Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Ab initio calculations of light-ion reactions

Workshop on "Electron-Nucleus Scattering XII"
June 25-29, 2012
Elba, Italy

Petr Navratil | TRIUMF

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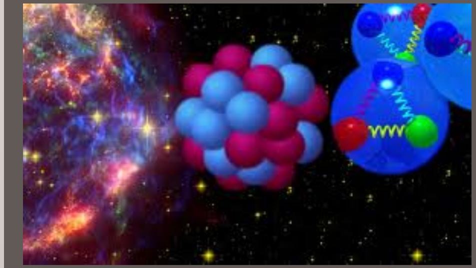
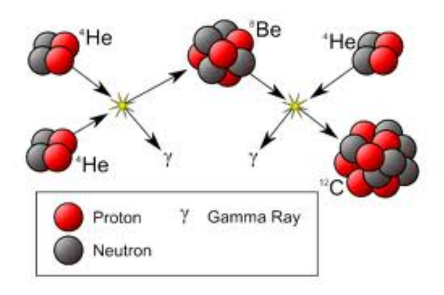
J. Langhammer (TU Darmstadt), G. Hupin (LLNL)

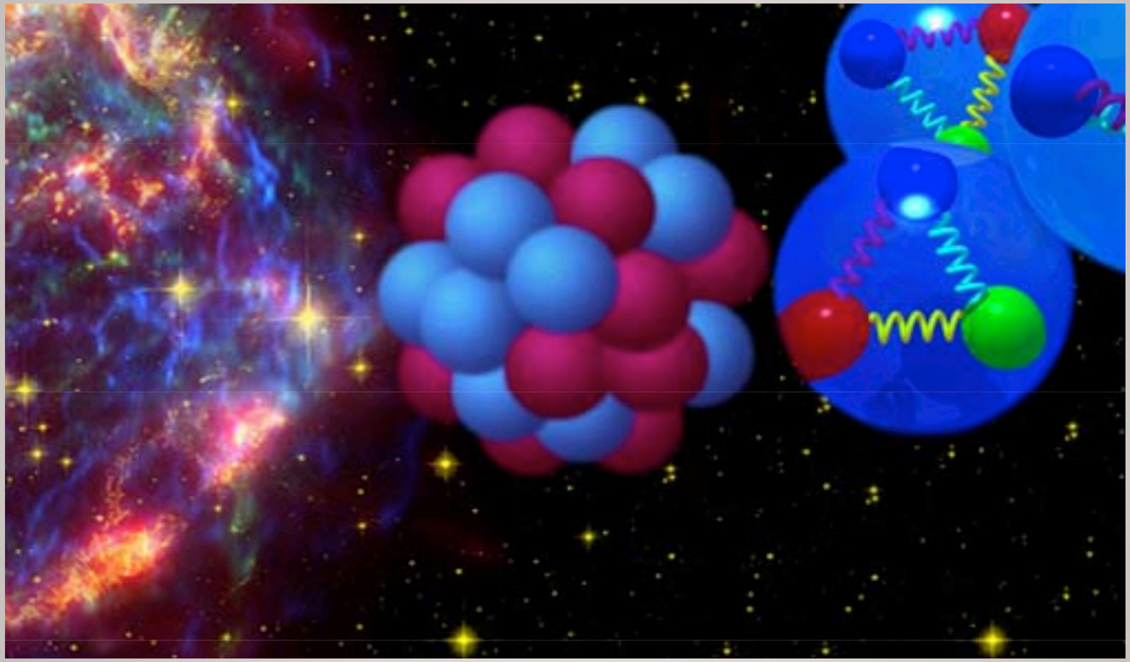

Marciana Marina, Isola d'Elba, Italy.





Outline

Connection to Astrophysics

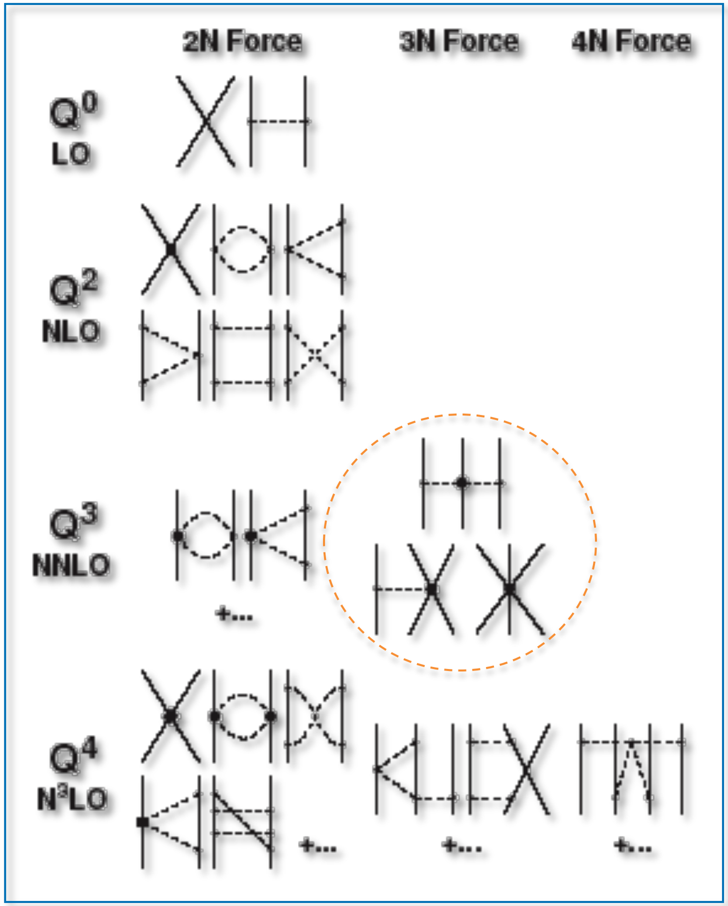


Connection to QCD

- Nuclear forces – from chiral EFT
- Many-body techniques – NCSM, NCSM/RGM
- Results for bound states, resonances, reactions

Nuclei from the first principles

- **First principles for Nuclear Physics:** **QCD**
  - Non-perturbative at low energies
  - Lattice QCD in the future
- ***For now a good place to start:***
- Inter-nucleon forces from chiral effective field theory
  - Based on the symmetries of QCD
    - Degrees of freedom: nucleons + pions
  - Systematic low-momentum expansion to a given order
  - Hierarchy
  - Consistency
  - Low energy constants (LEC)
    - Fitted to data
    - Can be calculated by lattice QCD



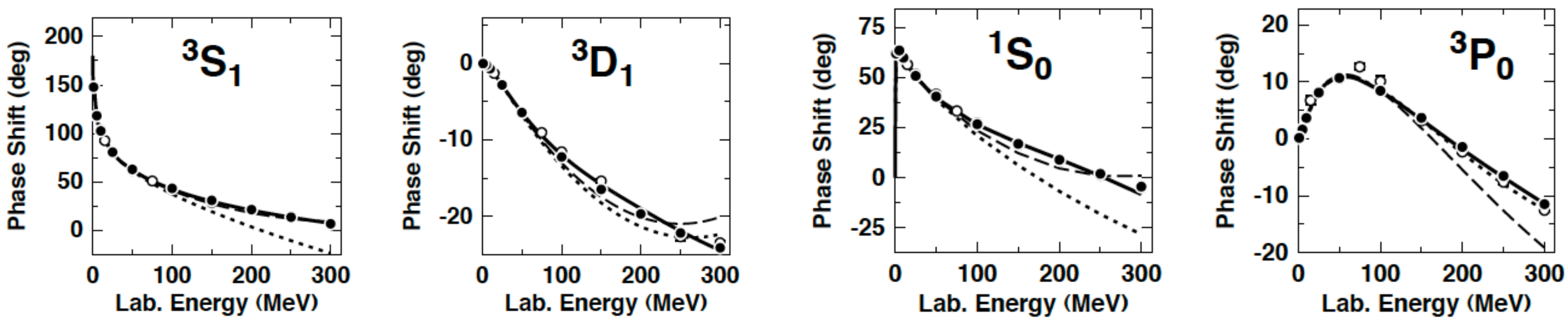
TRIUMF

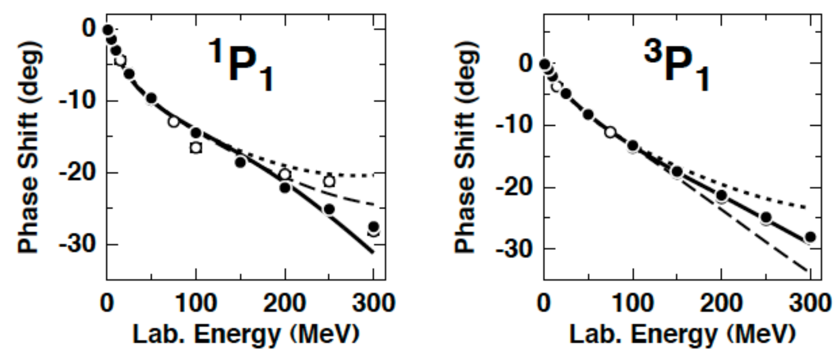
The NN interaction from chiral EFT

PHYSICAL REVIEW C **68**, 041001(R) (2003)

Accurate charge-dependent nucleon-nucleon potential at fourth order of chiral perturbation theory

D. R. Entem[1,2,*] and R. Machleidt[1,†]

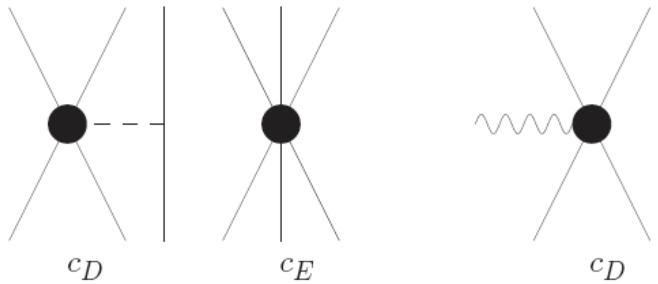




- 24 LECs fitted to the *np* scattering data and the deuteron properties
  - Including c_i LECs (i=1-4) from pion-nucleon Lagrangian

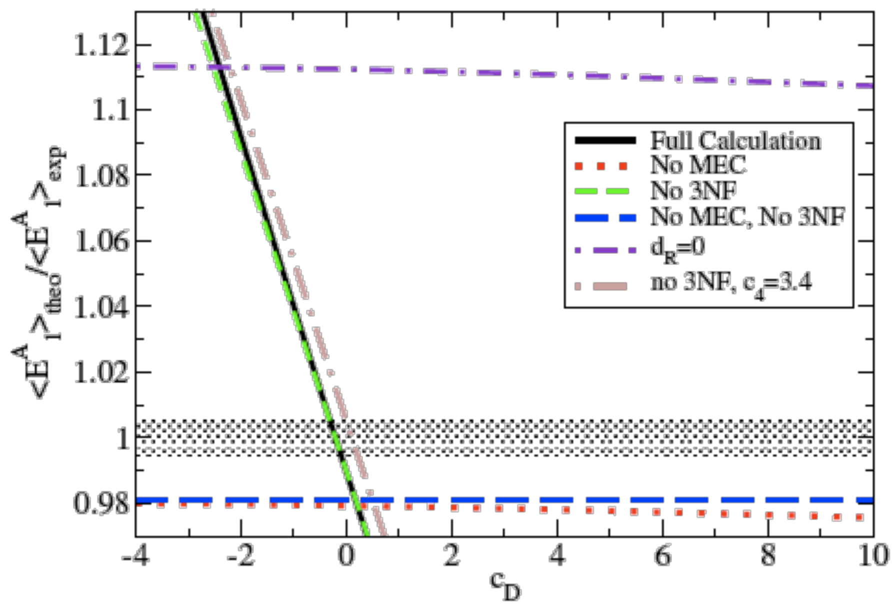
Determination of NNN LECs c_D and c_E from the triton binding energy and the half life

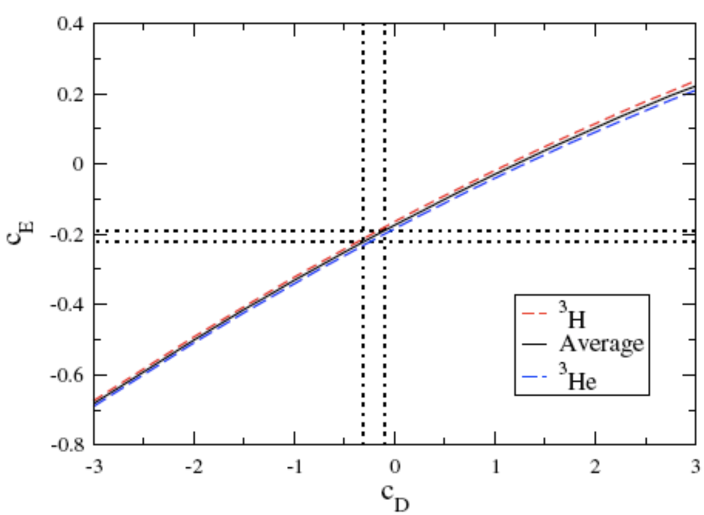
- **Chiral EFT**: c_D also in the two-nucleon contact vertex with an external probe
- Calculate $\langle E_1^A \rangle = |\langle {}^3\mathrm{He} || E_1^A || {}^3\mathrm{H} \rangle|$
  - Leading order GT
  - N^2LO: one-pion exchange plus contact

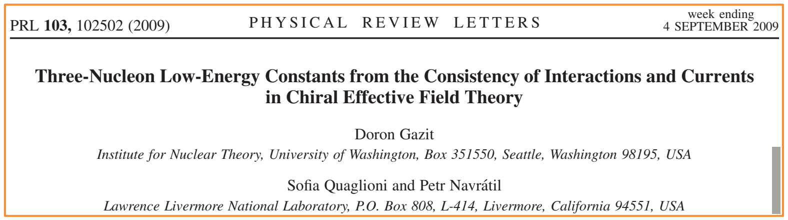


- *A*=3 binding energy constraint:

c_D=-0.2±0.1 c_E =-0.205±0.015






PRL **103**, 102502 (2009) PHYSICAL REVIEW LETTERS week ending 4 SEPTEMBER 2009

Three-Nucleon Low-Energy Constants from the Consistency of Interactions and Currents in Chiral Effective Field Theory

Doron Gazit

Institute for Nuclear Theory, University of Washington, Box 351550, Seattle, Washington 98195, USA

Sofia Quaglioni and Petr Navrátil

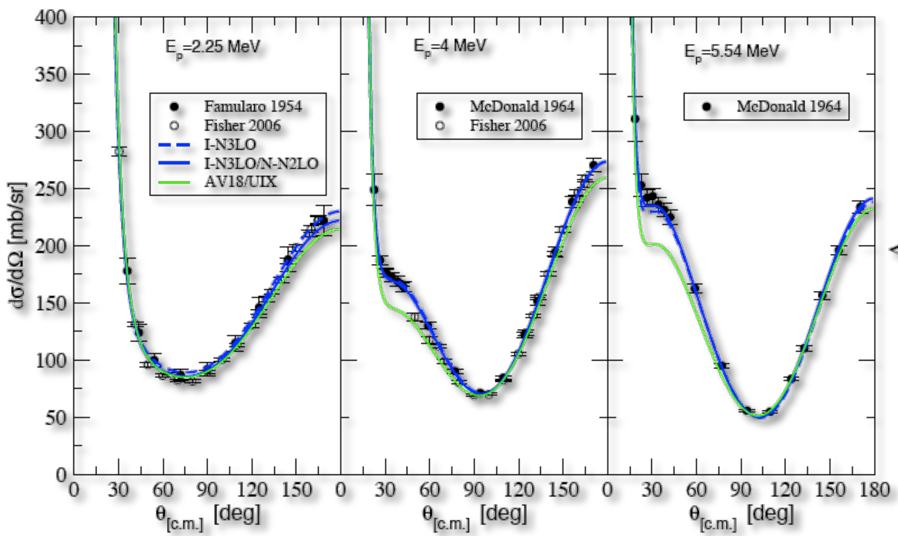
Lawrence Livermore National Laboratory, P.O. Box 808, L-414, Livermore, California 94551, USA

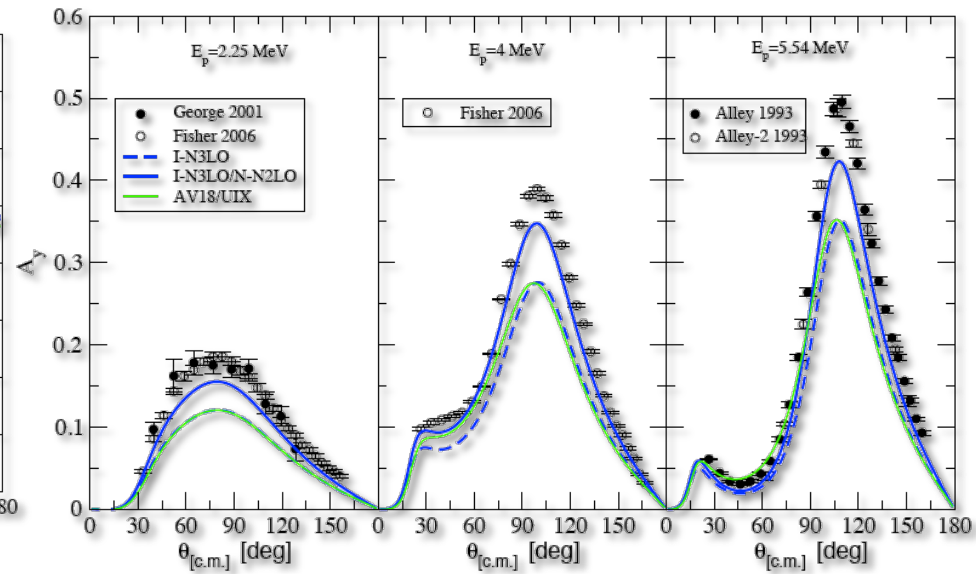
A=3,4 bound states

	^{3}H		^{3}He		^{4}He	
	$E_{g.s.}$	$\langle r_p^2 \rangle^{1/2}$	$E_{g.s}$	$\langle r_p^2 \rangle^{1/2}$	$E_{g.s}$	$\langle r_p^2 \rangle^{1/2}$
NN	−7.852(4)	1.651(5)	−7.124(4)	1.847(5)	−25.39(1)	1.515(2)
$NN + NNN$	−8.473(4)	1.605(5)	−7.727(4)	1.786(5)	−28.50(2)	1.461(2)
Expt.	−8.482	1.60	−7.718	1.77	−28.296	1.467(13) [31]

Proton-^{3}He elastic scattering with χEFT NN+NNN

- Variational calculations in hypherspherical-harmonics basis
  - M. Viviani, L. Girlanda, A. Kievski, L. E. Marcucci, and S. Rosati, arXiv:1004.1306
- ***A*$_y$ puzzle resolved** with the chiral N^{3}LO NN plus **local chiral N^{2}LO NNN**



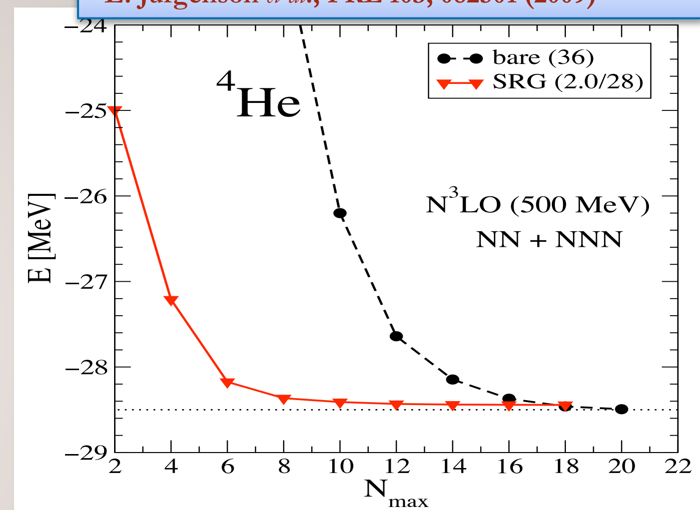


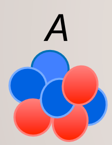
Chiral NN+NNN Hamiltonian provides the best agreement with the cross section and analyzing power data and with the new TUNL PSA analysis

No-core shell model combined with the resonating group method (NCSM/RGM)

- **The NCSM:** An approach to the solution of the *A*-nucleon bound-state problem
  - Accurate nuclear Hamiltonian
  - Finite harmonic oscillator (HO) basis
    - Complete $N_{max}\hbar\Omega$ model space
  - Effective interaction due to the model space truncation
    - Similarity-Renormalization-Group evolved NN(+NNN) potential
  - Short & medium range correlations
  - No continuum

E. Jurgenson *et al.*, PRL 103, 082501 (2009)

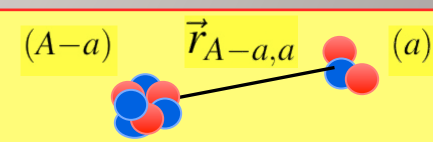




$$\Psi^A = \sum_{N=0}^{N_{max}} \sum_i c_{Ni} \Phi^A_{Ni}$$

- **The RGM:** A microscopic approach to the A-nucleon scattering of clusters
  - Long range correlations, relative motion of clusters

$$\Psi^{(A)} = \sum_\nu \int d\vec{r}\, \varphi_\nu(\vec{r})\, \hat{\mathcal{A}}\, \Phi^{(A-a,a)}_{\nu\vec{r}}$$



$$\psi^{(A-a)}_{1\nu}\, \psi^{(a)}_{2\nu}\, \delta(\vec{r} - \vec{r}_{A-a,a})$$

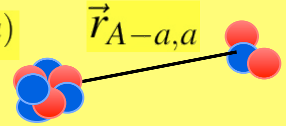
***Ab initio* NCSM/RGM**: Combines the best of both approaches
Accurate nuclear Hamiltonian, consistent cluster wave functions
Correct asymptotic expansion, Pauli principle and translational invariance

TRIUMF

The *ab initio* NCSM/RGM in a snapshot

- Ansatz: $\Psi^{(A)} = \sum_{\nu} \int d\vec{r}\, \varphi_{\nu}(\vec{r})\, \hat{\mathcal{A}}\, \Phi^{(A-a,a)}_{\nu\vec{r}}$

$(A-a)$ $\quad \vec{r}_{A-a,a} \quad$ (a)



$$\psi^{(A-a)}_{1\nu}\, \psi^{(a)}_{2\nu}\, \delta(\vec{r} - \vec{r}_{A-a,a})$$

eigenstates of $H_{(A\text{-}a)}$ and $H_{(a)}$ in the *ab initio* NCSM basis

- Many-body Schrödinger equation:

$$H\Psi^{(A)} = E\Psi^{(A)}$$

$$T_{\rm rel}(r) + \mathcal{V}_{\rm rel} + \bar{V}_{\rm Coul}(r) + H_{(A-a)} + H_{(a)}$$

realistic nuclear Hamiltonian

$$\sum_{\nu} \int d\vec{r} \left[\mathcal{H}^{(A-a,a)}_{\mu\nu}(\vec{r}\,', \vec{r}) - E\mathcal{N}^{(A-a,a)}_{\mu\nu}(\vec{r}\,', \vec{r}) \right] \varphi_{\nu}(\vec{r}) = 0$$

$$\langle \Phi^{(A-a,a)}_{\mu\vec{r}\,'} | \hat{\mathcal{A}} H \hat{\mathcal{A}} | \Phi^{(A-a,a)}_{\nu\vec{r}} \rangle$$

Hamiltonian kernel

$$\langle \Phi^{(A-a,a)}_{\mu\vec{r}\,'} | \hat{\mathcal{A}}^2 | \Phi^{(A-a,a)}_{\nu\vec{r}} \rangle$$

Norm kernel

Norm kernel (Pauli principle)

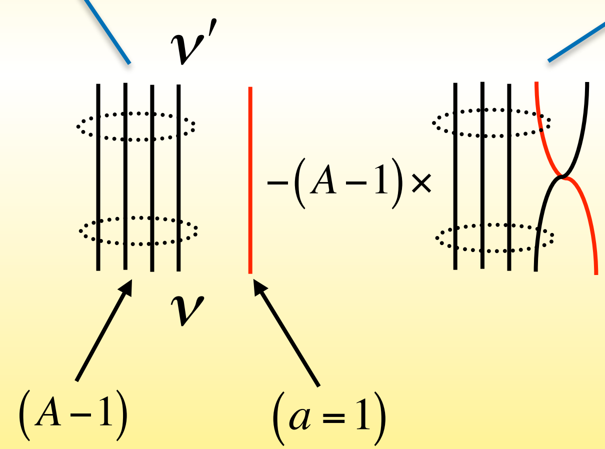
Single-nucleon projectile

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

$$N^{J^\pi T}_{\nu'\nu}(r', r) = \delta_{\nu'\nu} \frac{\delta(r'-r)}{r' r} - (A-1) \sum_{n'n} R_{n'\ell'}(r') R_{n\ell}(r) \left\langle \Phi^{J^\pi T}_{\nu' n'} \right| \hat{P}_{A-1,A} \left| \Phi^{J^\pi T}_{\nu n} \right\rangle$$

$${}_{SD}\left\langle \psi^{(A-1)}_{\mu_1} \right| a^+ a \left| \psi^{(A-1)}_{\nu_1} \right\rangle_{SD}$$

Direct term:
Treated exactly!
(in the full space)



Exchange term:
Obtained in the model space!
(Many-body correction due to the exchange part of the inter-cluster antisymmetrizer)

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

Hamiltonian kernel (projectile-target potentials)

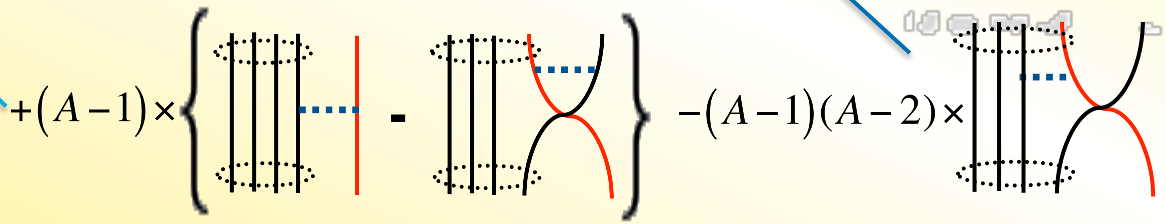
Single-nucleon projectile

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

$$H^{J^\pi T}_{\nu'\nu}(r',r) = \left[T_{rel}(r) + \bar{V}_{Coul}(r) + \varepsilon^{I_1'^{\pi_1'} T_1'}_{\alpha_1'}\right] N^{J^\pi T}_{\nu'\nu}(r',r)$$

$$+ (A-1)\sum_{n'n} R_{n'\ell'}(r') R_{n\ell}(r) \left\langle \Phi^{J^\pi T}_{\nu' n'} \right| V_{A-1,A}\left(1-\hat{P}_{A-1,A}\right) \left| \Phi^{J^\pi T}_{\nu n} \right\rangle$$

$$- (A-1)(A-2)\sum_{n'n} R_{n'\ell'}(r') R_{n\ell}(r) \left\langle \Phi^{J^\pi T}_{\nu' n'} \right| \hat{P}_{A-1,A} V_{A-2,A-1} \left| \Phi^{J^\pi T}_{\nu n} \right\rangle$$



Direct potential: in the model space (interaction is localized!)

Exchange potential: in the model space

TRIUMF

Solving the RGM equations

- Input: Realistic nuclear Hamiltonian, eigenfunctions of nucleon clusters
  - Macroscopic degrees of freedom: nucleon clusters
  - Unknowns: relative wave function between the two clusters
- Non-local integral-differential coupled-channel equations:

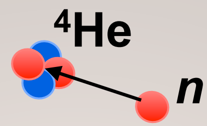
$$\left[T_{rel}(r) + V_C(r) + E_{\alpha_1}^{(A-a)} + E_{\alpha_2}^{(a)}\right] u_\nu^{(A-a,a)}(r) + \sum_{a'\nu'} \int dr' r' \, W_{a\nu,a'\nu'}(r,r') u_{\nu'}^{(A-a',a')}(r') = 0$$

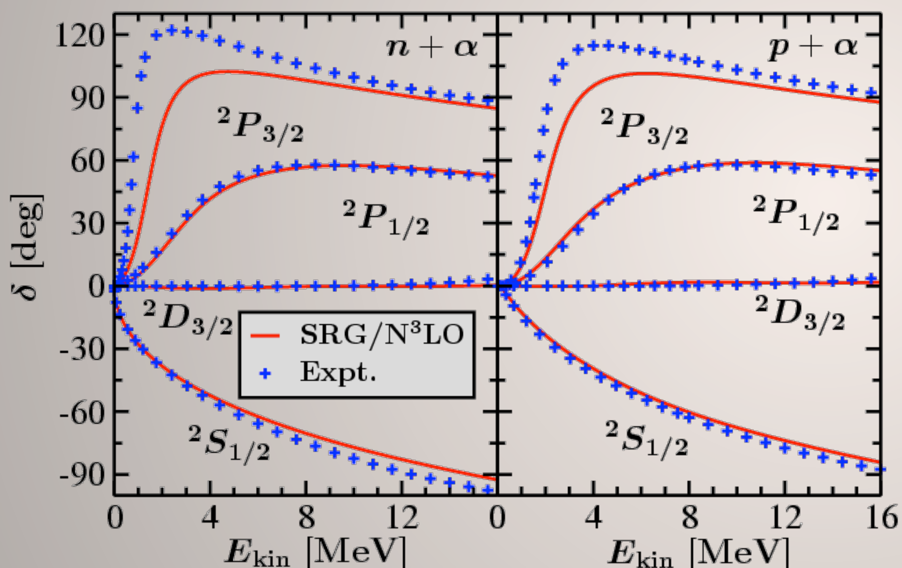
- Solve with R-matrix theory on Lagrange mesh imposing
  - Bound state boundary conditions ➔ eigenenergy + eigenfunction
  - Scattering state boundary conditions ➔ Scattering matrix
    - Phase shifts
    - Cross sections
    - …

The R-matrix theory on Lagrange mesh is an elegant and powerful technique, particularly for calculations with non-local potentials

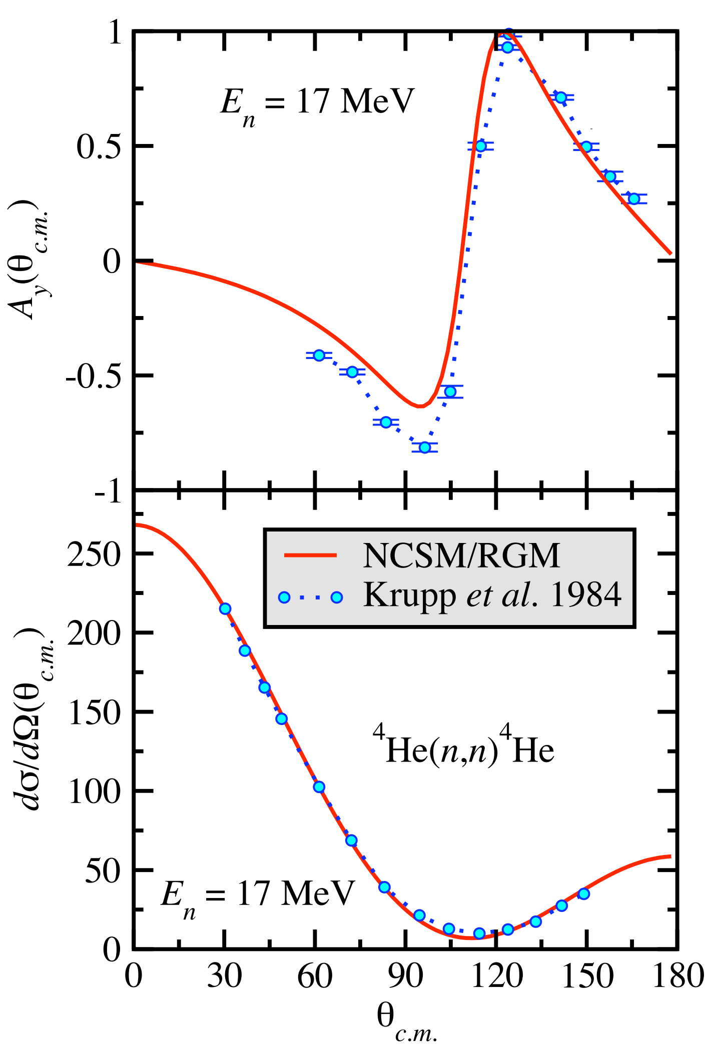
The best system to start with: n+^{4}He, p+^{4}He

- NCSM/RGM calculations with
  - N + ^{4}He(g.s., 0$^+$0)
  - SRG-N^{3}LO NN potential with Λ=2.02 fm^{-1}



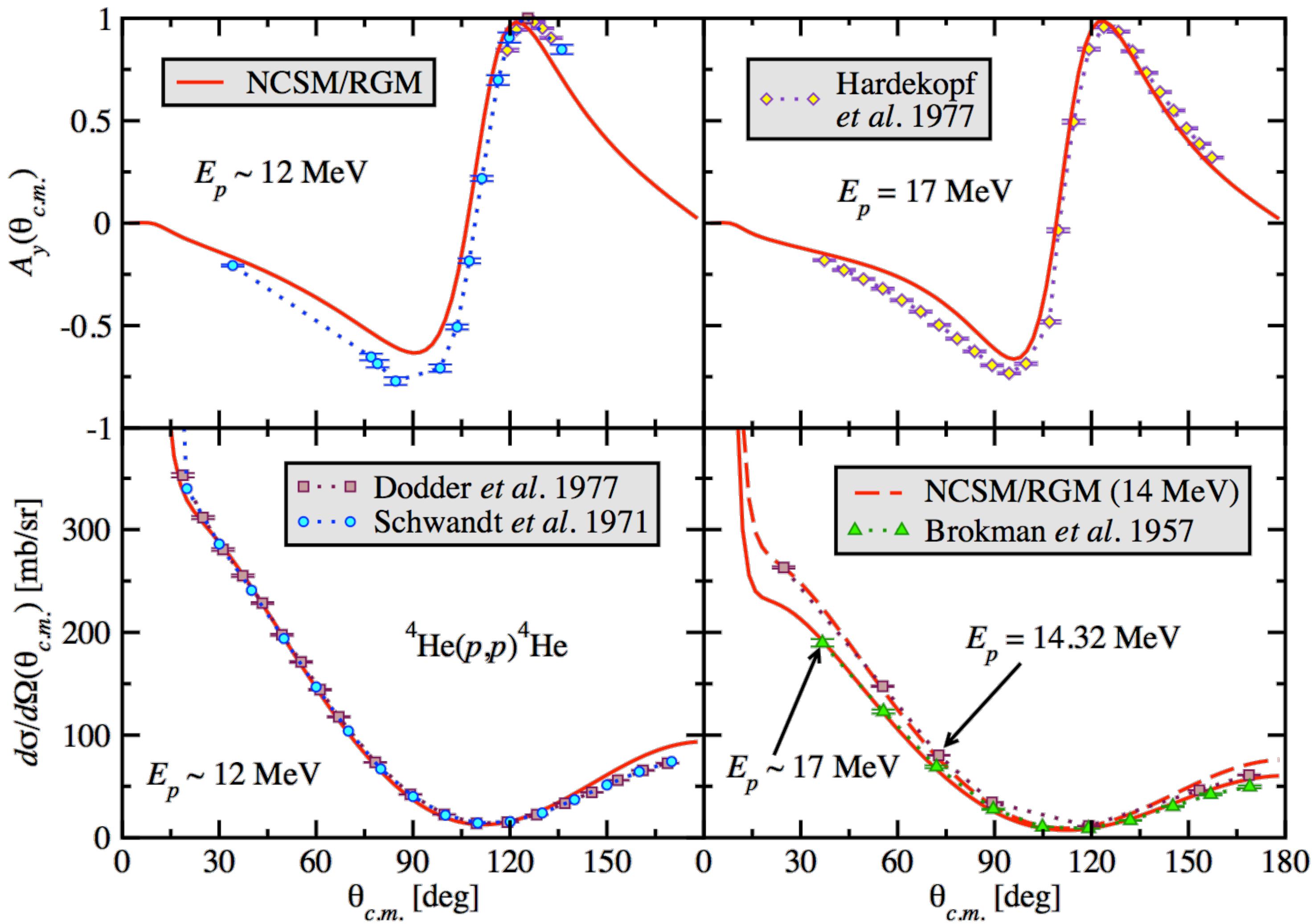


- Differential cross section and analyzing power @17 MeV neutron energy
  - Polarized neutron experiment at Karlsruhe



NNN missing: Good agreement only for energies beyond low-lying 3/2$^-$ resonance

p+^{4}He differential cross section and analyzing power

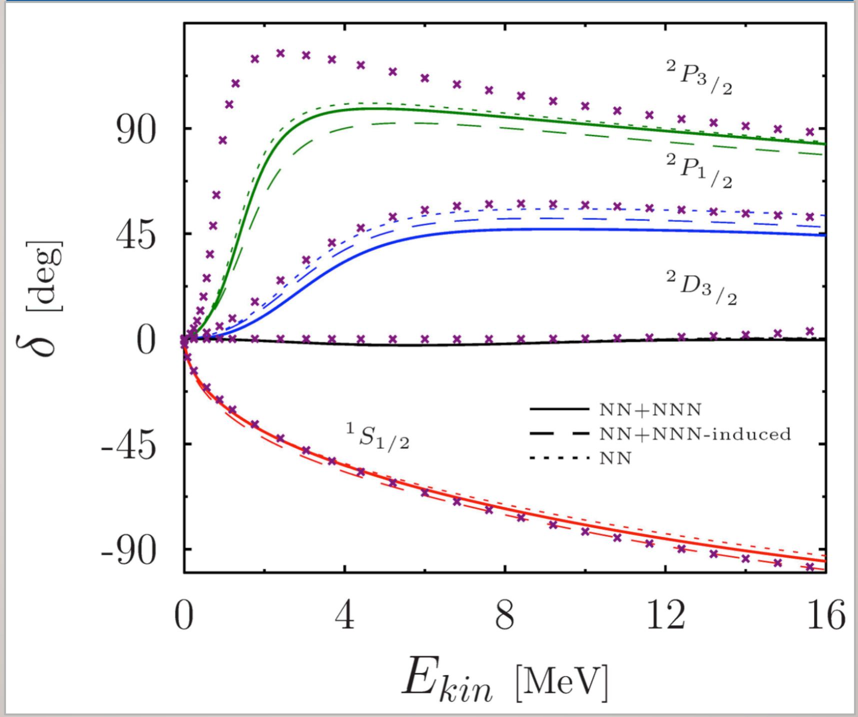


N-^{4}He scattering with NN+NNN interactions

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

n + ^{4}He(g.s.), SRG-(N^{3}LO NN + N^{2}LO NNN potential with (λ=2 fm^{-1}).

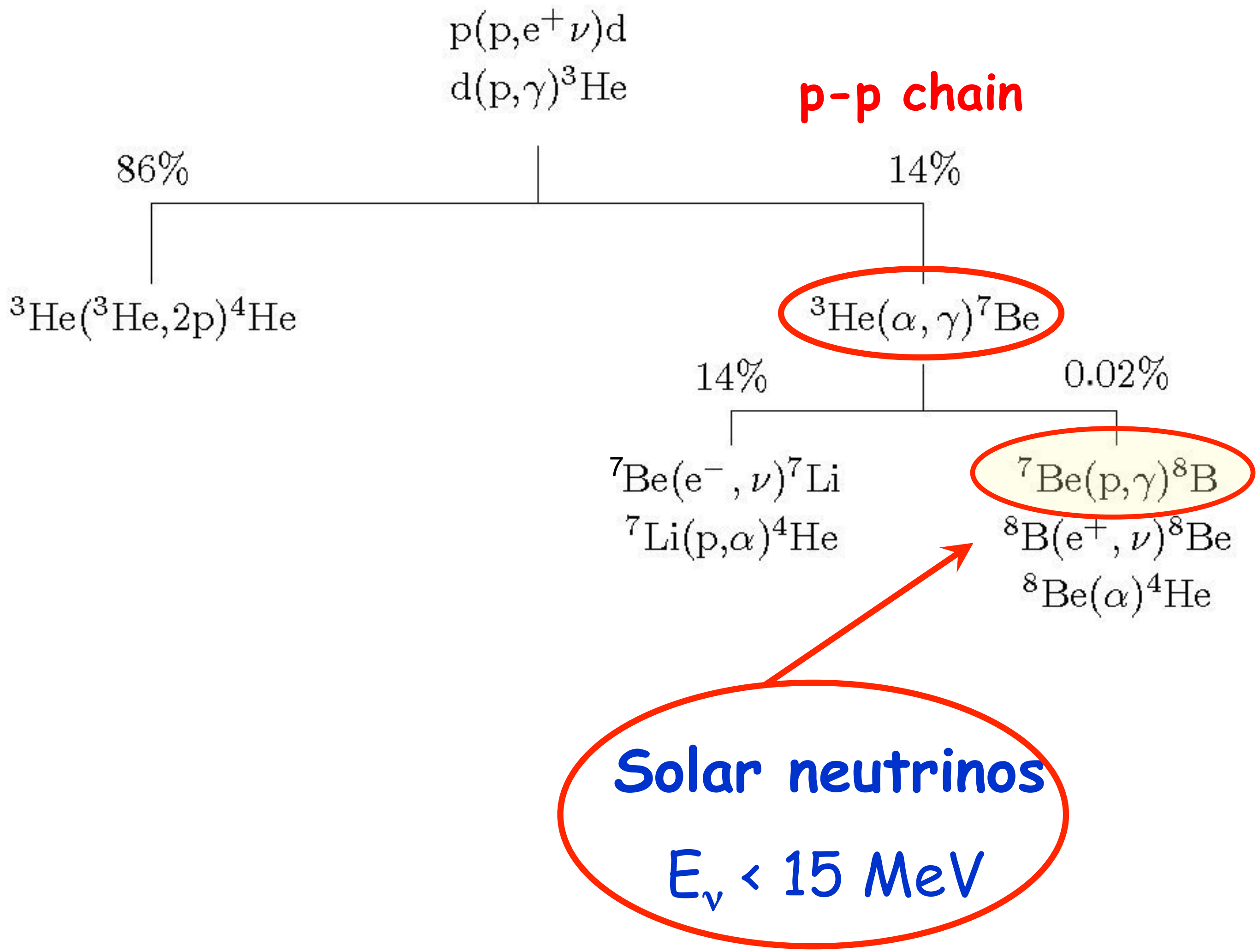
^{4}He(n,n)^{4}He phase shifts



Largest splitting between *P* waves obtained with NN+NNN. Need ^{4}He exited states and study with respect to SRG λ

TRIUMF

Solar *p-p* chain



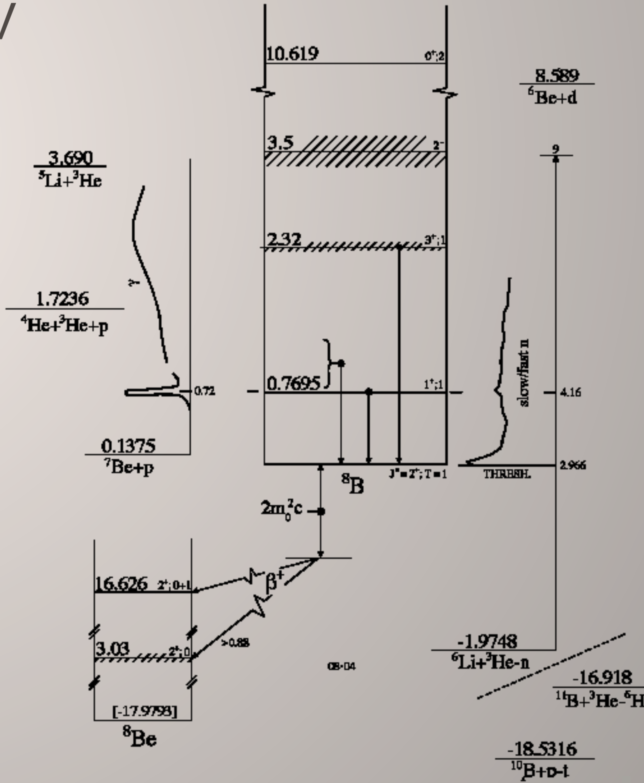
$^7Be(p,\gamma)^8B$ S-factor

- S_{17} one of the main inputs for understanding the solar neutrino flux
  - Needs to be known with high precision
- Current evaluation has uncertainty ~ 10%
  - Theory needed for extrapolation to ~ 10 keV

$$S(E) = E\sigma(E)\exp[2\pi\eta(E)]$$

$$\eta(E) = Z_{A-a}Z_a e^2/\hbar v_{A-a,a}$$

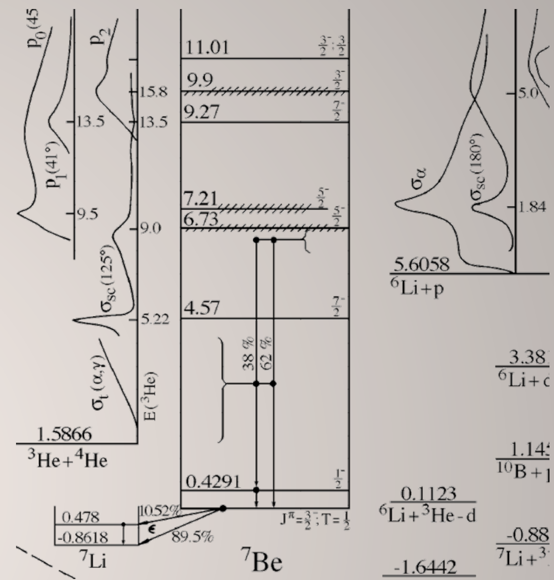
$$\left\langle {}^8\mathrm{B}_{\mathrm{g.s.}} \left| E1 \right| {}^7\mathrm{Be}_{\mathrm{g.s.}} + \mathrm{p} \right\rangle$$



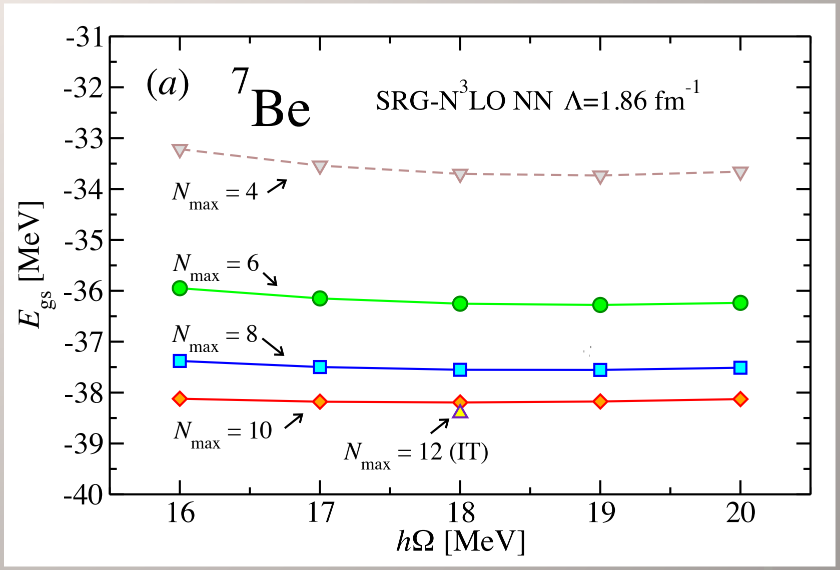
TRIUMF

$^7Be(p,\gamma)^8B$ radiative capture: Input - *NN* interaction, ^7Be eigenstates

- Similarity-Renormalization-Group (SRG) evolved chiral N^3LO *NN* interaction
  - Accurate
  - Soft: Evolution parameter Λ
    - Study dependence on Λ

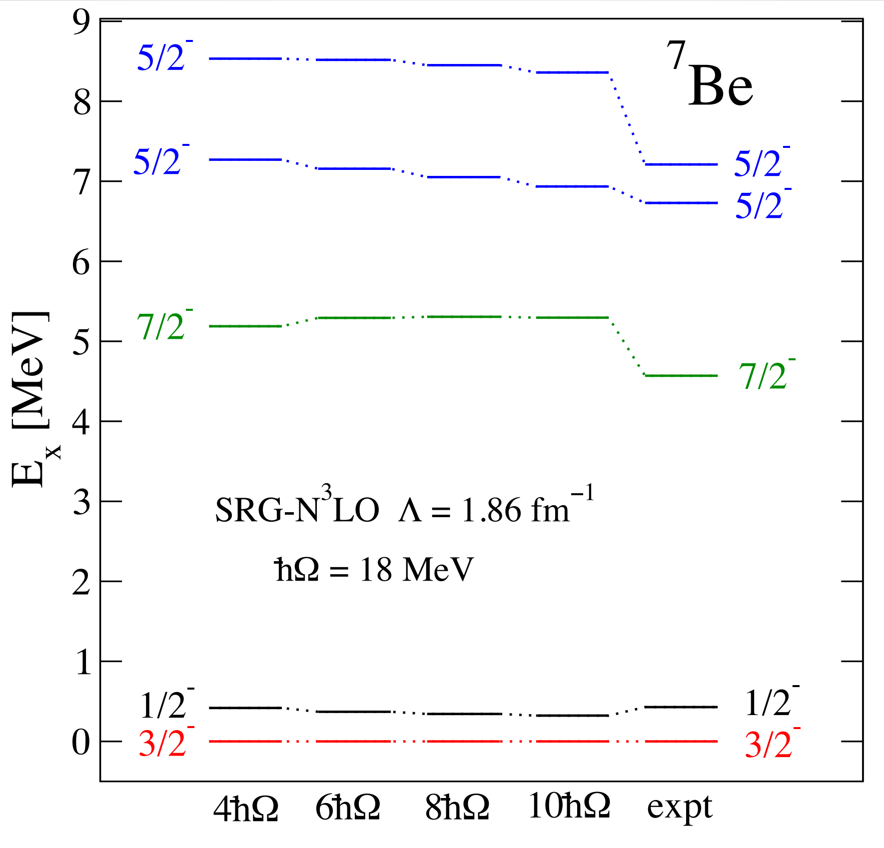


- ^7Be
  - NCSM up to N_{max}=10, Importance Truncated NCSM up to N_{max}=14
  - Variational calculation
    - optimal HO frequency from the ground-state minimum
    - For the selected NN potential with Λ=1.86 fm^{-1}: hΩ=18 MeV



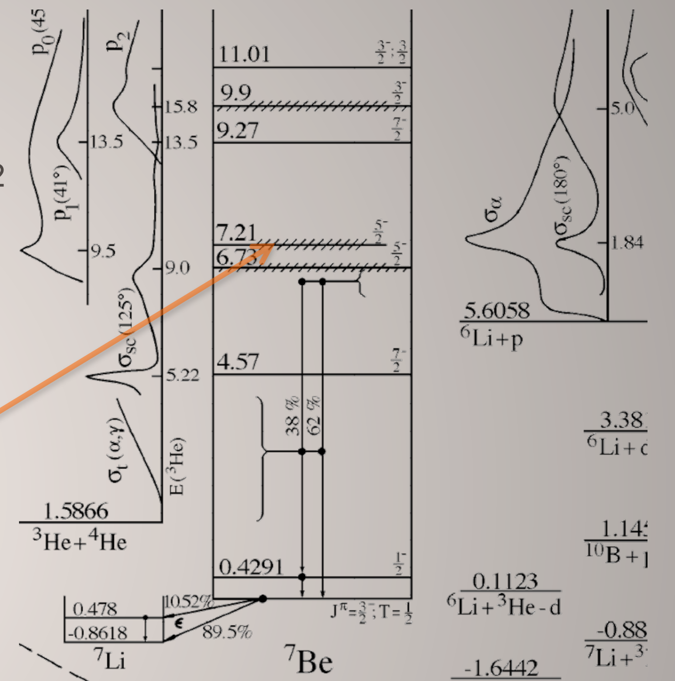
Input: ^{7}Be eigenstates

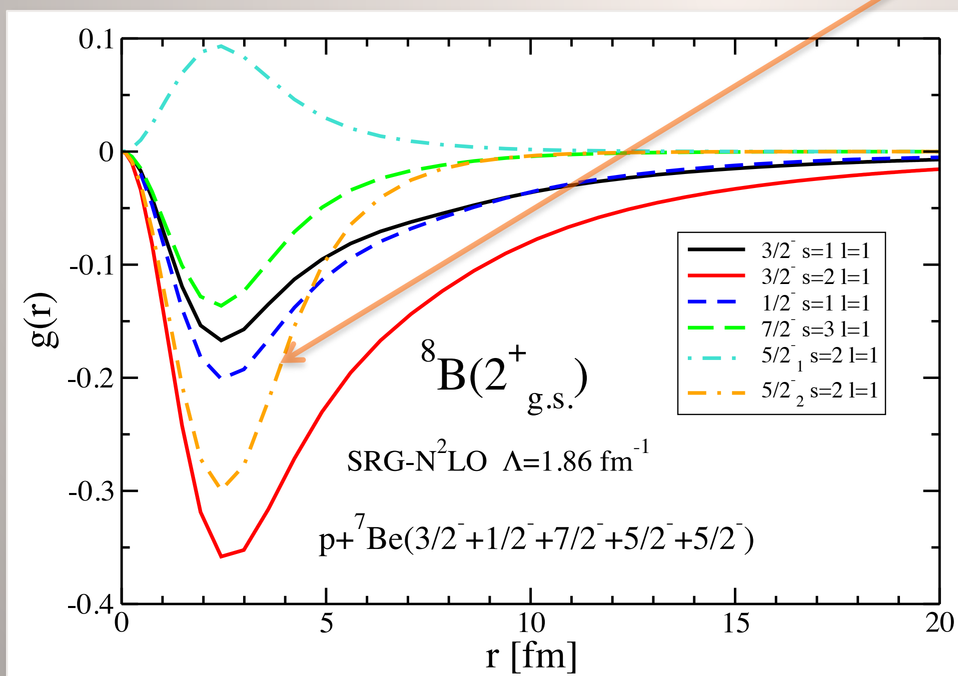
- Excited states at the optimal HO frequency, ħΩ=18 MeV



Structure of the ^{8}B ground state

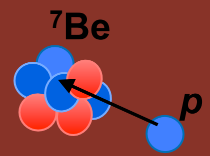
- NCSM/RGM *p*-^{7}Be calculation
  - five lowest ^{7}Be states: $3/2^-$, $1/2^-$, $7/2^-$, $5/2^-_1$, $5/2^-_2$
  - Soft NN SRG-N^{3}LO with $\Lambda = 1.86$ fm^{-1}
- ^{8}B 2^+ g.s. bound by 136 keV (Expt 137 keV)
  - Large *P*-wave $5/2^-_2$ component





$5/2^-_2$ state of ^{7}Be should be included in ^{7}Be$(p,\gamma)^8$B calculations

TRIUMF



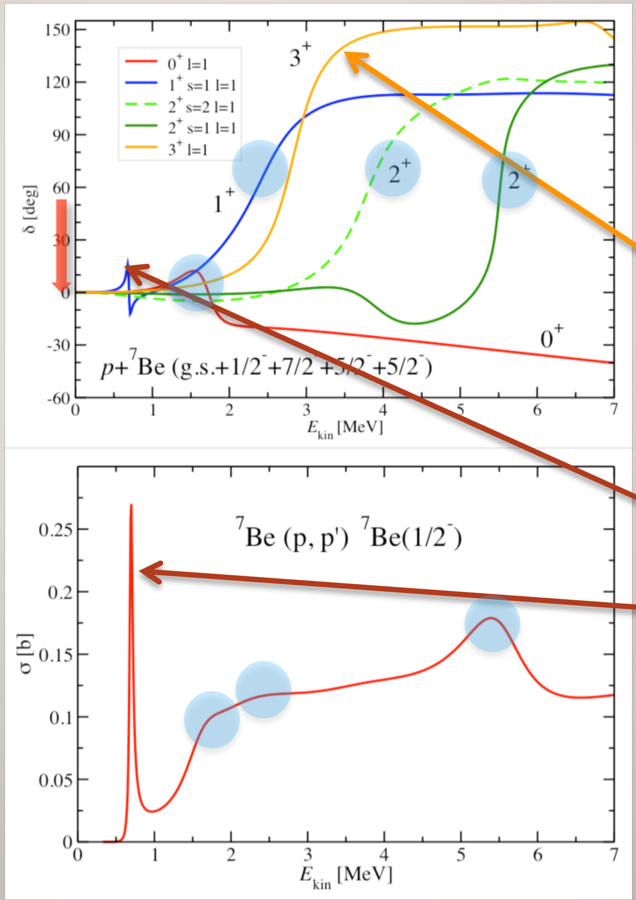
p-^{7}Be scattering

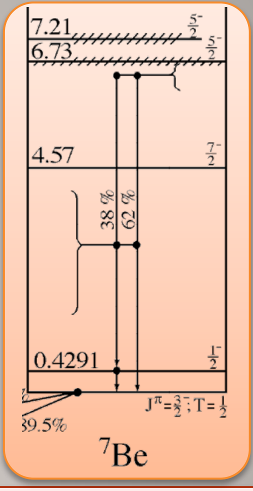
- NCSM/RGM calculation of p-^{7}Be scattering
  - ^{7}Be states $3/2^-$, $1/2^-$, $7/2^-$, $5/2^-_1$, $5/2^-_2$
  - Soft NN potential (SRG-N^{3}LO with Λ = 1.86 fm^{-1})

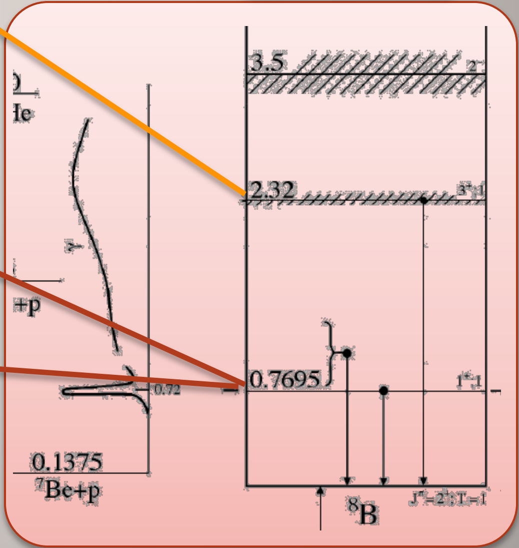
^{8}B 2^+ g.s. **bound** by 136 keV (expt. bound by 137 keV)

New 0^+, 1^+, and two 2^+ resonances **predicted**

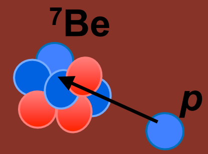
s =1 l =1 2^+ clearly visible in (p,p') cross sections







PRC **82**, 034609 (2010)



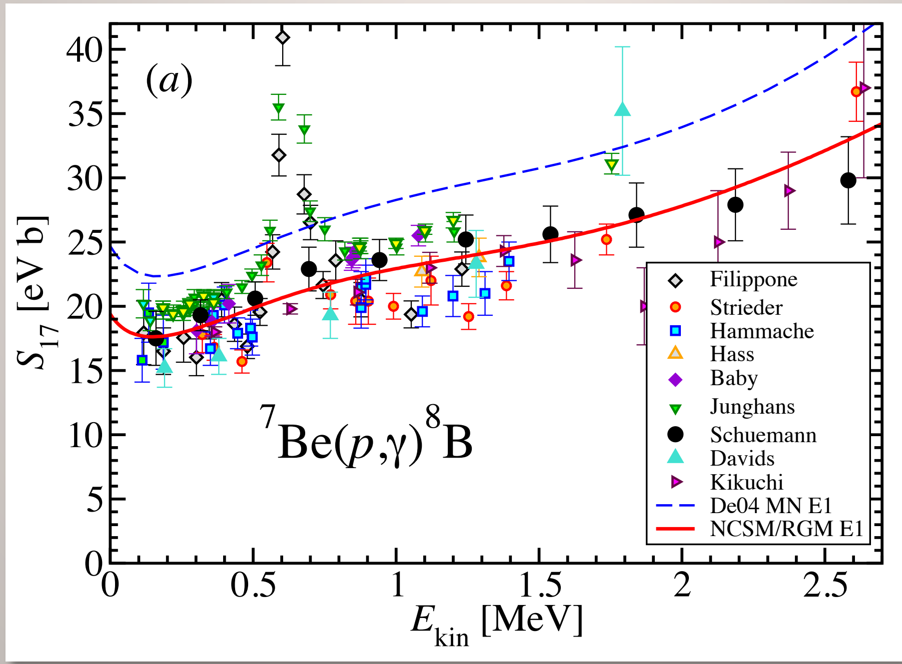
^{7}Be(p,γ)^{8}B radiative capture

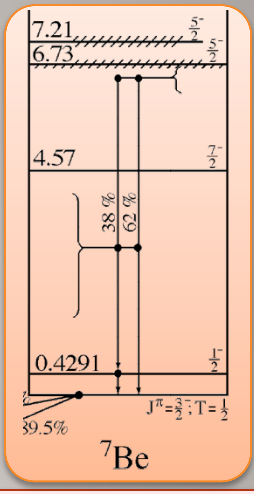
- NCSM/RGM calculation of ^{7}Be(p,γ)^{8}B radiative capture
  - ^{7}Be states $3/2^-$, $1/2^-$, $7/2^-$, $5/2^-_1$, $5/2^-_2$
  - Soft NN potential (SRG-N^{3}LO with $\Lambda = 1.86$ fm^{-1})

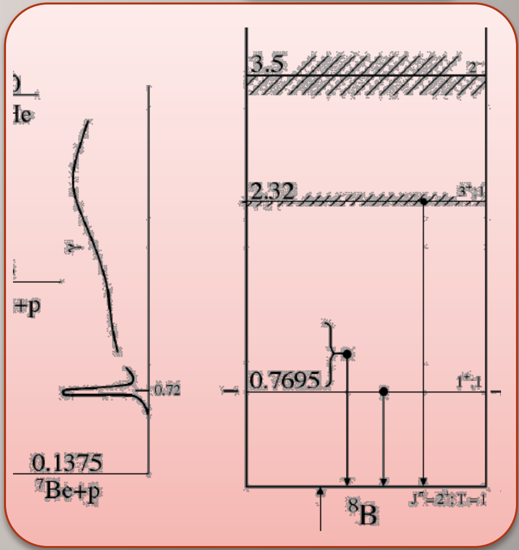
^{8}B 2^+ g.s. **bound** by 136 keV
(expt. 137 keV)

S(0) ~ 19.4(0.7) eV b

Data evaluation:
S(0)=20.8(2.1) eV b



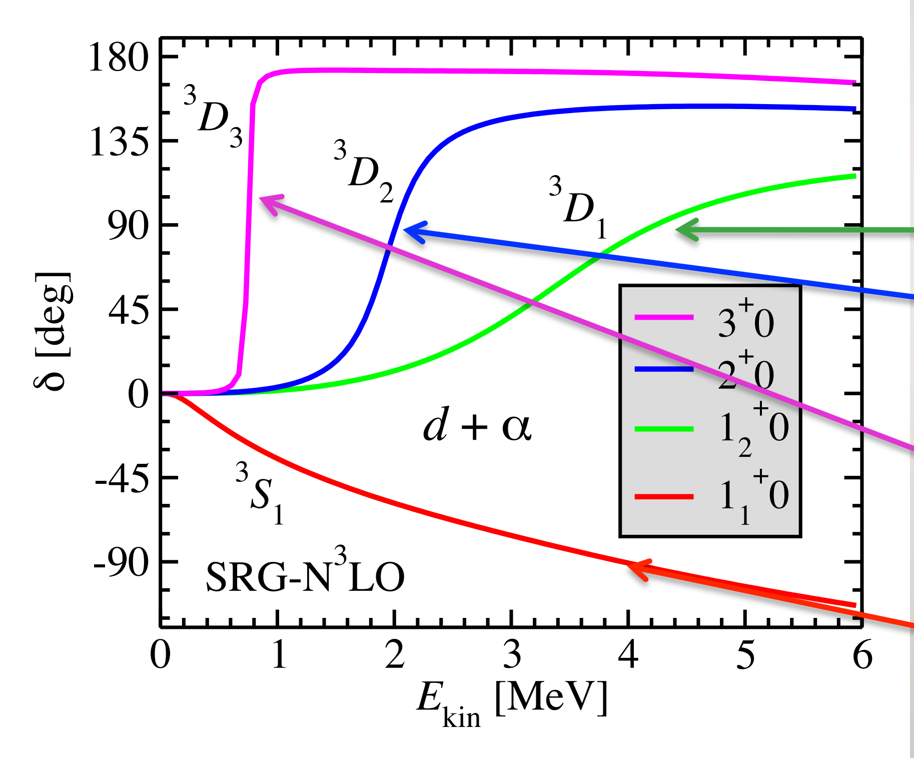


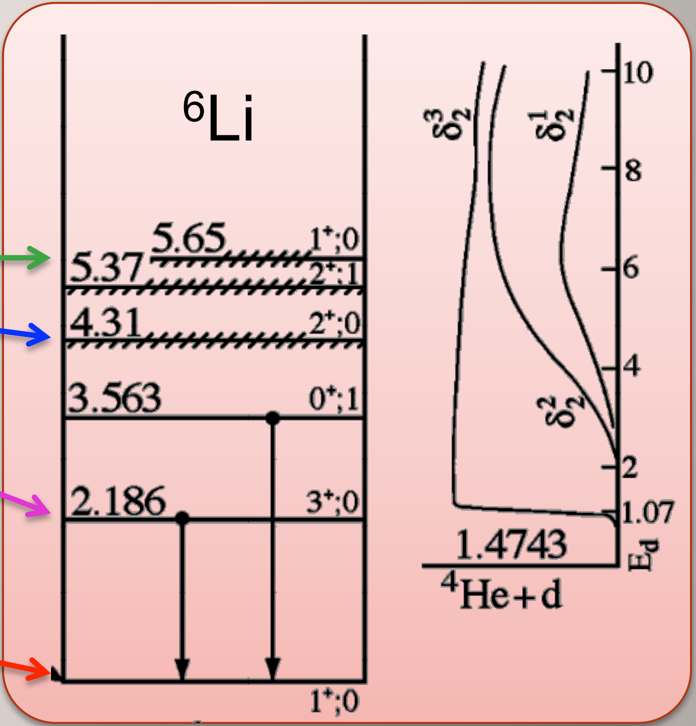


Physics Letters B 704 (2011) 379

NCSM/RGM *ab initio* calculation of d-^{4}He scattering

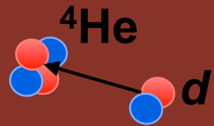
- NCSM/RGM calculation with d + ^{4}He(g.s.) up to N_{max} = 12
  - SRG-N^{3}LO potential with Λ = 1.5 fm^{-1}
  - Deuteron breakup effects included by continuum discretized by pseudo states in $^3S_1$-$^3D_1$, $^3D_2$ and $^3D_3$-$^3G_3$ channels





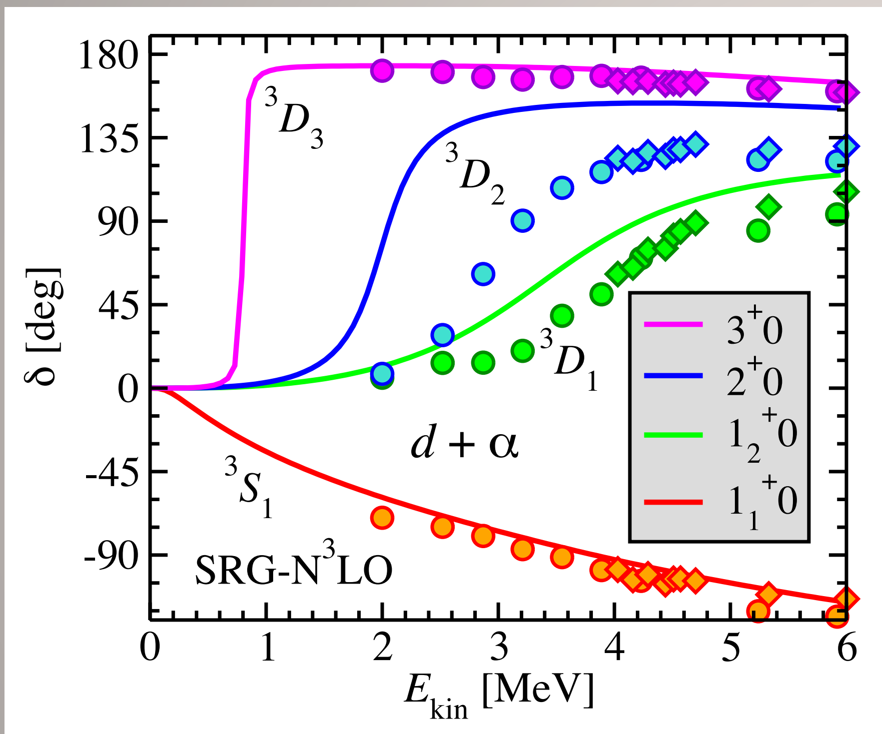
- The 1^+0 ground state bound by 1.9 MeV (expt. 1.47 MeV)
- Calculated T=0 resonances: 3^+, 2^+ and 1^+ in correct order close to expt. energies

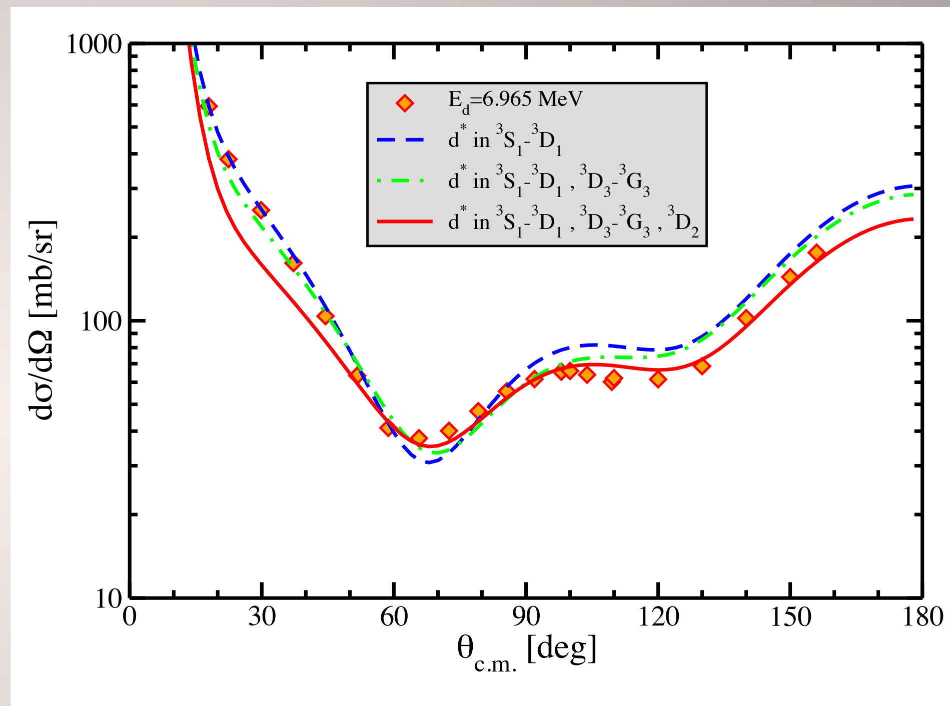
TRIUMF



NCSM/RGM *ab initio* calculation of *d*-^{4}He scattering

PHYS. REV. C **83**, 044609 (2011)





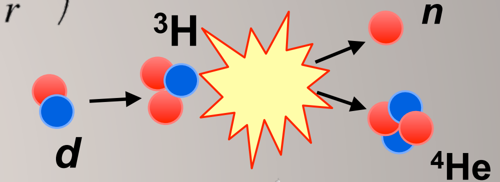
Scattering provides a strict test of NN and NNN forces

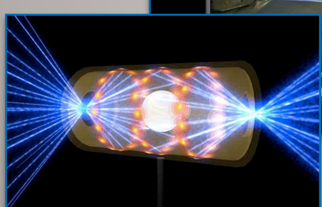
Important to include 6-nucleon correlations

– deuteron (virtual) breakup …

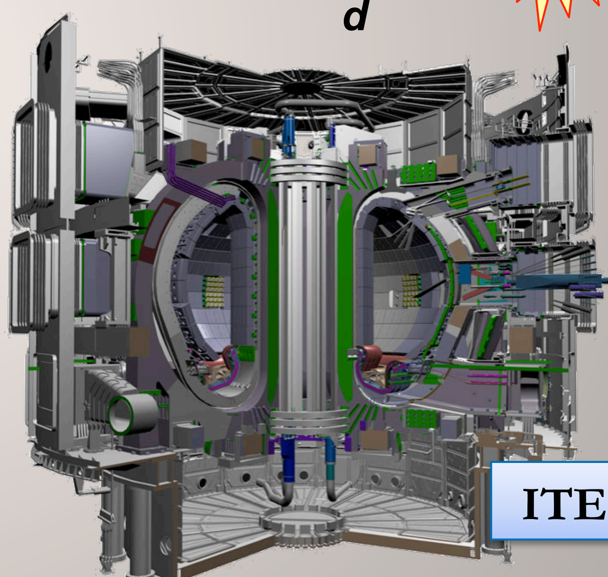
Ab initio calculation of the ^{3}H(d,n)^{4}He fusion

$$\int dr\, r^2 \begin{pmatrix} \left\langle \overset{r'}{n\ \alpha} \right| \hat{A}_1 (H-E) \hat{A}_1 \left| \overset{r}{\alpha\ n} \right\rangle & \left\langle \overset{r'}{n\ \alpha} \right| \hat{A}_1 (H-E) \hat{A}_2 \left| \overset{r}{{}^3\mathrm{H}\ d} \right\rangle \\ \left\langle \overset{r'}{d\ {}^3\mathrm{H}} \right| \hat{A}_2 (H-E) \hat{A}_1 \left| \overset{r}{\alpha\ n} \right\rangle & \left\langle \overset{r'}{d\ {}^3\mathrm{H}} \right| \hat{A}_2 (H-E) \hat{A}_2 \left| \overset{r}{{}^3\mathrm{H}\ d} \right\rangle \end{pmatrix} \begin{pmatrix} \frac{g_1(r)}{r} \\ \frac{g_2(r)}{r} \end{pmatrix} = 0$$





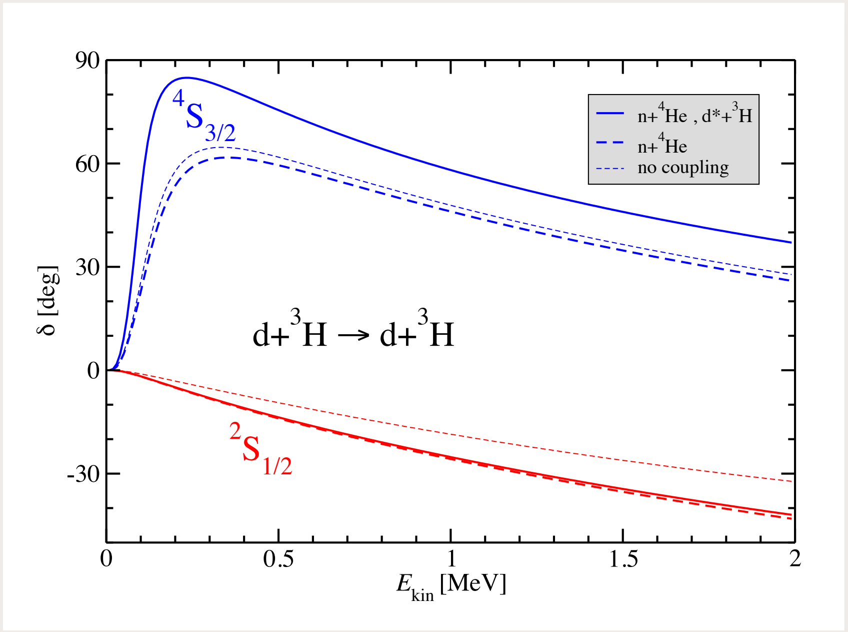
NIF

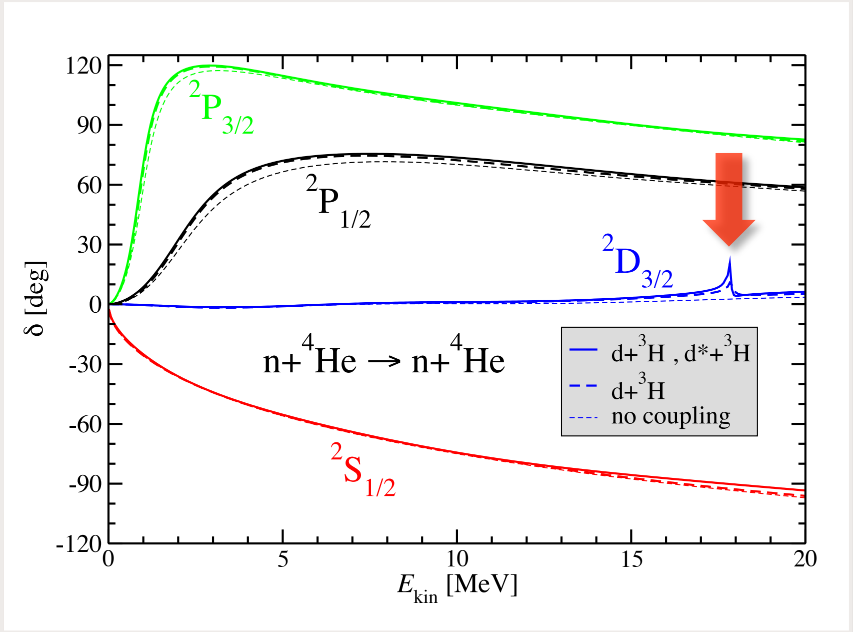


ITER

energy generation

d+^{3}H and n+^{4}He elastic scattering: phase shifts





- *d*+^{3}H elastic phase shifts:
  - Resonance in the $^4S_{3/2}$ channel
  - Repulsive behavior in the $^2S_{1/2}$ channel ➔ Pauli principle

*d** deuteron pseudo state in $^3S_1$-$^3D_1$ channel: deuteron polarization, virtual breakup

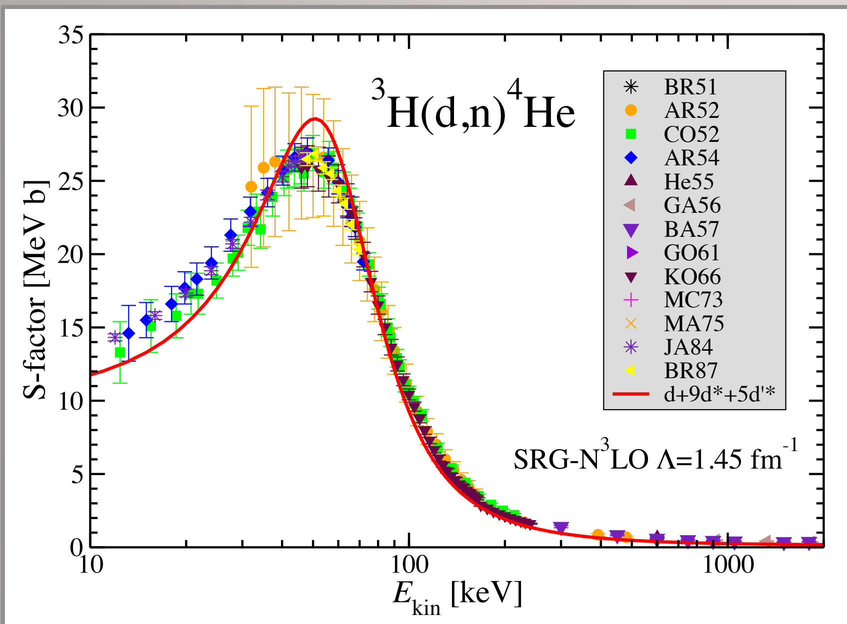
- *n*+^{4}He elastic phase shifts:
  - *d*+^{3}H channels produces slight increase of the *P* phase shifts
  - Appearance of resonance in the 3/2$^+$ *D*-wave, just above *d*-^{3}H threshold

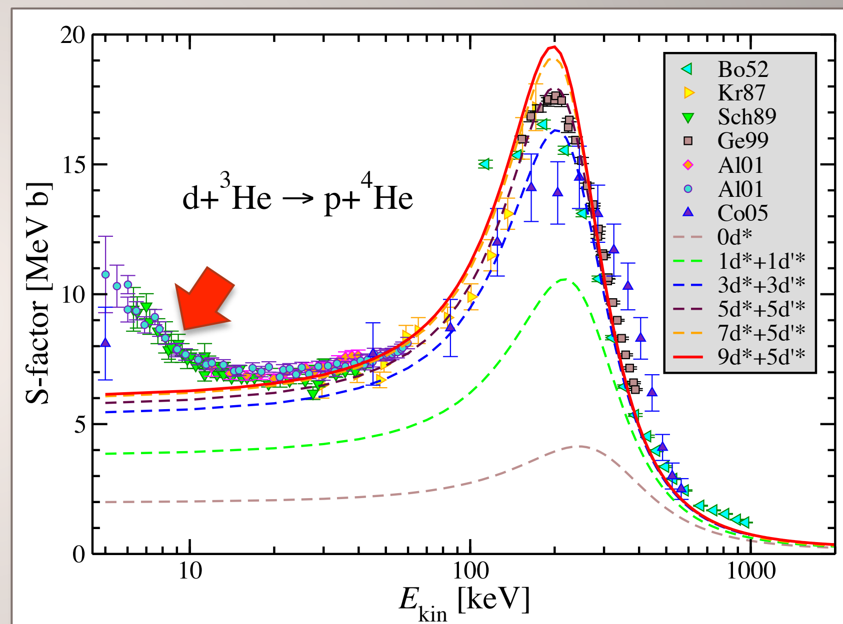
The *d*-^{3}H fusion takes place through a transition of *d*+^{3}H is *S*-wave to *n*+^{4}He in *D*-wave: Importance of the **tensor force**

TRIUMF

^{3}H(d,n)^{4}He & ^{3}He(d,p)^{4}He fusion

- NCSM/RGM with *SRG-N^{3}LO NN* potentials

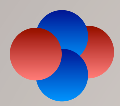
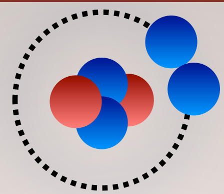
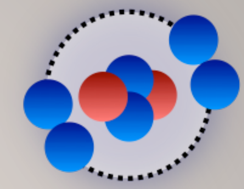




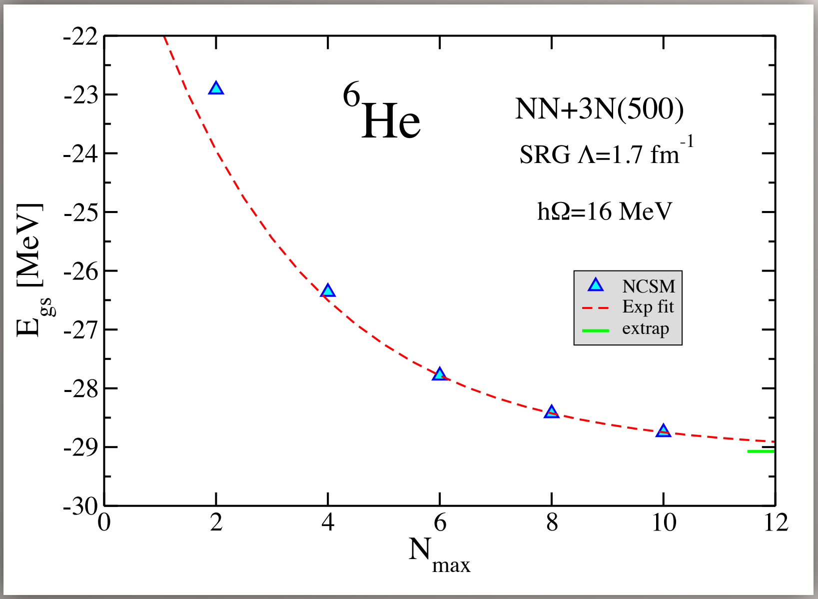
Potential to address unresolved fusion research related questions:
^{3}H(d,n)^{4}He fusion with polarized deuterium and/or tritium,
^{3}H(d,$n\gamma$)^{4}He bremsstrahlung,
Electron screening at very low energies …

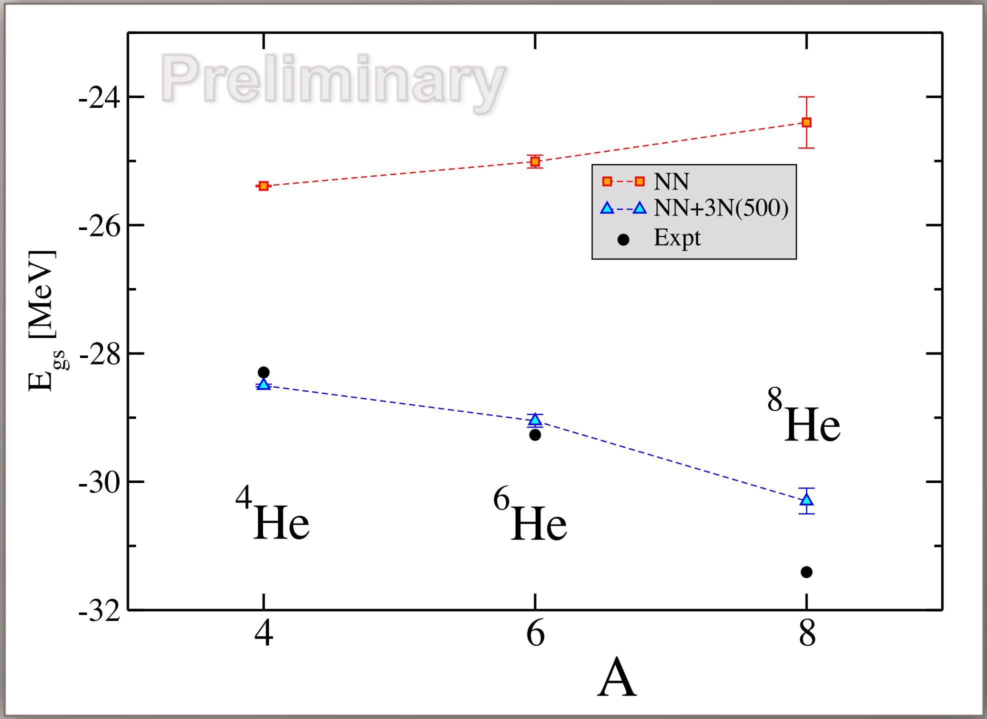
P.N., S. Quaglioni,
PRL **108**, 042503 (2012)

Borromean halo nuclei: He isotopes

^{4}He  ^{6}He  ^{8}He 

- ^{6}He and ^{8}He with chiral N^{3}LO NN + N^{2}LO 3N
  - chiral N^{3}LO NN: ^{4}He underbound, ^{6}He and ^{8}He unbound
  - chiral N^{3}LO NN + N^{2}LO 3N(500): ^{4}He OK, both ^{6}He and ^{8}He bound





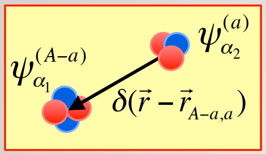
NNN interaction important to bind neutron rich nuclei

Three-body clusters in *ab initio* NCSM/RGM

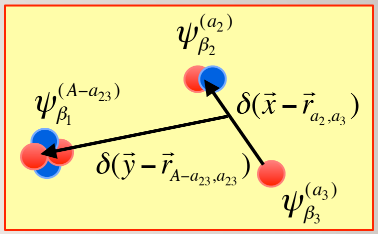
- Starts from:

$$\Psi^{(A)}_{RGM} = \sum_{\nu_2} \int g_{\nu_2}(\vec{r}\,)\hat{A}_{\nu_2} \left| \phi_{\nu_2 \vec{r}} \right\rangle d\vec{r} + \sum_{\nu_3} \iint G_{\nu_3}(\vec{x},\vec{y})\; \hat{A}_{\nu_3} \left| \Phi_{\nu_3 \vec{x}\vec{y}} \right\rangle d\vec{x}\, d\vec{y}$$

2-body channels

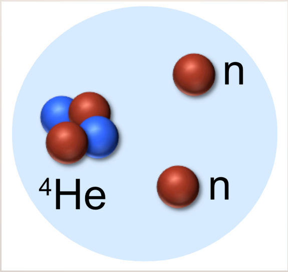


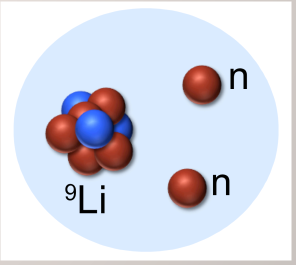
plus



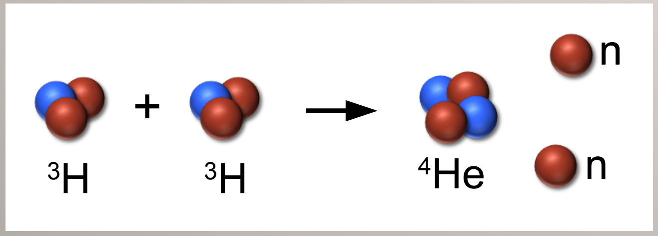
3-body channels

- Two-neutron halo nuclei

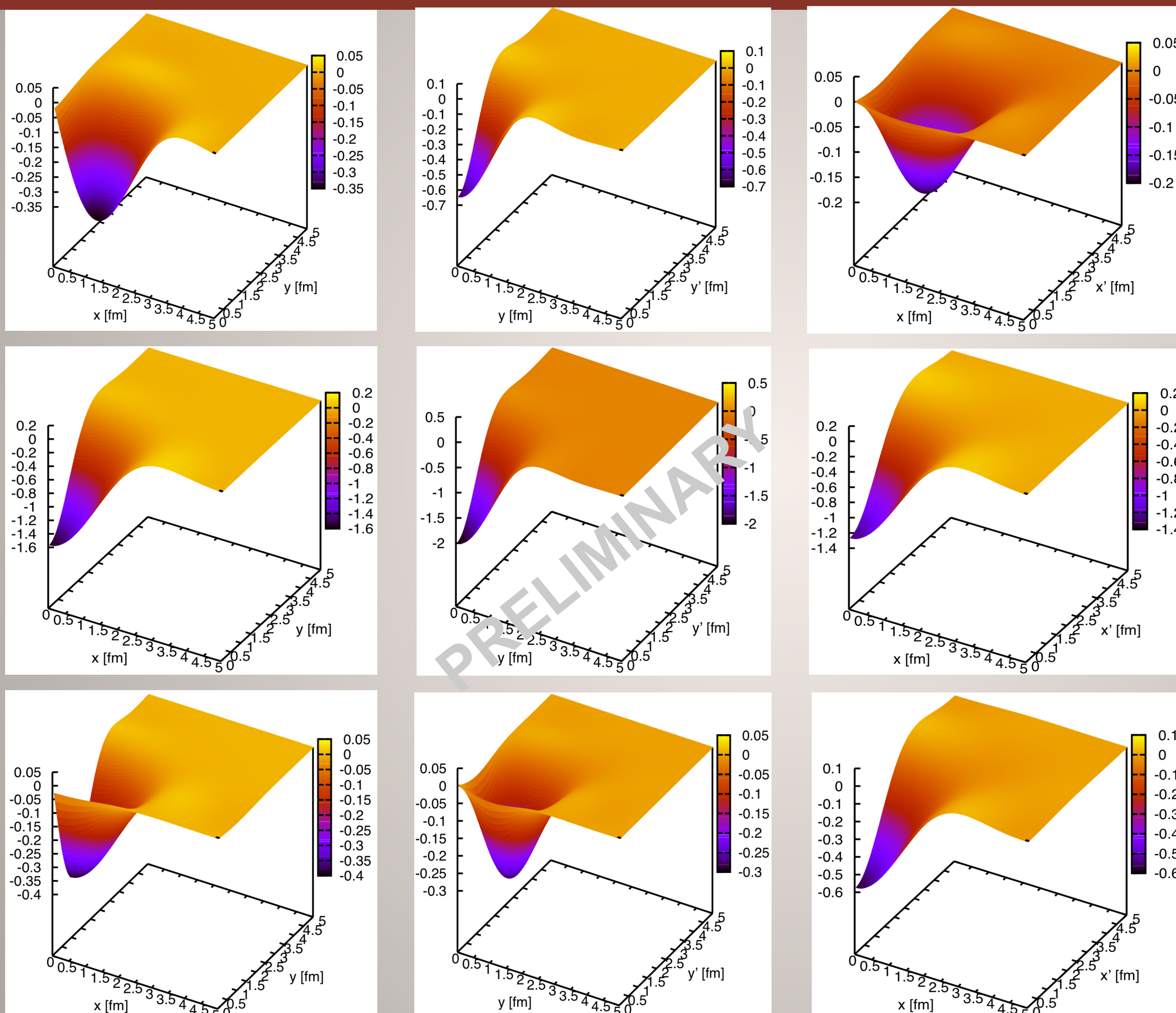




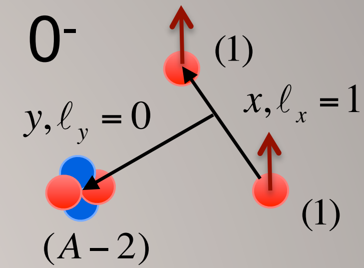
- Transfer reactions with three-body continuum final states



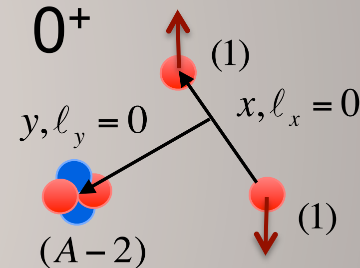
Norm kernel for n+n+^{4}He



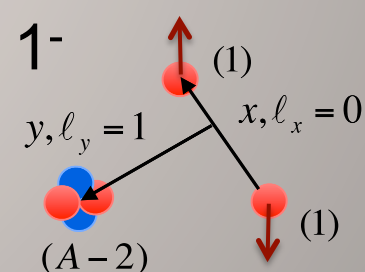
0^-



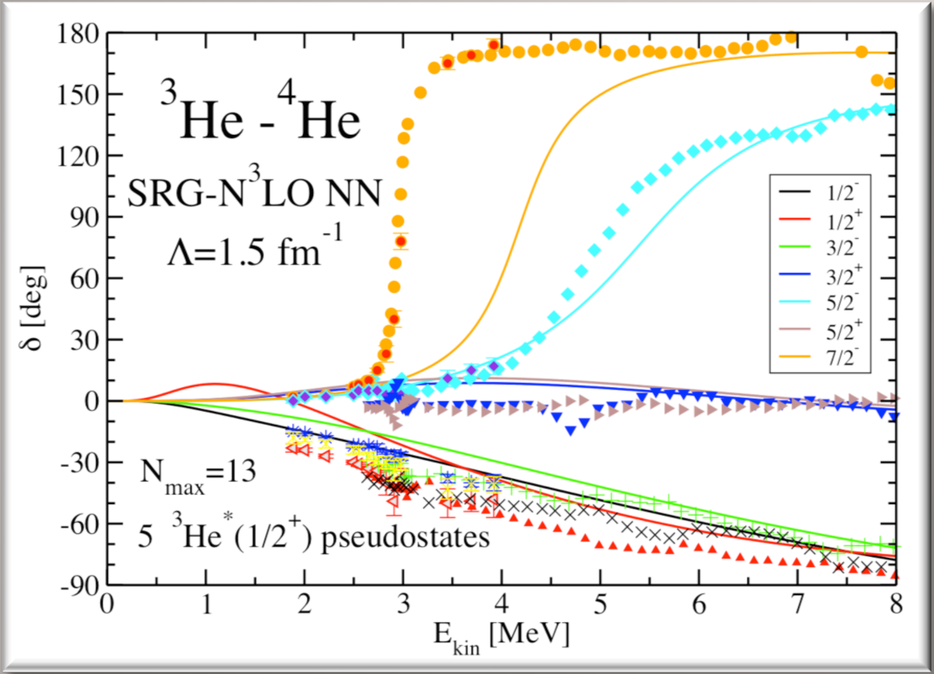
0^+

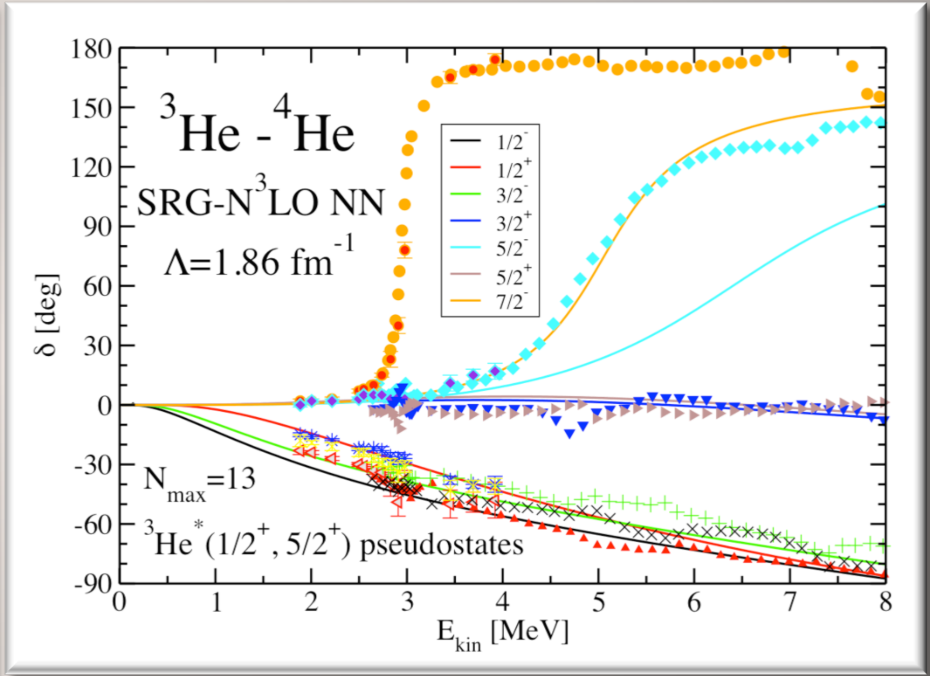


1^-



Ab initio calculations of $^3He+\alpha$ scattering: First results (preliminary, incomplete)



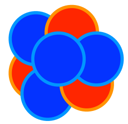


Calculations for *a*=3 projectile under way:
Soft SRG interactions (Λ=1.5 fm^{-1}, Λ=1.86 fm^{-1})
Virtual breakup of ^{3}He included by pseudostates (in 1/2$^+$, 5/2$^+$ channels so far)

TRIUMF

New developments: NCSM with continuum

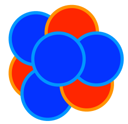
NCSM



$$\left|\Psi_A^{J^\pi T}\right\rangle = \sum_{Ni} c_{Ni} \left|ANiJ^\pi T\right\rangle$$

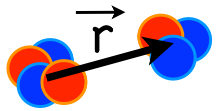
New developments: NCSM with continuum

NCSM



$$\left|\Psi_A^{J^\pi T}\right\rangle = \sum_{Ni} c_{Ni} \left| A N i J^\pi T \right\rangle$$

NCSM/RGM



$$|\Psi_A^{J^\pi T}\rangle = \sum_\nu \int d\vec{r} \chi_\nu(\vec{r}) \hat{A} \Phi_{\nu \vec{r}}^{J^\pi T (A-a,a)}$$

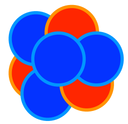
$$\mathcal{H}\chi = E\mathcal{N}\chi$$

$$\bar{\chi} = \mathcal{N}^{+\frac{1}{2}}\chi$$

$$\boxed{(\mathcal{N}^{-\frac{1}{2}}\mathcal{H}\mathcal{N}^{-\frac{1}{2}})\bar{\chi} = E\bar{\chi}}$$

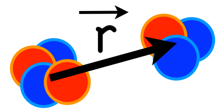
New developments: NCSM with continuum

NCSM



$$\left|\Psi_A^{J^\pi T}\right\rangle = \sum_{Ni} c_{Ni} \left|ANiJ^\pi T\right\rangle$$

NCSM/RGM



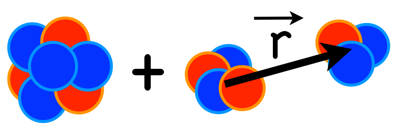
$$|\Psi_A^{J^\pi T}\rangle = \sum_\nu \int d\vec{r}\,\chi_\nu(\vec{r})\hat{A}\Phi_{\nu\vec{r}}^{J^\pi T(A-a,a)}$$

$$\mathcal{H}\chi = E\mathcal{N}\chi$$

$$\bar{\chi} = \mathcal{N}^{+\frac{1}{2}}\chi$$

$$\boxed{(\mathcal{N}^{-\frac{1}{2}}\mathcal{H}\mathcal{N}^{-\frac{1}{2}})\bar{\chi} = E\bar{\chi}}$$

NCSMC

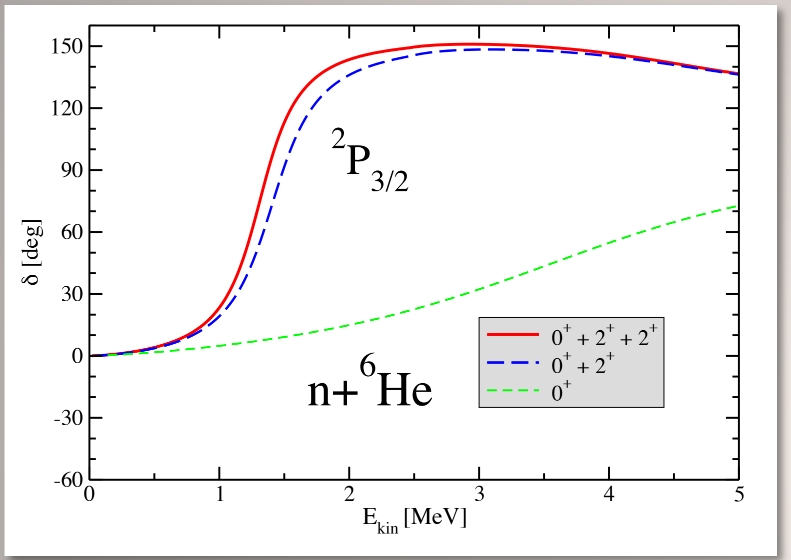


$$|\Psi_A^{J^\pi T}\rangle = \sum_\lambda c_\lambda |A\lambda J^\pi T\rangle + \sum_\nu \int d\vec{r} \left(\sum_{\nu'} \int d\vec{r}\,' \mathcal{N}_{\nu\nu'}^{-\frac{1}{2}}(\vec{r},\vec{r}\,')\bar{\chi}_{\nu'}(\vec{r}\,') \right) \hat{A}\Phi_{\nu\vec{r}}^{J^\pi T(A-a,a)}$$

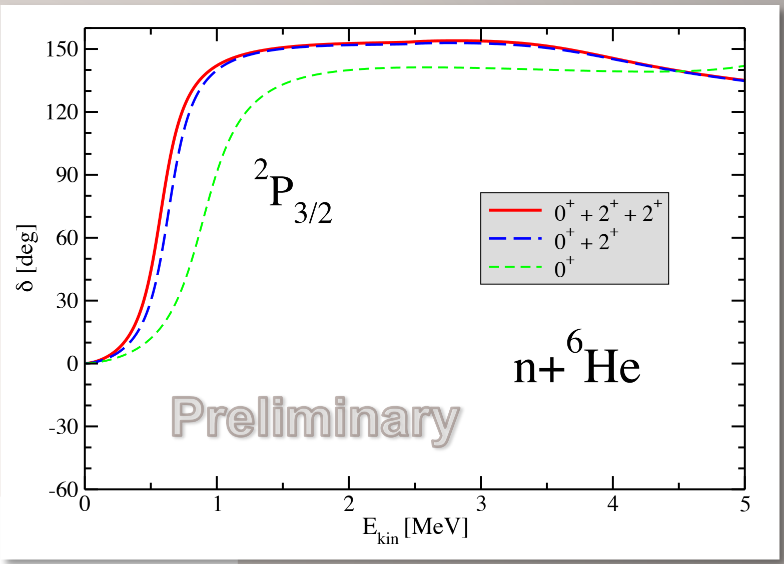
$$\boxed{\begin{pmatrix} H_{NCSM} & \bar{h} \\ \bar{h} & \mathcal{N}^{-\frac{1}{2}}\mathcal{H}\mathcal{N}^{-\frac{1}{2}} \end{pmatrix} \begin{pmatrix} c \\ \bar{\chi} \end{pmatrix} = E \begin{pmatrix} 1 & \bar{g} \\ \bar{g} & 1 \end{pmatrix} \begin{pmatrix} c \\ \bar{\chi} \end{pmatrix}}$$

TRIUMF

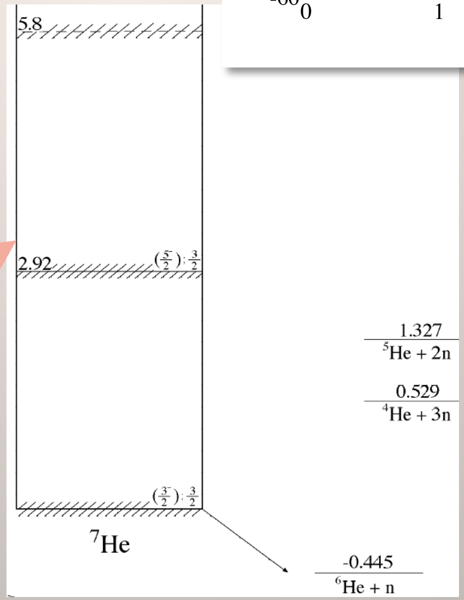
NCSM with continuum: ^{7}He ↔ ^{6}He+n

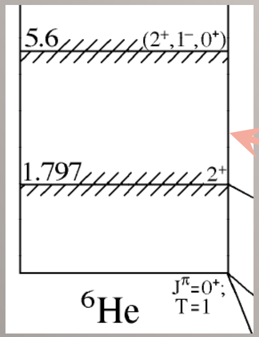


NCSM/RGM
with up to three ^{6}He states



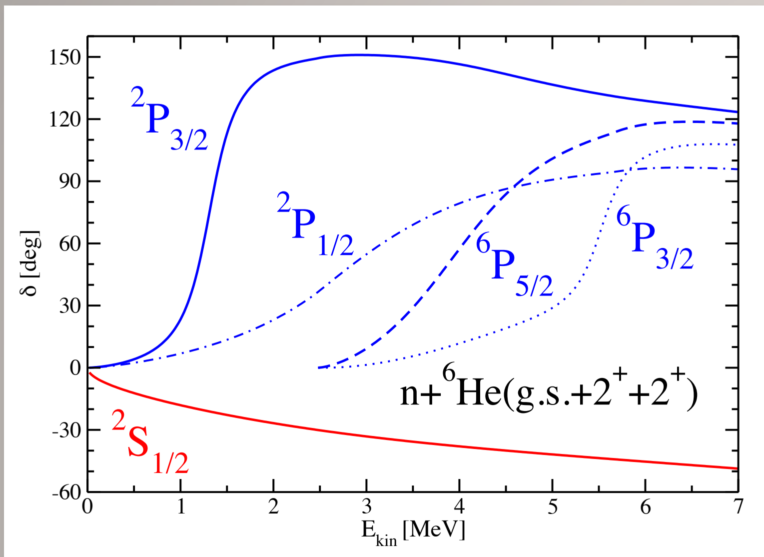
NCSMC
with up to three ^{6}He states
and three ^{7}He eigenstates
More **7-nucleon correlations**
Fewer target states needed



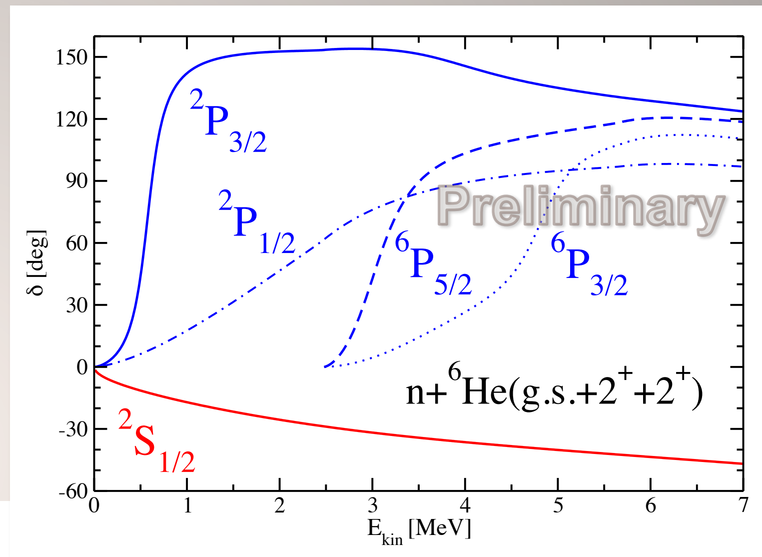


Expt.

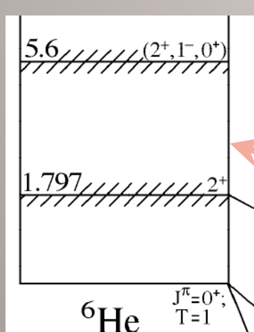
NCSM with continuum: ^{7}He ↔ ^{6}He+n



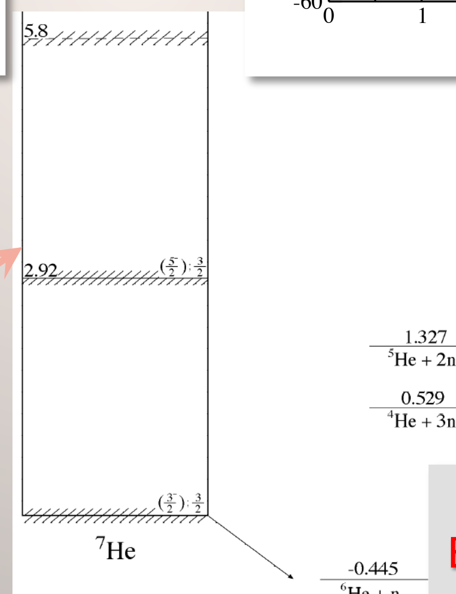
NCSM/RGM
with three ^{6}He states



NCSMC
with three ^{6}He states
and three ^{7}He eigenstates
More **7-nucleon correlations**
Fewer target states needed



Expt.



Experimental controversy:
Existence of low-lying 1/2$^-$ state
… not seen in this calculations

Conclusions and Outlook

- With the NCSM/RGM approach we are extending the *ab initio* effort to describe low-energy reactions and weakly-bound systems
- The first $^{7}Be(p,\gamma)^{8}B$ *ab initio* S-factor calculation

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- Deuteron-projectile results with SRG-N^{3}LO *NN* potentials:
  - *d*-^{4}He scattering
  - First *ab initio* study of $^{3}H(d,n)^{4}He$ & $^{3}He(d,p)^{4}He$ fusion

PRC **83**, 044609 (2011)

PRL **108**, 042503 (2012)

- Under way:
  - *n*-^{8}He scattering and ^{9}He structure
  - ^{3}He-^{4}He and ^{3}He-^{3}He scattering calculations
  - *Ab initio* NCSM with continuum (NCSMC)
  - Three-cluster NCSM/RGM and treatment of three-body continuum
  - Inclusion of NNN force
- To do:
  - Alpha clustering: ^{4}He projectile