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

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

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

Very slow process with $T_{1/2}^{0νββ} > 10^{25}$ 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 $M^{0\nu\beta\beta}$:

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

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

Present theoretical calculations cannot be directly tested against experiment

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

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>
<thead>
<tr>
<th>Decay</th>
<th>$M^{2\nu}$ (exp)</th>
<th>$q$</th>
<th>$M^{2\nu}$ (th)</th>
<th>INT</th>
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<tbody>
<tr>
<td>$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$</td>
<td>0.047 ± 0.003</td>
<td>0.74</td>
<td>0.047</td>
<td>kb3</td>
</tr>
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<td>$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$</td>
<td>0.047 ± 0.003</td>
<td>0.74</td>
<td>0.065</td>
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<tr>
<td>$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$</td>
<td>0.140 ± 0.005</td>
<td>0.60</td>
<td>0.116</td>
<td>gcn28:50</td>
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<tr>
<td>$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$</td>
<td>0.140 ± 0.005</td>
<td>0.60</td>
<td>0.120</td>
<td>jun45</td>
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<tr>
<td>$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$</td>
<td>0.098 ± 0.004</td>
<td>0.60</td>
<td>0.126</td>
<td>gcn28:50</td>
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<tr>
<td>$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$</td>
<td>0.098 ± 0.004</td>
<td>0.60</td>
<td>0.124</td>
<td>jun45</td>
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<tr>
<td>$^{128}\text{Te} \rightarrow ^{128}\text{Xe}$</td>
<td>0.049 ± 0.006</td>
<td>0.57</td>
<td>0.059</td>
<td>gcn50:82</td>
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<tr>
<td>$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$</td>
<td>0.034 ± 0.003</td>
<td>0.57</td>
<td>0.043</td>
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<tr>
<td>$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$</td>
<td>0.019 ± 0.002</td>
<td>0.45</td>
<td>0.025</td>
<td>gcn50:82</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th></th>
<th>2N force</th>
<th>3N force</th>
<th>4N force</th>
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<td><img src="image11.png" alt="Diagram" /></td>
<td><img src="image12.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

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

Park et al.
Short-range couplings fit to experiment once
2b currents in light nuclei

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

$^3$H $\beta$ decay
Gazit, Quaglioni, Navrátil
PRL103 102502(2009)

$A \leq 9$ magnetic moments
$^8$Be EM transitions

$^3$H $\mu$ capture
Gazit PLB666 472(2008)
Marcucci et al. PRC83 014002(2011)

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

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 $\beta$ 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

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?

Yao et al. PRC91 024316 (2015)

See talk by Y. Iwata on Wed. 3
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 $^{48}\text{Ca}$

Shell model very well tested in $pf$ shell
Spin-orbit partners included
(Ikeda Sum Rule, isoscalar pairing correlations)
Deformed nuclei well described (eg. $^{48}\text{Cr}$)
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:

$$M^{0\nu\beta\beta} = \sum J_{\pi} P_{J_{\pi}}^+ \hat{P}_J$$

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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

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:

$$M_{GT}^{0\nu\beta\beta} \sim \alpha_\pi \alpha_\nu \sqrt{N_\pi + 1} \sqrt{\Omega_\pi - N_\pi} \sqrt{N_\nu \sqrt{\Omega_\nu - N_\nu} + 1},$$

Barea, Iachello PRC79 044301(2009)
Seniority evolution of nuclear matrix elements

Agreement in $M^{0\nu\beta\beta}_{GT}$ between shell model and Energy Density Functional disappears when correlations are included in initial 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 ($\sim 1/r$), $M^0_{F\beta\beta}$ 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 $J, \pi$
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 strength 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

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

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 $^{76}\text{Ge}$, $^{82}\text{Se}$, $^{124}\text{Sn}$, $^{130}\text{Te}$, $^{136}\text{Xe}$ decays, missing spin-orbit partners (incomplete valence space)

Two different estimations:

- Subtract isoscalar pairing interaction to shell model interaction assuming same strength 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
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 $\sim 2$
- 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