Neutrino-less double-beta decay in the shell model and the IBM

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Neutrino-less $\beta\beta$ decay

The process:

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}X_{N-2} + 2e^{-} $$

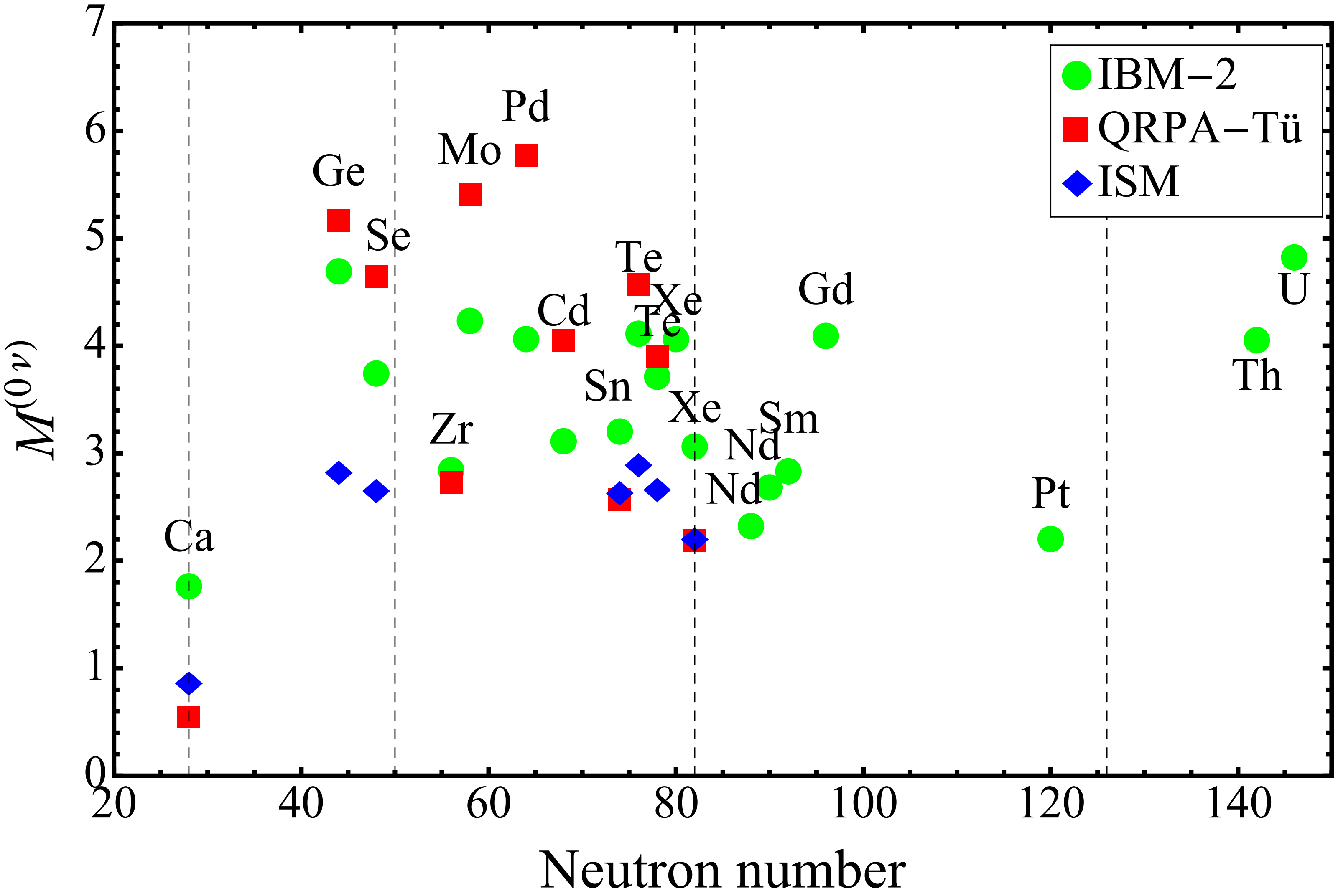
Importance: neutrinos are Majorana particles with mass, violation of lepton number, physics beyond the standard model,...

The half-life of this process is

$$ \frac{1}{\tau_{1/2}^{0\nu}} = G_{0\nu} \left| M_{0\nu} \right|^{2} \left| f\left(m_i, U_{ei} \right) \right|^{2} $$

Nuclear physics must provide the nuclear matrix element $M_{0\nu}$.

Comparison SM-QRPA-IBM



J. Barea *et al.*, Phys. Rev. C **91** (2015) 034304

Aims of this work

- To obtain a better understanding of the relation between IBM and SM.
- To use an isospin-invariant version of the IBM.
- To study the influence of neutron-proton pairing on double-beta decay.

Nucleon-pair shell model (NPSM)

Pairs of fermions

$$P^{+}_{j_1 j_2 JM} = \left(a^{+}_{j_1} \times a^{+}_{j_2}\right)^{(J)}_{M} \equiv P^{+}_{\alpha JM}$$

Basis states for 2*n* nucleons in NPSM

$$\left|\alpha_1 J_1 \ldots \alpha_n J_n; L_2 \ldots L_n\right\rangle \equiv \left(\cdots\left(\left(P^{+}_{\alpha_1 J_1} \times P^{+}_{\alpha_2 J_2}\right)^{(L_2)} \times P^{+}_{\alpha_3 J_3}\right)^{(L_3)} \times \cdots \times P^{+}_{\alpha_n J_n}\right)^{(L_n)} \left|\mathrm{O}\right\rangle$$

Isospin-invariant formulation: *J* -> *JT*.

Matrix elements can be calculated with a recursive technique.

J.-Q. Chen, Nucl. Phys. A **562** (1993) 218; **626** (1997) 686
Y. Zhao and A. Arima, Phys. Reports **545** (2014) 1
G.J. Fu *et al.*, Phys. Rev. C **87** (2013) 044310

Effective operators

Let $\mathbf{H}_P$ be the collective subspace, $\mathbf{H}_Q$ the excluded space and $\mathbf{H}=\mathbf{H}_P+\mathbf{H}_Q$ the full SM space.

The method of Okubo-Lee-Suzuki (OLS) defines an operator η that maps states in $\mathbf{H}_P$ to states in $\mathbf{H}_Q$ such that

$$\hat{\eta}\left(\hat{P}\left|E_k\right\rangle\right)=\hat{Q}\left|E_k\right\rangle, \quad k=1,\ldots,\omega, \quad \left|E_k\right\rangle \in \mathbf{H}$$

For small nucleon number η can be calculated exactly

$$\eta_{ri}=\left(\left(\boldsymbol{I}_\Omega-\boldsymbol{b}^T\times\boldsymbol{b}\right)\times\tilde{\boldsymbol{E}}^T\times\boldsymbol{d}^{-1}\right)_{ri}, \quad r=1,\ldots,\Omega, \quad i=1,\ldots\omega$$

S. Okubo, Prog. Theor. Phys. **12** (1954) 603
K. Suzuki & S.Y. Lee, Prog. Theor. Phys. **64** (1980) 2091

Mapping to bosons

Map fermion pairs to bosons

$$B^+_{JM} = \sum_{j_1 j_2} \alpha^J_{j_1 j_2} \left(a^+_{j_1} \times a^+_{j_2}\right)^{(J)}_M \Rightarrow b^+_{JM}$$

Basis states for *n* bosons

$$\left|b^n_i\right\rangle \equiv \left(\cdots\left(\left(b^+_{J_1} \times b^+_{J_2}\right)^{(L_2)} \times b^+_{J_3}\right)^{(L_3)} \times \cdots \times b^+_{J_n}\right)^{(L_n)} \left|\text{o}\right\rangle$$

Corresponding NPSM basis is not orthogonal. Mapping is based on the diagonalization of the overlap matrix.

P. Löwdin, J. Chem. Phys. **18** (1950) 365

Application to $0\nu\beta\beta$ decay

Shell-model Hamiltonian in the *pf* shell:

Modified Kuo-Brown KB3G

Collective separable approximation to it

Shell-model $0\nu\beta\beta$–decay operator defined via its matrix elements:

$$M_{0\nu\beta\beta} = M_{0\nu\beta\beta}^{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M_{0\nu\beta\beta}^{\mathrm{F}} + M_{0\nu\beta\beta}^{\mathrm{T}}$$

A. Poves *et al.*, Nucl. Phys. A **694** (2001) 157
M. Dufour and A.P. Zuker, Phys. Rev. C **54** (1996) 1641
J. Menéndez *et al.*, Phys. Rev. C **93** (2013) 014305

Mapping with different bosons

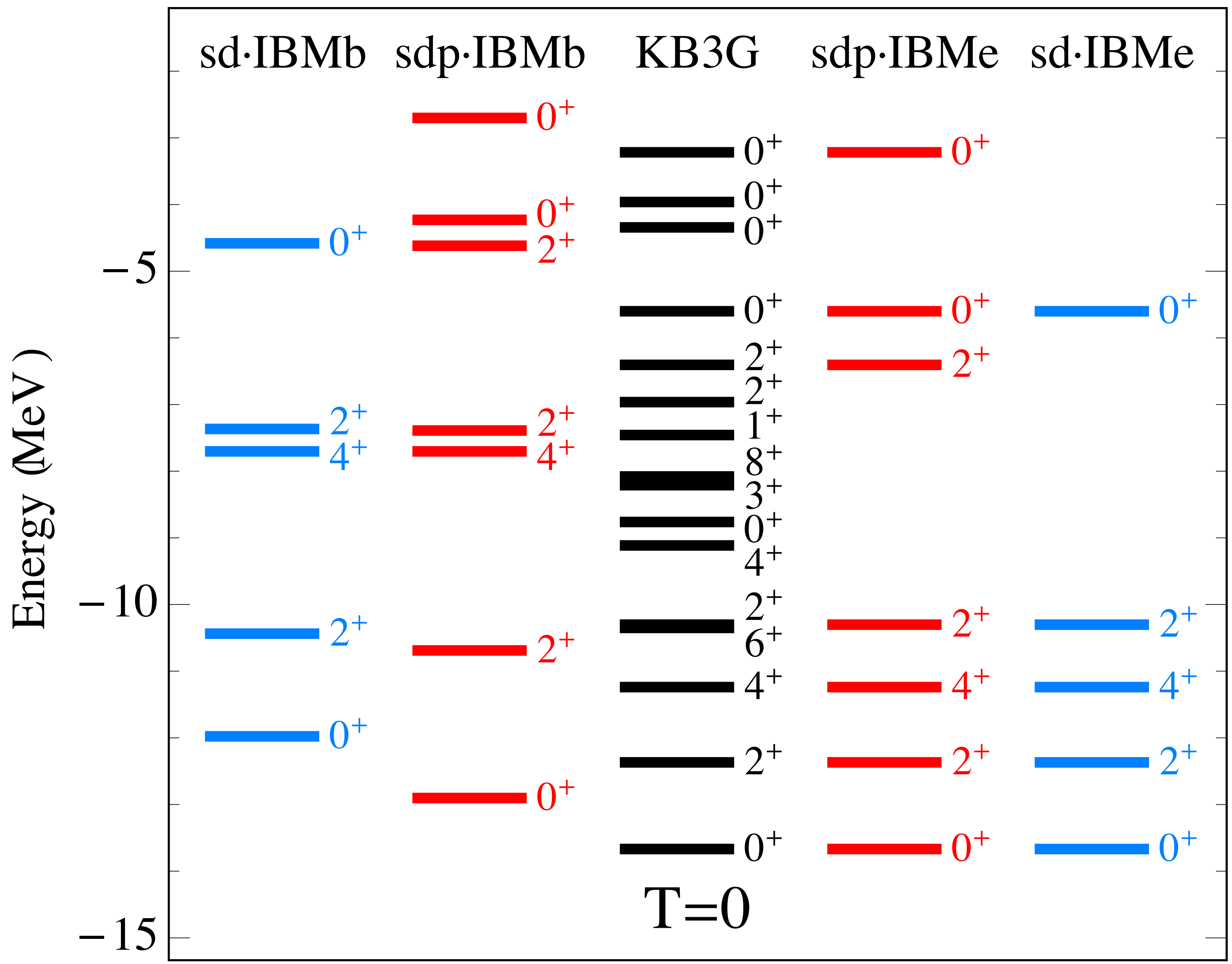
1. Bosons with *J*=0 (*s*) and *J*=2 (*d*) and isospin *T*=1. This is isospin-invariant *sd*–IBM (IBM–3).
2. In addition a boson with *J*=1 (*p*) and isospin *T*=0. This to probe the importance of isoscalar correlations in $0\nu\beta\beta$ decay. This is referred to as *sdp*–IBM.

Mapping of

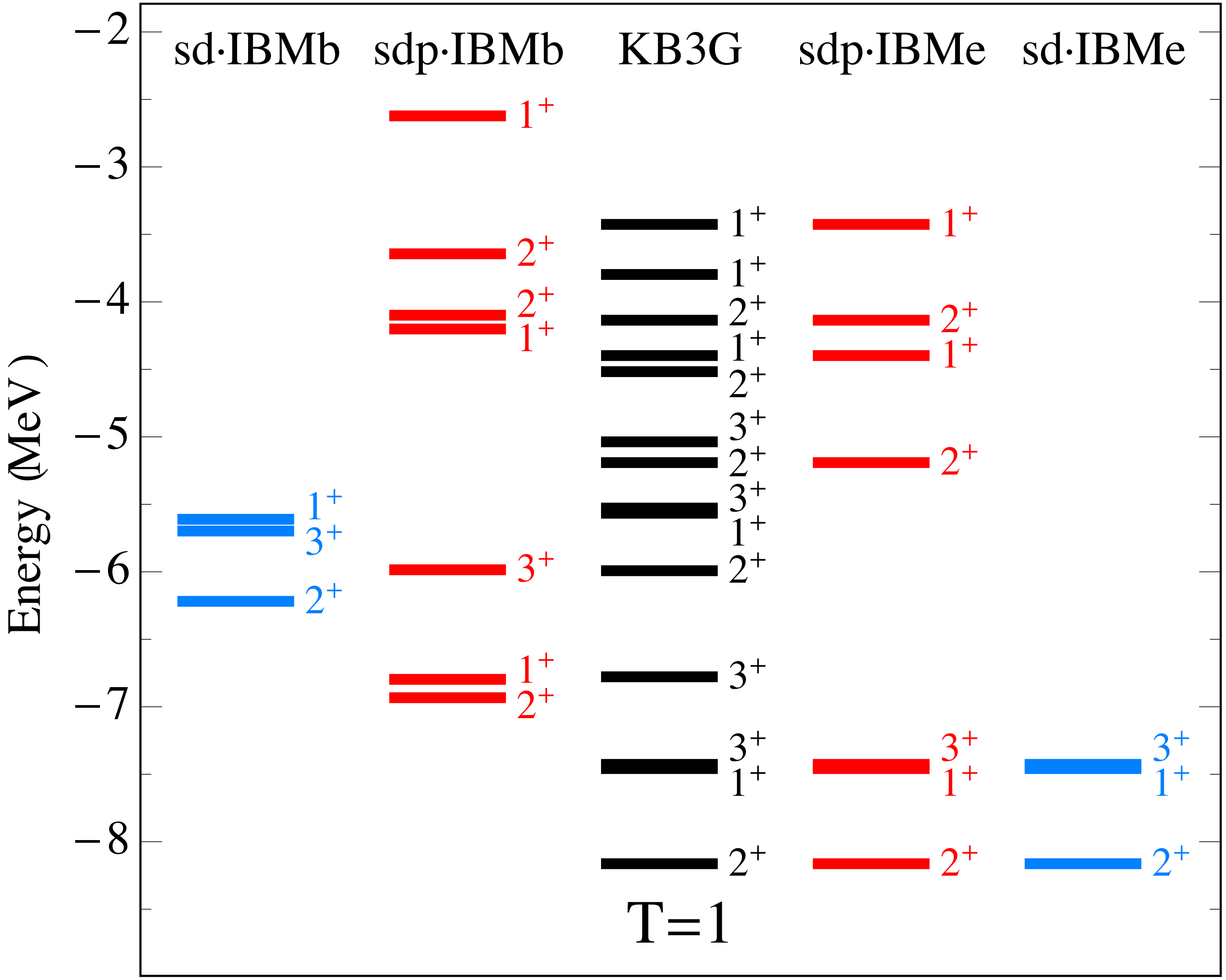
original SM operators -> IBMb (bare)

effective SM operators -> IBMe (effective)

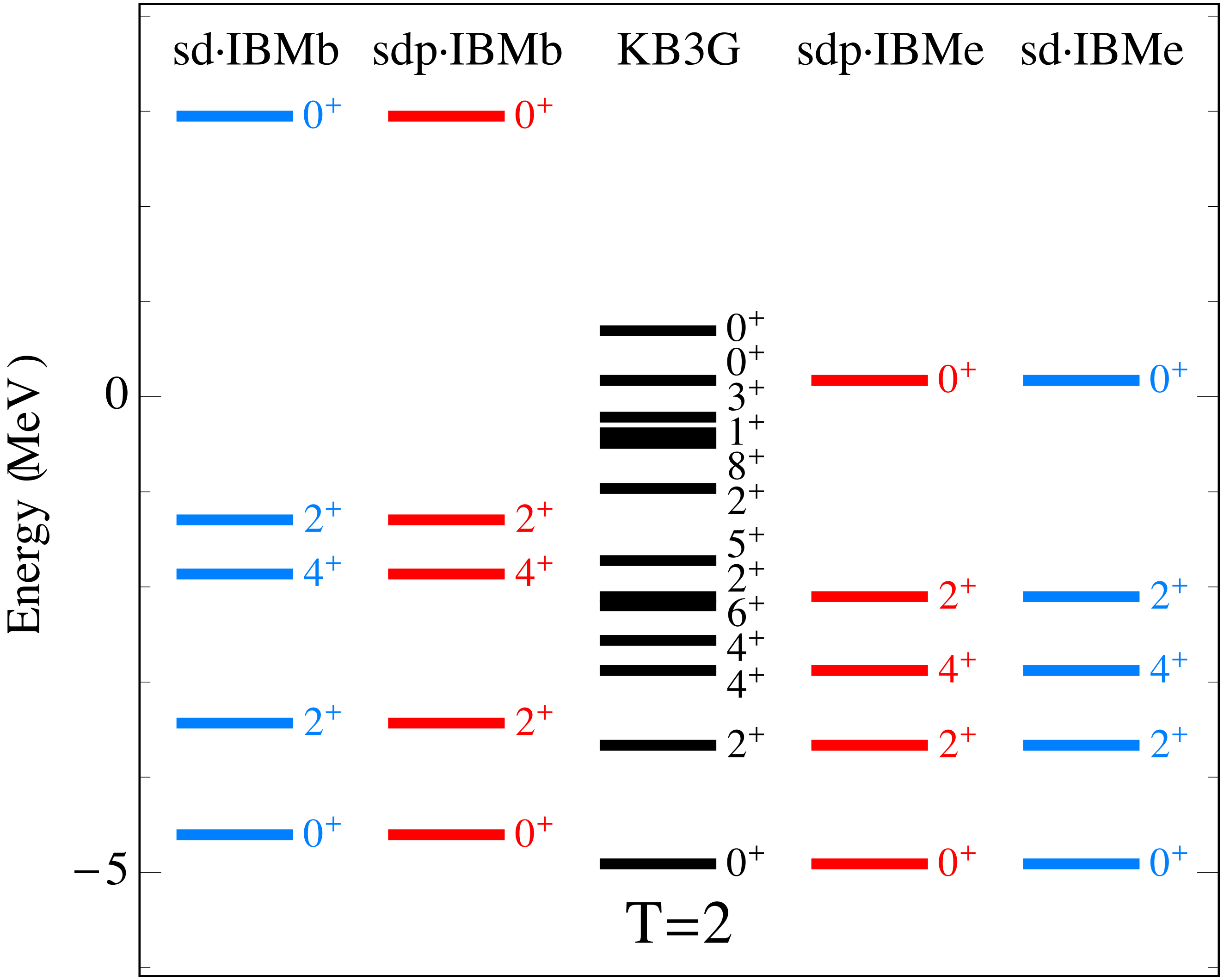
A=44 energy spectra



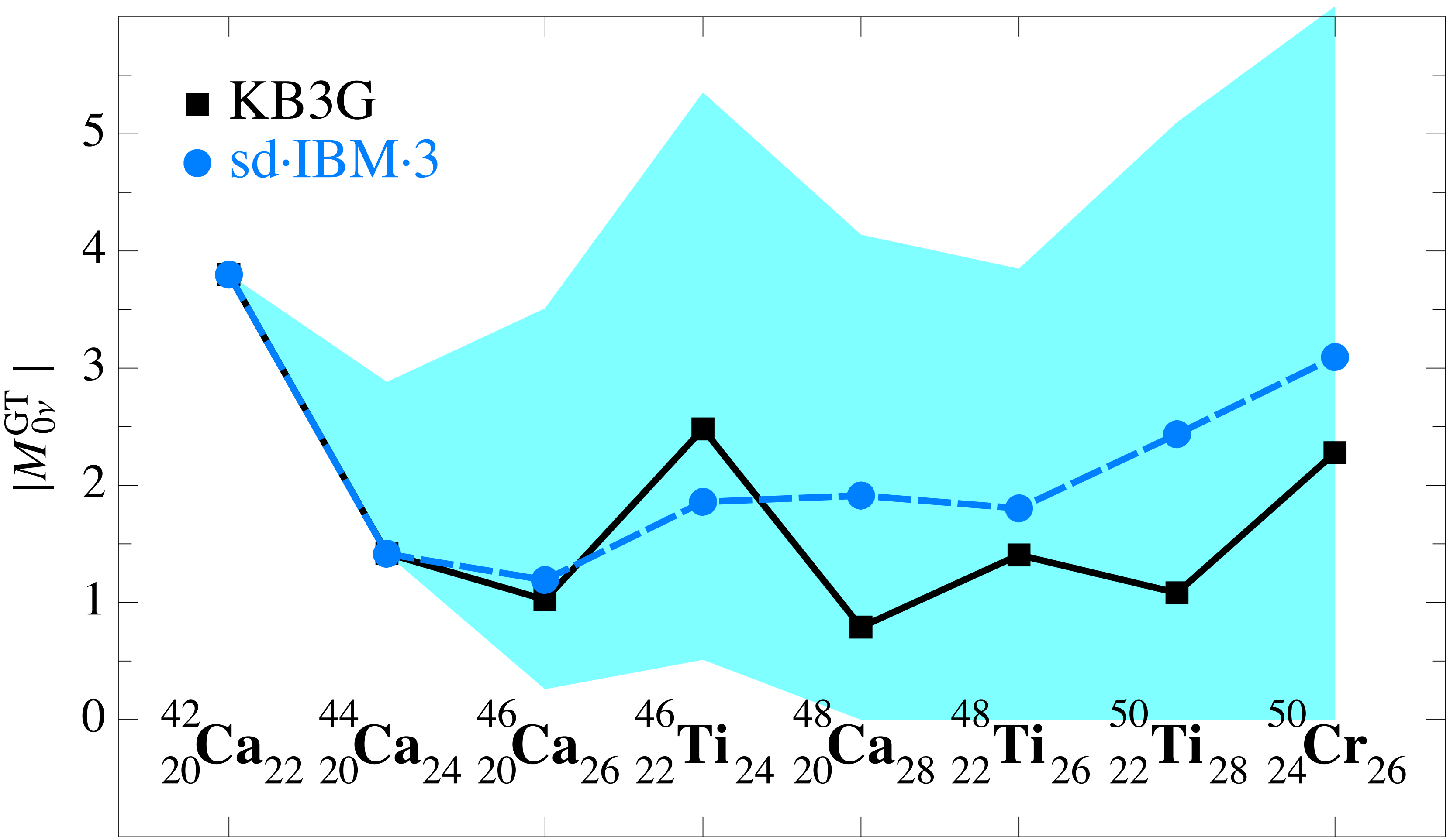
A=44 energy spectra



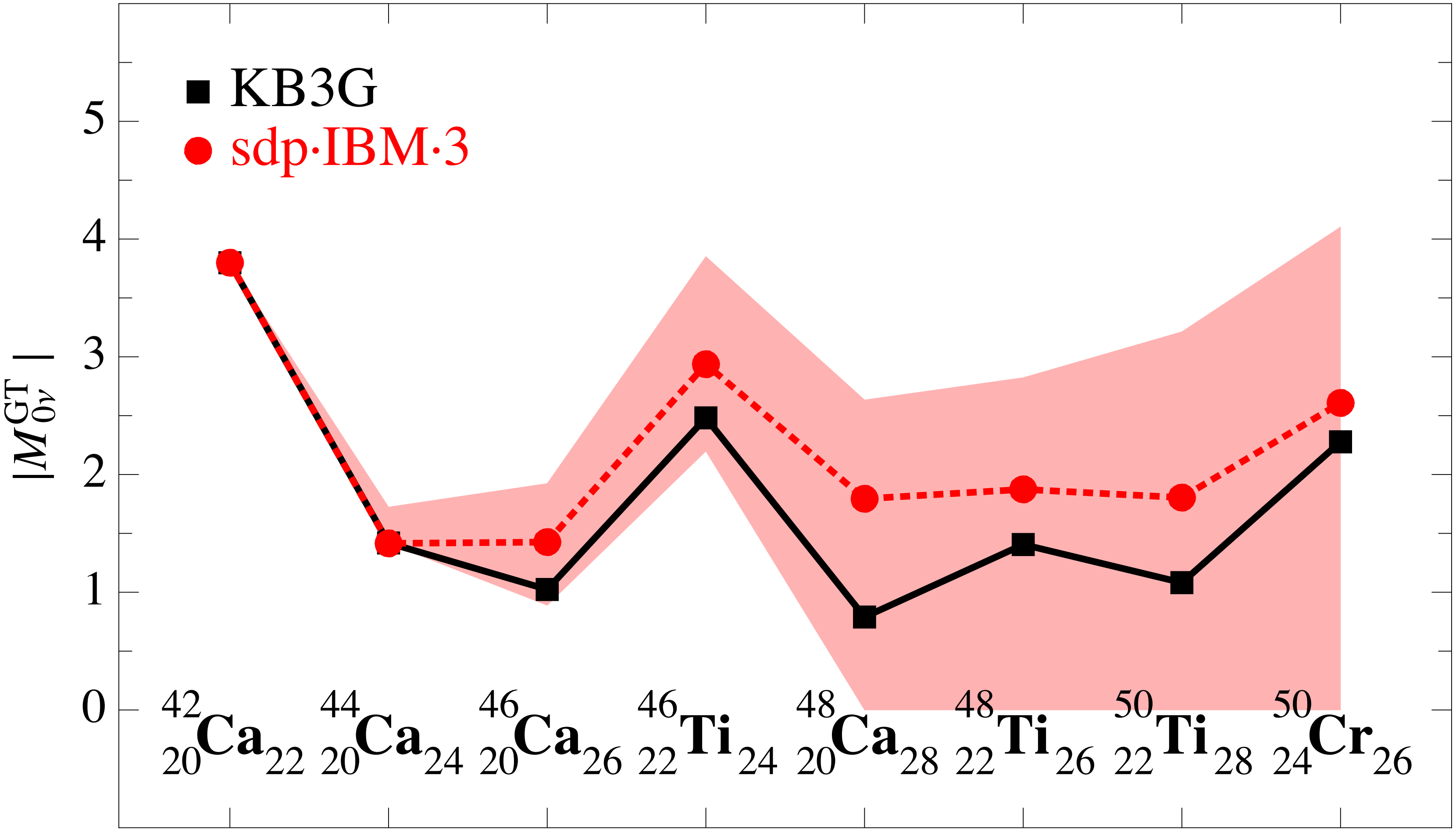
A=44 energy spectra



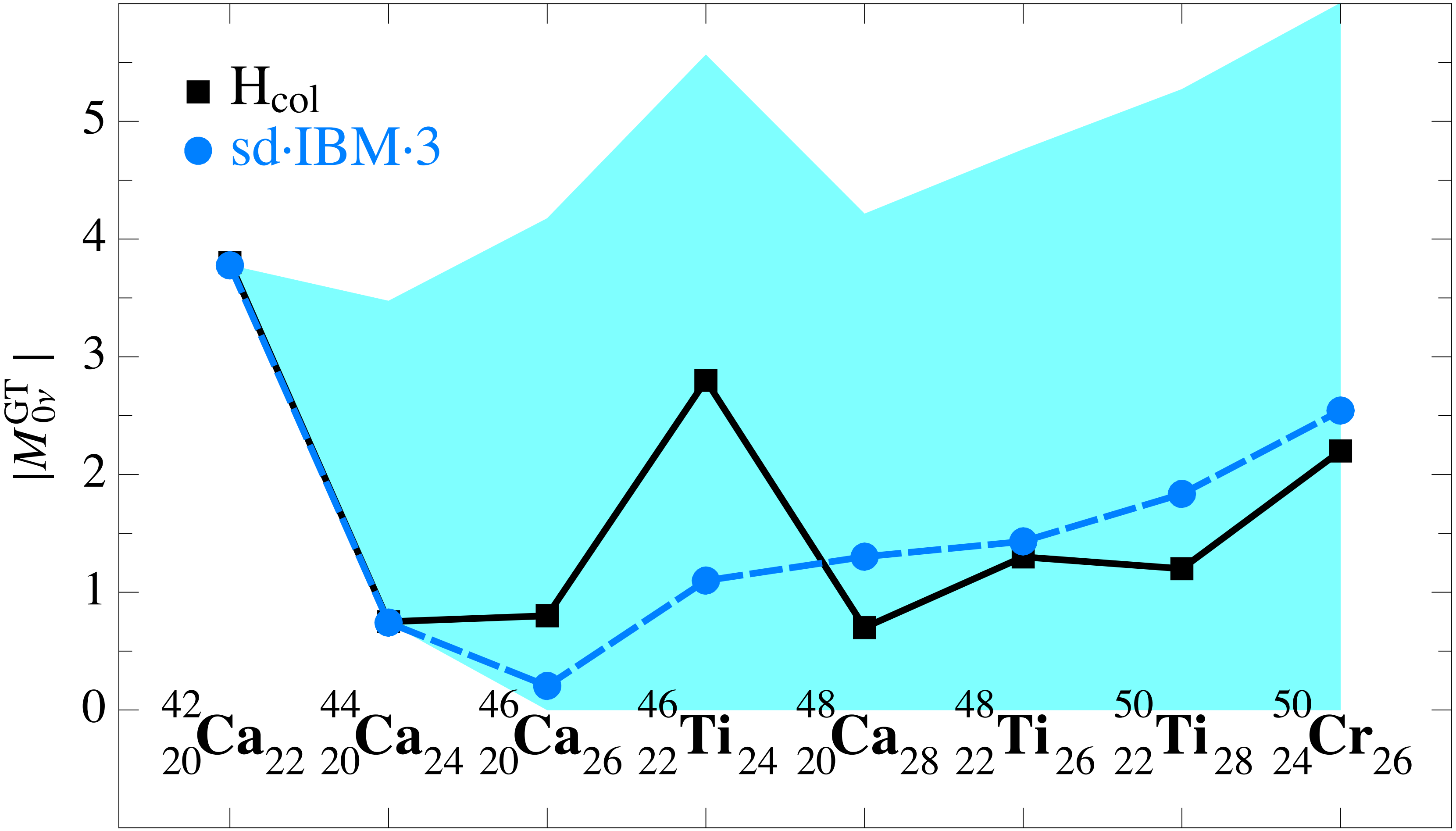
Gamow-Teller $0\nu\beta\beta$ in *sd*-IBM-3



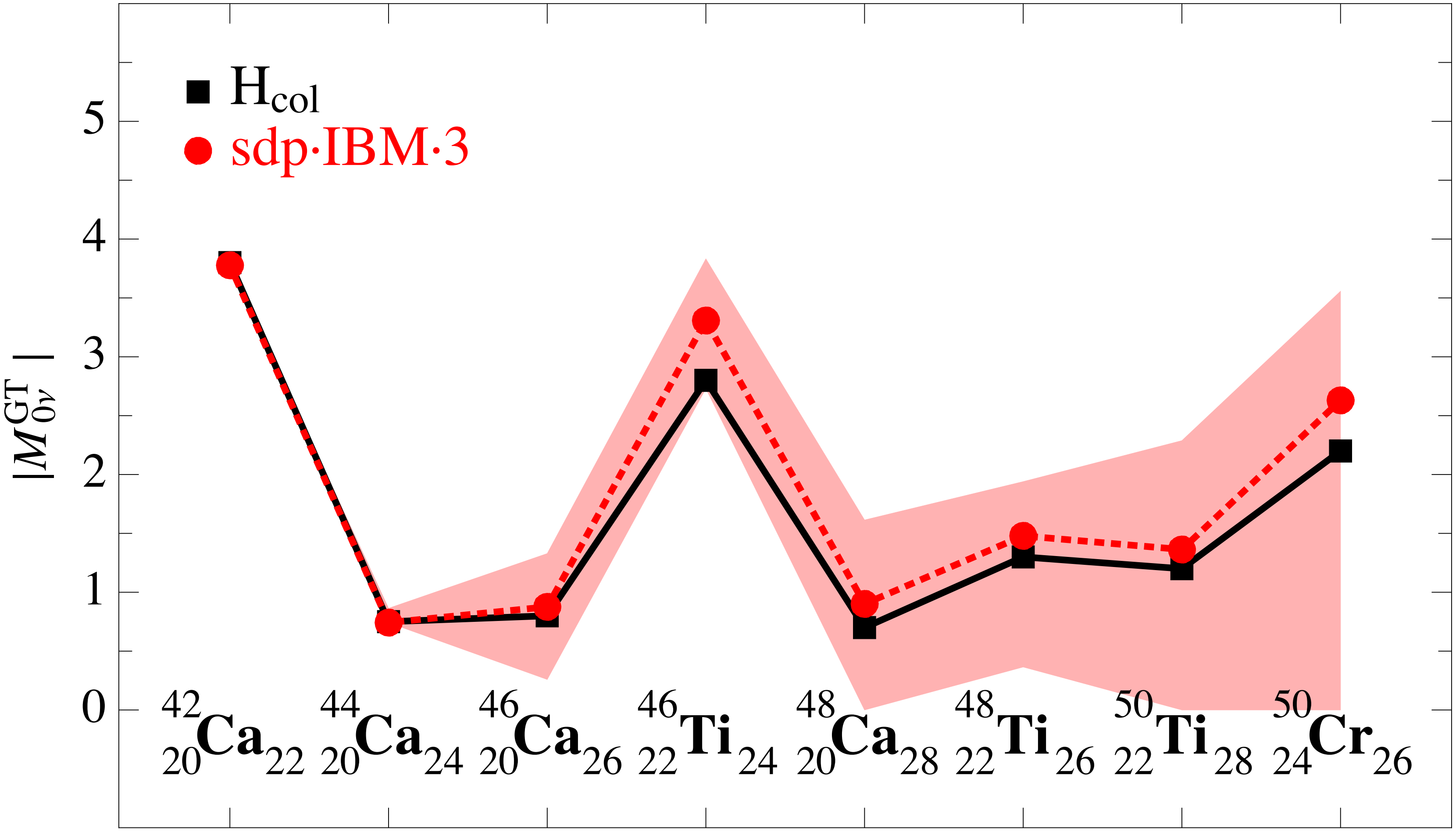
Gamow-Teller $0\nu\beta\beta$ in *sdp*-IBM-3



Gamow-Teller $0\nu\beta\beta$ in *sd*-IBM-3



Gamow-Teller $0\nu\beta\beta$ in *sdp*-IBM-3



Conclusions and outlook

Okubo-Lee-Suzuki transformation is used to define an effective collective Hamiltonian.

In light $\beta\beta$ emitters (^{48}Ca, ^{76}Ge, ^{82}Se):

Isospin invariance must be included in the IBM.

Isoscalar-pair bosons are not needed for energy spectra but they are important for $\beta\beta$ decay.

Questions/problems:

We need effective operators in the collective space.

How to couple this to phenomenology?

P. Van Isacker, J. Engel & K. Nomura, Phys. Rev. C **96** (2017) 064305