Ab initio $0\nu\beta\beta$ nuclear matrix elements

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<table>
<thead>
<tr>
<th>Decay</th>
<th>$2\nu\beta\beta$</th>
<th>$0\nu\beta\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diagram</strong></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Half-life Formula</strong></td>
<td>$[T_{1/2}^{2\nu}]^{-1} = G^{2\nu}</td>
<td>M^{2\nu}</td>
</tr>
<tr>
<td><strong>NME Formula</strong></td>
<td>$M^{2\nu} \approx M_{GT}^{2\nu}$</td>
<td>$M^{0\nu} = M_{GT}^{0\nu} - \left(\frac{g_\nu}{g_\alpha}\right)^2 M_{F}^{0\nu} + M_{T}^{0\nu}$</td>
</tr>
<tr>
<td><strong>LNV</strong></td>
<td>No</td>
<td>Yes!!!</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>Yes (extremely rare)</td>
<td>No</td>
</tr>
</tbody>
</table>

*NME : Nuclear matrix elements
**LNV : Lepton number violation*
Current calculations from phenomenological models have large spread in results.

All models missing essential physics
Impossible to assign rigorous uncertainties
Nuclear matrix elements

\[ NME = \sum_n \sum_m \langle n | \hat{O} | m \rangle \]

\( | n \rangle \) are the eigenstates of the nuclear hamiltonian involved in the transition. 
\( \hat{O} \) is the operator we wish to find the NME of.
Nuclear matrix elements

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⇒ We need the nuclei wave functions!
Valence-Space In Medium Similarity Renormalization Group

Valence-Space In Medium Similarity Renormalization Group

Courtesy, S. R. Stroberg

VS-IMSRG

Discovery, accelerated
**Truncations**

- \( e_{\text{max}} \): Truncations for 1-body states. Is given by \( 2n + 1 \)
- \( E_{3\text{max}} \): Truncations for 3-body forces. Optimally \( E_{3\text{max}} = 3 \times e_{\text{max}} \)
- IMSRG(2): All operators are truncated to the 2-body level

**Parameters**

- Input hamiltonian
- Harmonic oscillator frequency for hamiltonian basis (\( \hbar \omega \))
- Reference state
Benchmark with other ab initio method for fictitious decays in light nuclei.

Reasonable to good agreement in all cases.

Yao, Belley, et al., PhysRevC.103.014315
Ab Initio $0\nu\beta\beta$ Decay: $^{48}\text{Ca}$, $^{76}\text{Ge}$ and $^{82}\text{Se}$

Well converged results both in $e_{\text{max}}$ and $E_{3\text{max}}$ for the “magic” interaction (EM1.8/2.0)

Belley et al., PhysRevLett.126.042502
Results with 5 different input hamiltonians to study uncertainty from interaction choice.

Things to add: valence space variation, two-body currents, IMSRG(3), …
Ab Initio $0\nu\beta\beta$ Decay: $^{130}\text{Te}$, $^{136}\text{Xe}$

$^{130}\text{Te}$, $^{136}\text{Xe}$ major players in global searches with SNO+ and nEXO

Increased $E_{3\text{max}}$ capabilities allow first converged ab initio calculations [EM1.8/2.0, $\Delta G_O$]

Belley et al., in prep
Summary...

1) Computed first ever ab-initio NMEs of isotopes of experimental interest, which is a first step towards computing NME with reliable theoretical uncertainties.

2) Method has been benchmarked with exact methods in fictitious light decays.

3) Computed NME with multiple interactions for $^{48}$Ca, $^{76}$Ge and $^{82}$Se.

4) Computed preliminary results for $^{130}$Te and $^{136}$Xe.

... and outlook

1) Finish calculations with different interactions for $^{130}$Te and $^{136}$Xe

2) Analysis of undetermined leading order contact (and finite momentum 2bc)

3) Correlations with other operators: eg, double Gamow-Teller

4) Large scale ab initio uncertainty analysis with other methods for ‘final’ NMEs

5) Study other exotic mechanism proposed for $0\nu\beta\beta$. 
Questions?
where the functions $h$ are the neutrino potentials respective to each decay mode and $E_C$ is the closure energy.
Ab Initio $2\nu\beta\beta$ Decay: $^{48}$Ca

VS-IMSRG 1.8/2.0 (EM)

VS-IMSRG: decrease in final matrix element

Potential issues: limited $1^+$ states, missing IMSRG(3),... Benchmarks with CC underway!

Belley, Payne, Stroberg, JDH, in prep