Towards reliable nuclear matrix elements for neutrinoless $\beta\beta$ decay

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Nuclear physics and neutrinoless $\beta\beta$ decay

Neutrinos, dark matter studied in experiments using nuclei

Nuclear matrix elements depend on nuclear structure crucial to anticipate reach and fully exploit experiments

$0\nu\beta\beta$ decay: \( \left( T^{0\nu\beta\beta}_{1/2} \right)^{-1} \propto \left| M^{0\nu\beta\beta} \right|^2 m^2_{\beta\beta} \)

Dark matter: \( \frac{d\sigma_{\chi N}}{dq^2} \propto \left| \sum_i c_i \zeta_i F_i \right|^2 \)

$M^{0\nu\beta\beta}$: Nuclear matrix element

$F_i$: Nuclear structure factor
Neutrinoless $\beta\beta$ decay

Lepton-number violation, Majorana nature of neutrinos
Second order process only observable in rare cases with $\beta$-decay energetically forbidden or hindered by $\Delta J$

Present best limits $T_{1/2}^{0\nu\beta\beta} \gtrsim 10^{25}$ y:

$^{76}$Ge (GERDA, Majorana), $^{130}$Te (CUORE), $^{136}$Xe (EXO, KamLAND-Zen)
Signature of neutrinoless $\beta\beta$ decay

Very different signatures for neutrinoless and two-neutrino $\beta\beta$ decays

$$2\nu\beta\beta : \quad E_{e_1} + E_{e_2} + E_{\bar{\nu}_1} + E_{\bar{\nu}_2} = Q_{\beta\beta}$$

$$0\nu\beta\beta : \quad E_{e_1} + E_{e_2} = Q_{\beta\beta}$$

because only the electrons are detected in experiments

KamLAND-Zen, PRL110 062502 (2013)
Next generation experiments: inverted hierarchy

The decay lifetime is

\[ T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+) = G_{01} |M_{0\nu\beta\beta}|^2 m_{\beta\beta}^2 \]

sensitive to absolute neutrino masses, \( m_{\beta\beta} = |\sum U_{ek}^2 m_k| \), and hierarchy

Matrix elements needed to make sure next generation ton-scale experiments fully explore "inverted hierarchy"
Outline

Present status of $0\nu\beta\beta$ decay nuclear matrix elements

Future prospects for $0\nu\beta\beta$ nuclear matrix element calculations

How can other nuclear experiments help $0\nu\beta\beta$ decay studies?
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Calculating nuclear matrix elements

Nuclear matrix elements needed to study fundamental symmetries

\[ \langle \text{Final} | \mathcal{L}_{\text{leptons-nucleons}} | \text{Initial} \rangle = \langle \text{Final} | \int dx \, j^\mu(x) J_\mu(x) | \text{Initial} \rangle \]

- **Nuclear structure calculation of the initial and final states:**
  - Shell model Retamosa, Poves, JM, Horoi...
  - Energy-density functional Rodríguez, Yao...
  - QRPA Vogel, Faessler, Šimkovic, Suhonen...
  - Interacting boson model Iachello, Barea...
  - Ab initio many-body methods
    - Green’s Function MC, Coupled-cluster, IM-SRG...

- **Lepton-nucleus interaction:**
  - Study hadronic current in nucleus:
    - phenomenological approaches,
    - effective theory of QCD
0νββ nuclear matrix elements: last 5 years

Comparison of nuclear matrix element calculations: 2012 vs 2017

What have we learned in the last 5 years?
Configuration space

Nuclear shell model configuration space only keep essential degrees of freedom

- High-energy orbits: always empty
- Configuration space: where many-body problem is solved
- Inert core: always filled

\[
H \left| \psi \right\rangle = E \left| \psi \right\rangle \rightarrow H_{\text{eff}} \left| \psi \right\rangle_{\text{eff}} = E \left| \psi \right\rangle_{\text{eff}} \\
\left| \psi \right\rangle_{\text{eff}} = \sum_{\alpha} c_{\alpha} \left| \phi_{\alpha} \right\rangle, \quad \left| \phi_{\alpha} \right\rangle = a_{1}^{+}a_{2}^{+}\ldots a_{A}^{+} \left| 0 \right\rangle
\]

Shell model codes (1 major oscillator shell) \sim 10^{10} Slater dets. Caurier et al. RMP77 (2005)

QRPA calculations suggest larger spaces (\gtrsim 2 major shells) needed

\[
\text{Dimension} \sim \binom{p+1}{N}(p+2)_{\nu}\binom{p+1}{Z}(p+2)_{\pi}
\]
Shell model configuration space: two shells

For $^{48}\text{Ca}$ enlarge configuration space from $pf$ to $sdpf$

4 to 7 orbitals, dimension $10^5$ to $10^9$

increases matrix elements but only moderately 30%

Iwata et al. PRL116 112502 (2016)

Contributions dominated by pairing 2 particle – 2 hole excitations enhance the $\beta\beta$ matrix element,

Contributions dominated by 1 particle – 1 hole excitations suppress the $\beta\beta$ matrix element
76Ge matrix element in two shells: approximate

Large configuration space calculations in 2 major oscillator shells
Include all relevant correlations: isovector/isoscalar pairing, deformation
Many-body approach: generating coordinate method (GCM)

GCM approximates
shell model calculation

Degrees of freedom, or generating coordinates, validated against
exact shell model in small configuration space

Jiao et al. PRC96 054310 (2017)

76Ge nuclear matrix element in 2 major shells
very similar to shell model nuclear matrix element in 1 major shell
$^{76}$Ge matrix element in two shells: exact

Dimension of the shell-model many-body Hilbert space

From T. Otsuka, INT-18-1a program
76Ge matrix element in two shells: exact

0νββ decay Nuclear Matrix Element
by Monte Carlo shell model (MCSM)

76Ge ⇒ 76Se

MCSM:
wave function composed of
a superposition of
selected optimal
Slater determinants
with projection onto J and P

Benchmark

f5pg9 shell,
JUN45 int.
(Honma 2009)

Expectation value of
energy variance
(measure of approximation)

From T. Otsuka, INT-18-1a program
$^{76}$Ge matrix element in two shells: exact

$^{0\nu\beta\beta}$ decay Nuclear Matrix Element by the Monte Carlo shell model

$^{76}$Ge $\rightarrow ^{76}$Se

pf-shell $+$ $0g9/2$ $+$ $1d5/2$
A3DA-m int.

The exact value by the conventional shell model calculation cannot be obtained due to the prohibitively large dimension of the Hamiltonian matrix.

c.a. $3.17 \times 10^{17}$ dim.
against current limit $10^{10}$ dim.
in progress

From T. Otsuka, INT-18-1a program
Heavy-neutrino exchange nuclear matrix elements

Contrary to light-neutrino-exchange, for heavy-neutrino-exchange decay shell model, IBM, and EDF matrix elements agree reasonably!

Suggests differences in treating longer-range nuclear correlations dominant in light-neutrino exchange
Heavy-neutrino matrix element

Compared to light-neutrino exchange

heavy neutrino exchange dominated by shorter internucleon range, larger momentum transfers

heavy neutrino exchange contribution from $J > 0$ pairs smaller: pairing most relevant

⇒

Long-range correlations (except pairing) not under control

JM, JPG 45 014003 (2018)
Pairing correlations and $0^{\nu}\beta\beta$ decay

$0^{\nu}\beta\beta$ decay favoured by proton-proton, neutron-neutron pairing, but it is disfavored by proton-neutron pairing.

Ideal case: superfluid nuclei reduced with high-seniorities

Addition of isoscalar pairing reduces matrix element value

Related to approximate $SU(4)$ symmetry of the $\sum H(r)\sigma_i\sigma_j\tau_i\tau_j$ operator
IBM matrix elements with proton-neutron pairing

Energy-density functional (EDF) theory and interacting boson model (IBM) calculated nuclear matrix elements do not include explicitly proton-neutron pairing correlations. This effect (partially) accounted for by other degrees of freedom present in these approaches. Include \( p \)-boson \((L = 1)\) to IBM in addition to \( s \) and \( d \) bosons \((L = 0, 2)\).

First IBM results in calcium region suggest nuclear matrix elements could be somewhat reduced.

van Isacker et al. PRC96 064505 (2018)
Matrix elements: theoretical uncertainty

Systematic uncertainty hard to estimate for phenomenological matrix elements

Effective theory for $\beta\beta$ decay: spherical core coupled to one nucleon

Couplings adjusted to experimental data, uncertainty given by effective theory (breakdown scale, systematic expansion)

Take $\beta$ decay data to predict $2\nu\beta\beta$

$$M^{2\nu\beta\beta} = \sum_k \frac{\langle 0^+_f | \sum_n \sigma_n \tau_n^- | 1^+_k \rangle \langle 1^+_k | \sum_m \sigma_m \tau_m^- | 0^+_i \rangle}{E_k - (M_i + M_f)/2}$$

Good agreement with large errors (leading-order calculations)

Coello-Pérez, JM, Schwenk, arXiv:1708.06140
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How can other nuclear experiments help $0\nu\beta\beta$ decay studies?
Ab initio methods: No core shell model

No core shell model

Many-body wave function
linear combination of
Slater Determinants
from single particle states in the basis
(3D harmonic oscillator)

\[ |i\rangle = |n_i l_i j_i m_i m_t_i\rangle \]
\[ |\phi_\alpha\rangle = a_{i_1}^+ a_{j_2}^+ \cdots a_{kA}^+ |0\rangle \]
\[ |\psi\rangle = \sum_\alpha c_\alpha |\phi_\alpha\rangle \]
\[ H |\psi\rangle = E |\psi\rangle \]

Dimensions increase combinatorially...
Green’s function Monte Carlo

Pieper, Wiringa, Carlson...

NN forces do not reproduce binding energies and spectra: need 3N forces

Good agreement with 3N forces
Coupled Cluster, In-Medium SRG

Coupled Cluster method: operators (correlations) acting on reference impose no particle-hole excitations present in the reference state
Hagen, Papenbrock, Hjorth-Jensen...

\[ |\psi\rangle = e^{-\left(T_1 + T_2 + T_3 \cdots\right)} |\Phi\rangle \]

with \[ T_1 = \sum_{\alpha, \bar{\alpha}} t_{\alpha} \{ a_{\alpha}^{\dagger}, a_{\alpha} \} , \quad T_2 = \sum_{\alpha\beta, \bar{\alpha}\bar{\beta}} t_{\alpha\beta} \{ a_{\alpha}^{\dagger} a_{\beta}^{\dagger}, a_{\alpha} a_{\beta} \} , \cdots \]

solve \[ \langle \Phi_{\alpha}^{\bar{\alpha}} | e^{\sum T_i H_e - \sum T_i} | \Phi \rangle = 0 \], \[ \langle \Phi_{\alpha\beta}^{\bar{\alpha}\bar{\beta}} | e^{\sum T_i H_e - \sum T_i} | \Phi \rangle = 0 \]

In-medium similarity renormalization group method: apply a similarity (unitary) transformation to decouple reference state from particle-hole excitations
Bogner, Schwenk, Hergert, Stroberg...
Ab initio many-body methods

Oxygen dripline using chiral NN+3N forces correctly reproduced ab-initio calculations treating explicitly all nucleons. Excellent agreement between different approaches.

No-core shell model (Importance-truncated)
In-medium SRG
Hergert et al. PRL110 242501(2013)
Self-consistent Green’s function
Cipollone et al. PRL111 062501(2013)
Coupled-clusters
Jansen et al. PRL113 142502(2014)
Calcium isotopes with NN+3N forces

Calculations with NN+3N forces predict shell closures at $^{52}\text{Ca}$, $^{54}\text{Ca}$

$^{51-54}\text{Ca}$ masses [TRIUMF/ISOLDE]
$^{54}\text{Ca}$ $2^+_1$ excitation energy [RIBF, RIKEN]

Hebeler et al. ARNPS 65 457 (2015)
Chiral effective field theory

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

Approximate chiral symmetry: pion exchanges, 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="image12" alt="Diagram" /></td>
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Park, Baroni, Krebs...

2b currents applied to $\nu d$ scattering (SNO), $^3H \beta$-decay, $\mu$ moment...

Weinberg, van Kolck, Kaplan, Savage, Epelbaum, Kaiser, Meißner...
Gamow-Teller transitions: quenching

Single $\beta$ decays well described by nuclear structure (shell model)

\[ \langle F | \sum_i g_A^{\text{eff}} \sigma_i \bar{\tau}_i^- | I \rangle \]

\[ g_A^{\text{eff}} = q g_A, \quad q \sim 0.7 - 0.8. \]

Theory needs to “quench“ Gamow-Teller operator to reproduce Gamow-Teller lifetimes: problem in nuclear many-body wf or operator?

This puzzle has been the target of many theoretical efforts:

Arima, Rho, Towner, Bertsch and Hamamoto, Wildenthal and Brown...
2b currents in medium-mass nuclei

Normal-ordered 2b currents modify GT operator
JM, Gazit, Schwenk PRL107 062501 (2011)

\[ J_{n,2b}^{\text{eff}} \simeq - \frac{g_A \rho}{f_\pi^2} \tau_n^- \sigma_n \left[ l(\rho, P) \left( \frac{2c_4 - c_3}{3} \right) \right] - \frac{g_A \rho}{f_\pi^2} \tau_n^- \sigma_n \frac{2}{3} c_3 \frac{p^2}{m_\pi^2 + p^2}, \]

2b currents predict \( g_A \) quenching \( q = 0.85...0.66 \)
Quenching reduced at \( p > 0 \), relevant for \( 0\nu\beta\beta \) decay where \( p \sim m_\pi \)
β decay in very light nuclei: GFMC

Ab initio Green Function Monte Carlo β decay matrix elements in $A \leq 10$
Pastore et al. PRC97 022501 (2018)

Very good agreement to experiment in all cases except for $^{10}\text{C}$, very sensitive to nuclear structure details
Impact of 2b currents small (few %) enhancement of matrix elements
\[ \beta \text{ decay in very light nuclei: NCSM} \]

**Theory to experiment ratios for beta decays in light nuclei from NCSM**

**NNLO\textsubscript{sat}(c_D = 0.82)**

\[
\begin{align*}
3\text{H}_{\frac{1}{2}} & \to 3\text{He}_{\frac{1}{2}} \\
6\text{He}_0 & \to 6\text{Li}_1 \\
7\text{Be}_{\frac{3}{2}} & \to 7\text{Li}_{\frac{1}{2}} \\
7\text{Be}_{\frac{3}{2}} & \to 7\text{Li}_{\frac{3}{2}} \\
10\text{C}_0 & \to 10\text{B}_1 \\
14\text{O}_0 & \to 14\text{N}_1
\end{align*}
\]

From G. Hagen, INT-18-1a program
β decay in medium-mass nuclei: IMSRG

VS-IMSRG calculations of GT transitions in sd, pf shells

Minor effect from consistent effective operator

Significant effect from neglected 2-body currents

Ab initio calculations explain data with unquenched $g_A$

From J. Holt, INT-18-1a program
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
$\sim 20\% - 50\%$

Improved, ideally ab initio calculations are needed!
0$\nu\beta\beta$ decay matrix elements in very light nuclei

Variational Monte Carlo 0$\nu\beta\beta$ decay matrix elements in $A \leq 12$
Pastore et al. PRC97 014606 (2018)

Larger/smaller matrix elements given by same/different nuclear isospin
Anchor for other ab initio approaches that can extend to heavier nuclei
Outline

Present status of $0\nu\beta\beta$ decay nuclear matrix elements

Future prospects for $0\nu\beta\beta$ nuclear matrix element calculations

How can other nuclear experiments help $0\nu\beta\beta$ decay studies?
Tests of nuclear structure

Spectroscopy well described: masses, spectra, transitions, knockout...

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Schiffer et al. PRL100 112501 (2009)
Kay et al. PRC79 021301 (2009)
...
Szwec et al., PRC94 054314 (2016)

Rodríguez et al. PRL105 252503 (2010)
...
Vietze et al. PRD91 043520 (2015)
Two-neutrino $\beta\beta$ decay

Test of $0\nu\beta\beta$ decay: comparison of predicted $2\nu\beta\beta$ decay vs data

Shell model reproduce $2\nu\beta\beta$ data including "quenching" common to $\beta$ decays in same mass region

Shell model prediction previous to $^{48}\text{Ca}$ measurement!

<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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</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$</td>
<td>0.047 $\pm$ 0.003</td>
<td>0.74</td>
<td>0.047</td>
<td>kb3</td>
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<td>0.74</td>
<td>0.065</td>
<td>gwpf1</td>
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<tr>
<td>$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$</td>
<td>0.140 $\pm$ 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 $\pm$ 0.005</td>
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<td>jun45</td>
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<tr>
<td>$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$</td>
<td>0.098 $\pm$ 0.004</td>
<td>0.60</td>
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<tr>
<td>$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$</td>
<td>0.098 $\pm$ 0.004</td>
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<tr>
<td>$^{128}\text{Te} \rightarrow ^{128}\text{Xe}$</td>
<td>0.049 $\pm$ 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>
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<tr>
<td>$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$</td>
<td>0.019 $\pm$ 0.002</td>
<td>0.45</td>
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</tbody>
</table>

Caurier, Nowacki, Poves PLB711 62(2012)

$$M^{2\nu\beta\beta} = \sum_k \frac{\langle 0^+_f | \sum_n \sigma_n \tau_n^- | 1^+_k \rangle \langle 1^+_k | \sum_m \sigma_m \tau_m^- | 0^+_i \rangle}{E_k - (M_i + M_f)/2}$$
Muon-capture, neutrino-nucleus scattering (to low-energy states) probe similar momentum transfers than $0\nu\beta\beta$ decay

Several multipolarities ($J$ values) contribute, like in $0\nu\beta\beta$ decay
Gamow-Teller strength distributions

Gamow-Teller (GT) distributions well described by theory (quenched)

Freckers et al.
NPA916 219 (2013)

Iwata et al. JPSCP 6 03057 (2015)

\[ \langle 1_f^+ | \sum_i [\sigma_i \tau_i^{\pm}]_{\text{eff}} | 0_{\text{gs}}^+ \rangle, \quad [\sigma_i \tau_i^{\pm}]_{\text{eff}} \approx 0.7 \sigma_i \tau_i^{\pm} \]

\[ M_{2\nu\beta\beta} = \sum_k \frac{\langle 0_f^+ | \sum_n \sigma_n \tau_n^- | 1_k^+ \rangle \langle 1_k^+ | \sum_m \sigma_m \tau_m^- | 0_i^+ \rangle}{E_k - (M_i + M_f)/2} \]
Double Gamow-Teller strength distribution

Measurement of Double Gamow-Teller (DGT) resonance in double charge-exchange reactions $^{48}\text{Ca}(pp,nn)^{48}\text{Ti}$ proposed in 80’s
Auerbach, Muto, Vogel... 1980’s, 90’s

Recent experimental plans in RCNP, RIKEN ($^{48}\text{Ca}$), INFN Catania

Promising connection to $\beta\beta$ decay, two-particle-exchange process, especially the (tiny) transition to ground state of final state

Two-nucleon transfers related to $0\nu\beta\beta$ decay matrix elements
Brown et al. PRL113 262501 (2014)
$^{48}$Ca Double Gamow-Teller distribution

Calculate with shell model $^{48}$Ca $0^+_{gs}$ Double Gamow-Teller distribution

$$B(DGT^-; \lambda; i \rightarrow f) = \frac{1}{2J_i + 1} \left| \left\langle ^{48}\text{Ti} \left| \sum_i \sigma_i \tau_i^- \times \sum_j \sigma_j \tau_j^- \right\rangle^{(\lambda)} \left| ^{48}\text{Ca}_{gs} \right\rangle \right|^2$$

Shell model calculation with Lanczos strength function method

Double GT resonances in one and two shells rather similar result

Shimizu, JM, Yako, PRL accepted
48\text{Ca} double GT resonance and 0$\nu\beta\beta$ decay

Correlation between Double Gamow-Teller resonance in 48\text{Ca} and 0$\nu\beta\beta$ decay nuclear matrix element

Energy of DGT resonance with accuracy to $\sim$1MeV, can give insight on the value of 0$\nu\beta\beta$ decay matrix element

$$E_{av} = \frac{\sum_i E_i B(DGT^-, i \to f)}{\sum_i B(DGT^-, i \to f)}$$

Might be feasible in near future at LNS Catania or RIBF RIKEN

Uesaka, Takaki, Cappuzzello, Ejiri...

Shimizu, JM, Yako, PRL accepted
Double Gamow-Teller and $0\nu\beta\beta$ decay

DGT transition to ground state

$$M^{\text{DGT}} = \langle F_{gs} | \left[ \sum_i \sigma_i \tau_i^- \times \sum_j \sigma_j \tau_j^- \right]^0 | I_{gs} \rangle^2$$

very good linear correlation with $0\nu\beta\beta$ decay nuclear matrix elements

Correlation holds across wide range of nuclei, from Ca to Ge and Xe

Common to shell model and energy-density functional theory

$0 \lesssim M^{0\nu\beta\beta} \lesssim 5$

disagreement to QRPA

Shimizu, JM, Yako, PRL accepted
Short-range character of DGT, $0\nu\beta\beta$ decay

Correlation between DGT and $0\nu\beta\beta$ decay matrix elements explained by transition involving low-energy states combined with dominance of short distances between exchanged/decaying neutrons

Bogner et al. PRC86 064304 (2012)

$0\nu\beta\beta$ decay matrix element limited to shorter range

Short-range part dominant in double GT matrix element due to partial cancellation of mid- and long-range parts

Long-range part dominant in QRPA DGT matrix elements

Shimizu, JM, Yako, PRL accepted
Summary

Reliable nuclear matrix elements needed to plan and fully exploit impressive experiments looking for neutrinoless double-beta decay

- Matrix element differences between present calculations, factor 2 – 3 besides additional "quenching"?
- $^{48}\text{Ca}$ and $^{76}\text{Ge}$ matrix elements in large configuration space increase $\lesssim 30\%$, missing correlations introduced in IBM, EDF
- First ab initio calculations of $\beta$ decays do not need additional "quenching", stay tuned for ab initio $^{48}\text{Ca}$ matrix elements
- $2\nu\beta\beta$ decay, $\mu$-capture/$\nu$-nucleus scattering and double Gamow-Teller transitions can give insight on $0\nu\beta\beta$ matrix elements
Collaborators

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