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# SRG Evolution of Operators in the NCSM

Peter Gysbers[1]
A. Calci[2] & P. Navrátil[2]

[1]McMaster University, [2]TRIUMF

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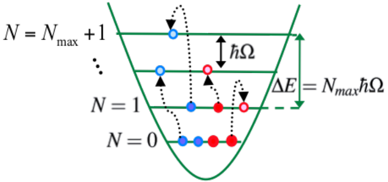
Want to solve the eigenvalue problem:

$$H\,|\Psi_k\rangle = E_k\,|\Psi_k\rangle\text{, where } H = \sum_i^A T_i + \sum_{i<j} V_{ij} + \sum_{i<j<f} V_{ijf} + \cdots$$

Expand in anti-symmetrized products of harmonic oscillator single-particle states




$$|\Psi_k\rangle = \sum_{N=0}^{N_{max}} \sum_j c_{Nj}^k\,|\Phi_{Nj}\rangle$$

Calculations should converge to the exact value as $N_{max} \to \infty$

Problem: the size of the model space increases rapidly with particle number

# Similarity Renormalization Group (SRG)

The SRG method uses a unitary transformation to decouple high and low momentum physics allowing faster convergence of calculations

$$H_\alpha = U_\alpha H U_\alpha^\dagger$$

$$\frac{\mathrm{d}H_\alpha}{\mathrm{d}\alpha} = [[T, H_\alpha], H_\alpha] \text{ where } H_{\alpha=0} = H$$

Note: SRG transformations introduce higher-body terms in the Hamiltonian

$$U_\alpha H U_\alpha^\dagger = H_\alpha^{(1)} + H_\alpha^{(2)} + H_\alpha^{(3)} + \dots$$

$$H\left|\Psi_k\right\rangle = E_k\left|\Psi_k\right\rangle \rightarrow H_\alpha\left|\Psi_{k,\alpha}\right\rangle = E_k\left|\Psi_{k,\alpha}\right\rangle$$

General operators must also be transformed:

$$\left\langle\Psi_f\right|\hat{O}\left|\Psi_i\right\rangle = \left\langle\Psi_{f,\alpha}\right|\hat{O}_\alpha\left|\Psi_{i,\alpha}\right\rangle \text{ where } \hat{O}_\alpha = U_\alpha \hat{O} U_\alpha^\dagger$$

$$U_\alpha = \sum_k \left|\Psi_{k,\alpha}\right\rangle\left\langle\Psi_k\right|$$

## Implementation in two-body relative coordinates:

For $\left|\Psi_k\right\rangle = \left|kJ^\pi T T_z\right\rangle$, $U_\alpha$ is constructed in blocks: $U_\alpha^{J^\pi T T_z}$
Non-scalar operators may connect states with different quantum numbers:

$$\left\langle k' J'^{\pi'} T' T_z'\right|\left|\hat{O}^{(K)}\right|\left|kJ^\pi T T_z\right\rangle = \left\langle k' J'^{\pi'} T' T_z', \alpha\right|\left| U_\alpha^{J'^{\pi'} T' T_z'} \hat{O}^{(K)} U_\alpha^{\dagger J^\pi T T_z} \right|\left|kJ^\pi T T_z, \alpha\right\rangle$$

$$\hat{O} = GT^{(1)} \rightarrow \hat{O}_\alpha = GT^{(1)} + GT^{(2)}_\alpha + \dots$$

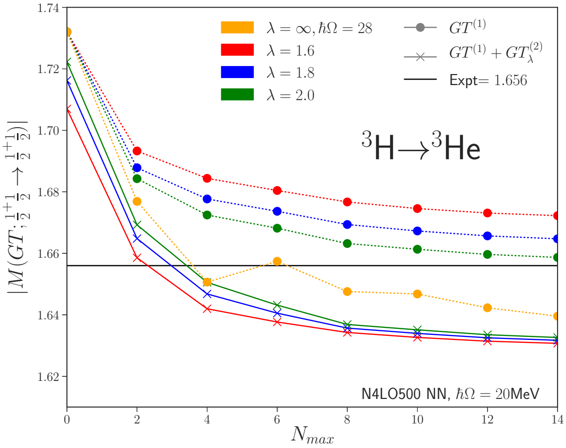
### Operator:

Gamow-Teller (1-body)

$\langle GT^{(2)}_\alpha \rangle_{A=2} = \langle (GT^{(1)})_\alpha \rangle_{A=2} - \langle GT^{(1)}_\alpha \rangle_{A=2}$

### Potential: "N$^4$LO NN"

- chiral NN @ N$^4$LO, Machleidt PRC91 (2015), 500MeV cutoff



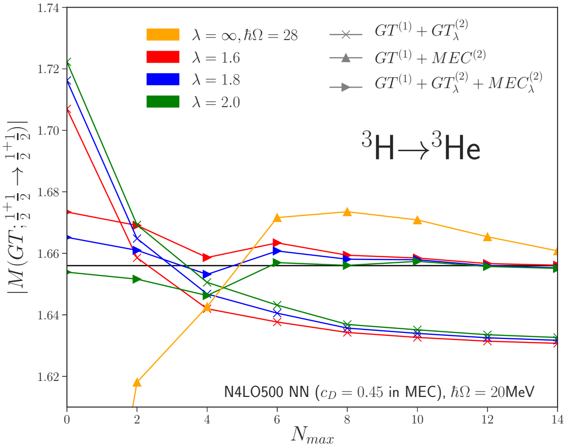
$$\hat{O} = GT^{(1)} + MEC^{(2)} \rightarrow \hat{O}_\alpha = GT^{(1)} + GT^{(2)}_\alpha + MEC^{(2)}_\alpha + \ldots$$

## Operator:

Gamow-Teller (1-body) + chiral meson exchange current (2-body) Park (2003)

## Potential: "N$^4$LO NN"

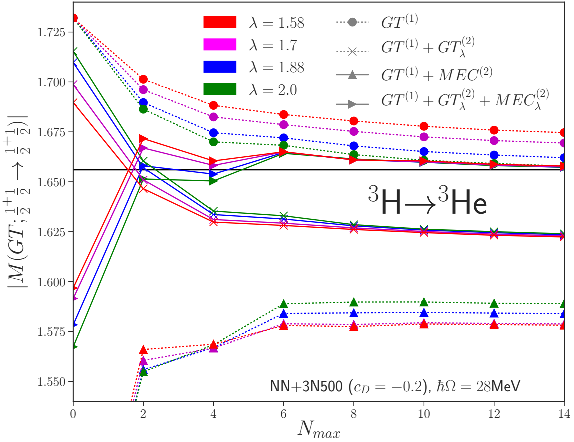
- chiral NN @ N$^4$LO, Machleidt PRC91 (2015), 500MeV cutoff
- LEC $c_D = 0.45$ determined



$$\hat{O} = GT^{(1)} + MEC^{(2)} \rightarrow \hat{O}_\alpha = GT^{(1)} + GT^{(2)}_\alpha + MEC^{(2)}_\alpha + \dots$$

## Potential: "NN+3N500"

- chiral NN @ N$^3$LO, Entem & Machleidt PRC68 (2003), 500MeV cutoff
- chiral 3N @ N$^2$LO, Navrátil Few-Body Sys. 41 (2007), 500MeV cutoff
- LEC $c_D = -0.2$ determined by Gazit PRL103 (2009)



$$\hat{O} = GT^{(1)} + MEC^{(2)} \rightarrow \hat{O}_\alpha = GT^{(1)} + GT^{(2)}_\alpha + MEC^{(2)}_\alpha + \dots$$

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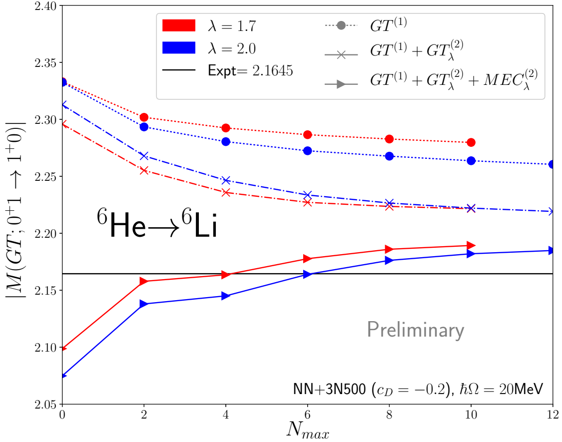

# Summary and Outlook

- Operators must be SRG evolved to converge to the correct result
- Used for $\beta$-decay strengths: $^3$H$\rightarrow$$^3$He and $^6$He$\rightarrow$$^6$Li
- SRG induced 3-body contributions are not significant
- $^3$H$\rightarrow$$^3$He used to determine the low-energy constant $c_D$ in chiral MEC
- Potential future calculations include:
  - Electromagnetic operators
  - Double-beta decay
  - Expansion to 3-body space