Renormalization of the electroweak current within the realistic shell model

NME2025
RCNP Workshop for "Theoretical and Experimental Approaches for Nuclear Matrix Elements of Double Beta decay"

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Giovanni De Gregorio

The renormalization of the shell-model Gamow-Teller operator starting from effective field theory for nuclear systems
L.Coraggio, N. Itaco, G. De Gregorio, A. Gargano, Z. H. Cheng, Y. Z. Ma, F. R. Xu, M. Viviani,
Physical Review C **109**, 014301 (2024)

Forbidden β decays within the realistic shell model
G. De Gregorio, R. Mancino, L.Coraggio, N. Itaco,
Physical Review C **110**, 014324 (2024)

Renormalization of $\sigma\tau$ matrix elements

Gamow-Teller transitions (β-decay, EC, $2\nu\beta\beta$,charge-exchange) are hindered from expected values based on sum rules derived by nuclear structure models.

Renormalization of στ matrix elements

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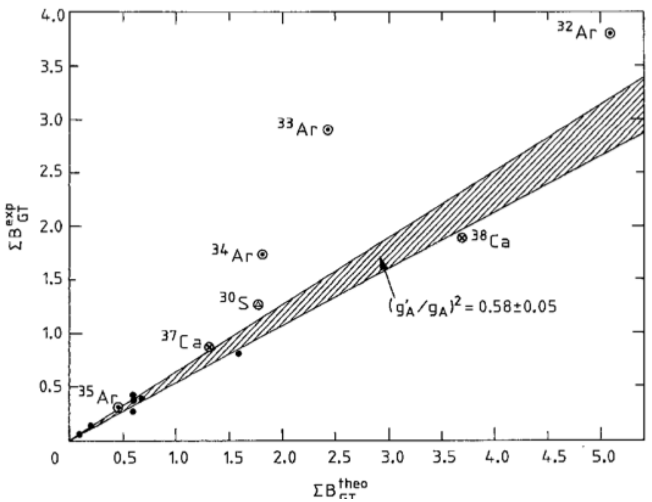
Quenching of στ matrix elements is quite a general phenomenon in nuclear-structure physics.

$$g_A = g_A^{eff} = q\, g_A$$

Renormalization of στ matrix elements

Z. Phys. A - Atomic Nuclei 332, 413417 (1989)



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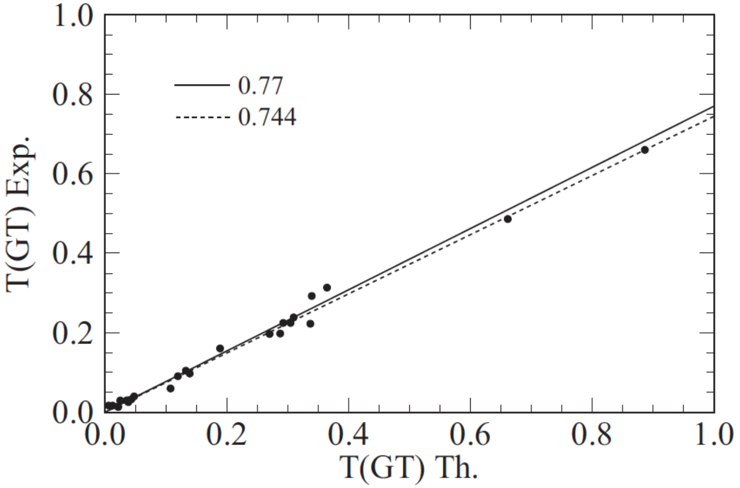
Martinez-Pinedo et al. PRC53 2602(1996)

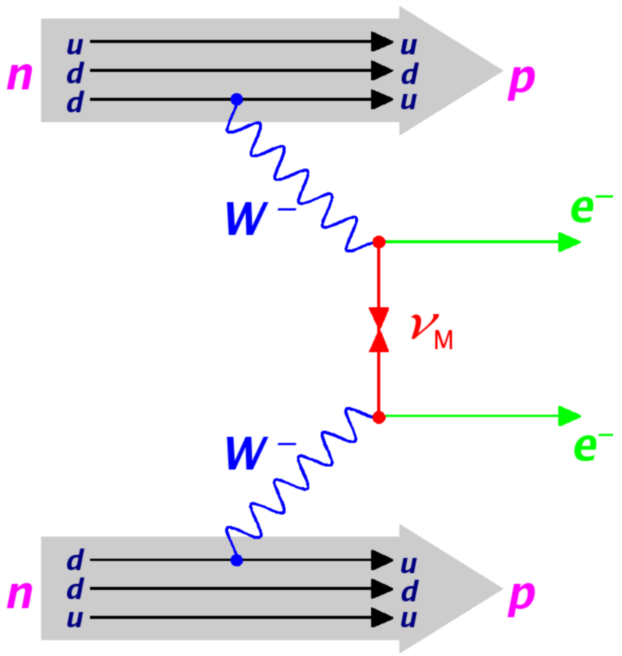


J. Suhonen, ACTA PHYSICA POLONICA B, 3 (2018)

Mass range	g_A^{eff}
Full $0p$ shell	$1.03^{+0.03}_{-0.02}$
$0p$–low $1s0d$ shell	1.18 ± 0.05
Full $1s0d$ shell	$0.96^{+0.03}_{-0.02}$
	1.0
$A = 41$–50 ($1p0f$ shell)	$0.937^{+0.019}_{-0.018}$
$1p0f$ shell	0.98
^{56}Ni	0.71
$A = 52$–67 ($1p0f$ shell)	$0.838^{+0.021}_{-0.020}$
$A = 67$–80 ($0f_{5/2}1p0g_{9/2}$ shell)	0.869 ± 0.019
$A = 63$–96 ($1p0f0g1d2s$ shell)	0.8
$A = 76$–82 ($1p0f0g_{9/2}$ shell)	0.76
$A = 90$–97 ($1p0f0g1d2s$ shell)	0.60
^{100}Sn	0.52
$A = 128$–130 ($0g_{7/2}1d2s0h_{11/2}$ shell)	0.72
$A = 130$–136 ($0g_{7/2}1d2s0h_{11/2}$ shell)	0.94
$A = 136$ ($0g_{7/2}1d2s0h_{11/2}$ shell)	0.57

Quenching of στ matrix elements & 0νββ decay

The inverse of the 0νββ-decay half-life is proportional to the squared nuclear matrix element (NME).
This evidences the relevance to calculate the NME ($M^{0\nu}$)



$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\,|M^{0\nu}|^2\langle m_\nu\rangle^2 \propto g_A^4$$

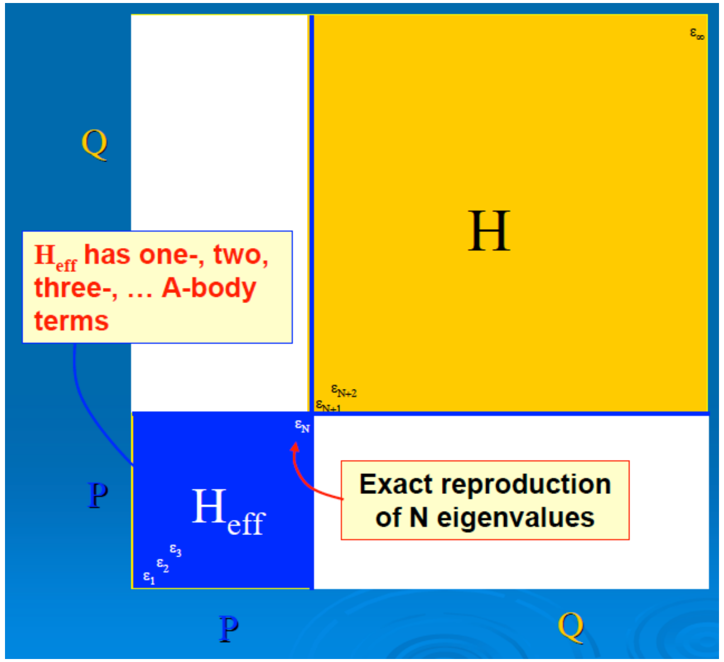
- $G^{0\nu}$ → phase space factor
- $\langle m_\nu\rangle = |\sum_k m_k U_{ek}|$, effective mass of the Majorana neutrino
  U_{ek} being the lepton mixing matrix

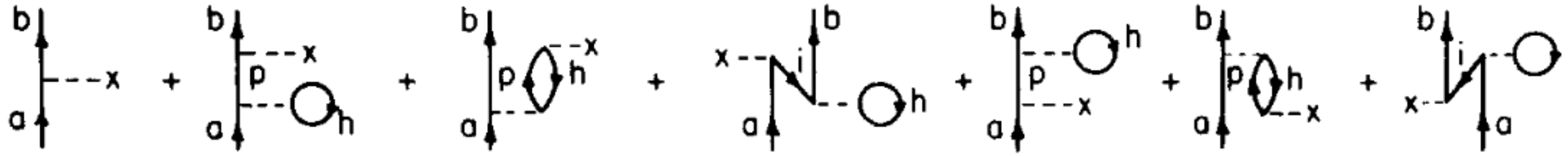
Quenching of στ matrix elements: truncated model space

Two main sources:

1) LIMITED MODEL SPACE

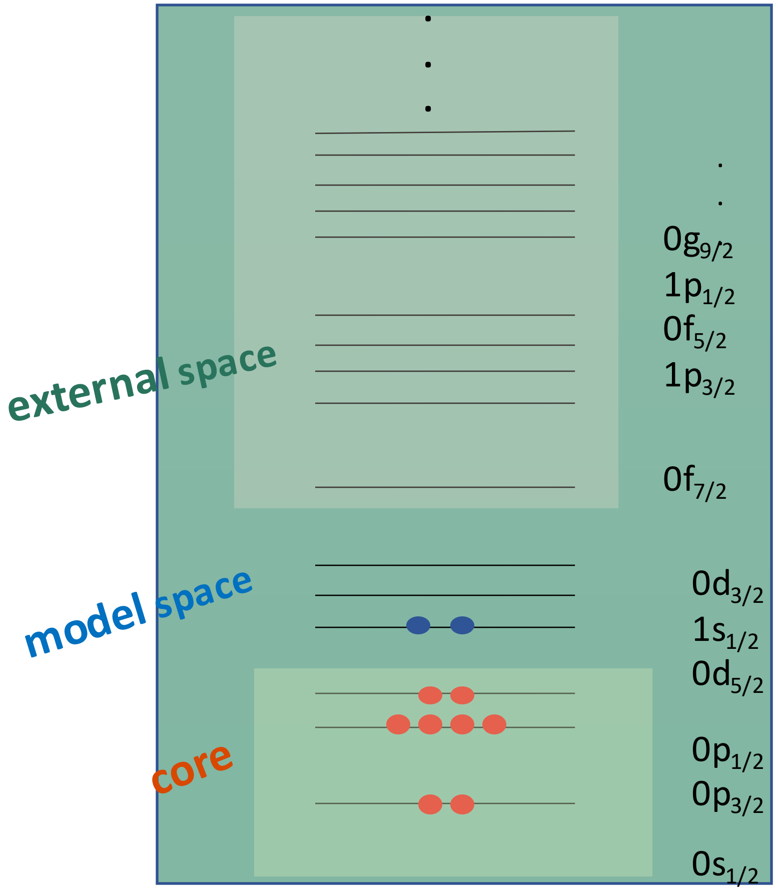
Nuclear Structure calculations are carried out in truncated model spaces
-> effective Hamiltonians and operators





Realistic Shell-Model

Shell model: A well-established approach to obtain a microscopic description of both collective and single-particle properties of nuclei



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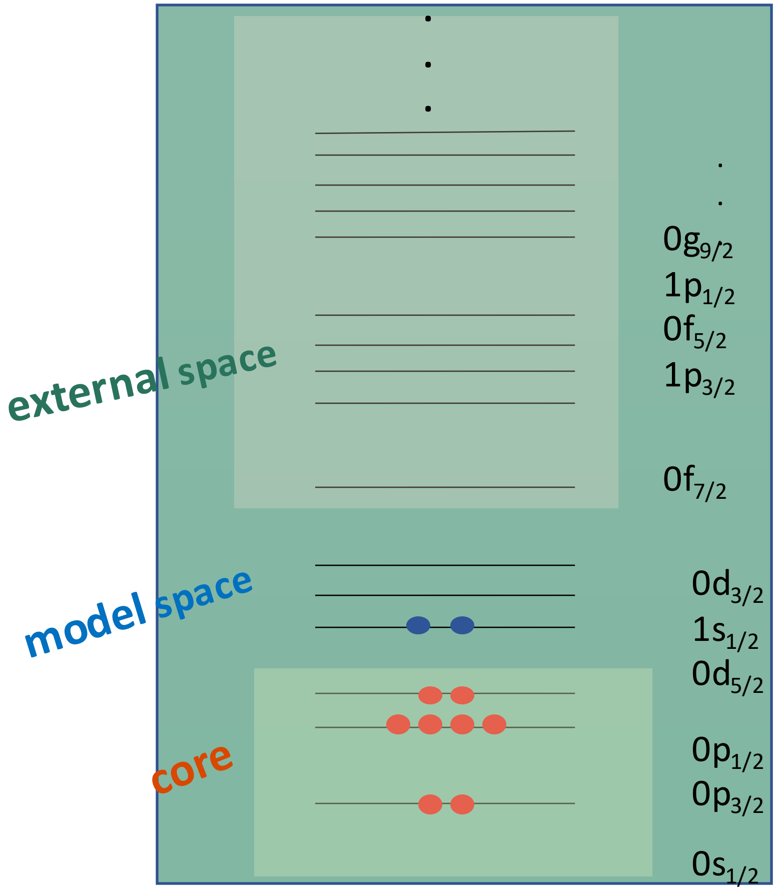

The degrees of freedom of the core nucleons and the excitations of the valence ones above the model space are not considered explicitly.

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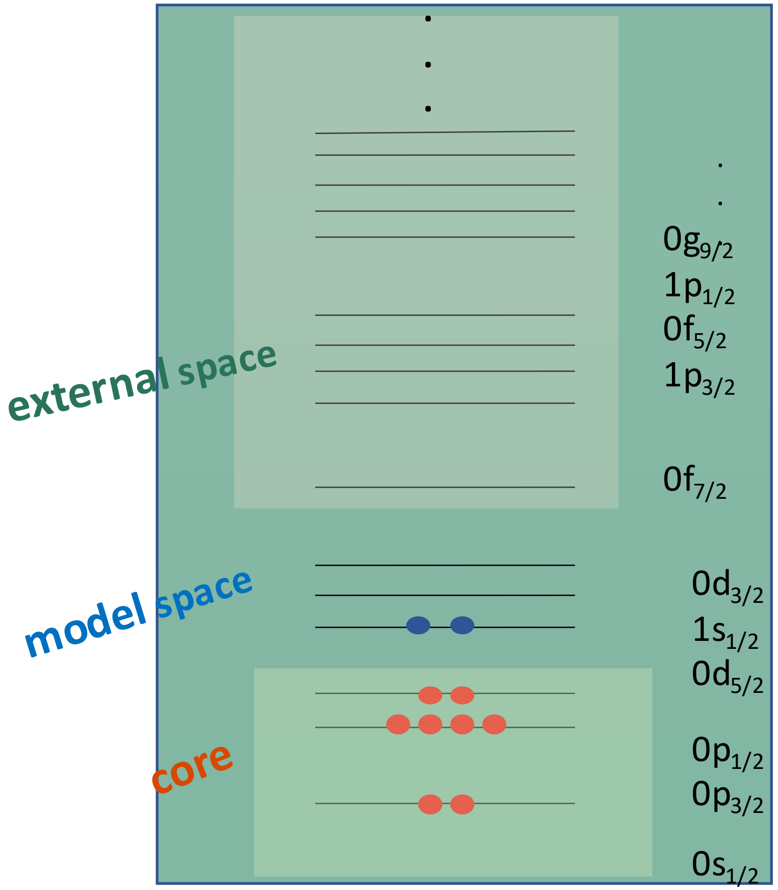

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$$V_{NN}\ (+V_{NNN})$$
$$\downarrow$$
$$MANY\ BODY\ PERTURBATION\ THEORY$$
$$\downarrow$$
$$H_{eff}$$

Realistic shell-model calculations starting from a nuclear Hamiltonian and decay operators derived consistently

Realistic Shell-Model

$$H \to H_{eff}$$

$$H|\psi_\nu\rangle = E_\nu|\psi_\nu\rangle \to H_{eff}|\varphi_\alpha\rangle = E_\nu|\varphi_\alpha\rangle$$

$|\varphi_\alpha\rangle$ = eigenvectors obtained diagonalizing H_{eff} in the reducedmodel space $|\varphi_\alpha\rangle$ = P $|\psi_\nu\rangle$

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$$\langle\varphi_\nu|\Theta|\varphi_\lambda\rangle \neq \langle\Psi_\nu|\Theta|\Psi_\lambda\rangle$$

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We then require an effective operator Θ_{eff} defined as follows

$$\Theta_{eff} = \sum_{\nu\lambda} |\varphi_\nu\rangle\langle\Psi_\nu|\Theta|\Psi_\lambda\rangle\langle\varphi_\lambda|$$

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$$\Theta^{GT} = g_A\sigma\tau^{\pm} \to \Theta^{GT}_{eff} = g_A^{eff}\sigma\tau^{\pm} \qquad \Theta^{E2} = er^2Y^2_\mu \to \Theta^{E2}_{eff} = e_{eff}r^2Y^2_\mu$$

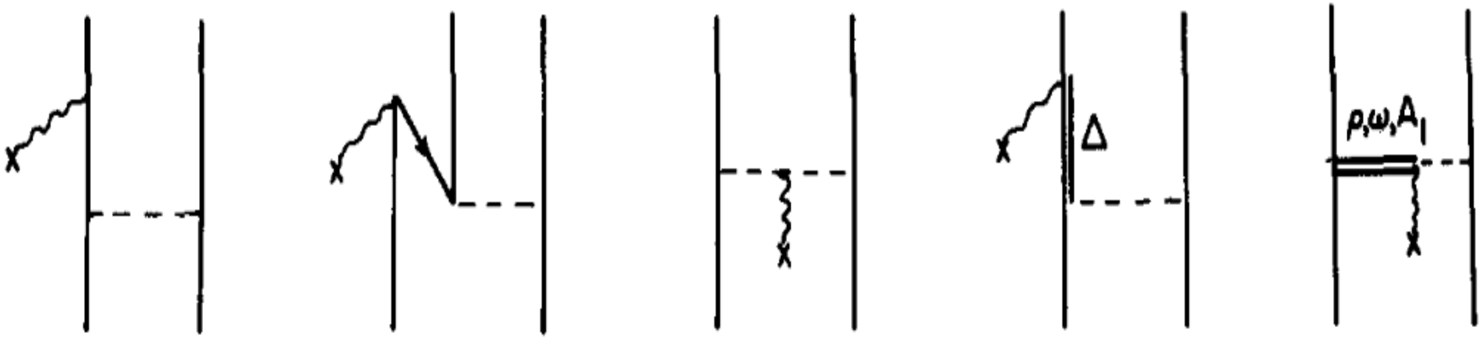
Quenching of $\sigma\tau$ matrix elements: theory

Two main sources:

2) NON-NUCLEONIC DEGREES OF FREEDOM

Processes in which the weak probe prompts a meson to be exchanged between two nucleons

→ meson-exchange two-body currents (2BC)



H. Hyuga and A. Arima, J. Phys. Soc. Jpn. Suppl. 34, 538 (1973)

Quenching of $\sigma\tau$ matrix elements: meson exchange currents

In the 80s starting from OBEP models two-nucleon meson-exchange current operators have been constructed consistently as required by the continuity equation for vector currents and the PCAC.

Nowadays, EFT provides a powerful approach where both nuclear potentials and two-body electroweak currents (2BC) may be consistently constructed, the latter appearing as subleading corrections to the one-body GT operator $\boldsymbol{\sigma\tau}^{\pm}$

Quenching of $\sigma\tau$ matrix elements: meson exchange currents

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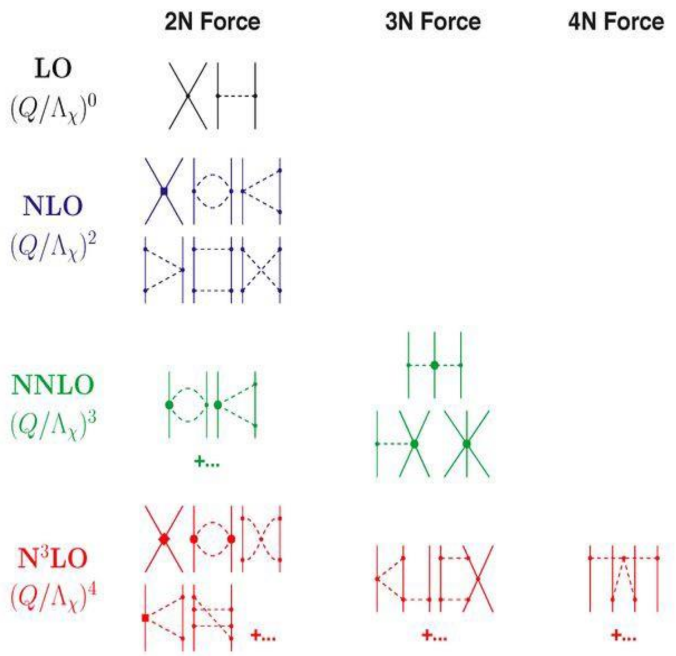
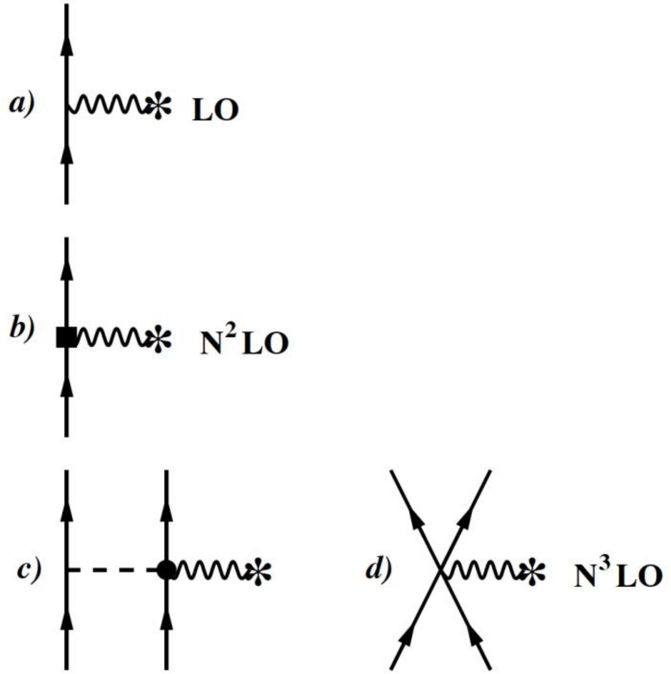
Nuclear potential



Electroweak axial currents



The axial current J_A

The matrix elements of the axial current J_A are derived through a chiral expansion up to N3LO, and employing the same LECs as in 2NF and 3NF

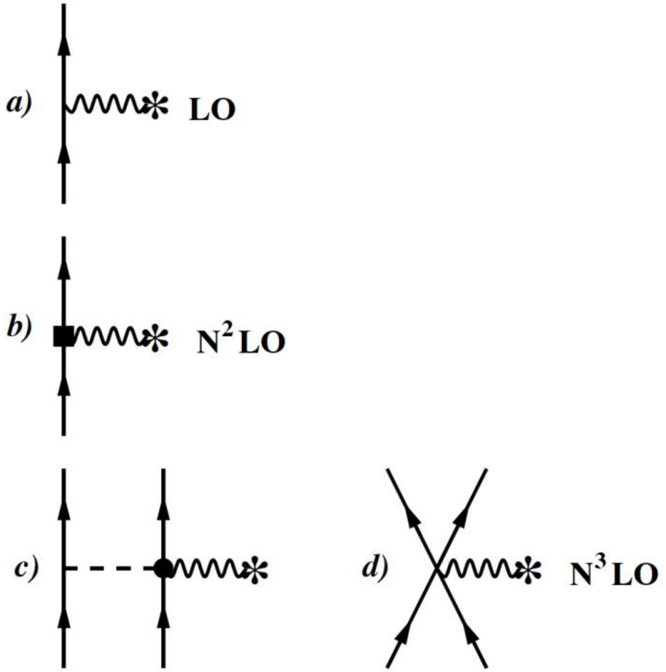
$$J_A^{LO} = -g_A \sum_i \sigma_i \tau_{i,\pm}$$

$$J_A^{N^2LO} = \frac{g_A}{2m_N^2} \sum_i K_i \times (\sigma_i \, x \, K_i) \, \tau_{i,\pm}$$

$$J_A^{N^3LO}(1PE; \boldsymbol{k}) = \sum_{i<j} \frac{g_A}{2f_\pi^2} \Big\{ 4c_3 \, \tau_j \boldsymbol{k} + (\tau_i \times \tau_j)_\pm \times \Big[\Big(c_4 + \frac{1}{4m} \sigma_i \times \boldsymbol{k} - \frac{i}{2m} K_i \Big) \Big] \Big\} \sigma_j \cdot \boldsymbol{k} \, \frac{1}{\omega_k^2}$$

$$J_A^{N^3LO}(CT; \boldsymbol{k}) = \sum_{i<j} z_0 \, (\tau_i \times \tau_j)_\pm (\sigma_i \times \sigma_j)$$

$$z_0 = \frac{g_A}{2f_\pi^2 m_N^2} \left[\frac{m_N}{4 g_A \Lambda_\chi} c_D + \frac{m_N}{3} (c_3 + 2c_4) + \frac{1}{6} \right]$$



A. Baroni, L. Girlanda, S. Pastore, R. Schiavilla, and M. Viviani, Phys. Rev. C 93, 015501 (2016)

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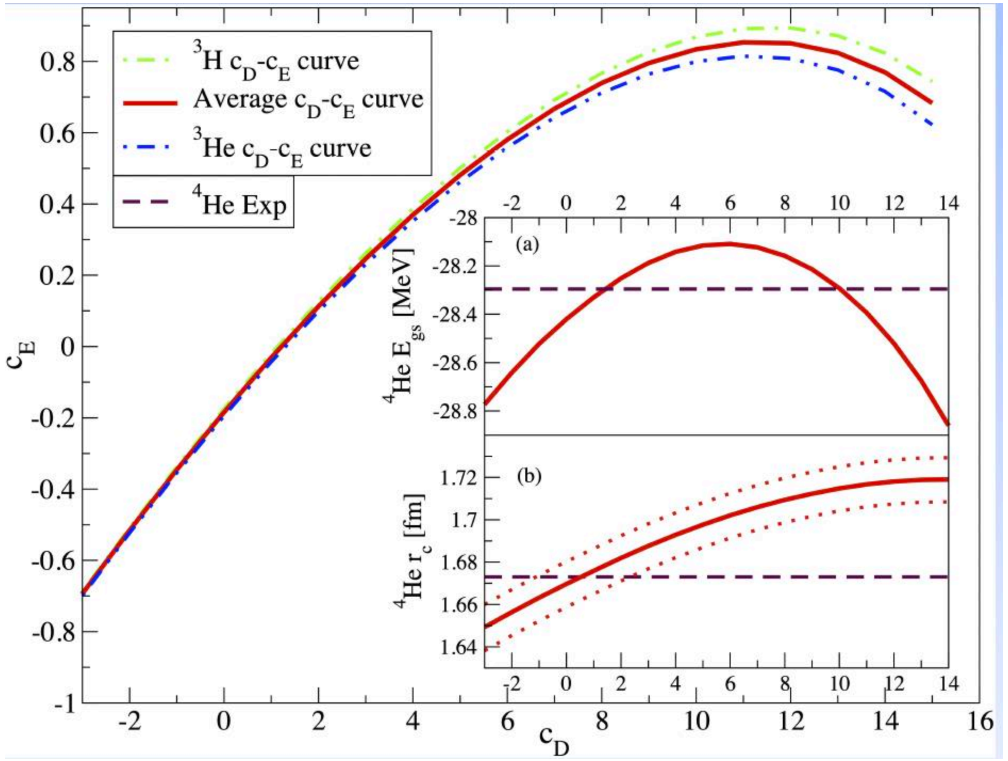
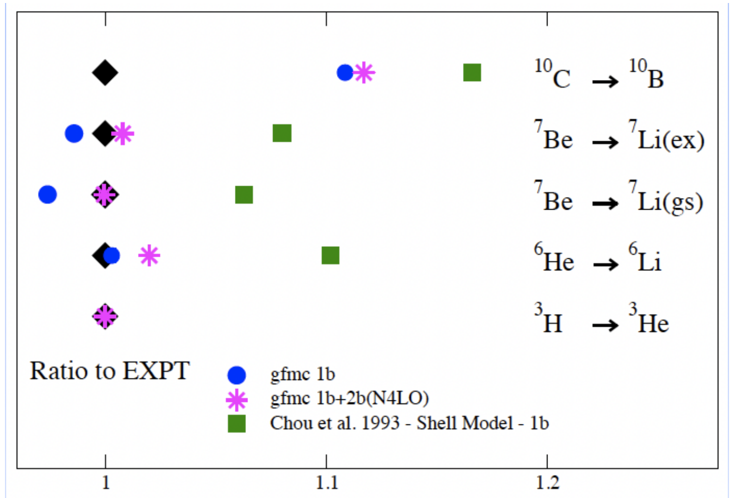


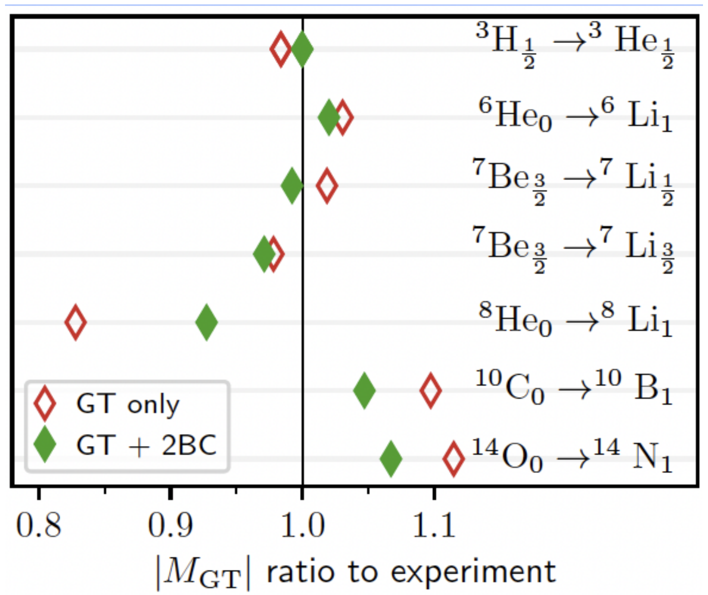
A. Baroni, L. Girlanda, S. Pastore, R. Schiavilla, and M. Viviani, Phys. Rev. C 93, 015501 (2016)

Two-body contribution to $\sigma\tau$: light nuclei

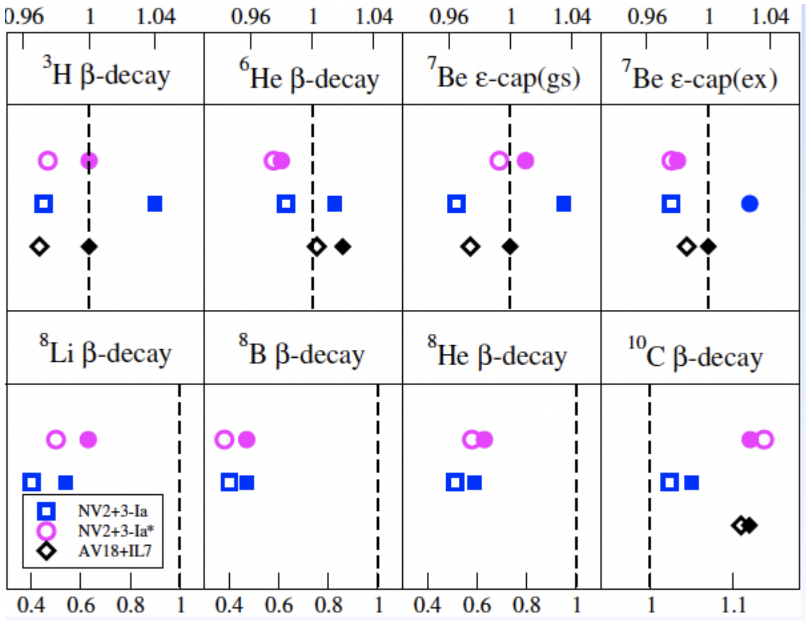
GT nuclear matrix elements of the β-decay of p-shell nuclei have been calculated with Green's function Monte Carlo (GFMC) and no-core shell model (NCSM) methods, including contributions from 2BC



S. Pastore et al., Phys. Rev. C 97 022501(R) (2018)



P. Gysbers et al., Nat. Phys. 15 428 (2019)

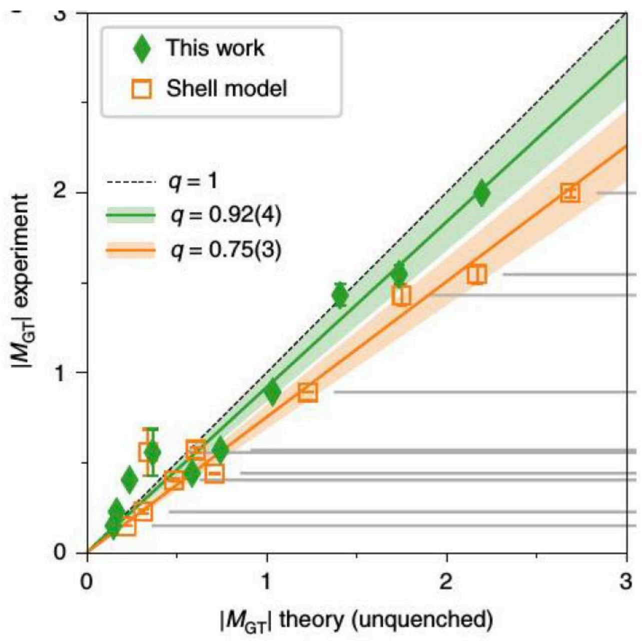


G. B. King et al., Phys. Rev. C 102 025501 (2020)

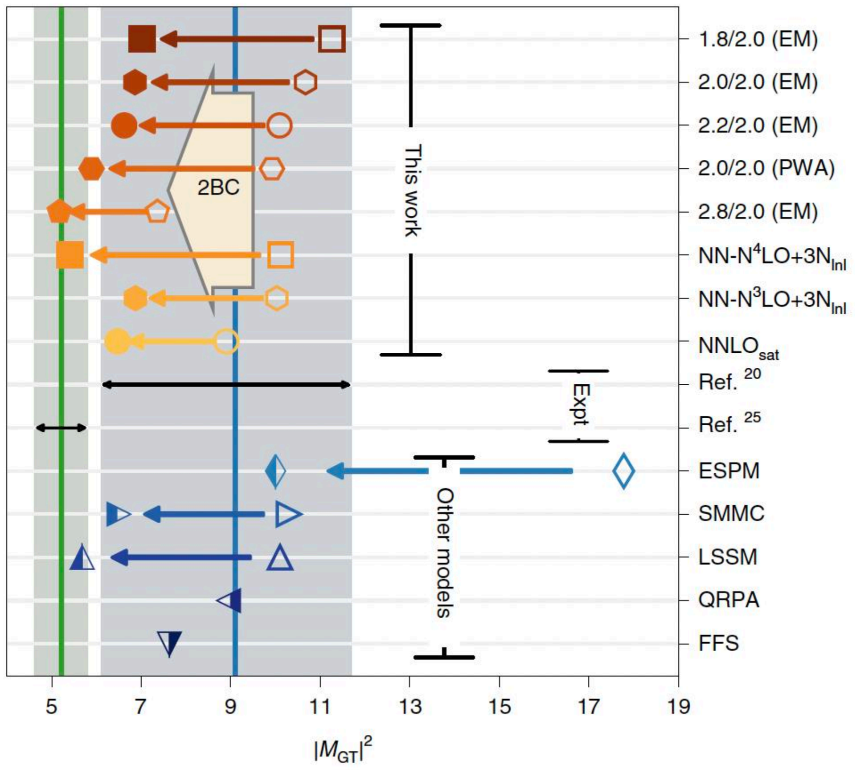
Two-body contribution to $\sigma\tau$: Medium-mass nuclei

The contribution of 2BC improves systematically the agreement between theory and experiment

In-Medium SRG



Gysbers et al. Nature Phys. 15 428 (2019)



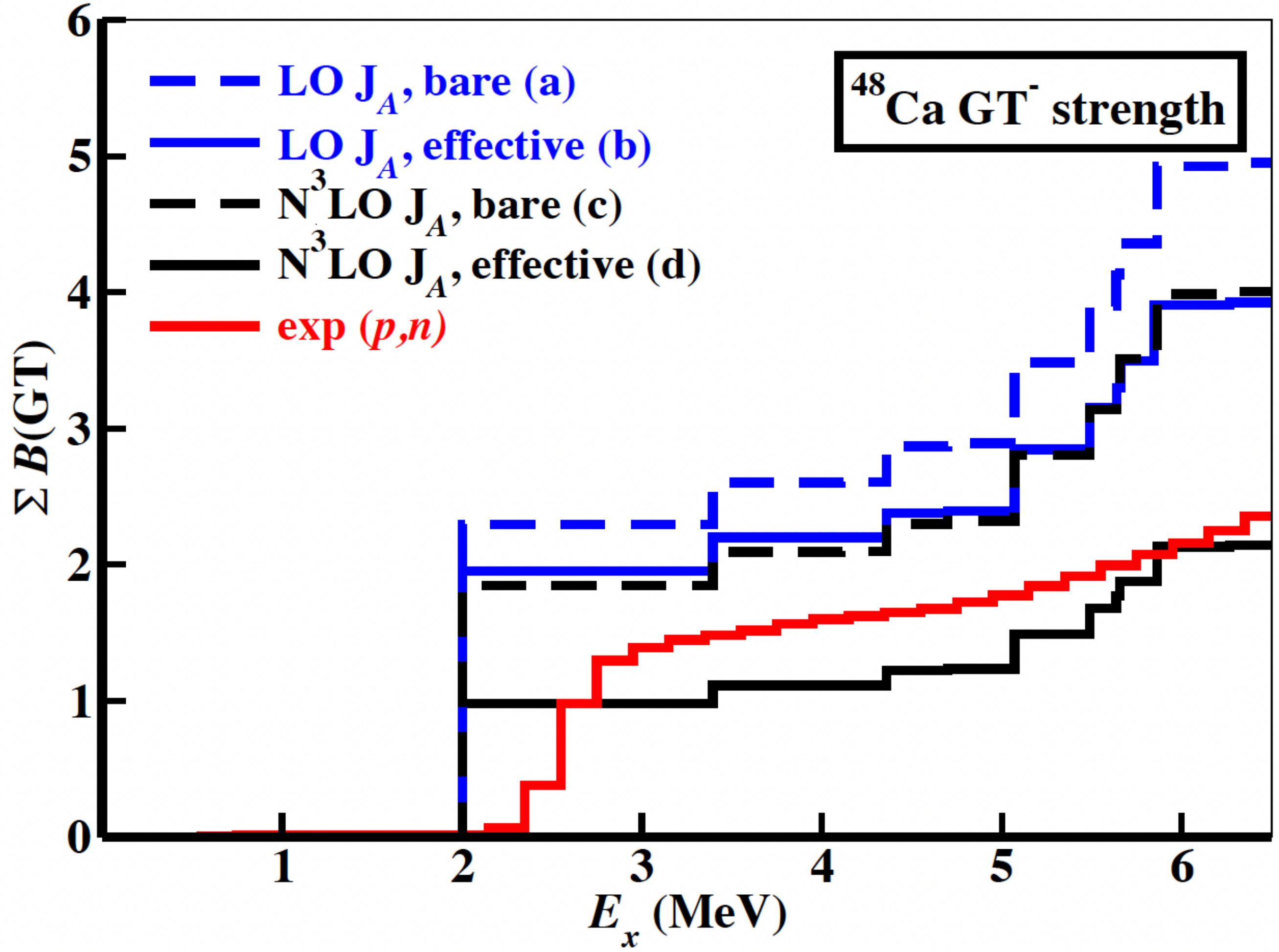
A proper treatment of nuclear correlations and consistency between GT two-body currents and 3N forces, derived in terms of ChPT, describes microscopically the "quenching puzzle"

Details of the Calculations

- Nuclear Hamiltonian: Entem-Machleidt N3LO two-body potential plus N2LO three-body potential (Λ = 500 MeV)
- Axial current J_A calculated at N3LO in ChPT
- Heff obtained calculating the Q-box up to the 3rd order in V_{NN} (up to 2p-2h core excitations) and up to the 1st order in V_{NNN}
- Effective operators are consistently derived by way of the MBPT
- fp-shell nuclei: four proton and neutron orbitals outside ^{40}Ca: 0f7/2, 0f5/2, 1p3/2, 1p1/2
- fpg-shell nuclei: four proton and neutron orbitals outside ^{56}Ni: 0f5/2, 1p3/2, 1p1/2, 0g9/2

RSM calculations, starting from ChPT two- and three-body potentials and two-body meson-exchange currents for spectroscopic and spin-isospin dependent observables of ^{48}Ca, ^{76}Ge, ^{82}Se

^{48}Ca: GT Strength

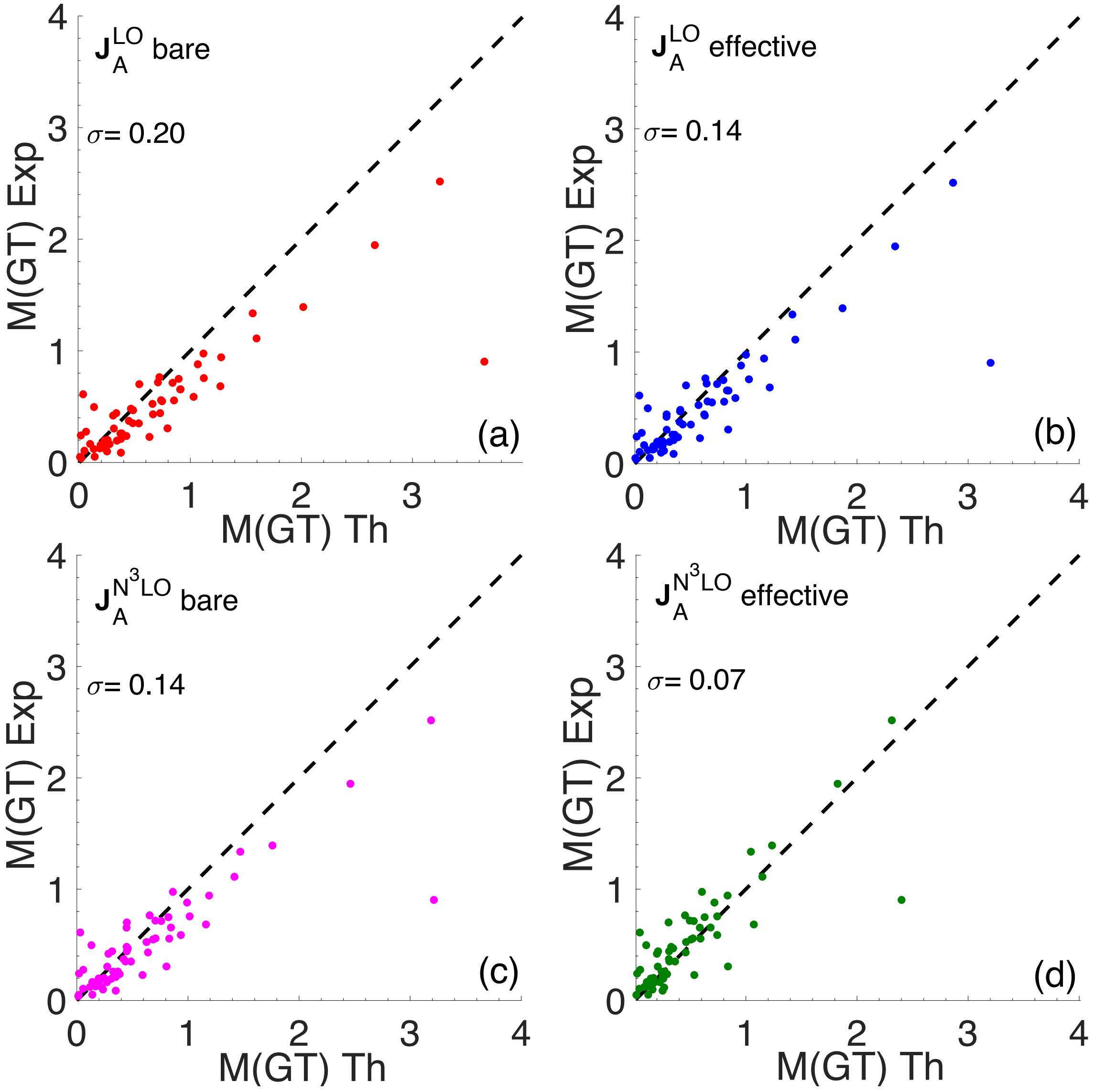


Charge exchange experiments

$$\left[\frac{d\sigma}{d\Omega}(q=0)\right] = \hat{\sigma} B_{exp}(GT)$$

$$B_{th}(GT) = \frac{\left|\langle \varphi_f || J_A || \varphi_i \rangle\right|^2}{2J_i + 1}$$

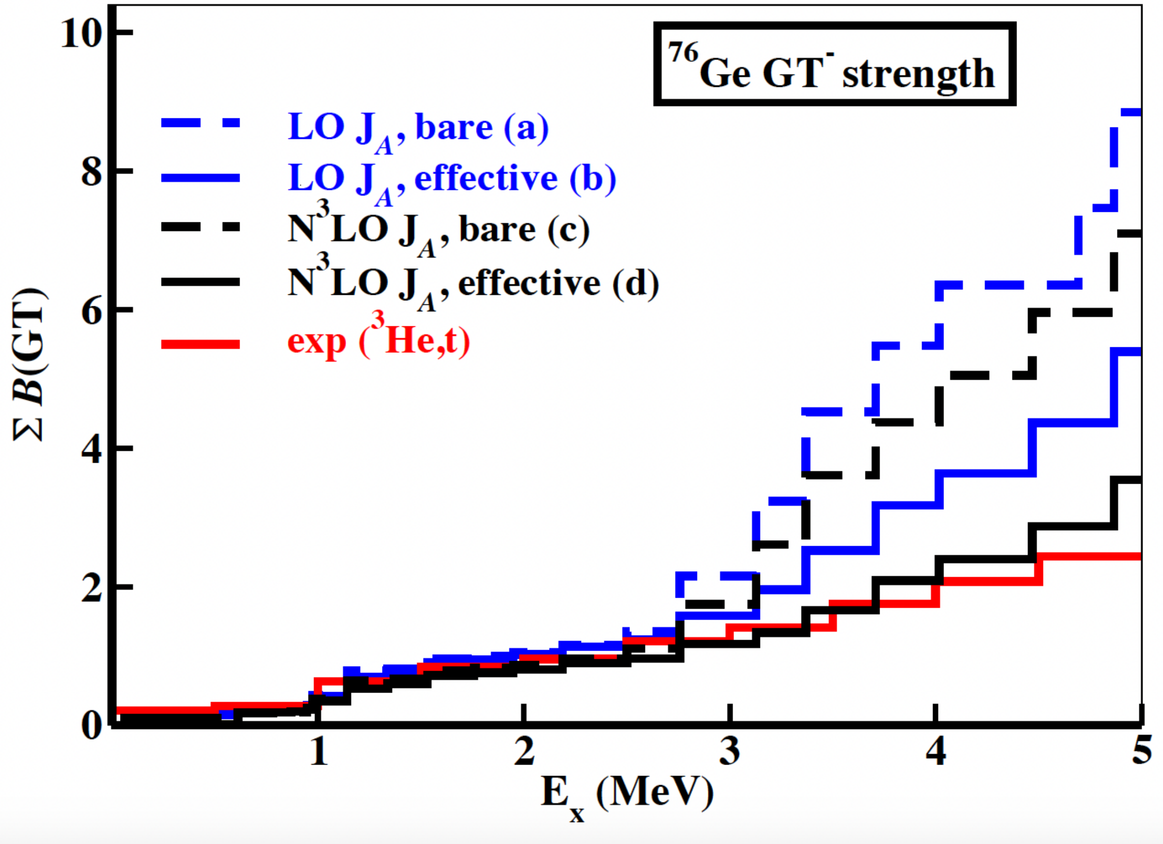
GT fp shell Nuclei

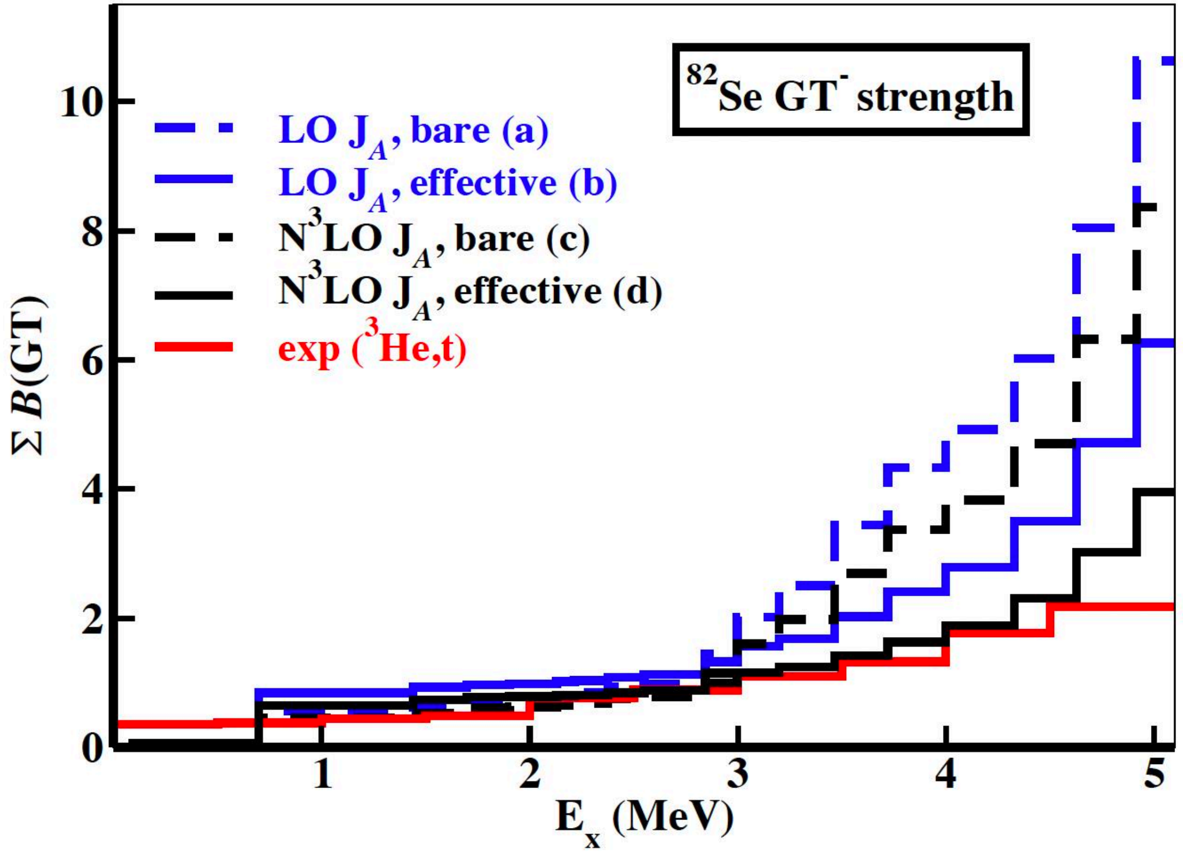


GT matrix elements of 60 experimental decays of 43 fp-shell nuclei

$$\sigma = \sqrt{\frac{\sum_i (x_i - \widehat{x_i})^2}{n}}$$

Fpg shell nuclei: GT strength





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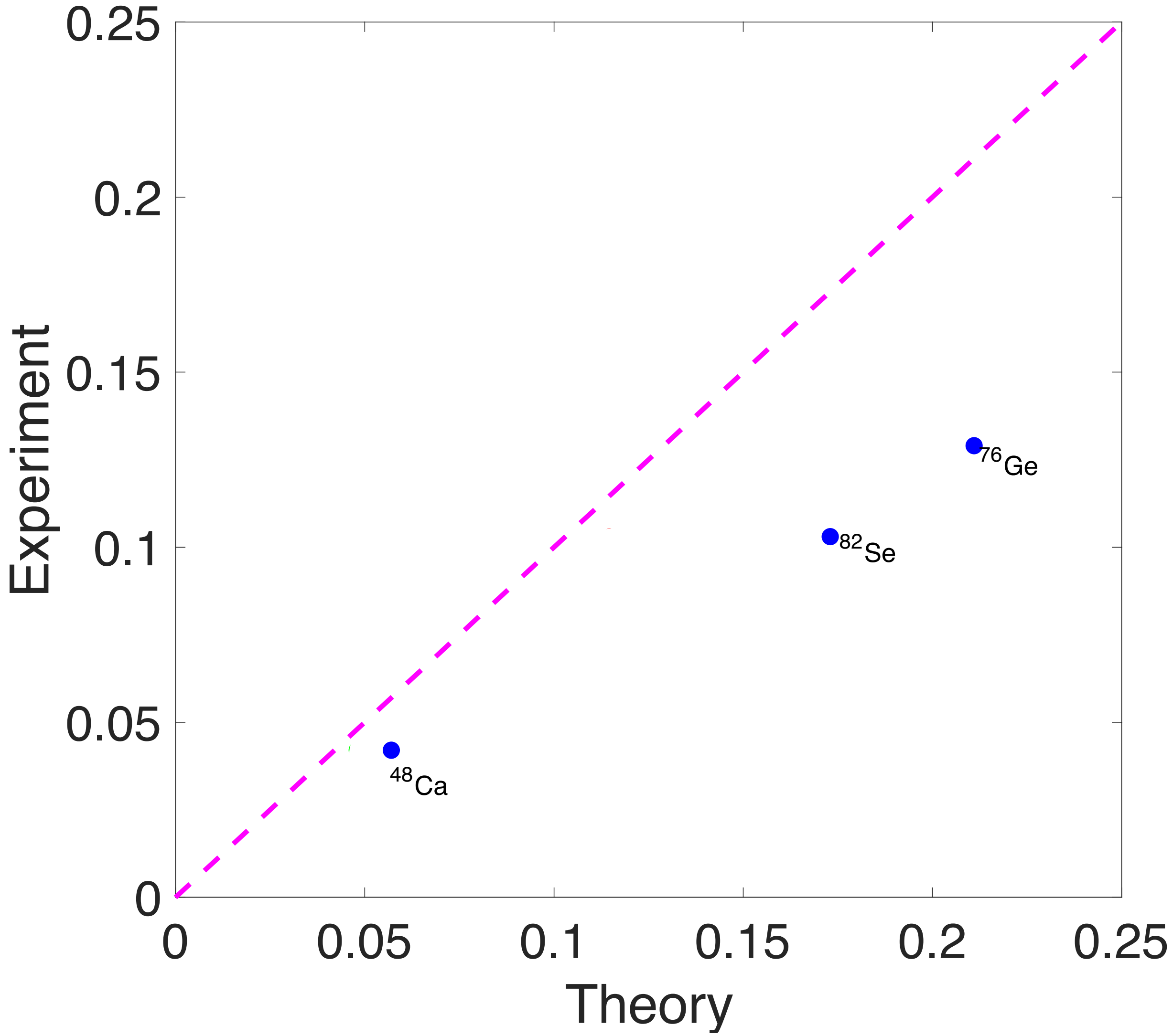
2νββ decay

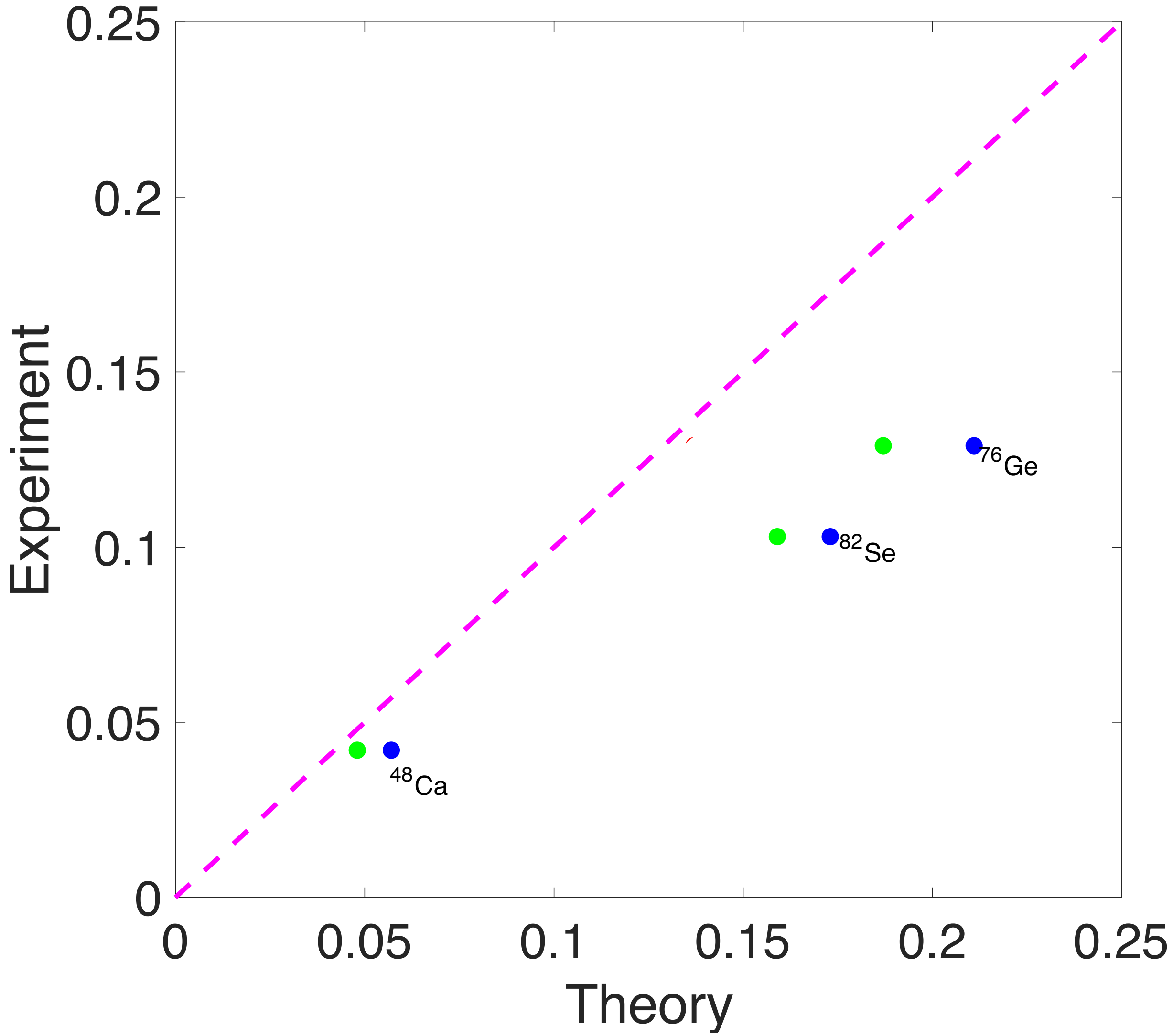


$$M_{GT}^{2\nu} = \sum_k \frac{\langle 0_f^+ || \vec{\sigma} \cdot \tau^- || k \rangle \langle k || \vec{\sigma} \cdot \tau^- || 0_i^+ \rangle}{E_k + E_0}$$

Blue: bare J_A at LO in ChPT
(namely the GT operator g_A)

L. Coraggio et al. Physical Review C **109**, 014301 (2024)

2νββ decay



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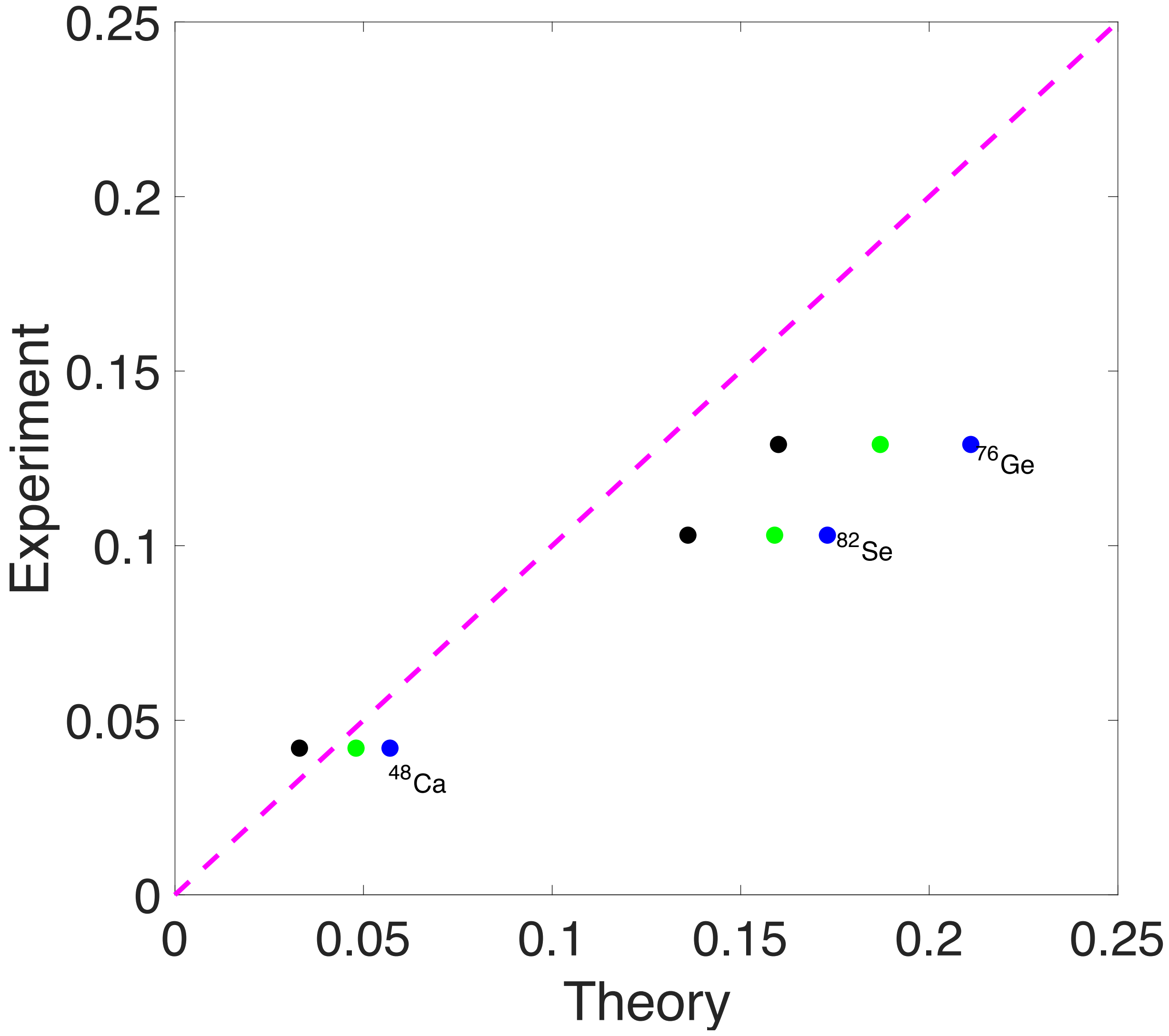

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Black: bare J_A at N3LO in ChPT

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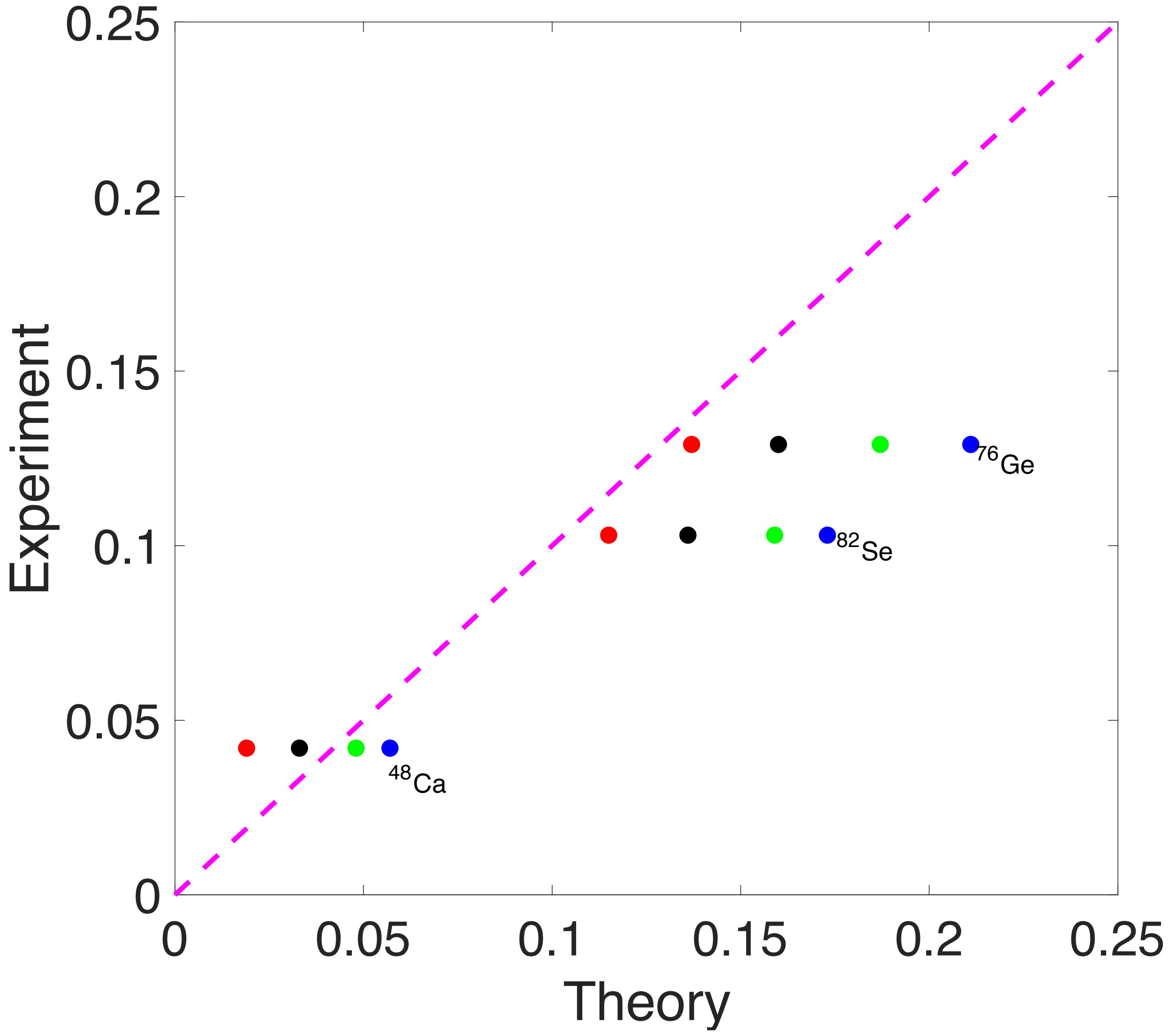
2νββ decay



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Green: effective J_A at LO in ChPT

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Red effective J_A at N3LO in ChPT

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Conclusions and persectives (1st part)

Conclusions

- Correlations + electroweak 2BC ⟹ quite good description of $\sigma\tau$ observables
- 2BC introduce ~ 20% reduction of GT matrix elements

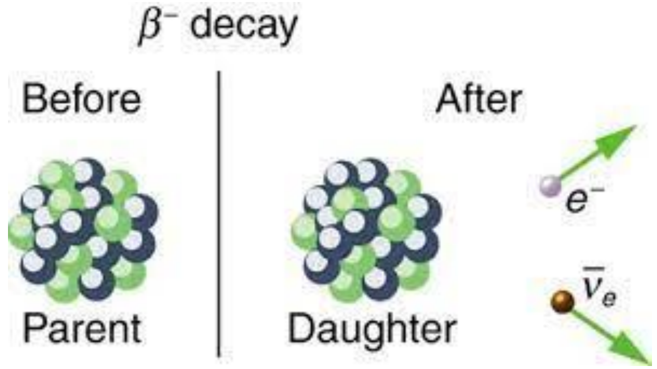
Perspectives

- Meson-exchange two-body currents for the M1 transitions
- Calculations for heavier-mass systems (100Mo, 130Te, 136Xe)
- Calculating $0\nu\beta\beta$ decay $M^{0\nu}$ including also the LO contact term

The β decay spectrum

The total half-life of the β decay is expressed in terms of the k-th partial decay half-life as

$$\frac{1}{T_{1/2}} = \sum_k \frac{1}{t^k_{1/2}} \qquad t^k_{1/2} = \frac{\kappa}{\tilde{C}}$$



where κ = 6144 s

H. Behrens and W. Büring, Nuclear Physics A162 (1971) 11 1 – 144

G. De Gregorio, R. Mancino, L.Coraggio, N. Itaco, Physical Review C **110**, 014324 (2024)

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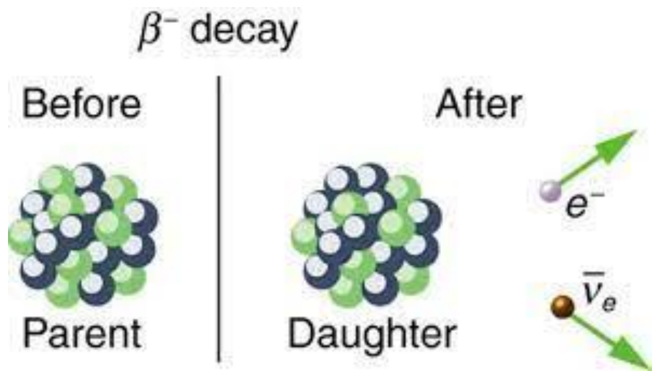

$\tilde{C}$ is the integrated shape function, whose integrand defines the β-decay energy spectrum

$$\tilde{C} = \int_1^{w_0} p_e w_e (w_0 - w_e)^2 F(Z, w_e) C_n(w_e) dw_e$$

- $F(Z, w_e) = F_0(Z, w_e) L_0(Z, w_e)$, F is the Fermi function and takes into account the distortion of the electron wave function by the nuclear charge and L_0 accounts for the finite size effect.
- w_e is the electron energy
- $C_n(w_e)$ is the shape factor of the n-th forbidden transition which depends on the nuclear matrix elements (NMEs) of the decay operators.

H. Behrens and W. Büring, Nuclear Physics A162 (1971) 11 1 – 144

G. De Gregorio, R. Mancino, L.Coraggio, N. Itaco, Physical Review C **110**, 014324 (2024)

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In general C_n is function of W_e.

For allowed transition: $C_n(w_e)$=Const=B(GT)= $g_A{}^2 \frac{|\langle f || \sum_k \sigma_k \tau_k^- || i \rangle|^2}{2J_i+1}$

Beta spectrum is insensitive to B(GT)

J. Kostensalo and J. Suhonen, Phys. Rev. C 96, 024317 (2017)

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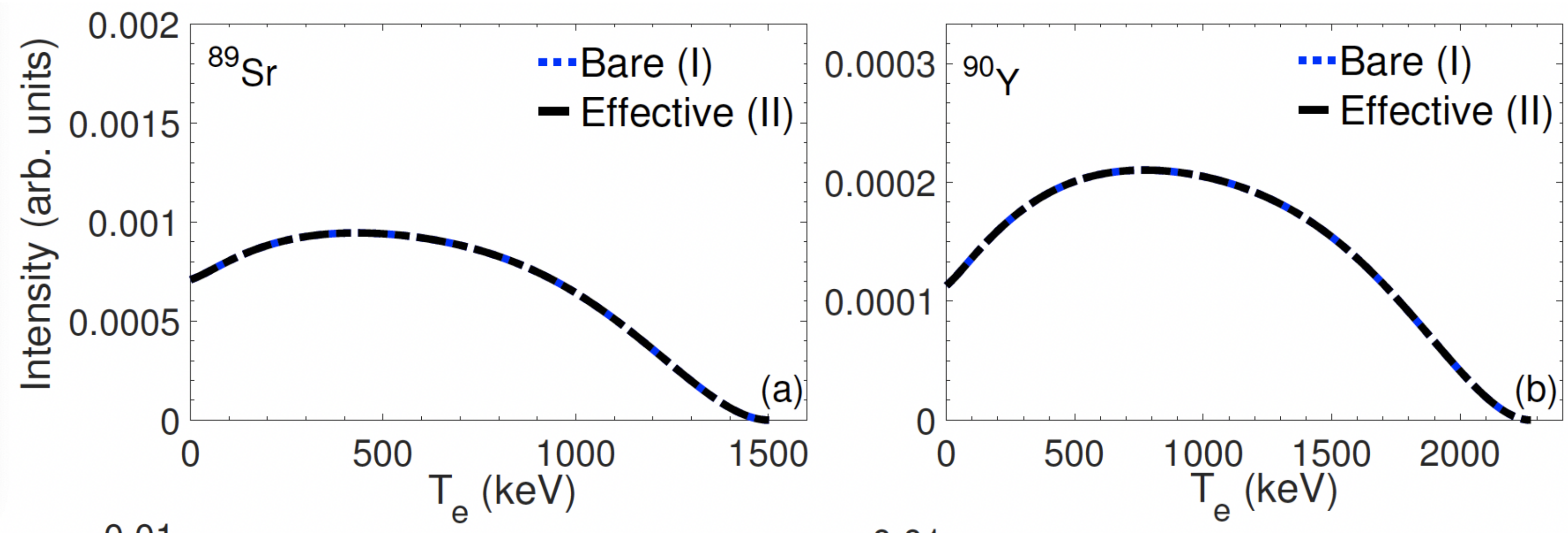
Beta spectrum is insensitive to Lth-unique decays



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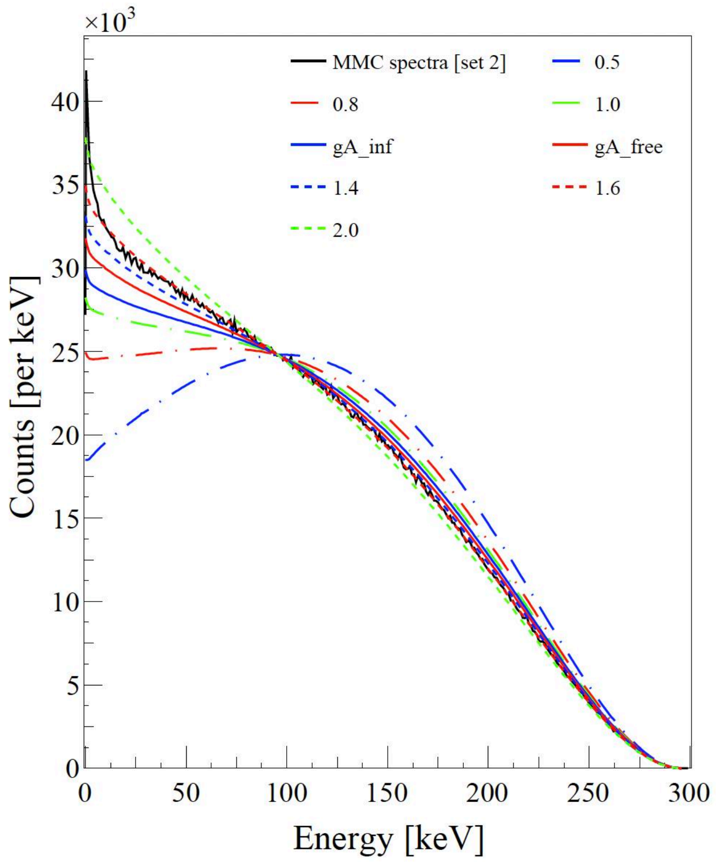

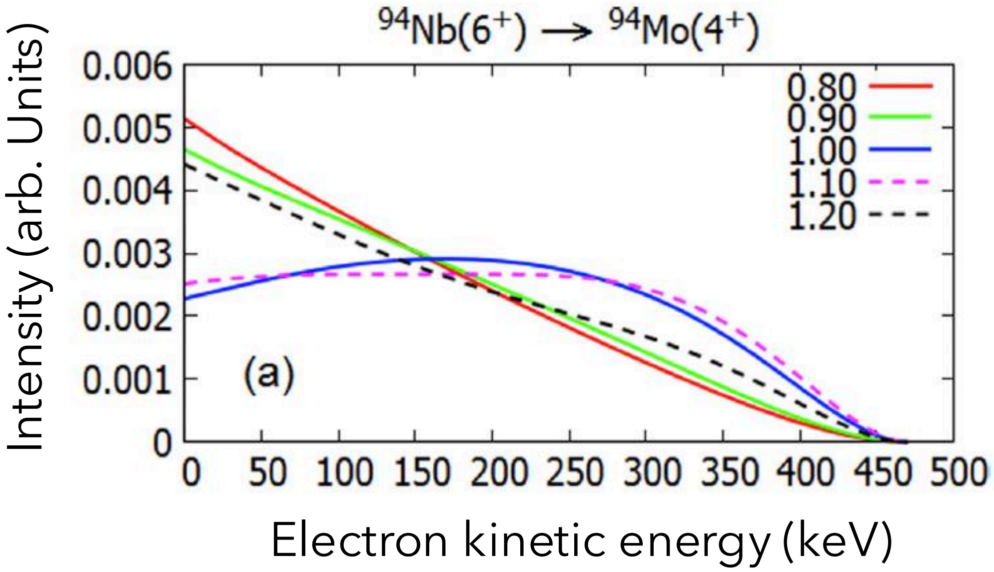

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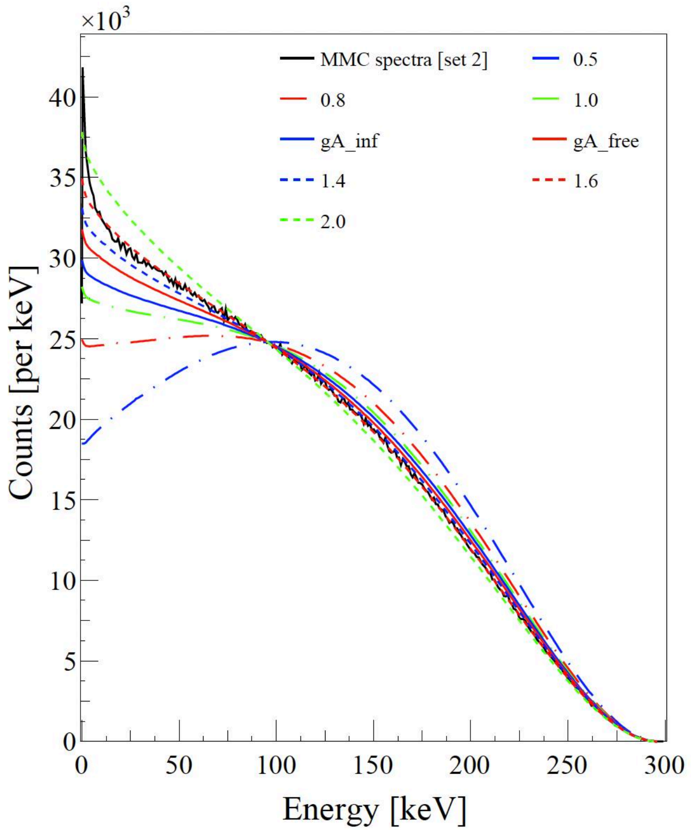

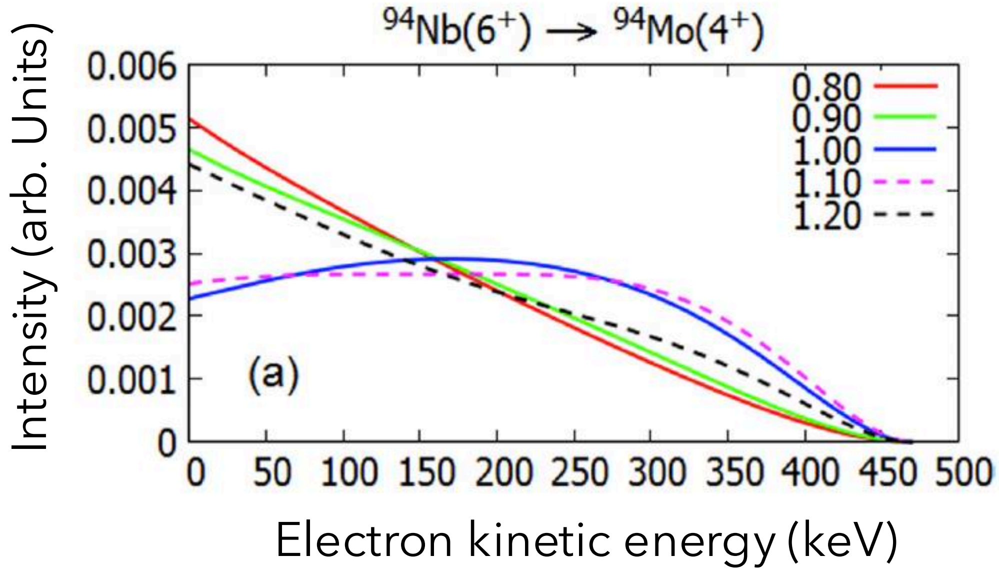

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1. One can extract the empirical value of q from the β spectrum on forbidden non-unique decays.

2. Alternatively, having a microscopic theory without free parameters, β spectra offer a further benchmark of the theoretical framework.

Details of the Calculations

Calculations for nuclei in the neighborhood of 0νββ candidates above 78Ni core:

- Second forbidden non-unique gs to gs β-decay of ^{94}Nb and ^{99}Tc
- Fourth forbidden non-unique gs to gs β-decay of ^{113}Cd and ^{115}In

One major proton and neutron shell above ^{78}Ni

Interaction

$V_{\text{low-k}}$ of CD-Bonn with Λ=2.6 fm^{-1} + Coulomb force for protons

↓

TBME +SP energies of H_{eff} & Θ_{eff} @ third order +3-body correlations

Logft

$$ft = \frac{\kappa}{\tilde{C}} \int_1^{w_0} p_e w_e (w_0 - w_e)^2 F(Z, w_e)\, dw_e$$

	Bare	Effective	Exp
^{94}Nb	11.30	11.58	11.95 (7)
^{99}Tc	11.580	11.876	12.325 (12)
^{113}Cd	21.902	22.493	23.127 (14)
^{115}In	21.22	21.64	22.53 (3)

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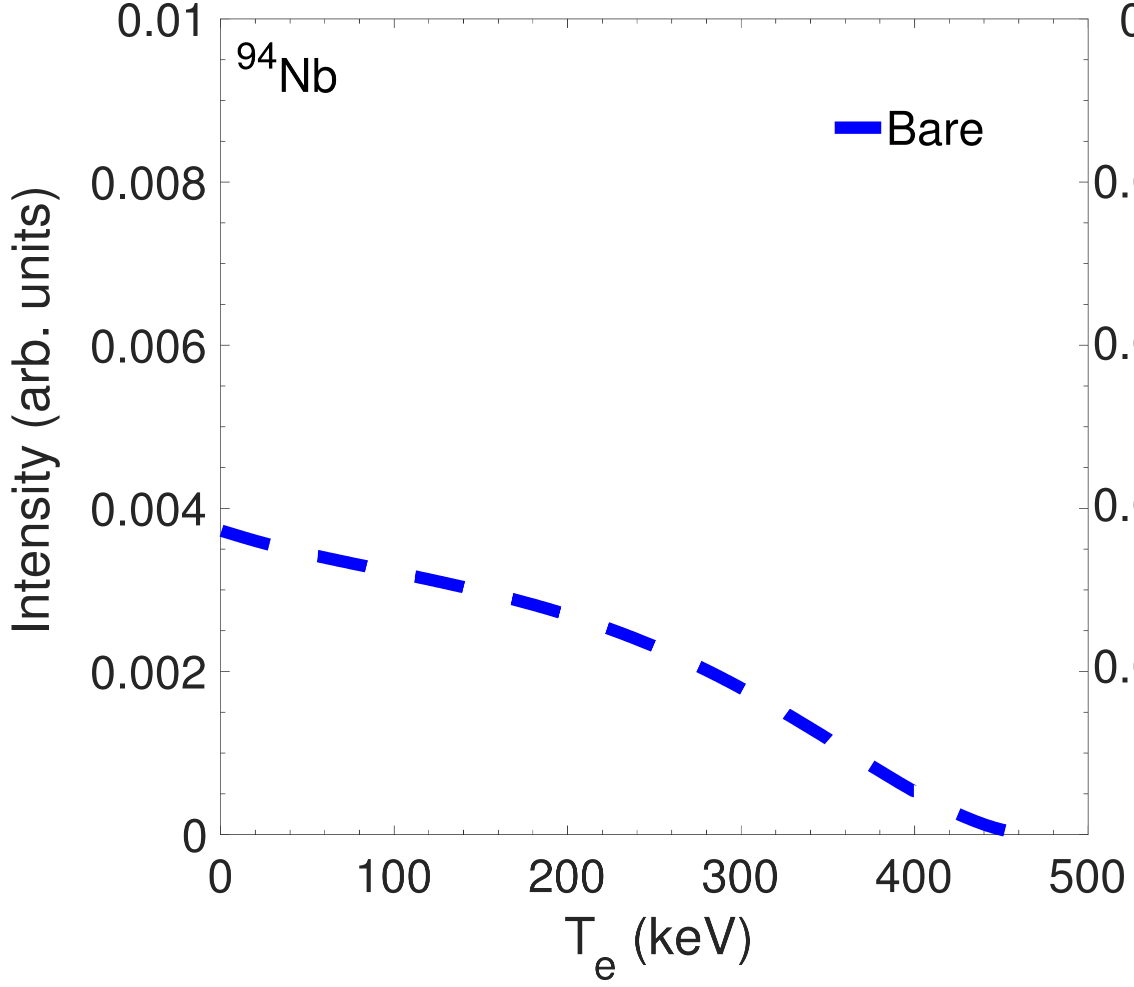
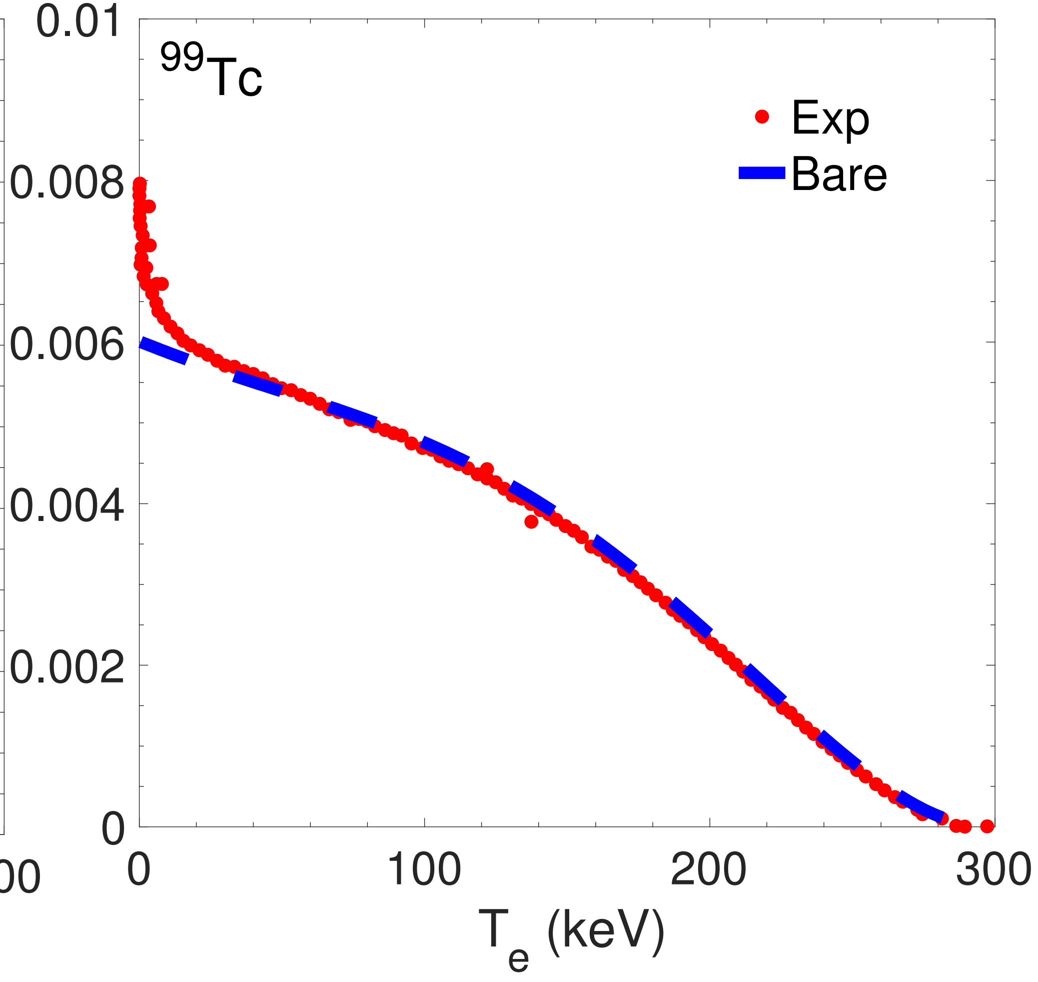
RSM β decay spectra





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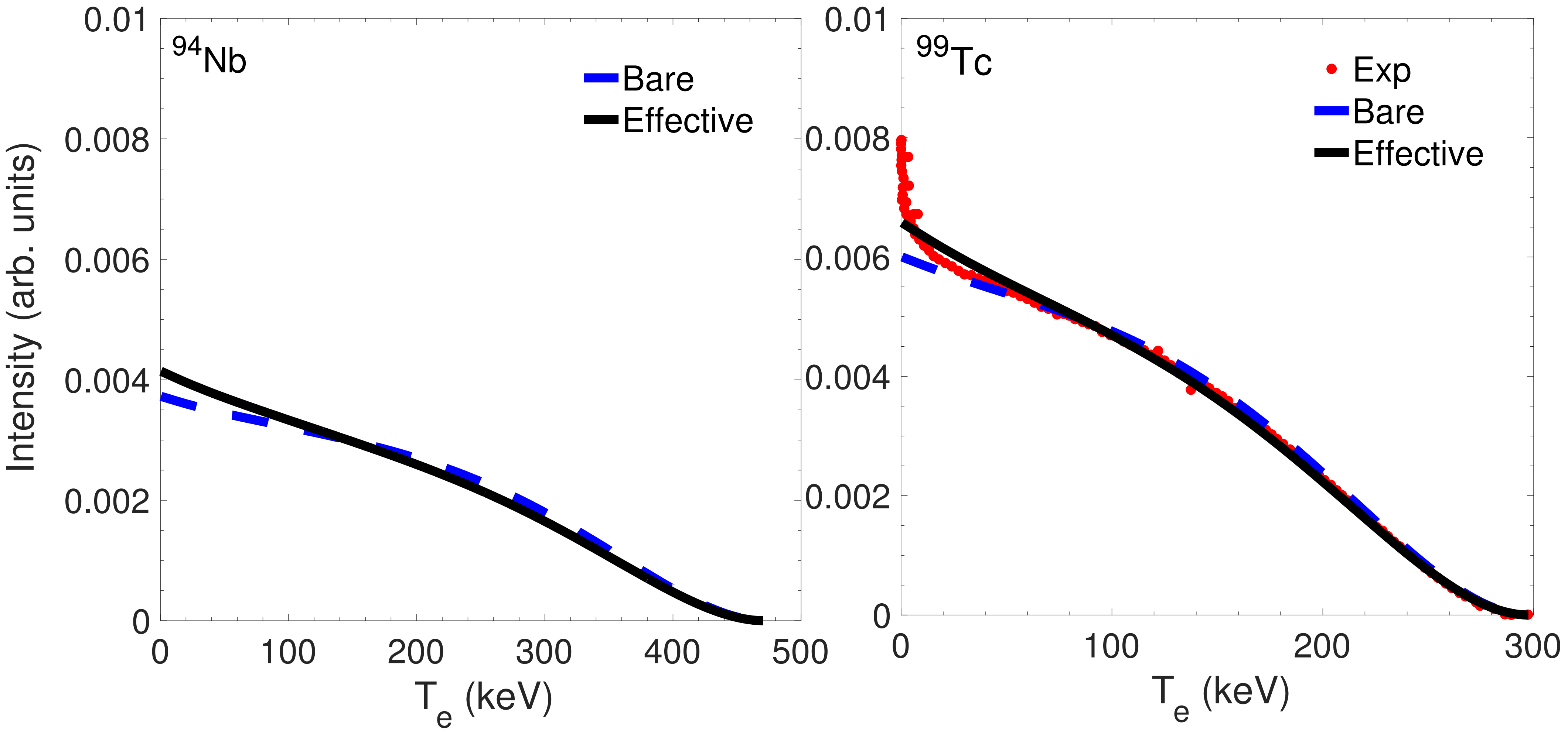

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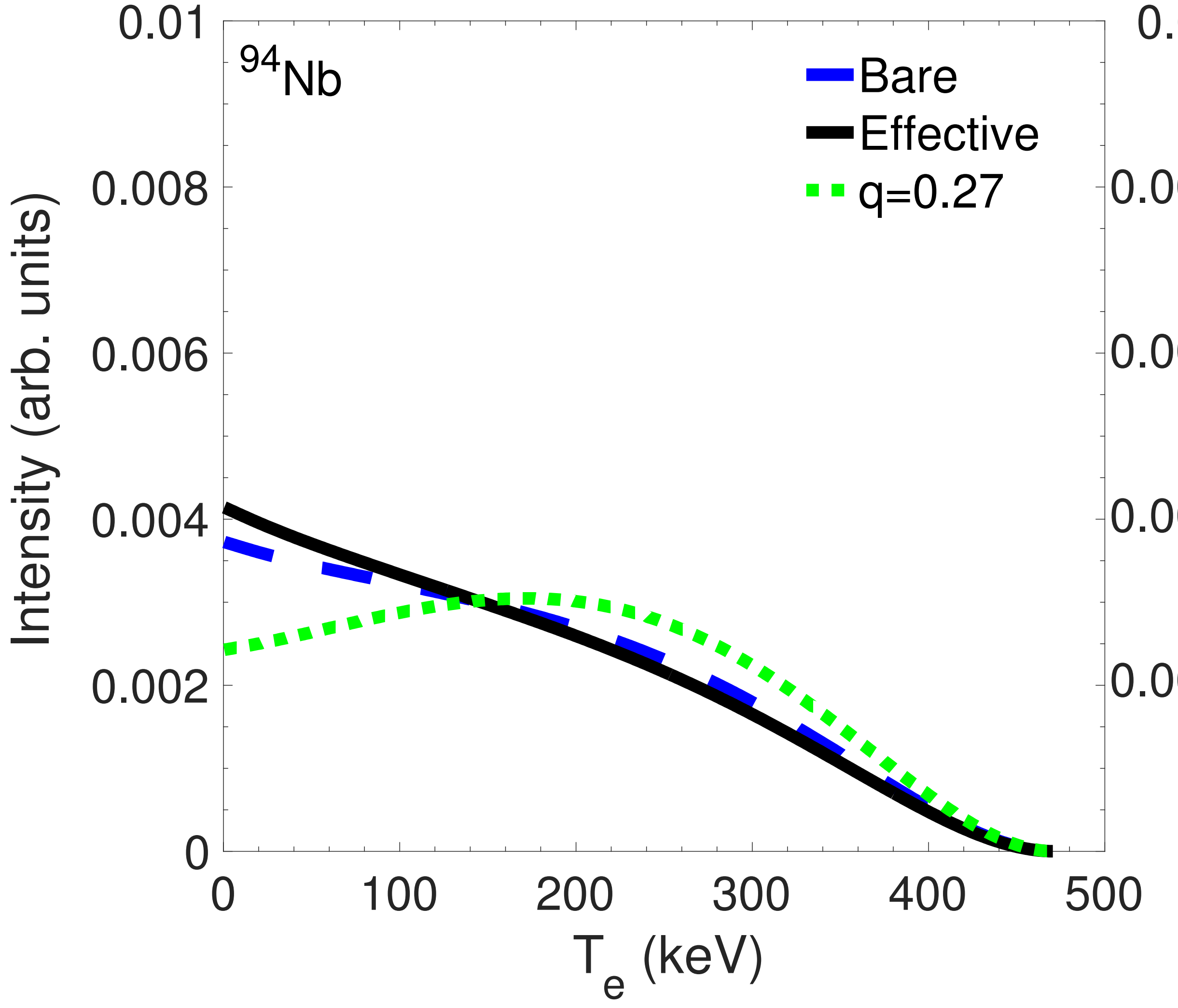

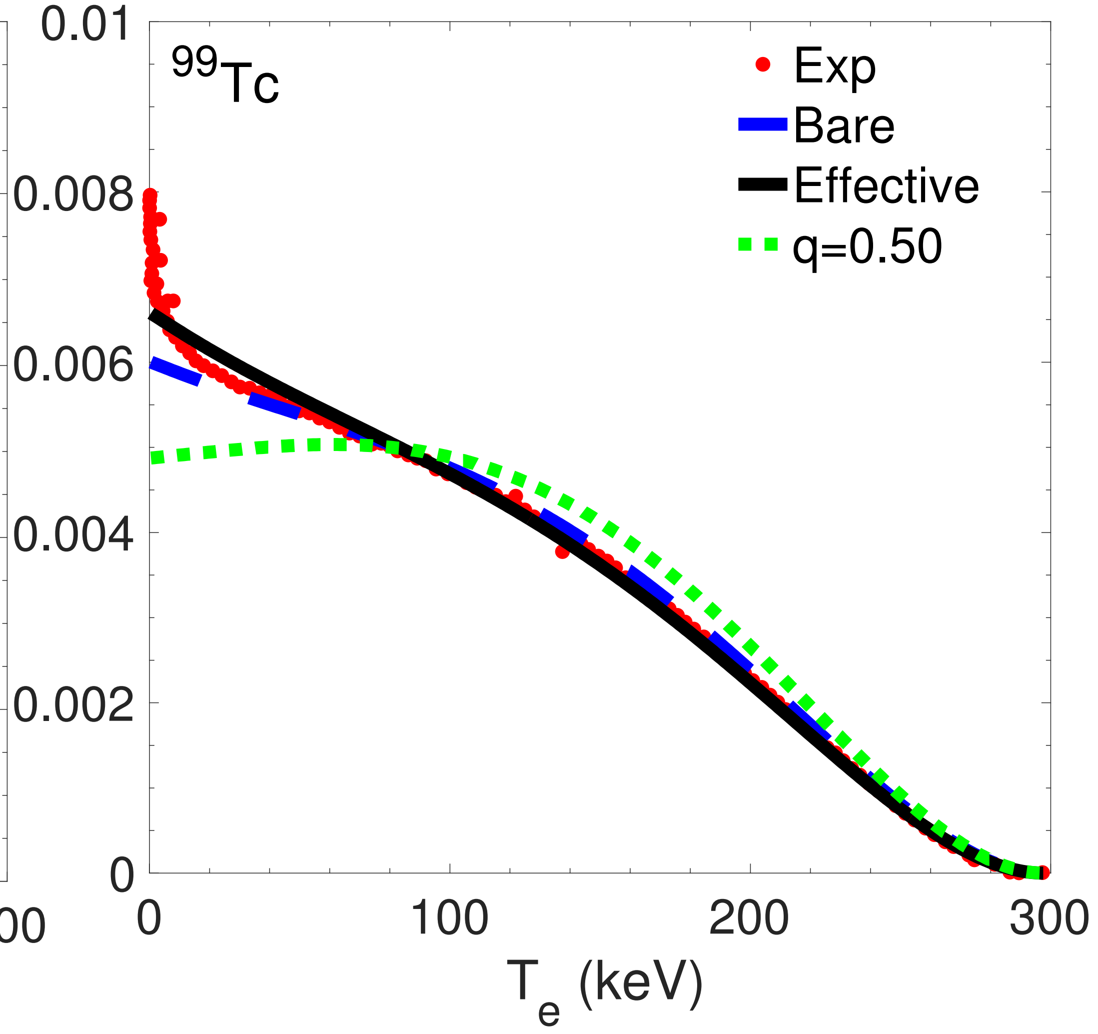

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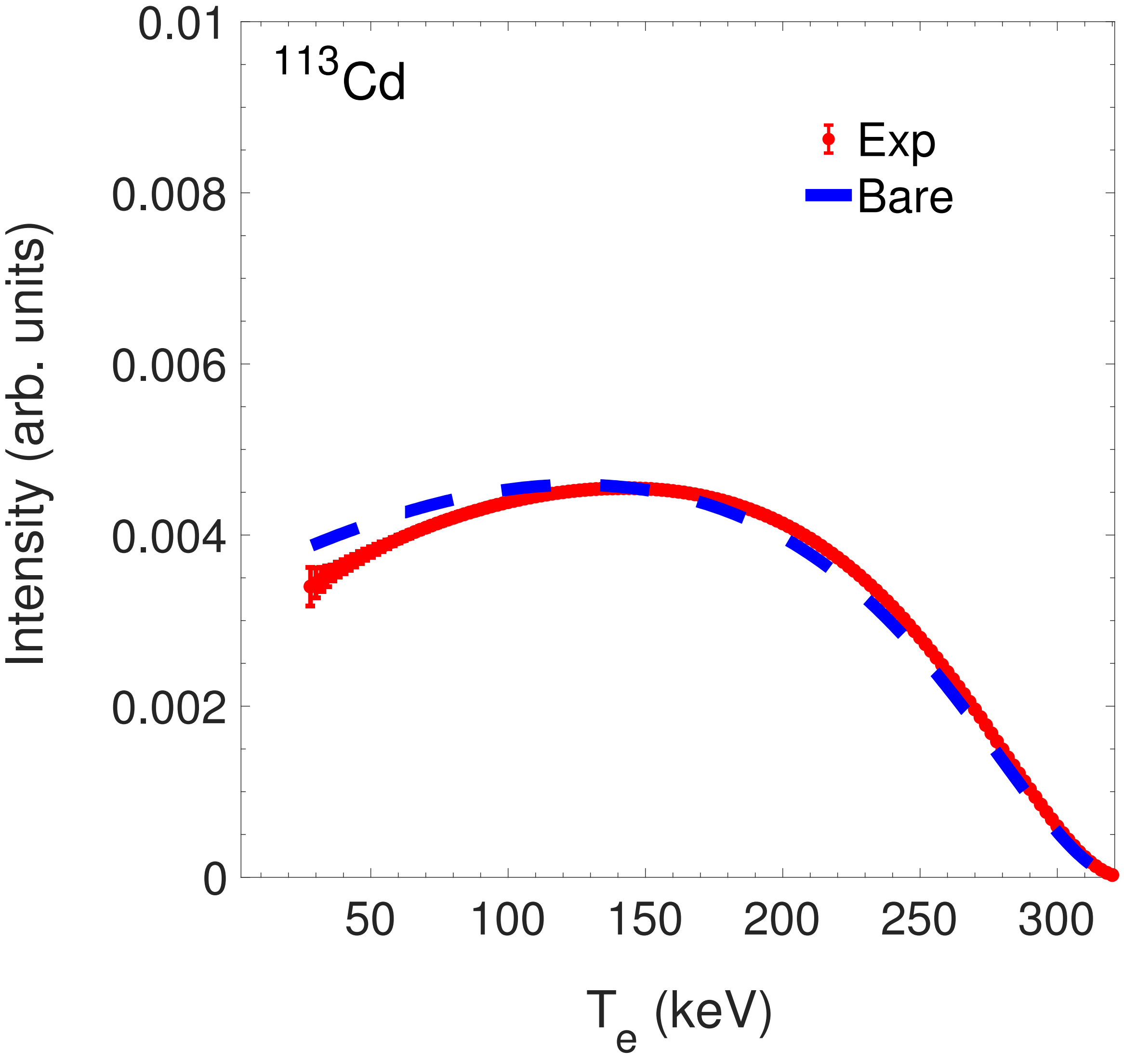

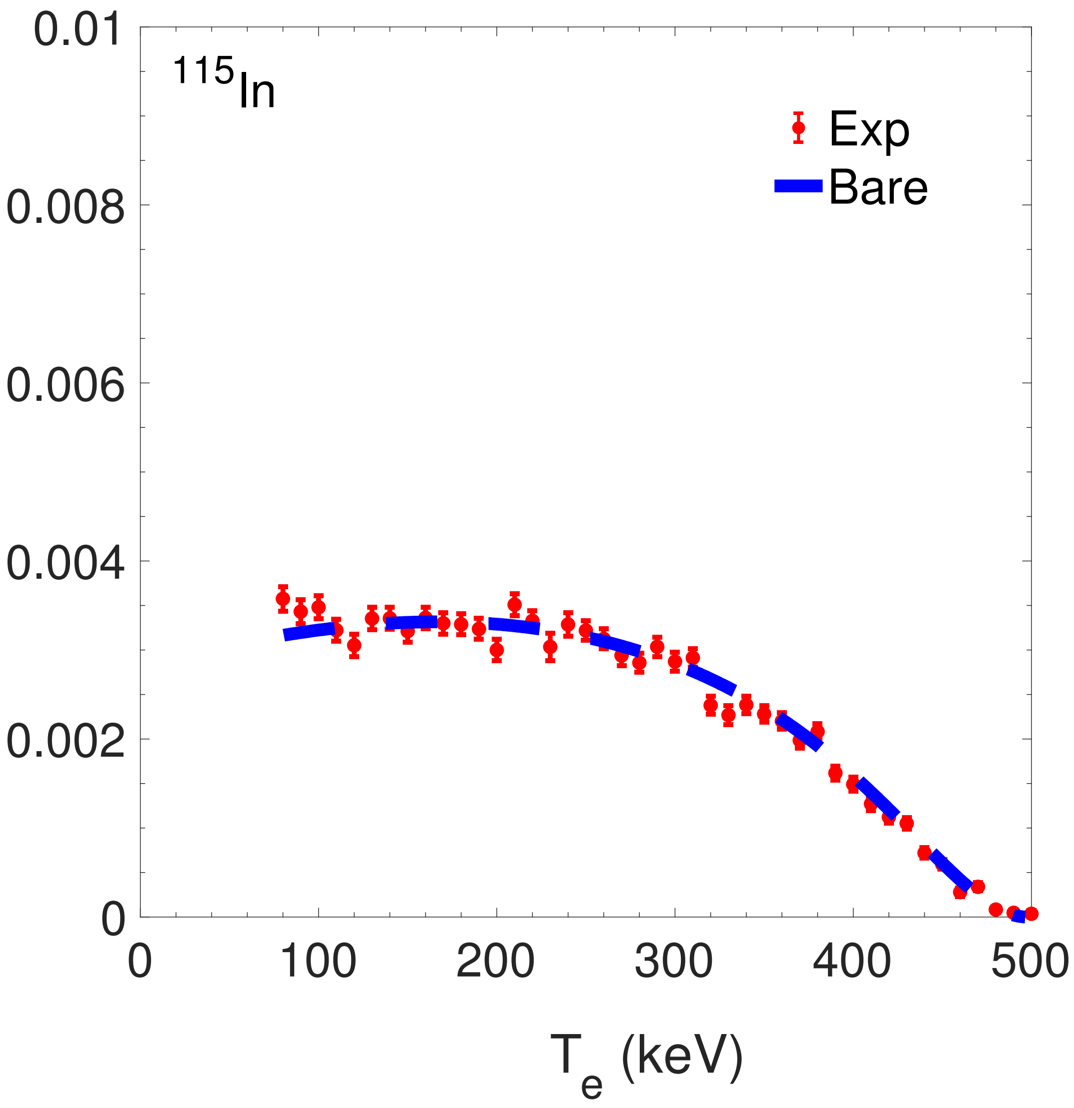

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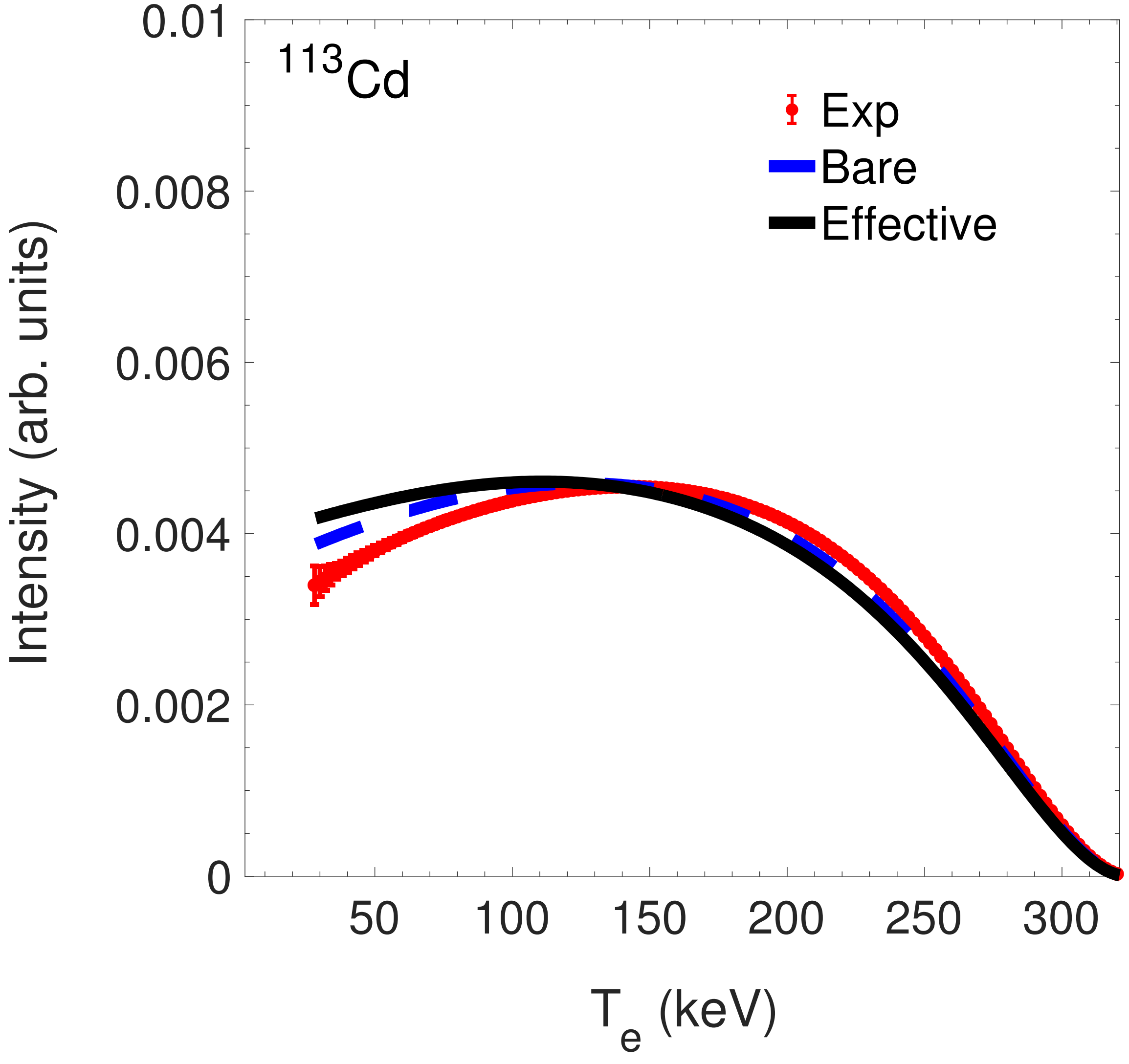

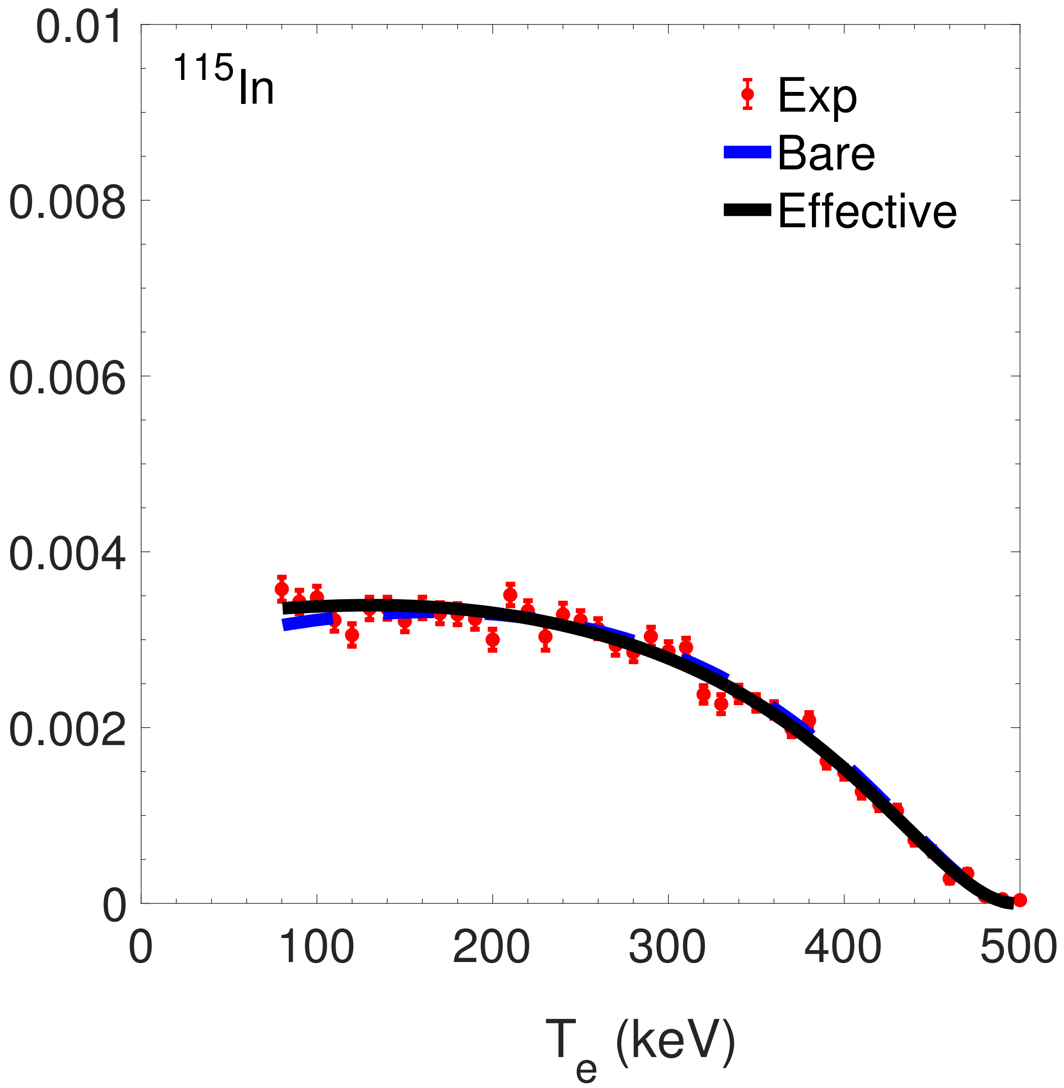

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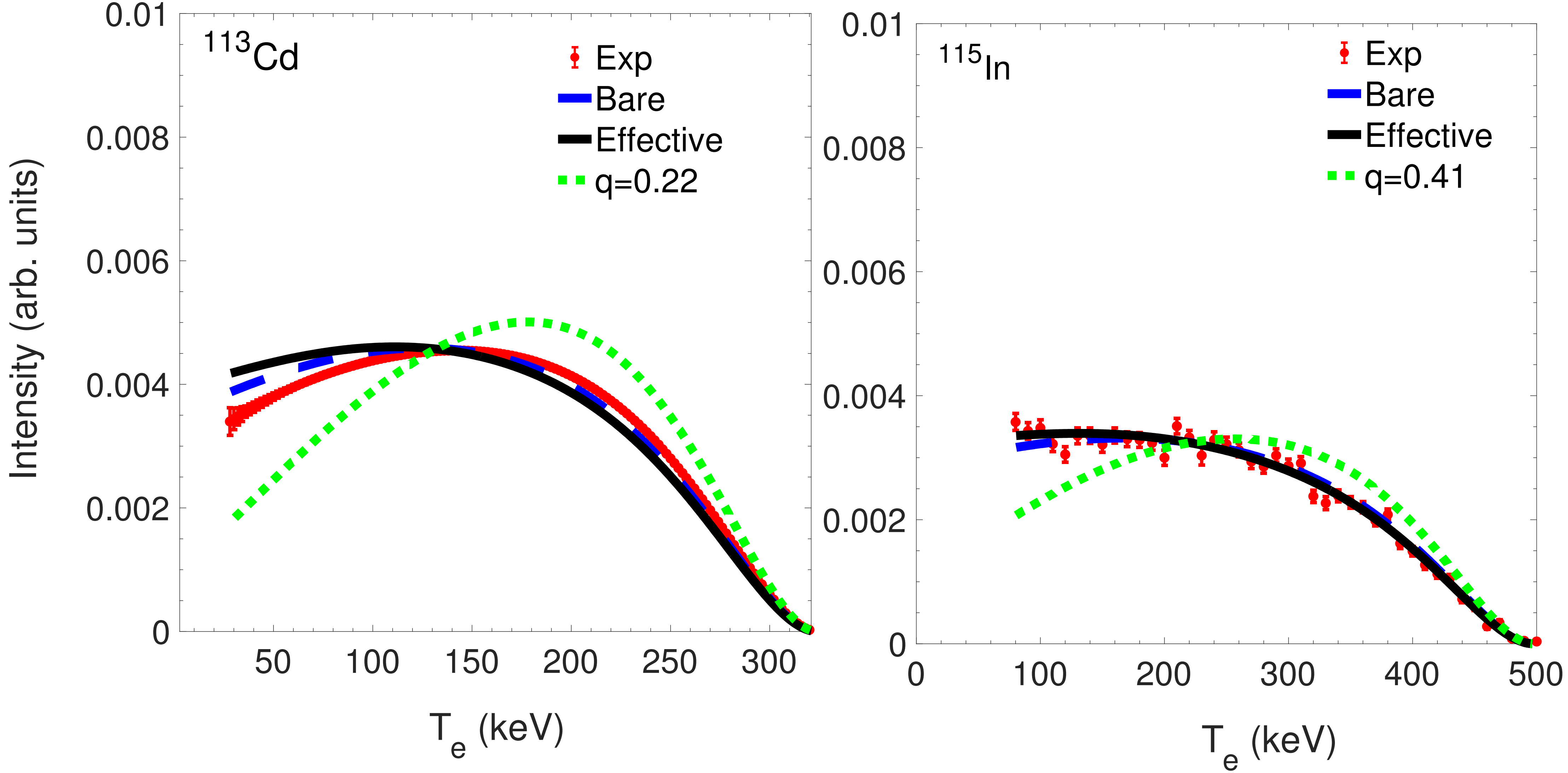

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- Study of forbidden β decays in other mass regions, close to nuclei that are candidates for detecting the 0νββ decay
- Tackle the forbidden β-decay problem starting from the derivation of electroweak currents by way of the chiral Perturbation theory

14th International Spring Seminar on Nuclear Physics: "Cutting-edge developments in nuclear structure physics"

https://agenda.infn.it/event/42803/

19th-23th May 2025

Main topics

- New frontiers in nuclear many-body theory and nuclear forces
- Experimental progress in nuclear structure studies
- Nuclear physics for testing fundamental physics
- Nuclear astrophysics
- Quantum computing and machine learning for nuclear physics