Gamow-Teller Transitions: Probing Nuclear Structure and Weak Interactions

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Quenching of $\boldsymbol{\sigma\tau}$ matrix elements

Quenching of $\boldsymbol{\sigma\tau}$ matrix elements is quite a general phenomenon in nuclear-structure physics.

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.

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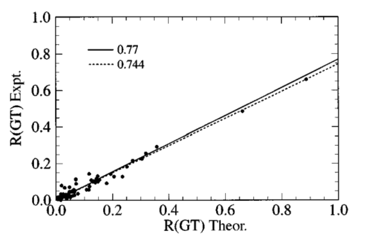

G. Martinez Pinedo et al., Phys. Rev. C 53, R2602 (1996)

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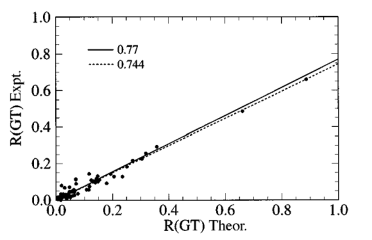


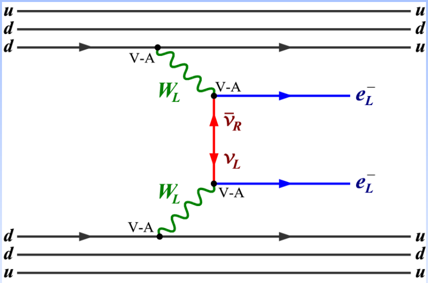
G. Martinez Pinedo et al., Phys. Rev. C 53, R2602 (1996)

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

J. T. Suhonen
Frontiers in Physics **5** *, 55 (2017)*

Quenching of $\sigma\tau$ matrix elements & $0\nu\beta\beta$ decay

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



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

- $G^{0\nu}$ $\rightarrow$ phase-space factor
- $\langle m_\nu\rangle = \mid \sum_k m_k U_{ek}^2 \mid$ effective mass of the Majorana neutrino, U_{ek} being the lepton mixing matrix

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

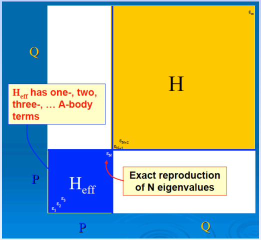
Two main sources $\Rightarrow$ missing degrees of freedom

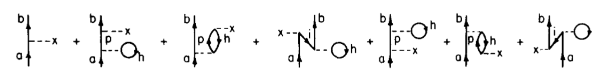
Quenching of $\sigma\tau$ matrix elements: theory

Two main sources $\Rightarrow$ missing degrees of freedom

Limited model space

Nuclear-structure calculations are carried out in truncated model spaces $\Rightarrow$ effective Hamiltonians and operators





Quenching of $\sigma\tau$ matrix elements: truncated model space

Reduced model space P

$$H \Rightarrow H_{\text{eff}}$$

$$H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle \Rightarrow H_{\text{eff}}|\Phi_\alpha\rangle = E_\alpha|\Phi_\alpha\rangle$$

$|\Phi_\alpha\rangle =$ eigenvectors obtained diagonalizing H_{eff} in the reduced model space $\Rightarrow |\Phi_\alpha\rangle = P|\Psi_\alpha\rangle$

$$\langle\Phi_\alpha|\hat{\Theta}|\Phi_\beta\rangle \neq \langle\Psi_\alpha|\hat{\Theta}|\Psi_\beta\rangle$$

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Quenching of $\sigma\tau$ matrix elements: truncated model space

Effective operator $\hat{\Theta}_{\rm eff}$: definition

$$\langle \Phi_\alpha | \hat{\Theta}_{\rm eff} | \Phi_\beta \rangle = \langle \Psi_\alpha | \hat{\Theta} | \Psi_\beta \rangle$$

$$\hat{\Theta}_{\rm eff} = \sum_{\alpha\beta} |\Phi_\alpha\rangle \langle \Psi_\alpha | \hat{\Theta} | \Psi_\beta \rangle \langle \Phi_\beta |$$

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Gamow-Teller operator

$$\hat{\Theta}^{GT} = g_A \boldsymbol{\sigma\tau}^{\pm} \Rightarrow \hat{\Theta}^{GT}_{\text{eff}} = g_A^{\text{eff}} \boldsymbol{\sigma\tau}^{\pm}$$

Quenching of $\sigma\tau$ matrix elements: truncated model space

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$$\hat{\Theta}^{GT} = g_A \boldsymbol{\sigma}\boldsymbol{\tau}^{\pm} \Rightarrow \hat{\Theta}^{GT}_{\rm eff} = g_A^{\rm eff} \boldsymbol{\sigma}\boldsymbol{\tau}^{\pm}$$

Electric quadrupole operator

$$\hat{\Theta}^{E2} = e r^2 Y^2_\mu \Rightarrow \hat{\Theta}^{E2}_{\rm eff} = e^{\rm eff} r^2 Y^2_\mu$$

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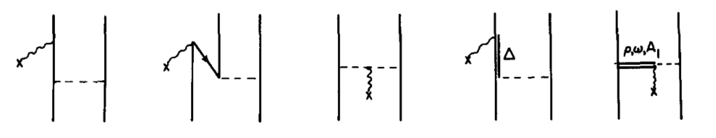
Quenching of $\sigma\tau$ matrix elements: theory

Two main reasons $\Rightarrow$ missing degrees of freedom

Non-nucleonic degrees of freedom

Processes in which the weak probe prompts a meson to be exchanged between two nucleons $\Longrightarrow$ 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 $\sigma\tau^{\pm}$

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

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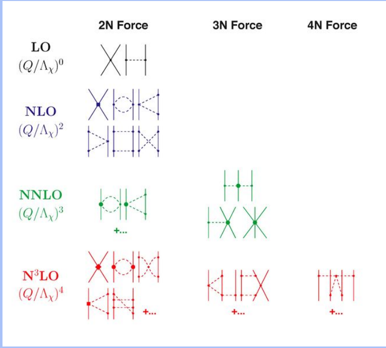
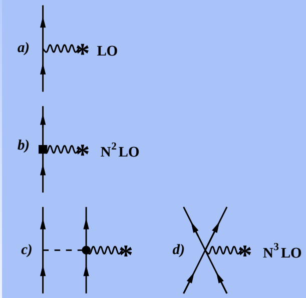
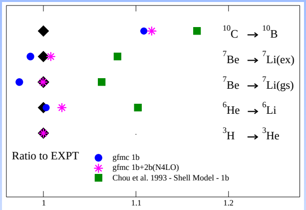
Nuclear potential



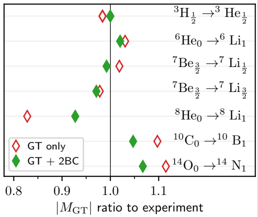
Electroweak axial currents



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

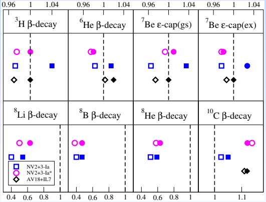


S. Pastore et al., Phys. Rev. C **97** *022501(R) (2018)*



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

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



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

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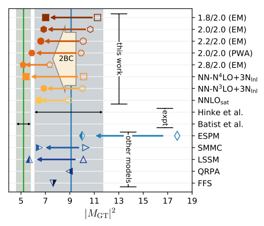
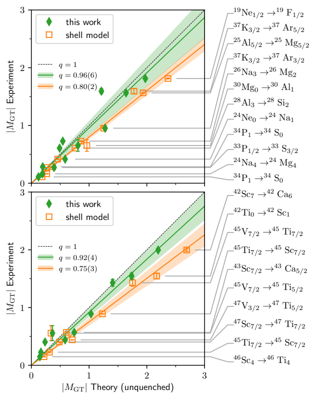
Two-body e.w. currents effects: medium mass nuclei

Coupled-cluster method CCM and in-medium SRG (IMRSG) calculations have recently performed to overcome the quenching problem g_A to reproduce β-decay observables in heavier systems

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



Coupled-Cluster Method



In-Medium SRG

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”

Realistic Shell-Model Calculations

Realistic shell-model calculations starting from a nuclear Hamiltonian and electroweak axial currents derived consistently by way of χPT.

Università "Vanvitelli" and INFN-Napoli

- L. Coraggio
- G. De Gregorio
- A. Gargano
- N. I.

INFN-Pisa

- M. Viviani

Peking University

- Z. H. Cheng
- Y. Z. Ma
- F. R. Xu

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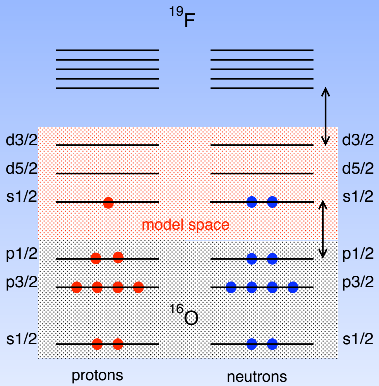
Realistic Shell-Model Calculations

Shell model $\Rightarrow$ well-established approach to obtain a microscopic description of both collective and single-particle properties of nuclei



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

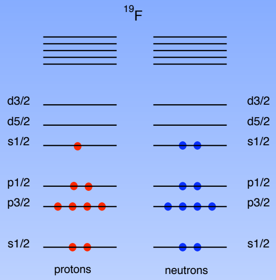
V_{NN} $(+V_{NNN}) \Rightarrow$ many-body theory $\Rightarrow H_{\text{eff}}$

Effective shell-model hamiltonian

A-nucleon system Schrödinger equation

$$H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$$

$$H = H_0 + H_1 = \sum_{i=1}^{A}(T_i + U_i) + \sum_{i<j}(V_{ij}^{NN} - U_i)$$



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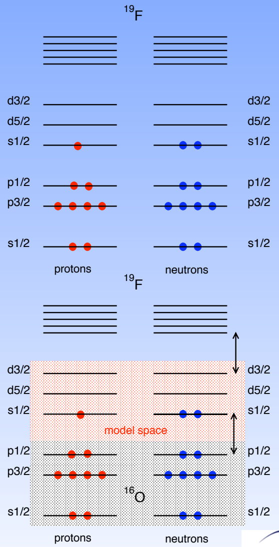
Model space

$$|\Phi_i\rangle = [a_1^\dagger a_2^\dagger \ldots a_n^\dagger]_i|c\rangle \Rightarrow P = \sum_{i=1}^{d}|\Phi_i\rangle\langle\Phi_i|$$

Model-space eigenvalue problem

$$H_{\text{eff}}P|\Psi_\alpha\rangle = E_\alpha P|\Psi_\alpha\rangle$$



Effective shell-model Hamiltonian

$$\left(\begin{array}{c|c} PHP & PHQ \\ \hline QHP & QHQ \end{array}\right) \underset{Q\mathcal{H}P=0}{\overset{\mathcal{H}=\Omega^{-1}H\Omega}{\Longrightarrow}} \left(\begin{array}{c|c} P\mathcal{H}P & P\mathcal{H}Q \\ \hline 0 & Q\mathcal{H}Q \end{array}\right)$$

$$H_{\mathrm{eff}} = P\mathcal{H}P$$

$$\text{Suzuki \& Lee} \Rightarrow \Omega = e^{\omega} \text{ with } \omega = \left(\begin{array}{c|c} 0 & 0 \\ \hline Q\omega P & 0 \end{array}\right)$$

$$H_1^{\mathrm{eff}}(\omega) = PH_1P + PH_1Q\frac{1}{\epsilon - QHQ}QH_1P - PH_1Q\frac{1}{\epsilon - QHQ}\omega H_1^{\mathrm{eff}}(\omega)$$

The shell-model effective hamiltonian

Folded-diagram expansion

$\hat{Q}$-box vertex function

$$\hat{Q}(\epsilon) = PH_1 P + PH_1 Q \frac{1}{\epsilon - QHQ} QH_1 P$$

$\Rightarrow$ Recursive equation for $H_{\rm eff}$ $\Rightarrow$ iterative techniques (Krenciglowa-Kuo, Lee-Suzuki, ...)

$$H_{\rm eff} = \hat{Q} - \hat{Q}' \int \hat{Q} + \hat{Q}' \int \hat{Q} \int \hat{Q} - \hat{Q}' \int \hat{Q} \int \hat{Q} \int \hat{Q} \cdots ,$$

generalized folding

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The perturbative approach to the shell-model H^{eff}

$$\hat{Q}(\epsilon) = PH_1P + PH_1Q\frac{1}{\epsilon - QHQ}QH_1P$$

The $\hat{Q}$-box can be calculated perturbatively

$$\frac{1}{\epsilon - QHQ} = \sum_{n=0}^{\infty}\frac{(QH_1Q)^n}{(\epsilon - QH_0Q)^{n+1}}$$

The diagrammatic expansion of the $\hat{Q}$-box

The perturbative approach to the shell-model $H^{\rm eff}$

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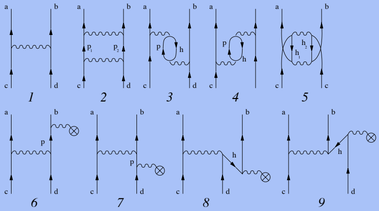
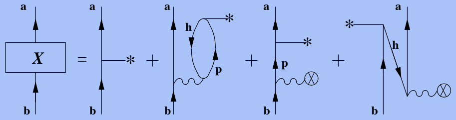


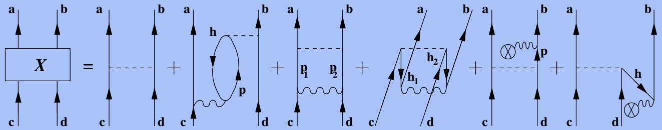
The shell-model effective operators

$\hat{\Theta}_{\rm eff}$ can be derived consistently in the MBPT framework

One-body operator



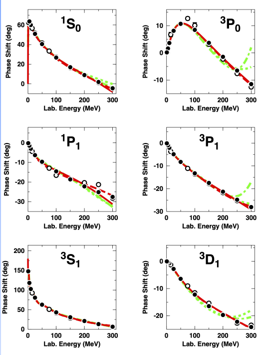
Two-body operator



K. Suzuki and R. Okamoto, Prog. Theor. Phys. **93** *, 905 (1995)*

Realistic Shell-Model Calculations

- Nuclear Hamiltonian: Entem-Machleidt N^{3}LO two-body potential plus N^{2}LO three-body potential (Λ = 500 MeV)
- Axial current $\mathbf{J}_A$ calculated at N^{3}LO in ChPT



- $H_{\rm eff}$ 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

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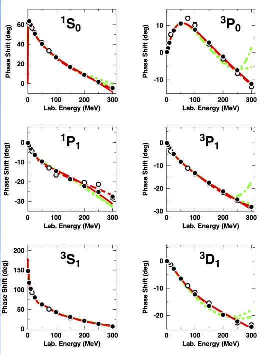

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The matrix elements of the axial current $\mathbf{J}_A$ are derived through a chiral expansion up to N^{3}LO, and employing the same LECs as in 2NF and 3NF

$$\mathbf{J}^{\rm LO}_{A,\pm} = -g_A \sum_i \boldsymbol{\sigma}_i \tau_{i,\pm} \quad ,$$

$$\mathbf{J}^{\rm N^2LO}_{A,\pm} = \frac{g_A}{2m_N^2} \sum_i \mathbf{K}_i \times (\boldsymbol{\sigma}_i \times \mathbf{K}_i)\, \tau_{i,\pm} \quad ,$$

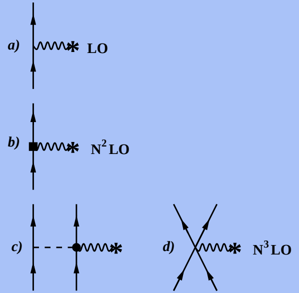
$$\mathbf{J}^{\rm N^3LO}_{A,\pm}({\rm 1PE};\mathbf{k}) = \sum_{i<j} \frac{g_A}{2f_\pi^2} \Big\{ 4c_3 \tau_{j,\pm} \mathbf{k} + (\boldsymbol{\tau}_i \times \boldsymbol{\tau}_j)_\pm$$

$$\times \left[\left(c_4 + \frac{1}{4m} \boldsymbol{\sigma}_i \times \mathbf{k} - \frac{i}{2m} \mathbf{K}_i \right) \right] \Big\} \boldsymbol{\sigma}_j \cdot \mathbf{k} \frac{1}{\omega_k^2} \quad ,$$

$$\mathbf{J}^{\rm N^3LO}_{A,\pm}({\rm CT};\mathbf{k}) = \sum_{i<j} z_0 (\boldsymbol{\tau}_i \times \boldsymbol{\tau}_j)_\pm (\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j) \quad ,$$

where

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



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

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$$\mathbf{J}^{\mathrm{N^3LO}}_{A,\pm}(\mathrm{CT};\mathbf{k}) = \sum_{i<j} z_0 (\boldsymbol{\tau}_i \times \boldsymbol{\tau}_j)_\pm (\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j) \quad ,$$

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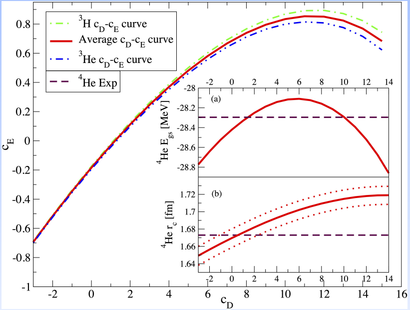

Realistic Shell-Model Calculations

- *fp*-shell nuclei: four proton and neutron orbitals outside *LS* core
  ^{40}Ca $\rightarrow$ $0f_{7/2}0f_{5/2}, 1p_{3/2}, 1p_{1/2}$
- *fpg*-shell nuclei: four proton and neutron orbitals outside *jj* core
  ^{56}Ni $\rightarrow$ $0f_{5/2}, 1p_{3/2}, 1p_{1/2}, 0g_{9/2}$

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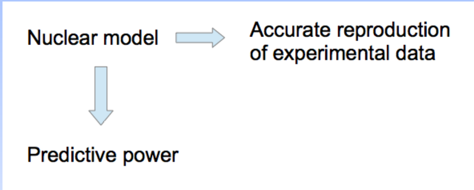
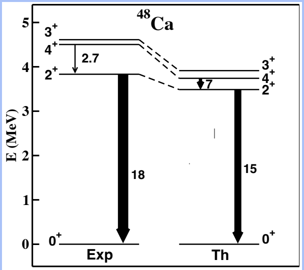
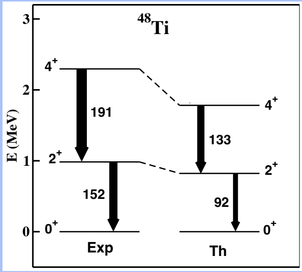


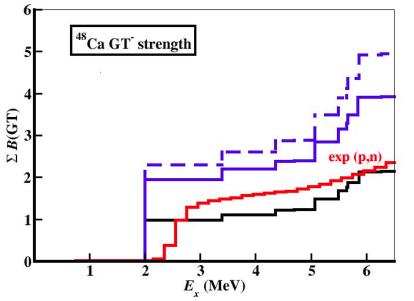
RSM calculations, starting from ChPT two- and three-body potentials and two-body meson-exchange currents for spectroscopic and spin-isospin dependent observables of ^{48}Ca, ^{76}Ge, ^{82}Se

fp-shell nuclei: spectroscopic properties





^{48}Ca GT strength distribution



Charge-exchange experiments

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

$$B_{Th}(GT) = \frac{|\langle \Phi_f || \mathbf{J}_A || \Phi_i \rangle|^2}{2J_i + 1}$$

- - - bare $\mathbf{J}_A$ at LO in ChPT
(namely the GT operator $g_A \boldsymbol{\sigma} \cdot \boldsymbol{\tau}$)
— effective $\mathbf{J}_A$ at LO in ChPT
— effective $\mathbf{J}_A$ at N^{3}LO in ChPT

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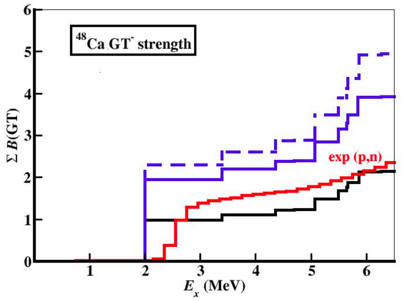

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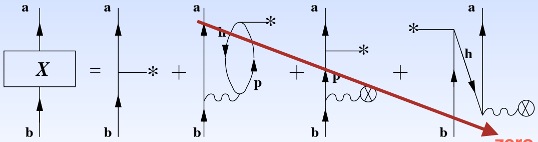

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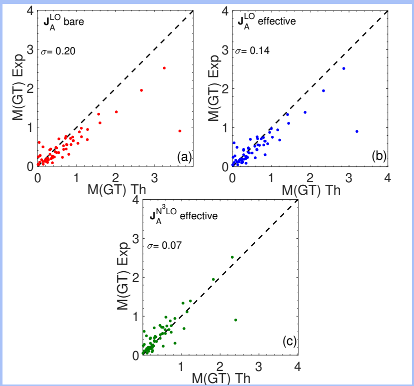
fp-shell nuclei: GT matrix elements



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

- (a) bare $\mathbf{J}_A$ at LO in ChPT (namely the GT operator $g_A \boldsymbol{\sigma} \cdot \boldsymbol{\tau}$);
- (b) effective $\mathbf{J}_A$ at LO in ChPT;
- (c) effective $\mathbf{J}_A$ at N^{3}LO in ChPT.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{n}}$$

	(a)		(b)		(d)
σ	0.20	$\rightarrow$	0.14	$\rightarrow$	0.07

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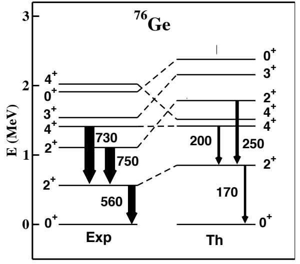
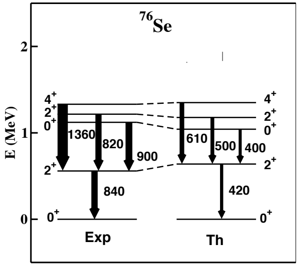
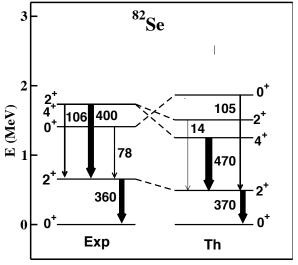
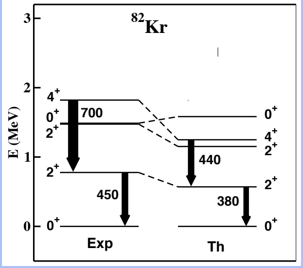
$0f_{5/2}1p0g_{9/2}$-shell nuclei spectroscopic properties

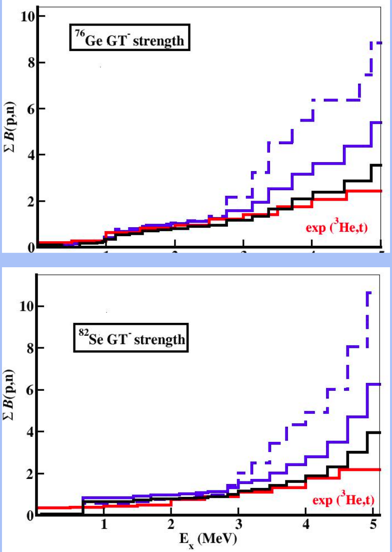








^{76}Ge & ^{82}Se GT strength distributions



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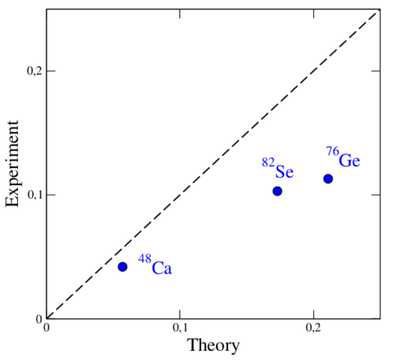
$2\nu\beta\beta$ nuclear matrix elements

$$M^{\mathrm{GT}}_{2\nu} = \sum_n \frac{\langle 0^+_f || \mathbf{J}_A || 1^+_n \rangle \langle 1^+_n || \mathbf{J}_A || 0^+_i \rangle}{E_n + E_0}$$



Blue dots:
bare $\mathbf{J}_A$ at LO in ChPT (namely the GT operator $g_A \boldsymbol{\sigma} \cdot \boldsymbol{\tau}$)

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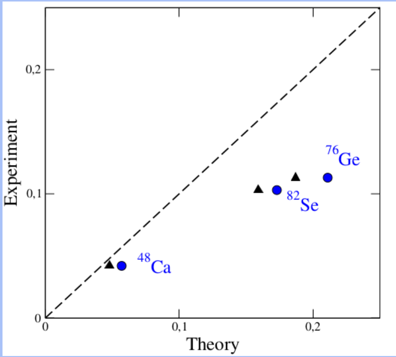
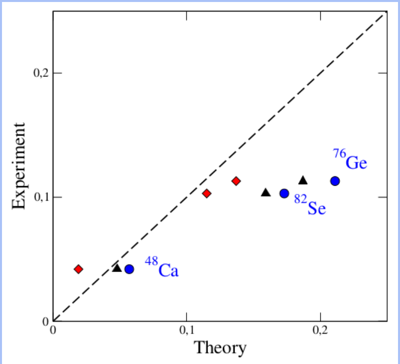


Blue dots:
bare $\mathbf{J}_A$ at LO in ChPT (namely the GT operator $g_A \boldsymbol{\sigma} \cdot \boldsymbol{\tau}$)

Black triangles:
effective $\mathbf{J}_A$ at LO in ChPT

$2\nu\beta\beta$ nuclear matrix elements

$$M^{\mathrm{GT}}_{2\nu} = \sum_n \frac{\langle 0_f^+ || \mathbf{J}_A || 1_n^+ \rangle \langle 1_n^+ || \mathbf{J}_A || 0_i^+ \rangle}{E_n + E_0}$$



Blue dots:
bare $\mathbf{J}_A$ at LO in ChPT (namely the GT operator $g_A \boldsymbol{\sigma} \cdot \boldsymbol{\tau}$)

Black triangles:
effective $\mathbf{J}_A$ at LO in ChPT

Red diamonds:
effective $\mathbf{J}_A$ at N^{3}LO in ChPT

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Conclusions & Perspectives

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

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

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Gamow-Teller Transitions: Probing Nuclear Structure and Weak Interactions

Nunzio Itaco

Università della Campania “Luigi Vanvitelli”
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