Nuclear matrix elements for neutrinoless double beta decay: multi-reference covariant DFT

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Outline

1 Introduction: status of studying $0\nu\beta\beta$ decay

2 Framework: multi-reference covariant density functional theory

3 Results and discussions
   - Structural properties of $0\nu\beta\beta$ decay candidate nuclei
   - Nuclear matrix elements for $0\nu\beta\beta$ decay

4 Summary and outlook
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Neutrinoless double beta decay

- Neutrinoless double beta decay $(0\nu\beta\beta)$:
  \[ A^Z X \rightarrow A^{Z+2} Y + 2e^- \]  
  \[ (1) \]
  \( \rightarrow \) one of the current main goals in nuclear and particle physics.

- The half-life of $0\nu\beta\beta$-decay (mechanism of exchange light Majorana neutrinos):
  \[ \left[ T_{1/2}^{0\nu} \right]^{-1} = G_{0\nu} g_A^4 \left| \langle m_{\beta\beta} \rangle / m_e \right|^2 \left| M^{0\nu} (0^+_I \rightarrow 0^+_F) \right|^2, \]
  \[ (2) \]
  $g_A$: axial coupl. constant; $m_e$: electron mass.
  - phase space factor $G_{0\nu}$ depending on both $Q_{\beta\beta}$ and $Z \leftarrow$ atomic physics
  - nuclear matrix element (NME) $M^{0\nu}$: $\leftarrow$ nuclear physics
  - effective neutrino mass $\langle m_{\beta\beta} \rangle$: $\leftarrow$ particle physics
  \( \rightarrow \) providing the direction information on effective neutrino mass $\langle m_{\beta\beta} \rangle$. 

Neutrinoless double beta decay
\(0\nu\beta\beta\)-decay: a key to solve the problem of mass hierarchy

- The measurements of neutrino oscillations (\(\nu_{\ell 1} \leftrightarrow \nu_{\ell 2}\)): providing the differences between the squares of the masses (\(\Delta m^2_{ij}\)) among three neutrino species (but not for the masses themselves).


\[
(m^2_1, m^2_2, m^2_3) = \frac{m^2_1 + m^2_2}{2} + \left\{ \begin{array}{c}
-(\delta m^2)_\text{sol}/2, \\
+(\delta m^2)_\text{sol}/2, \\
\pm(\Delta m^2)_\text{atm},
\end{array} \right. 
\]

(3)

Differences between the squares of the masses:

\((\delta m^2)_\text{sol} = 7.59^{+0.20}_{-0.18} \times 10^{-5} \text{ eV}^2\),
\((\Delta m^2)_\text{atm} = 2.40^{+0.08}_{-0.09} \times 10^{-3} \text{ eV}^2\).

Remaining problem of mass hierarchy:

- Normal mass hierarchy (NH) (+):
  \(m_1 < m_2 \ll m_3, \langle m_{\beta\beta} \rangle \sim 5 \text{ meV}\)

- Inverted mass hierarchy (IH) (−):
  \(m_3 \ll m_1 < m_2, \langle m_{\beta\beta} \rangle \sim 20 - 50 \text{ meV}\)

Measurements of $0\nu\beta\beta$ decay

**Heidelberg-Moscow claim ($^{76}$Ge)**

$$T_{1/2}^{0\nu} = 2.23^{+0.44}_{-0.31} \times 10^{25} \text{ yr} \Rightarrow \langle m_{\beta\beta} \rangle \sim 0.32 \text{ eV}$$


In confliction with:

1. total mass of neutrinos from the cosmology observations
2. latest measurements on the the $0\nu\beta\beta$ decay

**Cosmology constraint**

Neutrino contribution to the mass density of the Universe $\Omega_\nu$:

$$\Omega_\nu h^2 = \sum_{i=1}^{3} m_i/(92.5 \text{ eV}). \Rightarrow \sum_{i=1}^{3} m_i < 0.58 \text{ eV (95% C.L.)}$$


**Latest data about $T_{1/2}^{0\nu}$ with 90% C.L.**

$^{136}$Xe ($> 1.6 \times 10^{25}$ yr): M. Auger et al. (EXO Coll.), PRL109, 032505 (2012).

$^{136}$Xe ($> 3.4 \times 10^{25}$ yr): A. Gando et al. (KamLAND-Zen Coll.), PRL110, 062502 (2013).

$^{76}$Ge ($> 3.0 \times 10^{25}$ yr): M. Agostini et al. (GERDA Coll.), PRL111, 122503 (2013).
Status of computing the NMEs for $0\nu\beta\beta$ decay

- Great effort has been made to calculate the NME.
- Two key ingredients for computing the NME $M^{0\nu} = \langle 0^+_F | \hat{O}^{0\nu} | 0^+_I \rangle$.

1. Transition operator: Non-relativistic reduced transition operator is often used

$$\hat{O}^{0\nu} = [\hat{O}^{0\nu}_{GT} \sigma_1 \cdot \sigma_2 - (\frac{g_V}{g_A})^2 \hat{O}^{0\nu}_F + \hat{O}^{0\nu}_T S_{12}] \tau_1^- \tau_2^-, \quad \tau^- | n \rangle = | p \rangle$$

with $S_{12} = 3(\sigma_1 \cdot q_1)(\sigma_2 \cdot q_2) - \sigma_1 \cdot \sigma_2$.

- Correlation effects (for light neutrino): high-order currents (HOC), finite-nucleon-size (FNS) corrections, and radial short-range correlations (SRC).

2. Wavefunctions of the initial and final nuclei:

- (R)QRPA (Tübingen, Jyuaskyla, North Carolina)
- ISM (Strasbourg-Madrid, MSU, etc)
- IBM-2 (Yale)
- PHFB: 1DAMP+(PP+QQ) (Lucknow-UNAM)
- NREDF: GCM+PN1DAMP+D1S (GSI-Madrid)

The closure approximation is usually adopted.

$\rightarrow$ The results are different by a factor of 2 – 3.
Purpose of this work

The purpose of this work is to provide a systematic calculation of the NMEs for $0\nu\beta\beta$ based on the beyond mean-field covariant density functional theory (CDFT).

Key points in the present study

- The full relativistic transition operator ($\checkmark$)
- The tensor terms. ($\checkmark$) ($\sim 5\%$ error), J. Barea and F. Iachello, PRC79, 044301 (2009)
- The high-order-current (HOC) terms. ($\checkmark$) ($\sim 25\%$ reduction), F. Simkovic et al., PRC60, 055502 (1999)
- The finite-nucleon-size (FNS) corrections. ($\checkmark$) ($\sim 20\%$ reduction)
- The short-range-correlation (SRC) effect. ($\times$) ($\sim 5\%$ reduction once the FNS has been taken into account), F. Simkovic et al., PRC79, 055501 (2009)
- Without the closure approximation. ($\times$) (5% – 10% error)
- The effects of static and dynamical quadrupole deformation and particle-number conservation. ($\checkmark$), change significantly the NMEs.

$$\Rightarrow$$ The error/uncertainty in the NMEs: within 15%
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The Covariant DFT is developed based on the concept of DFT and Walecka model, in which the nucleons interact effectively via the exchange of effective mesons or contact coupling.

- **Finite-range meson-exchange**
  - scalar and vector couplings (saturation)
  - nonlinear couplings (compressibility) or Density-Dependent coupling
  - derivatives (finite range)
  - isovector channel (isospin characters)
  - electromagnetic interaction

- **Zero-range point-coupling**
  - $\alpha_s$
  - $\alpha_v$
  - $\alpha_{TV}$

Boguta & Bodmer, NPA 292, 413 (1977)
Brockmann & Toki, PRL 68, 3408 (1992)
Manakos & Mannel, ZPA 334, 481 (1989)
Serot, PIB 86, 146 (1979)
**Covariant density functional theory: point-coupling**

**Lagrangian density and EDF in the RMF–PC model**

\[
\mathcal{L} = \mathcal{L}^{\text{free}} + \mathcal{L}^{4f} + \mathcal{L}^{\text{hot}} + \mathcal{L}^{\text{der}} + \mathcal{L}^{\text{em}}
\]

\[
= \bar{\psi} (i \gamma \mu \partial^\mu - m) \psi
\]

\[
- \frac{1}{2} \alpha S (\bar{\psi} \gamma \mu \psi) \partial^\mu - \frac{1}{2} \alpha V (\bar{\psi} \gamma \mu \psi) (\bar{\psi} \gamma^\mu \psi)
\]

\[
- \frac{1}{2} \alpha T S (\bar{\psi} \gamma \mu \psi) (\bar{\psi} \gamma^\mu \psi) - \frac{1}{2} \alpha T V (\bar{\psi} \gamma \mu \psi) (\bar{\psi} \gamma^\mu \psi)
\]

\[
- \frac{1}{2} \frac{1}{2} \beta S \bar{\psi} (\bar{\psi} \gamma \mu \psi) \partial^\mu - \frac{1}{4} \gamma S (\bar{\psi} \gamma \mu \psi) \partial^\mu - \frac{1}{4} \gamma V [ (\bar{\psi} \gamma \mu \psi) (\bar{\psi} \gamma^\mu \psi)]
\]

**EDF for ph-channel:**

\[
E_{\text{RMF}} [\rho_s, \nabla \rho_s, j_{\mu}^p, \nabla j_{\mu}^p]
\]

\[
= \text{Tr} [(\alpha \cdot p + \beta m) \rho_s] + \int \mathcal{d}r \left( \frac{\alpha}{2} \rho_s^2 + \frac{\beta}{3} \rho_s^3 + \frac{\gamma}{4} \rho_s^4 + \frac{\delta}{2} \rho_s \nabla \rho_s \rho_s^4 \right)
\]

\[
+ \frac{\alpha}{2} j_{\mu}^p j_{\mu}^p + \frac{\gamma}{4} (j_{\mu}^p j_{\mu}^p)^2 + \frac{\delta}{2} j_{\mu}^p \Delta j_{\mu}^p
\]

\[
+ \frac{\alpha T V}{4} j_{\mu}^p (j T V)_{\mu} + \frac{\delta T V}{4} j_{\mu}^p \Delta (j T V)_{\mu}
\]

\[
+ \frac{1}{4} F_{\mu \nu} F^{\mu \nu} - F_{\mu \nu} \delta_{\mu 0} A_{\nu} + e \frac{1 - \tau_3}{2} j_{\mu} A_{\mu}
\]

**EDF for pp-channel:**

\[
E_{\text{pair}} = \frac{V_{pp}}{4} \int \mathcal{d}r \kappa_{\bar{i}}^*(r) \kappa_{\bar{i}} (r)
\]

**Parameters:** coupling strengths $\alpha, \beta, \gamma, \delta$ are fitted to the properties of some atomic nuclei (and nuclear matter).
Symmetry breaking in density functional theory

Deformed solutions in DFT calc.

Wave function \[ | q \rangle = \sum_{JK} C_{JK}^J | JK \rangle \]

Superfluidity (BCS) state:

\[ | \text{BCS} \rangle = \prod_k \left[ u_k + v_k a_k^+ a_k^+ \right] | 0 \rangle = \sum_{N,Z} C_{N,Z} | N, Z \rangle \]

Summary and outlook

\[ W_{\text{F}}: \]
e-e nuclei: quasi-particle vacuum
Quantum fluctuation in nuclear shapes

Quantify the mixing of different shapes with generator coordinate method (GCM)

Wavefunction: \[ | \text{GCM} \rangle = \sum_q f(q) | q \rangle \]

\[ g(q) = \sum_q N^{1/2}(q, q') f(q') \]

HWG equation

D. L. Hill and J. A. Wheeler, Phys. Rev. 89, 1102 (1953)
Implementation of projections and GCM: MR-CDFT

\[ |JNZ; \alpha \rangle = \sum_{q,K} f^{JK}_\alpha (q) \hat{P}^J_{MK} \hat{P}^N \hat{P}^Z |q\rangle, \]

- \( \alpha \) distinguishes the states with the same angular momentum \( J \)
- \(|q\rangle\) is a set of Slater determinants from the constrained CDFT calc.
- \( P^J \) and \( P^N \) are projection operators onto \( J \) and \( N \).
- \( K=0 \) if axial symm. is assumed.

Variation of energy with respect to the weight function \( f(q) \) leads to the Hill-Wheeler-Griffin (HWG) integral equation:

\[ \sum_{K',q'} \left[ \mathcal{H}_{KK'}^J (q, q') - E_{\alpha}^J \mathcal{N}_{KK'}^J (q, q') \right] f^{JK'}_\alpha (q') = 0, \]

Definition of kernels:

\[ \mathcal{O}^{J}_{KK'} (q; q') = \frac{2J + 1}{8\pi^2} \int d\Omega D^{J*}_{KK'} (\Omega) \langle q | \hat{O} \hat{R} (\Omega) \hat{P}^N \hat{P}^Z | q' \rangle. \]
MR-CDFT calculation of the NMEs

In our MR-CDFT calculation, the NME is calculated as follows

\[
M^{0\nu} = \frac{4\pi R}{g_A^2(0)} \int d^3x_1 \int d^3x_2 \int \frac{d^3q}{(2\pi)^3} \frac{e^{iq \cdot (x_1 - x_2)}}{q(q + E_d)} \times \langle 0^+_F | \mathcal{J}_{L,\mu}^+(x_1) \mathcal{J}_{L}^{\mu+}(x_2) | 0^+_I \rangle,
\]

where \( \mathcal{J}_{L,\mu}(x) = \bar{\psi}_p(x) \tau^- \left[ g_V(q^2) \gamma_\mu - g_A(q^2) \gamma_\mu \gamma_5 - ig_M(q^2) \frac{\sigma_{\mu\nu}}{2m_p} q^\nu + g_P(q^2) q_\mu \gamma_5 \right] \psi_\rho(x) \).

### Results and discussions

**Structural properties of 0\nuββ decay candidate nuclei**

**Nuclear matrix elements for 0\nuββ decay**

**Summary and outlook**

- The wave functions for the ground states are from the MR-CDFT calculations.


**Framework**: multireference covariant density functional theory

**Introduction**: status of studying 0\nuββ decay
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Structural properties of $0\nu\beta\beta$ decay candidate nuclei

- Exp. data are reproduced reasonable well for most candidate nuclei, except for $^{96}$Zr, which is dominated by p-h ex. at low E.
- The Q value of DBD is improved after taking into account the DCE.
Structural properties of $0\nu\beta\beta$ decay candidate nuclei

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Nuclear matrix elements for $0\nu\beta\beta$ decay: spherical case

Normalized NME $\tilde{M}^{0\nu}(\beta_I, \beta_F)$ for the $0\nu\beta\beta$-decay:

$$\tilde{M}^{0\nu}(\beta_I, \beta_F) = N_F N_I \langle \beta_F | \hat{O}^{0\nu} \hat{P}^{J=0} \hat{P}^N \hat{P}^Z | \beta_I \rangle,$$

with $N_a^{-2} = \langle \beta_a | \hat{P}^{J=0} \hat{P}^N \hat{P}^Z | \beta_a \rangle$ for $a = I, F$.

**Table:** The normalized NME $\tilde{M}^{0\nu}$ at $\beta_I = \beta_F = 0$ using both the relativistic and non-relativistic transition operators. The ratio $R_{AA}$ of the $AA$ term to the total NME $R_{AA} \equiv \tilde{M}^{0\nu}_{AA}/\tilde{M}^{0\nu}$, the relativistic effect $\Delta_{\text{Rel.}} \equiv (\tilde{M}^{0\nu} - \tilde{M}^{0\nu}_{\text{NR}}) / \tilde{M}^{0\nu}$ and the ratio $R_T$ of the tensor part to the total NME $R_T \equiv \tilde{M}^{0\nu}_{\text{NR},T}/\tilde{M}^{0\nu}_{\text{NR}}$ are also presented.

<table>
<thead>
<tr>
<th>Sph+PNP</th>
<th>$\tilde{M}^{0\nu}$</th>
<th>$R_{AA}$</th>
<th>$\tilde{M}^{0\nu}_{\text{NR}}$</th>
<th>$\Delta_{\text{Rel.}}$</th>
<th>$R_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca $\rightarrow^{48}$Ti</td>
<td>3.66</td>
<td>81%</td>
<td>3.74</td>
<td>-2.1%</td>
<td>-2.4%</td>
</tr>
<tr>
<td>$^{76}$Ge $\rightarrow^{76}$Se</td>
<td>7.59</td>
<td>94%</td>
<td>7.71</td>
<td>-1.6%</td>
<td>3.5%</td>
</tr>
<tr>
<td>$^{82}$Se $\rightarrow^{82}$Kr</td>
<td>7.58</td>
<td>93%</td>
<td>7.68</td>
<td>-1.4%</td>
<td>2.9%</td>
</tr>
<tr>
<td>$^{96}$Zr $\rightarrow^{96}$Mo</td>
<td>5.64</td>
<td>95%</td>
<td>5.63</td>
<td>0.2%</td>
<td>3.6%</td>
</tr>
<tr>
<td>$^{100}$Mo $\rightarrow^{100}$Ru</td>
<td>10.92</td>
<td>95%</td>
<td>10.91</td>
<td>0.1%</td>
<td>3.5%</td>
</tr>
<tr>
<td>$^{116}$Cd $\rightarrow^{116}$Sn</td>
<td>6.18</td>
<td>94%</td>
<td>6.13</td>
<td>0.7%</td>
<td>1.9%</td>
</tr>
<tr>
<td>$^{124}$Sn $\rightarrow^{124}$Te</td>
<td>6.66</td>
<td>94%</td>
<td>6.78</td>
<td>-1.8%</td>
<td>4.9%</td>
</tr>
<tr>
<td>$^{130}$Te $\rightarrow^{130}$Xe</td>
<td>9.50</td>
<td>94%</td>
<td>9.64</td>
<td>-1.4%</td>
<td>4.3%</td>
</tr>
<tr>
<td>$^{136}$Xe $\rightarrow^{136}$Ba</td>
<td>6.59</td>
<td>94%</td>
<td>6.70</td>
<td>-1.7%</td>
<td>4.1%</td>
</tr>
<tr>
<td>$^{150}$Nd $\rightarrow^{150}$Sm</td>
<td>13.25</td>
<td>95%</td>
<td>13.08</td>
<td>1.3%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>
Nuclear matrix elements for $0\nu\beta\beta$ decay: shape mixing

- Large shape fluctuation in light or mediate heavy nuclei.
- The DBD is favored if mother and daughter nuclei have the same shape.
- Deformation hinders the DBD for most cases.
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Framework:

multi-reference covariant density functional theory

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Summary and outlook

Normalized NME:

$\tilde{M}^{0\nu}(\beta_I, \beta_F) = N_F N_I \langle \beta_F | \hat{O}^{0\nu} \hat{P}^{J=0} \hat{P}^{N_I} \hat{P}^{Z_I} | \beta_I \rangle$,

with $N_a^{-2} = \langle \beta_a | \hat{P}^{J=0} \hat{P}^{N_a} \hat{P}^{Z_a} | \beta_a \rangle$ for $a = I, F$

$^{96}$Zr: overestimated collectivity of g.s.

$^{150}$Nd: critical nucleus of phase trans.

Large discrepancy

$^{48}$Ca to $^{156}$Nd

MR-DFT: Rodriguez et al. PRL (2010)

RQPRA: Faessler et al. JPG (2012)

PHFB: Rath et al. PRC (2010)

ISM: Menendez et al. NPA (2009)

IBM2: Barea et al. PRC (2009)

JMY, L. S. Song, K. Hagino, P. Ring, and J. Meng, to be submitted.
Nuclear matrix elements for $0\nu\beta\beta$ decay: eff. neutrino mass

**Table:** The upper limits of the effective neutrino mass $\langle m_{\beta\beta} \rangle$ (eV) based on the NMEs from the present MR-CDFT (PC-PK1) calculation, the lower limits of the half-life $T_{1/2}^{0\nu}(\times 10^{24} \text{ yr})$ for the $0\nu\beta\beta$-decay from most recent measurements and the phase-space factor $G_{0\nu}(\times 10^{-15} \text{ yr}^{-1})$ from Ref. Kotila and Iachello, PRC85 (2012).

<table>
<thead>
<tr>
<th></th>
<th>48 Ca</th>
<th>76 Ge</th>
<th>82 Se</th>
<th>100 Mo</th>
<th>130 Te</th>
<th>136 Xe</th>
<th>150 Nd</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{1/2}^{0\nu}$</td>
<td>0.058</td>
<td>30</td>
<td>0.36</td>
<td>1.1</td>
<td>2.8</td>
<td>34</td>
<td>0.018</td>
</tr>
<tr>
<td>$G_{0\nu}$</td>
<td>24.81</td>
<td>2.363</td>
<td>10.16</td>
<td>15.92</td>
<td>14.22</td>
<td>14.58</td>
<td>60.03</td>
</tr>
<tr>
<td>$\langle m_{\beta\beta} \rangle$</td>
<td>2.92</td>
<td>0.20</td>
<td>1.00</td>
<td>0.38</td>
<td>0.33</td>
<td>0.11</td>
<td>1.76</td>
</tr>
</tbody>
</table>

[Graph showing the relationship between nuclear matrix elements and effective neutrino mass, with data points from various experiments and calculations.]

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Summary

- A systematic calculation of the NMEs for the $0\nu\beta\beta$ by using the wave functions from the beyond relativistic mean-field calculation.
- Good agreement with the properties of $0^+_1$ and $2^+_1$ states for the $0\nu\beta\beta$ candidate nuclei.
- The relativistic effect, contributions of tensor terms and HOC terms and the effects of PNP and shape mixing have been discussed.
- The smallest upper limit on $\langle m_{\beta\beta} \rangle \leq 0.11$ eV.

Outlook

- Wavefunctions: Comparison of different model wave functions, inclusion of other degrees of freedom, etc.
- Operator: heavy-neutrino-exchange, SRC, etc.
- Other processes: $2\nu\beta\beta$, $\nu$-nucleus scattering, etc.
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Thanks for your attention!