Neutrinoless $\beta\beta$ decay and nuclear structure correlations

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東京大学
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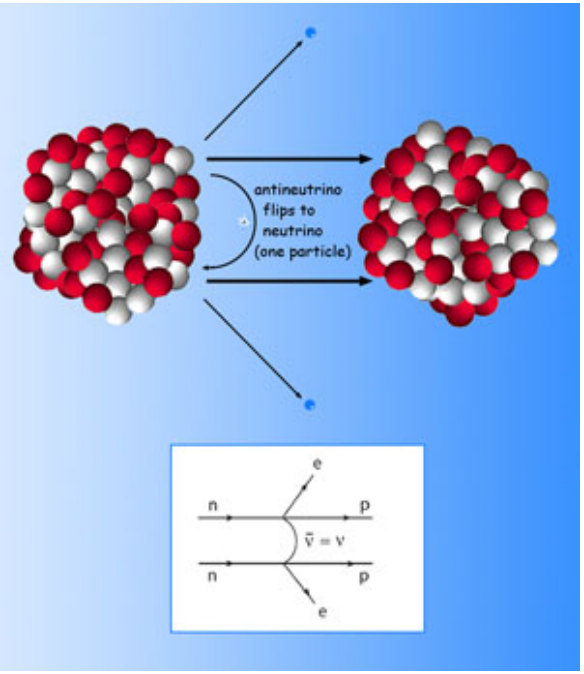
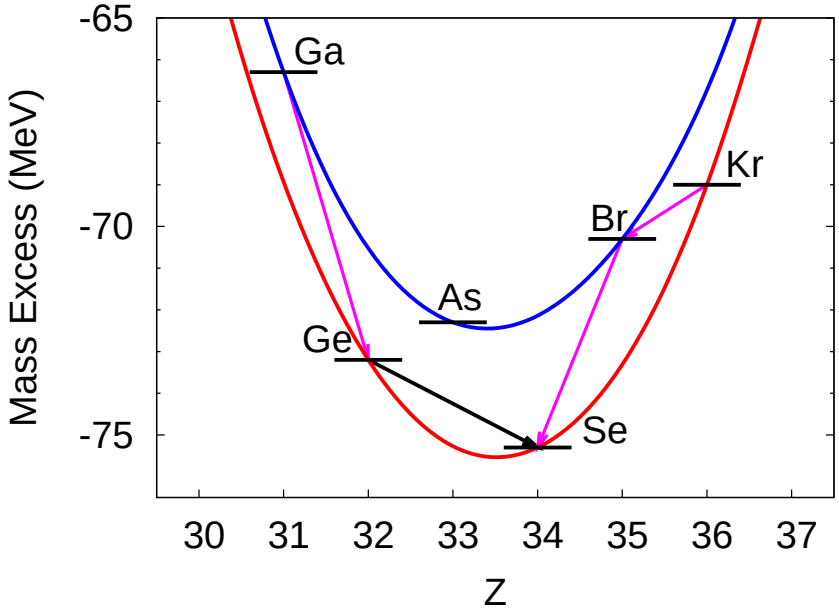
KAKENHI

Neutrinoless double-beta decay

Neutrinoless double-beta decay ($0\nu\beta\beta$):
Lepton-number violation, Majorana nature of neutrinos

Second order process only observable when single-β-decay is energetically forbidden or hindered by large ΔJ





^{48}Ca $\rightarrow$ ^{48}Ti
^{76}Ge $\rightarrow$ ^{76}Se
^{82}Se $\rightarrow$ ^{82}Kr
^{96}Zr $\rightarrow$ ^{96}Mo
^{100}Mo $\rightarrow$ ^{100}Ru
^{110}Pd $\rightarrow$ ^{110}Cd
^{116}Cd $\rightarrow$ ^{116}Sn
^{124}Sn $\rightarrow$ ^{124}Te
^{130}Te $\rightarrow$ ^{130}Xe
^{136}Xe $\rightarrow$ ^{136}Ba
^{150}Nd $\rightarrow$ ^{150}Sm

Very slow process with $T_{1/2}^{0\nu\beta\beta} > 10^{25}$ y (EXO, KamLAND-ZEN, GERDA)
challenging underground measurements with very low background

Nuclear matrix elements and neutrino mass

$0\nu\beta\beta$ linked to nuclear structure through the nuclear matrix element $M^{0\nu\beta\beta}$:

$$\left(T_{1/2}^{0\nu\beta\beta}\left(0^+ \to 0^+\right)\right)^{-1} = G_{01}\left|M^{0\nu\beta\beta}\right|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

$M^{0\nu\beta\beta}$ is necessary to identify best candidates for experiment,
and to obtain neutrino masses with $m_{\beta\beta} = |\sum U_{ek}^2 m_k|$,

Present theoretical calculations cannot be directly tested against experiment

$$M^{0\nu\beta\beta} = \langle 0_f^+ | \sum_{n,m} \tau_n^- \tau_m^- \sum_X H^X(r)\,\Omega^X \left|0_i^+\right\rangle$$

For reliable nuclear matrix elements we need

- Many-body method to describe initial and final nuclear states
  Test these states with nuclear structure and decay input
- Transition operator appropriate for the decay
  Test similar operators related to $0\nu\beta\beta$ decay (weak or electromagnetic)

Shell model spectra and occupancies

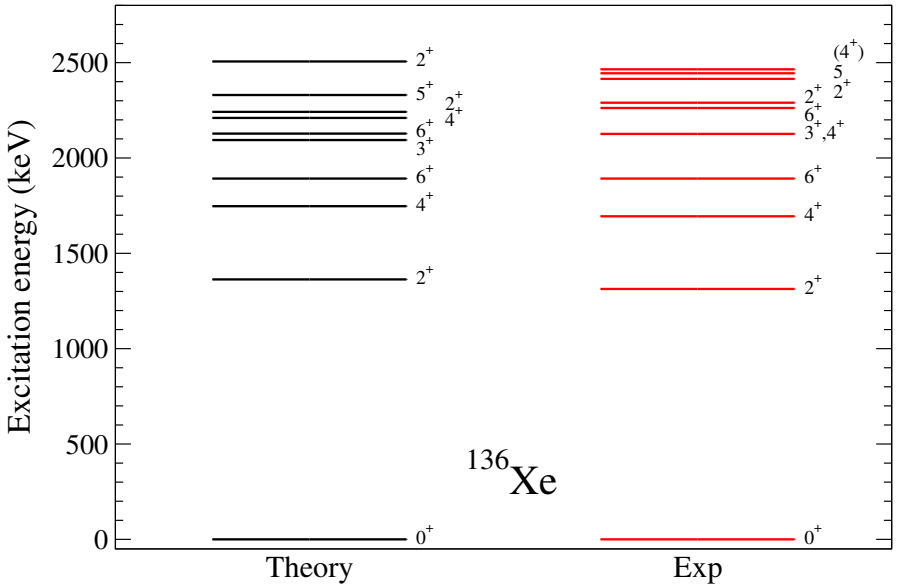
Shell model in one-major-shell spaces with phenomenological interactions

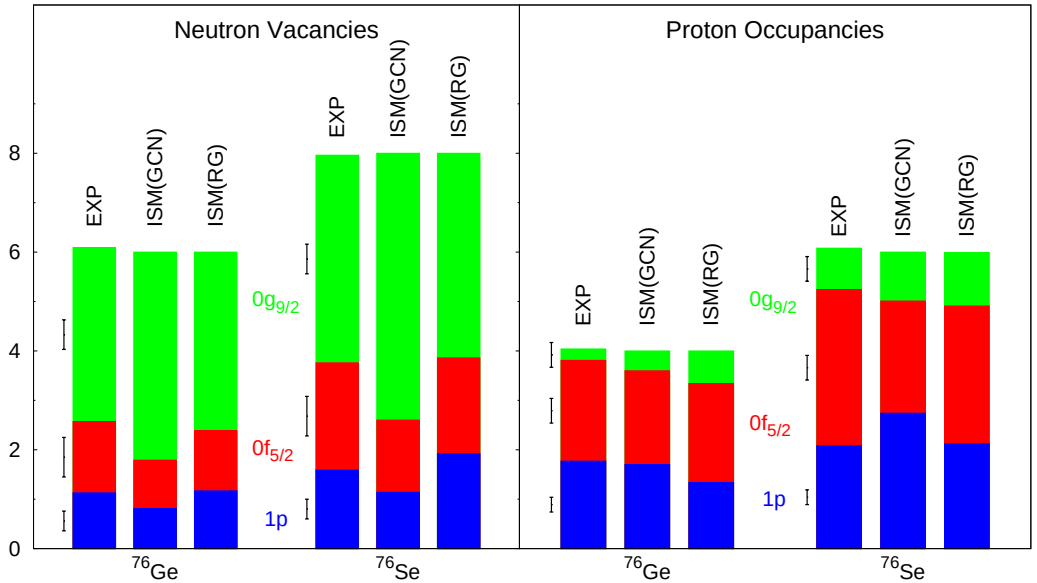
pf-shell, KB3G interaction: ^{48}Ca

$p_{3/2}, p_{1/2}, f_{5/2}, g_{9/2}$ space, GCN2850 interaction: ^{76}Ge, ^{82}Se

$d_{5/2}, s_{1/2}, d_{3/2}, g_{7/2}, h_{11/2}$ space, GCN5082 interaction: ^{124}Sn, ^{130}Te, ^{136}Xe

Experimental excitation spectra, transitions, and occupancies well reproduced





Exp: Schiffer et al. PRL100 112501(2009), Kay et al. PRC79 021301(2009)

Th: JM, Caurier, Nowacki, Poves PRC80 048501 (2009)

Shell model Gamow-Teller decays

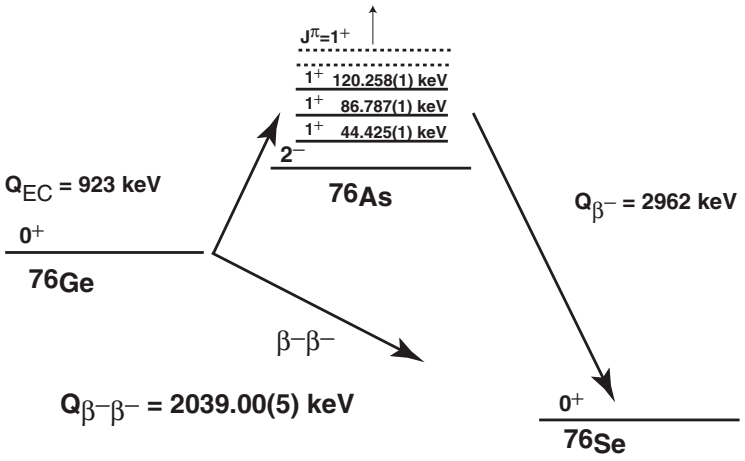
Shell Model predicts $2\nu\beta\beta$ decay

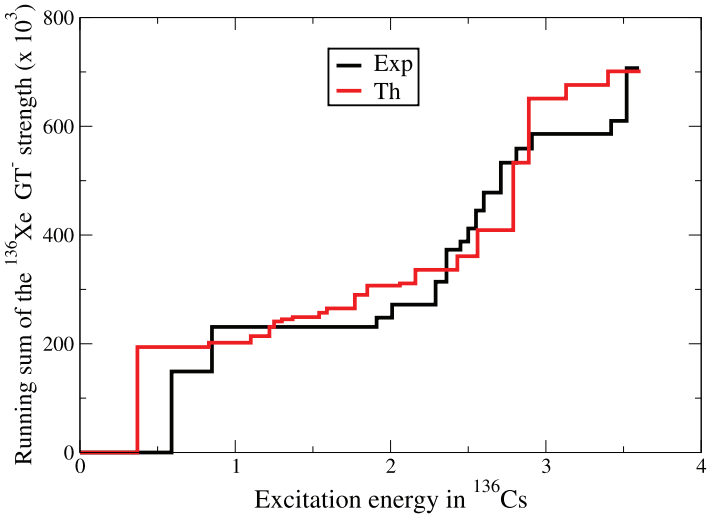
GT quenching is needed ⇓

Table 2
The ISM predictions for the matrix element of several 2ν double beta decays (in MeV^{-1}). See text for the definitions of the valence spaces and interactions.

	$M^{2\nu}$(exp)	q	$M^{2\nu}$(th)	INT
$^{48}\mathrm{Ca} \to {}^{48}\mathrm{Ti}$	0.047 ± 0.003	0.74	0.047	kb3
$^{48}\mathrm{Ca} \to {}^{48}\mathrm{Ti}$	0.047 ± 0.003	0.74	0.048	kb3g
$^{48}\mathrm{Ca} \to {}^{48}\mathrm{Ti}$	0.047 ± 0.003	0.74	0.065	gxpf1
$^{76}\mathrm{Ge} \to {}^{76}\mathrm{Se}$	0.140 ± 0.005	0.60	0.116	gcn28:50
$^{76}\mathrm{Ge} \to {}^{76}\mathrm{Se}$	0.140 ± 0.005	0.60	0.120	jun45
$^{82}\mathrm{Se} \to {}^{82}\mathrm{Kr}$	0.098 ± 0.004	0.60	0.126	gcn28:50
$^{82}\mathrm{Se} \to {}^{82}\mathrm{Kr}$	0.098 ± 0.004	0.60	0.124	jun45
$^{128}\mathrm{Te} \to {}^{128}\mathrm{Xe}$	0.049 ± 0.006	0.57	0.059	gcn50:82
$^{130}\mathrm{Te} \to {}^{130}\mathrm{Xe}$	0.034 ± 0.003	0.57	0.043	gcn50:82
$^{136}\mathrm{Xe} \to {}^{136}\mathrm{Ba}$	0.019 ± 0.002	0.45	0.025	gcn50:82

Caurier, Nowacki, Poves PLB711 62(2012)





Gamow-Teller Strengths well reproduced

Exp: Puppe et al. PRC84 051305(2011)⇒

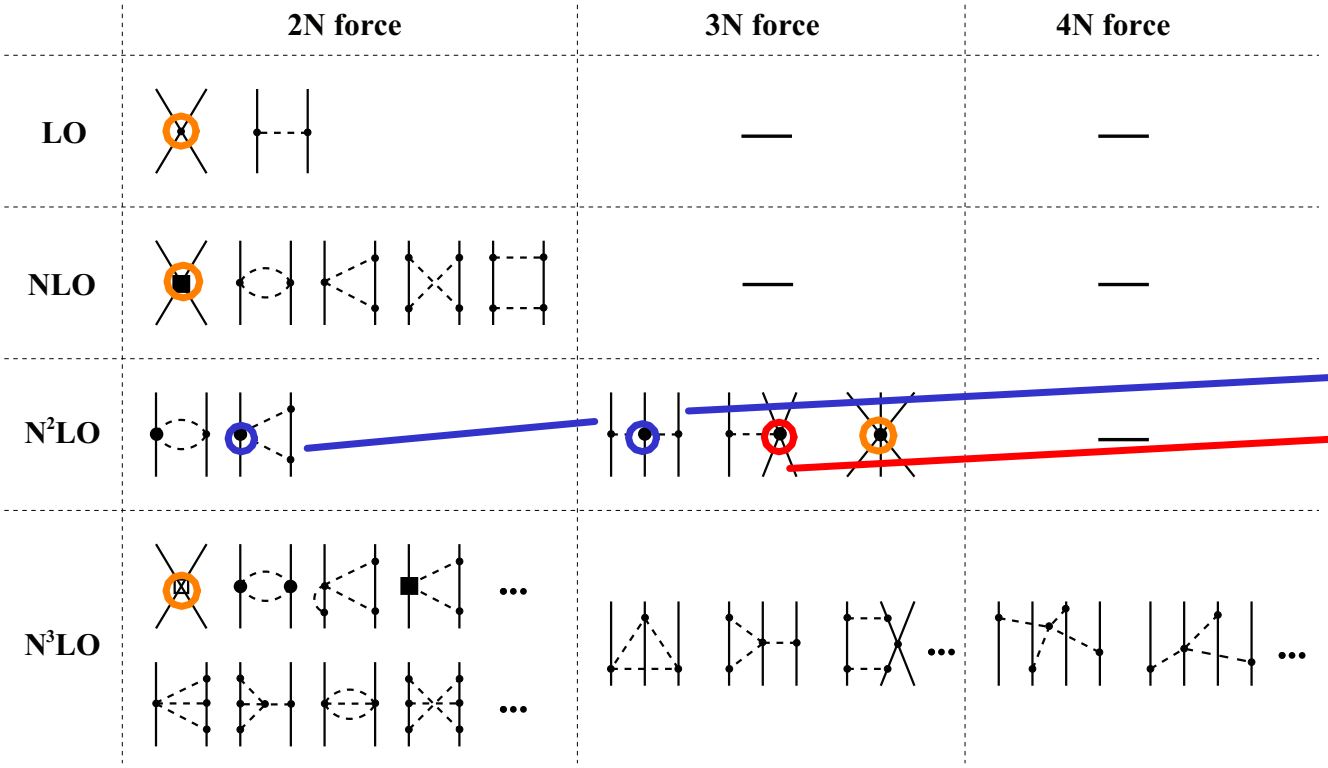
Quenching: major $M^{0\nu\beta\beta}$ uncertainty: $M^{0\nu\beta\beta} \propto g_A^2 \Rightarrow \left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4$

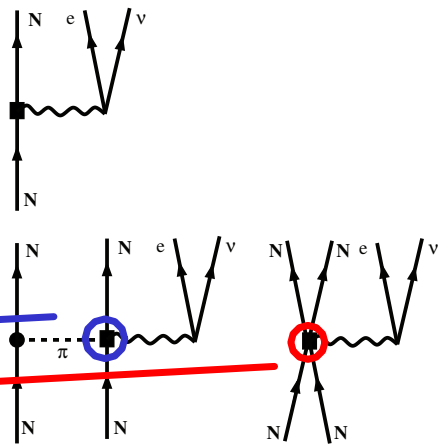
Chiral effective field theory

Chiral EFT: low energy approach to QCD for nuclear structure energies

Approximate chiral symmetry: pion exchanges and contact interactions

Systematic expansion: nuclear forces and electroweak currents





Park et al.
PRC67 055206(2003)

Weinberg, van Kolck, Kaplan, Savage, Epelbaum, Kaiser, Meißner...

Short-range couplings fit to experiment once

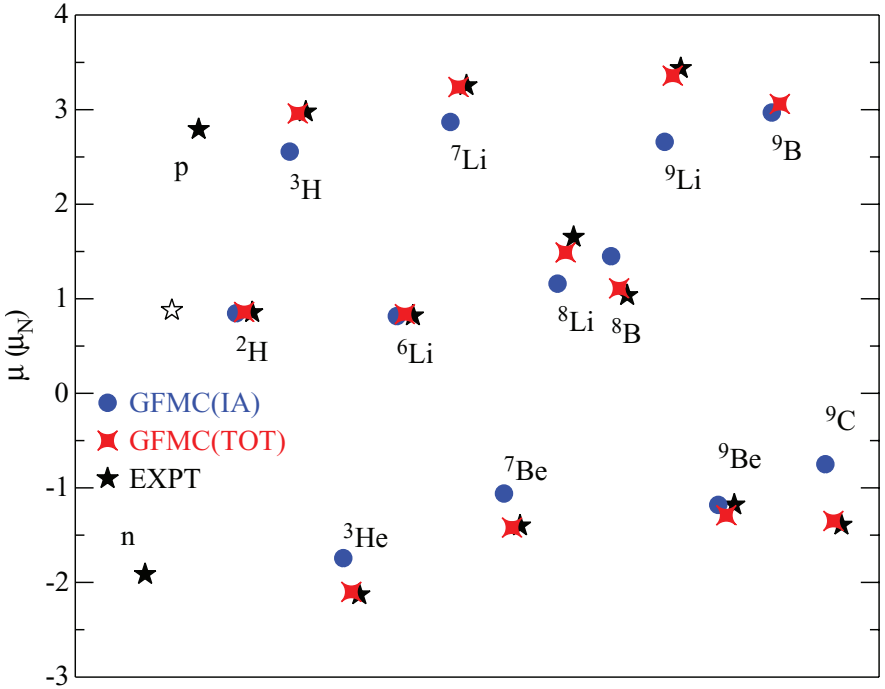
2b currents in light nuclei

2b currents (meson-exchange currents) tested in light nuclei:

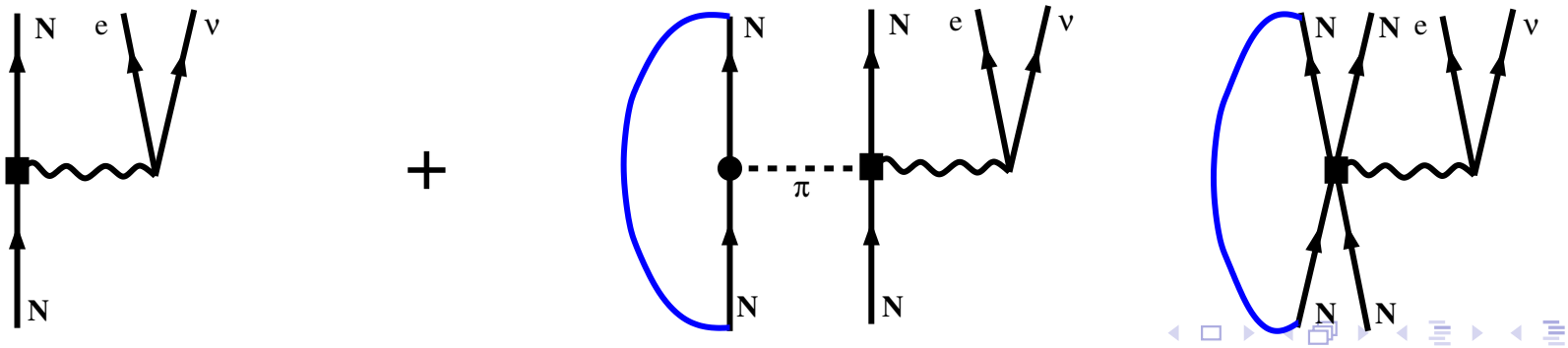
^{3}H β decay
Gazit, Quaglioni, Navrátil
PRL103 102502(2009)

$A \leq 9$ magnetic moments
^{8}Be EM transitions
Pastore et al. PRC87 035503(2013) $\Longrightarrow$
Pastore et al. PRC90 024321(2014)

^{3}H μ capture
Gazit PLB666 472(2008)
Marcucci et al. PRC83 014002(2011)



In medium-mass nuclei, chiral EFT 1b + 2b currents (normal ordering)

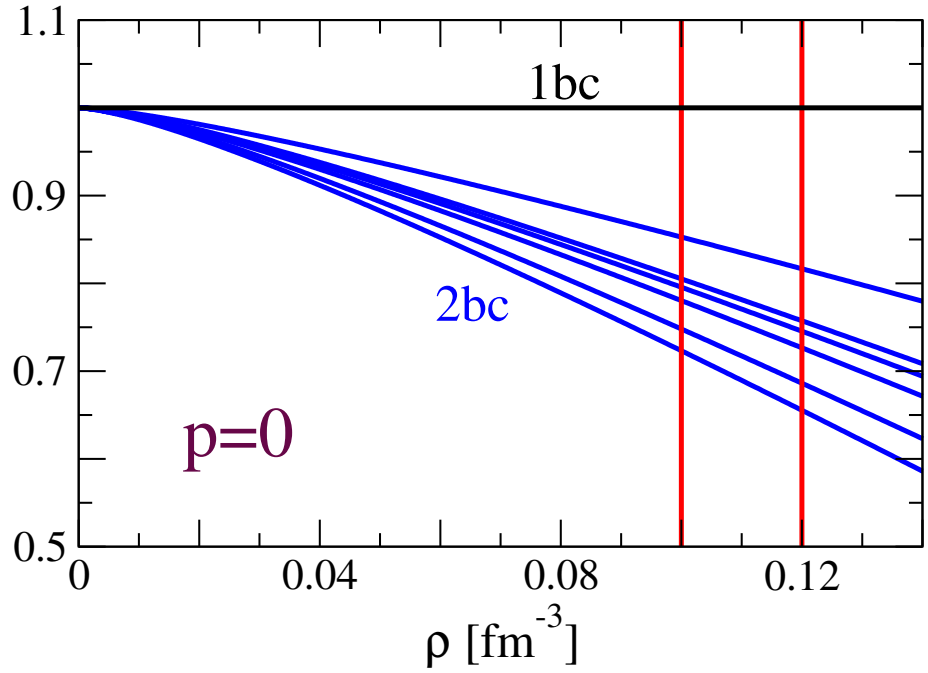


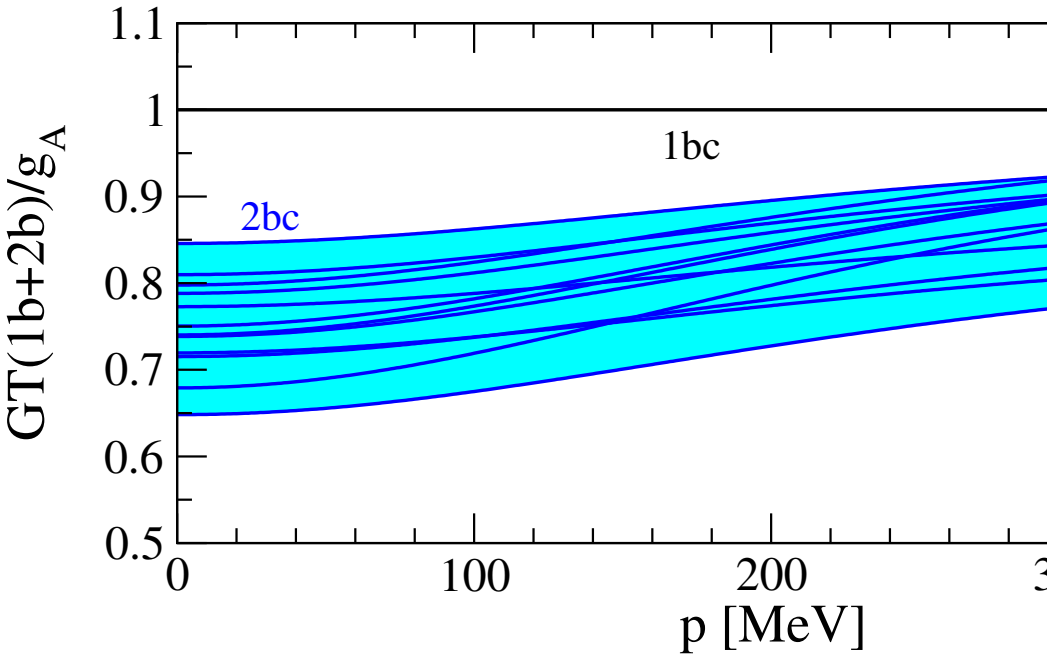
2b currents in medium-mass nuclei

Normal-ordered 2b currents modify GT operator

JM, Gazit, Schwenk PRL107 062501 (2011)

$$\mathbf{J}^{\rm eff}_{n,2b} \simeq -\frac{g_A\rho}{f_\pi^2}\tau_n^-\sigma_n\left[I(\rho,P)\left(\frac{1}{3}(2c_4-c_3)+\frac{1}{6m_N}\right)\right]-\frac{g_A\rho}{f_\pi^2}\tau_n^-\sigma_n\frac{2}{3}c_3\frac{\mathbf{p}^2}{4m_\pi^2+\mathbf{p}^2},$$

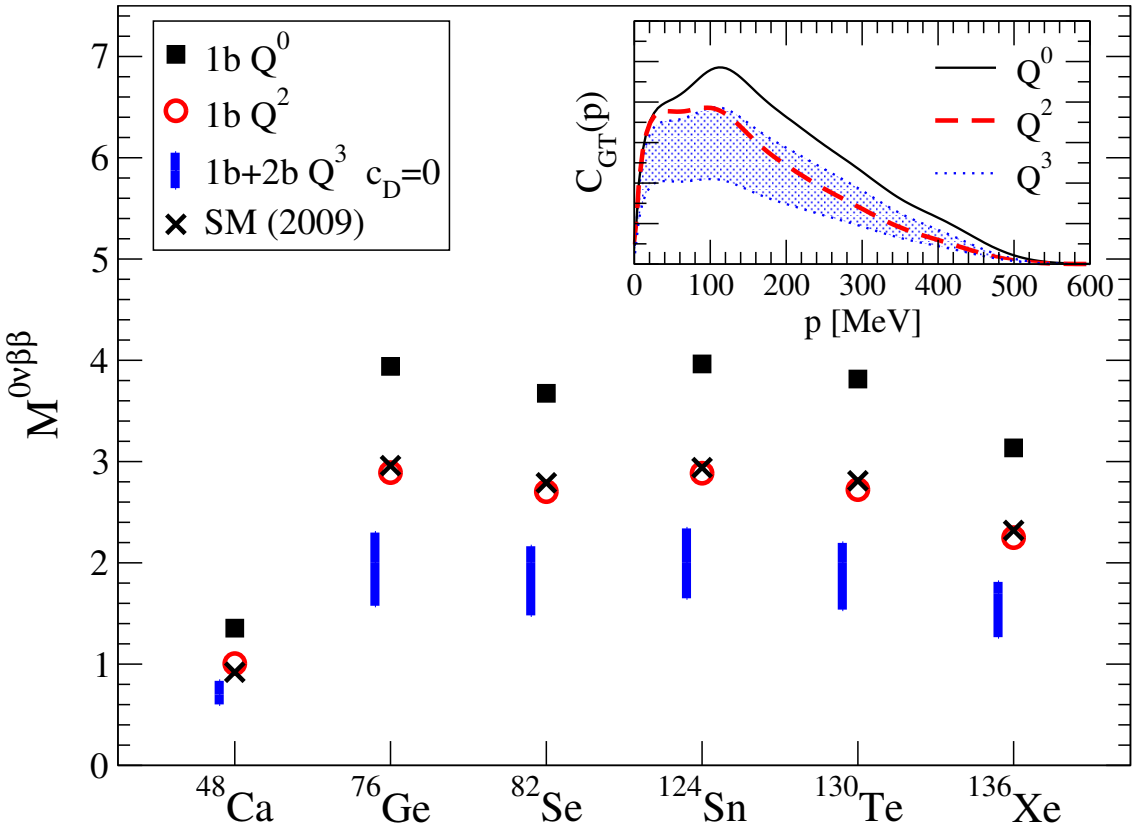




2b currents predict g_A quenching $q = 0.85...0.66$

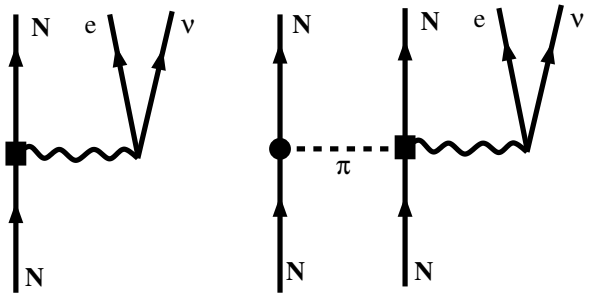
Quenching reduced at $p > 0$, relevant for $0\nu\beta\beta$ decay where $p \sim m_\pi$

Nuclear matrix elements with 1b+2b currents



JM, Gazit, Schwenk PRL107 062501 (2011)

Order Q^0+Q^2 similar to phenomenological currents
JM, Poves, Caurier, Nowacki
NPA818 139 (2009)



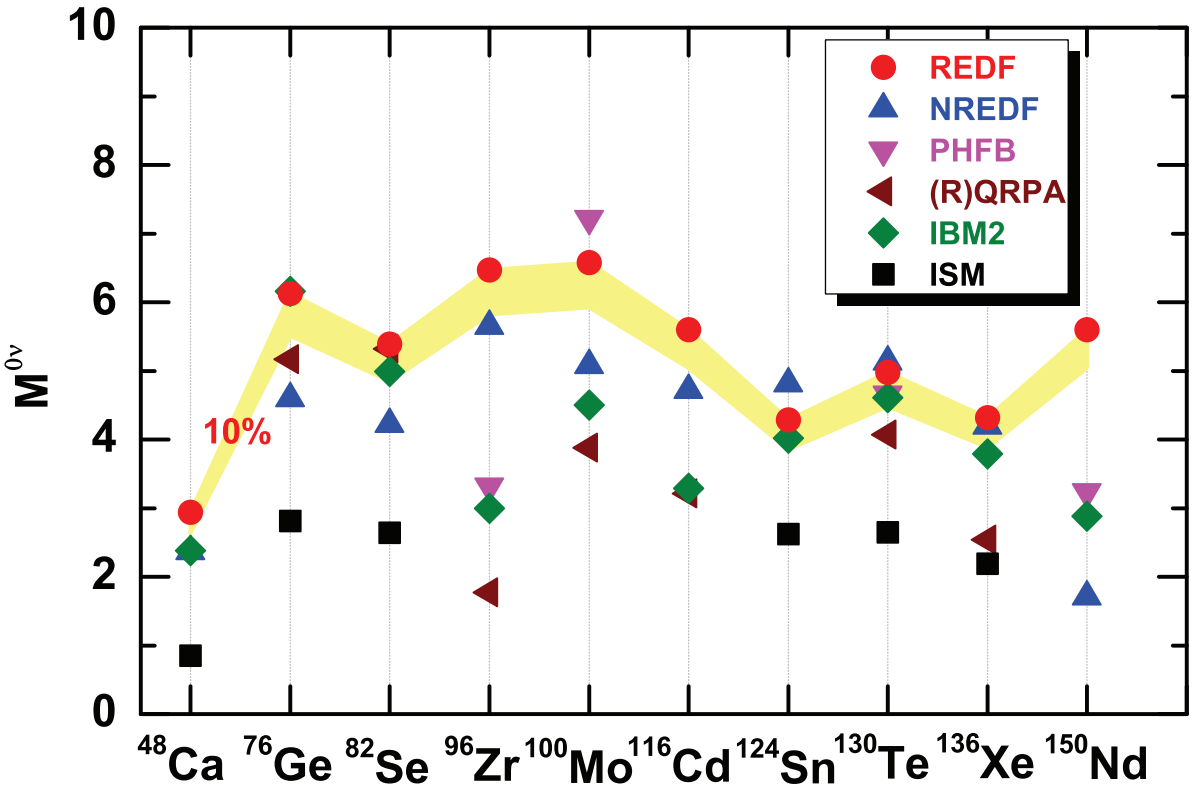
Order Q^3 2b currents reduce NMEs $\sim 15\% - 40\%$

Similar $\sim 15\% - 25\%$ reduction observed in QRPA with same 2b currents
Engel, Šimkovic, Vogel PRC89 064308 (2014)

Coupled-cluster β decay studies in C, O suggest smaller quenching $q \sim 0.9$
Ekström et al. PRL113 262504 (2014)

Neutrinoless $\beta\beta$ decay matrix elements

Large difference in matrix element calculations, same transition operator

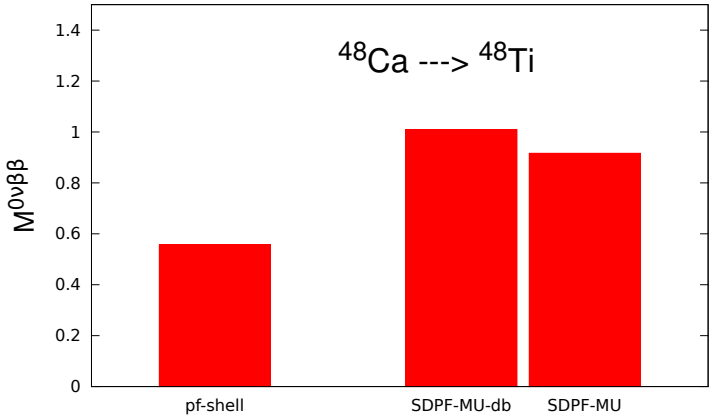


Yao et al. PRC91 024316 (2015)

See talk by Y. Iwata on Wed. 3

EDF, IBM, QRPA
large matrix elements:
How well they include nuclear structure correlations?

Shell model
small matrix elements:
What is the effect of the small valence space?



Neutrinoless $\beta\beta$ decay of *pf*-shell nuclei

Study of $0\nu\beta\beta$ decay in the *pf*-shell isotopes
for a systematic exploration of the role of nuclear structure correlations
Most decays are forbidden or of no practical interest, except for ^{48}Ca

Shell model very well tested in *pf* shell

Spin-orbit partners included
(Ikeda Sum Rule, isoscalar pairing correlations)

Deformed nuclei well described (eg. ^{48}Cr)

Corresponding separable interaction based on KB3 effective interaction including the most important collective terms available
Dufour, Zuker PRC54 1653(1996)

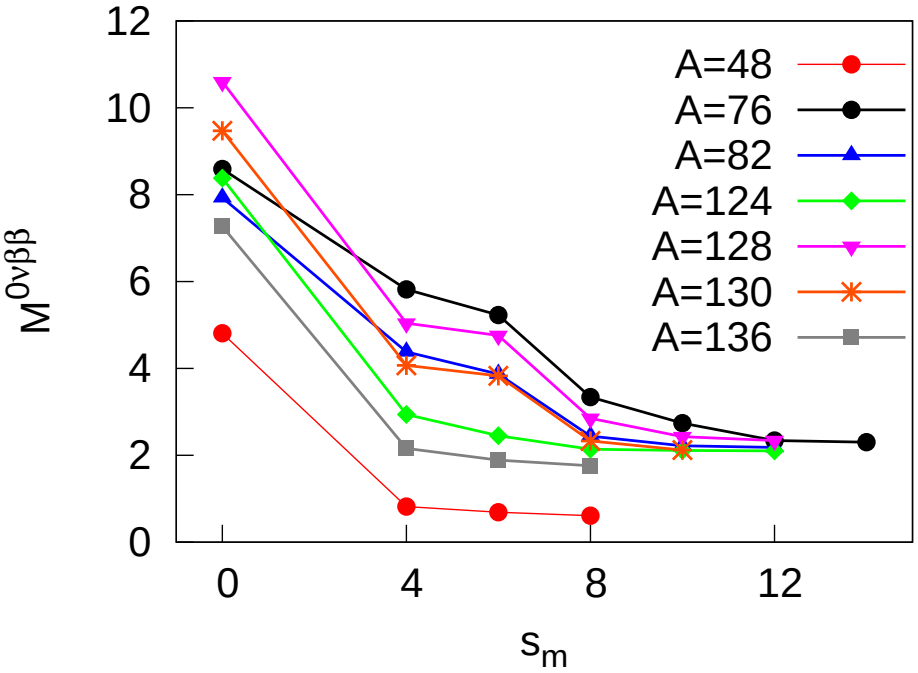
Calculate $\beta\beta$ decay along isotopic chains: Ca→Ti, Ti→Cr, Cr→Fe

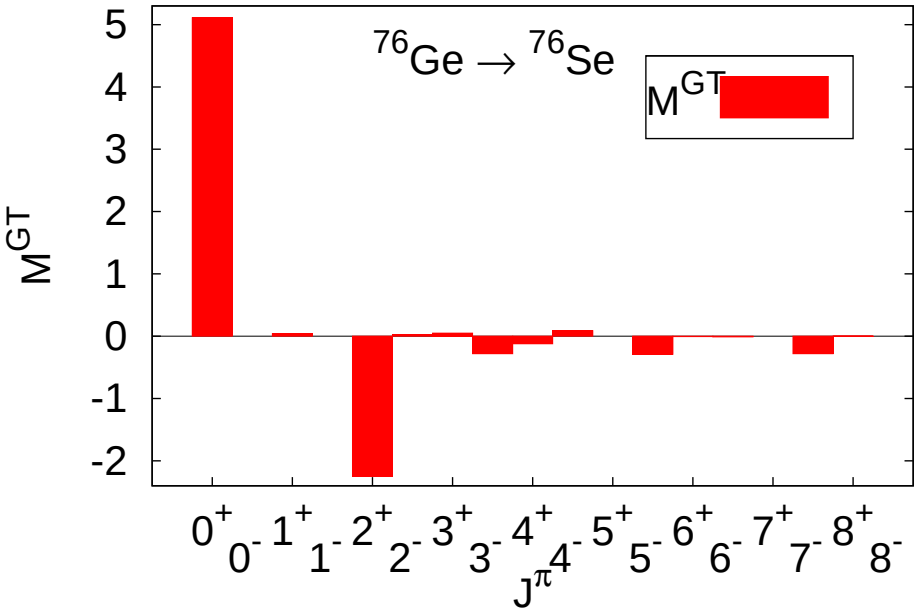
Focus on Gamow-Teller part of the NME: $M_{GT}^{0\nu\beta\beta}$
Dominant part of the NME
Avoids problems with isospin conservation (overestimation of $M_F^{0\nu\beta\beta}$)

Pairing correlations and $0\nu\beta\beta$ decay

$0\nu\beta\beta$ decay is favoured by pairing correlations

Maximum between superfluid nuclei, but not such a candidate
Decomposition in couplings of decaying neutrons: $M^{0\nu\beta\beta} = \sum_{J^\pi} \hat{P}^\dagger_{J^\pi} \hat{P}_{J^\pi}$





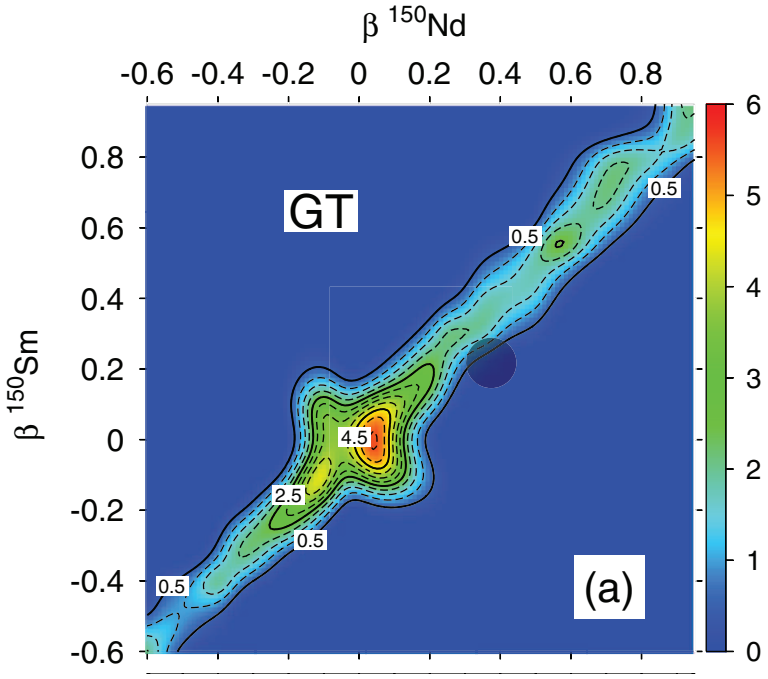
Caurier, JM, Nowacki, Poves PRL100 052503 (2008)

Nuclear matrix elements reduced with high-seniority components
How are these captured in other many-body approaches?

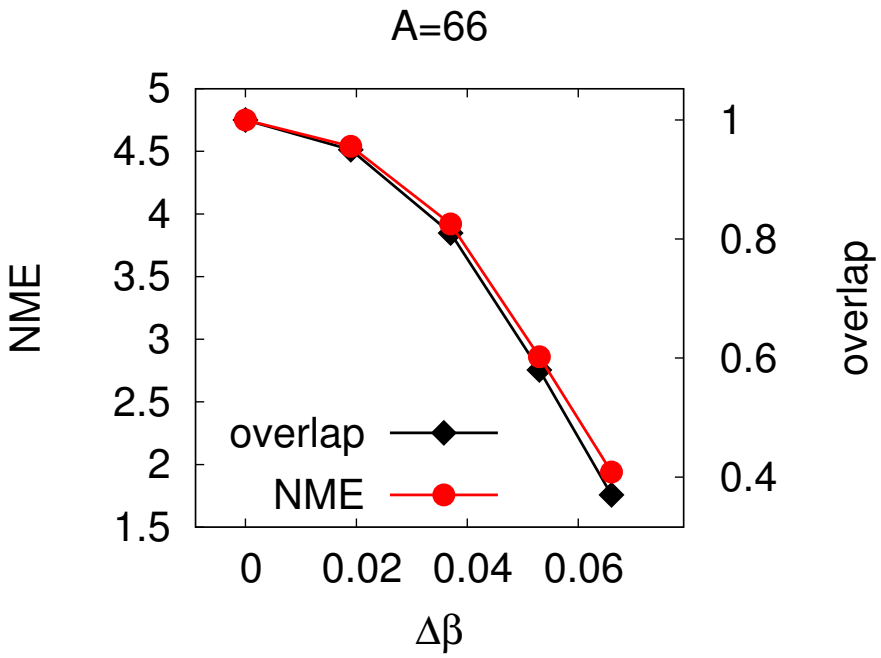
Deformation and $0\nu\beta\beta$ decay

$0\nu\beta\beta$ decay is disfavoured by quadrupole correlations

$0\nu\beta\beta$ decay very suppressed when nuclei have different structure



Rodríguez, Martínez-Pinedo
PRL105 252503 (2010)



JM, Caurier, Nowacki, Poves
JPCS267 012058 (2011)

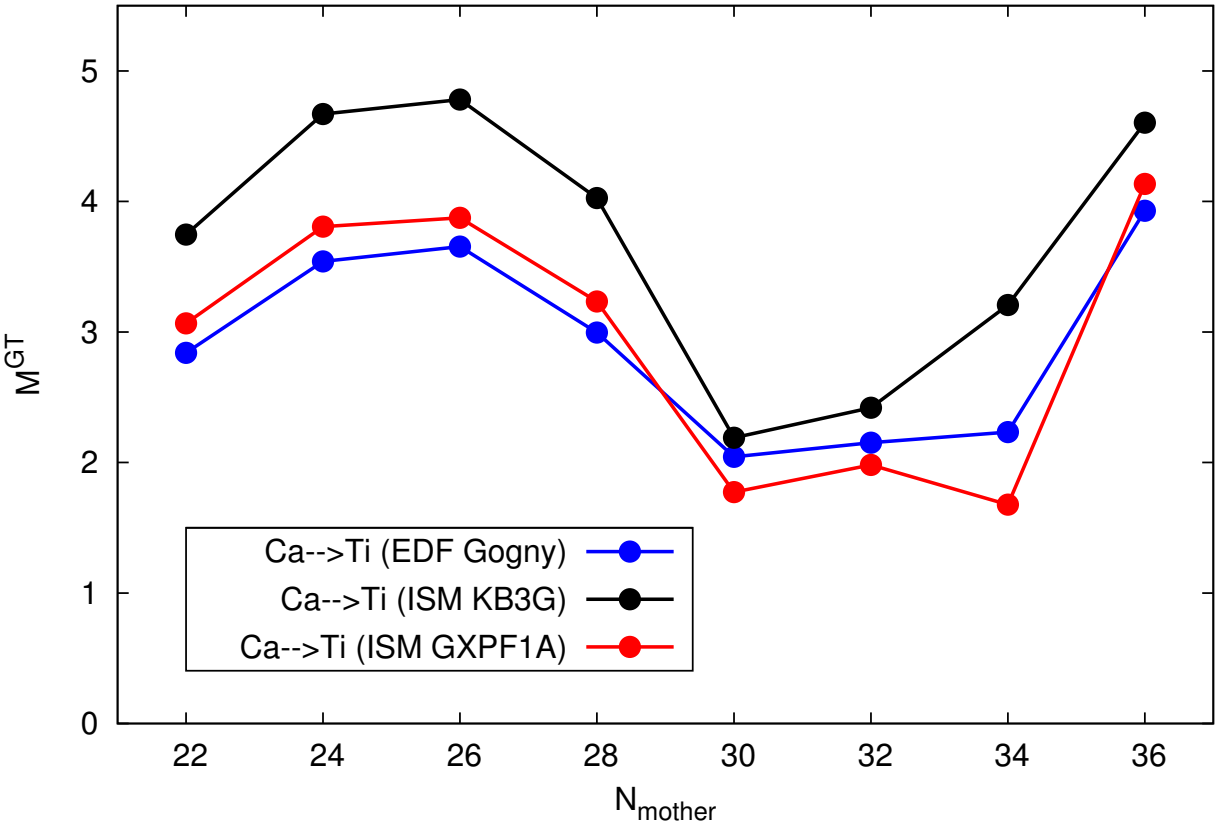
Suppression of NMEs due to deformation also observed with QRPA

Fang et al. PRC83 034320 (2011)

$0\nu\beta\beta$ decay without nuclear structure correlations

Calculate non-realistic spherical (uncorrelated) mother and daughter nuclei:

- Shell model (SM): zero seniority, nucleons in neutron, proton $J = 0$ pairs
- Energy density functional (EDF): only spherical contributions



In contrast to full (correlated) calculation SM and EDF NMEs agree!

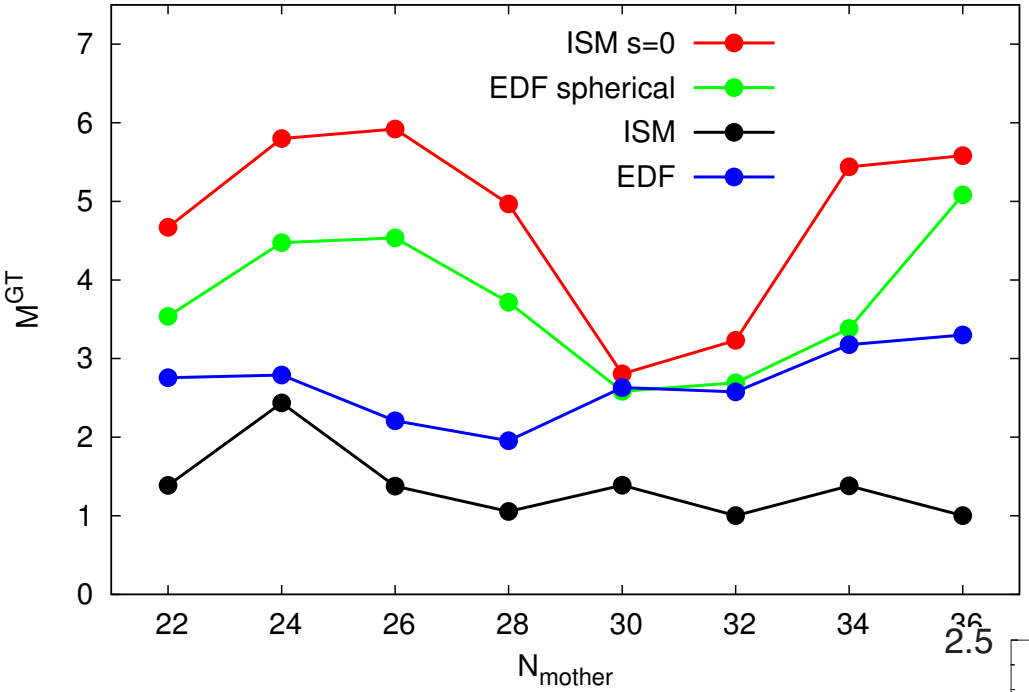
NME scale set by (isovector) pairing content of nuclear interaction

JM, Rodríguez, Martínez-Pinedo, Poves PRC90 024311(2014)

NME trend follows generalized seniority model:

$$M_{GT}^{0\nu\beta\beta} \simeq \alpha_\pi \alpha_\nu \sqrt{N_\pi + 1}\sqrt{\Omega_\pi - N_\pi}\sqrt{N_\nu}\sqrt{\Omega_\nu - N_\nu + 1},$$ Barea, Iachello PRC79 044301(2009)

Seniority evolution of nuclear matrix elements

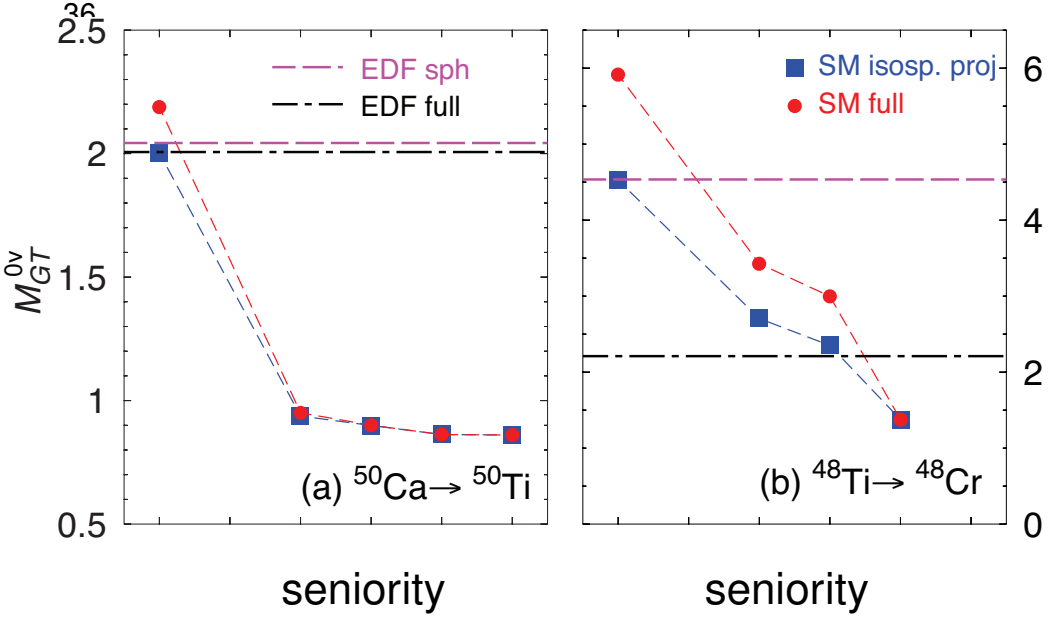


Agreement in $M_{GT}^{0\nu\beta\beta}$ between shell model and Energy Density Functional disappears when correlations are included in inital and final states

Different treatment of correlations

Shell model matrix elements more reduced by high-seniority components than collective quadrupole correlations (deformation) in Energy Density Functional

JM, Rodríguez, Martínez-Pinedo, Poves PRC90 024311(2014)



Exact isospin projection

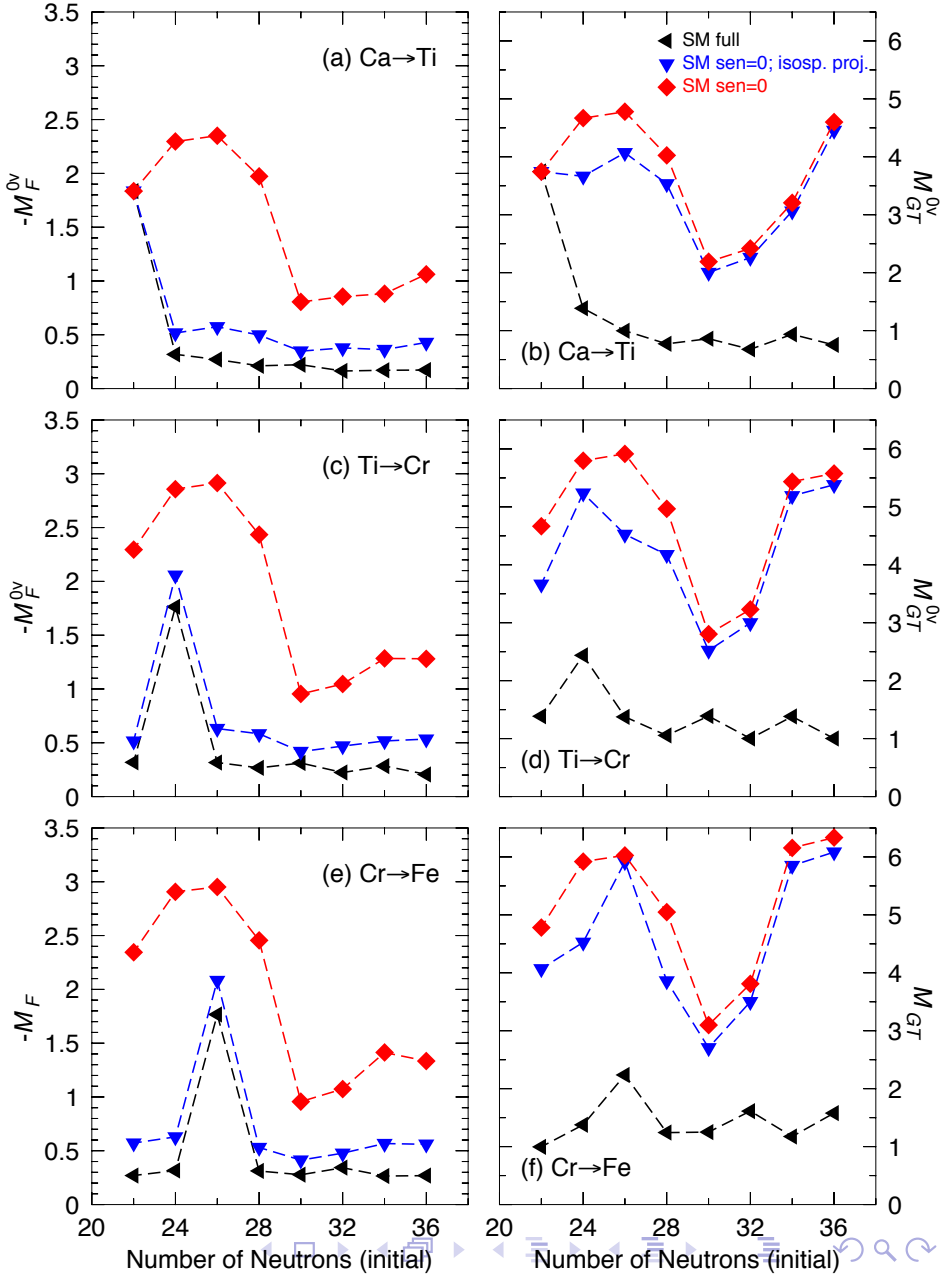
Quantify the importance of good isospin symmetry on nuclear structure calculation performing exact isospin projection (seniority-zero states mix isospin)

Good isospin critical for Fermi part, significantly decreasing its value

Without neutrino potential ($\sim 1/r$), $M_F^{0\nu\beta\beta}$ vanishes between states with different isospin: all cases except transitions between mirror nuclei

Effect of isospin projection on Gamow-Teller NMEs small

JM, Rodríguez, Martínez-Pinedo, Poves
PRC90 024311(2014)



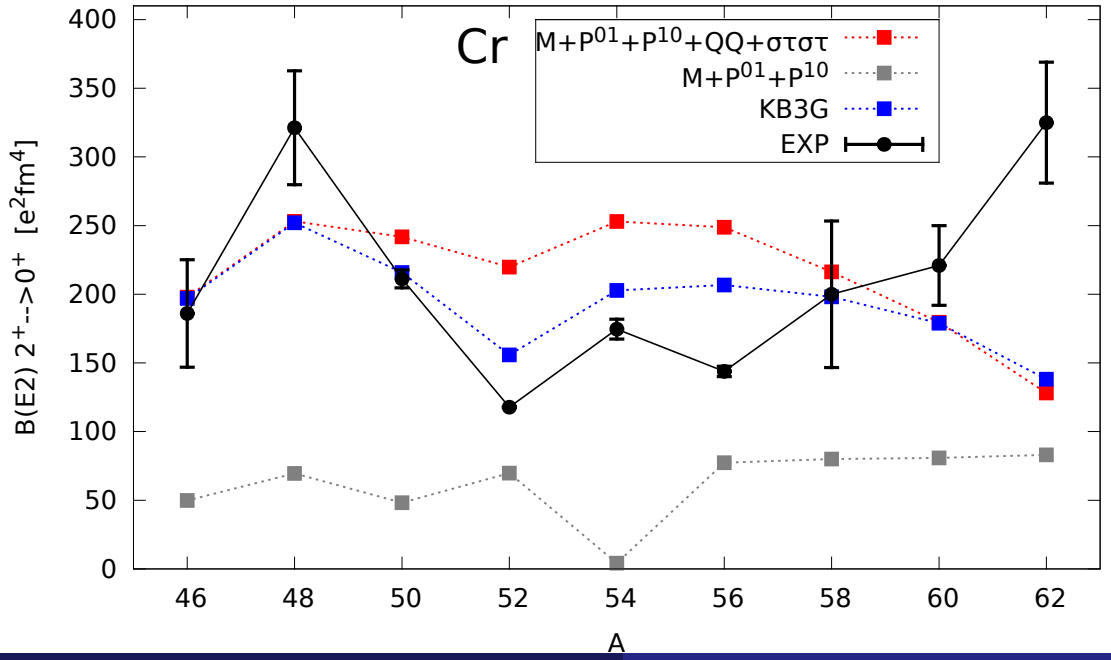
Separable collective interaction from KB3G

Separable collective interaction corresponding to shell model KB3G

Dufour, Zuker PRC54 1653(1996)

Monopole part: as of KB3G interaction

Multipole part:
Diagonalize interaction in paring, particle-hole representations for each J, π
Associate largest eigenvalues with most important collective terms: isovector/isoscalar pairing (P^{01}/P^{10}), quadrupole (QQ), spin-isospin ($\sigma\tau\sigma\tau$), and determine the strengh of each contribution

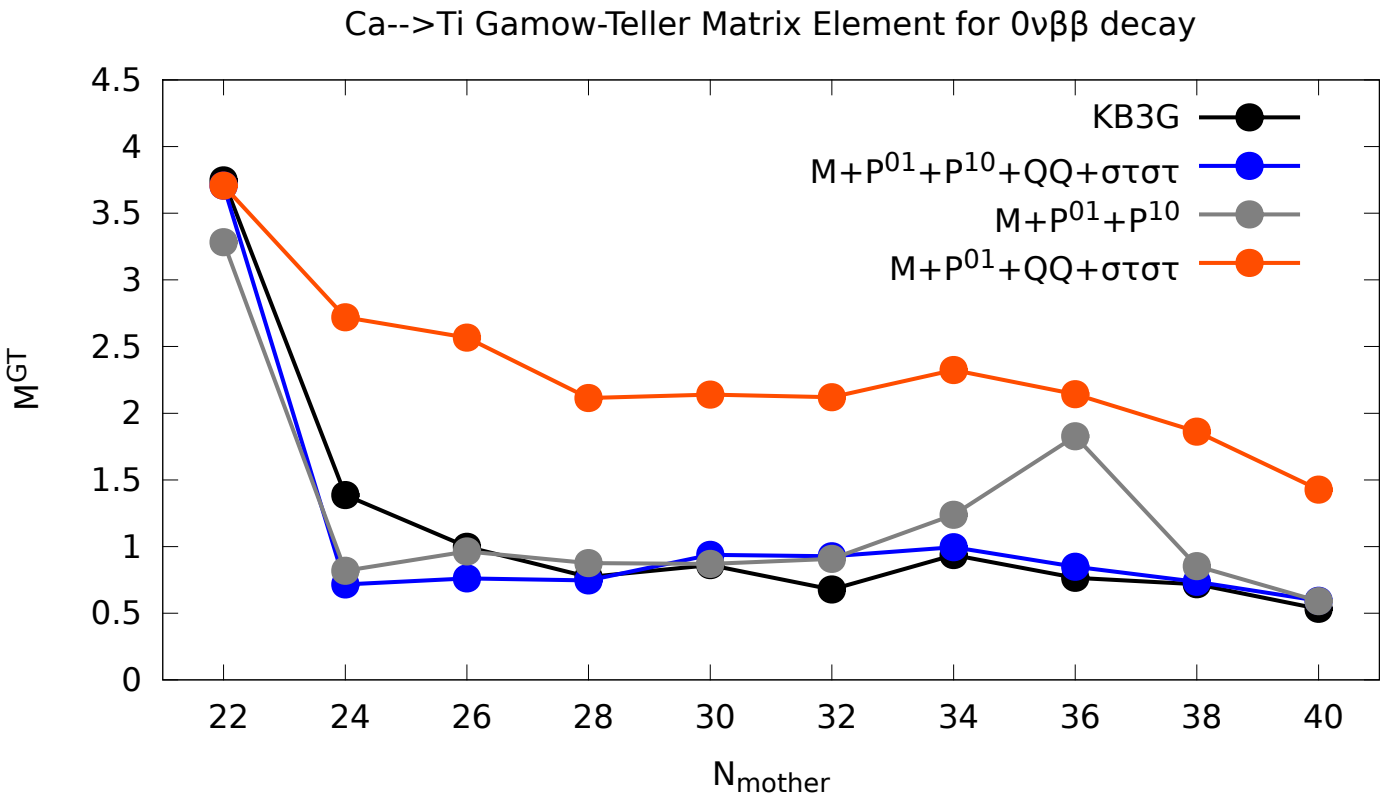


Resulting separable interaction describes well nuclear structure in *pf* shell

JM, Hinohara, Engel, Martínez-Pinedo in preparation

Collective correlations and $\beta\beta$ decay

Study $0\nu\beta\beta$ decay for different collective pieces of the nuclear interaction



JM, Hinohara, Engel, Martínez-Pinedo in preparation

Schematic separable interaction reproduces well full shell model result

Isoscalar (proton-neutron) pairing correlations strongly reduce M_{GT}

Quadrupole correlations in general not so relevant in *pf*-shell

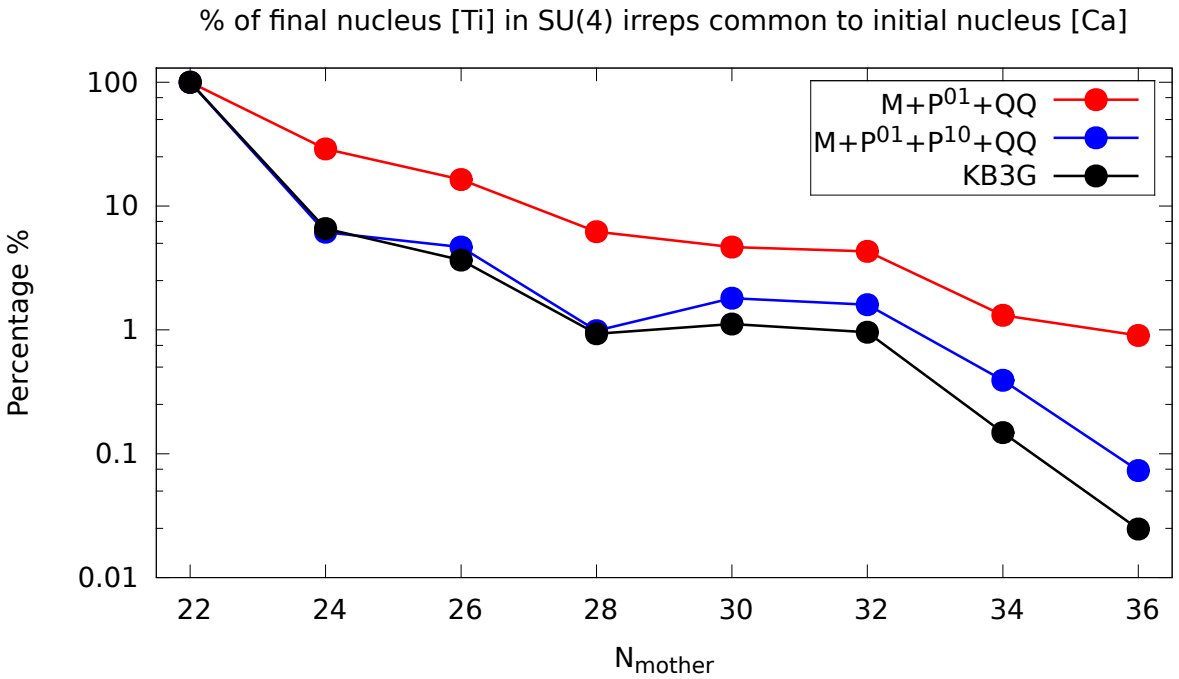
Spin-isospin symmetry and $\beta\beta$ decay

Neutrinoless $\beta\beta$ decay Gamow-Teller operator: $\sum_{n,m} H(r)\, \tau_n^- \tau_m^-\, \sigma_n \sigma_m$

Except $H(r) \sim 1/r$, invariant under spin-isospin transformations [SU(4)]

In good symmetry limit, M_{GT} vanish for states in different SU(4) irreps, just like M_F vanish between states with different isospin

Spin-isospin symmetry broken in *pf*-shell nuclei,
but still small fraction of mother and daughter states in common SU(4) irreps



Common spin-isospin irreps strongly depend on SU(4) breaking by excluding isoscalar pairing

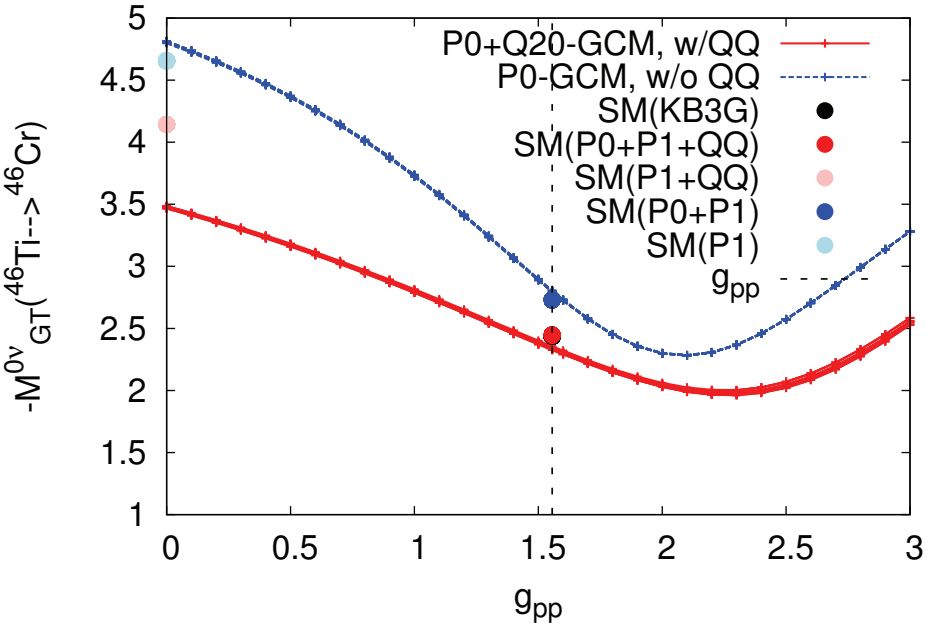
Exception: $\beta\beta$ transitions between mirror nuclei, common spin-isospin structure: maximum M_{GT} values

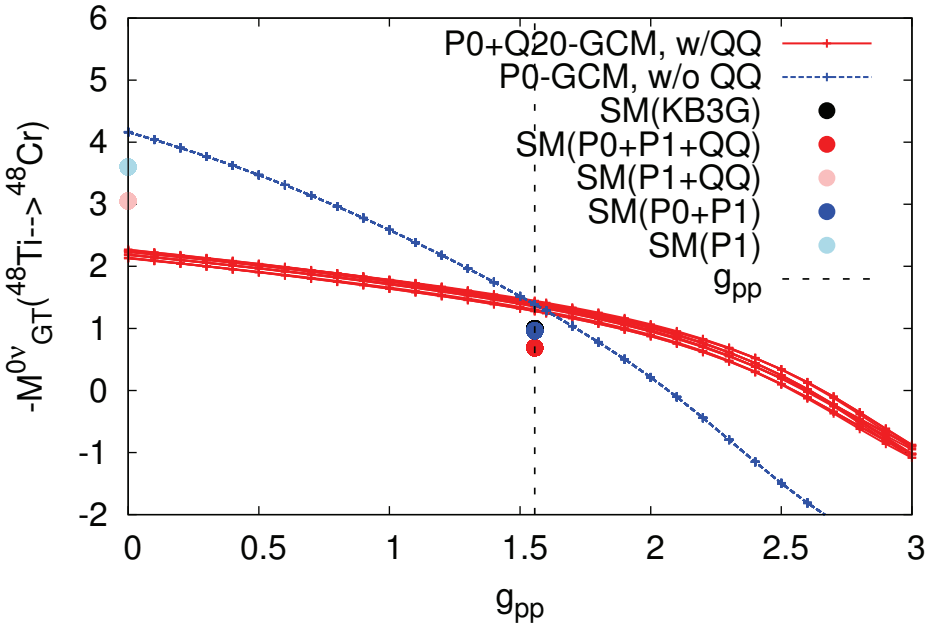
Shell model and generalized coordinate method

Compare shell model and GCM calculations with generators:
1D (isoscalar pairing) / 2D (isoscalar pairing + quadrupole)

Hinohara, Engel PRC90 031301 (2014)

Same collective Hamiltonian based on the KB3G interaction





JM, Hinohara, Engel, Martínez-Pinedo, in preparation

Nice overall agreement between shell model and 1D GCM calculations

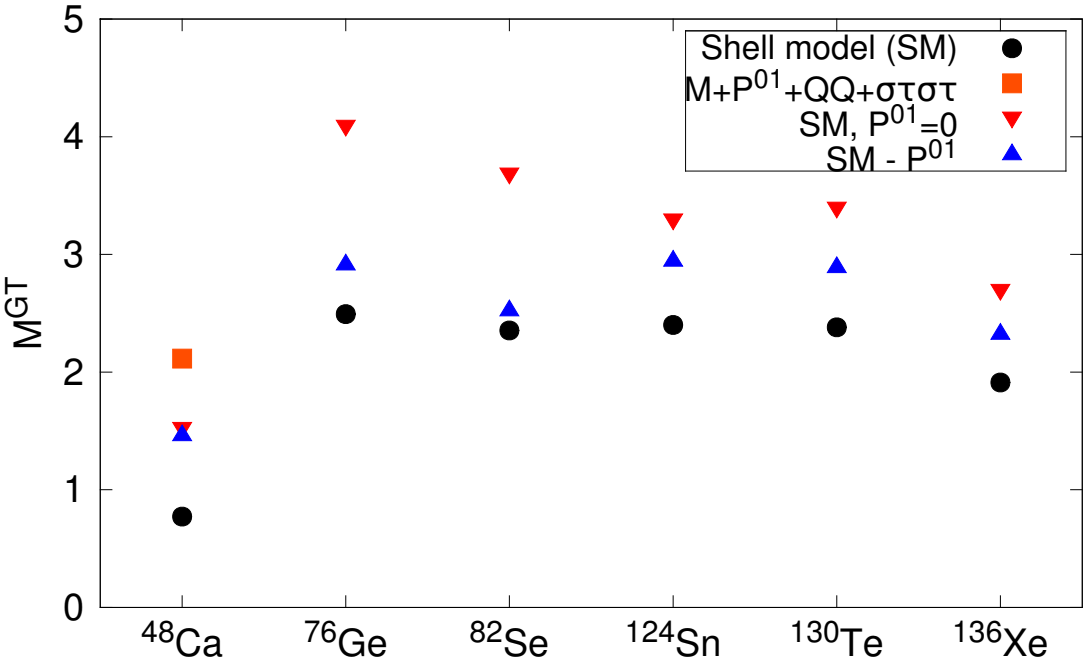
Effect of isoscalar pairing slightly smaller in 2D GCM with deformation

Isoscalar pairing in heavier systems

Collective parts of nuclear Hamiltonian difficult to extract beyond major-shell spaces as used in ^{76}Ge, ^{82}Se, ^{124}Sn, ^{130}Te, ^{136}Xe decays, missing spin-orbit partners (incomplete valence space)

Two different estimations:

- Subtract isoscalar pairing interaction to shell model interaction assuming same strengh as in the pf-shell
- Set to zero all interaction matrix elements receiving contributions from collective isoscalar pairing interaction (in the valence space)



Estimations suggest NMEs could be overestimated without isoscalar pairing around 10% – 50% effect

JM, Hinohara, Engel, Martínez-Pinedo, in preparation

Summary

Neutrinoless double-beta decay key process to understand
Majorana neutrino character and neutrino absolute mass and hierarchy

- Current nuclear matrix element calculations
  performed with different nuclear structure approaches in factor ~ 2
- Shell model matrix elements smaller than other approaches,
  but only method to include full correlations in configuration space
- Monopole interaction and main collective terms (pairing, quadrupole...)
  good approximation to nuclear matrix elements
- Nuclear structure correlations:
  high-seniority components in initial and final states
  and isoscalar (proton-neutron) pairing correlations
  needed for reliable nuclear matrix element calculation
- Larger spaces result in larger matrix elements: **Y. Iwata talk Wed. 3**
- 2b currents modify nuclear matrix elements, associated to g_A quenching

Collaborators

N. Hinohara

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