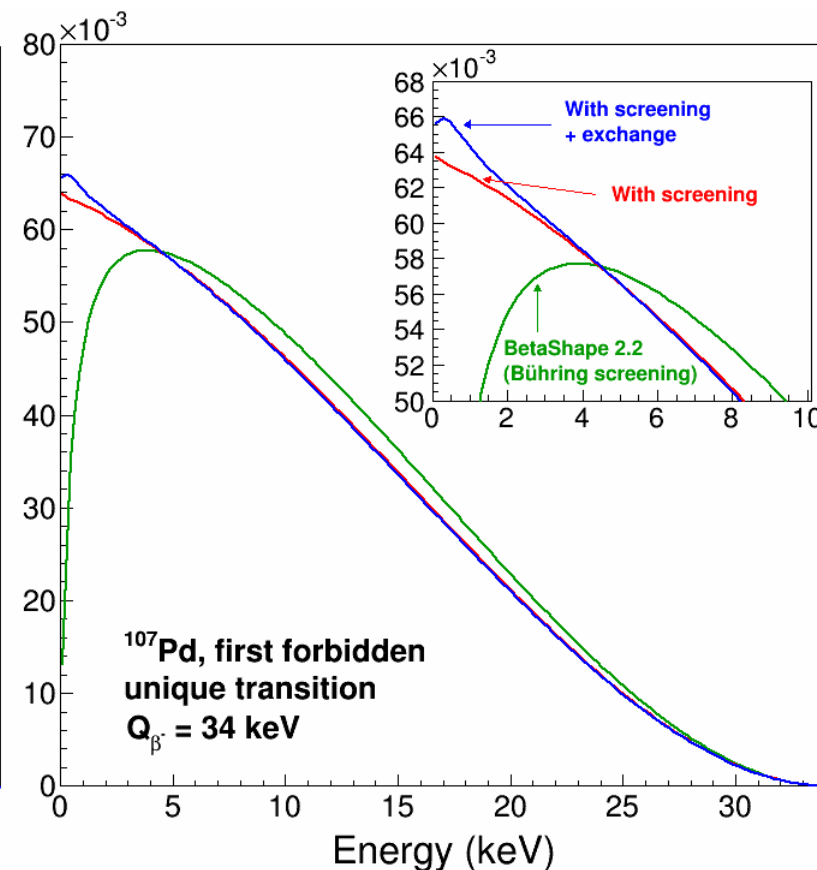
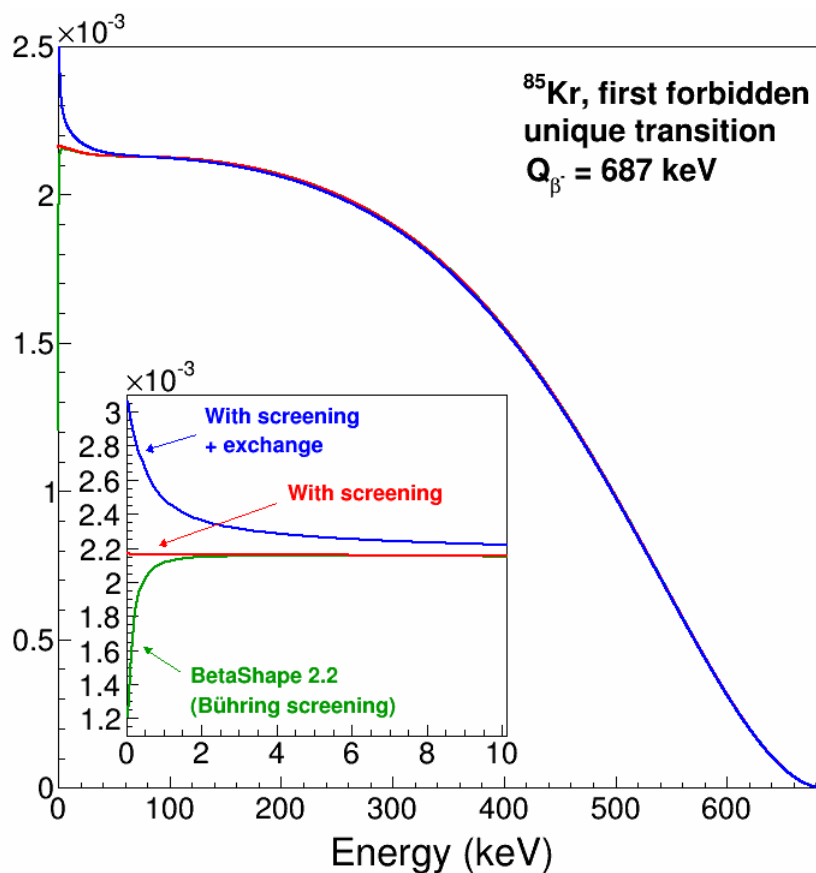
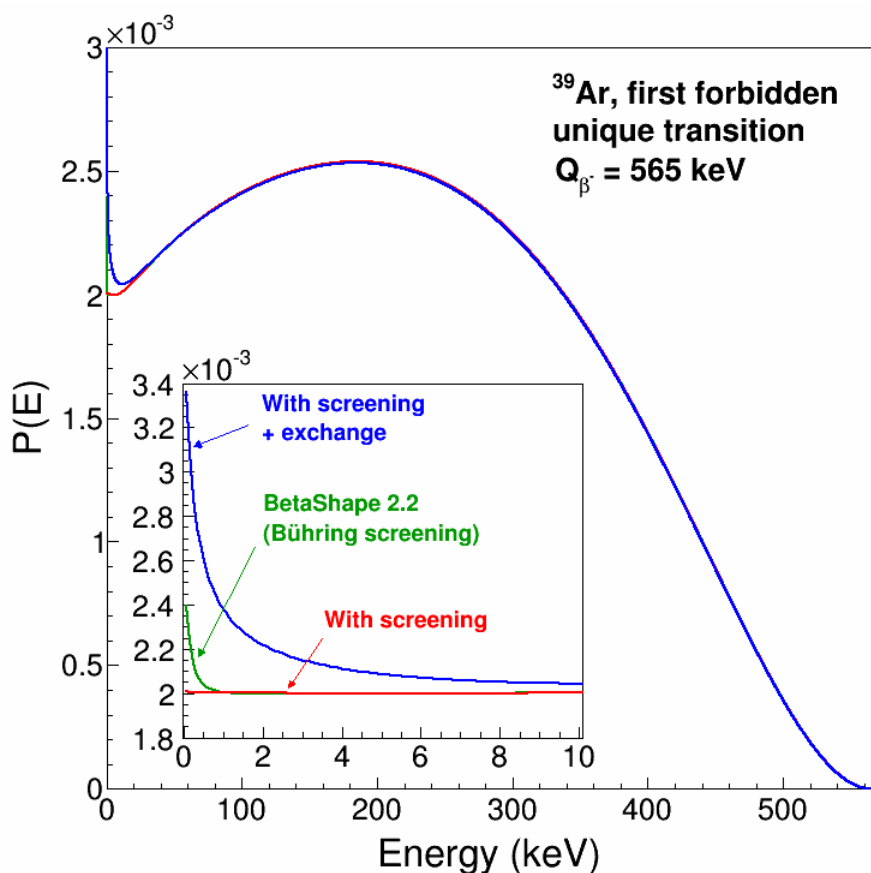
Atomic screening and exchange effects



Extension to forbidden unique transitions

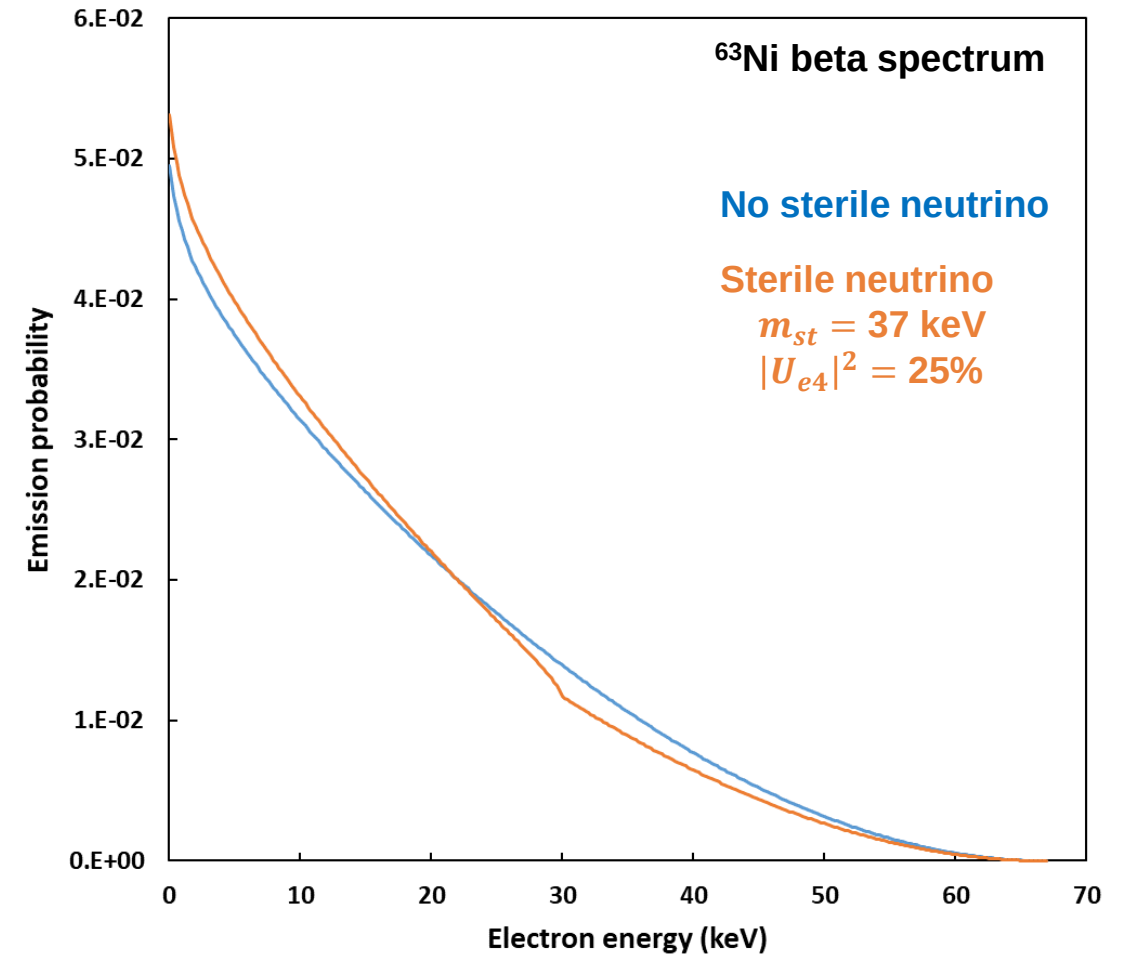
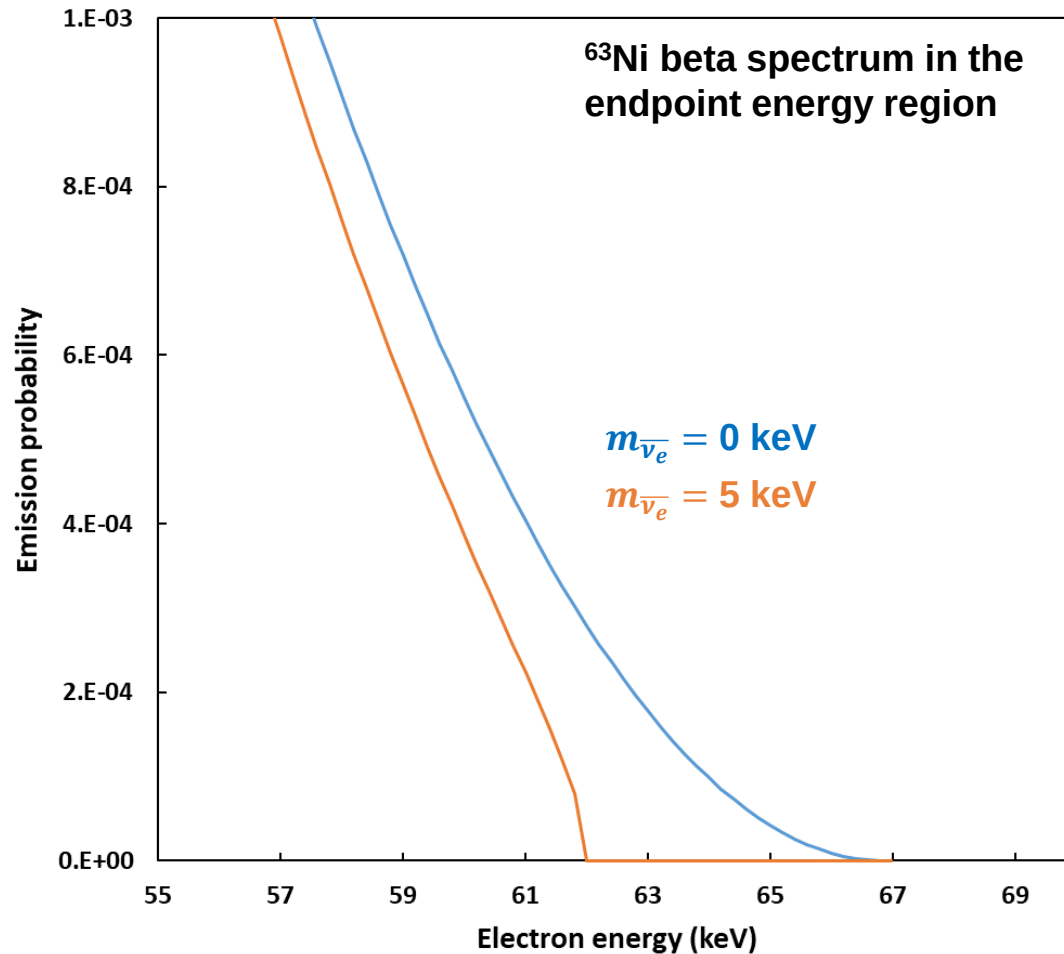
- Contribution of additional atomic orbitals
- Applied to dark matter (DarkSide-50 collaboration)

- ✓ X. Mougeot, *Appl. Radiat. Isot.* 201, 111018 (2023)
- ✓ P. Agnes et al., *Phys. Rev. D* 107, 063001 (2023)

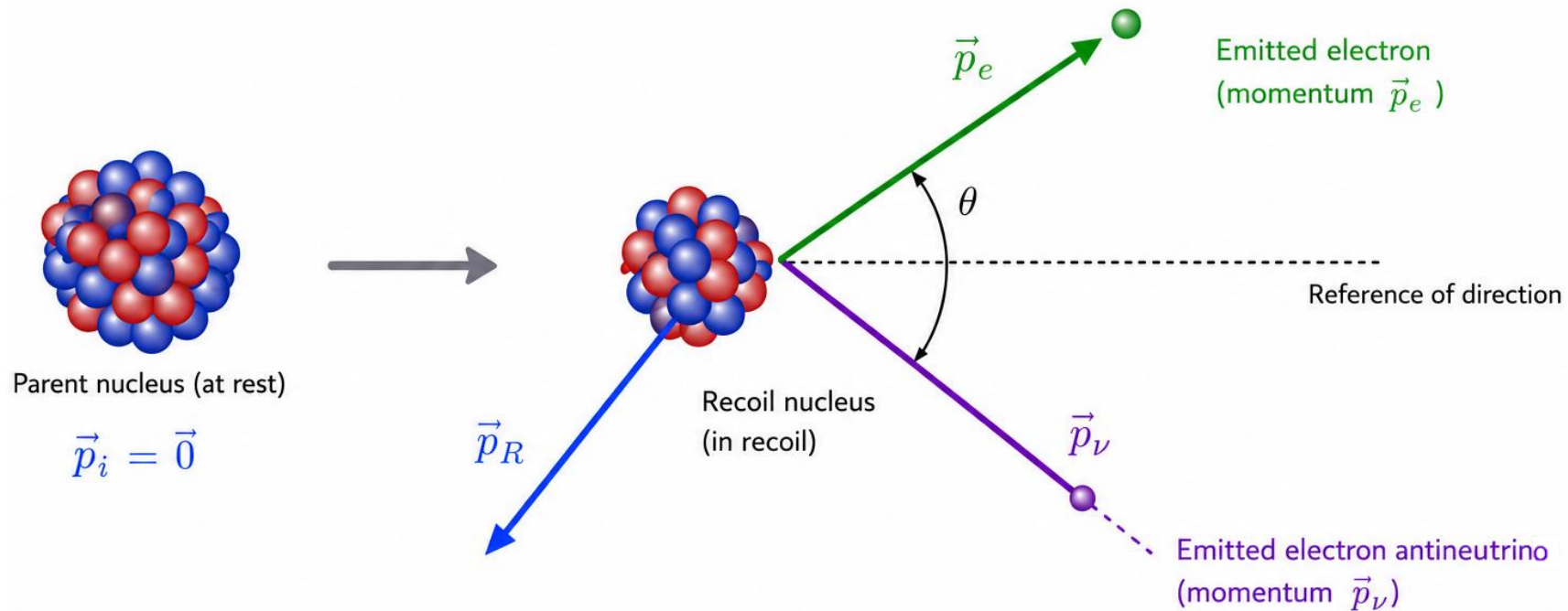


Massive neutrinos

- ✓ Full account of neutrino mass in beta decay formalism.
- **New options:** defining a neutrino mass, and a sterile neutrino.



Nucleus recoil in β decays



✓ 3-body kinematics: momentum and energy conservation

$$\vec{p}_R + \vec{p}_e + \vec{p}_\nu = \vec{0}$$

$$W_R + W_e + W_\nu = M_{\text{nuc},i}$$

✓ Noticeable configurations

- Null β particle energy: $E_R = \frac{(W_0 - m_e)^2 - m_\nu^2}{2(M_{\text{nuc},f} + W_0 - m_e)}$ (symmetric for $E_\nu = 0$)
- Maximum recoil for parallel β and ν , opposite to nucleus recoil:

$$p_{R,\text{max}}^2 = 2M_{\text{nuc},f} \left[M_{\text{nuc},f} + W_0 - \sqrt{(M_{\text{nuc},f} + W_0)^2 - [W_0^2 - (m_e + m_\nu)^2]} \right]$$

Probability density

Prior to integration over the particle directions (neglecting all the correction on the β spectrum):

$$dP = \frac{G_\beta^2}{2\pi^3} [p_e W_e p_\nu W_\nu] \times [F(Z, W_e) C(W_e)] dW_e d\Omega_e d\Omega_\nu$$

→ **Assumption: isotropic spectra and neutrino not observed.**

Energy and momentum conservation leads to:

$$\frac{dP}{dE_R} = \frac{G_\beta^2}{2\pi^3} \int_{W_{e,\min}}^{W_{e,\max}} [p_e W_e p_\nu W_\nu] \cdot [F(Z, W_e) C(W_e)] \cdot \left| \frac{W_R + W_\nu}{p_e p_\nu} + \frac{W_\nu \cos \theta}{p_\nu^2} \right| dW_e$$

Usual integration window $[1, W_0]$ is reduced at each E_R value due to the condition that $|\cos \theta| \leq \pm 1$, from which $W_{e,\min}$ and $W_{e,\max}$ can be deduced.

The integration window closes at $E_R = 0$ and $E_R = E_{R,\max}$ which leads to null probability at both ends of the recoil spectrum.

✓ Integrating the joint density in the same way for both β and ν spectra strictly maintains energy conservation.

Example: ^{11}C decay

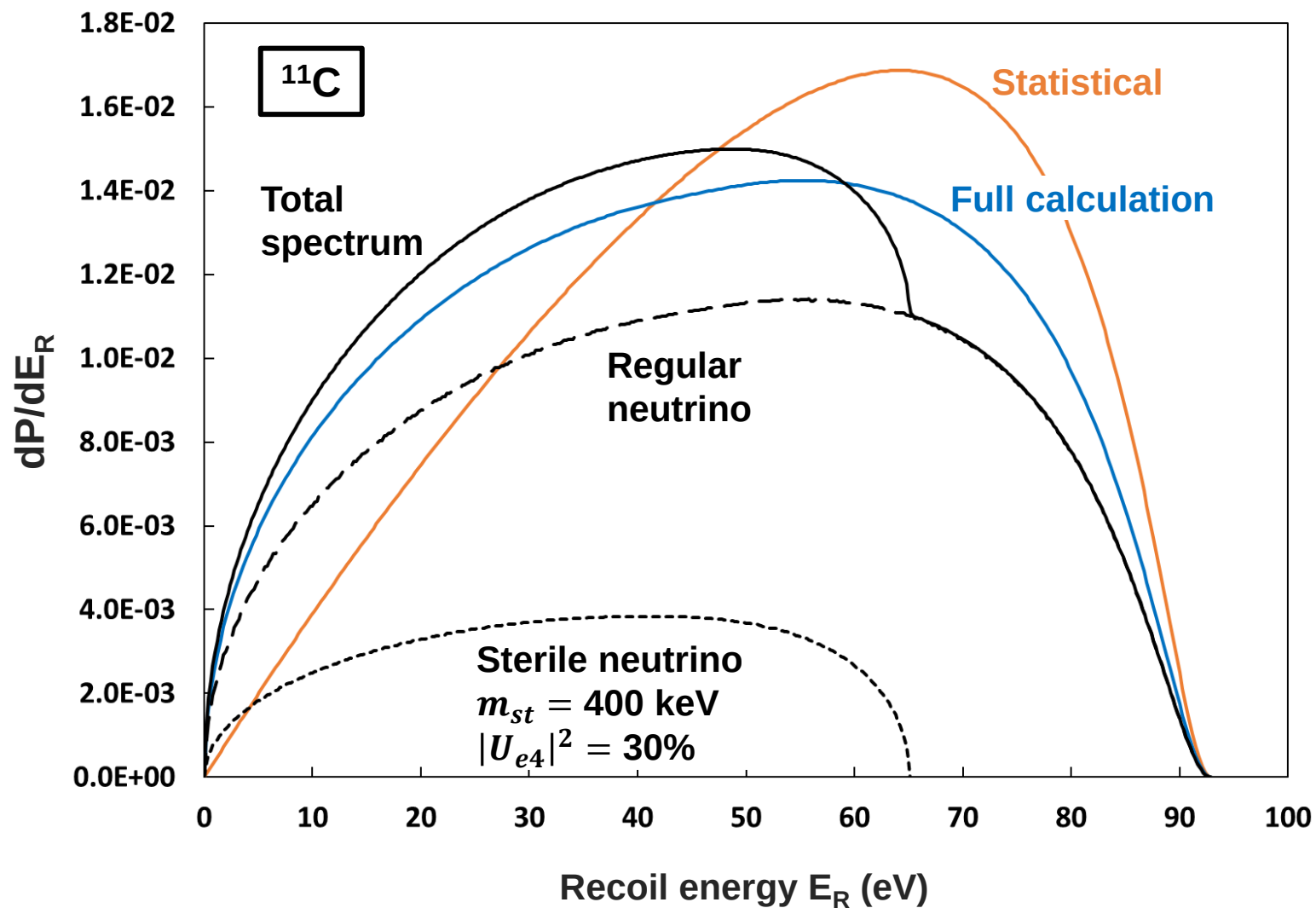
- ✓ 3-body kinematics, full relativistic formalism.
- ✓ Sensitivity to all effects on β spectrum.
- ✓ Accurate energies

$$E_{R,\text{max}} = 92.84 \text{ (14) eV}$$

$$\langle E_R \rangle = 52.51 \text{ (9) eV}$$

$$\langle E_R \rangle = 46.40 \text{ (8) eV}$$

$$\langle E_R \rangle = 44.01 \text{ (8) eV}$$



Internal Bremsstrahlung

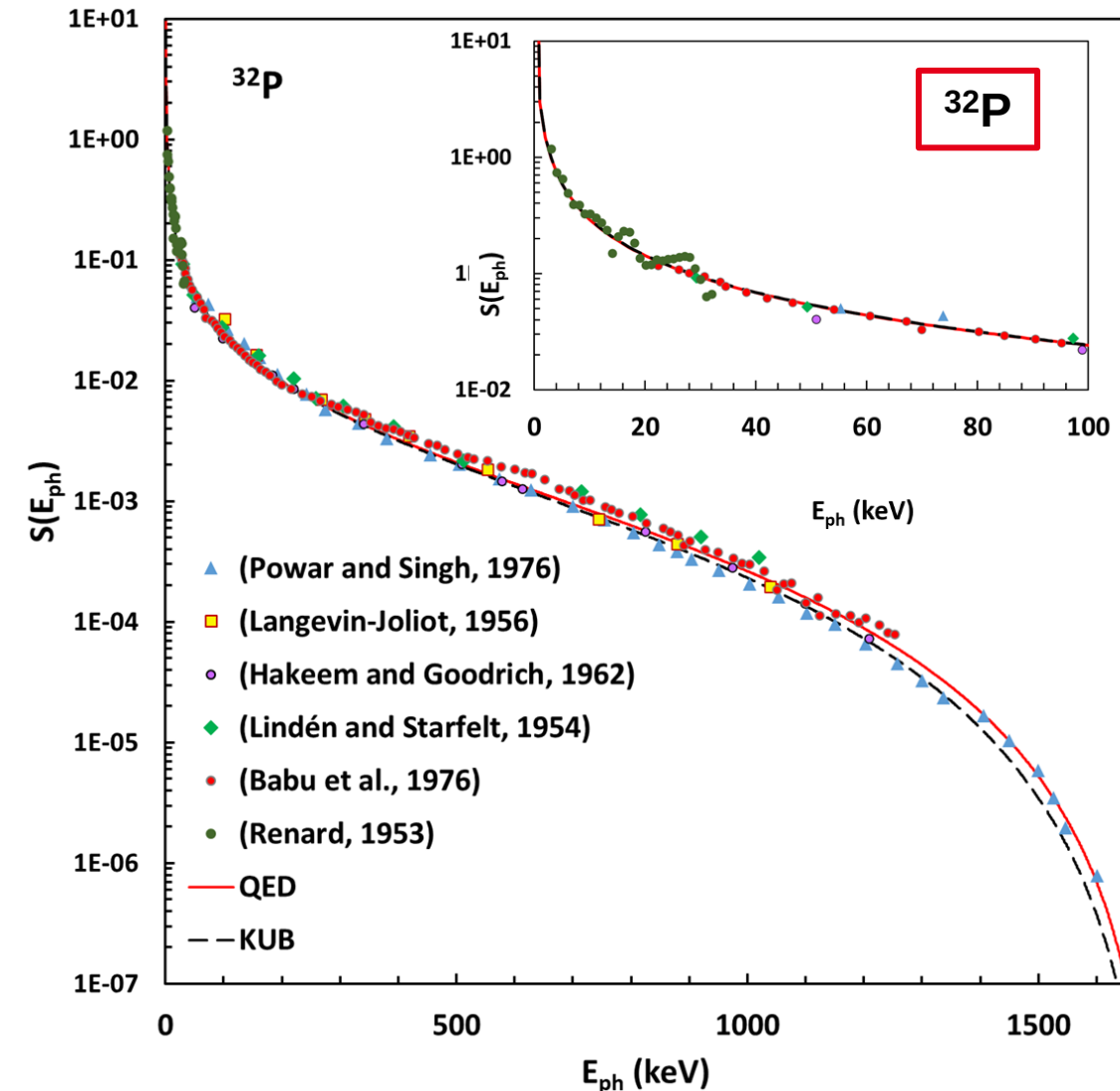
Second-order phenomenon ($\sim 10^{-3}$ %) in β -decays, but produces a continuous photon spectrum.

→ Important for high-activity applications: reactors, nuclear medicine.

Recent development of a dedicated computational code

- ✓ Two theoretical formalisms have been studied and generalized to forbidden β transitions:
 - Simple, without Coulomb effects (Knipp, Uhlenbeck, Bloch, 1936).
 - Precise, derived from QED (Ivanov et al., 2014). With Coulomb effects and nuclear recoil.

Appl. Radiat. Isot. 226, 112197 (2025)



Energy balance

Energy balance

Available energy: 3505.22 (5) keV

Average beta energy: 1559.614 (24) keV

Average antineutrino energy: 1940.181 (26) keV

Average recoil energy: 788.514 (20) eV

Average internal bremsstrahlung energy: 4.63648 (11) keV

--> Sum: 3505.220 (35) keV

Beta spectrum

Energy step: 11 keV

Maximum beta energy: 3503.80 (5) keV

[...] β spectra as in previous version

^6He

Antineutrino spectrum

Energy step: 11 keV

Maximum antineutrino energy: 3504.12 (5) keV

[...] ν spectra as in previous version

Nuclear recoil spectrum

Energy step: 4 eV

Maximum recoil energy: 1415.467 (36) eV

Mean energy from the calculated spectrum: 788.514 (20) eV

Mean energy from the experimental shape factor: 788.056 (20) eV

E(eV)	dN/dE calc.	unc.	dN/dE exp.	unc.
0	0.00000e+00	0.00000e+00	0.00000e+00	0.0
4	7.14063e-05	2.93366e-09	7.19185e-05	2.9
8	1.02541e-04	4.14299e-09	1.03272e-04	4.1

[...] in new version

Internal bremsstrahlung photon spectrum

Energy step: 11 keV

Maximum photon energy: 3504.12 (5) keV

Mean photon energy: 4.63648 (11) keV

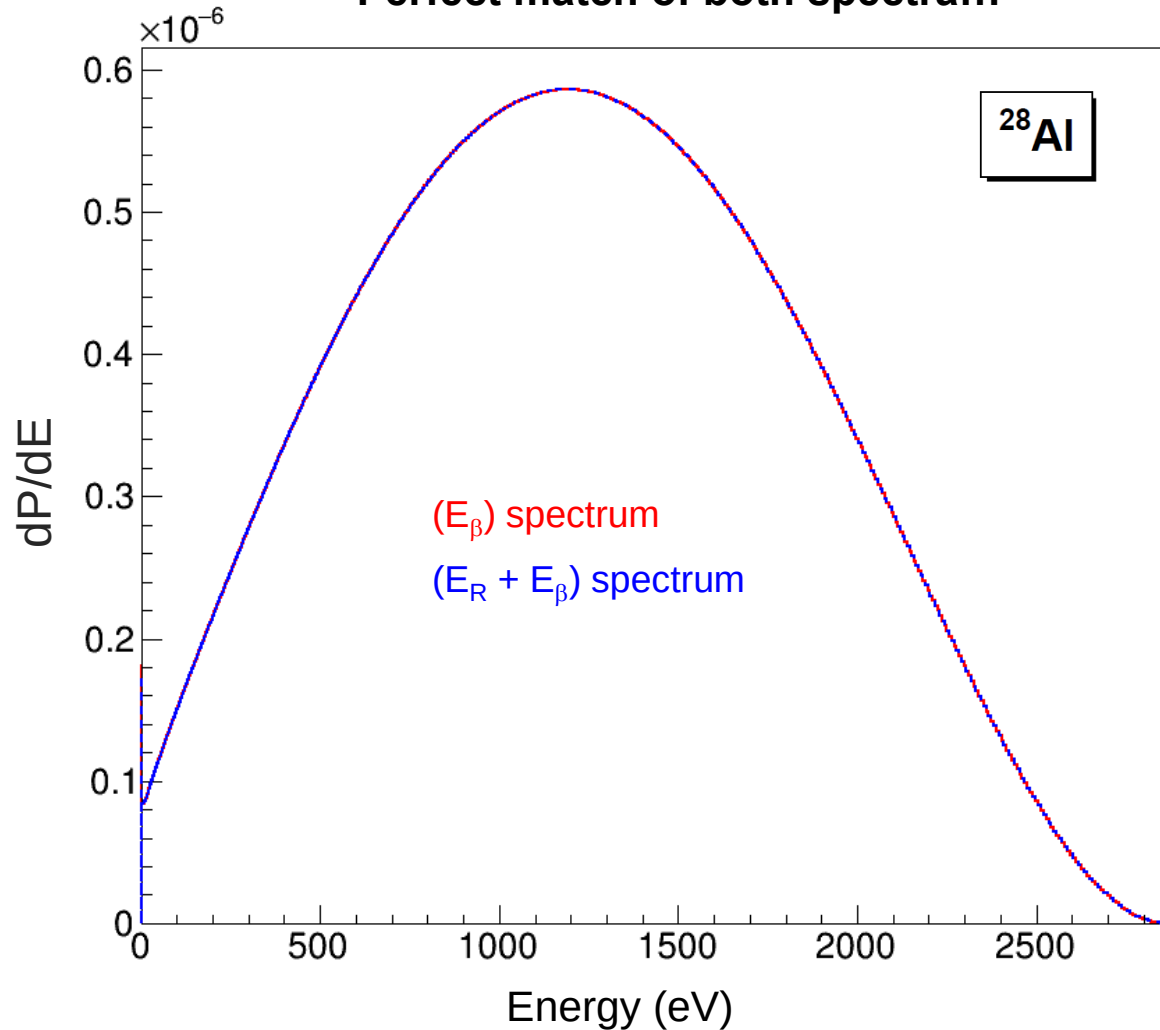
Photon intensity: 1.0328685 (44) %

E(keV)	dN/dE calc.	unc.
0	1.44406e-03	1.70118e-08
11	1.95811e-04	7.60437e-09

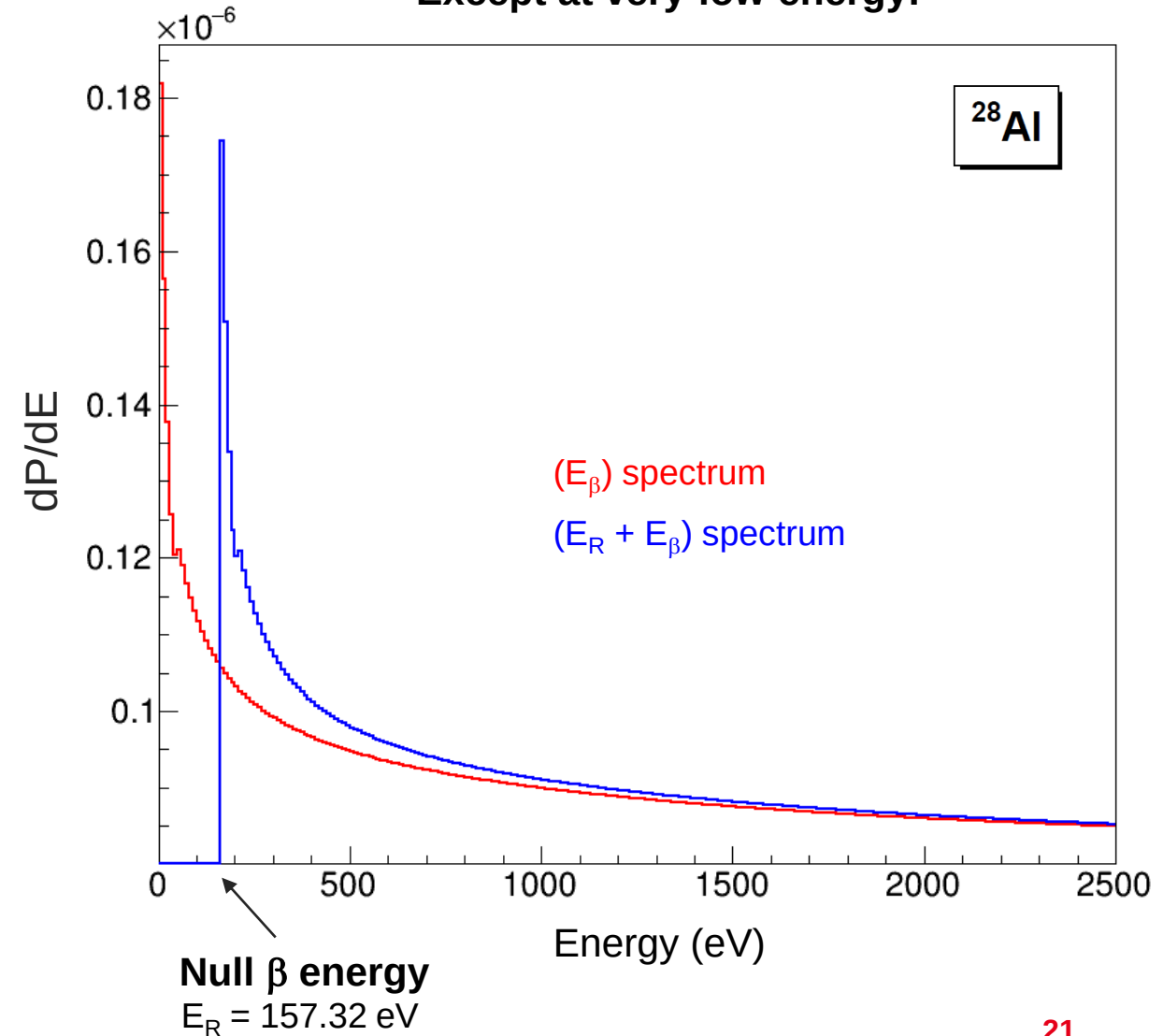
[...] in new version

Startpoint of the β spectrum

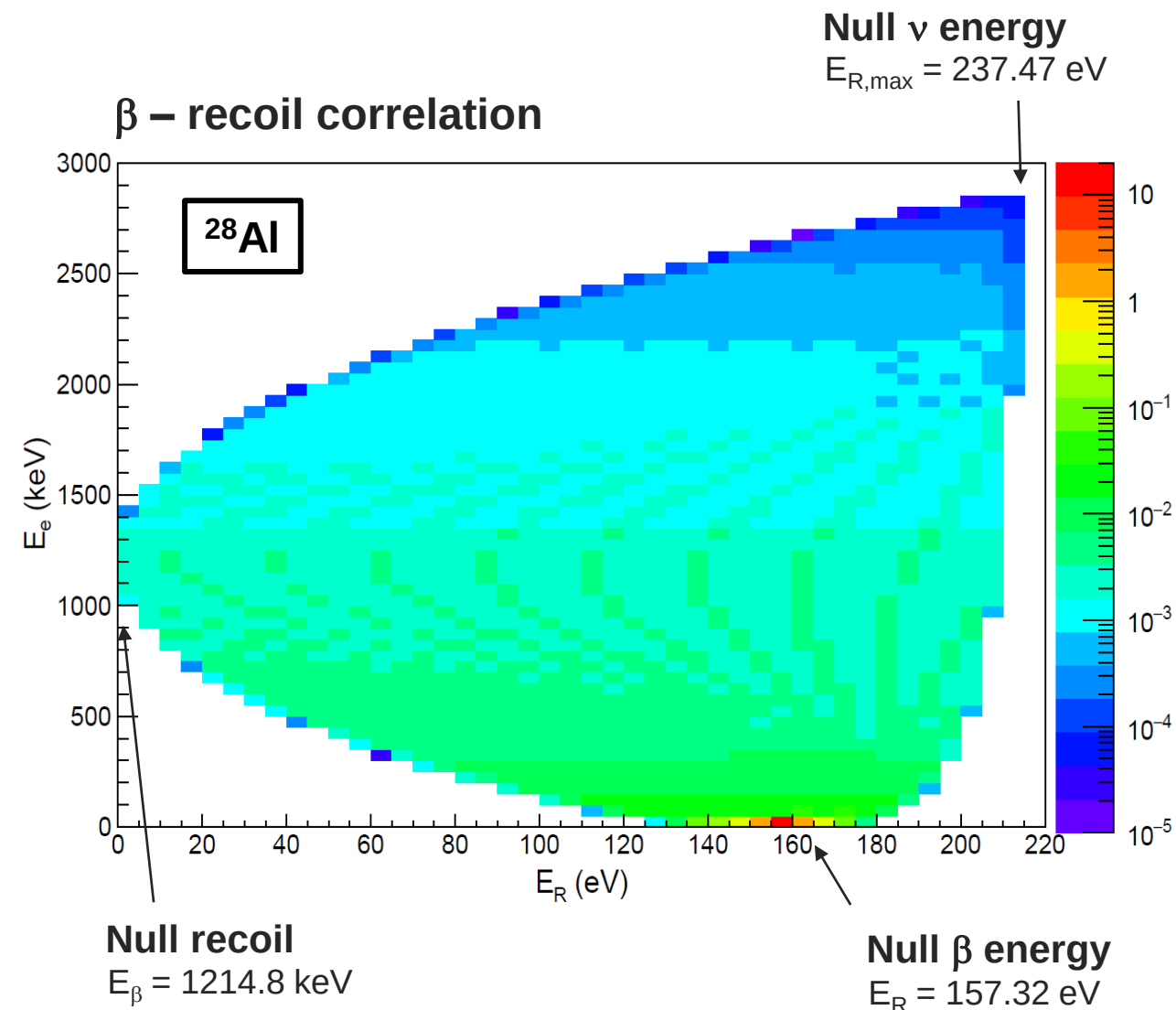
Perfect match of both spectra...



Except at very-low energy!

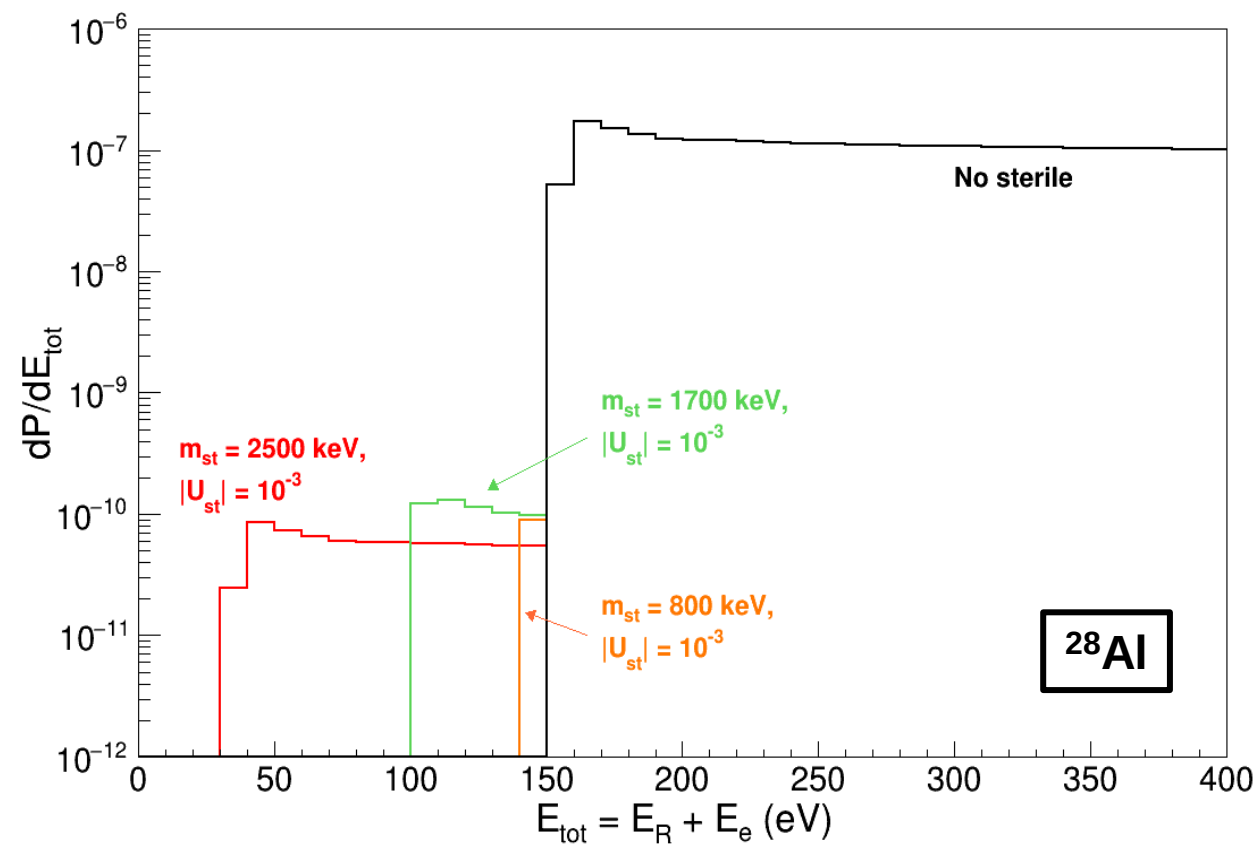


Heavy sterile neutrinos



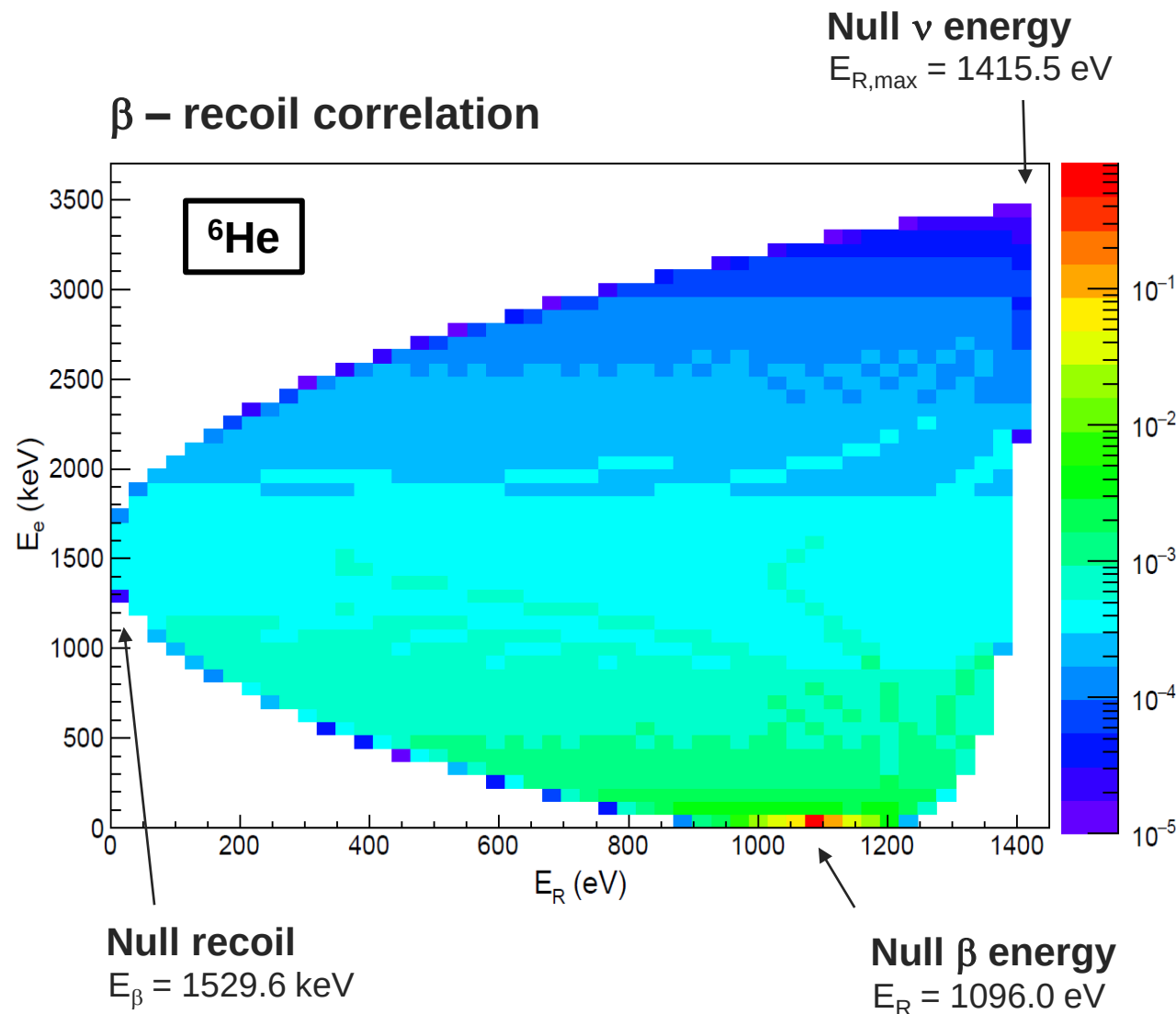
$(\beta + \text{recoil})$ detection: minimum, non-zero energy.

→ **Startpoint of β spectrum sensitive to keV sterile neutrino.**



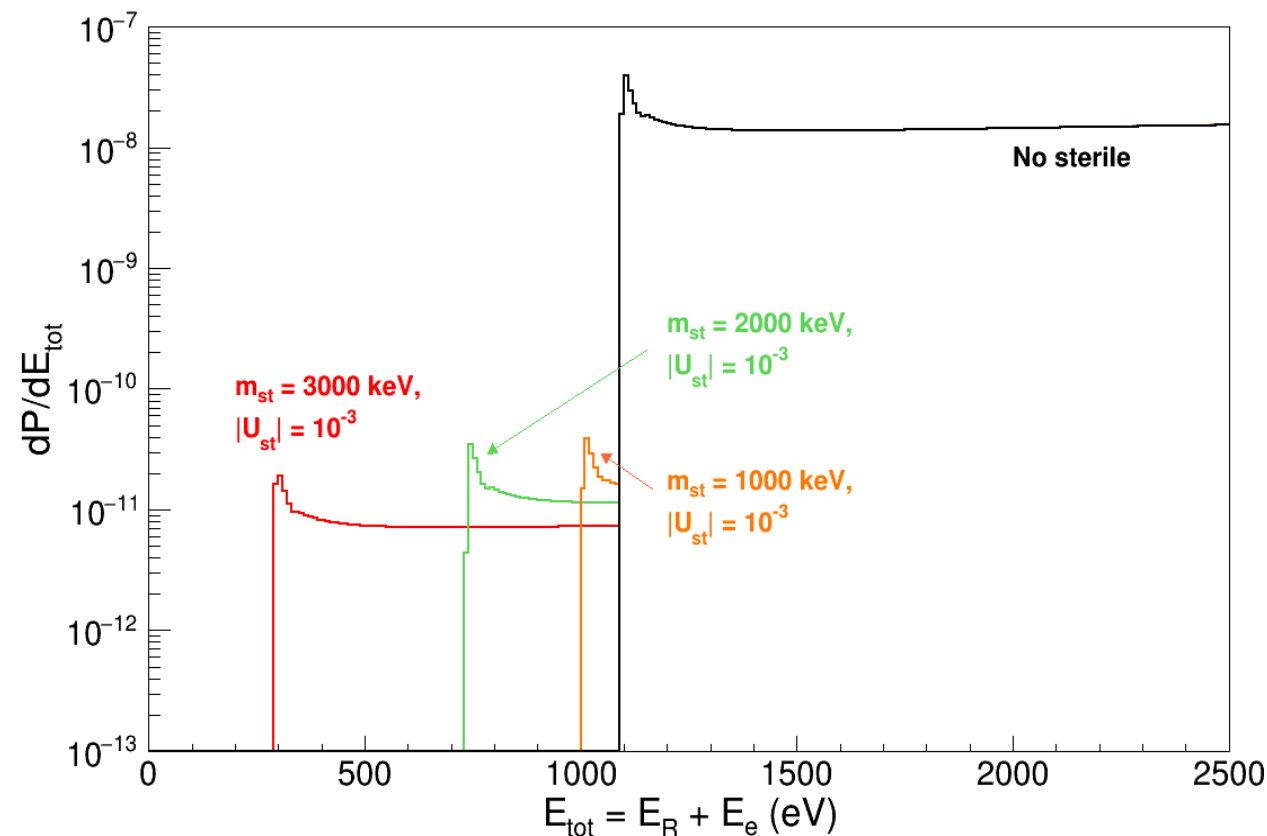
See also: Kodroff, Williams, *Ultralow-Energy Measurements using the Startpoint of β Decays*, <https://doi.org/10.48550/arXiv.2606.15014>

Heavy sterile neutrinos



$(\beta + \text{recoil})$ detection: minimum, non-zero energy.

→ **Startpoint of β spectrum sensitive to keV sterile neutrino.**



See also: Kodroff, Williams, *Ultralow-Energy Measurements using the Startpoint of β Decays*, <https://doi.org/10.48550/arXiv.2606.15014>



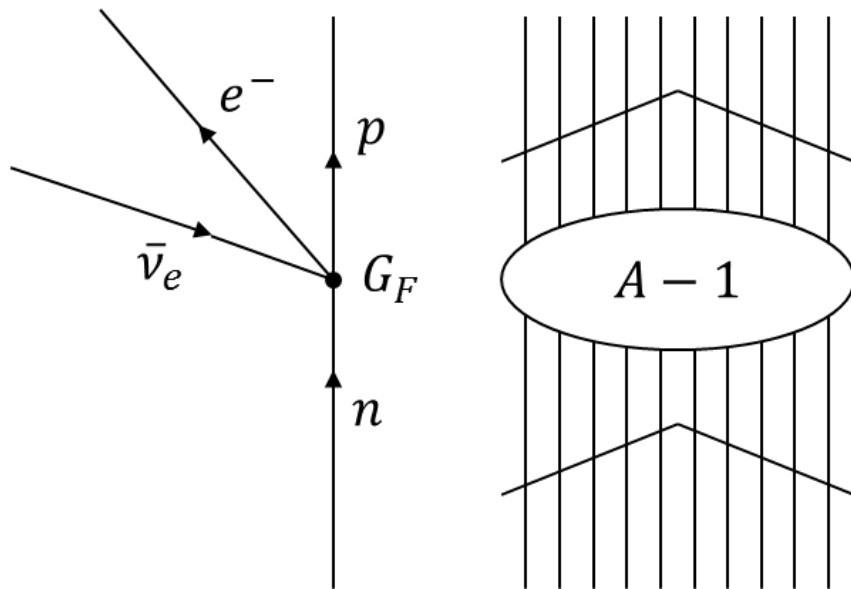
Forbidden non-unique transitions

Theoretical shape factor

$$C(W_e) = \sum_{K k_e k_\nu} \lambda_{k_e} \left[M_K^2(k_e, k_\nu) + m_K^2(k_e, k_\nu) - \frac{2\mu_{k_e} \gamma_{k_e}}{k_e W_e} M_K(k_e, k_\nu) m_K(k_e, k_\nu) \right]$$

H. Behrens, W. Bühring,
*Electron Radial Wave
functions and Nuclear Beta
Decay*, Oxford Science
Publications (1982)

Multipole expansion of lepton and nuclear currents. Calculation of shape factors, half-lives, branching ratios, log-*ft* values.



Fermi theory

- Vertex of the weak interaction is assumed to be point-like. No propagation of $W^\pm$ boson.
- Effective coupling constant G_F .
- Relativistic lepton and nuclear wave functions.
- Non-relativistic and relativistic vector or axial-vector matrix elements.

Impulse approximation

- The nucleon is assumed to feel only the weak interaction.
- Other nucleons are spectators.

Realistic nuclear structure

Nuclear state described as a **superposition of nucleon states**.

One-body transition densities must be given by a nuclear structure model.

$$\langle \xi_f J_f || T_\lambda || \xi_i J_i \rangle = \hat{\lambda}^{-1} \sum_{a,b} \langle a || T_\lambda || b \rangle \langle \xi_f J_f || [c_a^\dagger \tilde{c}_b]_\lambda || \xi_i J_i \rangle$$

transition matrix element tensor rank single particle matrix element one-body transition density (OBTD)

Transition described as a sum of transformations of single nucleons.

Example:
Nonrelativistic vector
matrix element

$${}^V \mathcal{M}_{KK0}(q^2) = \frac{\sqrt{2}}{\sqrt{2J_i + 1}} \cdot \frac{(2K + 1)!!}{(qR)^K}$$

Geometrical coefficients

$$\times \left[G_{KK0}(\kappa_f, \kappa_i) \int_0^\infty g_f(r, \kappa_f) j_K(qr) g_i(r, \kappa_i) r^2 dr \right. \\ \left. + S_{\kappa_f} S_{\kappa_i} G_{KK0}(-\kappa_f, -\kappa_i) \int_0^\infty f_f(r, \kappa_f) j_K(qr) f_i(r, \kappa_i) r^2 dr \right]$$

Components of the relativistic bound wave function of the nucleon

Forbidden non-unique transitions

$$M_K(k_e, k_\nu) = C_K(pR)^{k_e-1}(qR)^{k_\nu-1} \left\{ \underbrace{-\sqrt{\frac{2K+1}{K}} V F_{K,K-1,1}^{(0)}}_{\text{Relativistic matrix element}} - \frac{\alpha Z}{2k_e+1} \underbrace{V F_{K,K,0}^{(0)}(k_e, 1, 1, 1)}_{\text{Non-relativistic matrix elements}} \right. \\ \left. - \left[\frac{WR}{2k_e+1} + \frac{qR}{2k_\nu+1} \right] \underbrace{V F_{K,K,0}^{(0)}}_{\text{Non-relativistic matrix elements}} - \frac{\alpha Z}{2k_e+1} \sqrt{\frac{K+1}{K}} \underbrace{A F_{K,K,1}^{(0)}(k_e, 1, 1, 1)}_{\text{Non-relativistic matrix elements}} - \left[\frac{WR}{2k_e+1} - \frac{qR}{2k_\nu+1} \right] \sqrt{\frac{K+1}{K}} \underbrace{A F_{K,K,1}^{(0)}}_{\text{Non-relativistic matrix elements}} \right\}$$

Nuclear structure models are non-relativistic, but forbidden non-unique transitions are sensitive to $V F_{K,K-1,1}$

→ **Conserved Vector Current (CVC) hypothesis**

- Derived from the gauge invariance of the weak interaction.
- Provides relationships between non-relativistic and relativistic vector matrix elements.
- Depends on the Coulomb displacement energy ΔE_C .

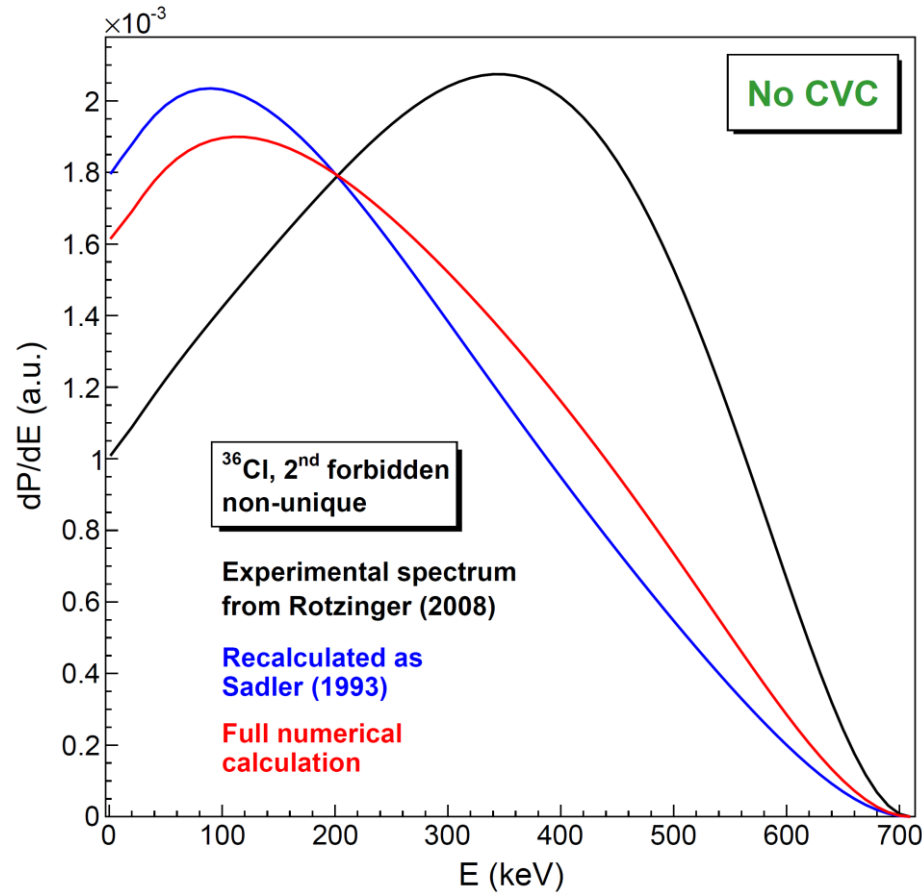
Influence of lepton current treatment: usually approximated only to dominant terms (formula here).

→ Full numerical treatment is also possible, avoiding approximations and next-to-leading-order terms.

^{36}Cl 2nd forbidden non-unique decay

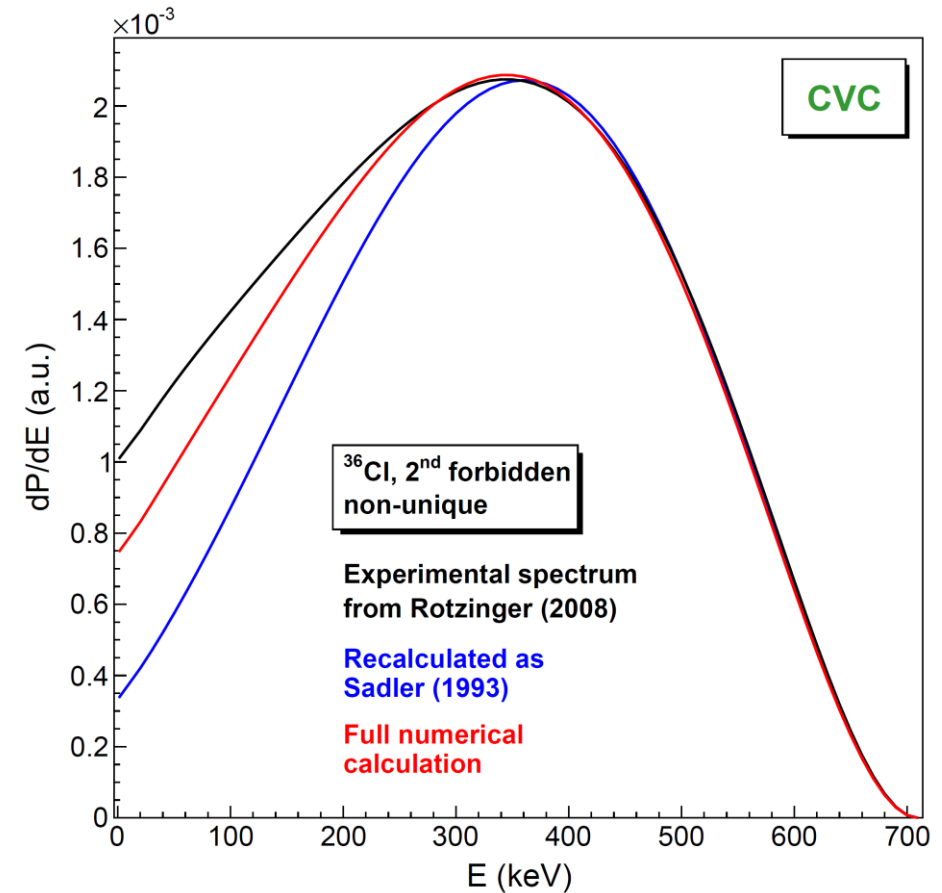
Precise measurement exists

Rotzinger et al., J. Low Temp. Phys. 151, 1087 (2008)



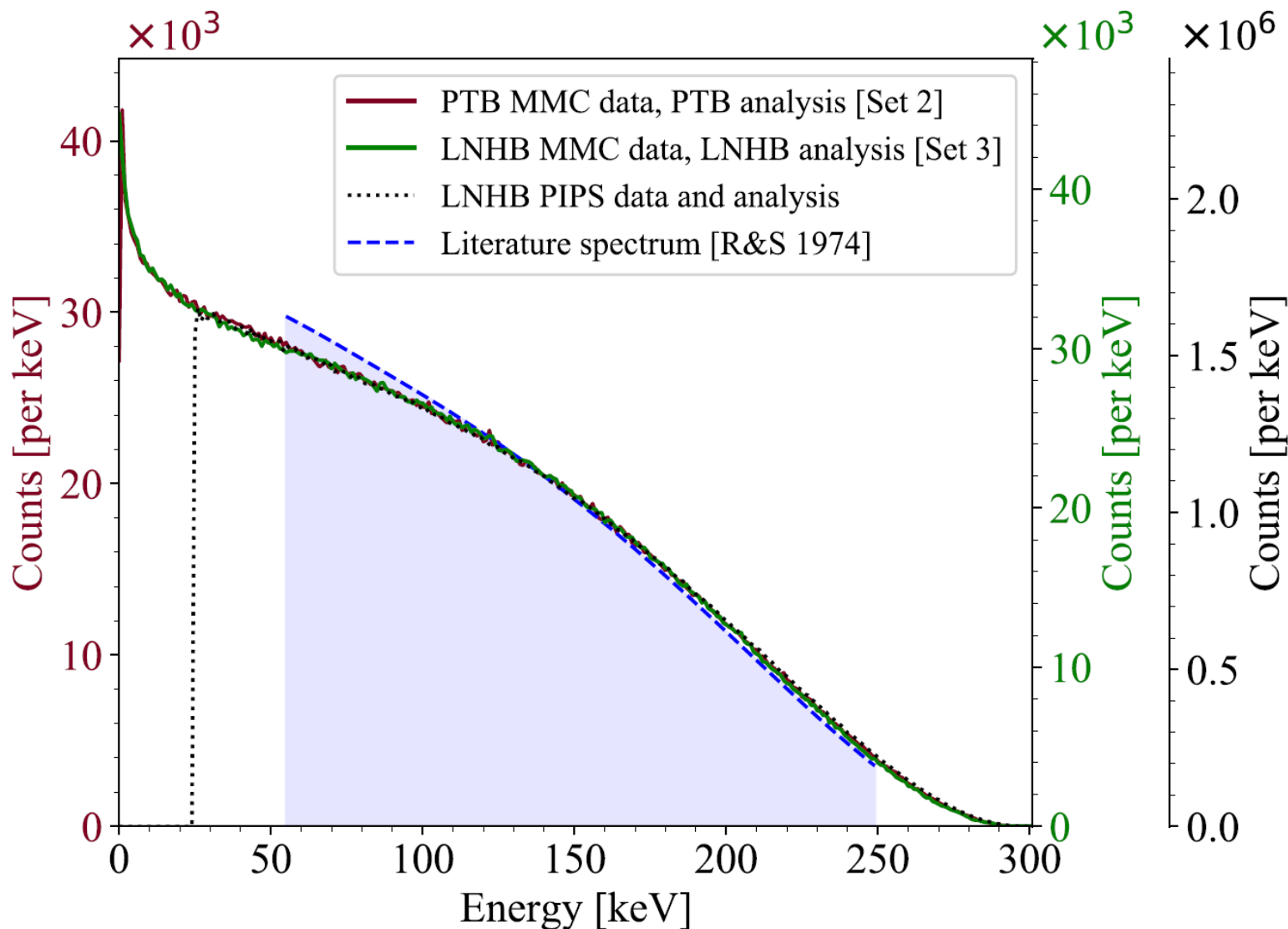
Detailed theoretical study (simplified lepton current)

Sadler, Behrens, Z. Phys. A 346, 25 (1993)



→ CVC hypothesis mandatory + Influence of lepton current treatment

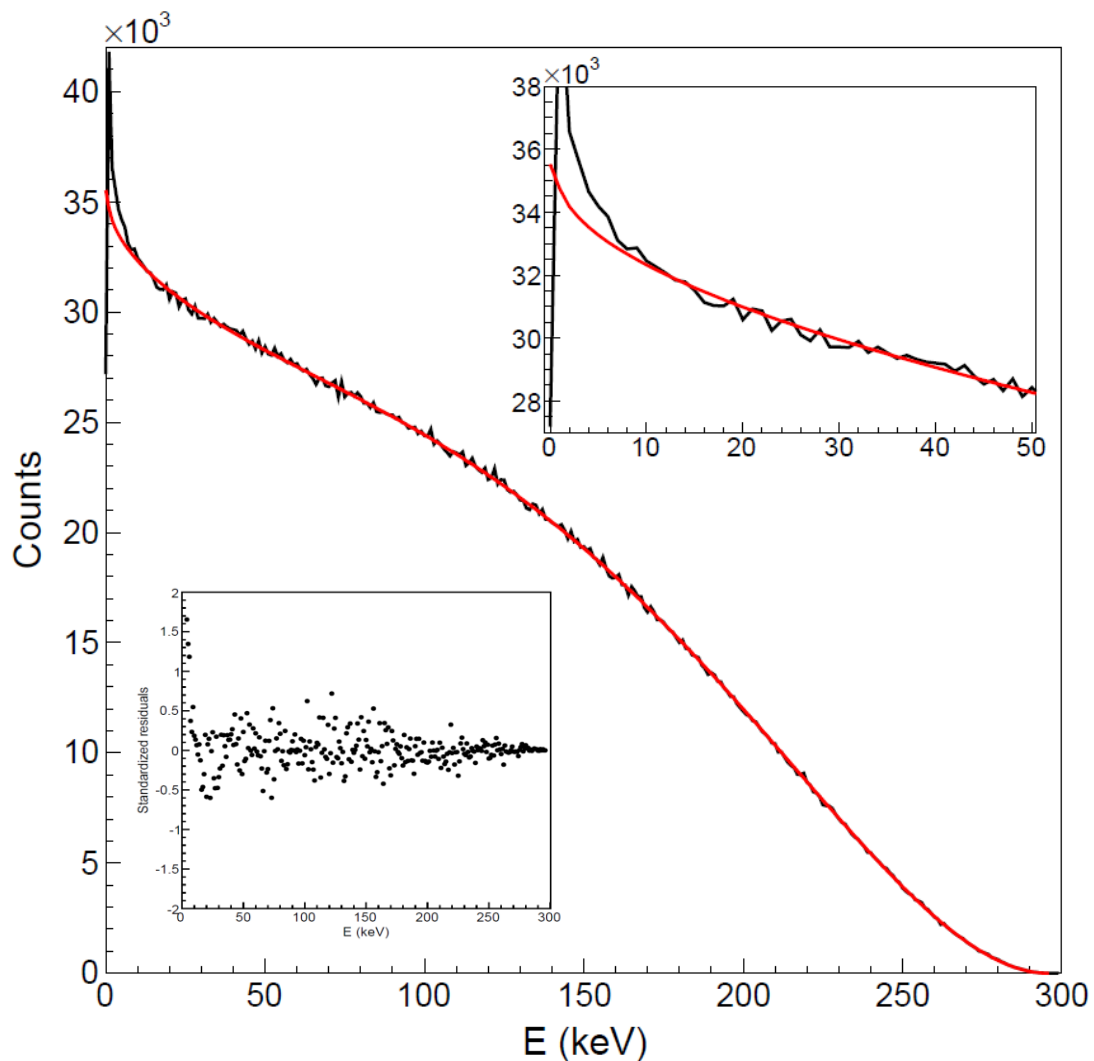
^{99}Tc 2nd forbidden non-unique decay



Within the European project PrimA-LTD

- ✓ High-precision measurements of ^{99}Tc spectrum with MMC at CEA-LNHB and PTB, and with Silicon detectors at CEA-LNHB.
- ✓ Excellent agreement of all the three spectra.
- ✓ **New Q-value = 295.82 (16) keV** not consistent with AME2020 value of 297.5 (9) keV.
- ✓ M. Paulsen et al., Phys. Rev. C 110, 055503 (2024).

^{99}Tc 2nd forbidden non-unique decay



- ✓ Three different model spaces used with NushellX (GL, GLEKPN, jj45pn) to quantify the influence of nuclear structure.
- ✓ Theoretical calculations with nuclear structure, CVC and complete lepton current. Uncertainties determined varying the different assumptions.
- ✓ Spectrum shape is sensitive to g_A value.
- ✓ Best adjustment : spectrum shape + evaluated half-life $T_{1/2} = 211.5 (11) \times 10^3 \text{ y}$

$$g_V^{\text{eff}} = 0.376 (5) \text{ and } g_A^{\text{eff}} = 0.574 (36)$$

- ✓ Excellent residuals, without any trend down to 6 keV.
- ✓ **Consistent with 1st forbidden non-unique results**

$$g_V^{\text{eff}} \sim 0.3 - 0.7 \text{ and } g_A^{\text{eff}} \sim 0.46 - 0.56$$

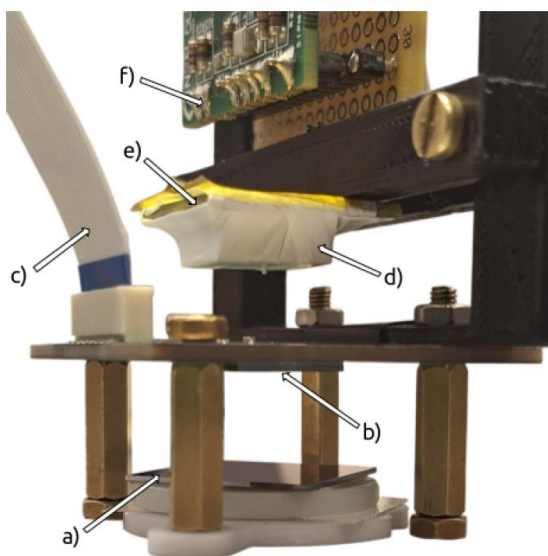
J. Suhonen, Frontier. Phys. 5, 55 (2017)

Recent ^{99}Tc study

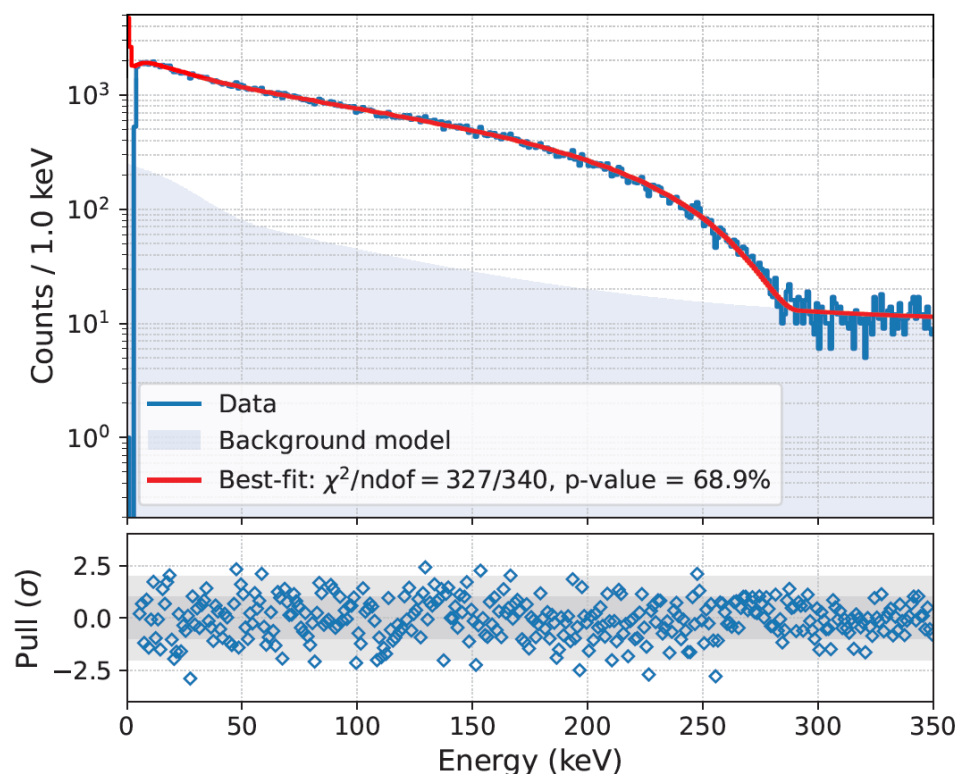
Measurement of the ^{99}Tc β spectrum with Silicon Drift Detectors

Andrea Nava^{1,2,*}, Andrea Del Contrasto¹, Leonardo Bernardini^{3,4}, Matteo Biassoni², Tommaso Bradanini^{1,2}, Chiara Brofferio^{1,2}, Marco Carminati^{3,4}, Silvia Capelli^{1,2}, Francesco Cappuzzello^{7,8}, Manuela Cavallaro⁸, Massimiliano Clemenza², Giovanni De Gregorio^{5,6}, Giulio Gagliardi^{1,2},

arXiv paper from 4
September 2026



a) Source b) SDD
d) LYSO crystal



Effective Realistic Shell Model

Hamiltonian and effective decay operators derived microscopically from the CD-Bonn nucleon-nucleon potential using the $V_{\text{low-k}}$ procedure.

Spectrum obtained using decay operators derived consistently with the effective Hamiltonian. Relativistic matrix element fixed according to CVC. Fit includes evaluated $T_{1/2}$.

→ Q-value = 291.6 (7) keV

→ $g_V^{\text{eff}} = 0.47$ (1) and $g_A^{\text{eff}} = 0.510$ (13)

⁹⁹Tc decay – Decay heat calculations

Eur. Phys. J. Plus (2022) 137:665
<https://doi.org/10.1140/epjp/s13360-022-02865-7>

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Regular Article



Nuclear data evaluation for decay heat analysis of spent nuclear fuel over 1–100 k year timescale

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² Scottish Universities Environmental Research Centre, East Kilbride G75 0QF, UK

Table 3 Mean beta energies from different evaluated libraries (keV)

Nuclide	Evaluated library					
	JEF2.2	JEFF3.1.1	JEFF3.3	ENDF/B-VIII.0	ENSDF	DDEP
⁹⁹ Tc	85.0	85.4 ± 0.6	95.3 ± 0.4	55.2 ± 0.3	84.6 ± 0.5	94.6 ± 1.7

→ From our study: $\overline{E_\beta} = 98.51$ (23) keV

✓ Value updated in JEFF4.0 (release in May 2025)



Conclusion

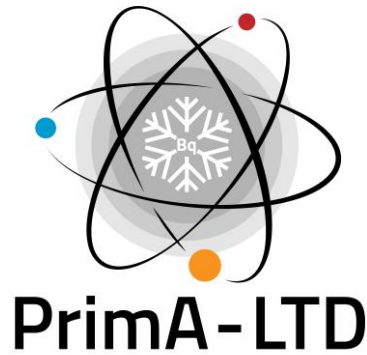
Conclusion

- **Allowed and forbidden unique transitions can be calculated with good accuracy**
- If targeted accuracy better than 1%, detailed models are necessary.
- ✓ When no nuclear structure is required, the BetaShape code already improves the situation.
 - Available on IAEA-NSDD GitHub: <https://github.com/IAEA-NSDDNetwork>
- **Forbidden non-unique transitions are sensitive to nuclear structure.** Some can be calculated accurately as allowed or forbidden unique.

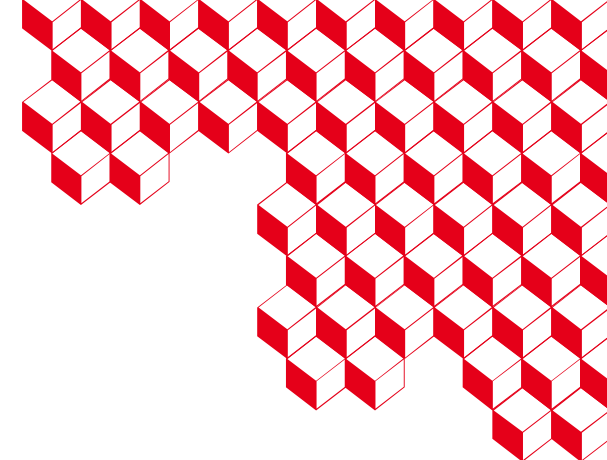
Challenges

- Modifying the weak interaction coupling constants is an effective method to retrieve the beta spectrum and the partial half-life.
 - Can we hope for average effective g_V and g_A ? Per mass region and per interaction?
- Ideally, the nuclear model should include such a renormalization within the nuclear operators.
 - Can we hope for applicability over the chart of nuclides?
 - Is the targeted accuracy reachable?

Acknowledgments



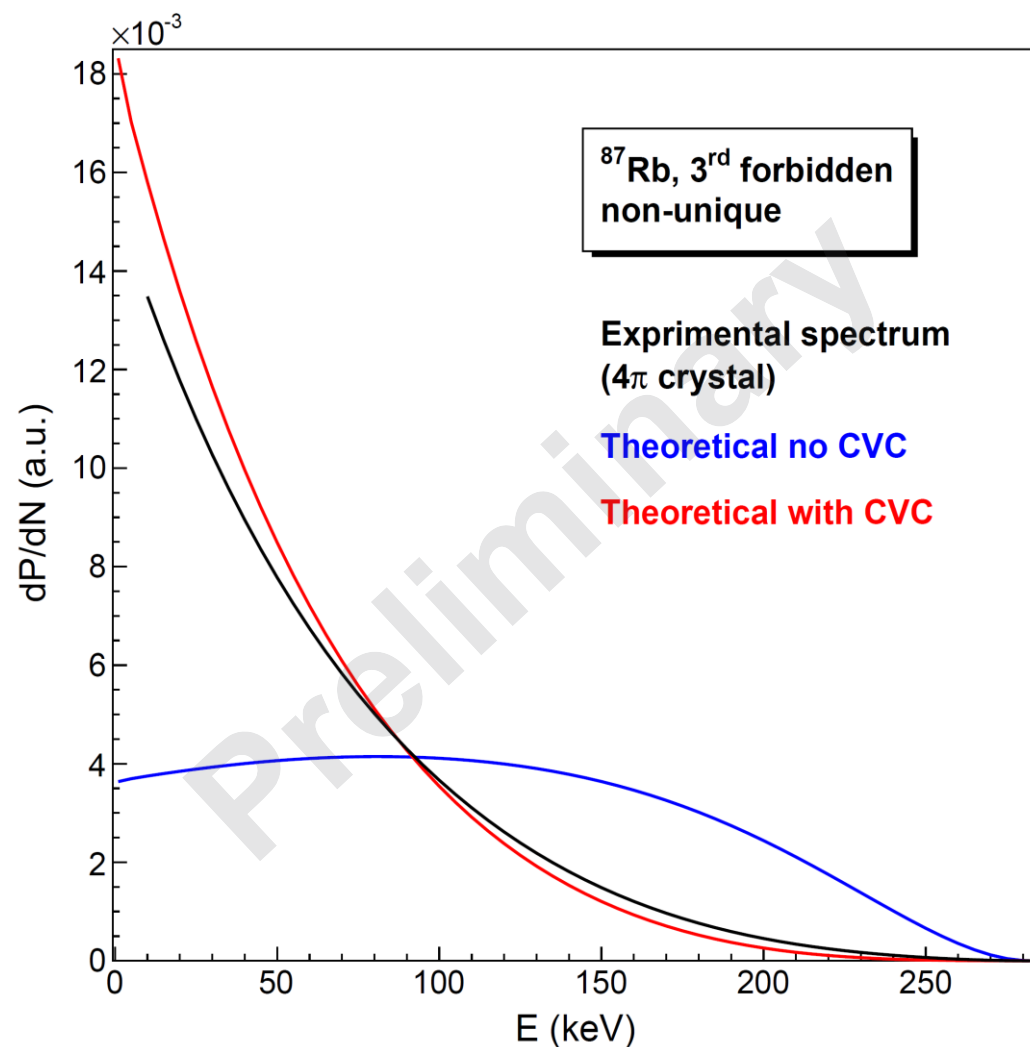
- ✓ This work has received support and funding for many years from the French metrology (LNE).
- ✓ Part of this work has received funding from the EMPIR project 20FUN04 PrimA-LTD, co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation program.



Thank you for your attention



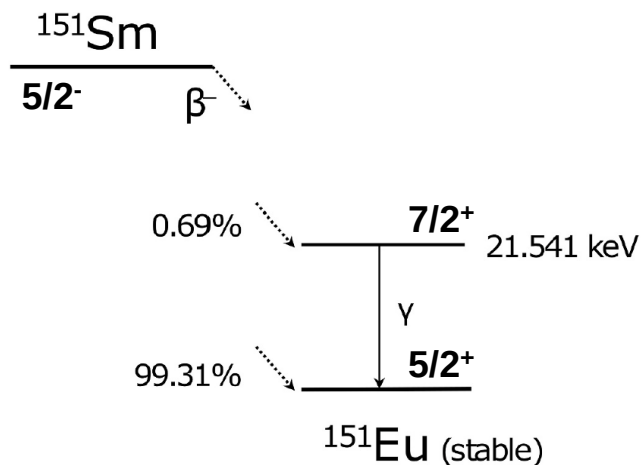
^{87}Rb 3rd forbidden non-unique decay



$$^{87}\text{Rb} (\text{gs}, 3/2^-) \rightarrow ^{87}\text{Sr} (\text{gs}, 9/2^+)$$

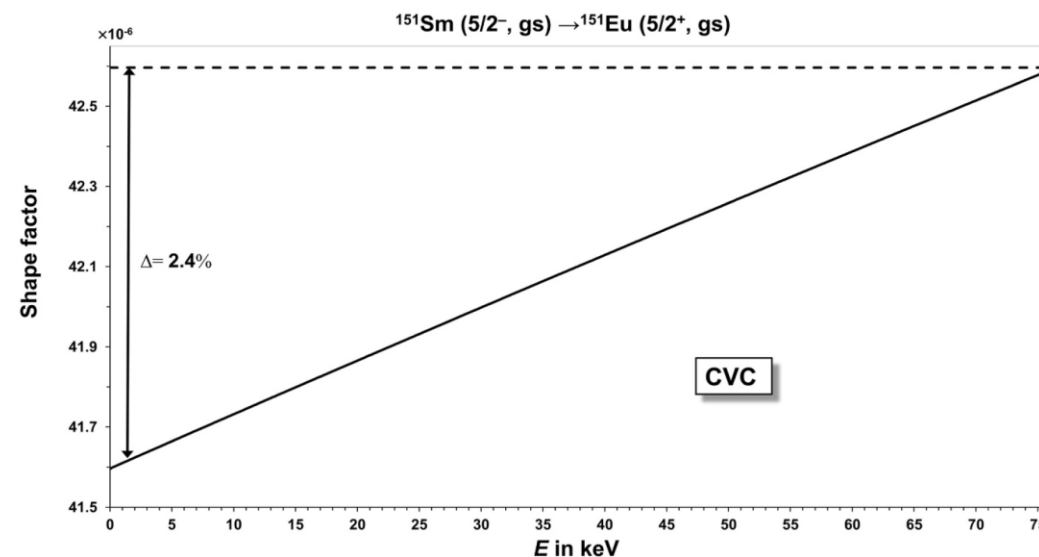
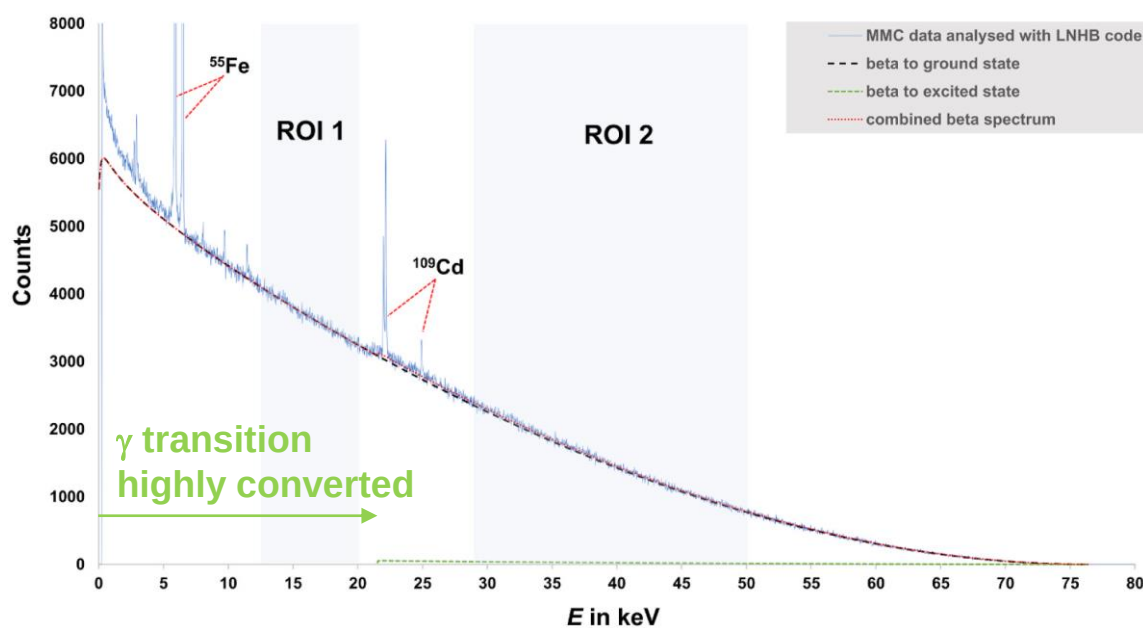
- Third forbidden non-unique transition
 - NushellX ^{56}Ni doubly magic core, jj44 model space, jj44b interaction
 - Preliminary measurement from the European MetroBeta project (4 π RbGd₂Br₇ crystal)
- **CVC hypothesis mandatory to describe the spectrum correctly**

^{151}Sm decay



First forbidden non-unique transitions

- ✓ High-precision measurement of ^{151}Sm spectrum with Metallic Magnetic Calorimeters (MMC) at LNHB.
- ✓ **New Q-value = 76.430 (68) keV** more precise than AME2020 value of 76.5 (5) keV.
- ✓ New determination of branching ratios: 99.31 (11)% and 0.69 (11)%.
- ✓ Kossert et al., Appl. Radiat. Isot. 185, 110237 (2022)



Detailed calculations with nuclear structure

→ Testing the accuracy of the ξ -approximation