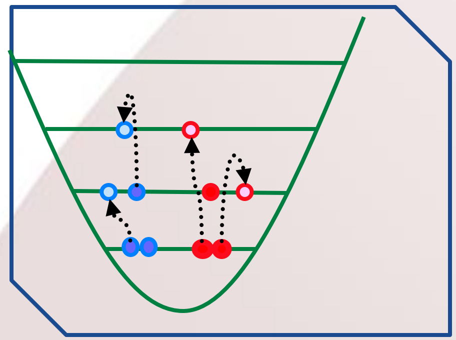
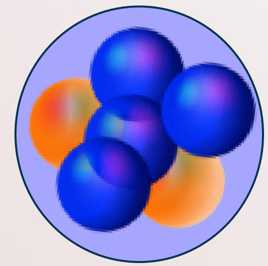
Ab initio theory for reactions and exotic nuclei

Guillaume Hupin, CNRS IPNO

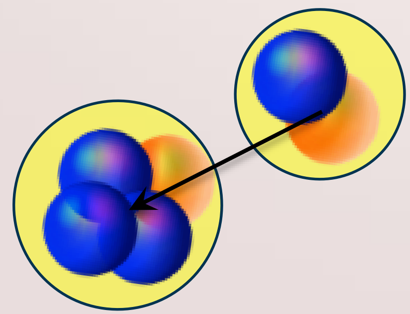
Recent advances and challenges in the description of nuclear reactions at the limit of stability, March 6th 2018

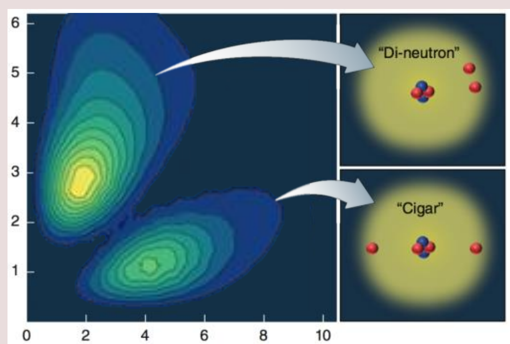


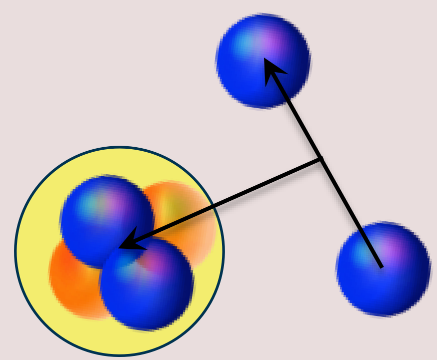


Collaborators

A. Calci (Industry)
J. Dohet-Eraly (ULB)
J. Langhammer (Industry)
P. Navrátil (TRIUMF)
F. Raimondi (Uni. of Surrey)
C. Romero-Redondo (Industry)
R. Roth (TU Darmstadt)
S. Quaglioni (LLNL)
M. Vorabbi (TRIUMF)





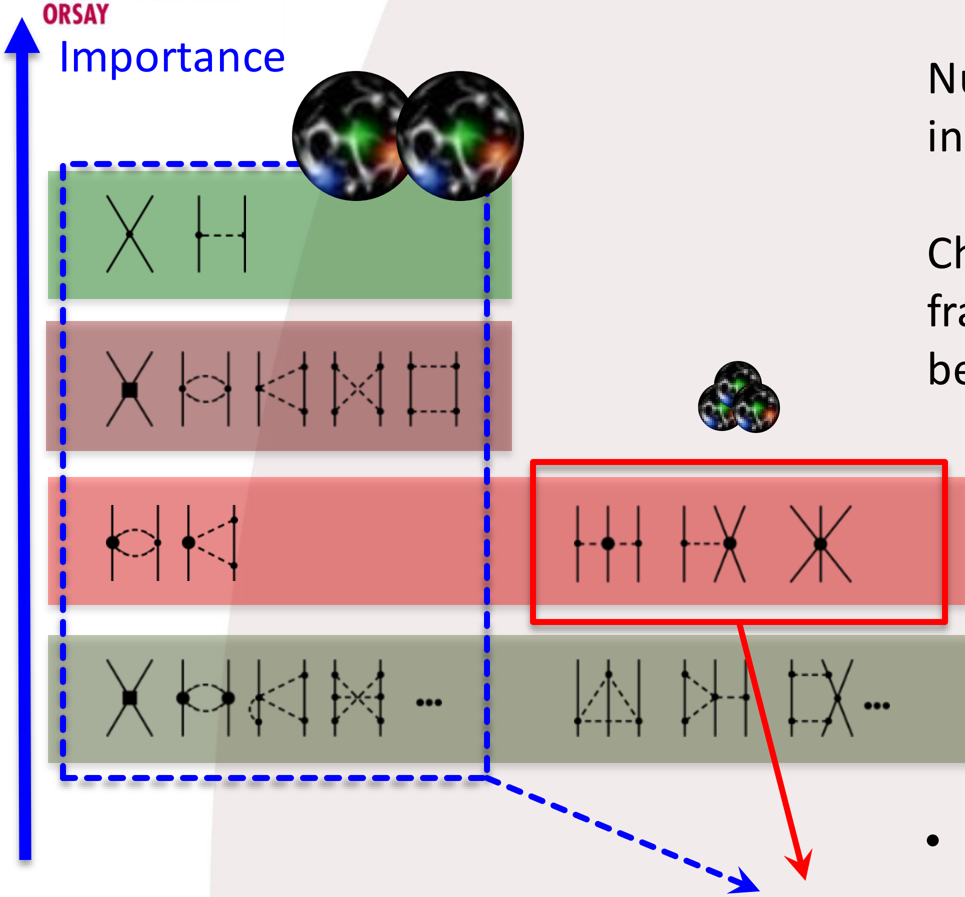


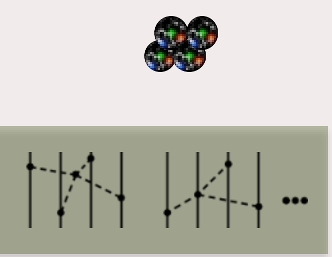
IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

CHIRAL EFFECTIVE FIELD THEORY, A MODERN DERIVATION OF NUCLEAR EFFECTIVE INTERACTION

Nucleons are composite objects. The nuclear interaction is complex by nature.

Chiral effective field theory offer a **consistent** framework to **organize** the interaction between nucleons.





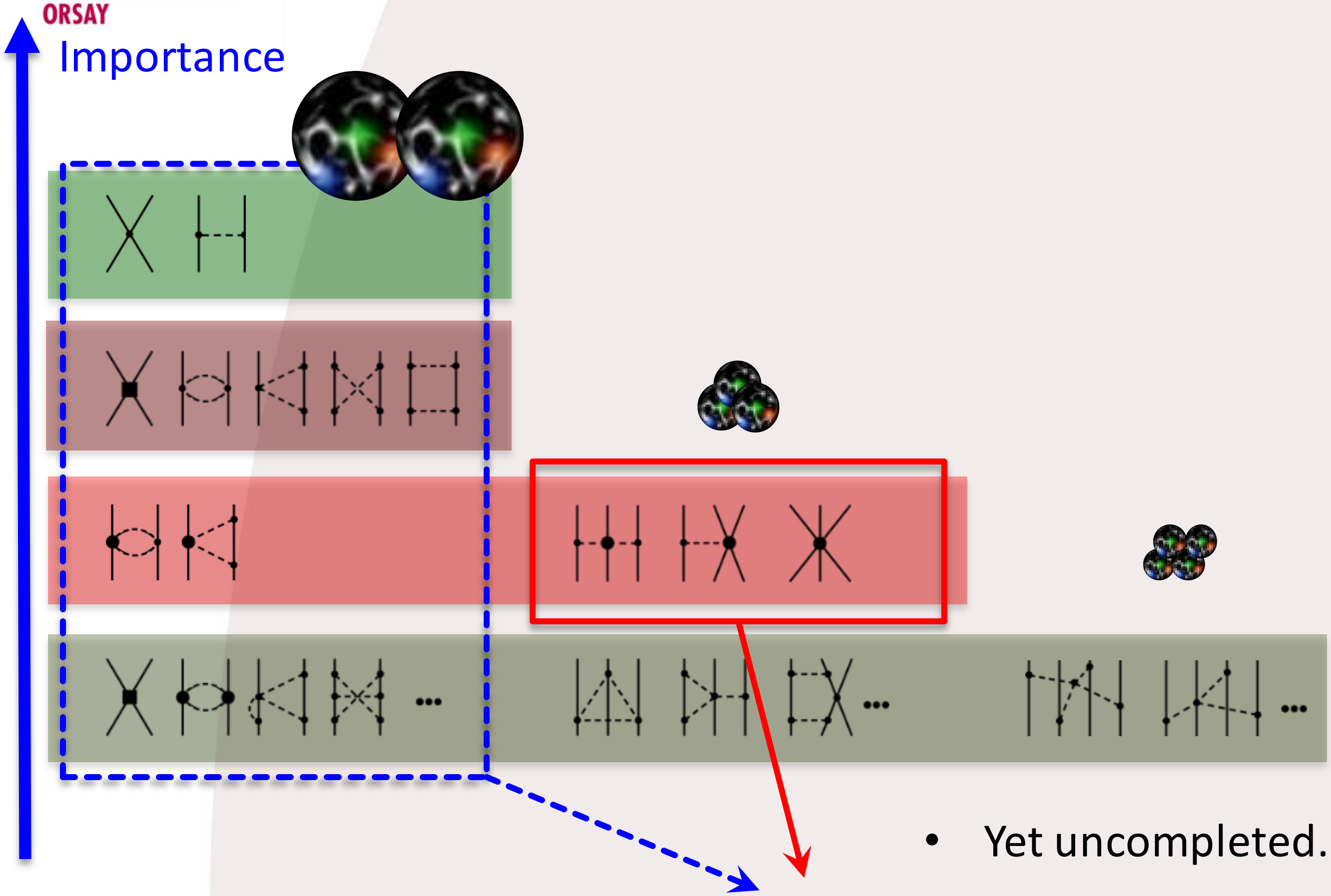
- Yet uncompleted…

Constrained to provide an accurate description of the A=2 and A=3 systems.

↓

Predictions for nuclear structure and dynamic (A>3).

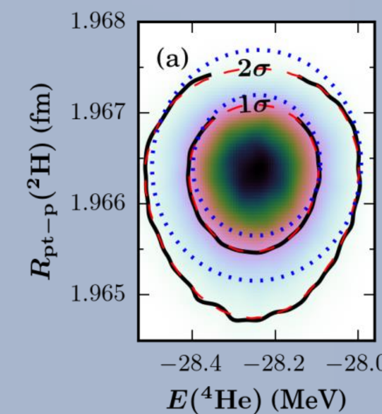
CHIRAL EFFECTIVE FIELD THEORY, A MODERN DERIVATION OF NUCLEAR EFFECTIVE INTERACTION



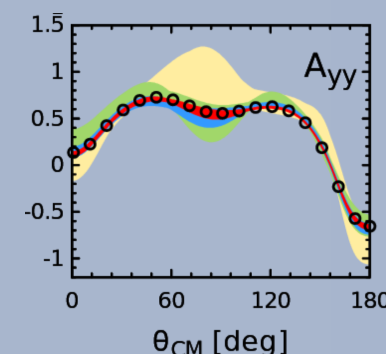
- Yet uncompleted…

Constrained to provide an accurate description of the A=2, A=3 and A=4 or A>3 systems?

Predictions for nuclear structure and dynamic (A>3).



B. D. Carlsson *et. al.*
PRX6 (2016)



E. Epelbaum, *et al.*
PRL115 (2015)

INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

EFFECTIVE INTERACTION ADAPTED TO MANY-BODY MODEL SPACE (I.E. PREDIAGONALIZED)

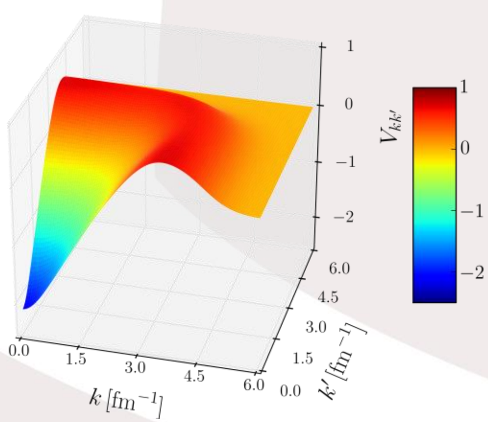
In configuration interaction methods we need to soften interaction to address the hard core. We use the Similarity-Renormalization-Group (SRG) method.

$$H_\lambda = U_\lambda H U_\lambda^\dagger \qquad \begin{cases} \dfrac{dH_\lambda}{d\lambda} = -\dfrac{4}{\lambda^5}[\eta(\lambda), H_\lambda] \\ \eta(\lambda) = \dfrac{dU_\lambda}{d\lambda} U_\lambda^\dagger \end{cases}$$

Unitary transformation

Flow parameter

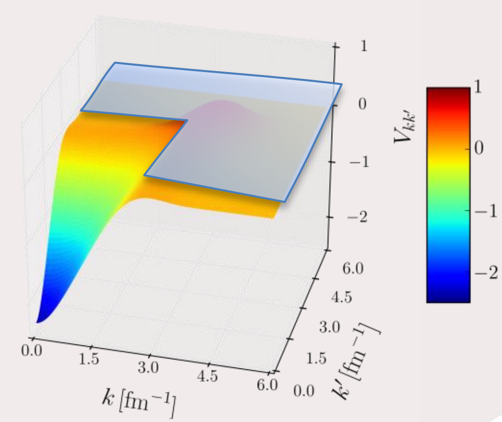
Bare potential



Evolution with flow parameter λ

- Preserves the physics
- Decouples high and low momentum
- Induces many-body forces

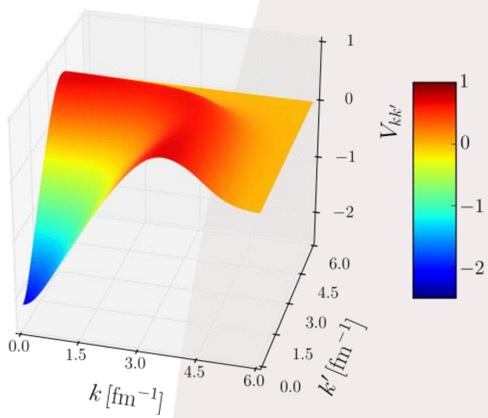
Evolved potential



EFFECTIVE INTERACTION ADAPTED TO MANY-BODY MODEL SPACE (I.E. PREDIAGONALIZED)

E. D. Jurgenson, P. Navrátil, R. J. Furnstahl PRL103 (2009); PRC83 (2011)…

Bare potential



Evolution with flow parameter λ

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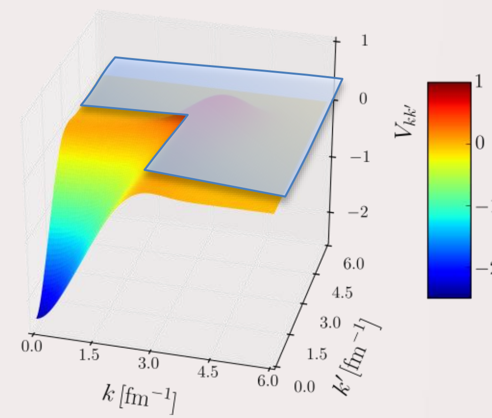
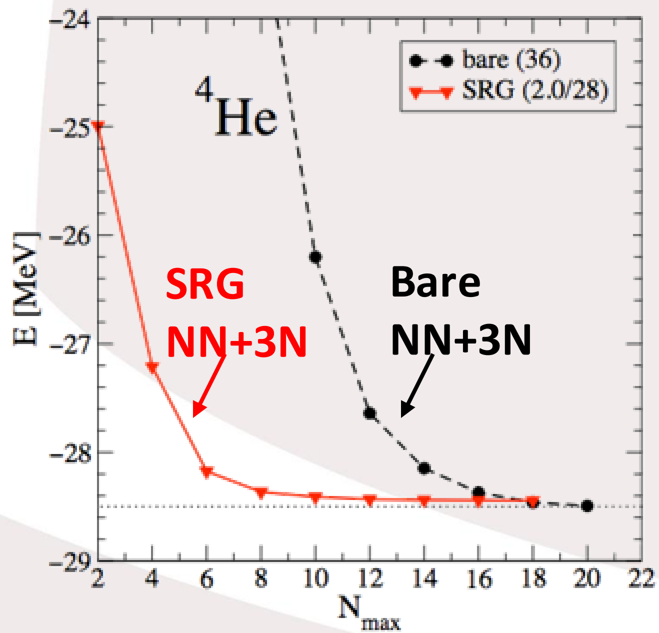
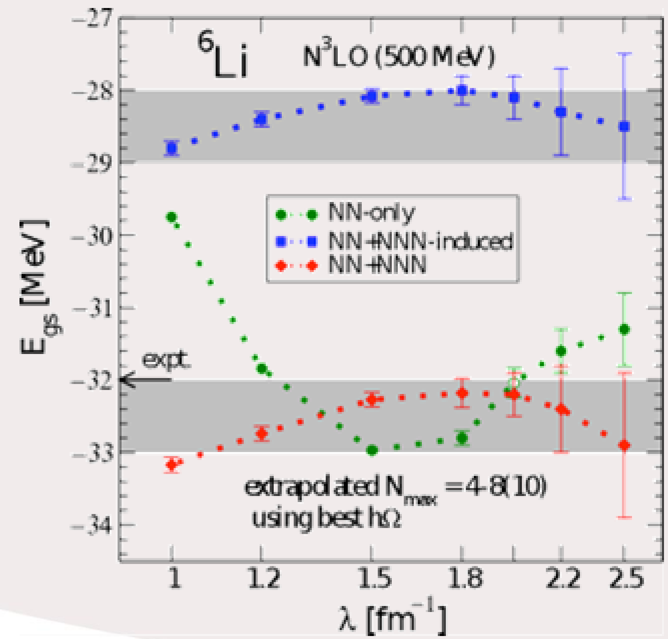






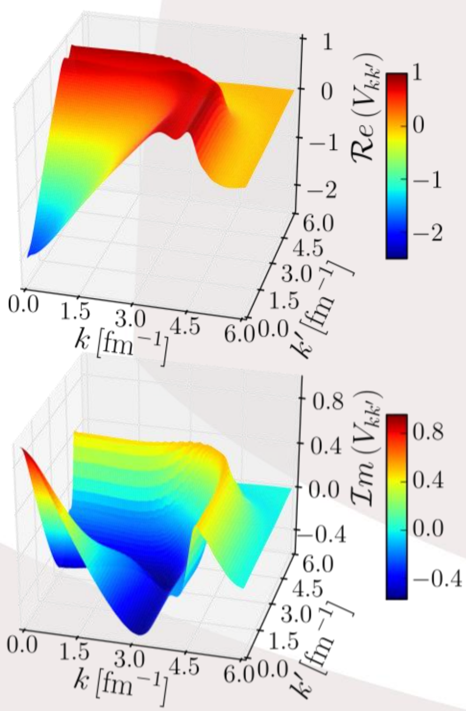
SRG FOR NON-HERMITIAN : NON-LOCAL TO LOCAL POTENTIAL

Effective techniques applied to the non-Hermitian world.
Maybe a technical way to study shape and non-localities in optical potential ? "R. Lazauskas"

$$H_\lambda(\theta) = U_\lambda H(\theta) U_\lambda^T$$

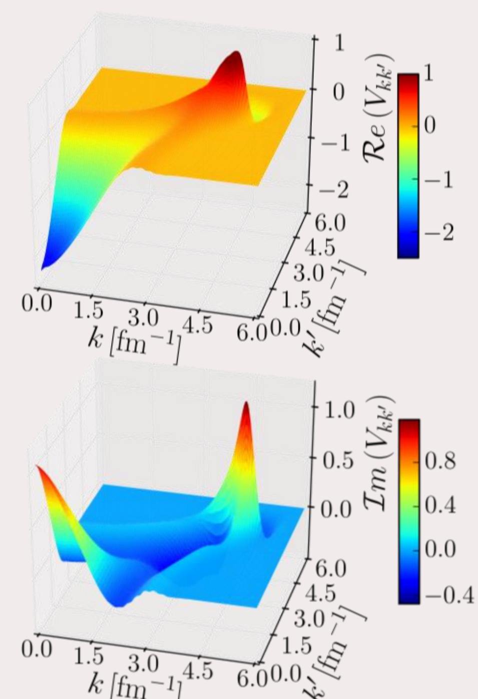
Similarity Transformation

$$\begin{cases} \dfrac{dH_\lambda(\theta)}{d\lambda} = -\dfrac{4}{\lambda^5}[\eta(\lambda), H_\lambda(\theta)] \\ \eta(\lambda) = \dfrac{dU_\lambda}{d\lambda} U_\lambda^T \end{cases}$$



Evolution with flow parameter λ

Consistent evolution of the imaginary part



NON-HERMITIAN POTENTIAL TYPICALLY USED IN THE CONTEXT OF COMPLEX SCALING TECHNIQUE

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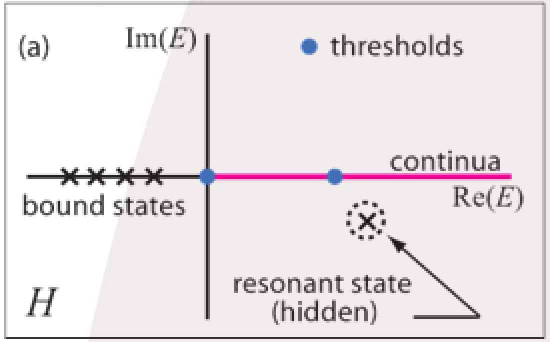
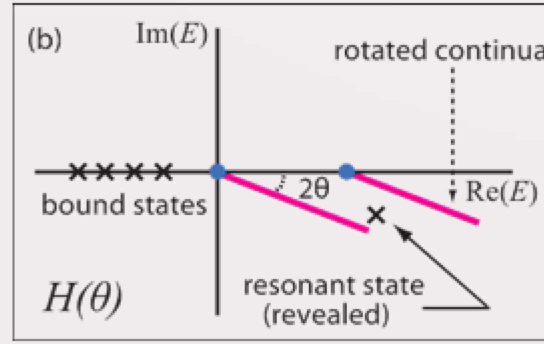


Complex scaling



Kruppa *et al.* PRC89 (2014)

The complex scaling and the resonance states

$$\hat{H}(r) = \hat{T} + \hat{V}(r)$$

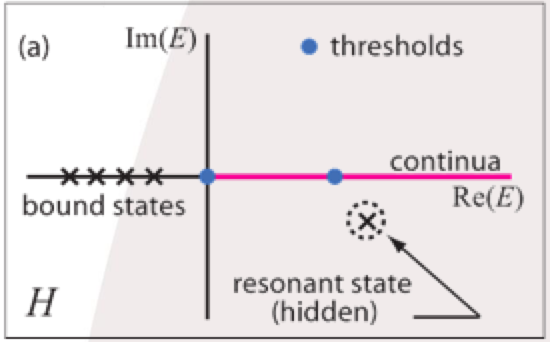
$$\hat{H}(\theta) = e^{-2i\theta}\hat{T} + \hat{V}\left(re^{i\theta}\right)$$
$$\hat{H}(r) = \hat{U}(\theta)\hat{H}(r)\hat{U}^{-1}(\theta)$$

Aguilar-Balslev-Combes theorem: the resonant states of the original Hamiltonian are invariant and the non-resonant scattering states are rotated and distributed on a 2θ ray that cuts the complex energy plane with a corresponding threshold being the rotation point.

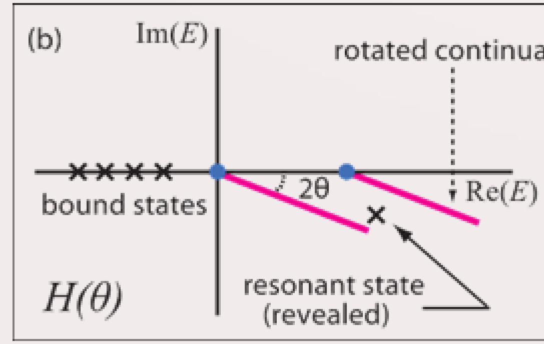
$$\hat{H}(r,\theta)\psi(r,\theta) = (E + i\Gamma)\psi(r,\theta)$$

Energy ↑ (E) ↑ (Γ) Half-life

NON-HERMITIAN POTENTIAL TYPICALLY USED IN THE CONTEXT OF COMPLEX SCALING TECHNIQUE



Complex scaling



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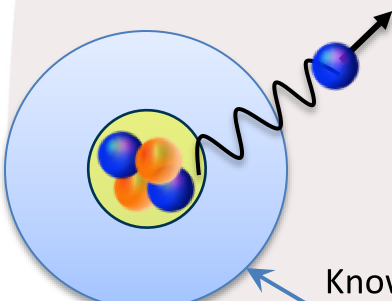
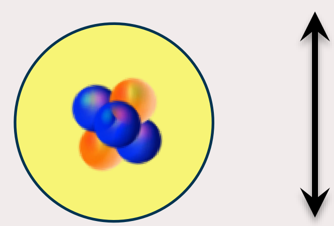


Known asymptotic

$$U(\theta)H(r)U(\theta)^{-1}$$

$$\psi(r,\theta) \underset{\infty}{\sim} e^{-kr\sin\theta}$$



Spatially extended but falls off exponentially

Boundary limit problem

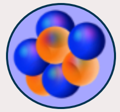
Bound state problem

NO-CORE SHELL MODEL: BEST FOR WELL BOUND STATES

B.R. Barrett, P. Navrátil, J.P. Vary, J.P. Progr. Part. Nucl. Phys. 69 (2013).

- Methods develop in this presentation to solve the many body problem

$$\Psi^{(A)}_{NCSM} = |A\lambda J^{\pi} T\rangle = \sum_{\alpha} c_{\alpha} |A\alpha j_z{}^{\pi} t_z\rangle \Leftrightarrow$$



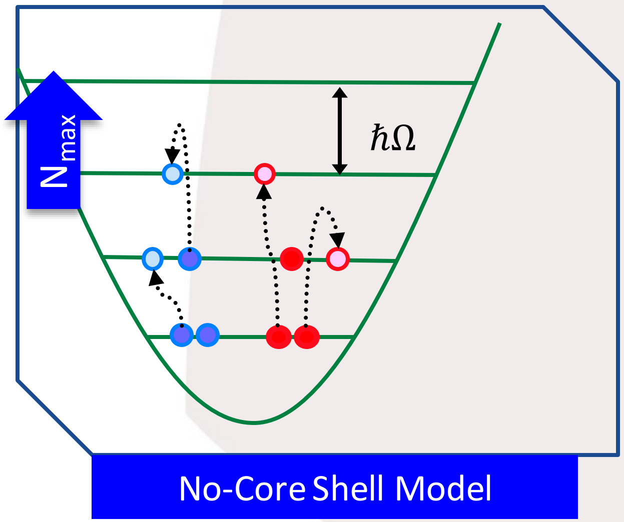
$$|A\lambda J^{\pi} T\rangle_{SD}\, \phi_{00}(\vec{R}^{A}_{c.m.})$$

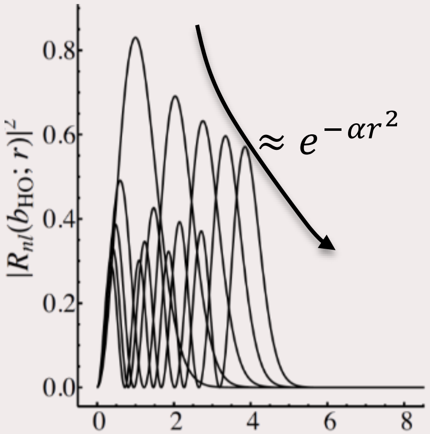
Mixing coefficients(unknown)

A-body harmonic oscillator states

Second quantization

Can address bound and low-lying resonances (short range correlations)





$$\Psi^{(A)}_{NCSMC} = \sum_{\lambda} c_{\lambda} |A\lambda J^{\pi} T\rangle$$

RESONATING GROUP METHOD FOR NCSM: LONG-RANGE DYNAMICS AND SCATTERING

S. Quaglioni, P. Navrátil PRL101 (2008).

- Methods develop in this presentation to solve the many body problem

$$\Psi^{(A)}_{NCSM} = |A\lambda J^{\pi} T\rangle = \sum_{\alpha} c_{\alpha} \, |A\alpha j_z{}^{\pi} t_z\rangle$$

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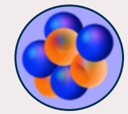
A-body harmonic oscillator states



$|A\lambda J^{\pi} T\rangle_{SD}\,\phi_{00}(\vec{R}^{A}_{c.m.})$

Second quantization

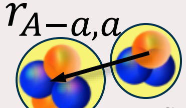
Can address bound and low-lying resonances (short range correlations)

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

Relative wave function (unknown)

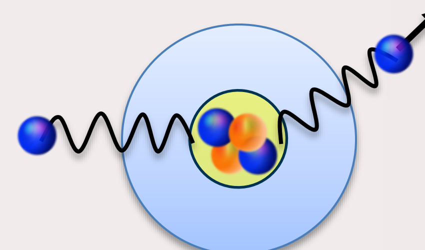
Antisymmetrizer

Channel basis



$\psi^{(A-a)}_{\alpha_1}\psi^{(a)}_{\alpha_2}\,\delta(\vec{r}-\vec{r}_{A-a,a})$

Cluster expansion technique



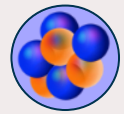
NCSM/RGM
Cluster formalism for elastic/inelastic

EQUAL TREATMENT OF BOUND AND RESONANT STATES: COUPLE NCSM AND NCSM/RGM (NCSMC)

S. Baroni, P. Navrátil and S. Quaglioni PRL110 (2013); PRC93 (2013)

- Methods develop in this presentation to solve the many body problem

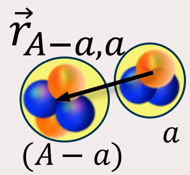
$$\Psi^{(A)}_{NCSM} = |A\lambda J^{\pi} T\rangle = \sum_{\alpha} c_{\alpha} \, |A\alpha j_z{}^{\pi} t_z\rangle \;\Leftrightarrow\; |A\lambda J^{\pi} T\rangle_{SD}\,\phi_{00}(\vec{R}^{A}_{c.m.})$$



Mixing coefficients (unknown) — A-body harmonic oscillator states — Second quantization

Can address bound and low-lying resonances (short range correlations)

$$\Psi^{(A)}_{RGM} = \sum_{\nu} \int d\vec{r}\, g_{\nu}(\vec{r})\, \hat{A}_{\nu} \left|\Phi^{(A-a,a)}_{\nu\vec{r}}\right\rangle \;\Leftrightarrow\; \psi^{(A-a)}_{\alpha_1}\psi^{(a)}_{\alpha_2}\,\delta(\vec{r}-\vec{r}_{A-a,a})$$



Relative wave function (unknown) — Antisymmetrizer — Channel basis — Cluster expansion technique

Design to account for scattering states (best for long range correlations)

- The many body quantum problem is best described by the superposition of both type of wave functions

$$\Psi^{(A)}_{NCSMC} = \sum_{\lambda} c_{\lambda} |A\lambda J^{\pi} T\rangle + \sum_{\nu} \int d\vec{r}\, g_{\nu}(\vec{r})\, \hat{A}_{\nu} \left|\Phi^{(A-a,a)}_{\nu\vec{r}}\right\rangle$$

NCSMC

NCSM/RGM AND NCSMC FOR THREE-BODY CLUSTERS

S. Quaglioni and C. Romero-Redondo *et al.* PRC88 (2013); PRL113 (2014)

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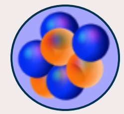
- Methods develop in this presentation to solve the many body problem

$$\Psi^{(A)}_{NCSM} = |A\lambda J^{\pi} T\rangle = \sum_{\alpha} c_{\alpha} \, |A\alpha j_z{}^{\pi} t_z\rangle$$

Mixing coefficients (unknown)

A-body harmonic oscillator states



$|A\lambda J^{\pi} T\rangle_{SD} \, \phi_{00}(\vec{R}^{A}_{c.m.})$

Second quantization

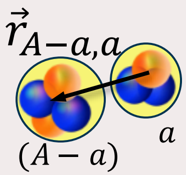
Can address bound and low-lying resonances (short range correlations)

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

Relative wave function (unknown)

Antisymmetrizer

Channel basis



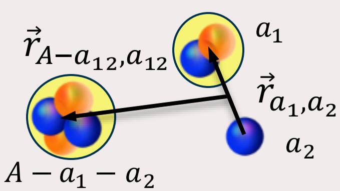
$\psi^{(A-a)}_{\alpha_1} \psi^{(a)}_{\alpha_2} \, \delta(\vec{r} - \vec{r}_{A-a,a})$

Cluster expansion technique

Design to account for scattering states (best for long range correlations)

- Adding three-cluster degrees of freedom:

$$+ \sum_{v} \iint d\vec{x} d\vec{y} x^2 y^2 G_v(\vec{x},\vec{y}) \, \hat{A}_v \left| \Phi^{(A-a_1-a_2,a_1,a_2)}_{v\vec{x}\vec{y}} \right\rangle$$



$\psi^{(A-a_1-a_2)}_{\alpha_1} \psi^{(a_1)}_{\alpha_2} \psi^{(a_2)}_{\alpha_3} \, \delta(\vec{r} - \vec{r}_{a_1,a_2}) \times \delta(\vec{r} - \vec{r}_{A-a_{12},a_{12}})$

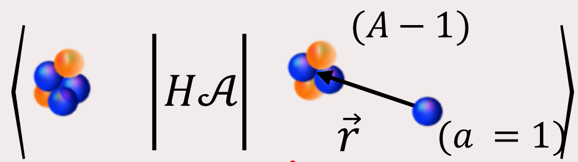
Cluster expansion technique

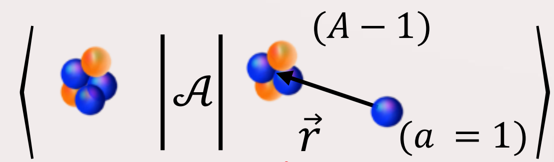
…

C. Romero-Redondo, *et al.* arXiv:1606.00066

COUPLED NCSMC EQUATIONS

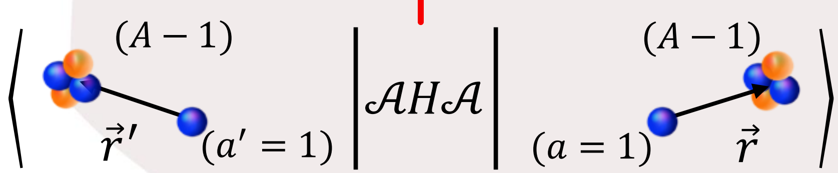
S. Baroni, P. Navrátil and S. Quaglioni PRL110 (2013); PRC93 (2013)





$E_\lambda \, \delta_{\lambda\lambda'}$

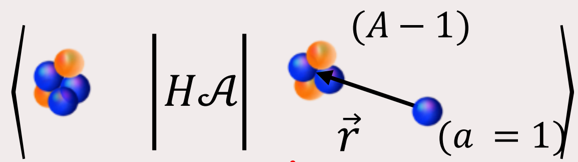
$$\begin{pmatrix} H_{NCSM} & h \\ h & H_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix} = E \begin{pmatrix} 1_{NCSM} & g \\ g & N_{RGM} \end{pmatrix}$$

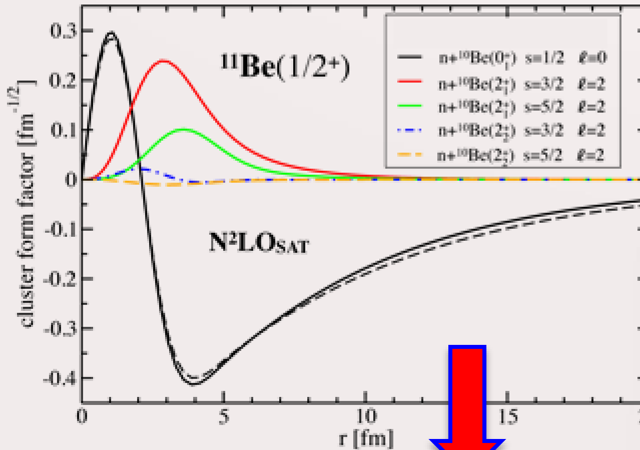


Scattering matrix (and observables) from matching solutions to known asymptotic with microscopic R-matrix on Lagrange mesh.

COUPLED NCSMC EQUATIONS

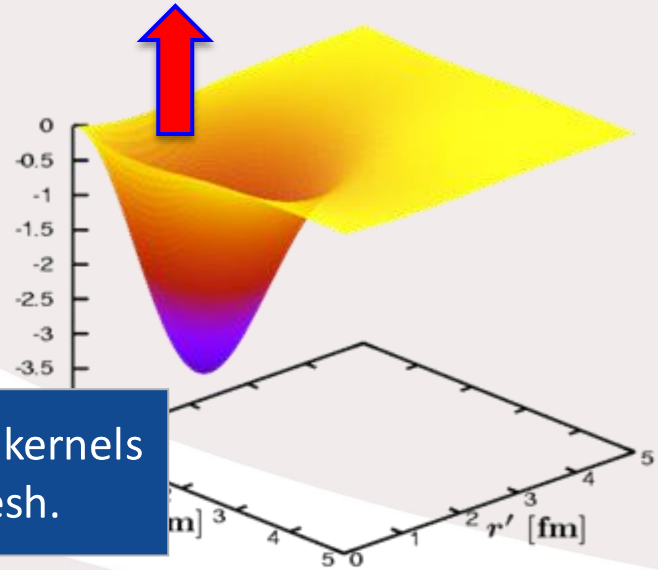
S. Baroni, P. Navrátil and S. Quaglioni PRL110 (2013); PRC93 (2013)

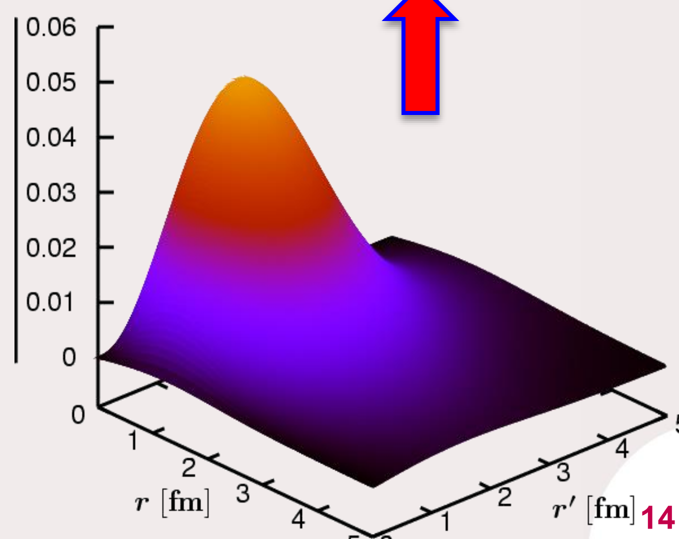




$E_\lambda \, \delta_{\lambda\lambda'}$

$$\begin{pmatrix} H_{NCSM} & h \\ h & H_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix} = E \begin{pmatrix} 1_{NCSM} & g \\ g & N_{RGM} \end{pmatrix}$$

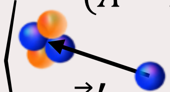
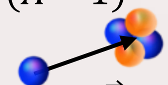




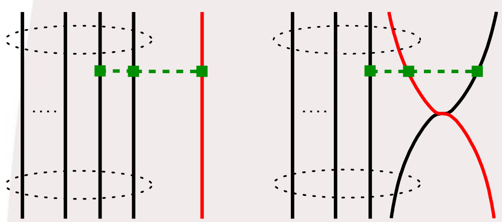
Long-range part of the kernels is computed on the mesh.

INCLUDING THE 3N FORCE INTO THE NCSM/RGM APPROACH

nucleon-nucleus formalism

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

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



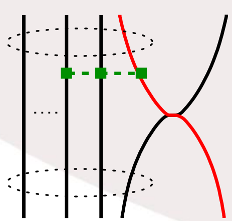
(a) (b)

Direct potential:

$\propto {}_{SD}\langle A - a\alpha'_1 I'^{\pi'_1}_1 T'_1 | a^\dagger a^\dagger a a | A - a\alpha_1 I^{\pi_1}_1 T_1 \rangle_{SD}$ ~1Go

~7.10^3 two-body states

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

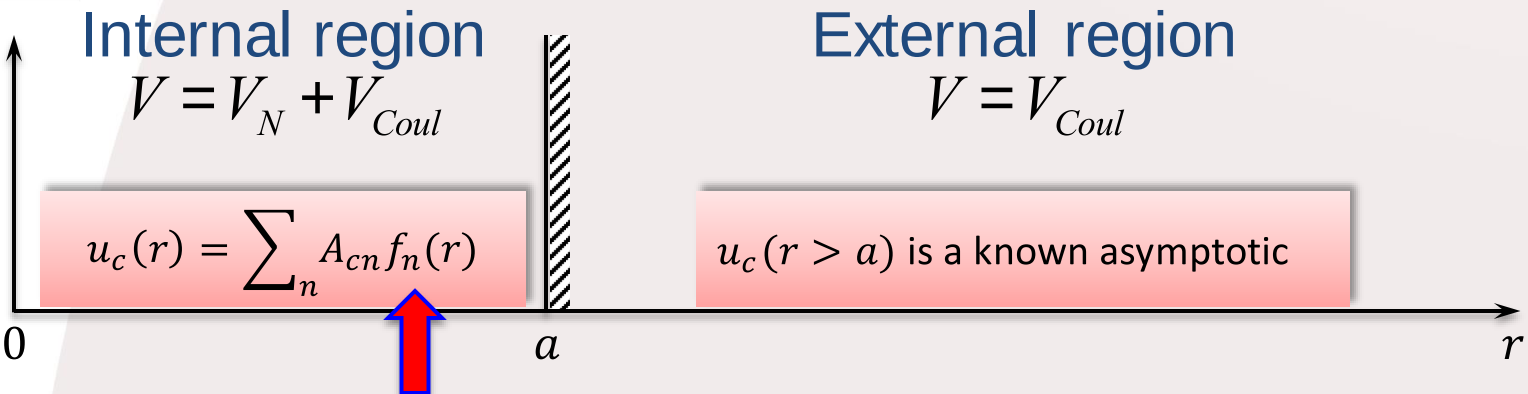


(c)

Exchange potential:

$\propto {}_{SD}\langle A - a\alpha'_1 I'^{\pi'_1}_1 T'_1 | a^\dagger a^\dagger a^\dagger a a a | A - a\alpha_1 I^{\pi_1}_1 T_1 \rangle_{SD}$

SOLUTION OF THE SCATTERING PROBLEM WITH R-MATRIX METHOD



Decomposition on a Lagrange mesh.

NCSMC can be cast as Bloch-Schrödinger equation:

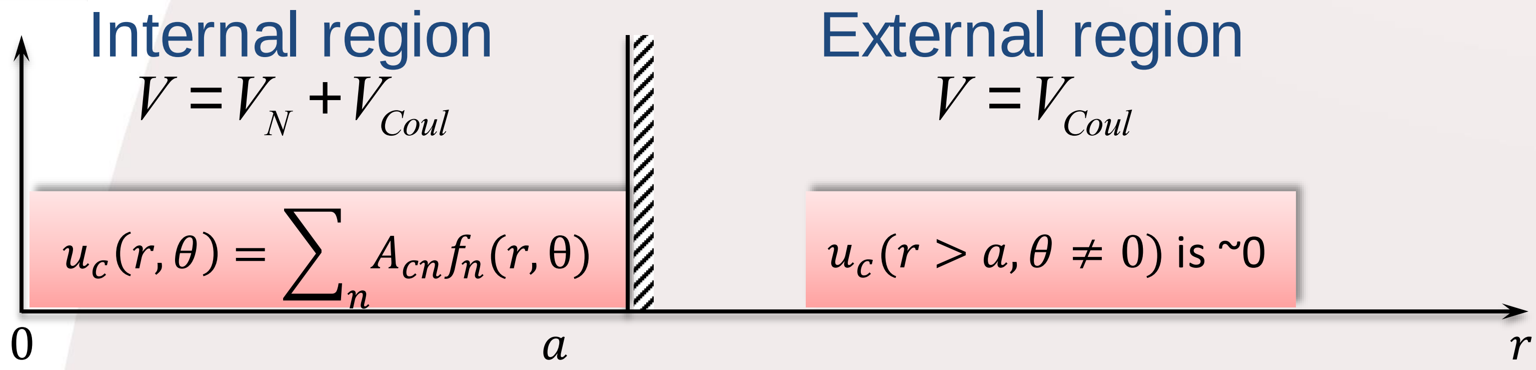
$$(C - EI)\vec{X} = Q(B)$$

And solved using R-matrix, which in the eigen basis of $C - EI$ reads:

$$R_{cc'} = \sum_{\lambda} \frac{\gamma_{\lambda c}\gamma_{\lambda c'}}{E_\lambda - E}$$

Simple for binary reacting system, more involved for neutral ternary system and extremely challenging for charged breakup !

ALTERNATIVE: COMPLEX SCALING



Complex scaling brings us back to Hilbert space; NCSMC will be solved with (two-body) Schrödinger equation

$$(H(\theta) - EI)\psi(\Theta) = 0$$

i.e. no inhomogeneous term. Scattering observables need to be derived using integral relations like Green's theorem

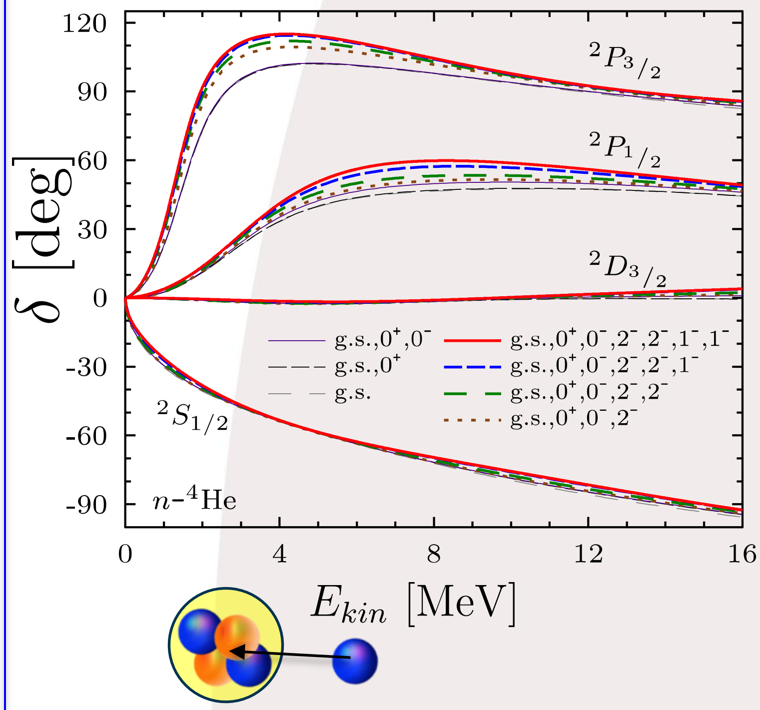
$$A(\boldsymbol{k}) = \frac{m}{\hbar}\left[\left\langle F^{\mathrm{in}}(\boldsymbol{k}e^{i\boldsymbol{\theta}}) \middle| V(\theta) \middle| \psi(\boldsymbol{k},\theta)\right\rangle - \left\langle \psi(\boldsymbol{k},\theta) \middle| V(\theta) \middle| F^{\mathrm{in}}(\boldsymbol{k}e^{i\boldsymbol{\theta}})\right\rangle\right]$$

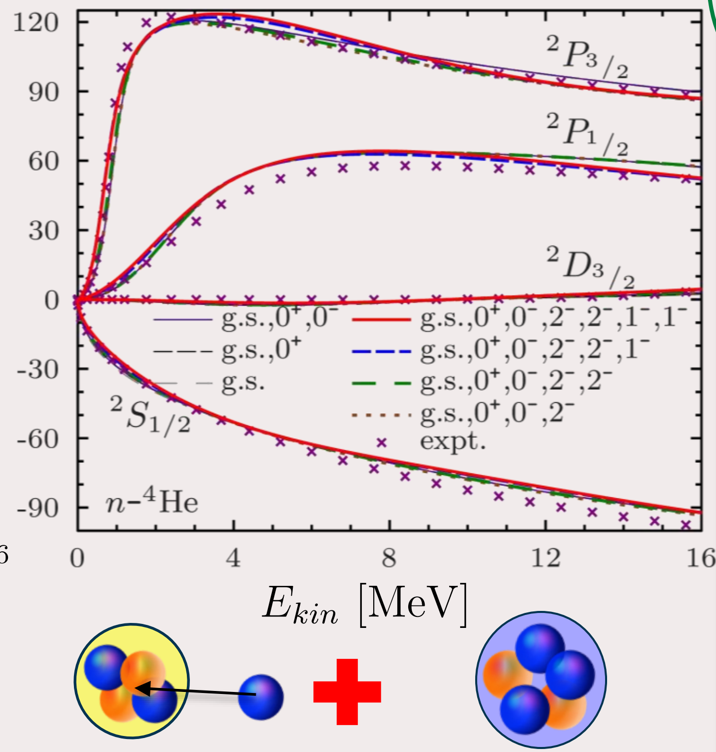
- Long-range coulomb problem is avoided.
- "Simple" to solve.
- Useful for charged breakup.

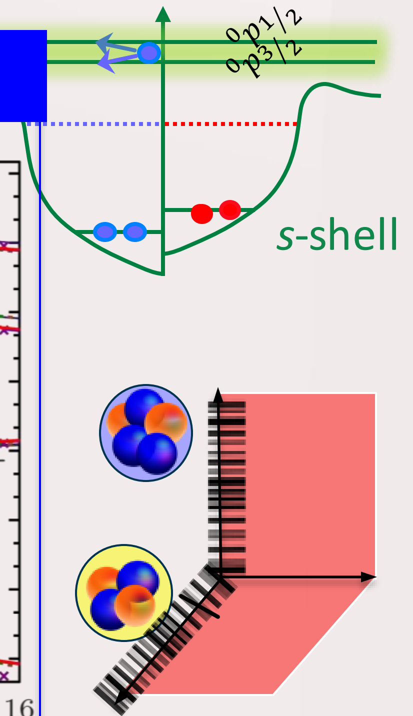
AB INITIO ≡ STUDY OF CONVERGENCE

G. Hupin, J. Langhammer *et al.* PRC88 (2013); G. Hupin, S. Quaglioni and P. Navrátil, Physica Scripta Special Edition - Nobel Prize '75 anniversary

Convergence with respect to the # of ^{4}He low-lying states



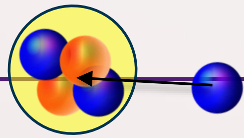




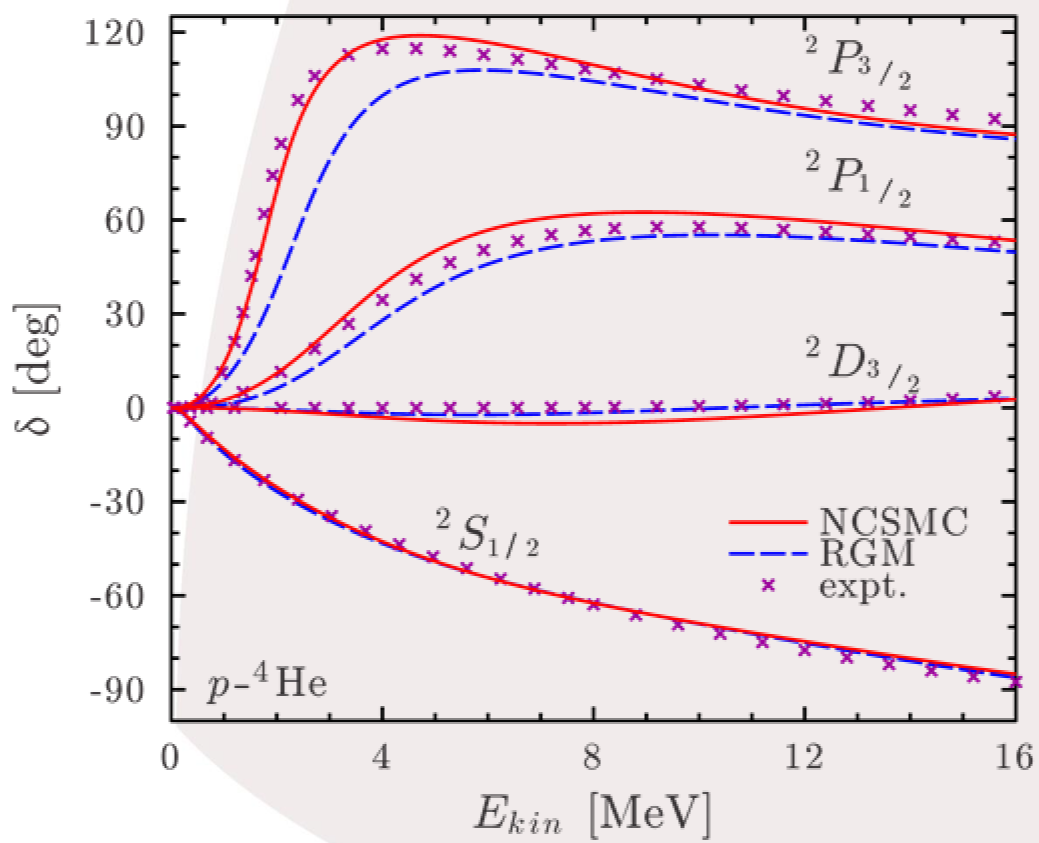
n-^{4}He scattering phase-shifts for NN+3N potential with λ=2.0 fm^{-1}.

- The convergence pattern much better with NCSMC
- The experimental phase-shifts are well reproduced.

AB INITIO: NCSM/RGM → NCSMC



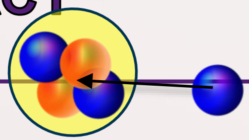
Two scenarii of nuclear Hamiltonians



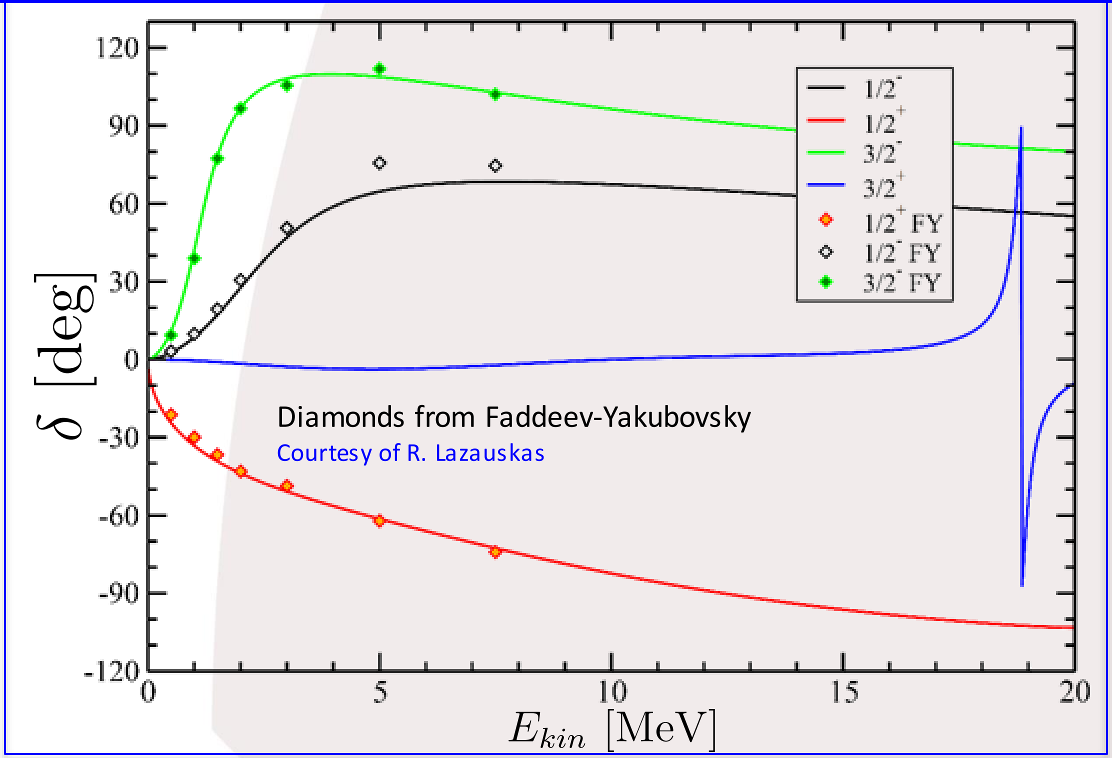
- NCSMC outperforms the binary cluster model for all resonant waves.
- Good agreement of NCSMC with experiment.

Comparison between NCSM/RGM (i.e. a binary cluster approximation) and NCSMC

n-^{4}He SCATTERING: *AB INITIO* VS EXACT



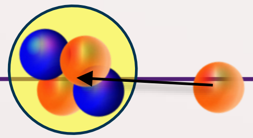
Benchmark: scattering phase shifts NCSMC/FY



- **Good agreement** between the two methods.

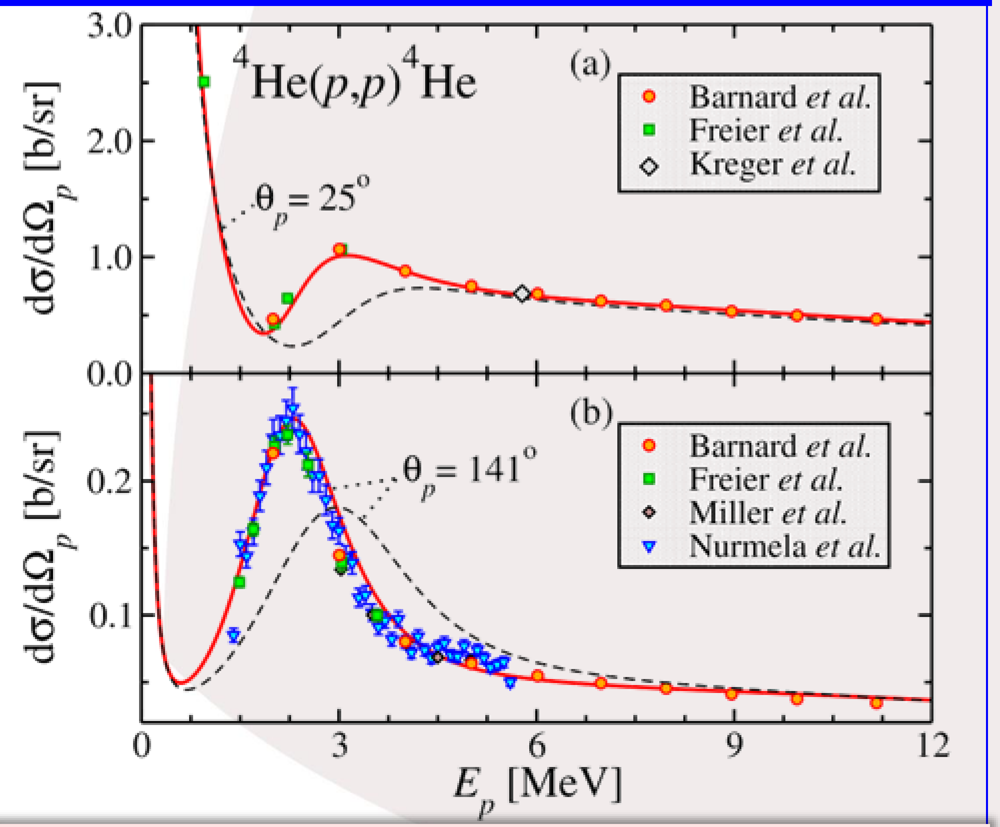
POSTDICTION FOR RUTHERFORD BACKSCATTERING (RBS)

G. Hupin, S. Quaglioni and P. Navrátil, PRC90 (2014)



p-^{4}He scattering

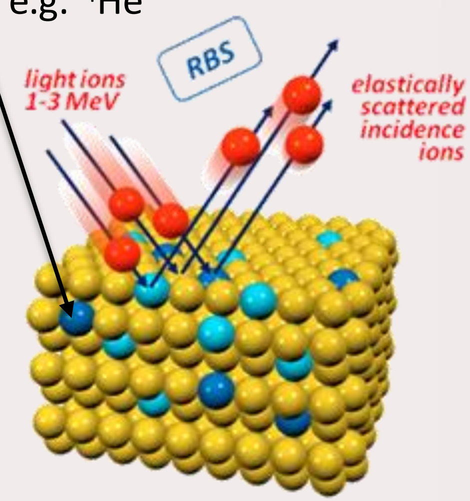
p-^{4}He differential cross-section compared to experiment



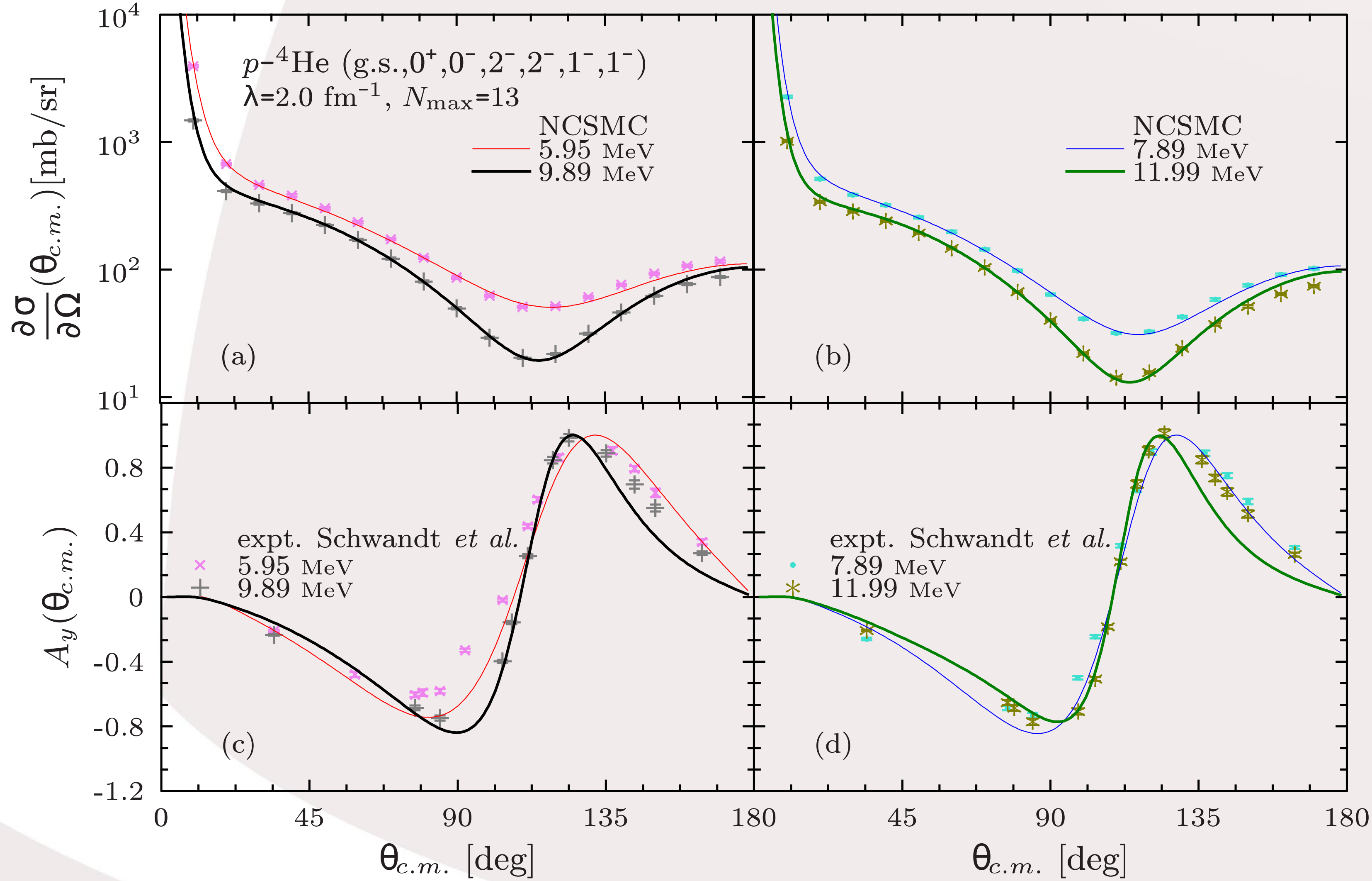
p-^{4}He differential cross-section for NN+3N.

For the non-destructive physical, electrical and chemical characterization of materials, nuclear physics is routinely used for energies above the Rutherford scattering.

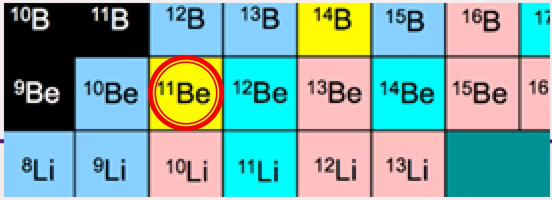
Impurities, e.g. ^{4}He



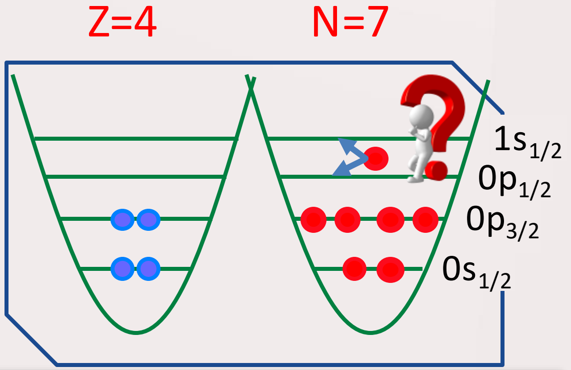
p-^{4}He SCATTERING FOLLOWS THE TREND OBSERVED IN p-^{3}He CONCERNING THE REDUCED A_Y PROBLEM



ν-RICH HALO NUCLEUS ^{11}Be



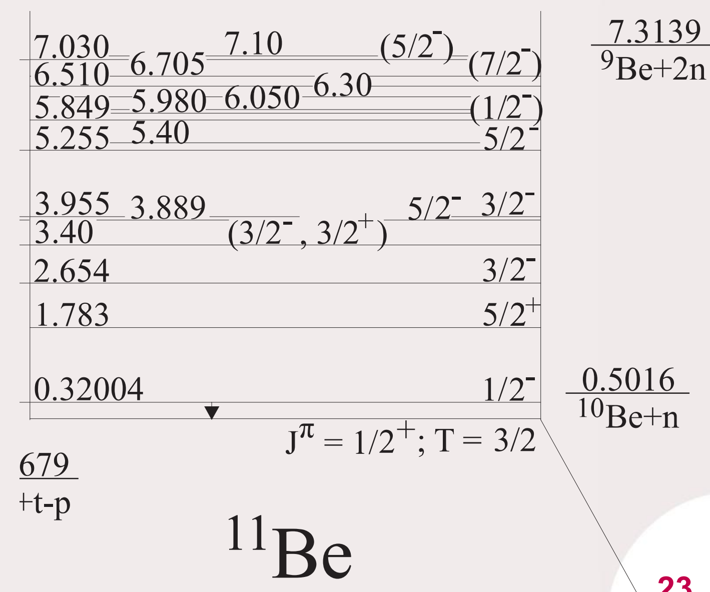
- In a shell model picture, the g.s. expected to be $J^{\pi} = 1/2^{-}$.
- In reality, ^{11}Be g.s. is $J^{\pi} = 1/2^{+}$ -- parity inversion.
- Very weakly bound: E_{th}=-0.5 MeV Halo state -- dominated by n-^{10}Be in a S-wave.
- The 1/2$^-$ state also bound -- only by 180 keV.



Single particle interpretation using nuclear shell model

Can we describe ^{11}Be in *ab initio* calculations?

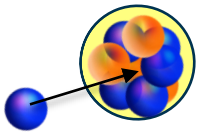
- Continuum must be included.
- Does the 3N interaction play a role in the parity inversion?



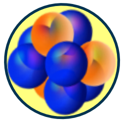
STRUCTURE OF ^{11}Be FROM CHIRAL NN+3N FORCES

A. Calci *et al.* PRL117 (2016)

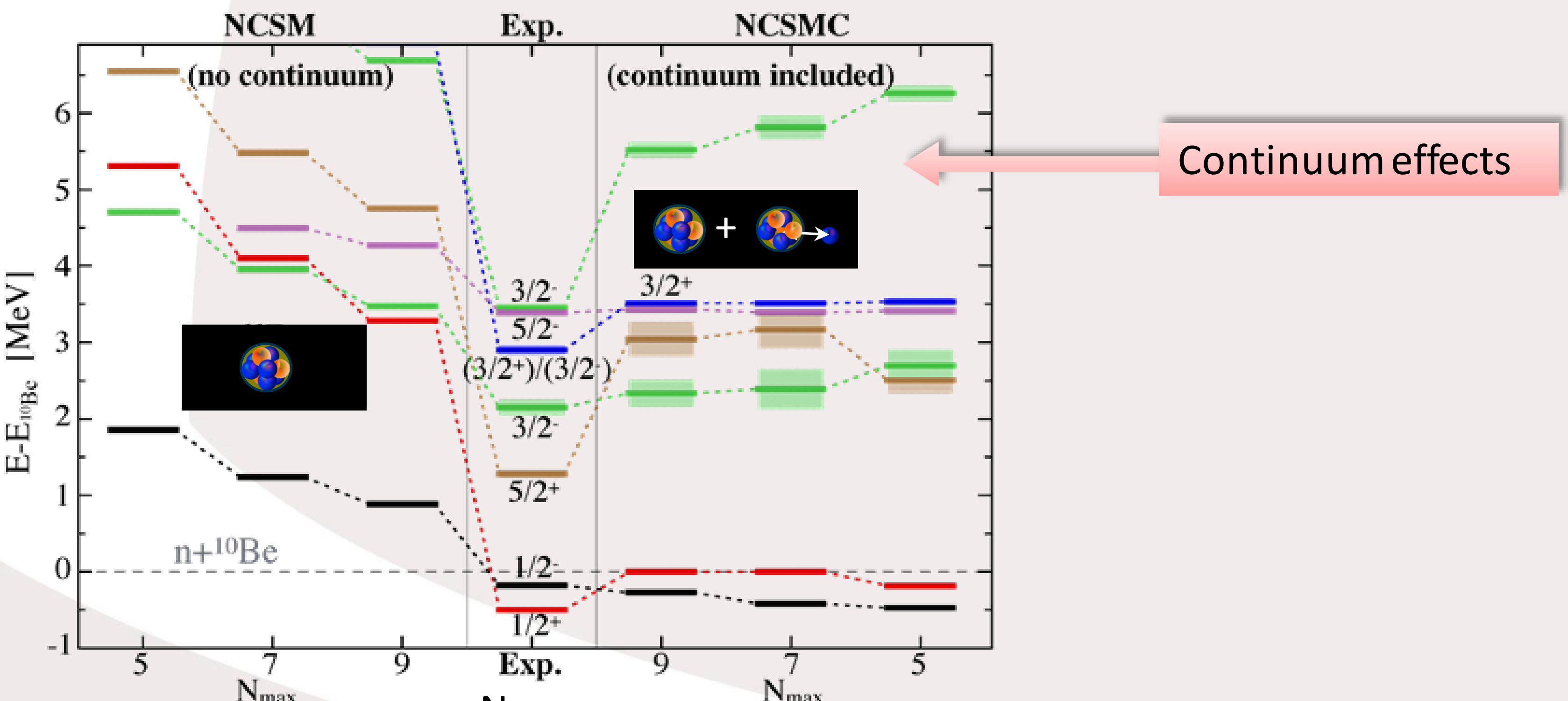
NCSMC calculations **including chiral 3N** (N^3LO NN+N^2LO 3NF400)



^{10}Be: 0^+, 2^+, 2^+ NCSM eigenstates

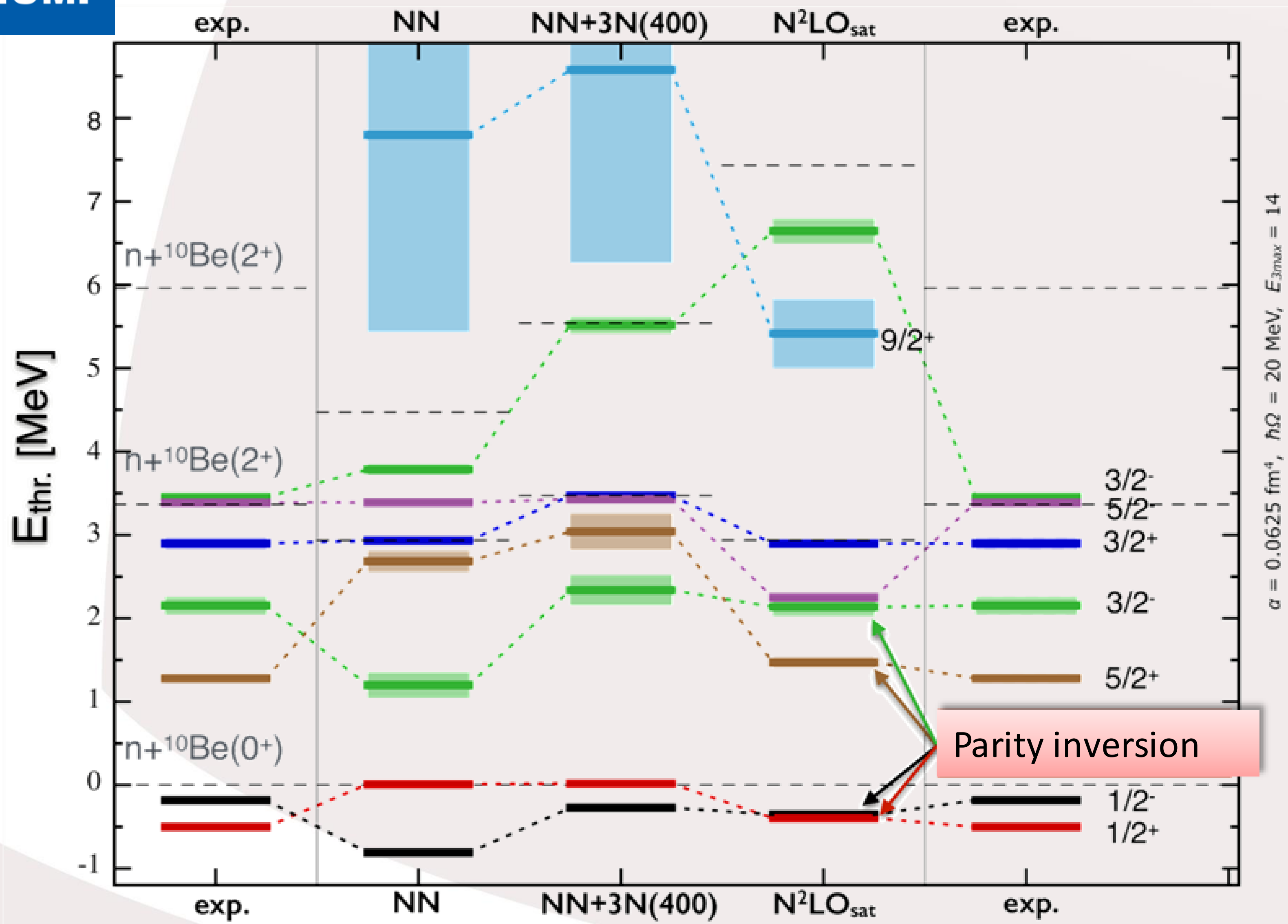


^{11}Be: ≥6 ($\pi=-1$) and ≥3 ($\pi=1$) NCSM eigenstates



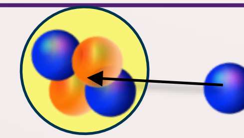
N_{max}

^{11}Be WITHIN NCSMC: DISCRIMINATION AMONG CHIRAL NUCLEAR FORCES
A. Calci et al. PRL117 (2016)

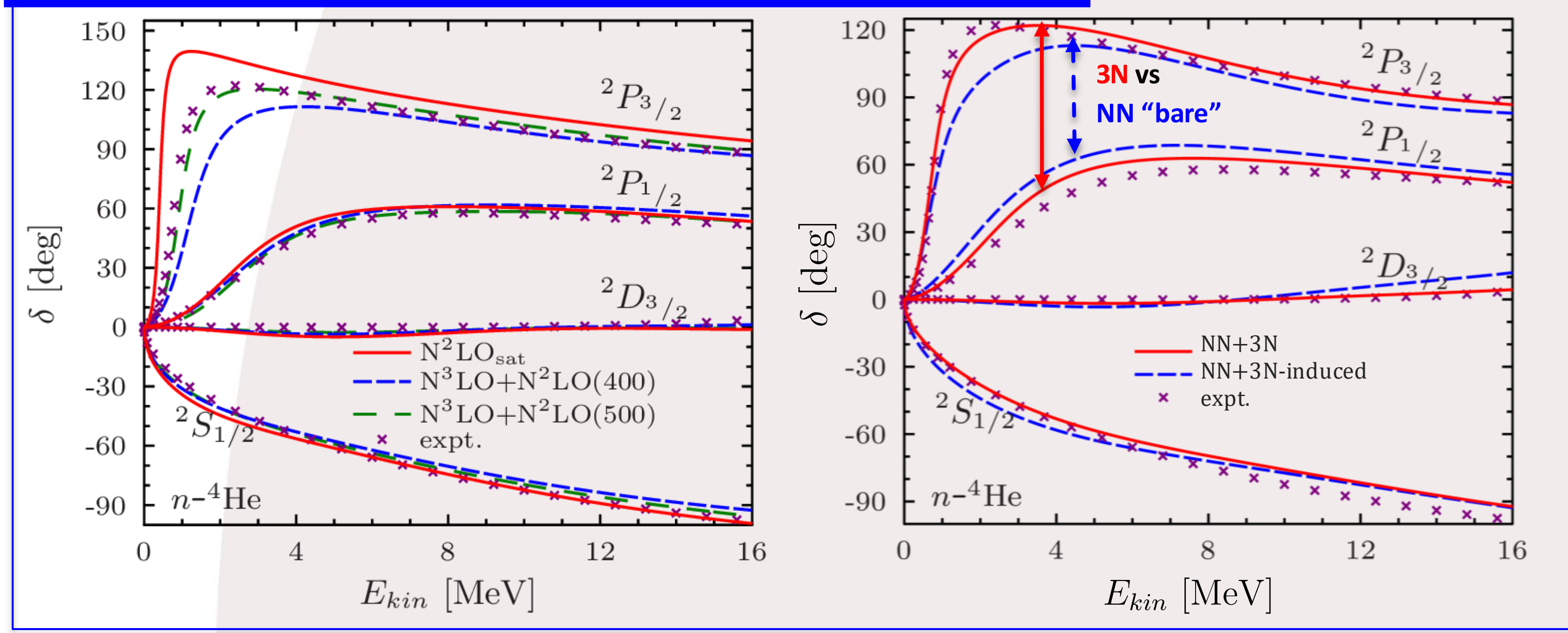


n-^{4}He SCATTERING: A LABORATORY FOR NUCLEAR INTERACTIONS

G. Hupin, J. Langhammer *et al.*, PRC88 (2013); P. Navrátil, S. Quaglioni, G. Hupin *et al.*, Phys. Scri.91 (2016) Celebrating the 1975 Nobel Prize



n-^{4}He scattering phase shifts

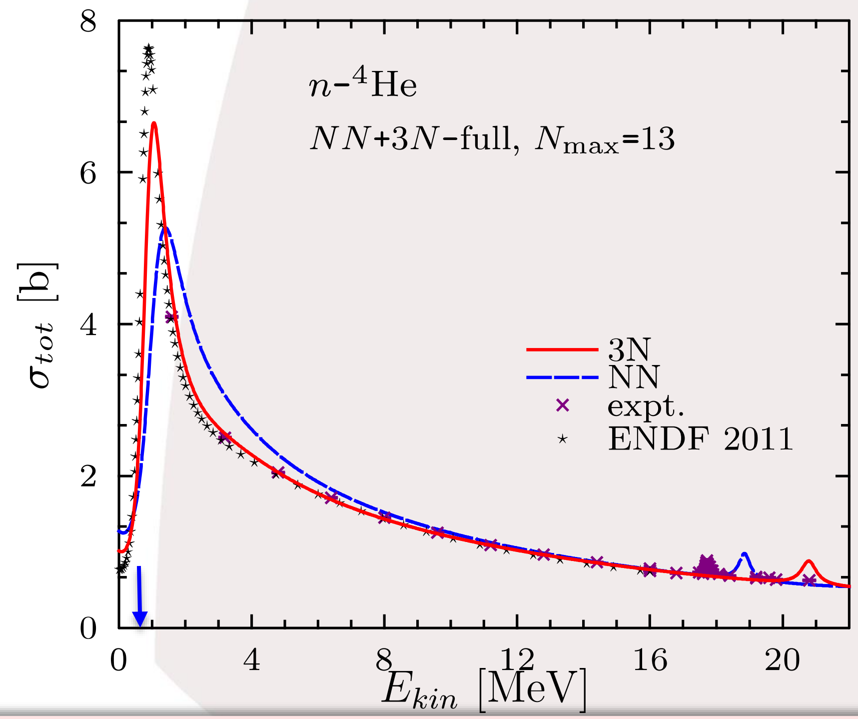


Some of the shortcomings of the nuclear interaction can already be **probed** in p-shell nuclei **through reactions**.
[NN p-waves are not perfectly reproduced by $N^{2}LO_{sat}$]

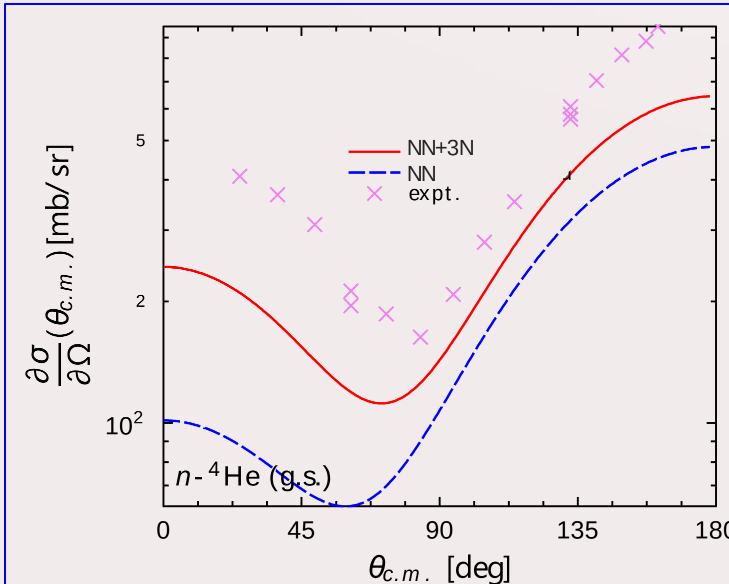
- The 3N interactions **influence** mostly the ***P* waves**.
- The **largest splitting** between P waves is obtained with **NN+3N**.

n-^{4}He ELASTIC CROSS-SECTIONS

Comparison of the elastic cross-section between NN and NN+3N with ^{4}He (g.s.)



n-^{4}He elastic cross-section for NN+3N-induced, NN+3N potentials compared to expt. and ENDF evaluation.

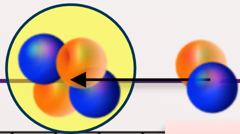


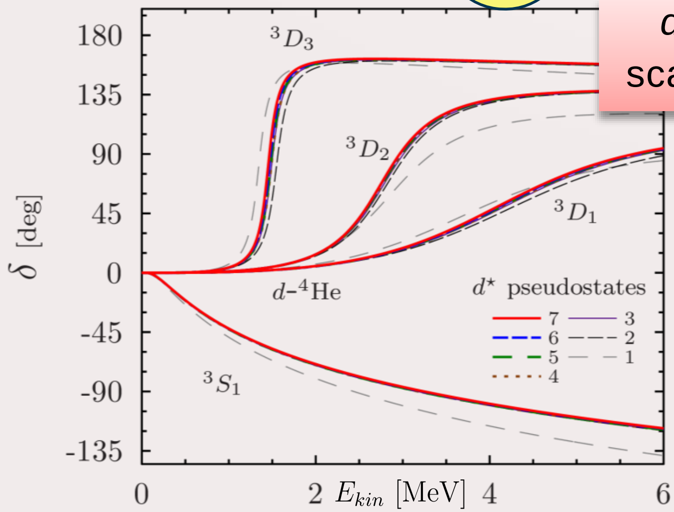
Differential cross-section at $E_{neutron}$ =0.84 MeV between NN+3N-ind and NN+3N.

- We obtained a better agreement with data when using NN+3N.
- The 3N force is constitutive to the reproduction of the $^3/_2{}^+$ resonance.

$^4He(d,d)^4He$ COMPARISON OF INTERACTION

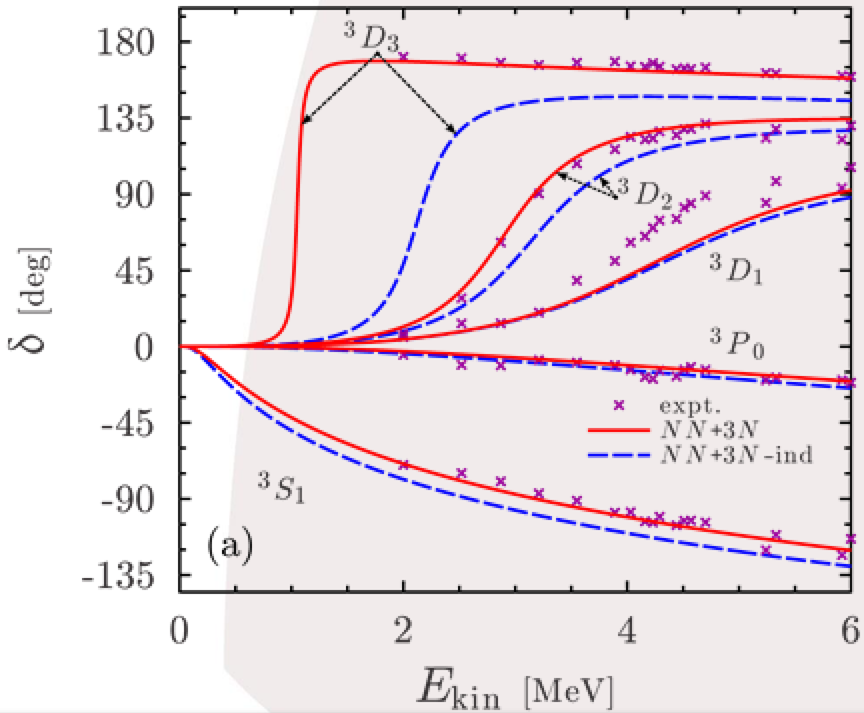
G. Hupin, S. Quaglioni and P. Navrátil, PRL114 (2015)





d-^{4}He scattering

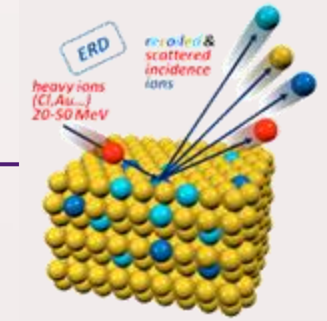
Comparison of the d-α phase-shifts with different interactions (N_{max}=11)



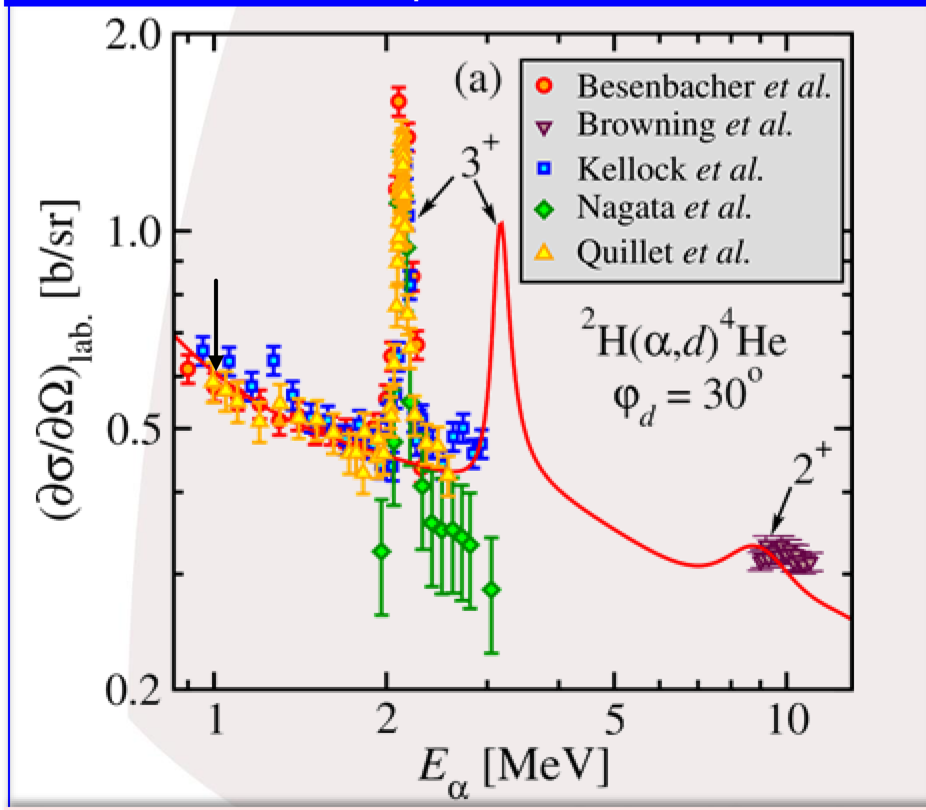
d-^{4}He(g.s.) scattering phase-shifts for NN-only, NN+3N-induced, NN+3N-full potential with λ=2.0 fm^{-1}.

- Best results in a decent model space (N_{max}=11).
- The $^3D_3$ resonance is reproduced but the $^3D_2$ and $^3D_1$ resonance positions are underestimated.
- The 3N force corrects the D-wave resonance positions by increasing the spin-orbit splitting.
- There is room for improvements.

^{4}He(d,^{4}He)d CROSS-SECTION

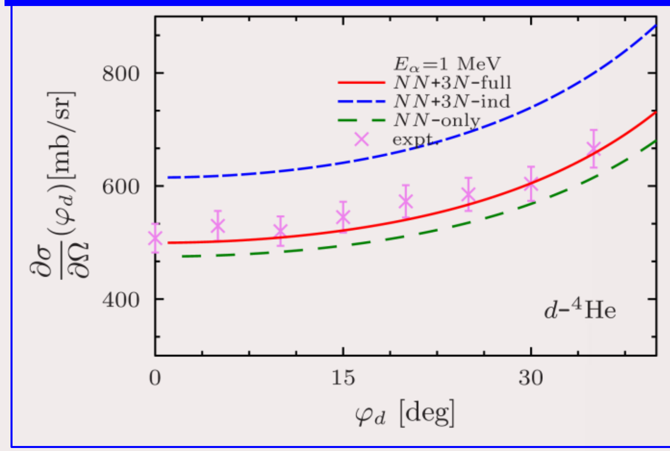


^{4}He(d,^{4}He)d differential cross section at φ=30^0



Comparison to experiment of the d-^{4}He elastic recoil differential cross section of NCSMC with NN+3N potential at λ=2.0 fm^{-1}.

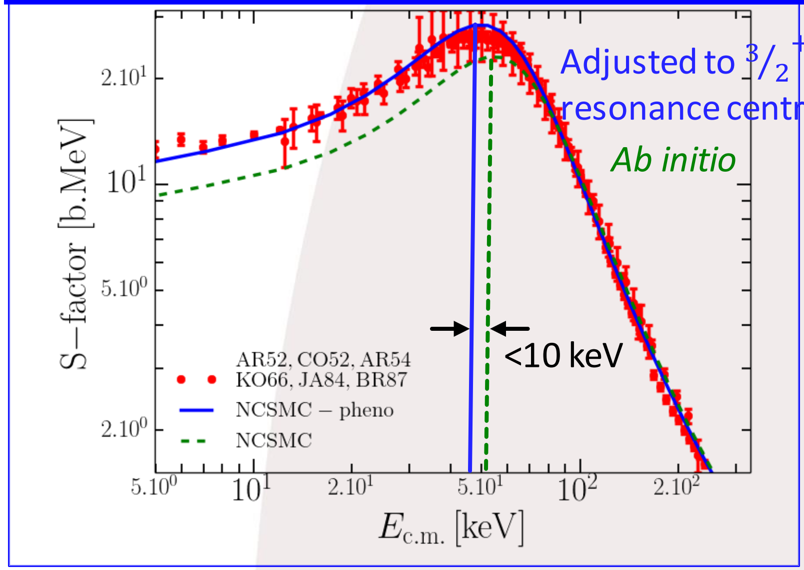
Comparison between potentials



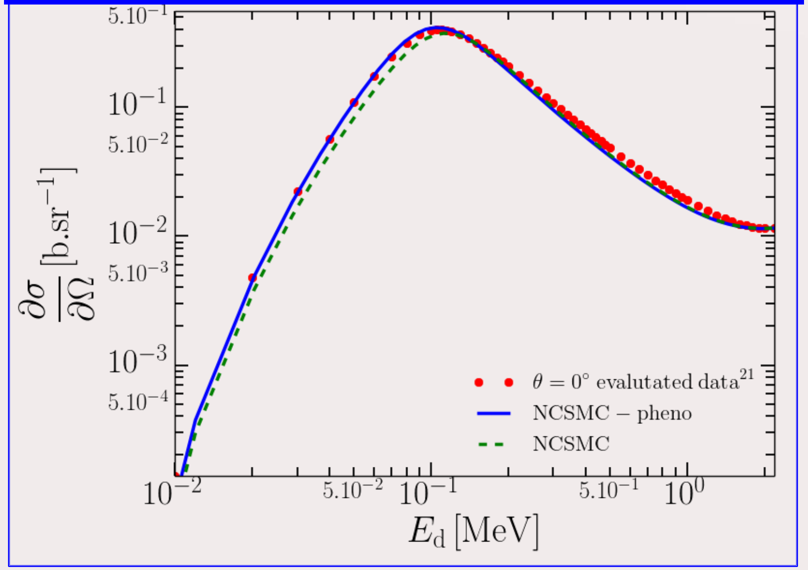
The 3$^+$ resonance is missed. As its width is very narrow, it has little impact and the bulk of the cross-section.

$^{2}H(t,n)^{4}He$ FUSION REACTION: BENCHMARK TO DATA AND EVALUATION

S-factor: computed and data



Angular distribution at $\theta = 0^{\circ}$

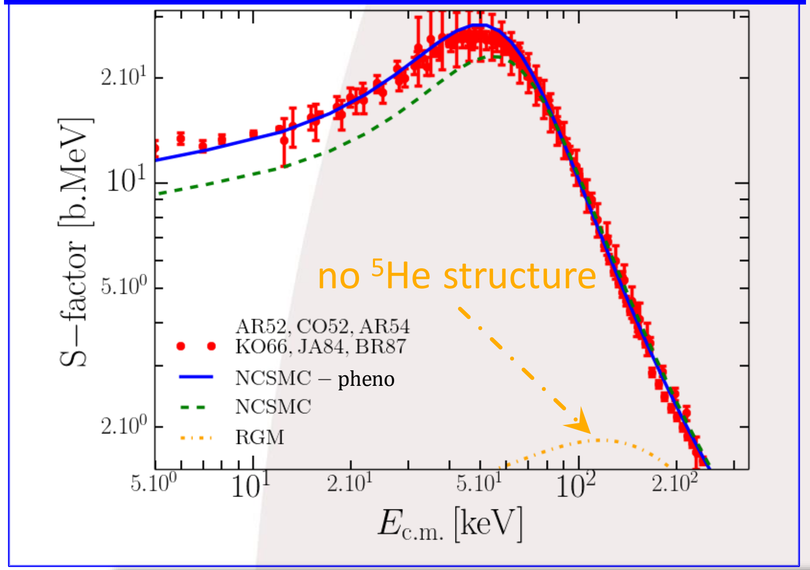


M. Drosg and N. Otuka, INDC(AUS)-0019 (2015).

- The S-factor is globally well reproduced.
- The accurate **reproduction** (of the order of keV) of the **resonance position**/width is **essential**.
- Shape of a the angular distribution **agrees** with recent **evaluation**.

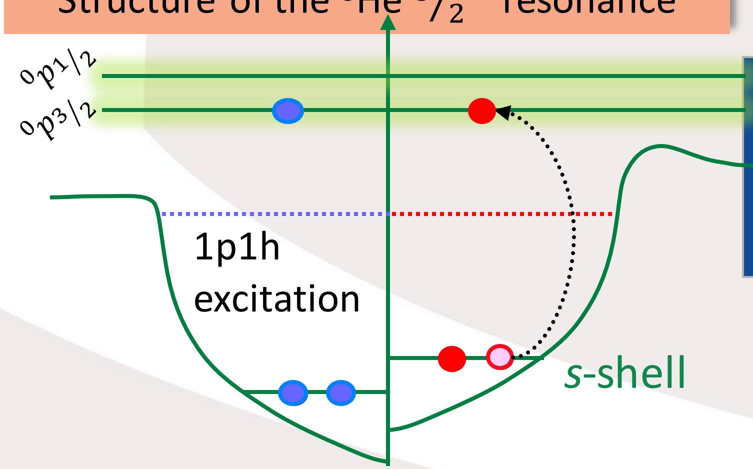
$^2H(t,n)^4He$ FUSION REACTION: IMPACT OF THE RESONANCE STRUCTURE

S-factor: NCSMC vs binary cluster



$^5He(^4S_{3/2})$	E_r (keV)	Γ_r (keV)
Cluster basis (D g.s. only)	105	1100
Cluster basis	120	570
NCSMC (D g.s. only)	65	160
NCSMC	55	110
NCSMC-pheno	50	98
R-matrix	48	25

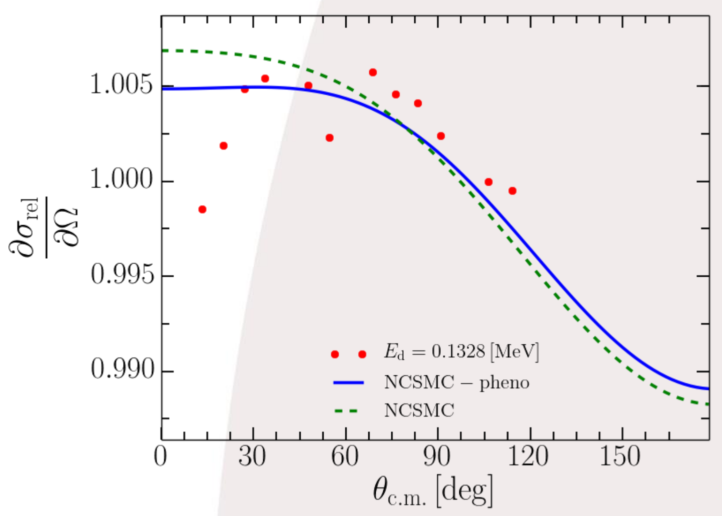
Structure of the ^5He $^3/_2{}^+$ resonance



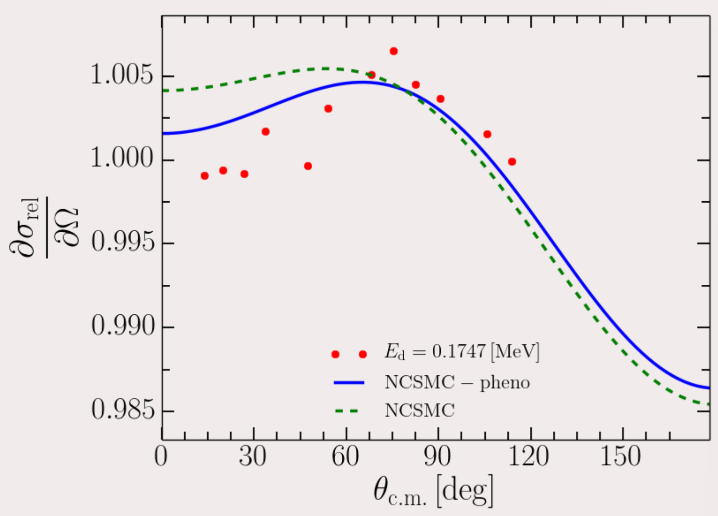
- **Importance** of **structure** of neighboring resonances is magnified in **transfer reactions**.

$^2H(t,n)^4He$ FUSION REACTION: CORRECTNESS OF S-MATRIX

Angular distribution relative to integral



Angular distribution relative to integral



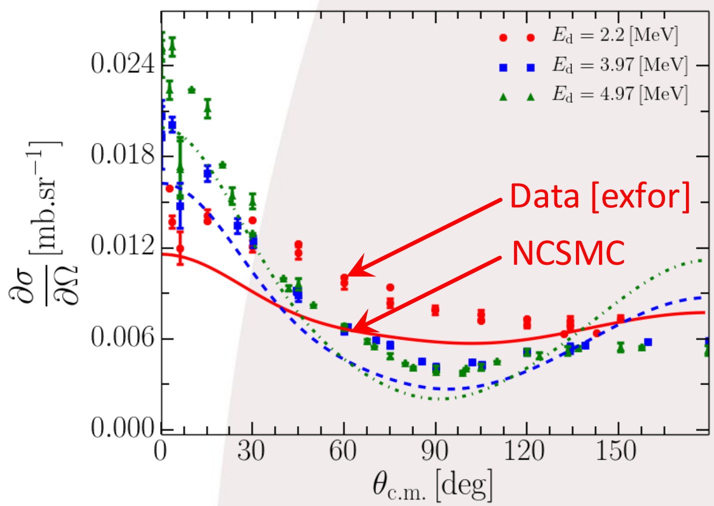
P. Bém *et al.*, Few-Body Syst **22**, 77 (1997).

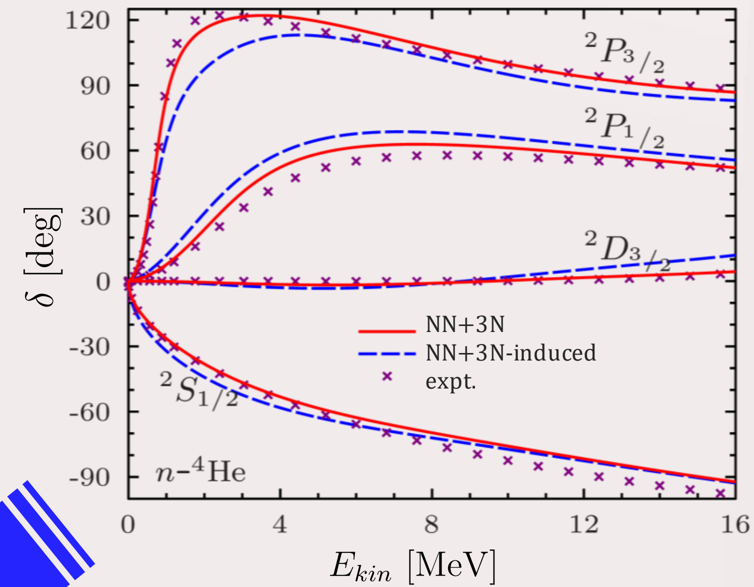
- Influence of p- and d-waves in the slope and bump of $\partial\sigma_{\mathrm{rel}}/\partial\Omega$, respectively.
- Overall good reproduction of data: **collision matrix** is expected to be **accurate**.

^{2}H(t,n)^{4}He FUSION REACTION: BACKGROUND WAVES

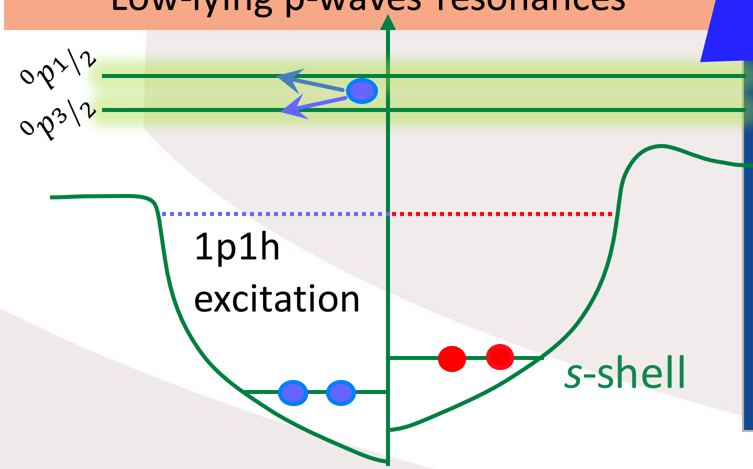
IPN
INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

Differential cross section at $E > E_{3/2^+}$





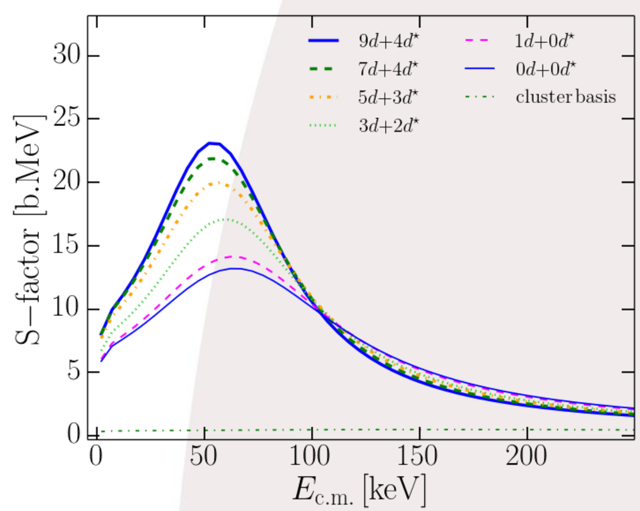
Low-lying p-waves resonances



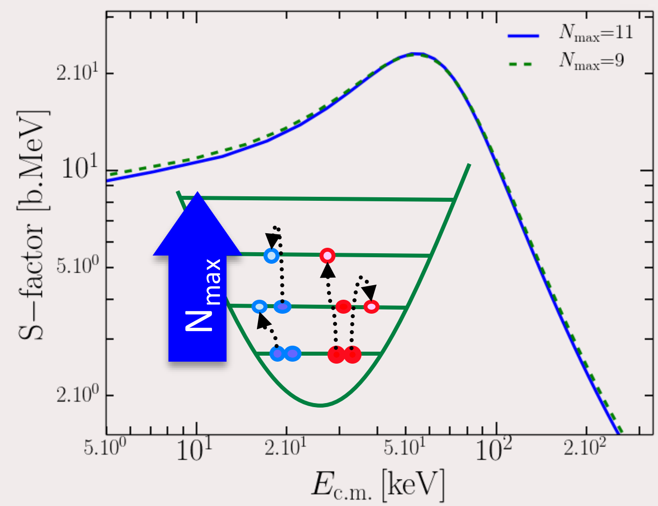
- **Away from** the **DT** fusion peak, the **effects** of low-lying **background phase-shifts** can be seen.
- No effects of the adjustment of the $3/2^+$ resonance position (i.e. **NCSMC≡NCSMC-pheno**).

$^{2}H(t,n)^{4}He$ FUSION REACTION: MODEL CONVERGENCE

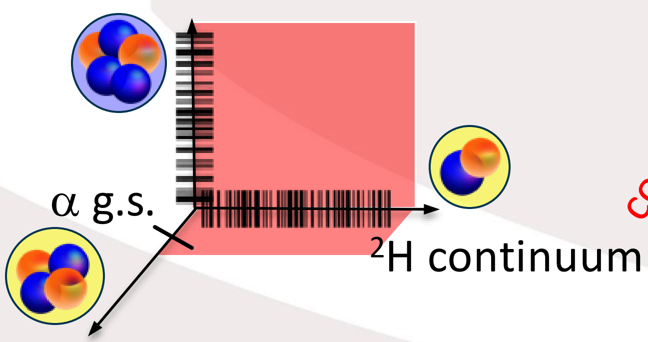
Convergence wrt ^{2}H continuum



Convergence with Nmax



^{5}He resonances



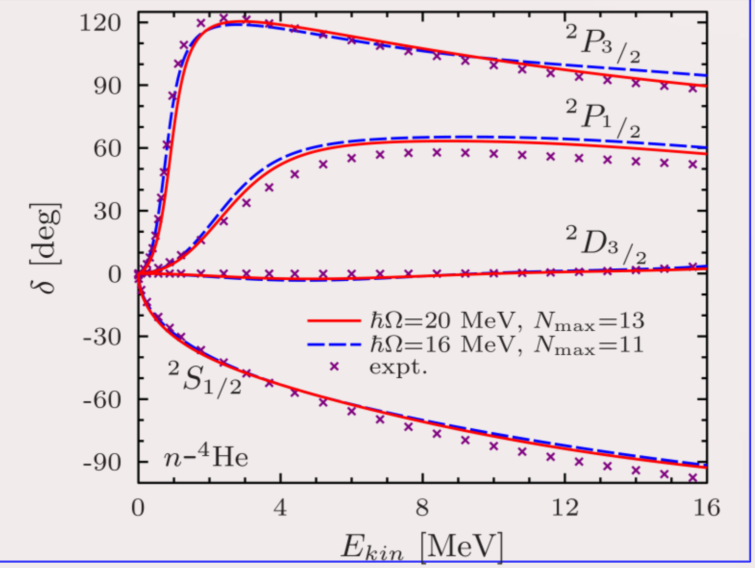
- Discretization of ^{2}H is **essential** for the reproduction of the S-factor.
- Stable behavior with respect to the number of ^{2}H pseudo states.
- Converged with N_{max}.

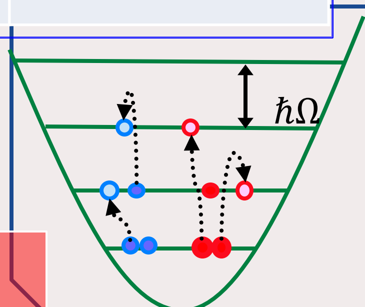
^{2}H(t,n)^{4}He FUSION REACTION: MODEL CONVERGENCE

Convergence of $^3/_2{}^+$ resonance

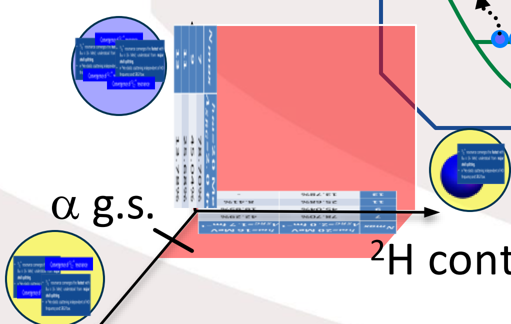
N_{max}	$\hbar\omega$=20 MeV Λ_{SRG}=2.0 fm^{-1}	$\hbar\omega$=16 MeV Λ_{SRG}=1.7 fm^{-1}
7	78.70%	42.29%
9	45.04%	18.85%
11	25.68%	8.41%
13	13.78%	-

n-^{4}He phase shifts





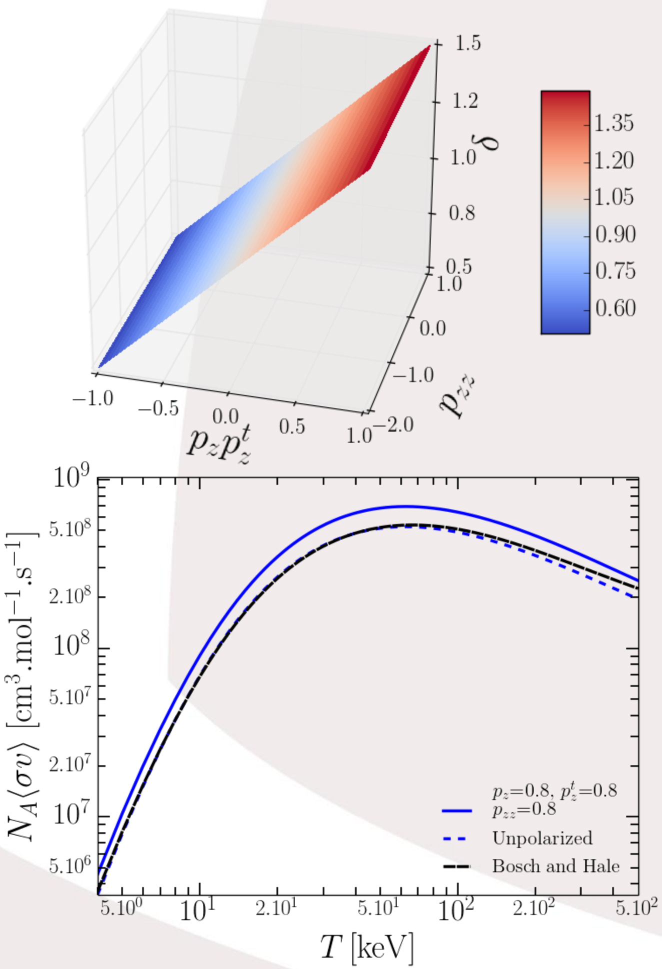
^{5}He resonances

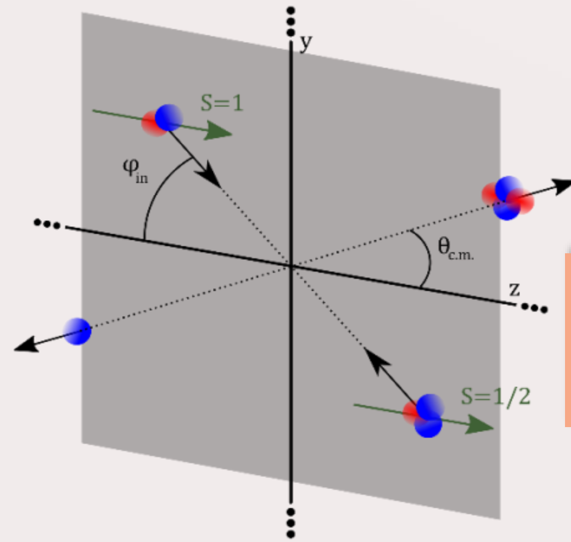


- $^3/_2{}^+$ resonance converges the **fastest** with $\hbar\omega = 16$ MeV, understood from **major shell splitting**.
- n-^{4}He elastic scattering independent of HO frequency and SRG flow.

DT POLARIZED THERMONUCLEAR FUSION

Enhancement factor and reaction rate





Reactant spins are prepared in a configuration

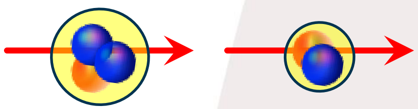
$$\sigma^{\text{polar}}(\theta) = \sigma(\theta)\left(1 + \frac{1}{3}p_{zz}A_{zz} + \frac{3}{2}p_z p_{z^t} C_{z,z^t}\right)$$

- **Predictions** for polarized $^3\vec{\mathrm{H}}(\vec{d},n)^4\mathrm{He}$ enhancement factor and reaction rate.
- **Confirmation** of maximum enhancement ($\delta = 1.5$) scenario.
- *Ab initio* calculation shows that $\delta = 1.38$ can be achieved in lab.

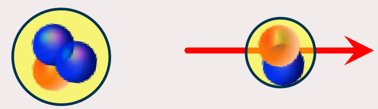
G. Hupin, S. Quaglioni and P. Navrátil to be submitted

ANISOTROPIES FROM POLARIZED REACTION

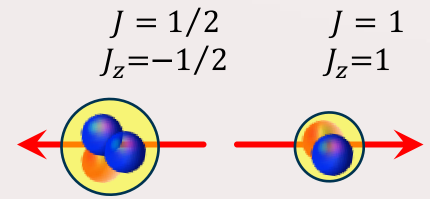
Angular distribution in different polarization scenarios



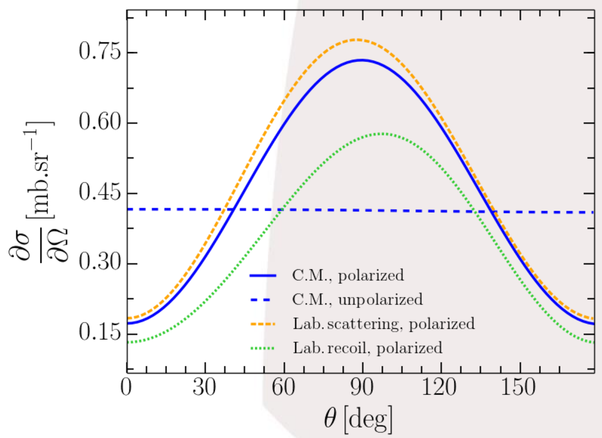
Total cross section increased

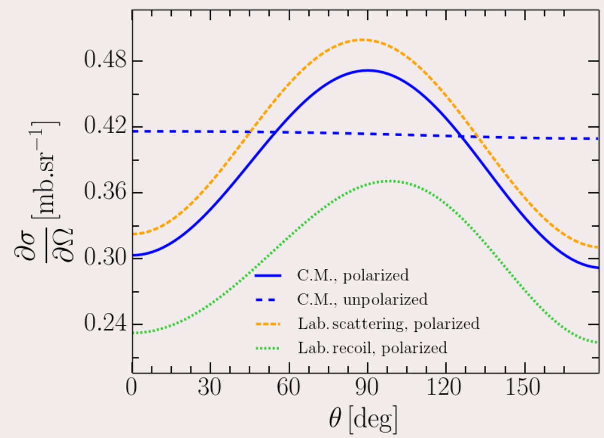


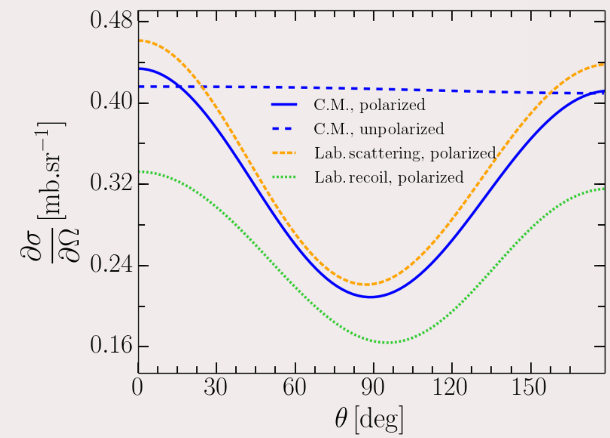
on average no effects



Total cross section decreased







Spin tensor properties of the deuteron give the angular shape.
(Same as in $^3\overrightarrow{\mathrm{He}}(\vec{d},p)^4\mathrm{He}$)

THANK YOU !

Summary:

- Binary cluster states and (elastic, transfer..) reactions with NN and 3N.
- Three-cluster bound state and continuum with NN (and 3N).
- Reasonable control over model uncertainties.
- Challenging for heavier systems.
- Reaction observables/complete information on the continuum to probe nuclear forces.

Personal questions:

- How to use *ab initio* reactions to test approximations in reaction modeling ?
- Effective method to study optical potential ?