Interacting Boson Model approaches for neutrinoless ββ decay matrix elements

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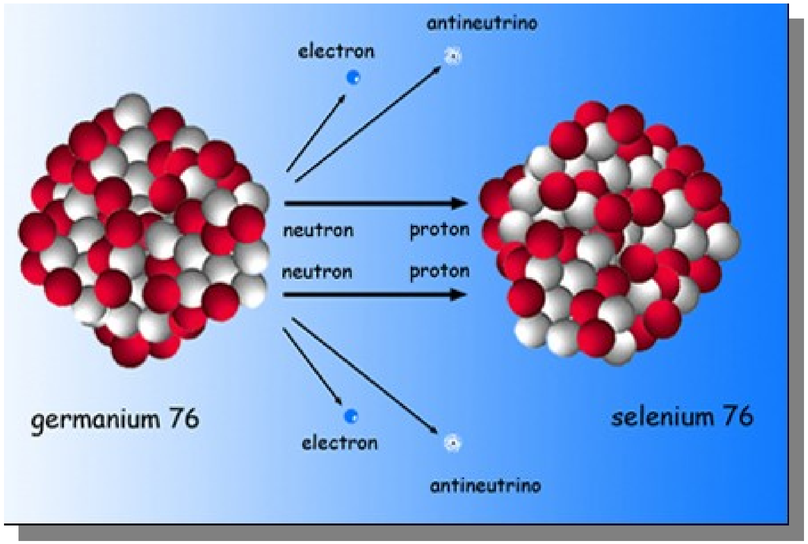
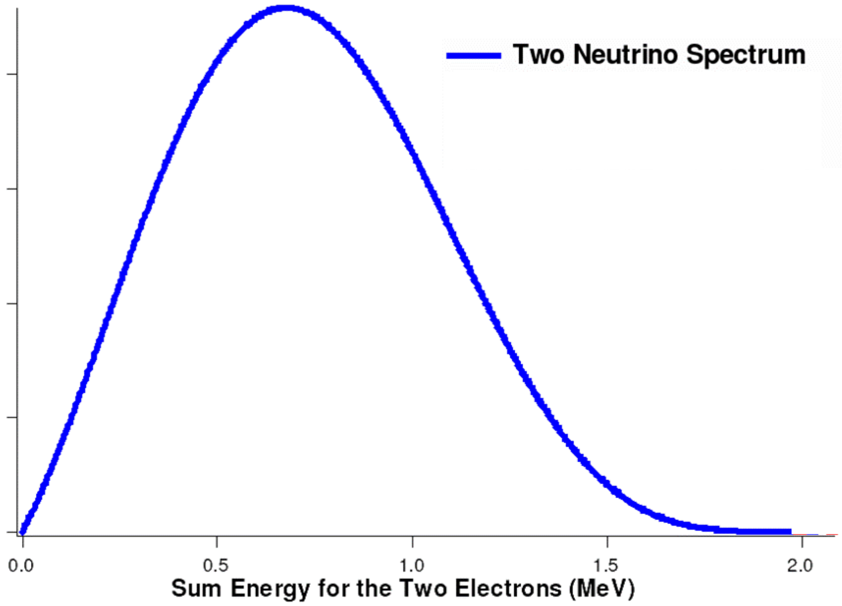
Contents

- Neutrinoless double-beta decay
- The Interacting Boson Model (IBM)
- The role of the energies of the single particle levels (SPE)
- Some results obtained with updated SPE
- Summary

Double beta decay





Experimental status

National Nuclear Data Center

BROOKHAVEN NATIONAL LABORATORY
Home

NNDC Databases: NuDat | NSR | XUNDL | ENSDF | MIRD | ENDF | CSISRS | Sigma

List of Adopted Double Beta (ββ) Decay Values

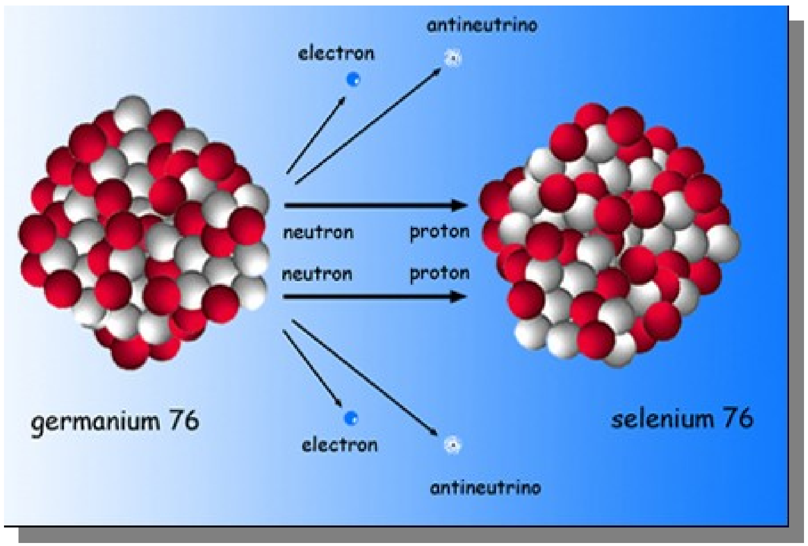
ββ-Decay Reference Paper: Nuclear Data Sheets 120, 102 (2014)

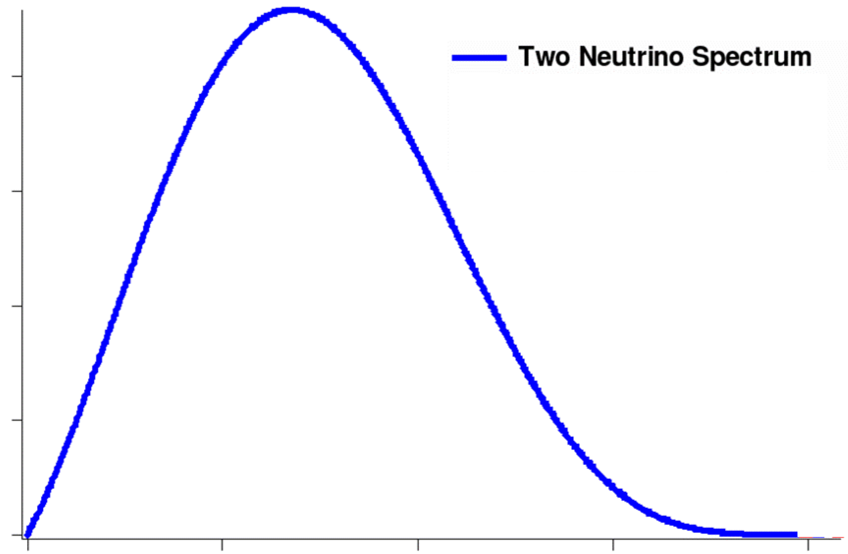
Additional information on adopted ββ-decay values and their systematics may be found in the ND2013 Conference Proceedings or Brookhaven National Laboratory Report BNL-99822-2013-CP. These results could be compared with the **Original $\beta^-\beta^-$-decay Evaluation**.

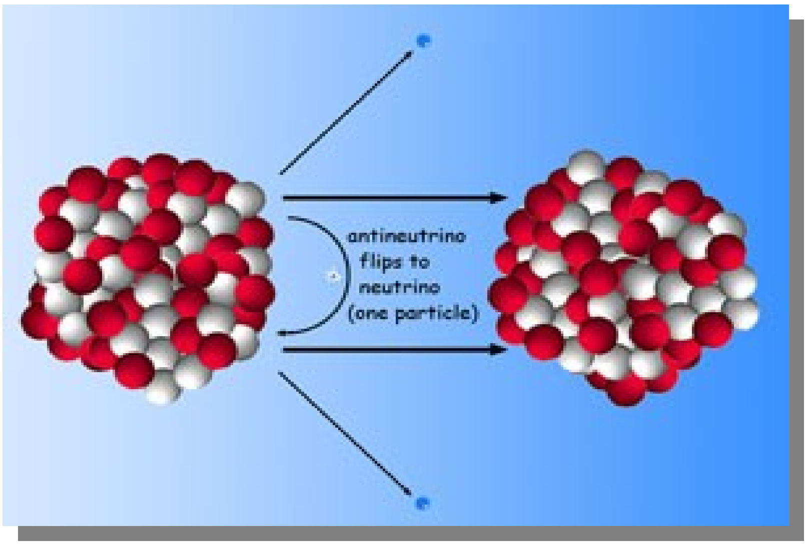
#	Nuclide	Process	Transition	$T_{1/2}^{2\nu}$(y)	$T_{1/2}^{0\nu}$(y)	$T_{1/2}^{0\nu+2\nu}$(y)	Evaluation
1	48Ca	$\beta^-\beta^-$	$0^+ \to 0^+$	$(4.39 \pm 0.58)\times10^{19}$			2013
2	76Ge	$\beta^-\beta^-$	$0^+ \to 0^+$	$(1.43 \pm 0.53)\times10^{21}$			2013
3	82Se	$\beta^-\beta^-$	$0^+ \to 0^+$	$(9.19 \pm 0.76)\times10^{19}$			2013
4	96Zr	$\beta^-\beta^-$	$0^+ \to 0^+$	$(2.16 \pm 0.26)\times10^{19}$			2013
5	100Mo	$\beta^-\beta^-$	$0^+ \to 0^+$	$(6.98 \pm 0.44)\times10^{18}$			2013
6	100Mo	$\beta^-\beta^-$	$0^+ \to 0^+_1$	$(5.70 \pm 1.36)\times10^{20}$			2013
7	100Mo	$\beta^-\beta^-$	$0^+ \to 0^+_1$			$(6.12 \pm 0.20)\times10^{20}$	2013
8	116Cd	$\beta^-\beta^-$	$0^+ \to 0^+$	$(2.89 \pm 0.25)\times10^{19}$			2013
9	128Te	$\beta^-\beta^-$	$0^+ \to 0^+$			$(3.49 \pm 1.99)\times10^{24}$	2013
10	130Te	$\beta^-\beta^-$	$0^+ \to 0^+$	$(7.14 \pm 1.04)\times10^{20}$			2013
11	136Xe	$\beta^-\beta^-$	$0^+ \to 0^+$	$(2.34 \pm 0.13)\times10^{21}$			2013
12	130Ba	2ε	$0^+ \to 0^+$			$(1.40 \pm 0.80)\times10^{21}$	2013
13	150Nd	$\beta^-\beta^-$	$0^+ \to 0^+$	$(8.37 \pm 0.45)\times10^{18}$			2013
14	150Nd	$\beta^-\beta^-$	$0^+ \to 0^+_1$			$(1.33 \pm 0.40)\times10^{20}$	2013
15	238U	$\beta^-\beta^-$	$0^+ \to 0^+$			$(2.00 \pm 0.60)\times10^{21}$	2013

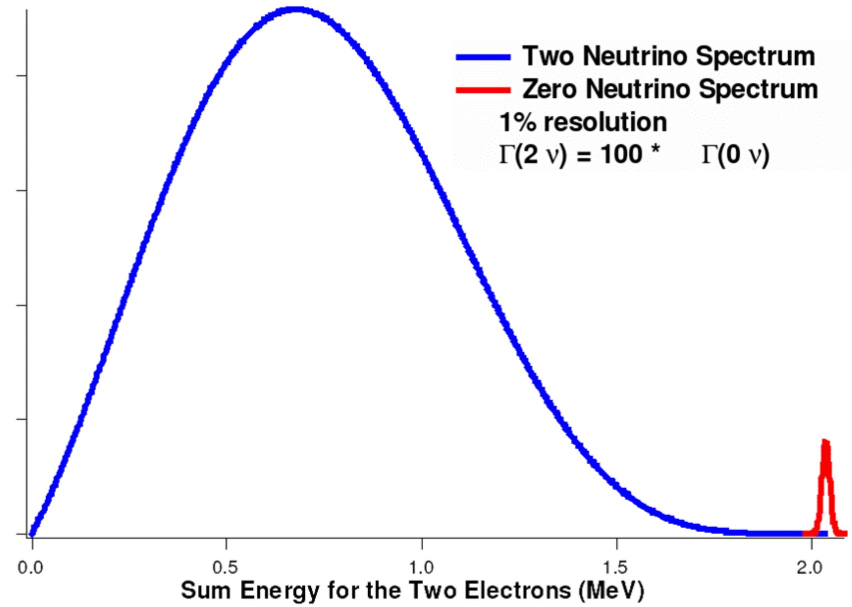
Database Manager: Boris Pritychenko, NNDC, Brookhaven National Laboratory
Web Programming: Boris Pritychenko, NNDC, Brookhaven National Laboratory

Double beta decay









Neutrinoless double beta decay

- Supports for finite neutrino mass
- Provides an absolute scale of neutrino mass
- Dirac or Majorana character is fixed
- Quantum lepton number is not conserved

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Physics beyond Standard Model:
- Right handed currents
- Sterile neutrinos
- ...

Theory of the double beta decay

$$\left[\tau_{1/2}^{(0\nu)}\right]^{-1} \simeq G_{0\nu} \left|M_{0\nu}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

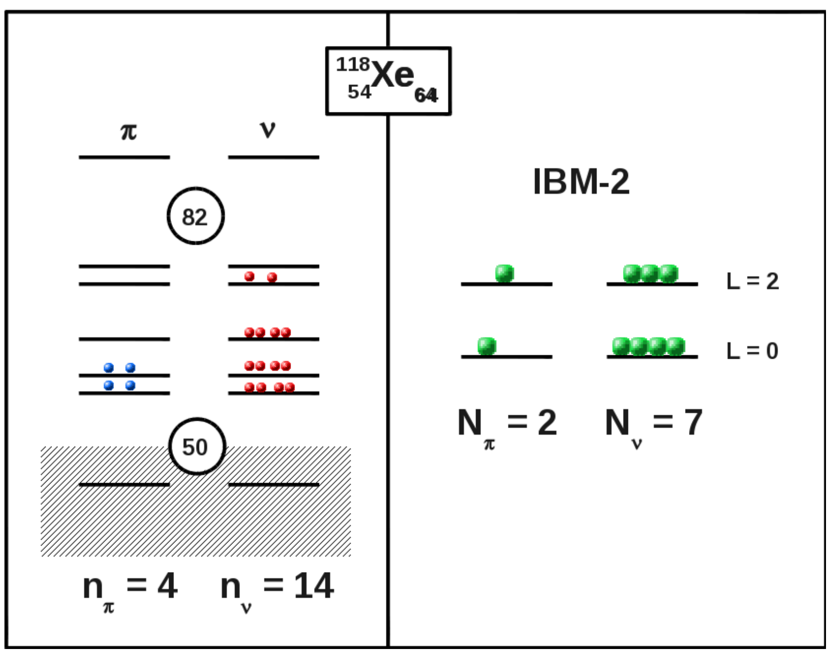
$$M_{0\nu} \simeq \left\langle F; J_F \left| -(g_V/g_A)^2 h_{0\nu}^F + h_{0\nu}^{GT} + h_{0\nu}^T \right| I; 0_1^+ \right\rangle$$

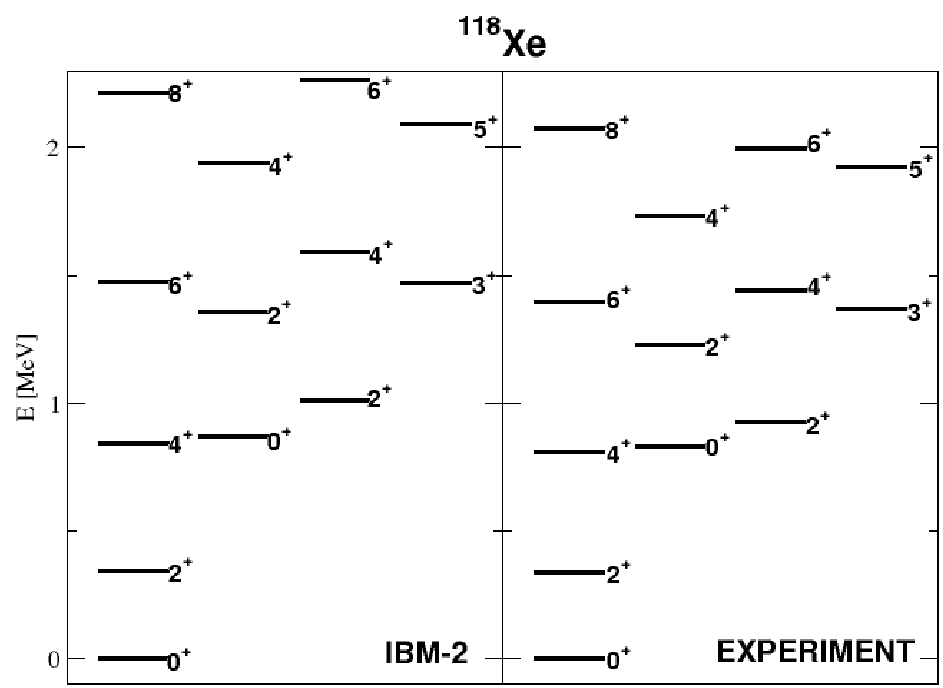
The interacting boson model

- Bosons as building blocks
- Suitable to describe collective degrees of freedom
- Moderate model space
- Phenomenological character

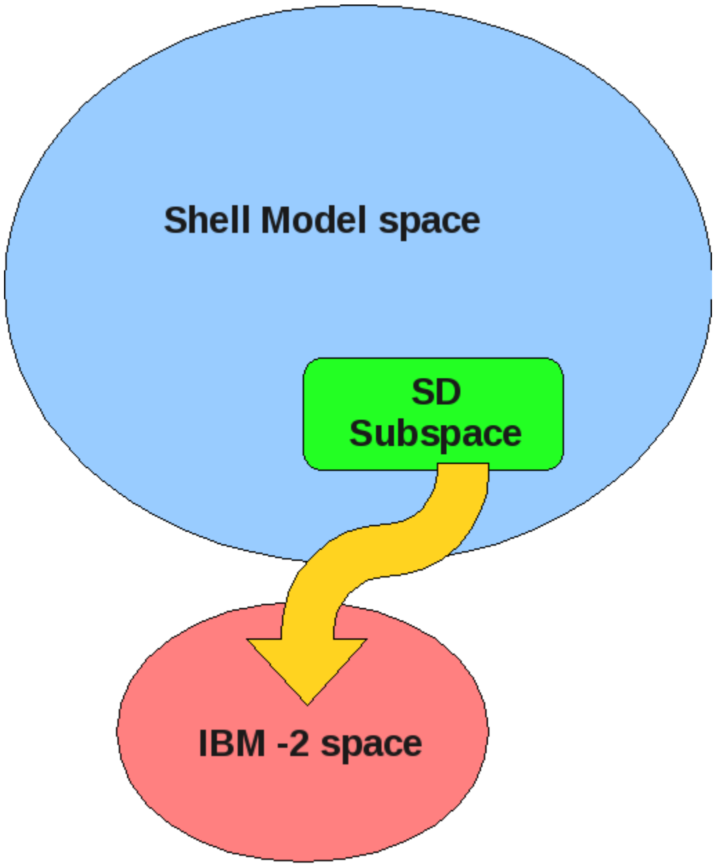
The microscopic IBM: IBM-2

$$
\begin{aligned}
H_{IBM2} &= H_\pi + H_\nu + \kappa Q_\pi^{(2)} \cdot Q_\nu^{(2)} + M_{\pi\nu}\left(\xi_1, \xi_2, \xi_3\right) \\
H_\rho &= \epsilon \hat{n}_{d_\rho} + \sum_{L=0,2,4} c_L^\rho \left(d_\rho^\dagger d_\rho^\dagger\right)^{(L)} \cdot \left(\tilde{d}_\rho \tilde{d}_\rho\right)^{(L)} \\
Q_\rho^{(2)} &= \left(s_\rho^\dagger \times \tilde{d}_\rho + d_\rho^\dagger \times \tilde{s}_\rho\right)^{(2)} + \chi_\rho \left(d_\rho^\dagger \times \tilde{d}_\rho\right)^{(2)}
\end{aligned}
$$





IBM-2 and Shell Model



$$\begin{aligned} S_+ &= \sum_j \alpha_j \frac{\sqrt{j+\frac{1}{2}}}{2} \left(C_j^\dagger C_j^\dagger\right)_0^{(0)} \\ D_+ &= \sum_{j\le j'} \frac{\beta_{jj'}}{\sqrt{1+\delta_{jj'}}} \left(C_j^\dagger C_{j'}^\dagger\right)_M^{(2)} \end{aligned}$$

$$\begin{aligned} (S_+)^N |0\rangle / \eta_{2N,0,0} &\rightarrow |s^N\rangle \\ (S_+)^N C_{jm}^\dagger |0\rangle / \eta_{2N+1,1,j} &\rightarrow |s^N j\rangle \\ (S_+)^N D_+ |0\rangle / \eta_{2N+2,2,2} &\rightarrow |s^N d\rangle \\ &\cdots \end{aligned}$$

$$O_{SM} \rightarrow o_{IBM} = \sum_k \gamma_k f_k [s,d,j]$$

$$\langle F |O_{SM}| I\rangle = \langle f |o_{IBM}| i\rangle = \left\langle f \left| \sum_k \gamma_k f_k [s,d,j] \right| i \right\rangle$$

Structure of the S and D pairs

- Single particle energies extracted from experimental spectra

$$\boxed{H = \sum_j \epsilon_j + A_T V_{SDI}}$$

- A_T fitted to reproduced experimental E[2_1^+] of semimagic nuclei with only 2 nucleons active

$$\left|0_1^+\right\rangle = \sum_j A_j \left|j^2;0\right\rangle \rightarrow \alpha_j = \sqrt{\frac{\sum_j \left(j+\frac{1}{2}\right)}{j+\frac{1}{2}}} A_j$$

$$\left|2_1^+\right\rangle = \sum_{j\leq j'} B_{jj'} \left|jj';2\right\rangle \rightarrow \beta_{jj'} = B_{jj'}$$

ββ decay transition operator

$$M_{0\nu} \simeq \left\langle F; J_F \left| -\left(g_V/g_A\right)^2 h_{0\nu}^{F} + h_{0\nu}^{GT} + h_{0\nu}^{T} \right| I; 0_1^+ \right\rangle$$

$$h_{0\nu}^{F,GT,T} = \sum_{\substack{j_\pi j'_\pi \\ j_\nu j'_\nu \\ J}} -\frac{1}{4}(-1)^J G_{0\nu}^{F,GT,T}(j_\pi j'_\pi j_\nu j'_\nu; J) \times \sqrt{1+(-1)^J \delta_{j_\pi j'_\pi}} \sqrt{1+(-1)^J \delta_{j_\nu j'_\nu}} \times \left(C^\dagger_{j_\pi} \times C^\dagger_{j'_\pi}\right)^{(J)} \cdot \left(\tilde{C}_{j_\nu} \times \tilde{C}_{j'_\nu}\right)^{(J)}$$

$$h_{0\nu}^{F,GT,T} \mapsto A_{0\nu}^{F,GT,T} s^\dagger_\pi \cdot \tilde{s}_\nu + B_{0\nu}^{F,GT,T} d^\dagger_\pi \cdot \tilde{d}_\nu$$

IBM-2 DBD calculation

Single Particle Energies

S.D.I. Calculation

Structure Coefficients of S and D pairs

Mapping coefficients of the transition operator

Experimental data: spectra, EM transitions, ...

IBM-2 wavefunctions

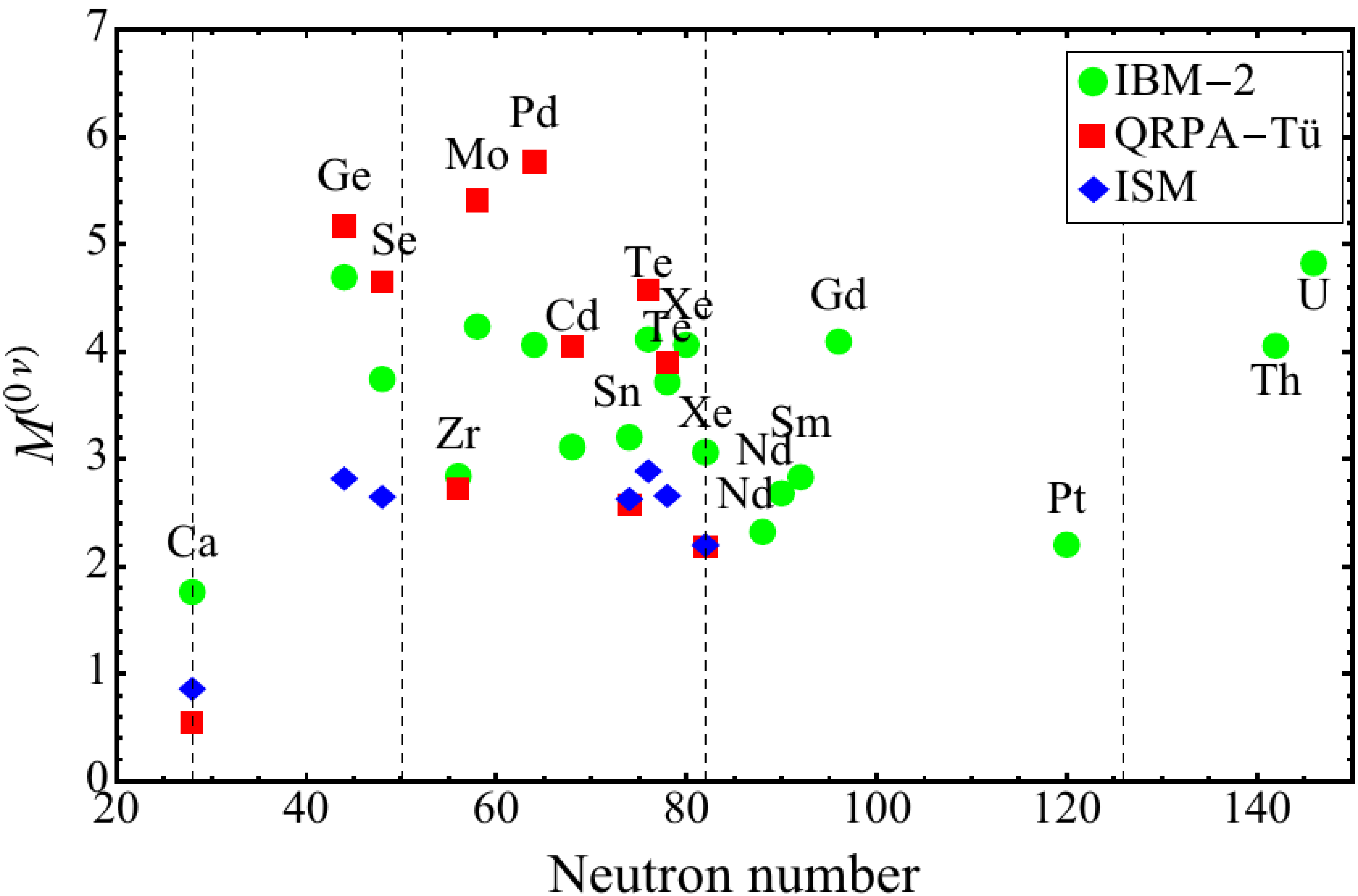
Bosonic matrix elements:

$$\left\langle F \left| s_\pi^\dagger \cdot \tilde{s}_\nu \right| I \right\rangle$$

$$\left\langle F \left| d_\pi^\dagger \cdot \tilde{d}_\nu \right| I \right\rangle$$

$$\left[\tau_{1/2}^{(0\nu)}\right]^{-1} \simeq G_{0\nu} \left|M_{0\nu}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

Results



J.Barea, J. Kotila & F. Iachello, PRC91,034304(2015)

Occupancies in the IBM-2

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Occupation probabilities of single particle levels using the microscopic interacting boson model: Application to some nuclei of interest in neutrinoless double-β decay

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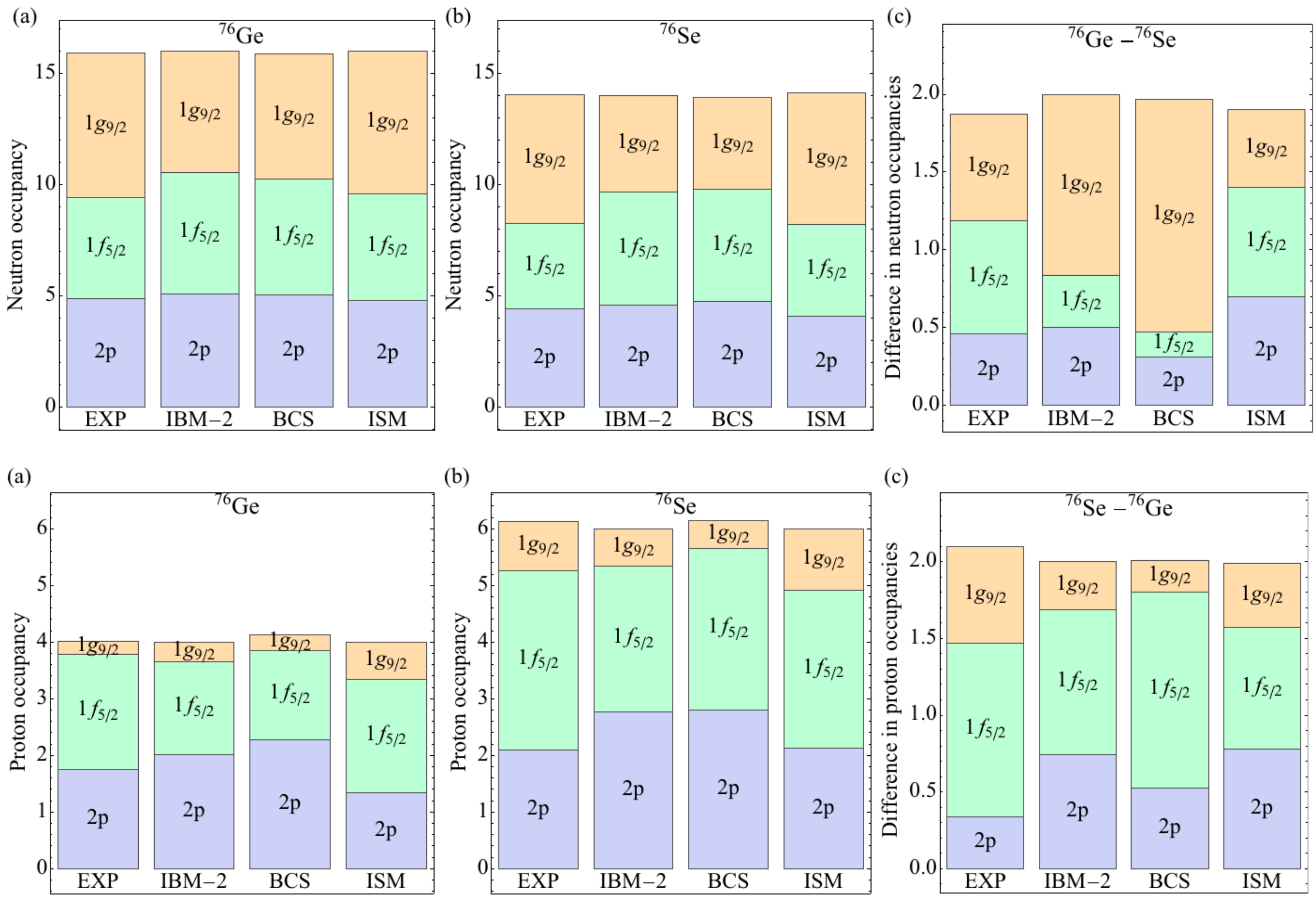
$$\hat{n}_j = C_j^\dagger \cdot \tilde{C}_j \mapsto \hat{n}_j^B = A_j s^\dagger \cdot \tilde{s} + B_j d^\dagger \cdot \tilde{d}$$

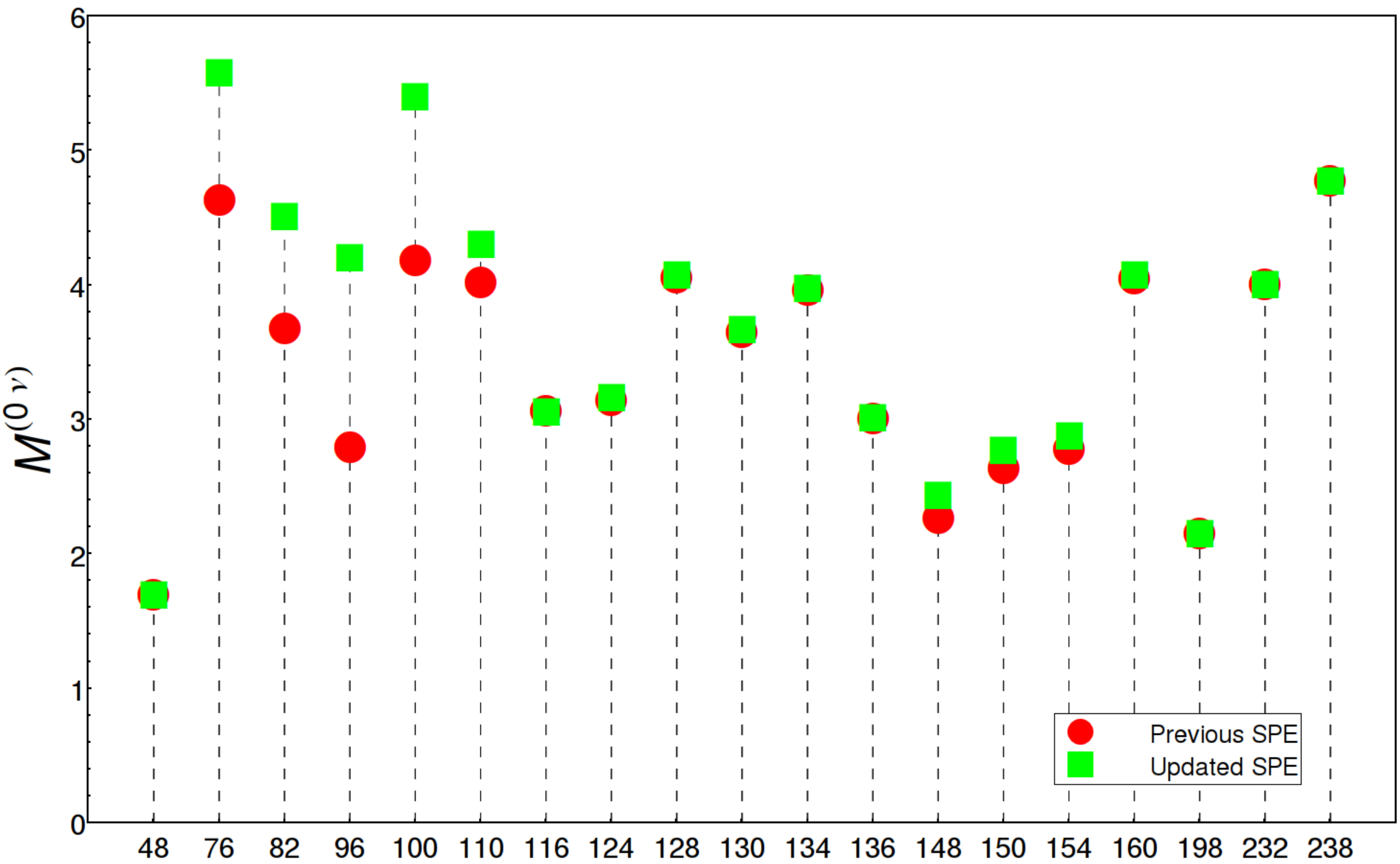
$$\begin{aligned} A_j &= \langle 2N, 0, 0 \,\|\hat{n}_j\|\, 2N, 0, 0 \rangle \\ B_j &= \frac{1}{\sqrt{5}} \langle 2N, 2, 2 \,\|\hat{n}_j\|\, 2N, 2, 2 \rangle \\ &- \left(1 - \frac{1}{N}\right) \langle 2N, 0, 0 \,\|\hat{n}_j\|\, 2N, 0, 0 \rangle \end{aligned}$$

Updated Single Particle Energies

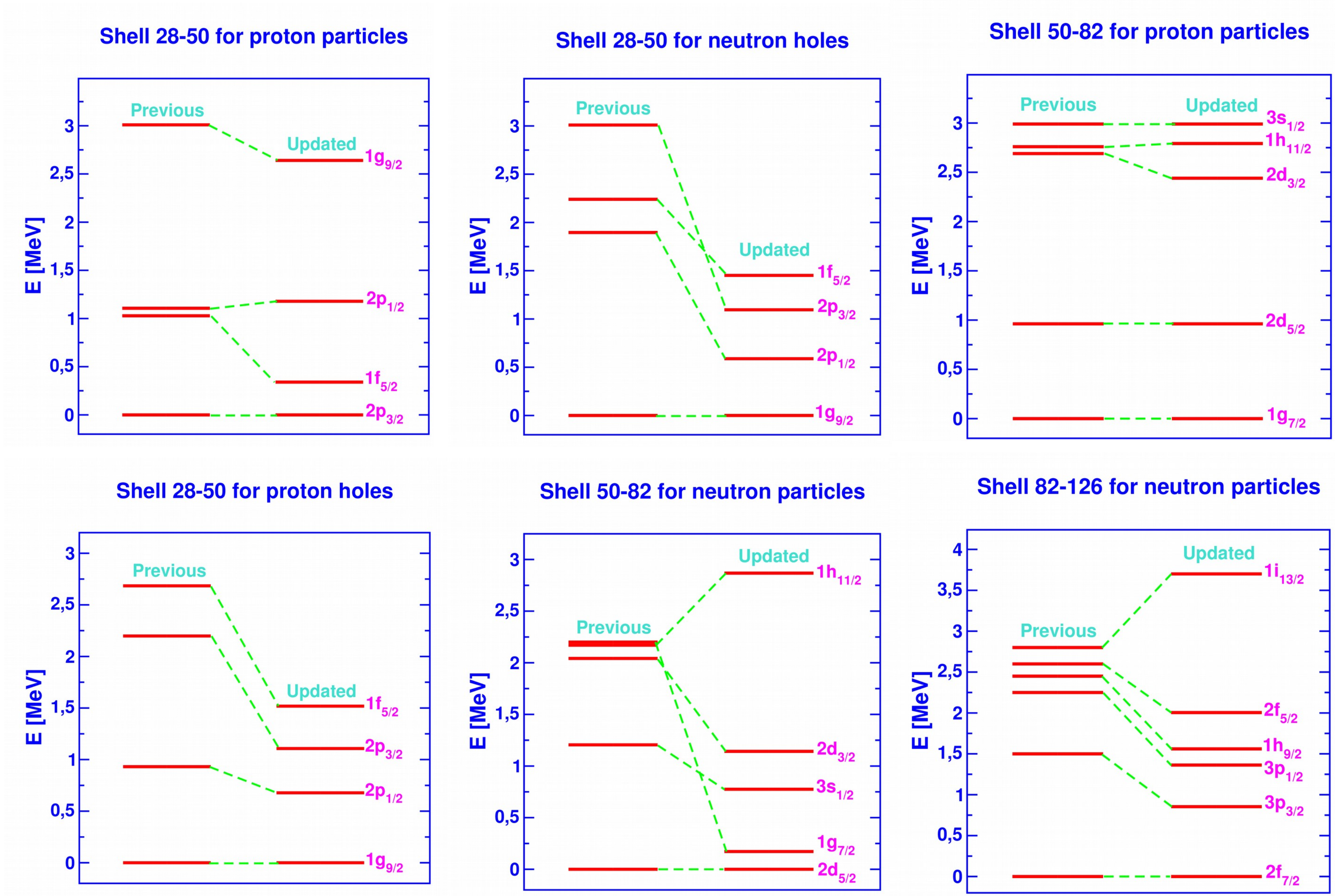
Occupancies for A = 76



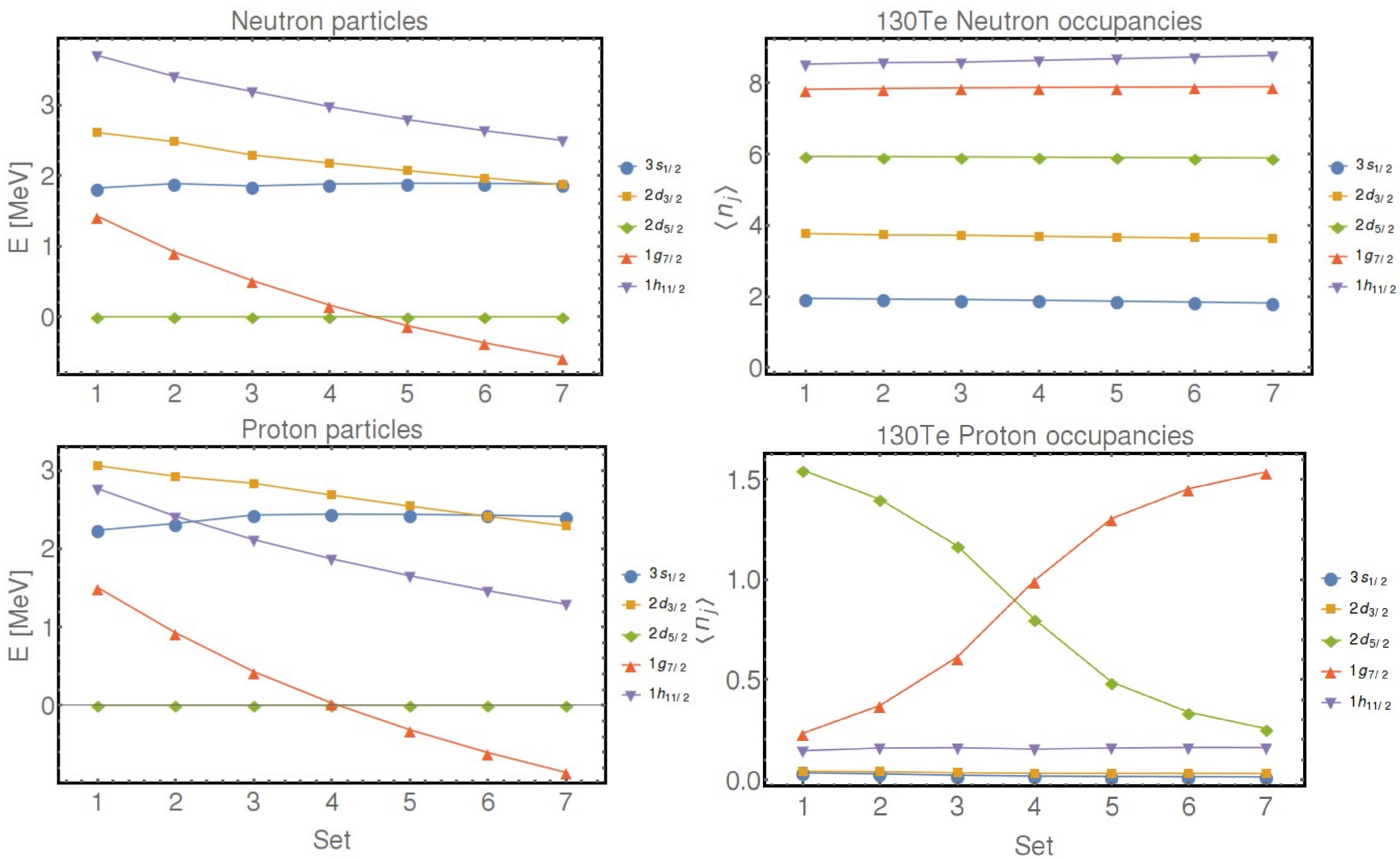
Neutrinoless DBD, light ν



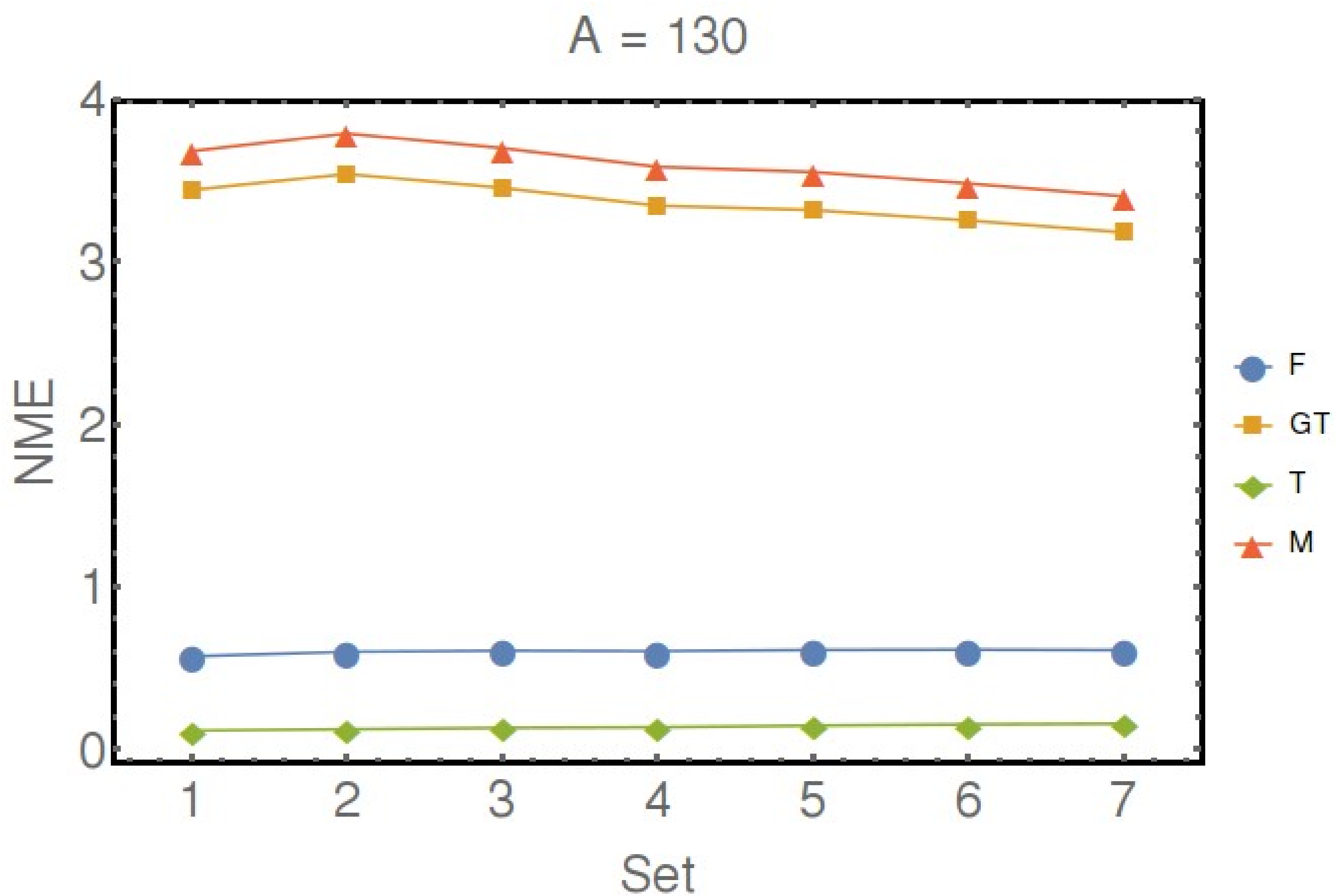
Changes in the S.P.E.



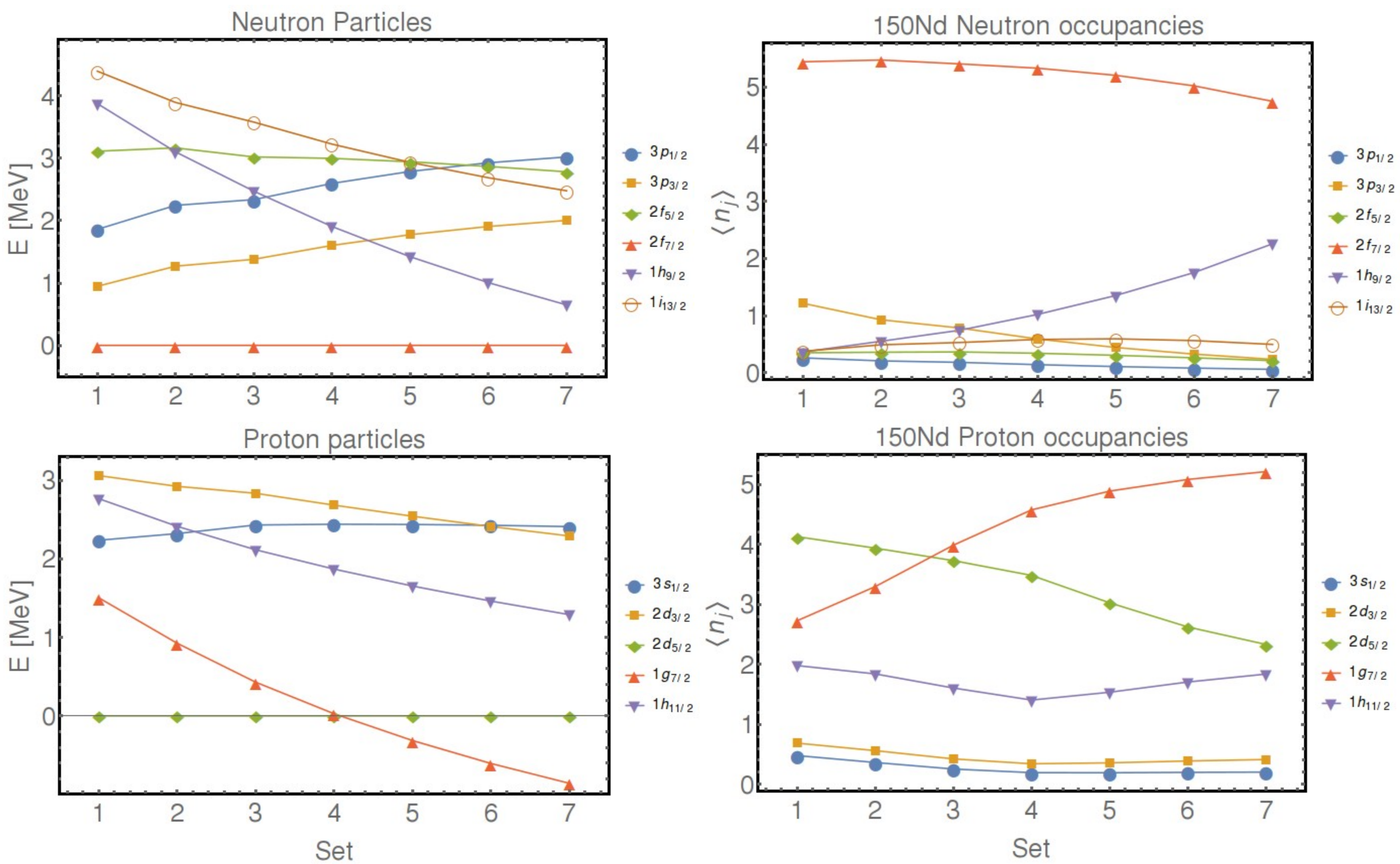
Occupations for ^{130}Te



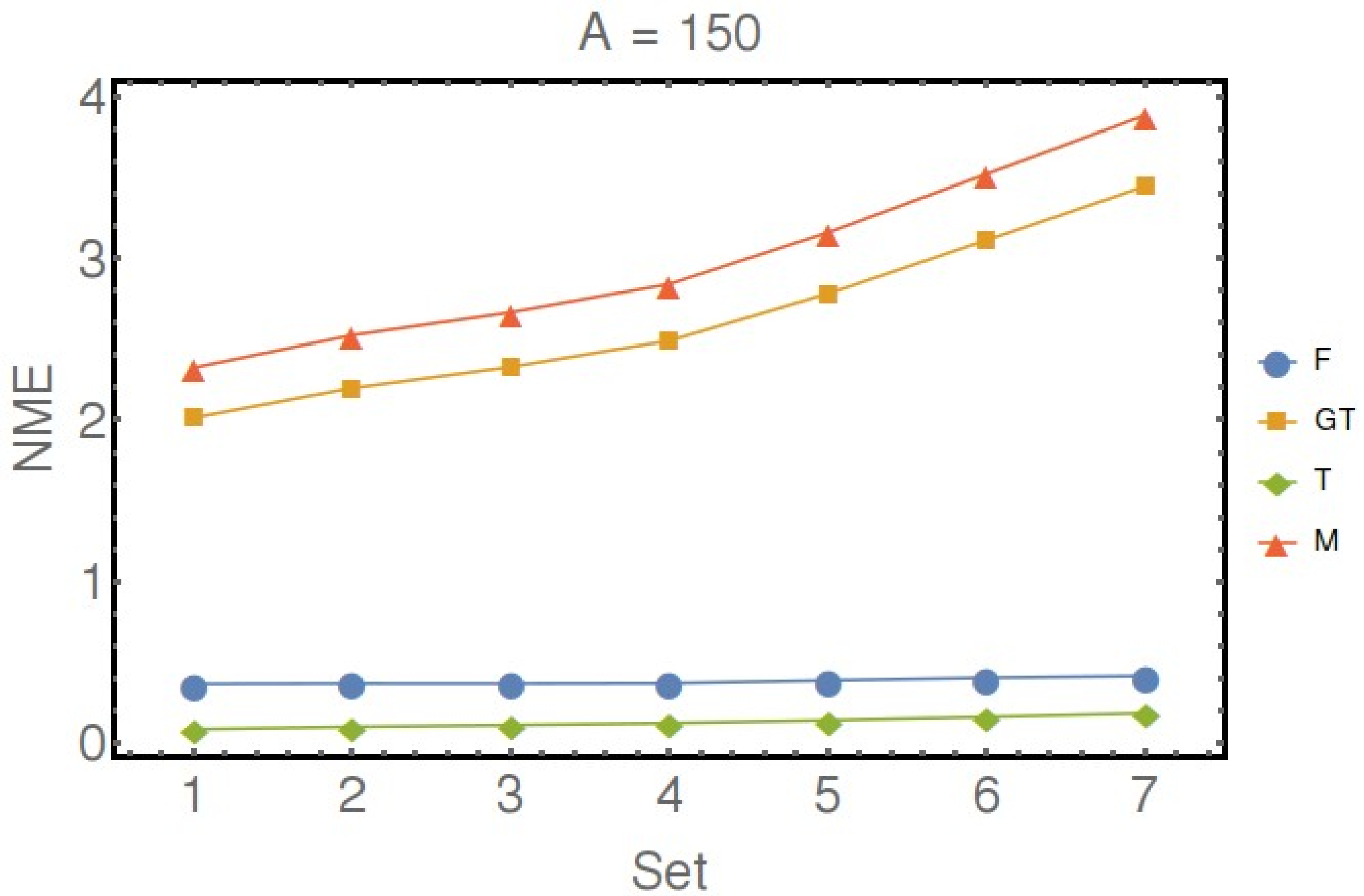
Evolution of the NME for A = 130



Occupations for ^{150}Nd



Evolution of the NME for A = 150



Summary

- Double beta decay has been and still continues providing a source to get new methods in nuclear theory and also in experiments
- IBM provides a framework where the DBD matrix elements can be calculated in a simple way.
- There is still a lot of work to do respect to how to incorporate key correlations in the wave-functions or extend the transitions to other mechanisms.

Thanks

Collaborators:

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Francesco Iachello (Yale)