Toward Realistic Calculations of Light-Ion Fusion Reactions

INT "Structure of light Nuclei"

Seattle, October 2012.

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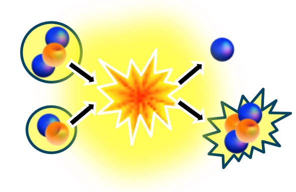
From nucleons to nuclei to fusion reactions

Lawrence Livermore National Laboratory

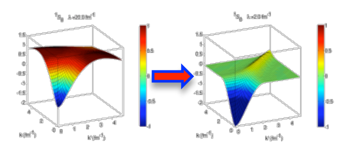
A TOP500 SUPERCOMPUTER SITES lab proofed.

- Objective:

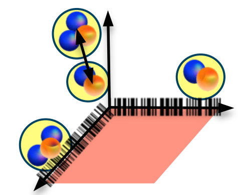
  Address static and dynamical properties of light ions and describe fusion reactions.

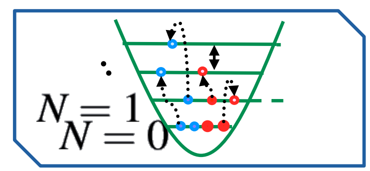


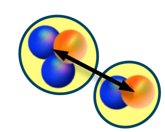
- Ingredients
  - High-precision nuclear interaction, two- plus three-nucleon, derived from the Chiral Effective Field Theory (EFT) and softened by the Similarity Renormalization Group technique.



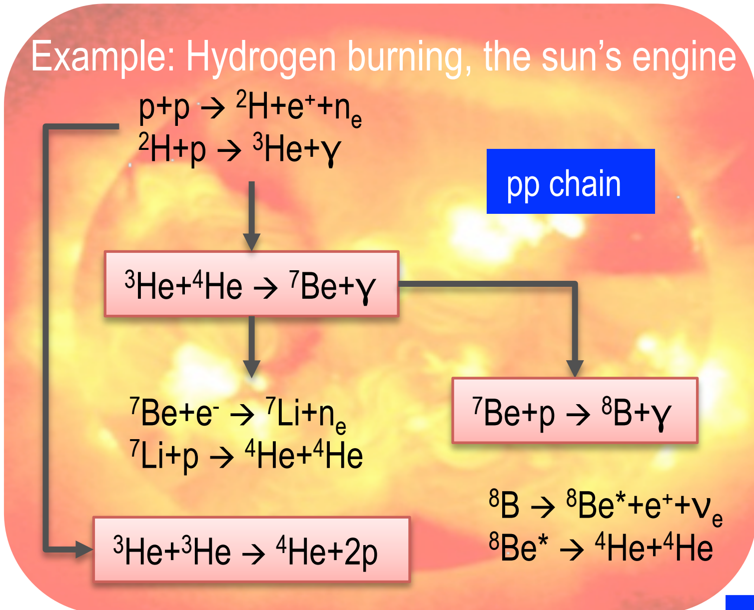
- Recipe
  - Solve the Schrödinger equation.
  - Address structural properties. (bound states, narrow resonances)
    - — *Ab initio* many-body approaches (A ≤ ~16); No-Core Shell Model (NCSM)
  - Address dynamical properties. (scattering, reactions)
    - — Extend No-Core Shell-Model with the Resonating Group Method (RGM)







Some of the building block of our universe are driven by fusion processes: nucleosynthesis, stellar evolution …

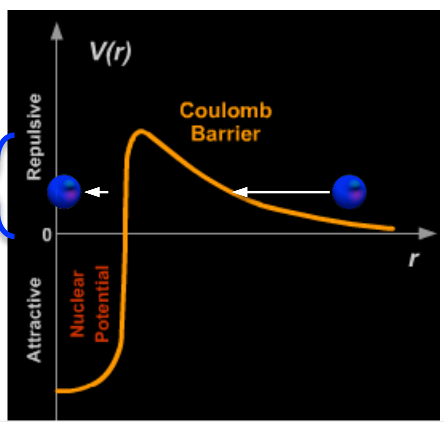


Nuclear astrophysics community relies on accurate fusion reactions observables.

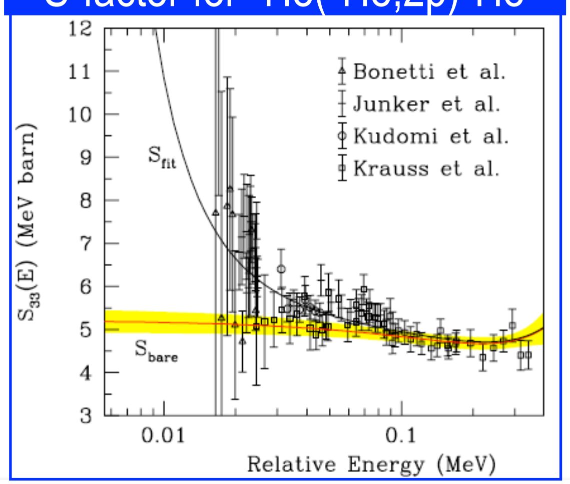
Turn out to be experimentally challenging:

- Low rates: Coulomb repulsion + Low energy (quantum tunneling effects).
- Projectile and target are not fully ionized in a lab. This leads to laboratory electron screening

Low energy fusion



S-factor for ${}^{3}He({}^{3}He,2p){}^{4}He$



A fundamental theory is needed to enhance predictive capability of stellar modeling

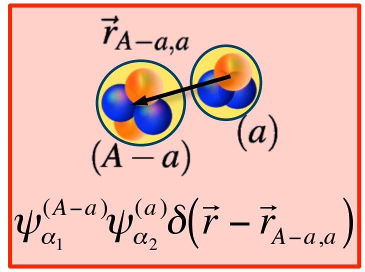
Ab initio NCSM/RGM Formalism for binary clusters

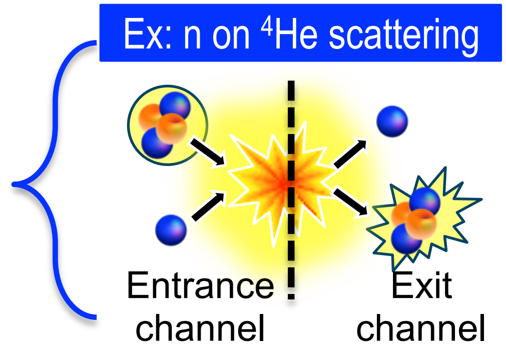
S. Quaglioni and P. Navrátil, Phys. Rev. Lett. 101, 092501 (2008); Phys. Rev. C 79, 044606 (2009)

- Starts from:

$$\Psi^{(A)}_{RGM} = \sum_{\nu} \int d\vec{r}\; g_{\nu}(\vec{r})\; \hat{A}_{\nu} \left| \Phi^{(A-a,a)}_{\nu\vec{r}} \right\rangle$$

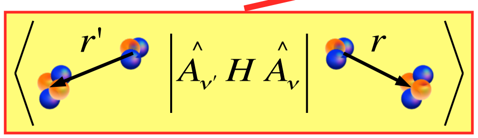
Relative wave function (unknown) — Channel basis



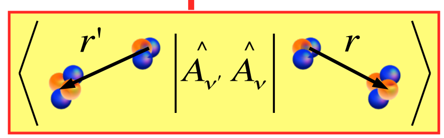


- Schrödinger equation on channel basis:

$$H\Psi^{(A)}_{RGM} = E\Psi^{(A)}_{RGM} \Rightarrow \sum_{\nu} \int d\vec{r}\; \left[H_{\nu'\nu}(\vec{r}',\vec{r}) - E\; N_{\nu'\nu}(\vec{r}',\vec{r}) \right] g_{\nu}(\vec{r}) = 0$$



Hamiltonian kernel



Norm (overlap) kernel

∝ NCSM densities

- Constructs integration kernels (≈ projectile-target potentials) starting from:
  - Underlying (realistic) interactions among nucleons
  - NCSM *ab initio* wave functions

Navrátil and Quaglioni, PRL 101, (2008)
Navrátil and Quaglioni, PRL 108, (2012)

RGM accounts for: 1) nucleon-nucleon interaction (Hamiltonian kernel), 2) Pauli principle (Norm kernel) between clusters and 3) center of mass motion of cluster; NCSM accounts for: internal structure of clusters

Ab initio NCSM/RGM Formalism for binary clusters

a few details

$$\left|\Psi^{J^\pi T}\right\rangle = \sum_\nu \int \frac{g_\nu^{J^\pi T}(r)}{r} \hat{A}_\nu \left[\left(\left|A-a\ \alpha_1 I_1^{\pi_1} T_1\right\rangle \left|a\ \alpha_2 I_2^{\pi_2} T_2\right\rangle\right)^{(sT)} Y_\ell(\hat{r}_{A-a,a})\right]^{(J^\pi T)} \frac{\delta(r-r_{A-a,a})}{r r_{A-a,a}}\, r^2 dr$$

Relative wave functions subject to the boundary/scattering asymptotic solution within R-matrix theory

$\left|\Phi_{\nu r}^{J^\pi T}\right\rangle$ (Jacobi) channel basis

We use the closure properties of HO radial wave function

$$\delta(r-r_{A-a,a}) = \sum_n R_{n\ell}(r) R_{n\ell}(r_{A-a,a})$$

We defined the RGM model space such that $n<N_{max}$, this expansion is good for localized parts of the integration kernels.

Since we are using NCSM wave functions, it is convenient to introduce Jacobi channel states in the HO space

$$\left|\Phi_{\nu n}^{J^\pi T}\right\rangle = \left[\left(\left|A-a\ \alpha_1 I_1^{\pi_1} T_1\right\rangle \left|a\ \alpha_2 I_2^{\pi_2} T_2\right\rangle\right)^{(sT)} Y_\ell(\hat{r}_{A-a,a})\right]^{(J^\pi T)} R_{n\ell}(r_{A-a,a})$$

The coordinate space channel states are given by

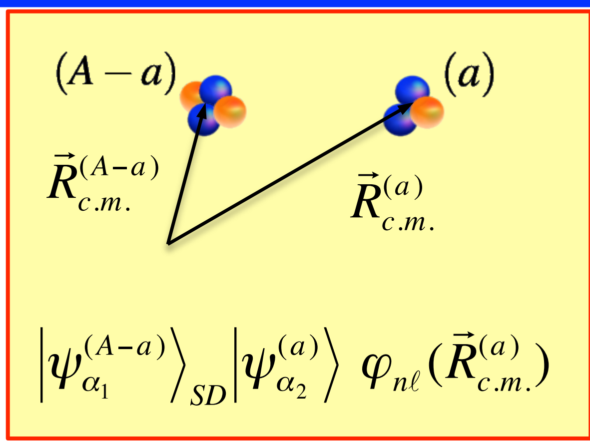
$$\left|\Phi_{\nu r}^{J^\pi T}\right\rangle = \sum_n R_{n\ell}(r) \left|\Phi_{\nu n}^{J^\pi T}\right\rangle$$

Matrix elements of translationally invariant operators

- Translational invariance is preserved (exactly!) also with SD cluster basis

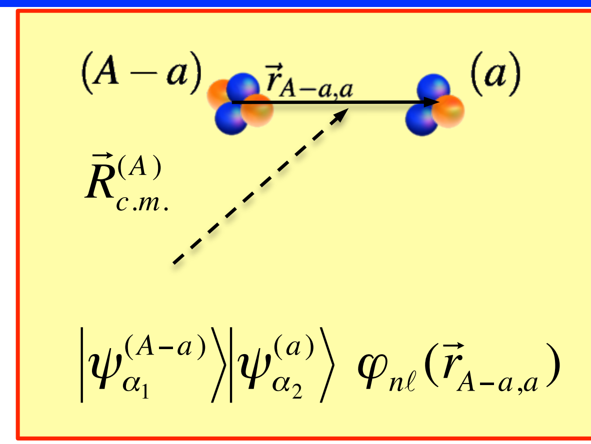
$$ {}_{SD}\left\langle \Phi^{(A-a',a')}_{f_{SD}} \middle| \hat{O}_{t.i.} \middle| \Phi^{(A-a,a)}_{i_{SD}} \right\rangle_{SD} = \sum_{i_R f_R} M_{i_{SD} f_{SD}, i_R f_R} \left\langle \Phi^{(A-a',a')}_{f_R} \middle| \hat{O}_{t.i.} \middle| \Phi^{(A-a,a)}_{i_R} \right\rangle $$

What we calculate in the "SD" channel basis



Matrix inversion

Observables calculated in the translationally invariant basis



- Advantage: can use powerful second quantization techniques

$$ {}_{SD}\left\langle \Phi^{(A-a',a')}_{\nu'n'} \middle| \hat{O}_{t.i.} \middle| \Phi^{(A-a,a)}_{\nu n} \right\rangle_{SD} \propto {}_{SD}\left\langle \psi^{(A-a')}_{\alpha_1'} \middle| a^+ a \middle| \psi^{(A-a)}_{\alpha_1} \right\rangle_{SD}, \; {}_{SD}\left\langle \psi^{(A-a')}_{\alpha_1'} \middle| a^+ a^+ a a \middle| \psi^{(A-a)}_{\alpha_1} \right\rangle_{SD}, \; \cdots $$

Matrix elements of translationally invariant operators

Then the SD channel states are defined such that the eigenstates of the heaviest of the two clusters (target) are described by a SD wave function:

$$\left|\Phi^{J^\pi T}_{\nu n}\right\rangle_{SD} = \left[\left(\left|A-a\ \alpha_1 I_1^{\pi_1} T_1\right\rangle_{SD} \left|a\ \alpha_2 I_2^{\pi_2} T_2\right\rangle\right)^{(sT)} Y_\ell\left(\hat{R}^{(a)}_{c.m.}\right)\right]^{(J^\pi T)} R_{n\ell}\left(R^{(a)}_{c.m.}\right)$$

$$\left|A-a\ \alpha_1 I_1^{\pi_1} T_1\right\rangle \varphi_{00}\left(\vec{R}^{(A-a)}_{c.m.}\right)$$

Vector proportional to the c.m. coordinate of the A-a nucleons

Vector proportional to the c.m. coordinate of the a nucleons

In the case of the nucleon-nucleus system we can applied the following basis change

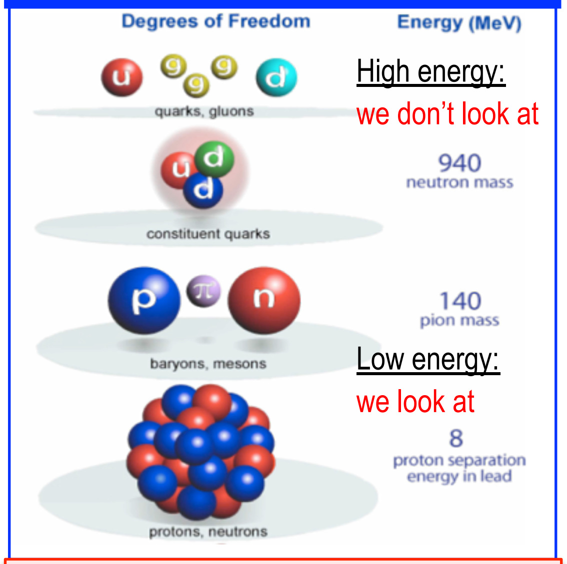
$$|\Phi^{J^\pi T}_{\nu n}\rangle_{\rm SD} = \sum_j \hat{s}\hat{j}\ (-1)^{I_1+J+j} \left\{\begin{matrix} I_1 & \frac{1}{2} & s \\ \ell & J & j \end{matrix}\right\}$$

$$\times \left[|A{-}1\,\alpha_1 I_1^{\pi_1} T_1\rangle \quad \varphi_{n\ell j\frac{1}{2}}(\vec{r}_A \sigma_A \tau_A)\right]^{(J^\pi T)}$$

This basis is convenient to express the kernels with the help of second quantization.

Effective interaction using SRG technique

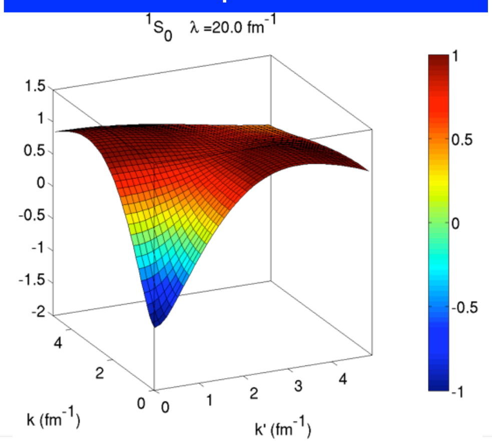
Nuclear scales



Observables function of energy

1. From Quantum Chromo Dynamic (QCD), derive the bare nuclear (NN+NNN) interaction as an expansion selecting relevant degrees of freedom with the Chiral EFT.
2. Evolve (1) to extract a low-energy effective interaction using the SRG technique. This greatly improves the convergence of Many Body calculations.
3. Solve the non-relativistic Schrödinger equation with evolved two- plus three-("induced" + "real") interactions.

Bare potential

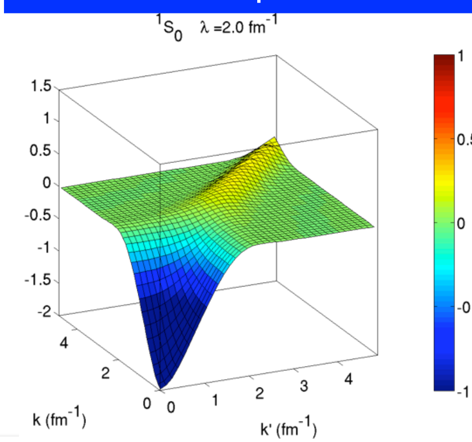


SRG evolution

Preserves the physics

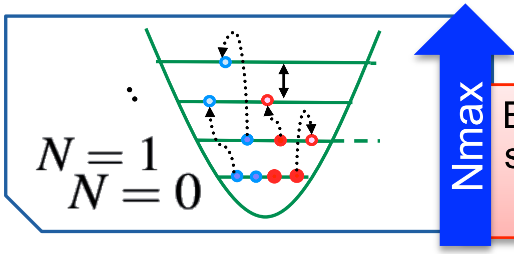
Decouples high and low momentum

Evolved potential

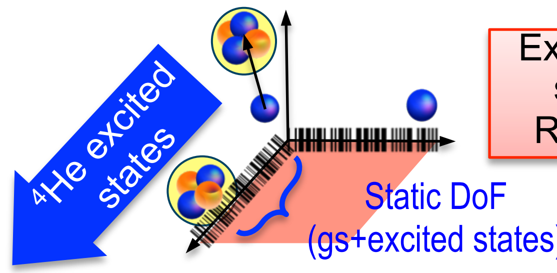


Convergence properties

S. Quaglioni and P. Navrátil, Phys. Rev. Lett. 101, 092501 (2008); Phys. Rev. C 79, 044606 (2009)

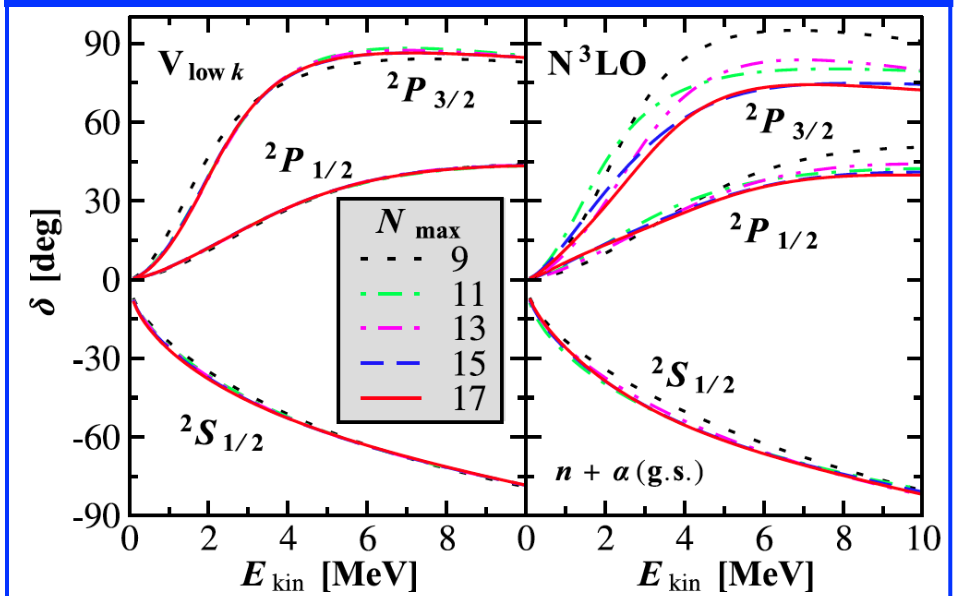


Expanding the size in the HO space.



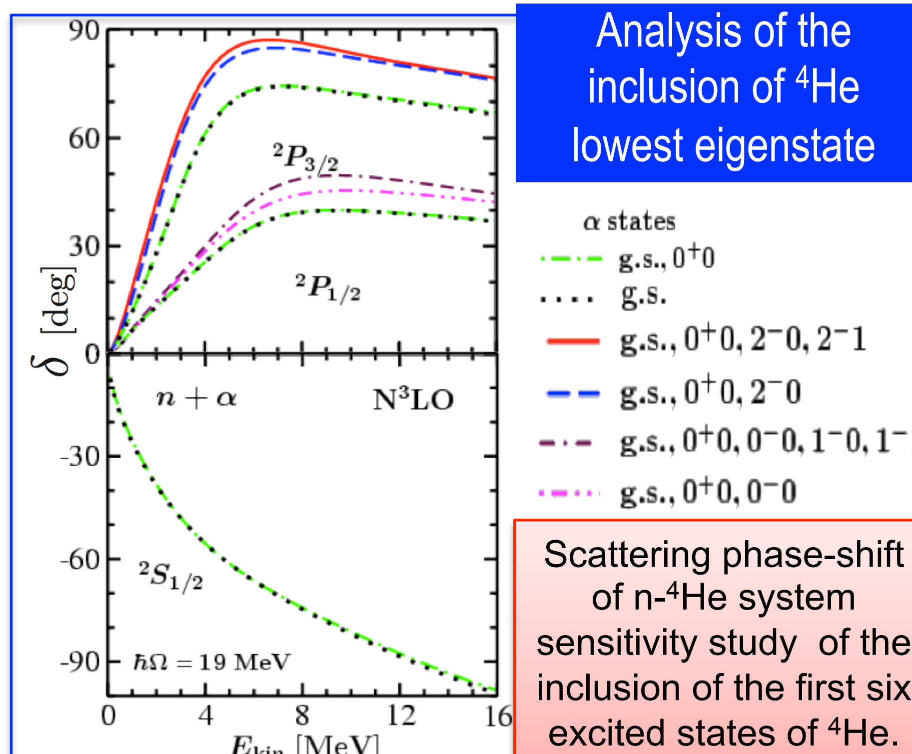
Expanding the size in the RGM space.

Analysis of model space dependence



Scattering phase-shift of n-^{4}He system as a function of Nmax, for V_{lowk} and chiral EFT N3LO

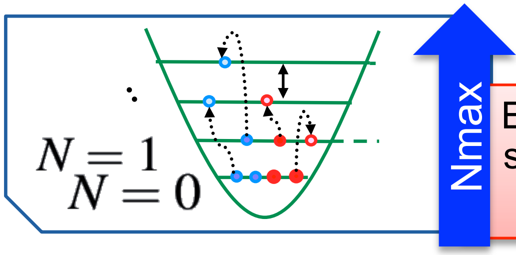
Analysis of the inclusion of ^{4}He lowest eigenstate



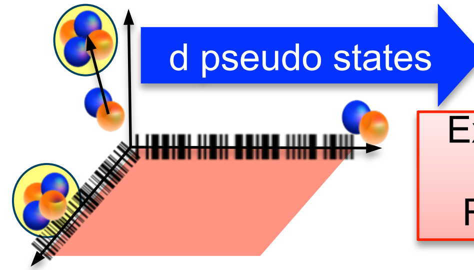
Scattering phase-shift of n-^{4}He system sensitivity study of the inclusion of the first six excited states of ^{4}He.

Convergence properties

S. Quaglioni and P. Navrátil, Phys. Rev. Lett. 101, 092501 (2008); Phys. Rev. C 79, 044606 (2009)

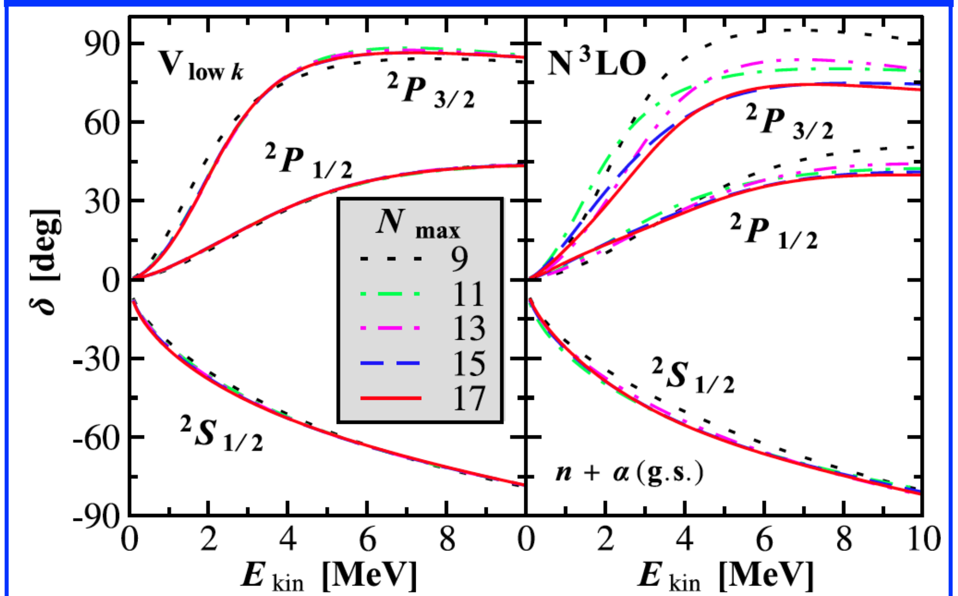


Expanding the size in the HO space.

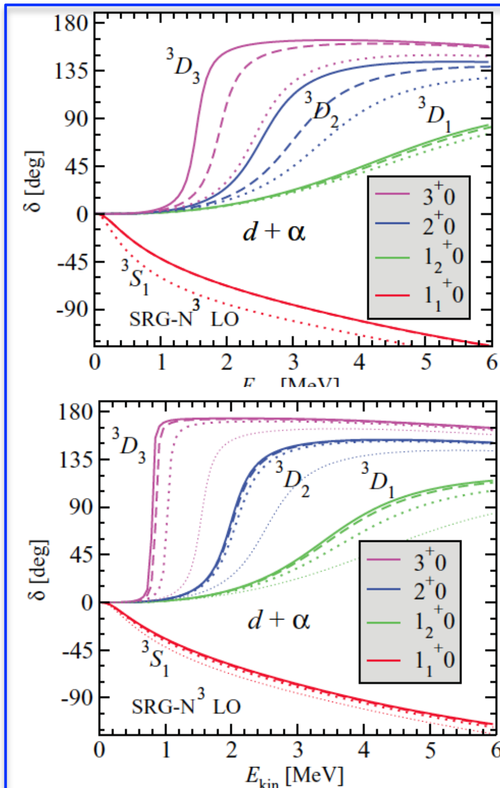


Expanding the size in the RGM space.

Analysis of model space dependence



Scattering phase-shift of n-^{4}He system as a function of Nmax, for V_{lowk} and chiral EFT N3LO



Scattering phase-shifts of d-^{4}He system

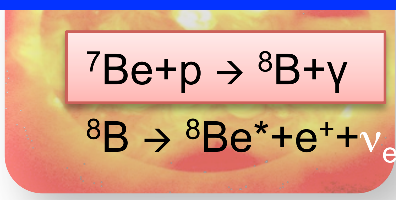
Sensitivity study of the inclusion of deuterium pseudo excited states.

Sensitivity study of the number deuterium pseudo excited states.

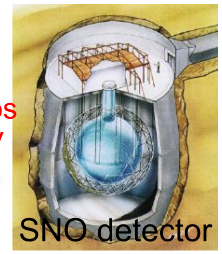
Ab initio many-body calculation of the ^{7}Be(p,γ)^{8}B radiative capture

P. Navrátil, R. Roth, and S. Quaglioni, Phys. Lett. B704, 379 (2011)

Footprints of pp chain on earth



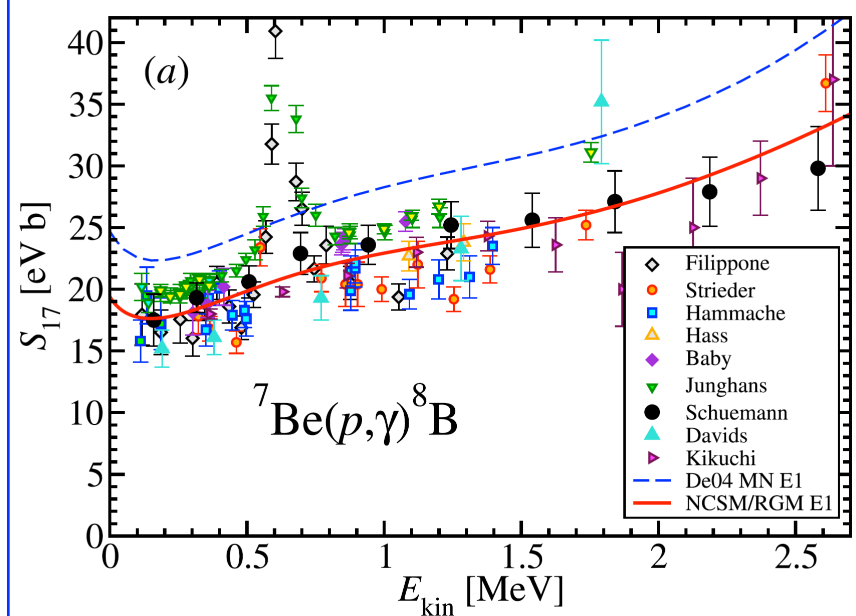
solar neutrinos
E_n < 15 MeV



The ^{7}Be(p,γ)^{8}B is the final step in the nucleosynthetic chain leading to ^{8}B and one of the main inputs of the standard model of solar neutrinos

- ~10% error in latest $S_{17}(0)$: dominated by uncertainty in theoretical models
- NCSM/RGM results with largest realistic model space (N_{max} = 10):
  - p+^{7}Be(g.s., 1/2$^-$, 7/2$^-$, 5/2$_1^-$, 5/2$_2^-$)
  - Siegert's E1 transition operator
- Parameter λ of SRG NN interaction chosen to reproduce separation energy: 136 keV (Expt. 137 keV)
- $S_{17}(0)$ = 19.4(7) eVb on the lower side of, but consistent with latest evaluation

^{7}Be(p,γ)^{8}B astrophysical S-factor



Ab initio theory predicts simultaneously both normalization and shape of S_{17}

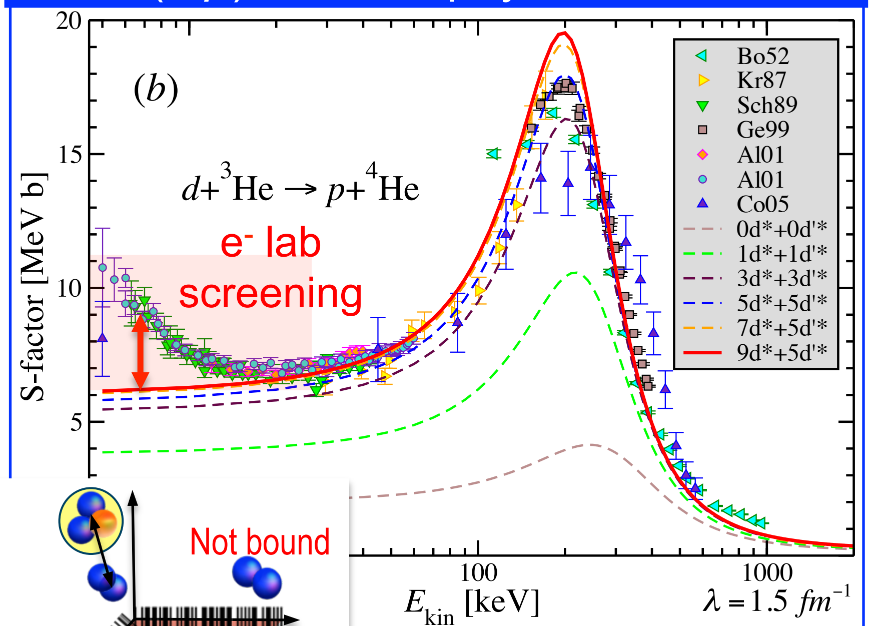
Astrophysical S-factor:

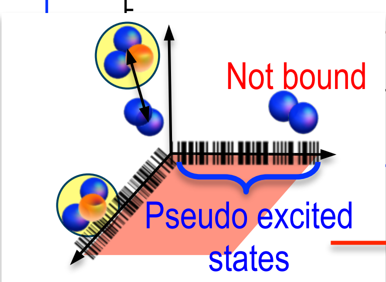
$$\sigma(E) = \frac{S(E)}{E}\exp\left(-\frac{2\pi Z_1 Z_2 e^2}{\hbar\sqrt{2mE}}\right)$$

Ab initio many-body calculations of the $^{3}H(d,n)^{4}He$ and $^{3}He(d,p)^{4}He$ fusion

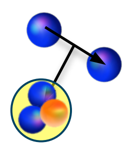
P. Navrátil, S. Quaglioni, PRL 108, 042503 (2012)

$^{3}He(d,p)^{4}He$ astrophysical S-factor



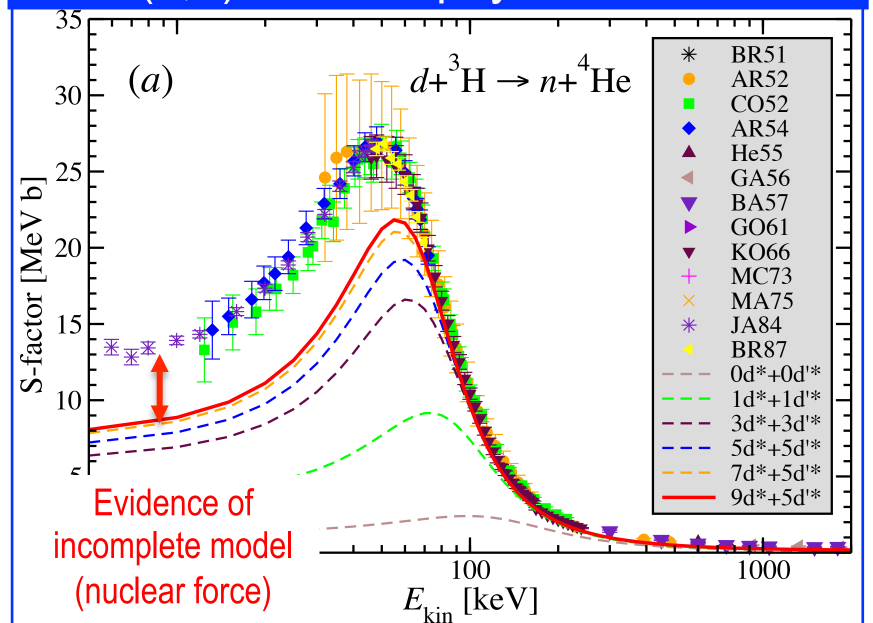


A more complete picture would be an expansion in terms of breakup DoF



Calculated S-factors converge with the inclusion of the virtual breakup of the deuterium, obtained by means of excited $^{3}S_{1}$-$^{3}D_{1}$ (d^{*}) and $^{3}D_{2}$ (d'^{*}) pseudo-states.

$^{3}H(d,n)^{4}He$ astrophysical S-factor

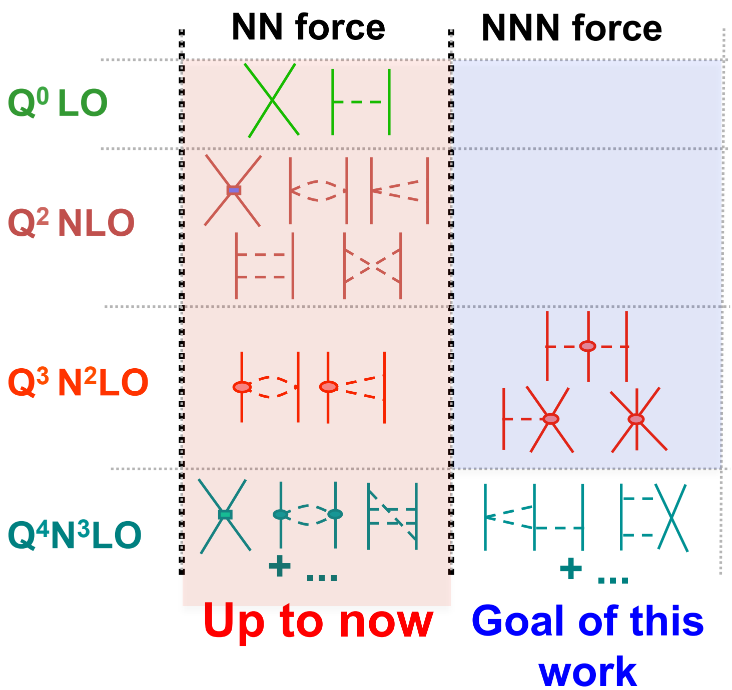


NCSM/RGM results for the $^{3}He(d,n)^{4}He$ astrophysical S-factor compared to beam-target measurements.

Incomplete nuclear interaction: requires NNN force (SRG-induced + "real")

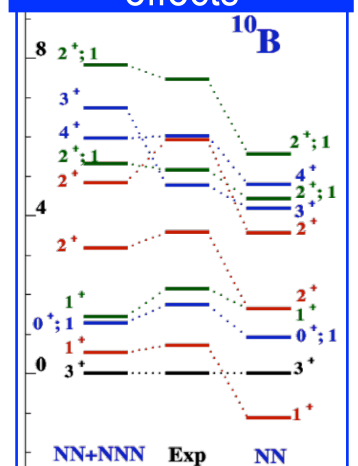
$$\sigma(E) = \frac{S(E)}{E} \exp\left(-\frac{2\pi Z_1 Z_2 e^2}{\hbar\sqrt{2mE}}\right)$$

Including the NNN force into the NCSM/RGM approach



- Three-nucleon interaction derives from the underlying QCD theory.
- NNN force is fundamentally important.
- NNN-force components arise also from the SRG evolution of the NN interaction.

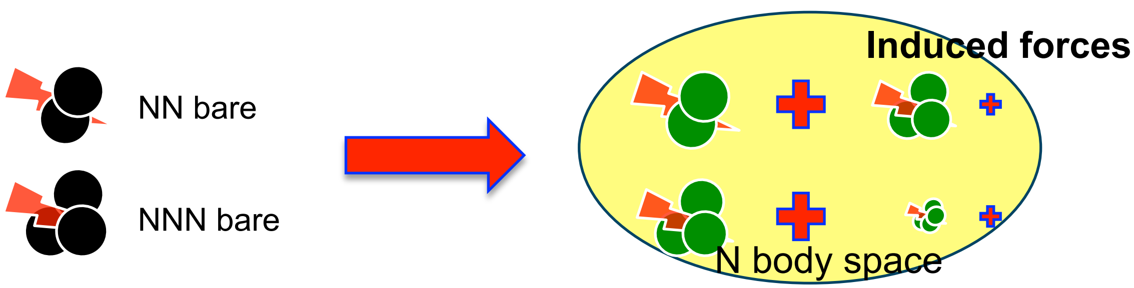
Example of NNN effects



Without NNN force g.s. has wrong spin.

R. Roth, J. Langhammer, A. Calci, S. Binder, and P. Navratil, PRL 107, 072501 (2011).

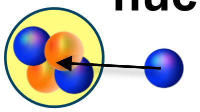
Chiral EFT interaction



NNN-induced interaction needs to be accounted in order to preserve the unitarity

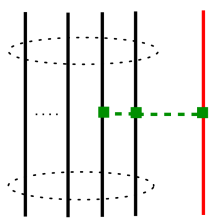
Including the NNN force into the NCSM/RGM approach

nucleon-nucleus formalism

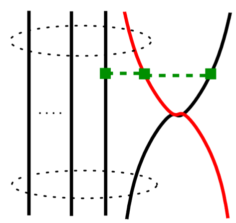


$$\left\langle \Phi^{J^\pi T}_{\nu' r'} \middle| \hat{A}_{\nu'} V^{NNN} \hat{A}_{\nu} \middle| \Phi^{J^\pi T}_{\nu r} \right\rangle = \left\langle (A-1)\; r'\; (a'=1) \middle| V^{NNN} \left(1 - \sum_{i=1}^{A-1} \hat{P}_{iA}\right) \middle| (a=1)\; r\; (A-1) \right\rangle$$

$$\mathcal{V}^{NNN}_{\nu'\nu}(r,r') = \sum R_{n'l'}(r') R_{nl}(r) \left[\frac{(A-1)(A-2)}{2} \langle \Phi^{J^\pi T}_{\nu' n'} | V_{A-2A-1A}(1 - 2P_{A-1A}) | \Phi^{J^\pi T}_{\nu n} \rangle \right.$$



(a)

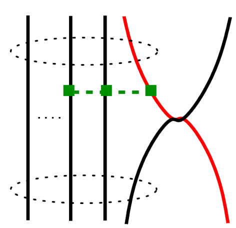


(b)

Direct potential:

$$\propto {}_{SD}\left\langle \psi^{(A-1)}_{\alpha_1'} \middle| a_i^+ a_j^+ a_l a_k \middle| \psi^{(A-1)}_{\alpha_1} \right\rangle_{SD}$$

$$\left. - \frac{(A-1)(A-2)(A-3)}{2} \langle \Phi^{J^\pi T}_{\nu' n'} | P_{A-1A} V_{A-3A-2A-1} | \Phi^{J^\pi T}_{\nu n} \rangle \right] .$$



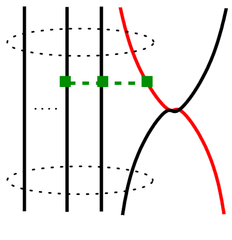
(c)

Exchange potential:

$$\propto {}_{SD}\left\langle \psi^{(A-1)}_{\alpha_1'} \middle| a_h^+ a_i^+ a_j^+ a_m a_l a_k \middle| \psi^{(A-1)}_{\alpha_1} \right\rangle_{SD}$$

Including the NNN force into the NCSM/RGM approach

nucleon-nucleus formalism



(c)

Exchange potential:

$$\propto {}_{SD}\left\langle \psi^{(A-1)}_{\alpha_1'} \middle| a_h^+ a_i^+ a_j^+ a_m a_l a_k \middle| \psi^{(A-1)}_{\alpha_1} \right\rangle_{SD}$$

$$\propto {}_{SD}\left\langle \psi^{(A-1)}_{\alpha_1'} \middle\|\middle| \left[\left(\left(a_h^+ a_i^+ \right)^{h'} a_j^+ \right)^{g'} \left(\left(a_m a_l \right)^{h} a_k \right)^{g} \right]^K \middle\|\middle| \psi^{(A-1)}_{\alpha_1} \right\rangle_{SD}$$

$$\frac{1}{(A-1)(A-2)(A-3)} \sum_{\substack{j_0 j_0'\, t_0 t_0' \\ K J_0\, \tau T_0}} \sum_{\substack{n_a l_a j_a \\ n_b l_b j_b}} \sum_{\substack{n_\alpha l_\alpha j_\alpha \\ n_a' l_a' j_a'}} \sum_{\substack{n_b' l_b' j_b' \\ g' t_g'}} \hat{\tau}\hat{K}\hat{J}_0\hat{T}_0\hat{g}'\hat{t}_g' \left\{ \begin{array}{ccc} T_1 & \tau & T_1' \\ 1/2 & T & 1/2 \end{array} \right\} \left\{ \begin{array}{ccc} 1/2 & \tau & 1/2 \\ t_g' & t_0' & T_0 \end{array} \right\}$$

$$\left\{ \begin{array}{ccc} I_1 & K & I_1' \\ j' & J & j \end{array} \right\} \left\{ \begin{array}{ccc} j' & K & j \\ g' & j_0' & J_0 \end{array} \right\} (-1)^{j_a'+j_b'-j_0'+j'+K+I_1+J} (-1)^{3/2-t_0'+j'+\tau+T_1+T}$$

$$\left\langle \left[(n_a' l_a' j_a' : n_b' l_b' j_b') j_0' t_0' :\ n' l' j' \right] J_0 T_0 \right| V_{A-3\, A-2\, A-1} \left| \left[(n_\alpha l_\alpha j_\alpha : n_a l_a j_a) j_0 t_0 :\ n_b l_b j_b \right] J_0 T_0 \right\rangle$$

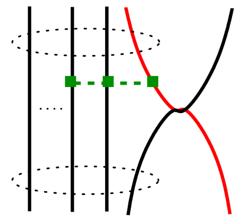
$${}_{SD}\left\langle A-1 \alpha_1' I_1' T_1' \middle\|\middle| \left[\left(a^\dagger_{nlj} \left(a^\dagger_{n_b' l_b' j_b'} a^\dagger_{n_a' l_a' j_a'} \right)^{j_0' t_0'} \right)^{g' t_g'} \left(\left(\tilde{a}_{n_\alpha l_\alpha j_\alpha} \tilde{a}_{n_a l_a j_a} \right)^{j_0 t_0} \tilde{a}_{n_b l_b j_b} \right)^{J_0 T_0} \right]^{K\tau} \middle\|\middle| A-1 \alpha_1 I_1 T_1 \right\rangle_{SD}$$

We use NNN matrix elements in the JT-coupled basis

The matrix elements of the three-body density become quickly too large to be stored

Including the NNN force into the NCSM/RGM approach

nucleon-nucleus formalism



(c)

Exchange potential:

$$\propto {}_{SD}\left\langle \psi^{(A-1)}_{\alpha_1'} \middle| a_h^+ a_i^+ a_j^+ a_m a_l a_k \middle| \psi^{(A-1)}_{\alpha_1} \right\rangle_{SD}$$

$$\propto {}_{SD}\left\langle \psi^{(A-1)}_{\alpha_1'} \middle\| \left(\left(a_h^+ a_i^+ \right)^{g'} a_j^+ \right)^{K'} \middle\| \psi^{(A-4)}_{\beta} \right\rangle_{SD} {}_{SD}\left\langle \psi^{(A-4)}_{\beta} \middle\| \left(\left(a_m a_l \right)^{g} a_k \right)^{K} \middle\| \psi^{(A-1)}_{\alpha_1} \right\rangle_{SD}$$

$$\frac{1}{(A-1)(A-2)(A-3)} \sum_{\substack{j_0 j_0' t_0 t_0' \\ J_0 T_0}} \sum_{\substack{n_a l_a j_a \\ n_b l_b j_b}} \sum_{\substack{n_\alpha l_\alpha j_\alpha \\ n_a' l_a' j_a'}} \sum_{\substack{n_b' l_b' j_b' g' t_g' \\ \alpha_\beta I_\beta T_\beta}} \hat{J}_0 \hat{T}_0 \hat{g}' \hat{t}_g' \left\{ \begin{array}{ccc} I_\beta & g' & I_1' \\ J_0 & j_0' & j' \\ J_1 & j & J \end{array} \right\} \left\{ \begin{array}{ccc} T_\beta & t_g' & T_1' \\ T_0 & t_0' & 1/2 \\ T_1 & 1/2 & T \end{array} \right\}$$

$$(-1)^{j_a'+j_b'+J_0+g'+I_\beta-I_1+j} (-1)^{3/2+T_0+t_g'+T_\beta-T_1}$$

$$\left\langle \left[(n_a' l_a' j_a' {:} n_b' l_b' j_b') j_0' t_0' {:}\ n' l' j' \right] J_0 T_0 \right| V_{A-3\,A-2\,A-1} \left| \left[(n_\alpha l_\alpha j_\alpha {:} n_a l_a j_a) j_0 t_0 {:}\ n_b l_b j_b \right] J_0 T_0 \right\rangle$$

$${}_{SD}\left\langle A-1 \alpha_1' I_1' T_1' \middle|\middle|\middle| \left(a^\dagger_{nlj} \left(a^\dagger_{n_b' l_b' j_b'} a^\dagger_{n_a' l_a' j_a'} \right)^{j_0' t_0'} \right)^{g' t_g'} \middle|\middle|\middle| A-4 \alpha_\beta I_\beta T_\beta \right\rangle_{SD}$$

$${}_{SD}\left\langle A-4 \alpha_\beta I_\beta T_\beta \middle|\middle|\middle| \left(\left(\tilde{a}_{n_\alpha l_\alpha j_\alpha} \tilde{a}_{n_a l_a j_a} \right)^{j_0 t_0} \tilde{a}_{n_b l_b j_b} \right)^{J_0 T_0} \middle|\middle|\middle| A-1 \alpha_1 I_1 T_1 \right\rangle_{SD} .$$

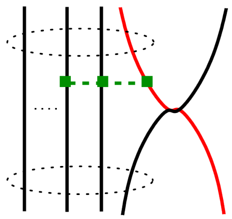
We introduce a closure relationship

These amplitudes can be stored

But only for light nuclei...

Including the NNN force into the NCSM/RGM approach

nucleon-nucleus formalism



(c)

Exchange potential: $\propto {}_{SD}\left\langle \psi_{\alpha_1'}^{(A-1)} \middle| a_h^+ a_i^+ a_j^+ a_m a_l a_k \middle| \psi_{\alpha_1}^{(A-1)} \right\rangle_{SD}$

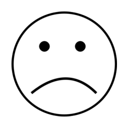
Coming back to NCSM

$$\frac{1}{(A-1)(A-2)(A-3)} \sum_{\substack{n_a l_a j_a \\ n_b l_b j_b}} \sum_{\substack{n_\alpha l_\alpha j_\alpha \\ n_a' l_a' j_a'}} \sum_{\substack{n_b' l_b' j_b' \\ m_j' m_j \cdots}} \sum_{\substack{M_{1'} M_1 \\ M_{T_1'} M_{T_1}}} C^{JM}_{I_1' M_1' \, j' m_j'} C^{JM}_{I_1 M_1 \, j m_j} C^{T M_T}_{T_1' M_{T_1'} \, \frac{1}{2} m_{t'}} C^{T M_T}_{T_1 M_{T_1} \, \frac{1}{2} m_t}$$

$$\langle n_a' l_a' j_a' : n_b' l_b' j_b' : n' l' j' | \, V_{A-3\,A-2\,A-1} \, | n_\alpha l_\alpha j_\alpha : n_a l_a j_a : n_b l_b j_b \rangle$$

$${}_{SD}\left\langle A-1 \alpha_1' I_1' M_1' T_1' M_{T_1'} \middle| a^\dagger_{nlj} a^\dagger_{n_b' l_b' j_b'} a^\dagger_{n_a' l_a' j_a'} a_{n_\alpha l_\alpha j_\alpha} a_{n_a l_a j_a} a_{n_b l_b j_b} \middle| A-1 \alpha_1 I_1 M_1 T_1 M_{T_1} \right\rangle_{SD} .$$

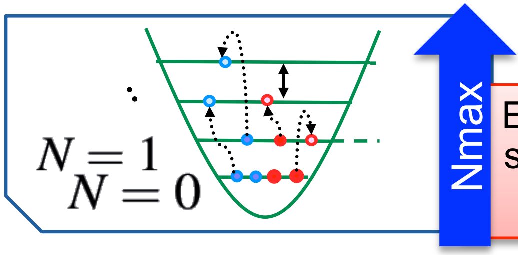
The M-scheme NCSM is a promising path to perform the calculation of the kernels



No Information is stored

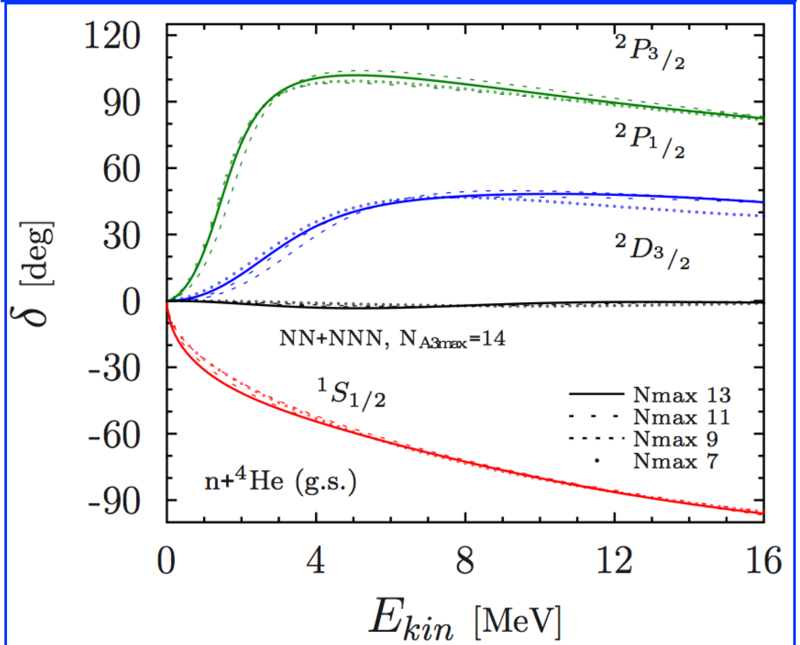
N-^{4}He scattering with NN+NNN interactions

G. Hupin, J. Langhammer, S. Quaglioni, P. Navrátil, R. Roth, work in progress



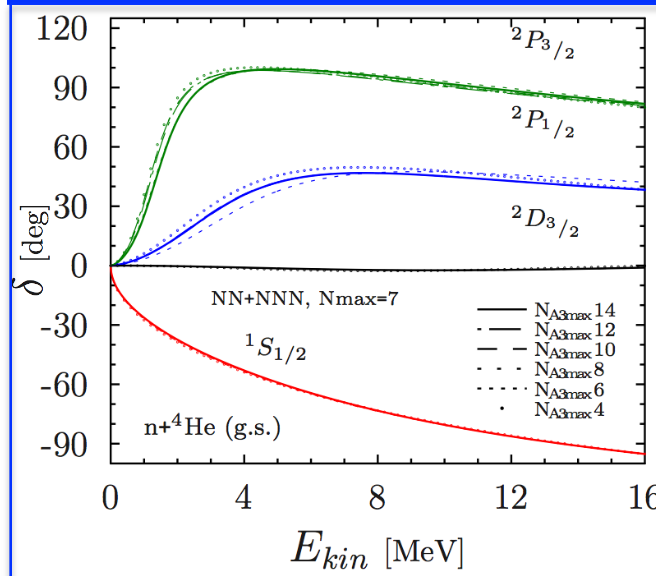
Expanding the size in the HO space.

NNN case: convergence with respect to the number of HO major shells



Convergence of the phase shifts when accounting for ^{4}He excited states.

Model space convergence of the NNN interaction (Target Nmax=7)



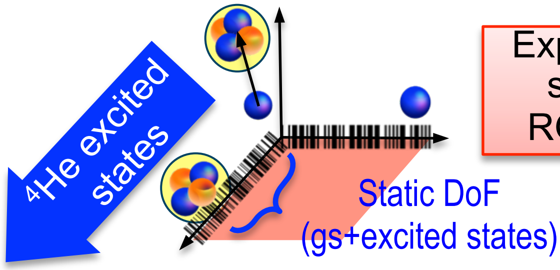
Convergence is ok ✓

Convergence pattern is similar to the NN case.
Also needed: exploration of the λ SRG and ħω parameters (ongoing).

N-^{4}He scattering with NN+NNN interactions

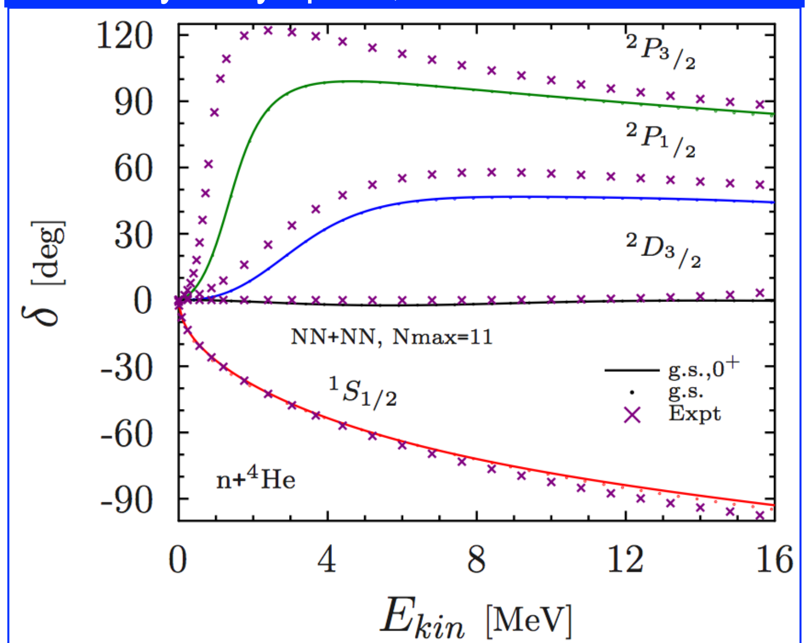
G. Hupin, J. Langhammer, S. Quaglioni, P. Navrátil, R. Roth, work in progress

Navrátil and Quaglioni, PRC83 044609, (2011)

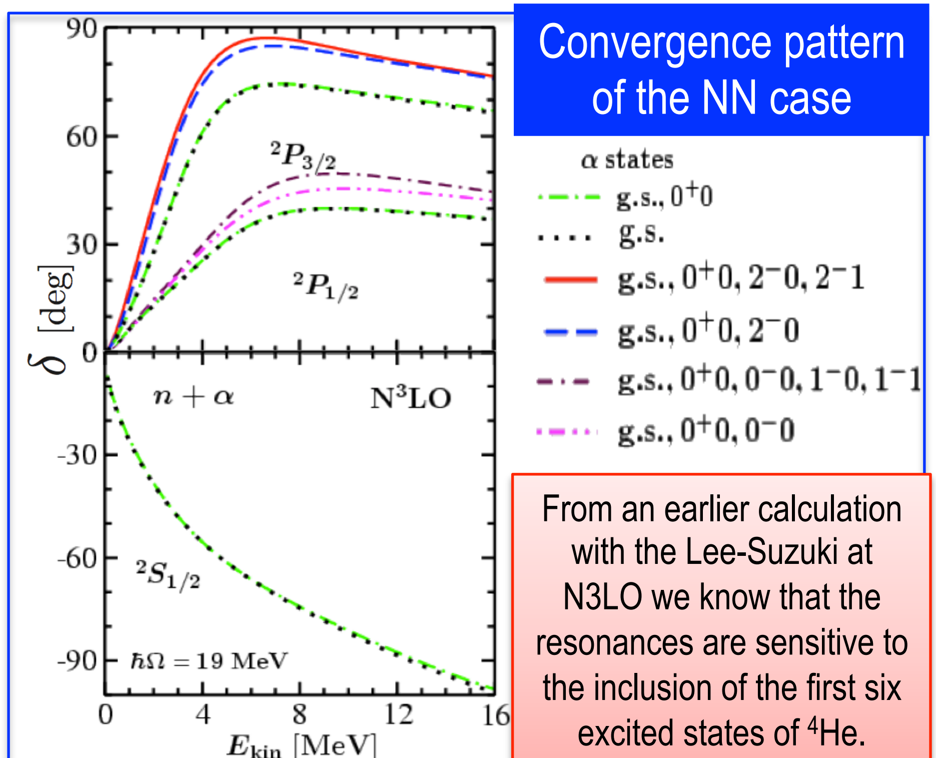


Expanding the size in the RGM space.

NNN case: convergence with respect to the many body space, first excited states



Convergence of the phase shifts when accounting for ^{4}He excited states.



Convergence pattern of the NN case

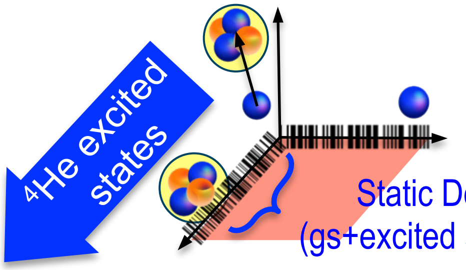
From an earlier calculation with the Lee-Suzuki at N3LO we know that the resonances are sensitive to the inclusion of the first six excited states of ^{4}He.

Convergence pattern seems to be similar to the NN case.
A systematic exploration of the Nmax and # of target eigenstates is ongoing.

N-^{4}He scattering with NN+NNN interactions

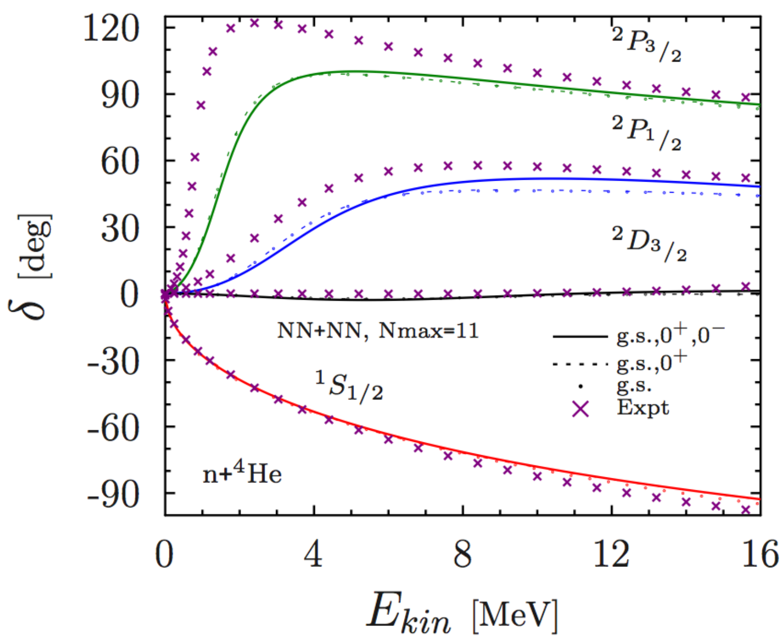
G. Hupin, J. Langhammer, S. Quaglioni, P. Navrátil, R. Roth, work in progress

Navrátil and Quaglioni, **PRC83 044609, (2011)**



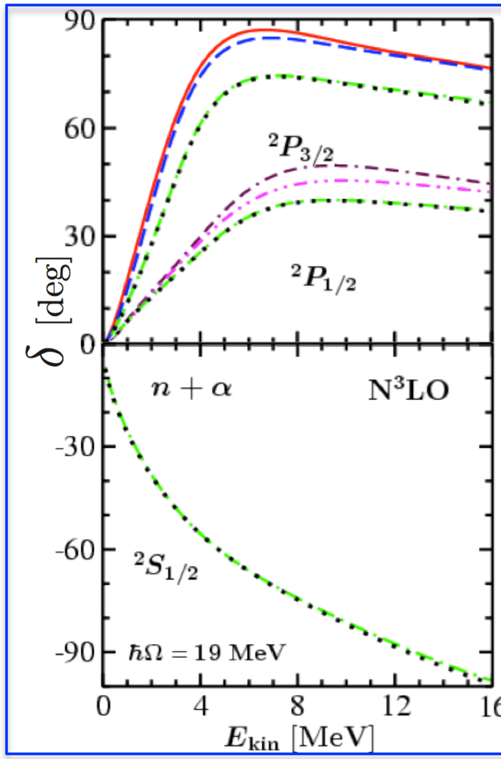
Expanding the size in the RGM space.

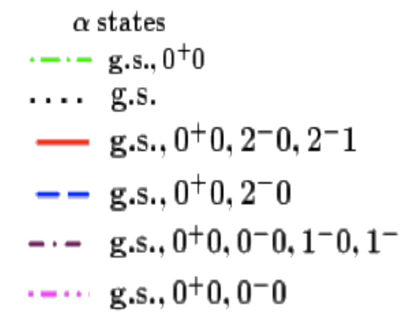
NNN case: convergence with respect to the many body space, first excited states



Convergence of the phase shifts when accounting for ^{4}He excited states.

Convergence pattern of the NN case





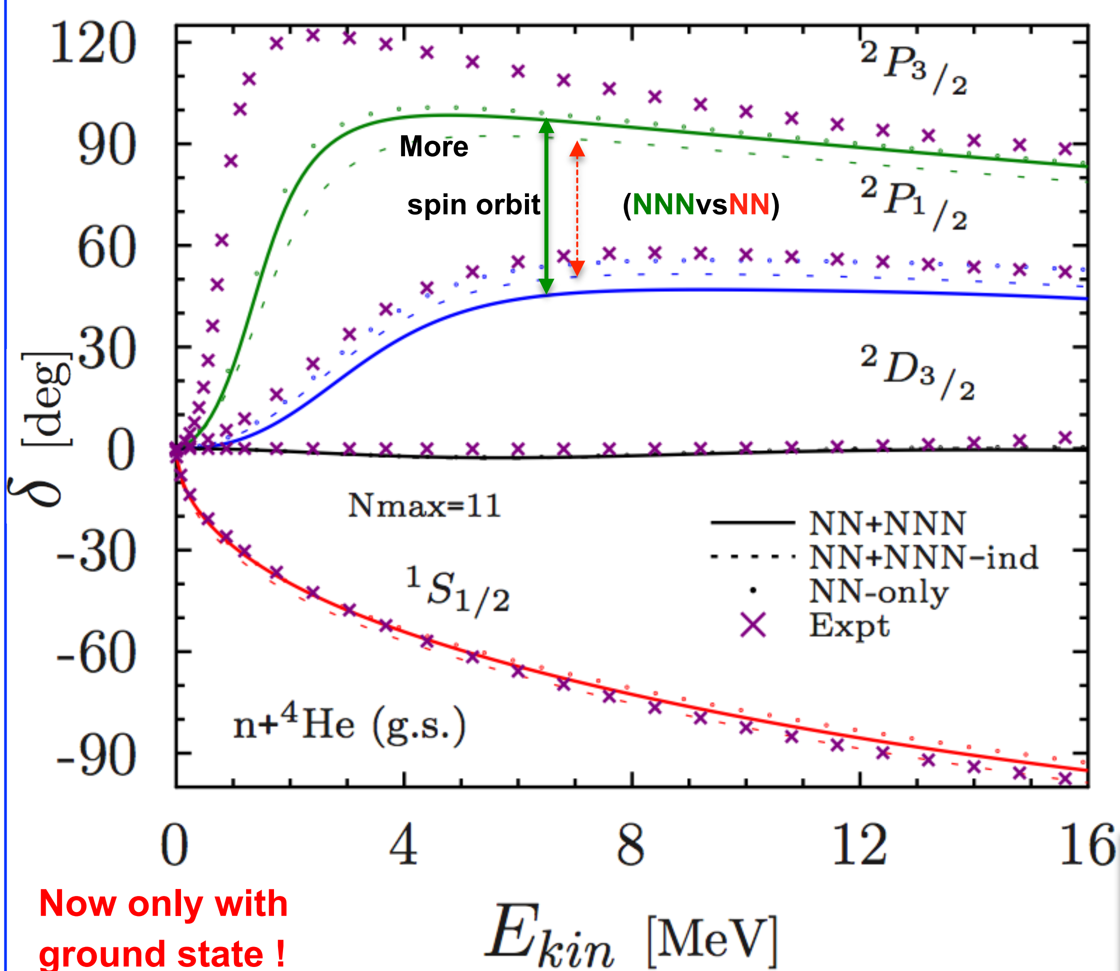
From an earlier calculation with the Lee-Suzuki at N3LO we know that the resonances are sensitive to the inclusion of the first six excited states of ^{4}He.

Convergence pattern seems to be similar to the NN case.
A systematic exploration of the Nmax and # of target eigenstates is ongoing.

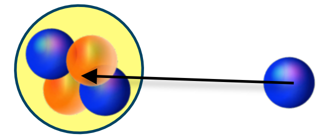
N-^{4}He scattering: NN versus NNN interactions, first results

G. Hupin, J. Langhammer, S. Quaglioni, P. Navrátil, R. Roth, work in progress

Nuclear interaction NN→NN+NNN



Now only with ground state !



n on ^{4}He scattering

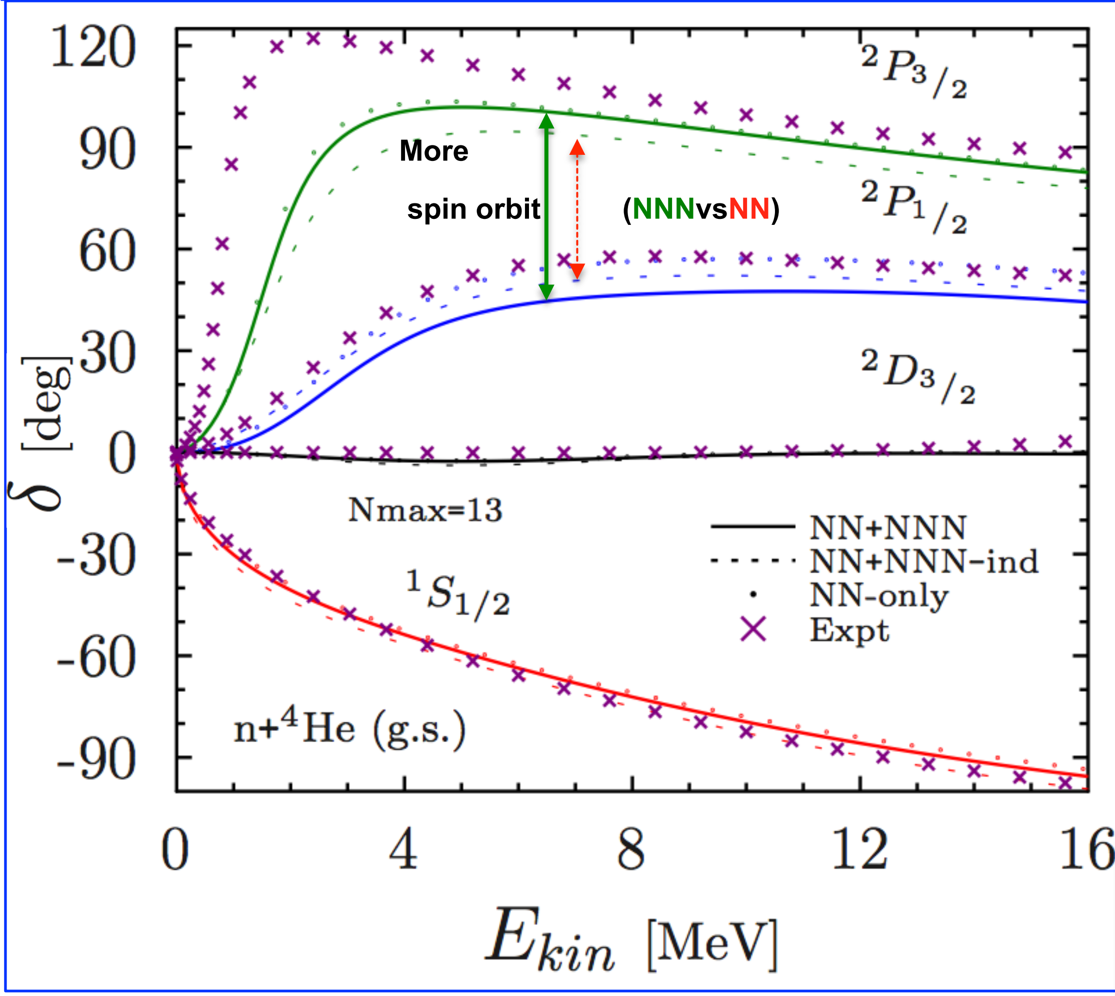
The largest splitting between *P* waves is obtained with NN +NNN.
The NN only agrees better than the full NN interaction (NN +NNN-ind).
Static DoF should be explored.

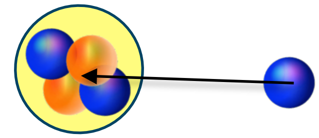
Comparison between NN, NN +NNN-ind and NN+NNN at Nmax=11

N-^{4}He scattering: NN versus NNN interactions, first results

G. Hupin, J. Langhammer, S. Quaglioni, P. Navrátil, R. Roth, work in progress

Nuclear interaction NN→NN+NNN





n on ^{4}He scattering

The largest splitting between *P* waves is obtained with NN +NNN.

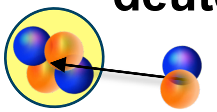
The NN only agrees better than the full NN interaction (NN +NNN-ind).

Static DoF should be explored.

Comparison between NN, NN +NNN-ind and NN+NNN at Nmax=13

Including the NNN force into the NCSM/RGM approach

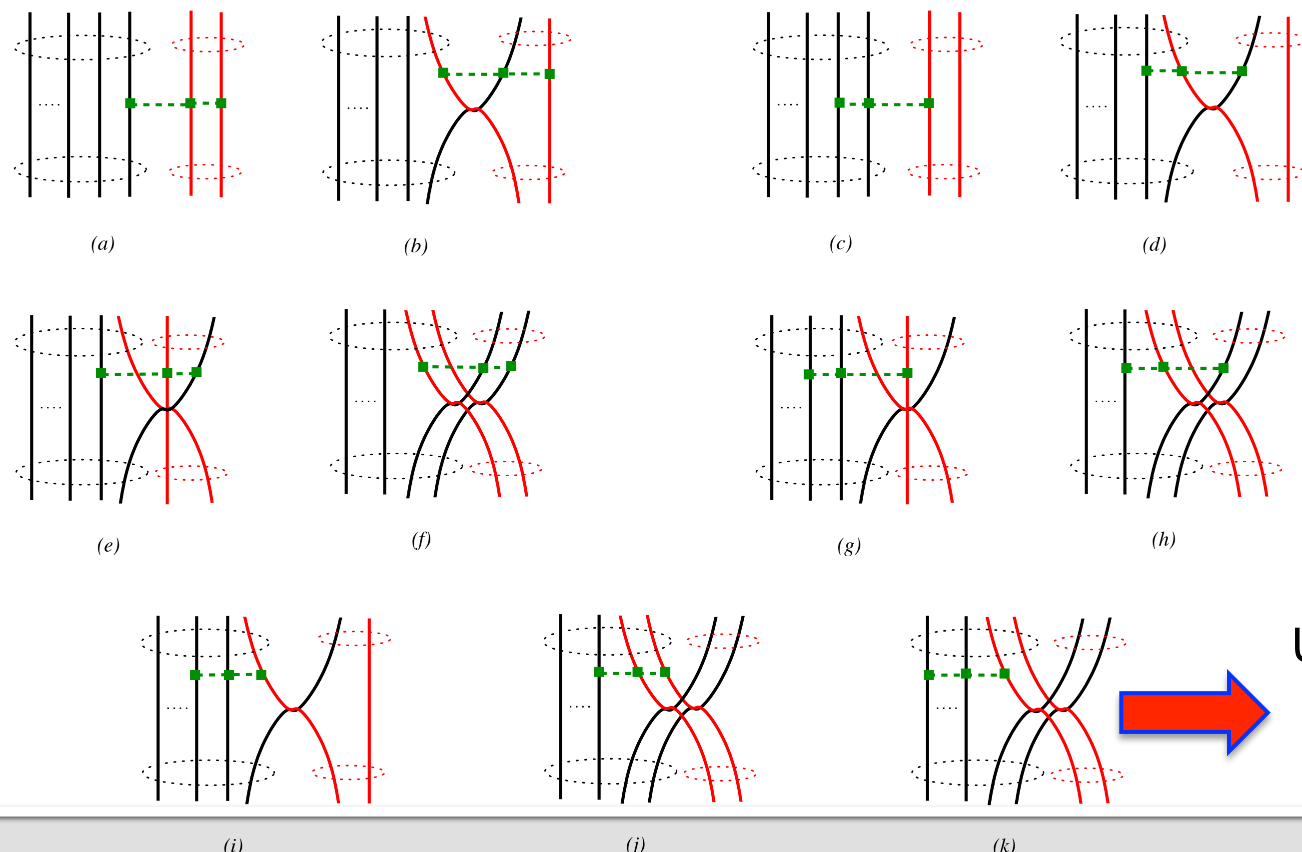
deuteron-nucleus formalism



$$\left\langle \Phi^{J^\pi T}_{\nu' r'} \middle| \hat{A}_{\nu'} V^{NNN} \hat{A}_{\nu} \middle| \Phi^{J^\pi T}_{\nu r} \right\rangle = \left\langle \begin{matrix}(A-2)\\ r' \\ (a'=2)\end{matrix} \middle| V^{NNN}\left(1 - \sum_{i=1}^{A-2}\sum_{k=A-1}^{A} \hat{P}_{i,k} + \sum_{i<j=1}^{A-2} \hat{P}_{i,A-1}\hat{P}_{j,A}\right) \middle| \begin{matrix}(A-2)\\ r \\ (a=2)\end{matrix} \right\rangle$$

Direct

Exchange

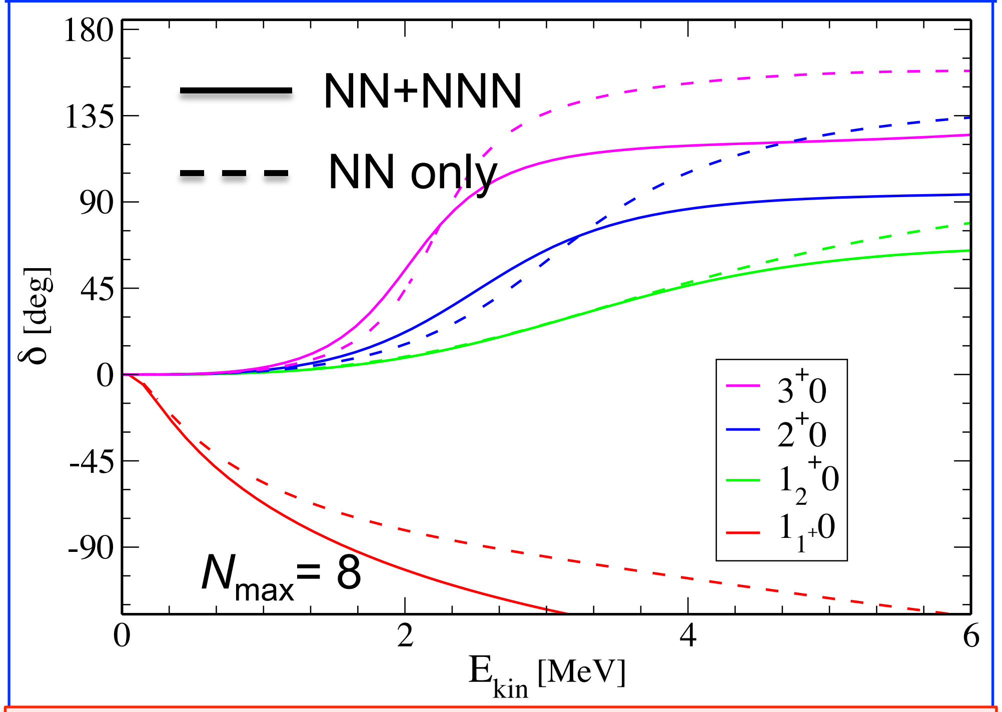


Up to four body density

^{4}He(d,d)^{4}He with SRG-evolved chiral NN+NNN force

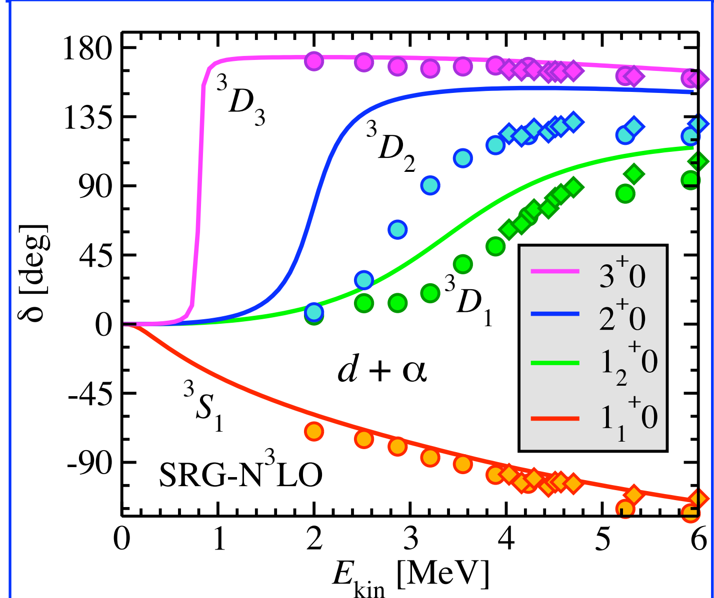
G. Hupin, S. Quaglioni, P. Navratil, work in progress

Phase shifts with λ= 2 fm^{-1}

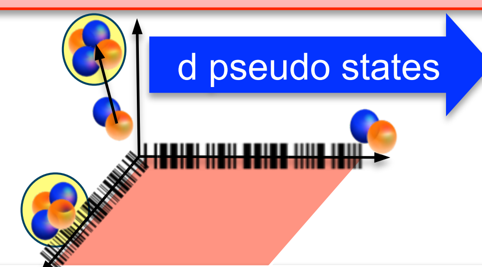


d(g.s.) + ^{4}He(g.s.) scattering phase shifts for SRG- NN +NNN potential with λ=2 fm^{-1}.

Phase shifts with λ= 1.5 fm^{-1}



N_{max}= 12 d(g.s.,$^3S_1$-$^3D_1$, $^3D_2$, $^3D_3$-$^3G_3$) + ^{4}He(g.s.) SRG-N^{3}LO NN potential with λ=1.5 fm^{-1}.



Preliminary results in a small model space and with only d and 4He g.s., look promising

Conclusions and Outlook

- With the NCSM/RGM approach we are extending the *ab initio* effort to describe low-energy reactions and weakly-bound systems
- Ability to describe:
  - Nucleon-nucleus collisions
  - Deuterium-nucleus collisions
  - (*d*,*N*) transfer reactions
  - ^{3}H- and ^{3}He-nucleus collisions
- Recent results with SRG-N^{3}LO NN pot.:
  - ^{3}H(n,n)^{3}H, ^{4}He(d,d)^{4}He, ^{3}H(d,n)^{4}He, ^{3}He(d,p)^{4}He, ^{7}Be(p,γ)^{8}B
- Work in progress
  - Inclusion of NNN force in nucleon-nucleus formalism: applications to N+^{4}He
  - Calculation of ^{4}He+p → ^{4}He+p+γ bremsstrahlung process

Thanks to my collaborators:

S. Quaglioni *(LLNL)*
P. Navrátil *(TRIUMF,LLNL)*
R. Roth *(TU Darmstadt)*
J. Langhammer *(TU Darmstadt)*
W. Horiuchi *(Hokkaido Univ.)*