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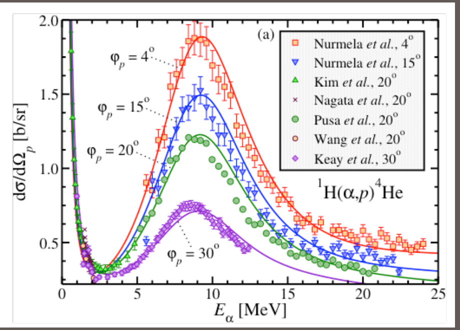
Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire
et en physique des particules

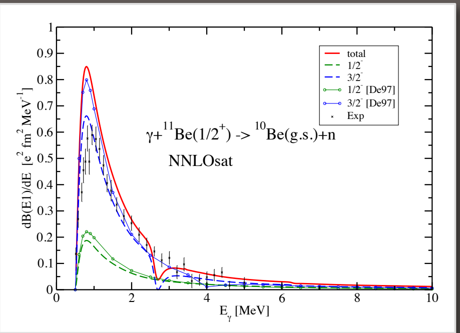
# *Ab Initio* Unified Approach to Nuclear Structure and Reactions

**INT Program INT 16-1**
**Nuclear Physics from Lattice QCD**
**April 5, 2016**

**Petr Navratil | TRIUMF**

Collabrorators:
Sofia Quaglioni, Carolina Romero-Redondo (LLNL)
**Guillaume Hupin** (CEA/DAM)
**Jeremy Dohet-Eraly**, **Angelo Calci** (TRIUMF)
Francesco Raimondi (Surrey), Wataru Horiuchi (Hokkaido)
Robert Roth (TU Darmstadt)



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# Outline

- No-Core Shell Model with Continuum (NCSMC) approach
- Connection to nuclear lattice EFT
- N-$^{4}$He scattering
- $^{6}$Li structure & d-$^{4}$He scattering
- $^{11}$Be as a laboratory for testing of nuclear forces
- $^{11}$N and $^{10}$C-p scattering
- $^{3}$He-$^{4}$He and $^{3}$H-$^{4}$He radiative capture

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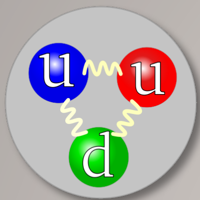
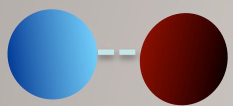
# From QCD to nuclei

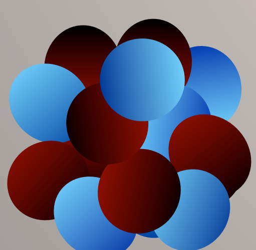



Low-energy QCD



NN+3N interactions from chiral EFT

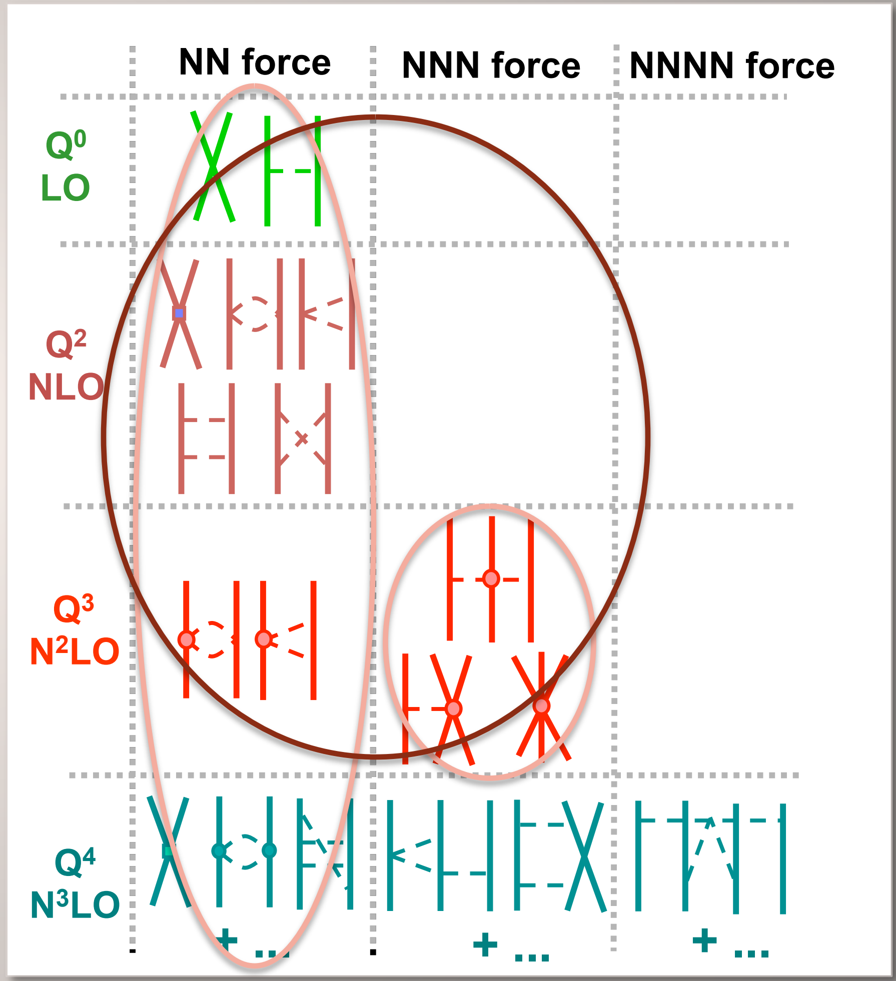
…or accurate meson-exchange potentials



Nuclear structure and reactions

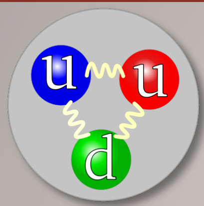
# Chiral Effective Field Theory

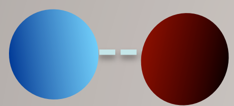
- Inter-nucleon forces from chiral effective field theory
  - Based on the symmetries of QCD
    - Chiral symmetry of QCD ($m_u \approx m_d \approx 0$), spontaneously broken with pion as the Goldstone boson
    - Degrees of freedom: nucleons + pions
  - Systematic low-momentum expansion to a given order ($Q/\Lambda_\chi$)
  - Hierarchy
  - Consistency
  - Low energy constants (LEC)
    - Fitted to data
    - Can be calculated by lattice QCD




$\Lambda_\chi$~1 GeV :
Chiral symmetry breaking scale

# From QCD to nuclei



**Low-energy QCD**

↓

NN+3N interactions from chiral EFT

…or accurate meson-exchange potentials

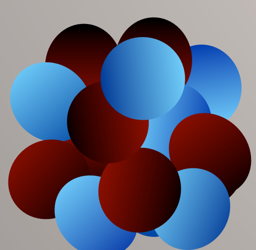
↓

$$H|\Psi\rangle = E|\Psi\rangle$$

Many-Body methods

NCSM, NCSM/RGM, NCSMC, CCM, SCGF, GFMC, HH, Nuclear Lattice EFT…

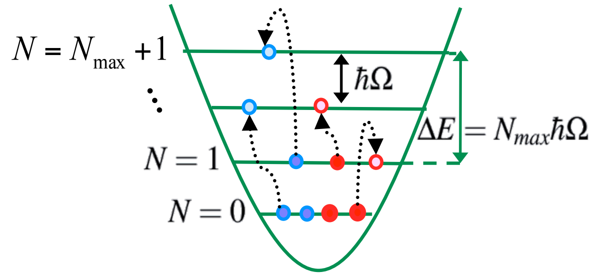
↓



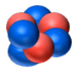
**Nuclear structure and reactions**

# Unified approach to bound & continuum states; to nuclear structure & reactions

- *Ab initio* no-core shell model
  - Short- and medium range correlations
  - Bound-states, narrow resonances




Harmonic oscillator basis

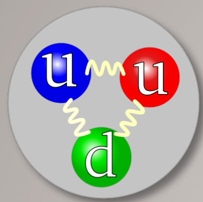


NCSM

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| {}^{(A)}, \lambda \right\rangle$$

Unknowns

# From QCD to nuclei

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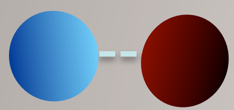

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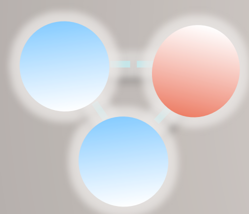
Unitary/similarity transformations

> Identity or SRG or OLS or UCOM … Softens NN, induces 3N



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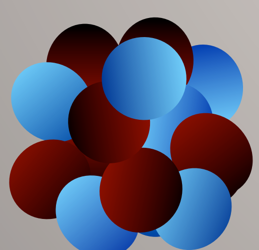
Many-Body methods

> NCSM, NCSM/RGM, CCM, SCGF, GFMC, HH, Nuclear Lattice EFT…

$$H|\Psi\rangle = E|\Psi\rangle$$

↓

**Nuclear structure and reactions**



# Unified approach to bound & continuum states; to nuclear structure & reactions

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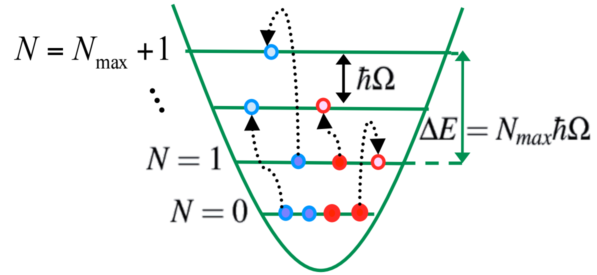


Harmonic oscillator basis

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$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| {}^{(A)} \, \text{[nucleus]}, \lambda \right\rangle$$

Unknowns

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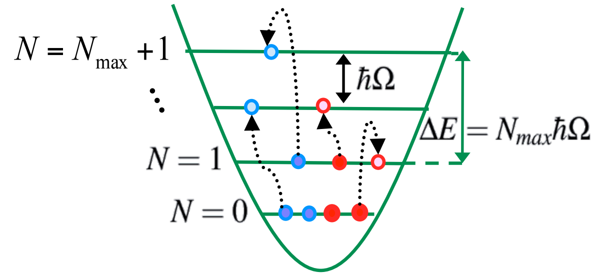
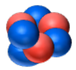
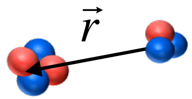



Harmonic oscillator basis



NCSM

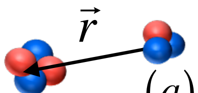
- …with resonating group method
  - Bound & scattering states, reactions
  - Cluster dynamics, long-range correlations




NCSM/RGM

NCSM/RGM channel states

$$\Psi^{(A)} = \sum_{\nu} \int d\vec{r}\, \gamma_{\nu}(\vec{r}\,)\, \hat{A}_{\nu} \left| \underset{(A-a)}{} \overset{\vec{r}}{\longleftarrow} \underset{(a)}{}, \nu \right\rangle$$



Unknowns

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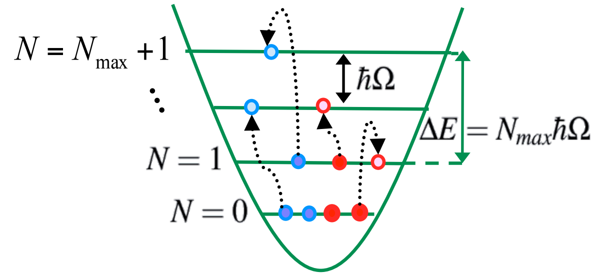
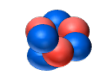


Harmonic oscillator basis



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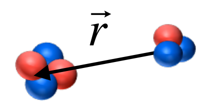



NCSM/RGM

S. Baroni, P. Navratil, and S. Quaglioni, PRL **110**, 022505 (2013); PRC **87**, 034326 (2013).

- Most efficient: *ab initio* no-core shell model with continuum

NCSMC

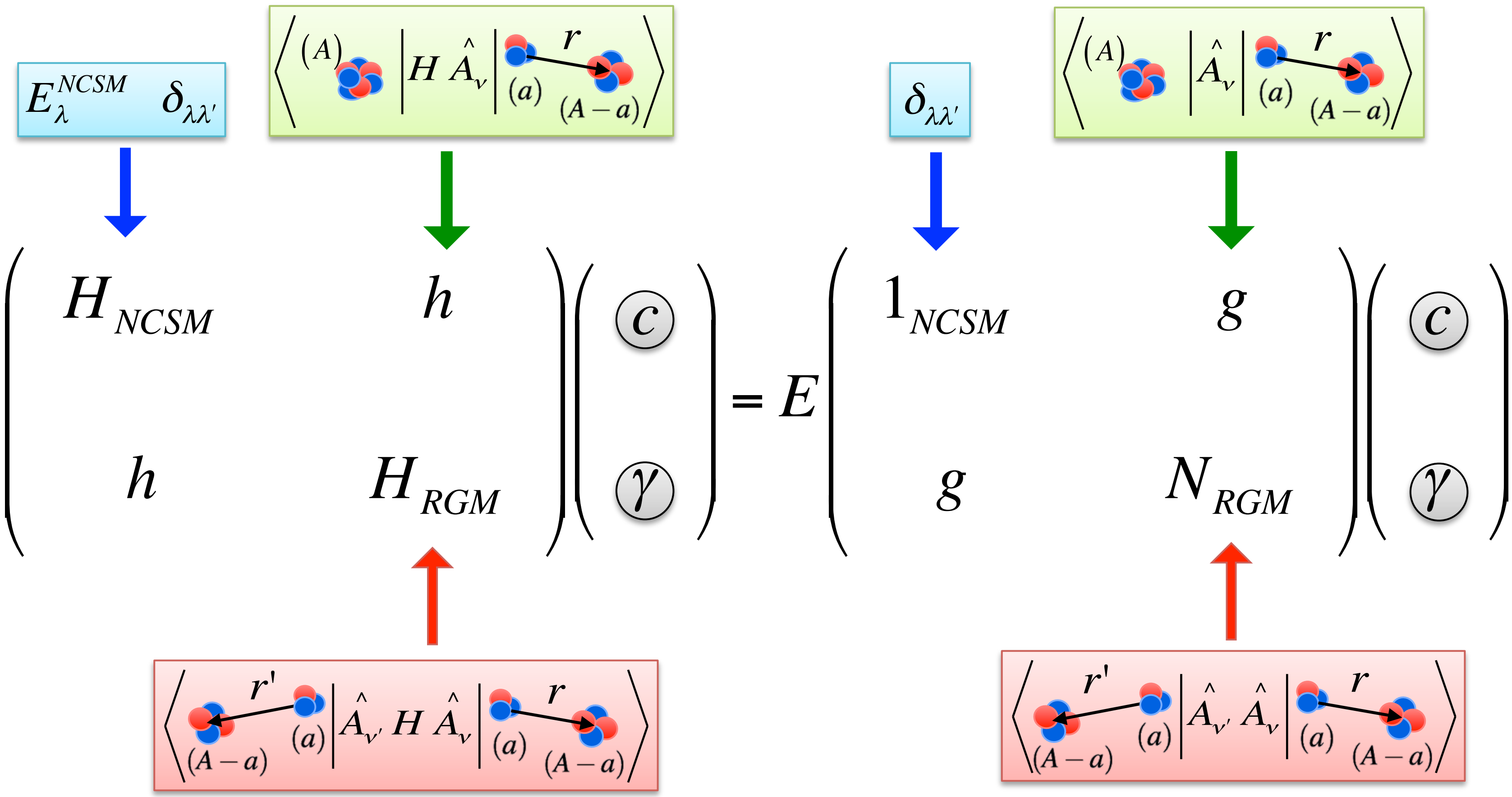
NCSM eigenstates

NCSM/RGM channel states

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| {}^{(A)} \, , \lambda \right\rangle + \sum_{\nu} \int d\vec{r} \; \gamma_{\nu}(\vec{r}) \; \hat{A}_{\nu} \left| \vec{r} \; {}_{(A-a)} \; {}_{(a)} \, , \nu \right\rangle$$

Unknowns

# Coupled NCSMC equations




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

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

# Connection to nuclear lattice EFT

doi:10.1038/nature16067

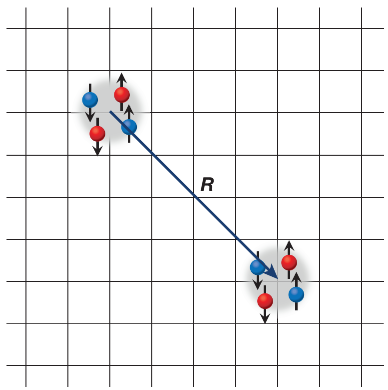
## *Ab initio* alpha–alpha scattering

Serdar Elhatisari[1], Dean Lee[2], Gautam Rupak[3], Evgeny Epelbaum[4], Hermann Krebs[4], Timo A. Lähde[5], Thomas Luu[1,5] & Ulf-G. Meißner[1,5,6]

Scattering states

Lattice EFT – hard spherical wall

NCSM/RGM – Microscopic R-matrix



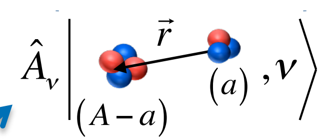

Lattice EFT
Adiabatic projection method

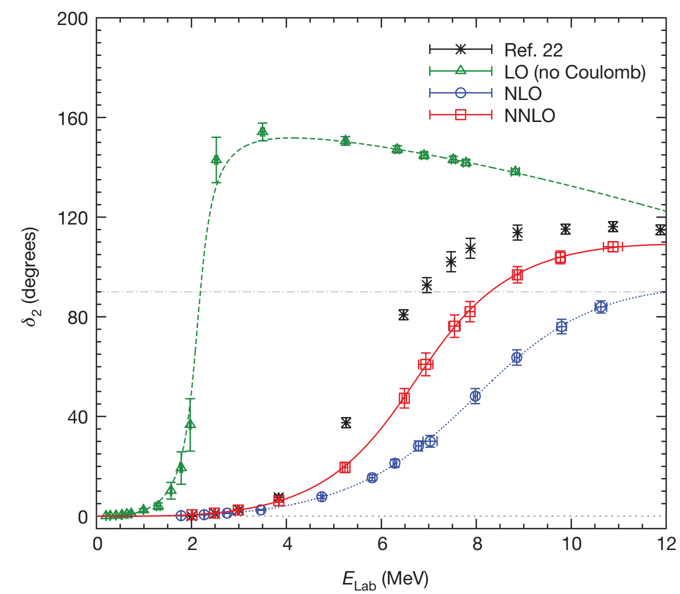
$$|\boldsymbol{R}\rangle = \sum_{\boldsymbol{r}} |\boldsymbol{r}+\boldsymbol{R}\rangle_1 \otimes |\boldsymbol{r}\rangle_2$$

$$|R\rangle^{\ell,\ell_z} = \sum_{\boldsymbol{R}'} Y_{\ell,\ell_z}(R')\delta_{R,|\boldsymbol{R}'|}|\boldsymbol{R}'\rangle$$

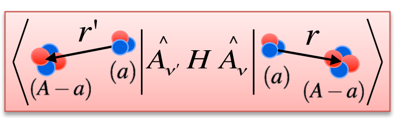
$$|R\rangle_\tau^{\ell,\ell_z} = \exp(-H\tau)|R\rangle^{\ell,\ell_z}$$

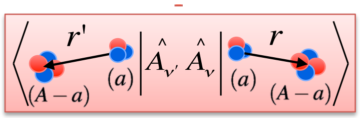
NCSM/RGM




NCSM/RGM



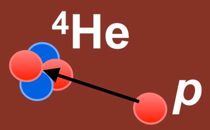

Lattice EFT
Auxiliary field MC

$$[H_\tau]^{\ell,\ell_z}_{R,R'} = {}^{\ell,\ell_z}_{\tau}\langle R|H|R'\rangle^{\ell,\ell_z}_{\tau}$$

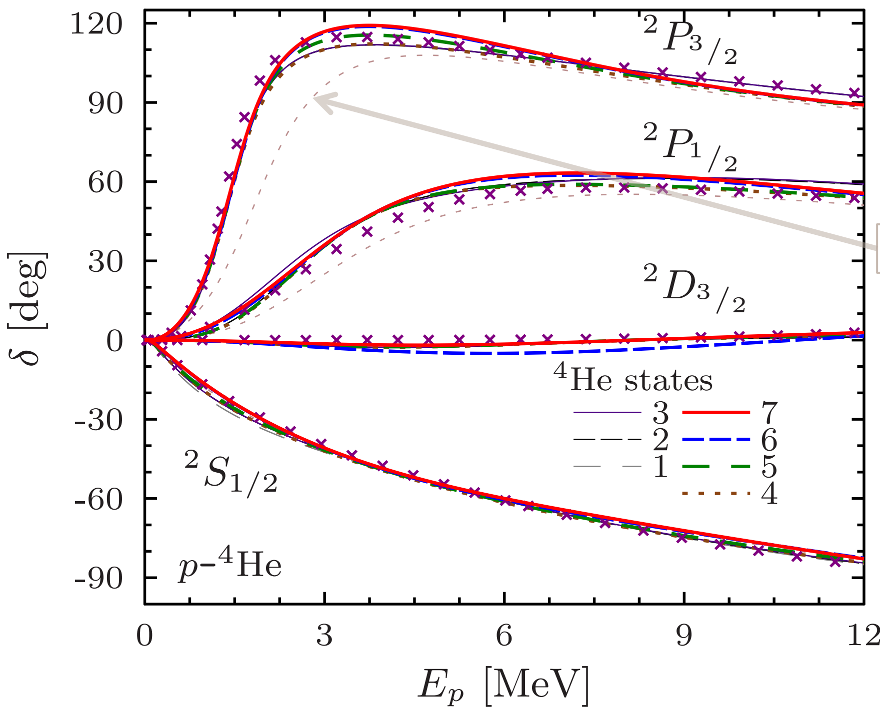
$$[N_\tau]^{\ell,\ell_z}_{R,R'} = {}^{\ell,\ell_z}_{\tau}\langle R|R'\rangle^{\ell,\ell_z}_{\tau}$$

$$[H^a_\tau]^{\ell,\ell_z}_{R,R'} = [N_\tau^{-1/2} H_\tau N_\tau^{-1/2}]^{\ell,\ell_z}_{R,R'}$$

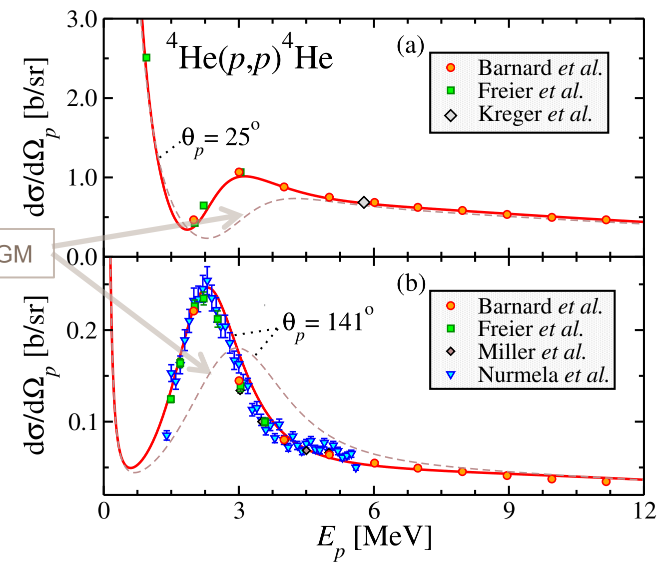
# $p$-$^4$He scattering within NCSMC

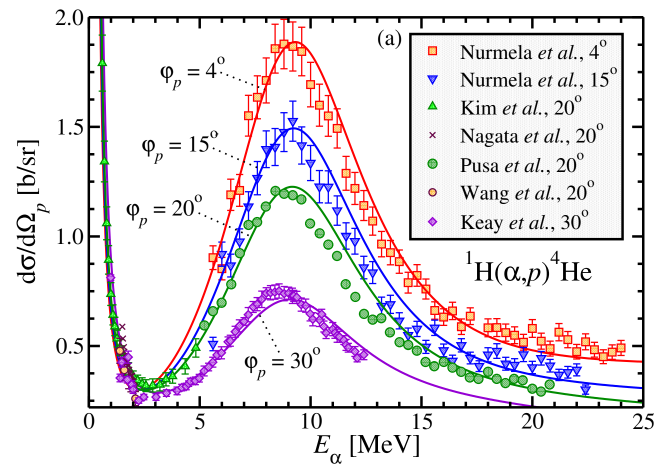



## $p$-$^4$He scattering phase-shifts for NN+3N potential: Convergence




## Differential $p$-$^4$He cross section with NN+3N potentials




**Predictive power in the 3/2$^-$ resonance region: Applications to material science**


PHYSICAL REVIEW C **90**, 061601(R) (2014)


**Predictive theory for elastic scattering and recoil of protons from $^4$He**


Guillaume Hupin,[1,*] Sofia Quaglioni,[1,†] and Petr Navrátil[2,‡]

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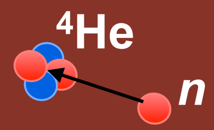
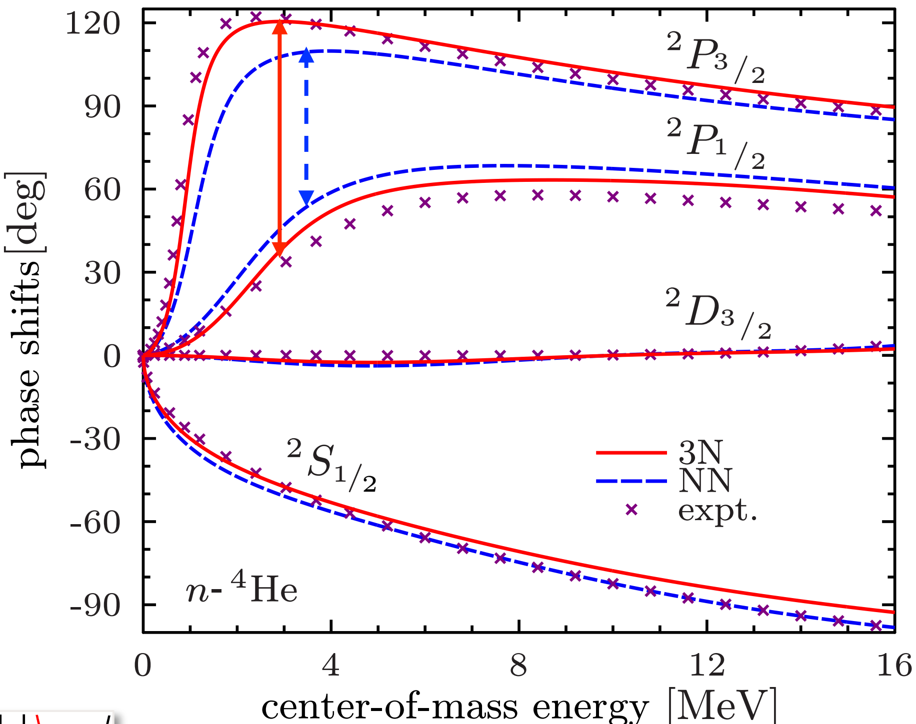
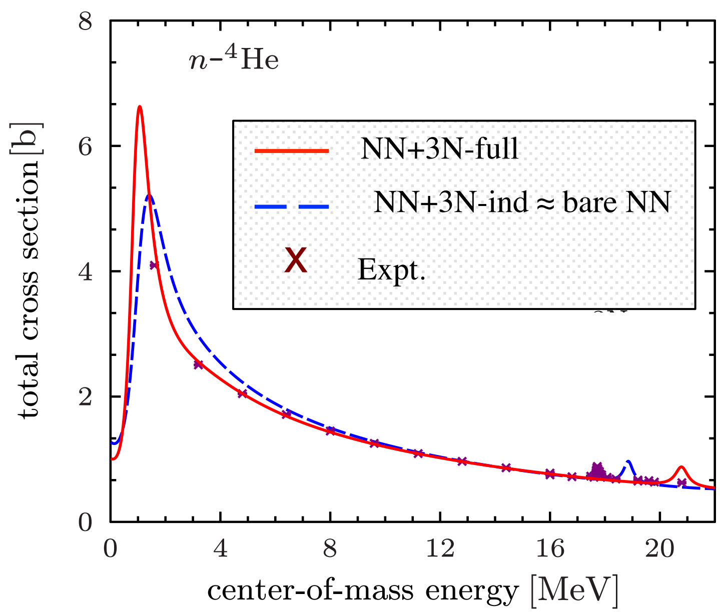


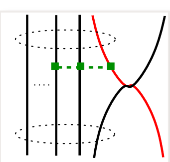

# $n$-$^4$He scattering within NCSMC

$n$-$^4$He scattering phase-shifts for chiral NN and NN+3N potential

Total $n$-$^4$He cross section with NN and NN+3N potentials



**3N force enhances 1/2⁻ ←→ 3/2⁻ splitting: Essential at low energies!**

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Phys. Scr. 00 (2016) 000000 (37pp)

Invited Comment

**Unified *ab initio* approaches to nuclear structure and reactions**

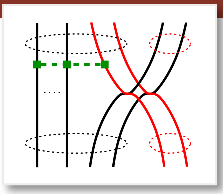
Petr Navrátil[1], Sofia Quaglioni[2], Guillaume Hupin[3,4], Carolina Romero-Redondo[2] and Angelo Calci[1]

PHYSICAL REVIEW C **88**, 054622 (2013)

***Ab initio* many-body calculations of nucleon-$^4$He scattering with three-nucleon forces**

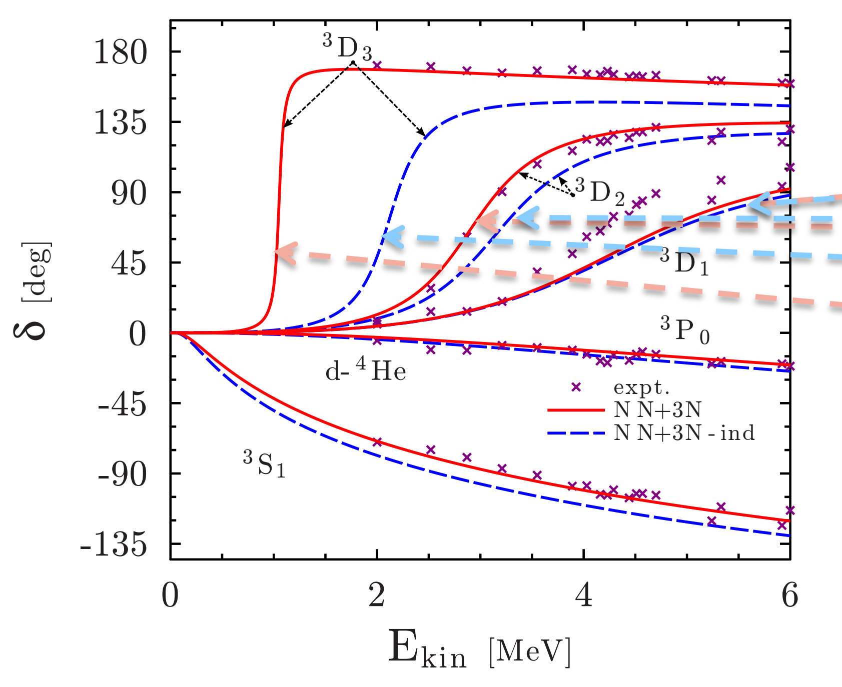
Guillaume Hupin,[1,*] Joachim Langhammer,[2,†] Petr Navrátil,[3,‡] Sofia Quaglioni,[1,§] Angelo Calci,[2,‖] and Robert Roth[2,¶]

# Unified description of $^6$Li structure and d+$^4$He dynamics

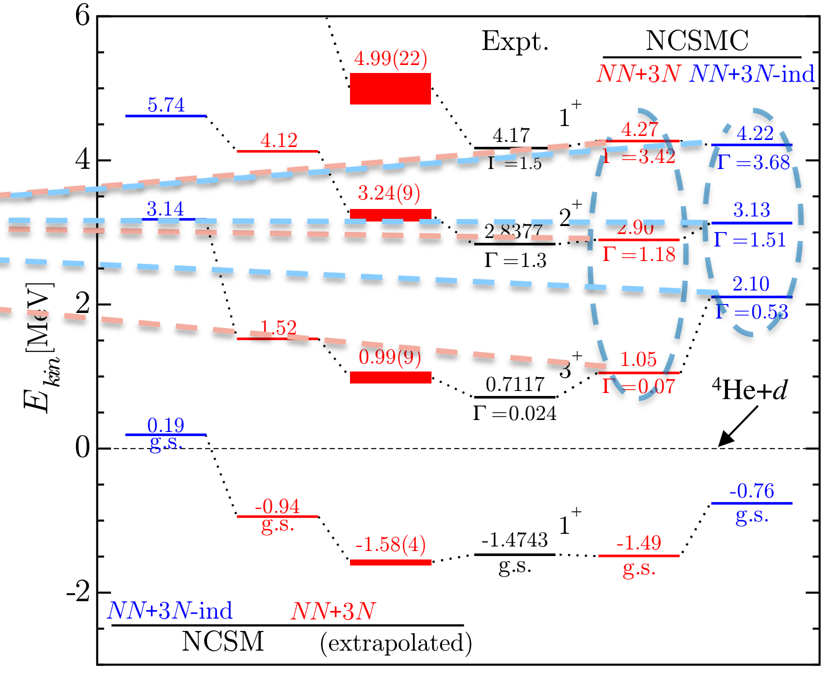


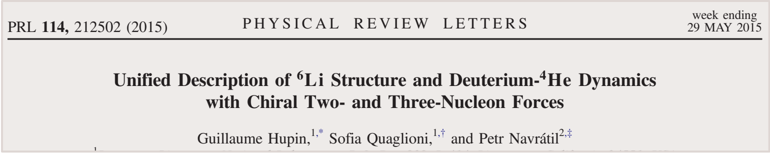
- Continuum and three-nucleon force effects on d+$^4$He and $^6$Li

## d+$^4$He Scattering Phase Shifts




## $^6$Li vs. ($^4$He+d)+$^6$Li calculation





PRL **114,** 212502 (2015) PHYSICAL REVIEW LETTERS week ending 29 MAY 2015

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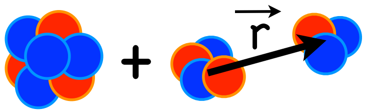
Guillaume Hupin,[1,*] Sofia Quaglioni,[1,†] and Petr Navrátil[2,‡]

NCSMC



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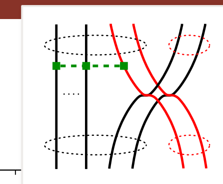

- Continuum and three-nucleon force effects on d+$^4$He and $^6$Li

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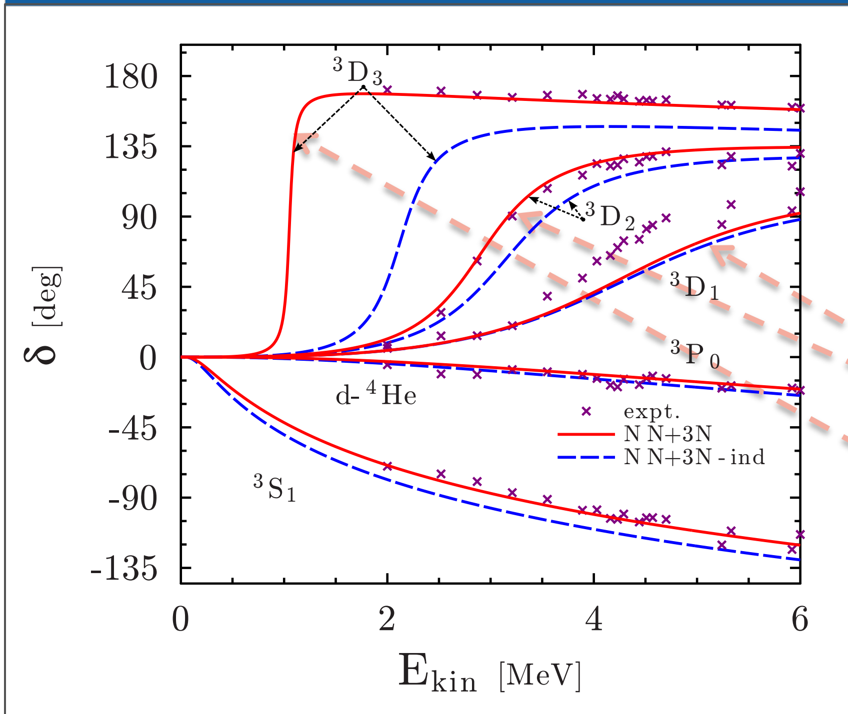


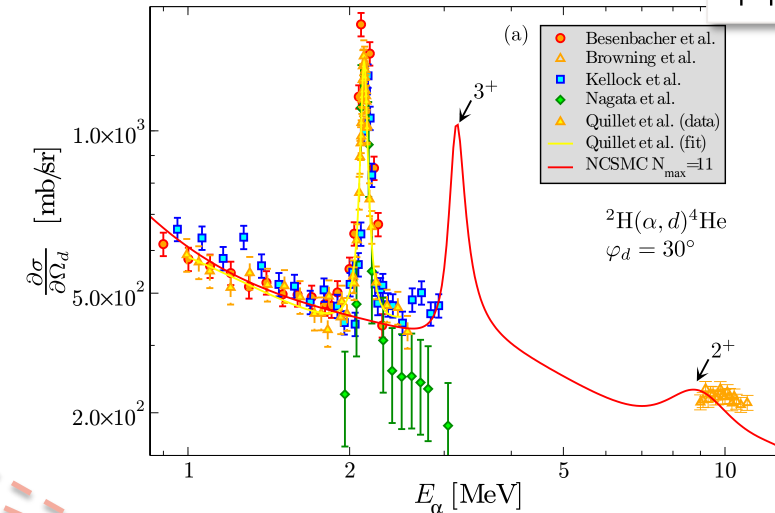


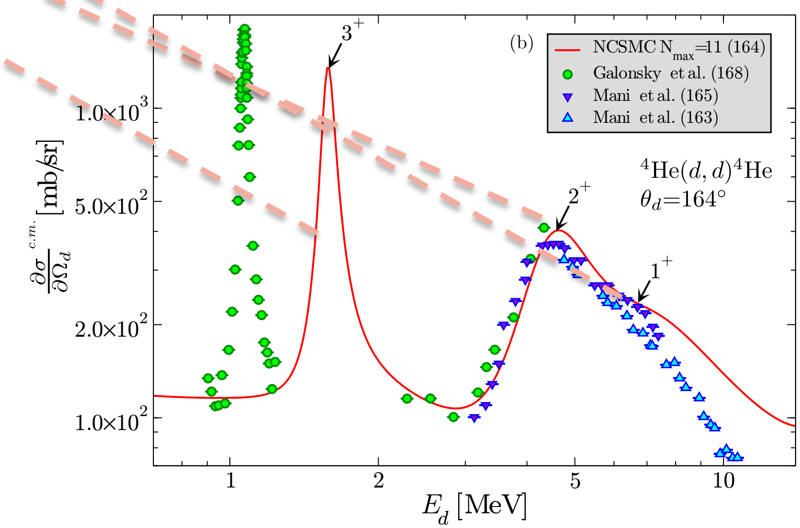


PRL 114, 212502 (2015) PHYSICAL REVIEW LETTERS week ending 29 MAY 2015

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Guillaume Hupin,[1,*] Sofia Quaglioni,[1,†] and Petr Navrátil[2,‡]

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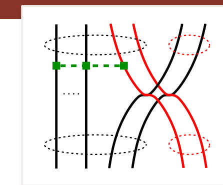
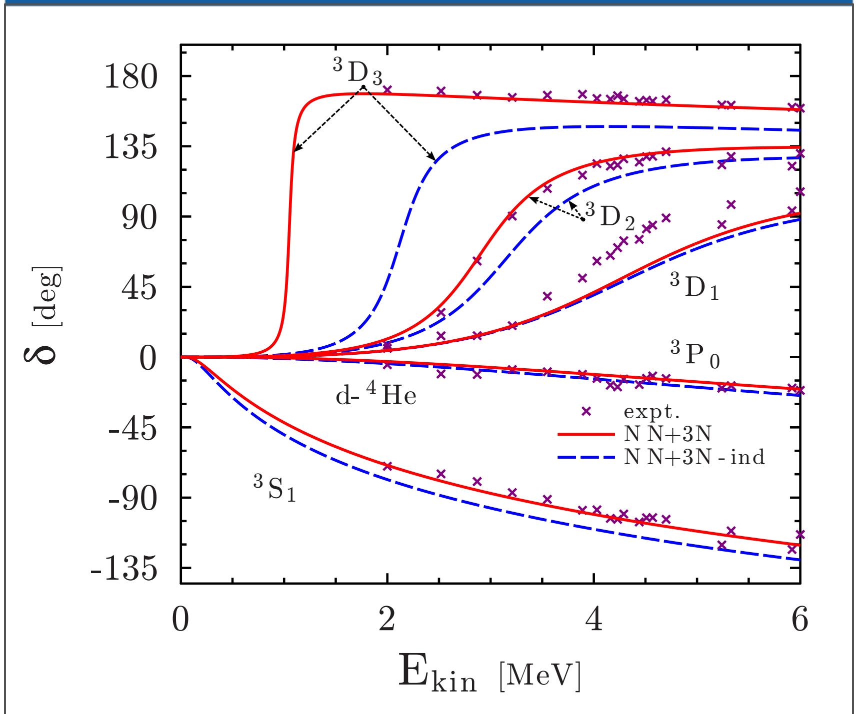
# Unified description of $^6$Li structure and d+$^4$He dynamics

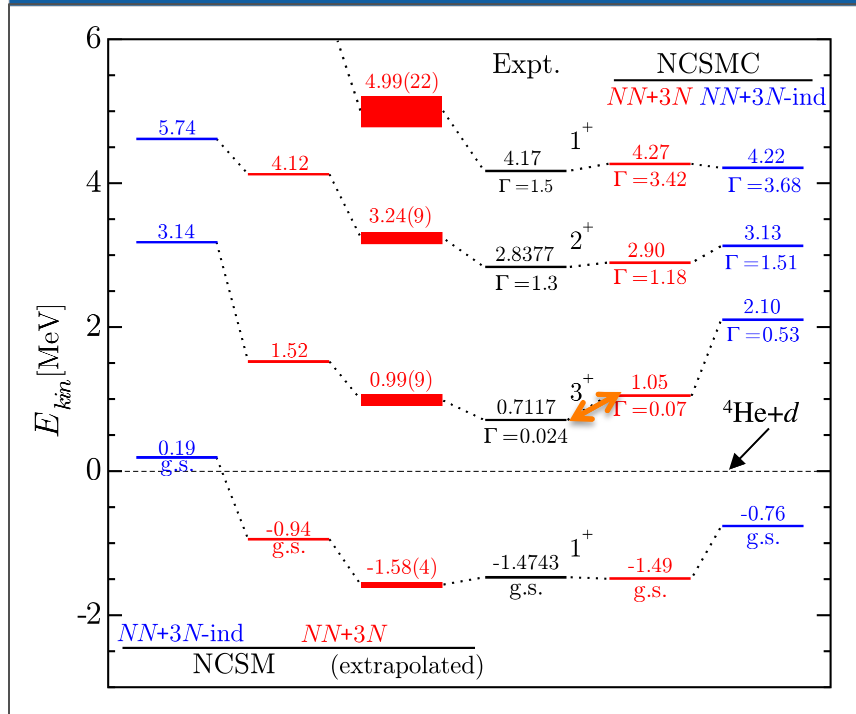
- Continuum and three-nucleon force effects on d+$^4$He and $^6$Li



## d+$^4$He Scattering Phase Shifts




## $^6$Li vs. ($^4$He+d)+$^6$Li calculation

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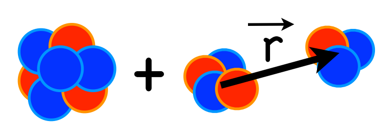
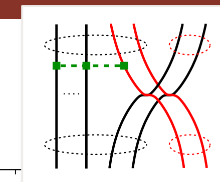
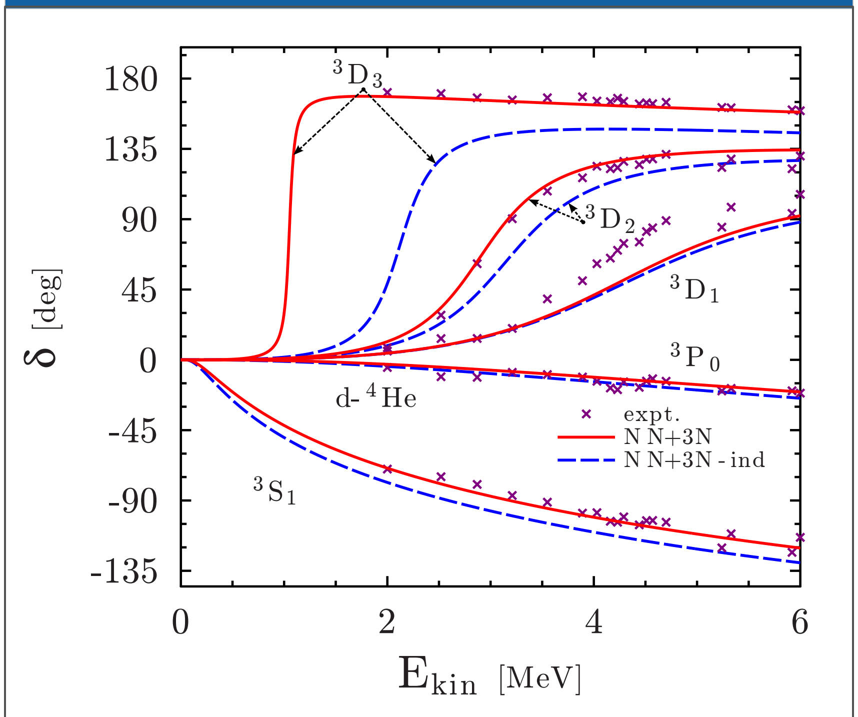


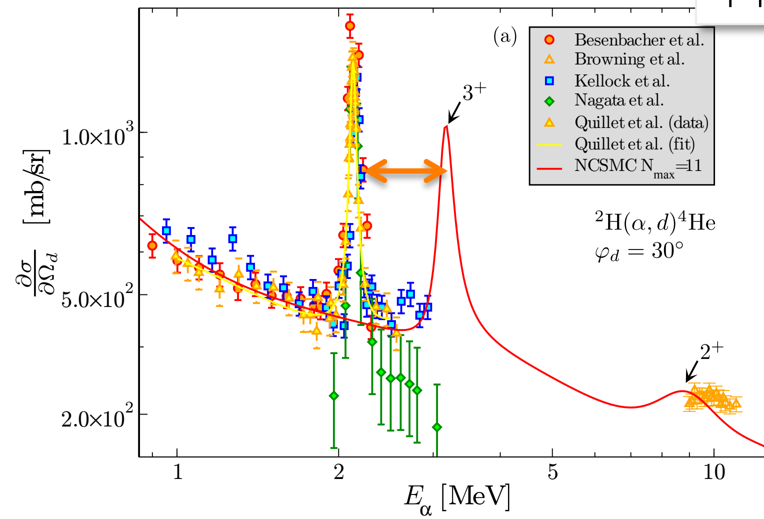
# Unified description of $^6$Li structure and d+$^4$He dynamics

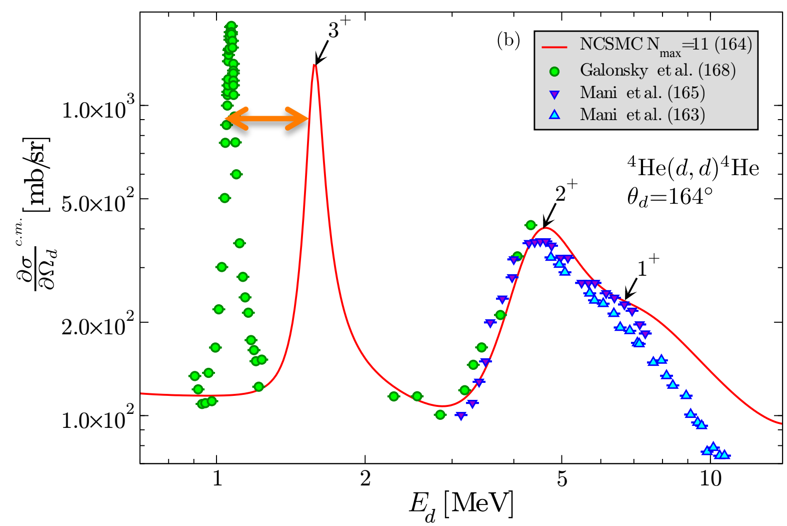


- Continuum and three-nucleon force effects on d+$^4$He and $^6$Li

## d+$^4$He Scattering Phase Shifts




PRL 114, 212502 (2015) PHYSICAL REVIEW LETTERS week ending 29 MAY 2015

**Unified Description of $^6$Li Structure and Deuterium-$^4$He Dynamics with Chiral Two- and Three-Nucleon Forces**

Guillaume Hupin,[1,*] Sofia Quaglioni,[1,†] and Petr Navrátil[2,‡]

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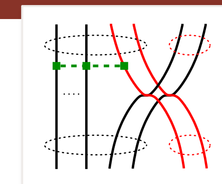

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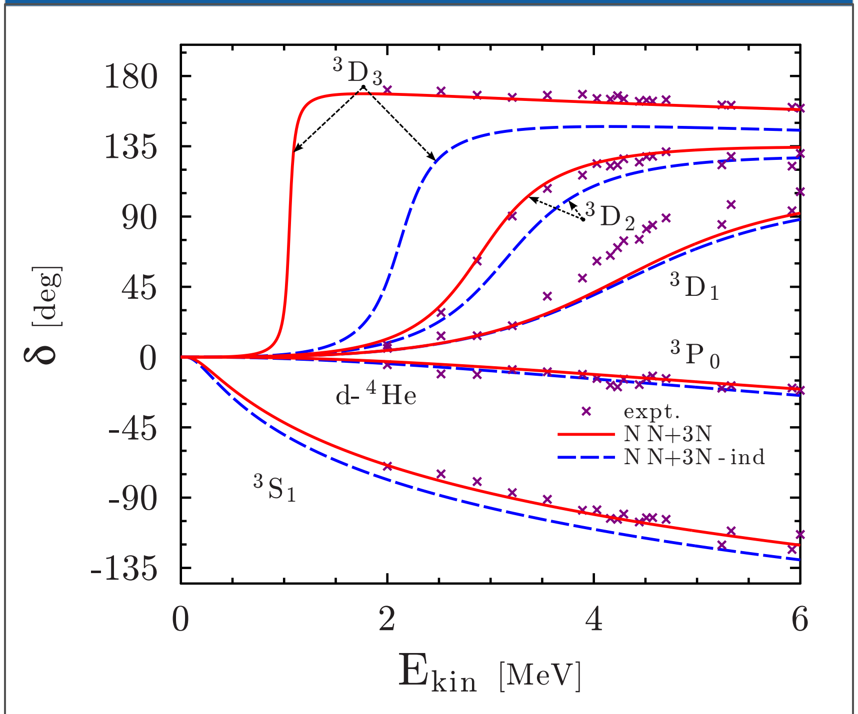


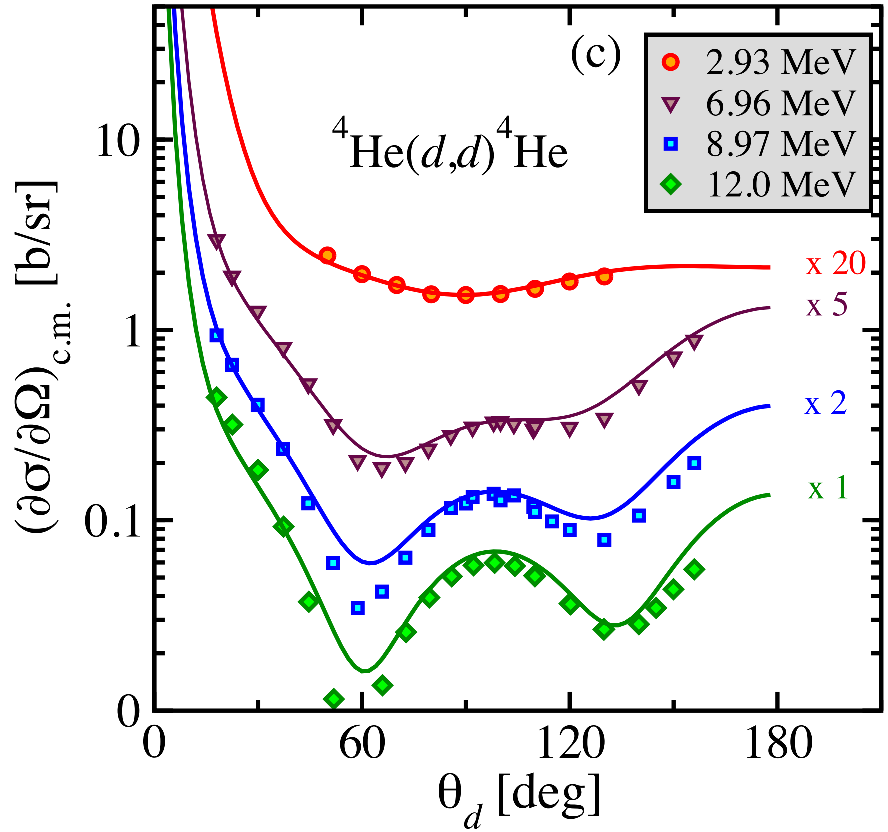


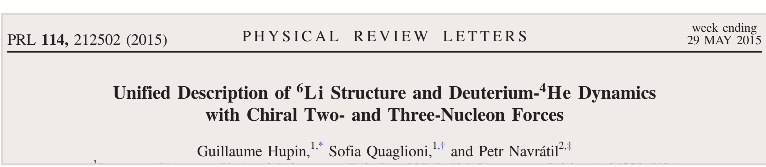

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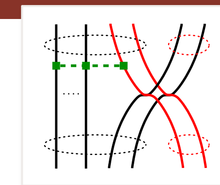
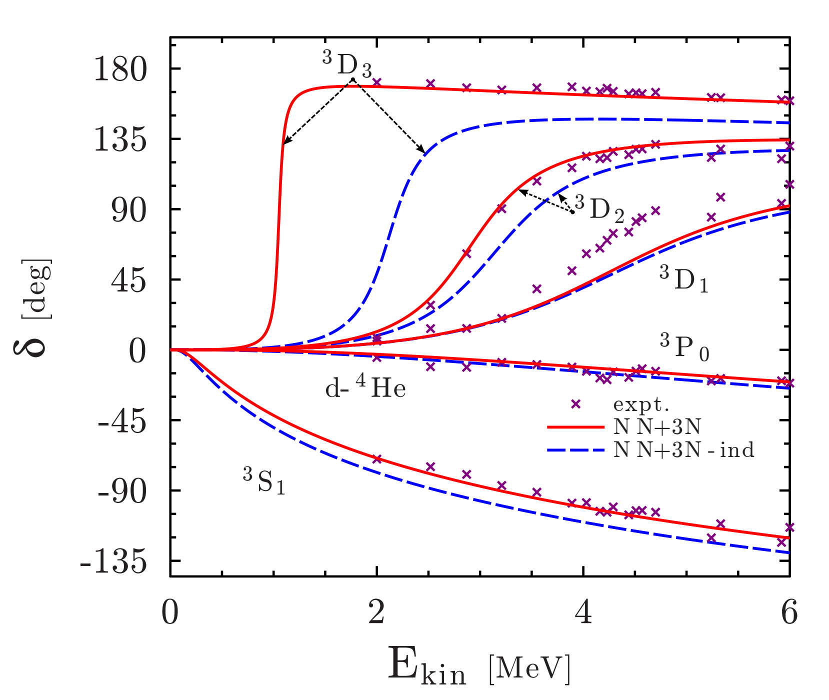


- *S*- and *D*-wave asymptotic normalization constants

## d+$^4$He Scattering Phase Shifts




| | NCSMC | Experiment | |
|---|---|---|---|
| $C_0$ [fm$^{-1/2}$] | 2.695 | 2.91(9) [39] | 2.93(15) [38] |
| $C_2$ [fm$^{-1/2}$] | −0.074 | −0.077(18) [39] | |
| $C_2/C_0$ | −0.027 | −0.025(6)(10) [39] | 0.0003(9) [41] |


[38] L. D. Blokhintsev, V. I. Kukulin, A. A. Sakharuk, D. A. Savin, and E. V. Kuznetsova, Phys. Rev. C **48**, 2390 (1993).

[39] E. A. George and L. D. Knutson, Phys. Rev. C **59**, 598 (1999).

[41] K. D. Veal, C. R. Brune, W. H. Geist, H. J. Karwowski, E. J. Ludwig, A. J. Mendez, E. E. Bartosz, P. D. Cathers, T. L. Drummer, K. W. Kemper, A. M. Eiró, F. D. Santos, B. Kozlowska, H. J. Maier, and I. J. Thompson, Phys. Rev. Lett. **81**, 1187 (1998).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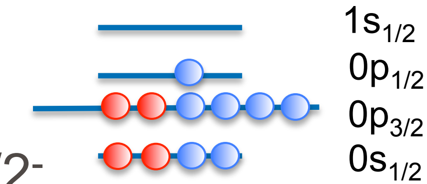
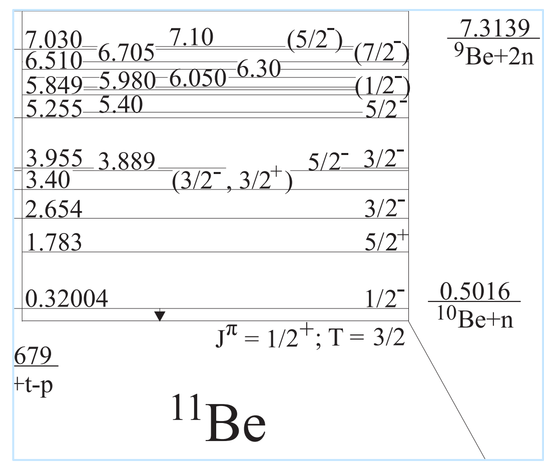
# Neutron-rich halo nucleus $^{11}$Be



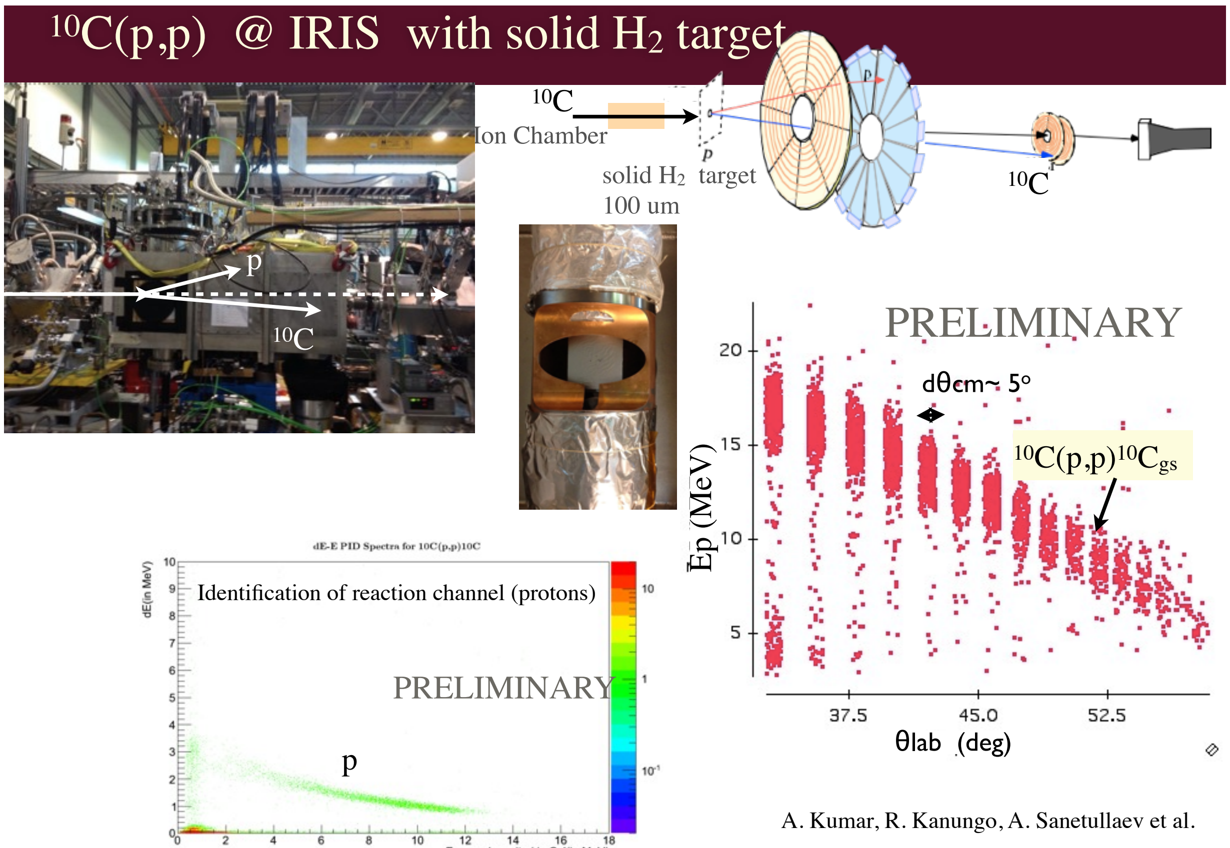

- Z=4, N=7
  - In the shell model picture g.s. expected to be $J^{\pi}=1/2^{-}$
    - Z=6, N=7 $^{13}$C and Z=8, N=7 $^{15}$O have $J^{\pi}=1/2^{-}$ g.s.
  - In reality, $^{11}$Be g.s. is $\mathbf{J^{\pi}=1/2^{+}}$ - parity inversion
  - Very weakly bound: $E_{th}$=-0.5 MeV
    - Halo state – dominated by $^{10}$Be-n in the *S*-wave
  - The $1/2^{-}$ state also bound – only by 180 keV

- Can we describe $^{11}$Be in *ab initio* calculations?
  - Continuum must be included
  - Does the 3N interaction play a role in the parity inversion?



# $^{10}C(p,p)$ @ IRIS with solid $H_2$ target

- New experiment at ISAC TRIUMF with reaccelerated $^{10}C$
  - The first ever $^{10}C$ beam at TRIUMF
  - Angular distributions measured at $E_{CM}$ ~ 4.16 MeV and 4.4 MeV

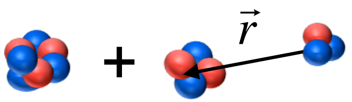


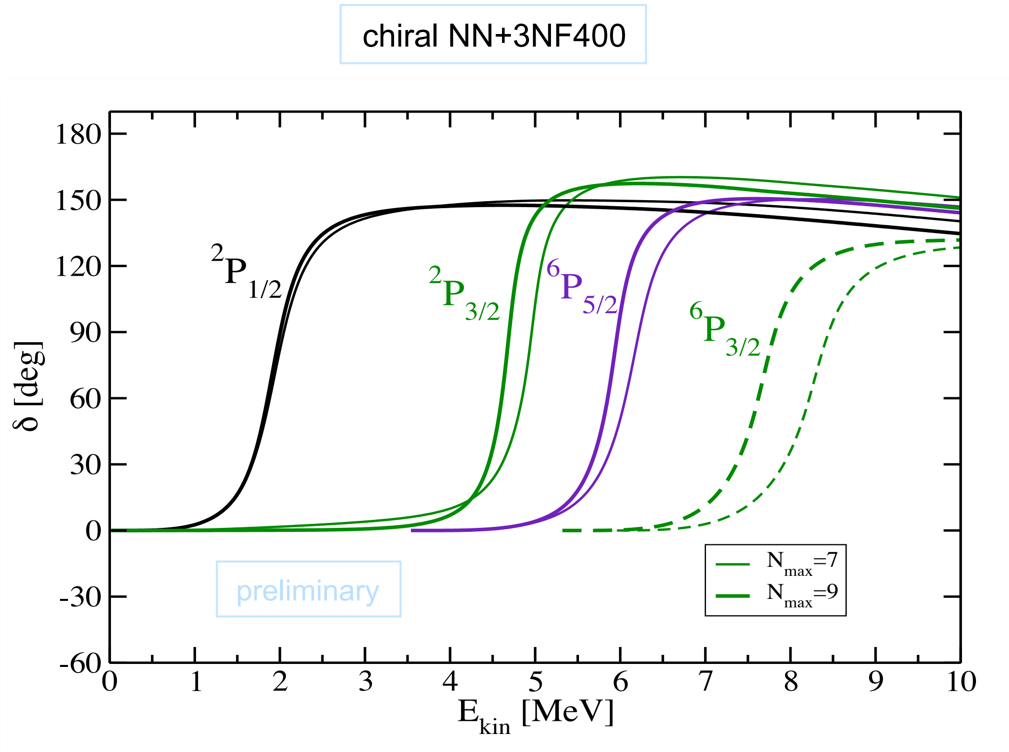

A. Kumar, R. Kanungo, A. Sanetullaev et al.

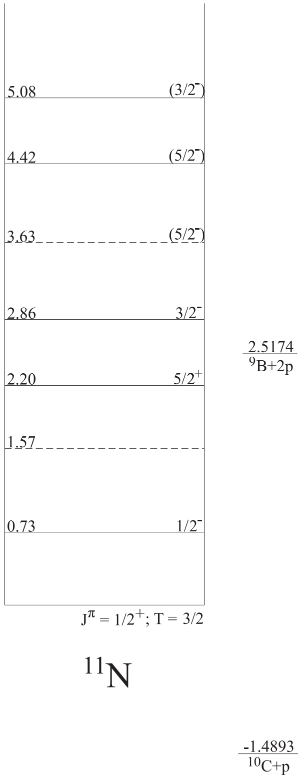
IRIS collaboration:
A. Kumar, R. Kanungo,
A. Sanetullaev *et al.*

# p+$^{10}$C scattering: structure of $^{11}$N resonances

- NCSMC calculations with **chiral NN+3N** ($N^3LO$ NN+$N^2LO$ 3NF400, NNLOsat)
  - p-$^{10}$C + $^{11}$N
    - $^{10}$C: $0^+$, $2^+$, $2^+$ NCSM eigenstates
    - $^{11}$N: ≥4 π = -1 and ≥3 π = +1 NCSM eigenstates

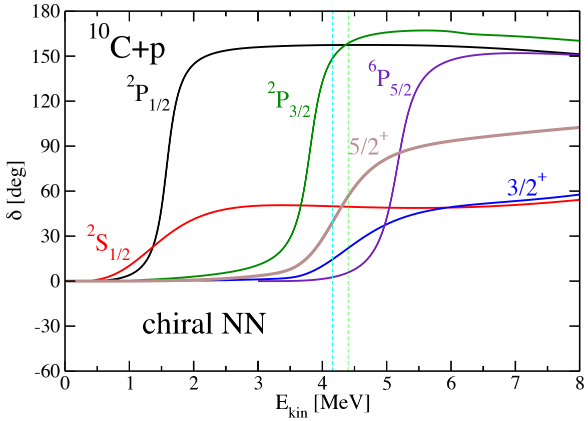


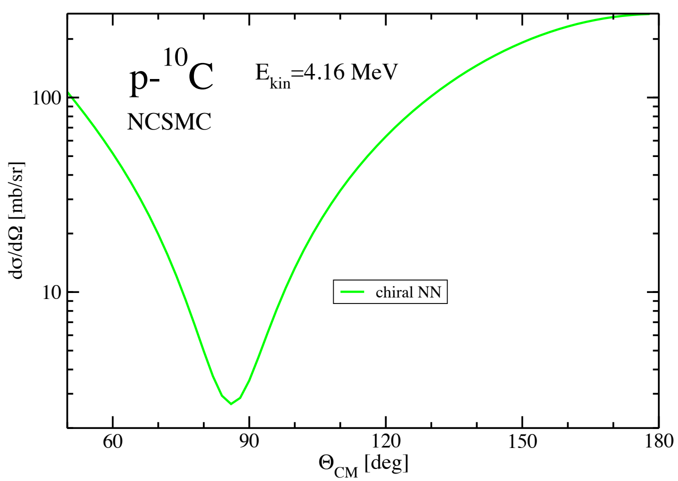



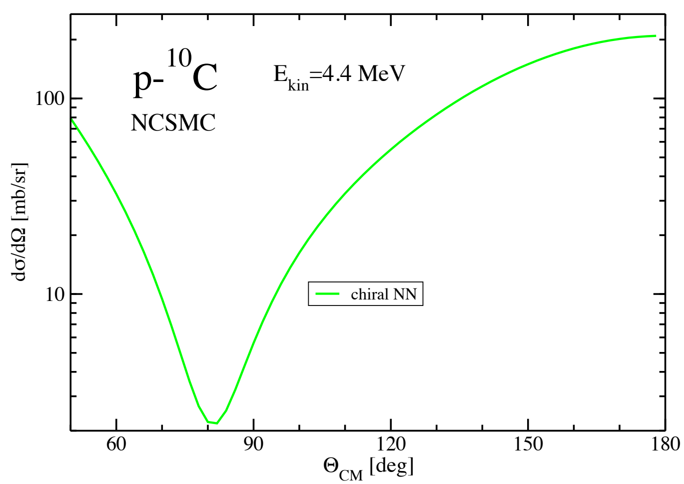




A. Calci, P. Navratil, G. Hupin, S. Quaglioni, R. Roth *et al* with IRIS collaboration, in preparation

# p+$^{10}$C scattering: structure of $^{11}$N resonances

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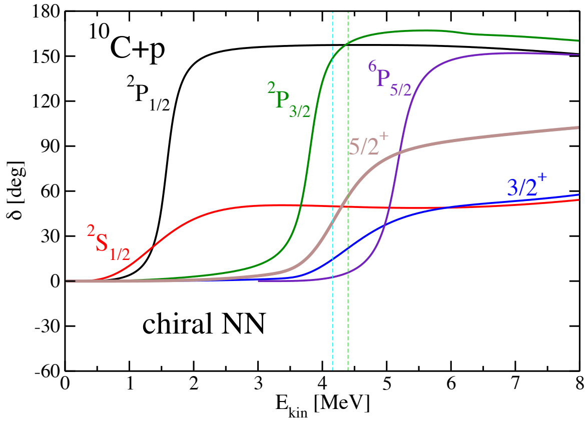
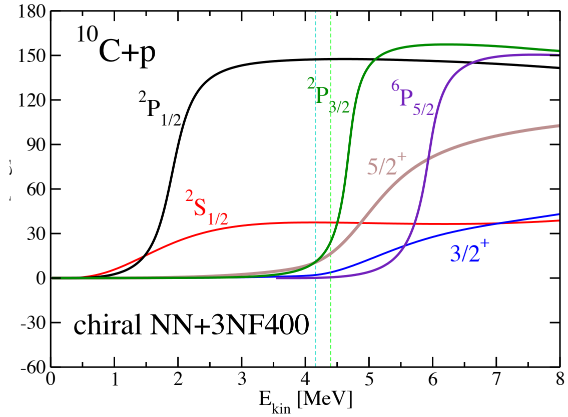
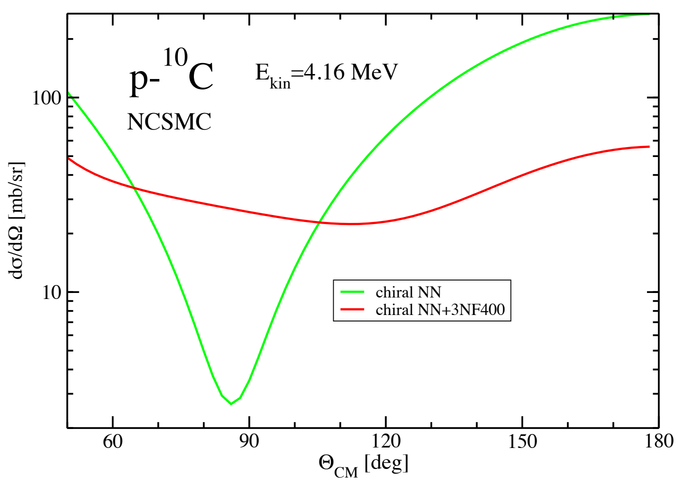
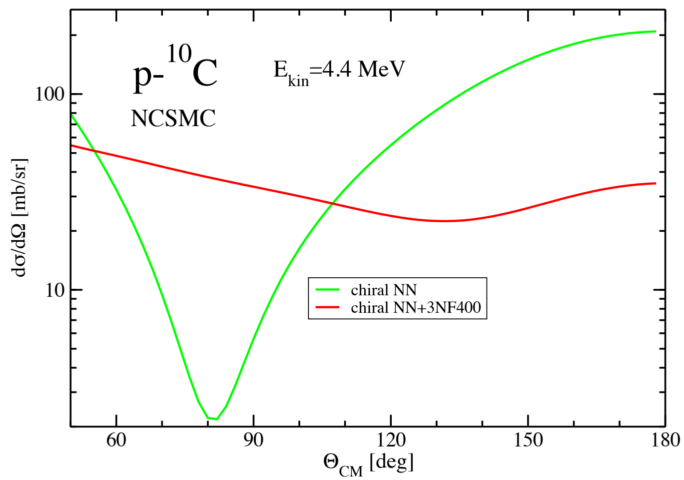


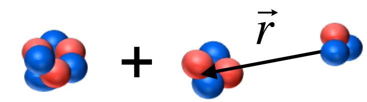



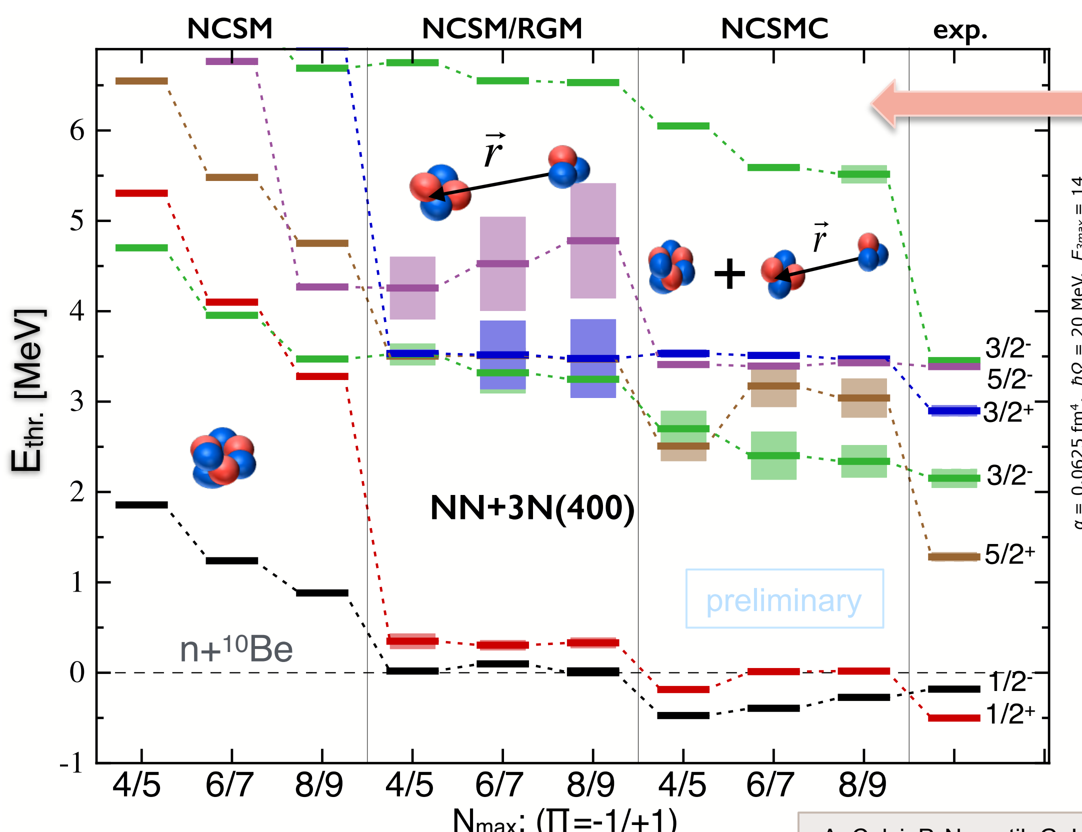




A. Calci, P. Navratil, G. Hupin, S. Quaglioni, R. Roth *et al* with IRIS collaboration, in preparation

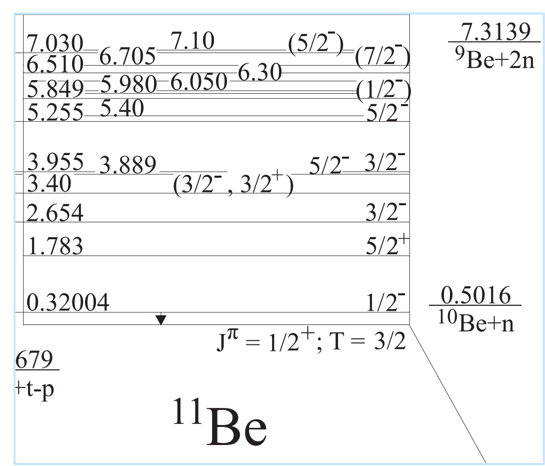
# Structure of $^{11}$Be from chiral NN+3N forces

- NCSMC calculations **including chiral 3N** ($N^3$LO NN+$N^2$LO 3NF400)
  - n-$^{10}$Be + $^{11}$Be
    - $^{10}$Be: $0^+$, $2^+$, $2^+$ NCSM eigenstates
    - $^{11}$Be: ≥6 π = -1 and ≥3 π = +1 NCSM eigenstates



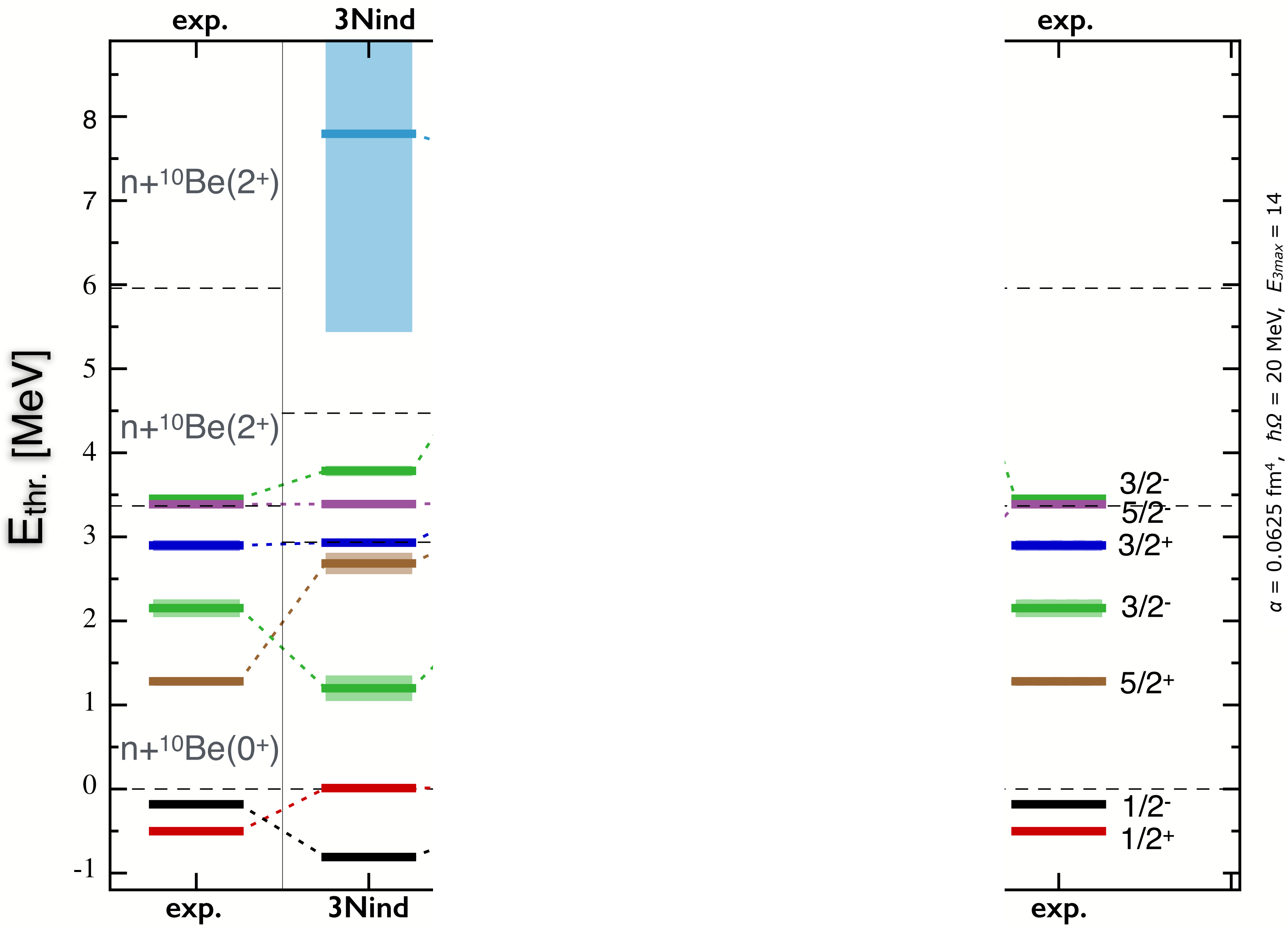

Continuum effects






A. Calci, P. Navratil, G. Hupin, S. Quaglioni, R. Roth *et al.*, in preparation

# $^{11}$Be within NCSMC: Discrimination among chiral nuclear forces

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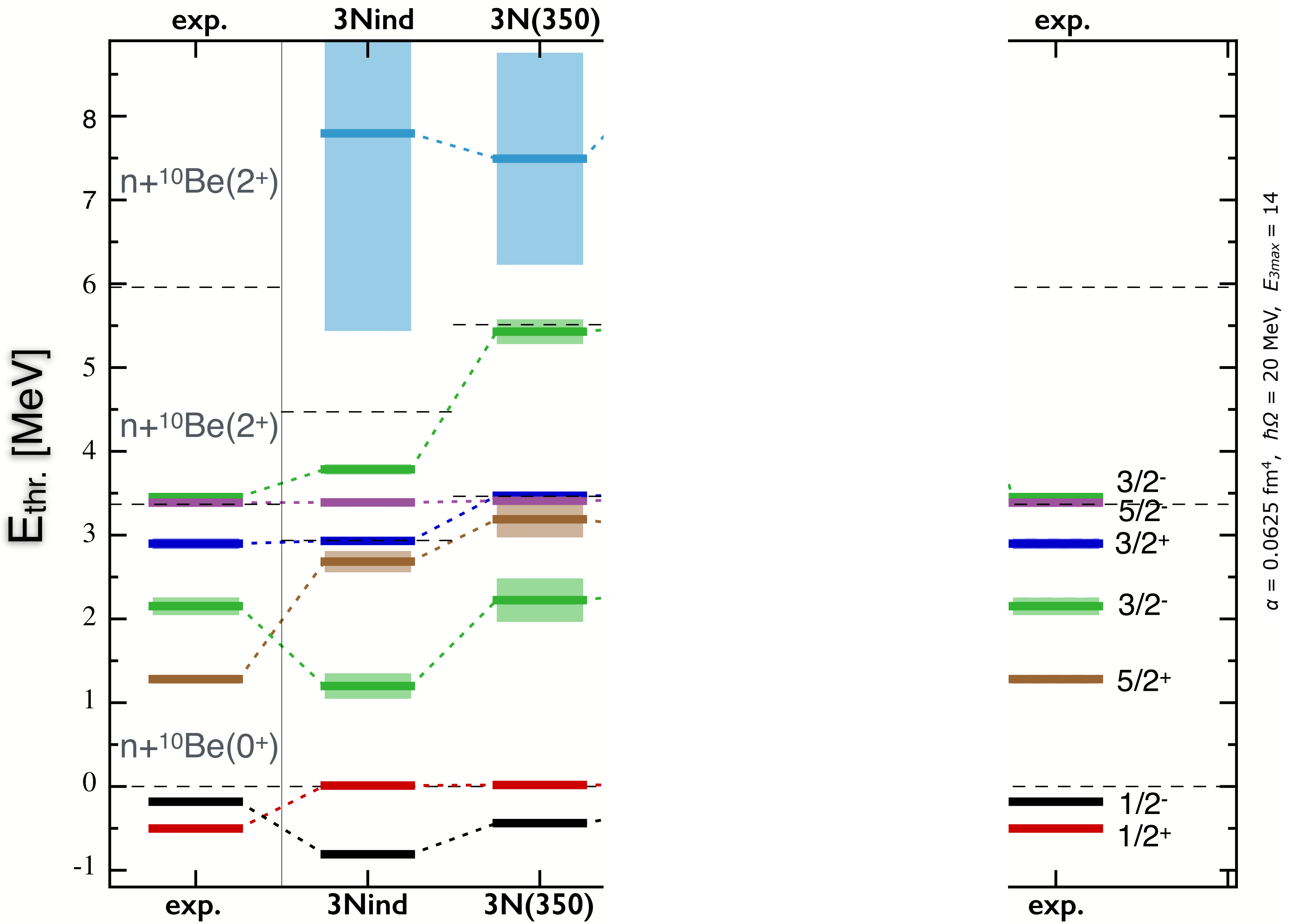


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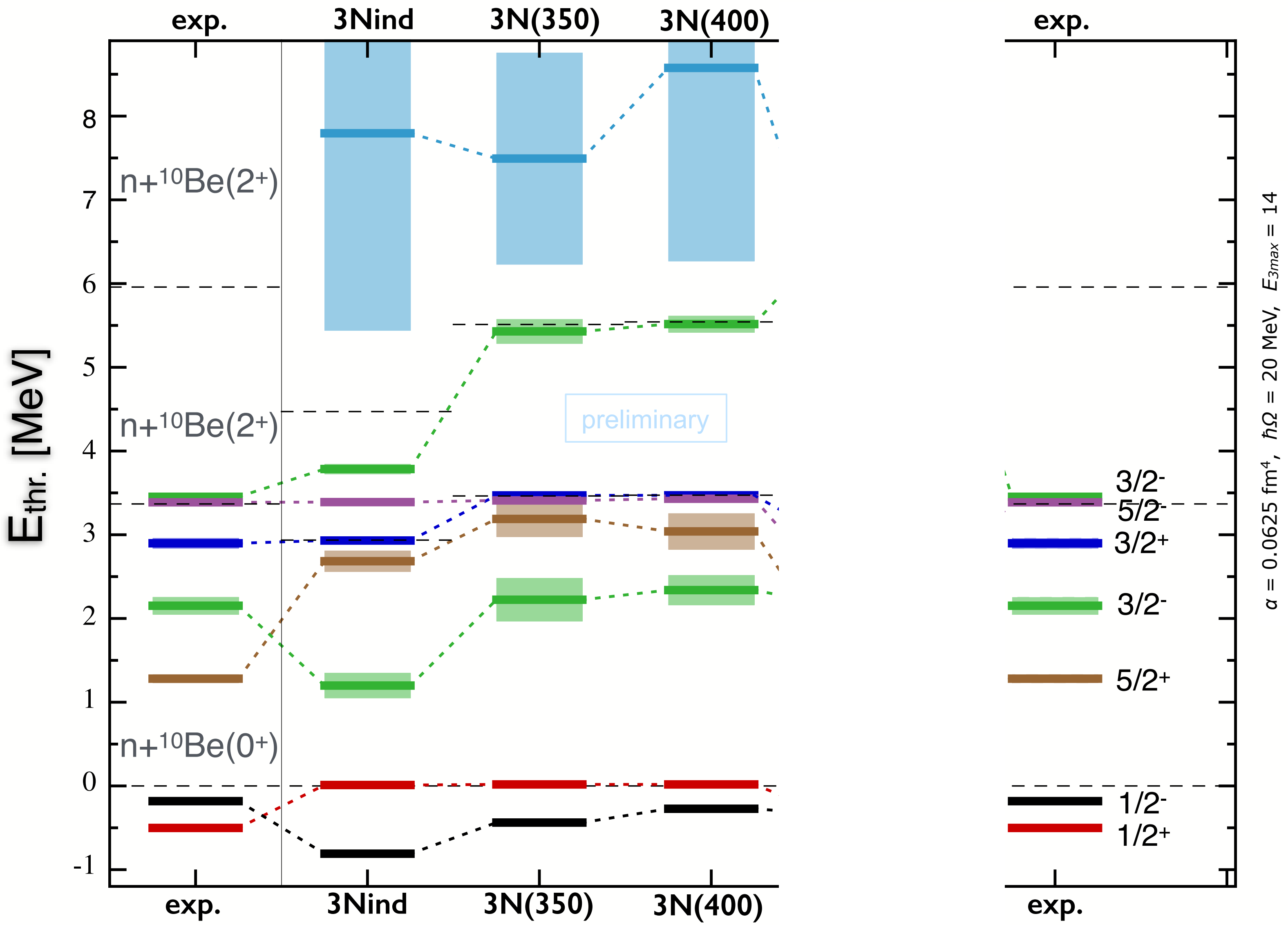


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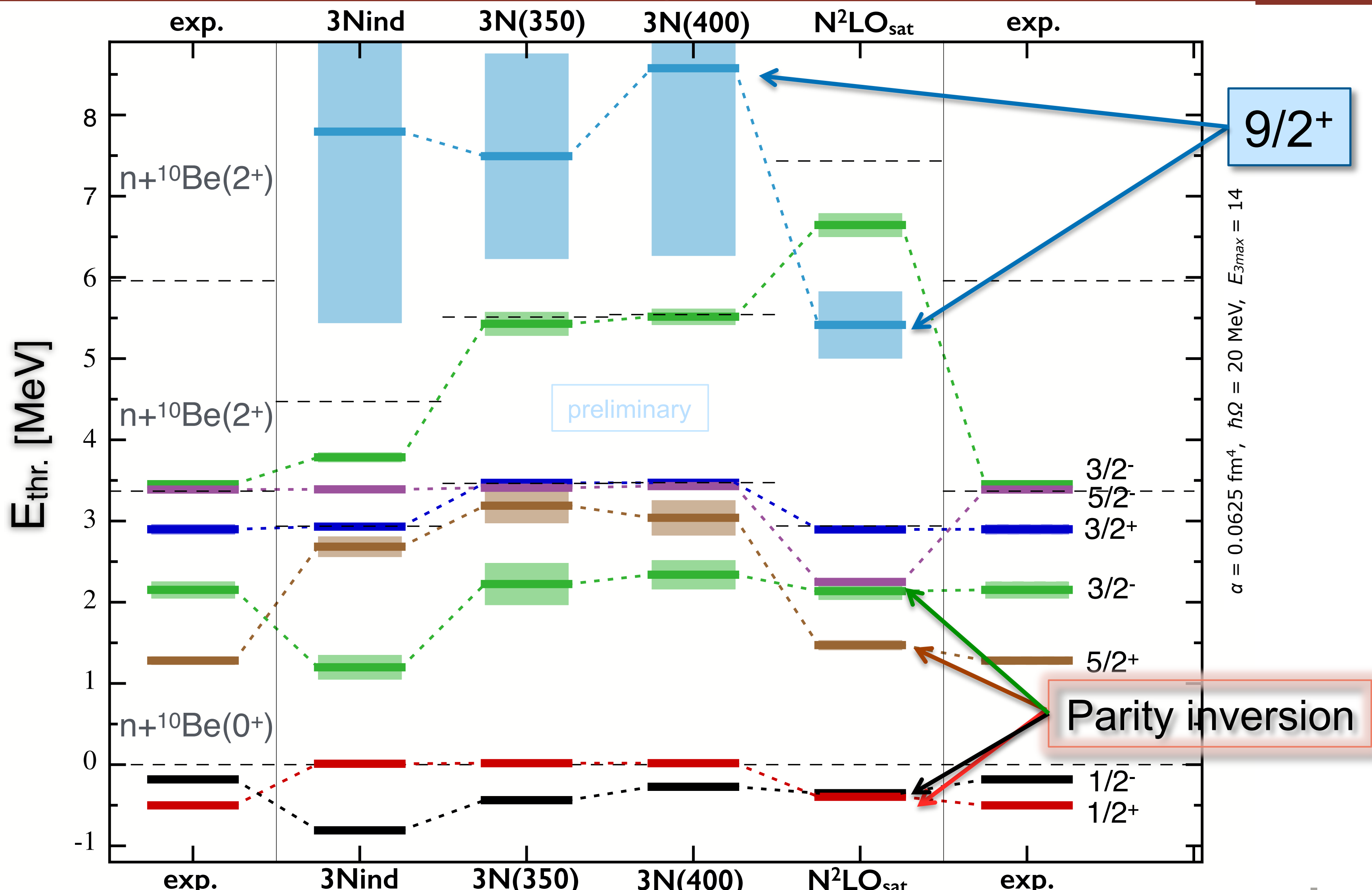


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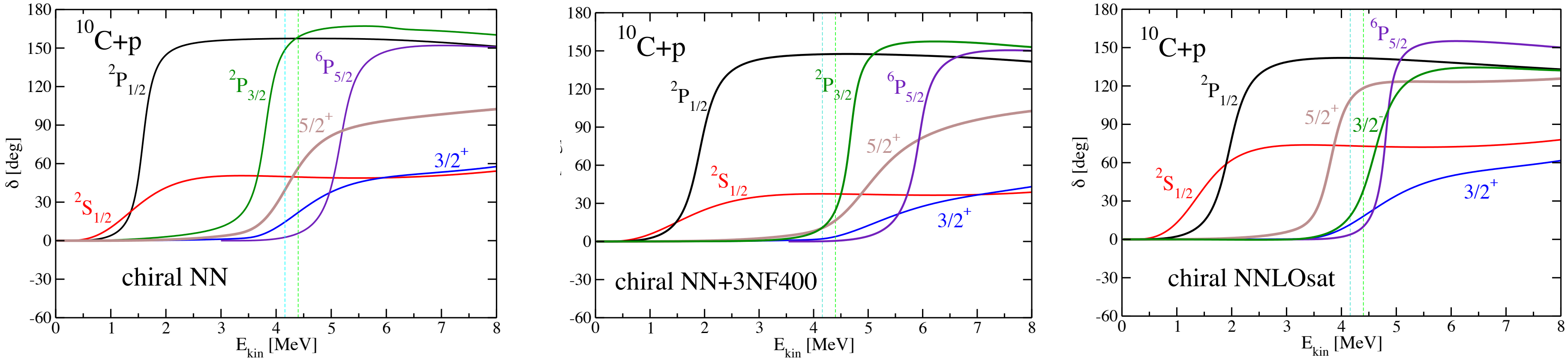
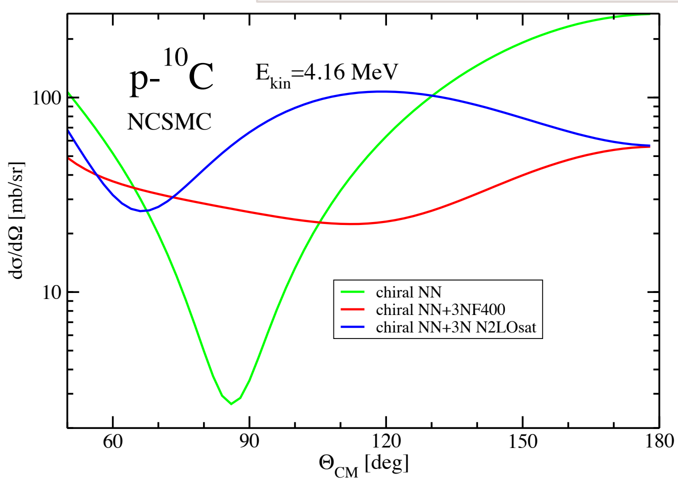
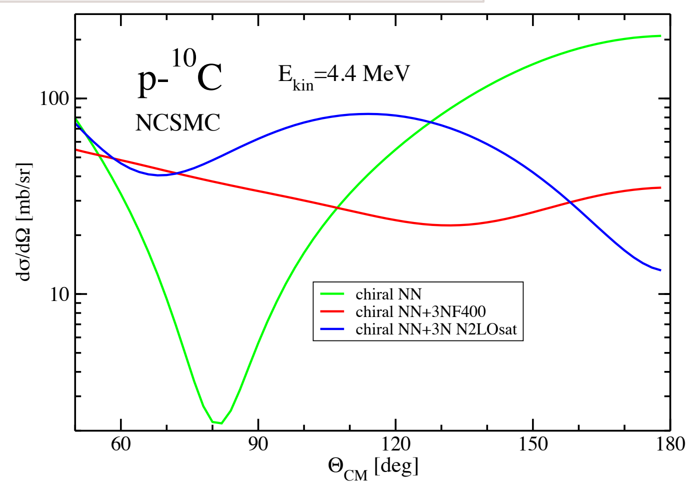
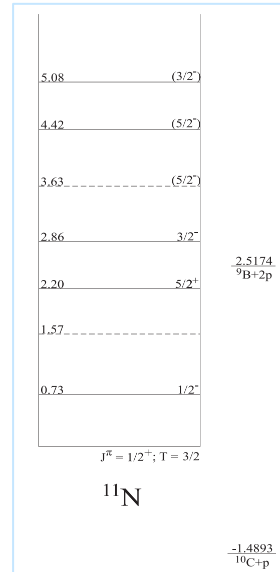
# p+$^{10}$C scattering: structure of $^{11}$N resonances




Discrimination among chiral nuclear forces

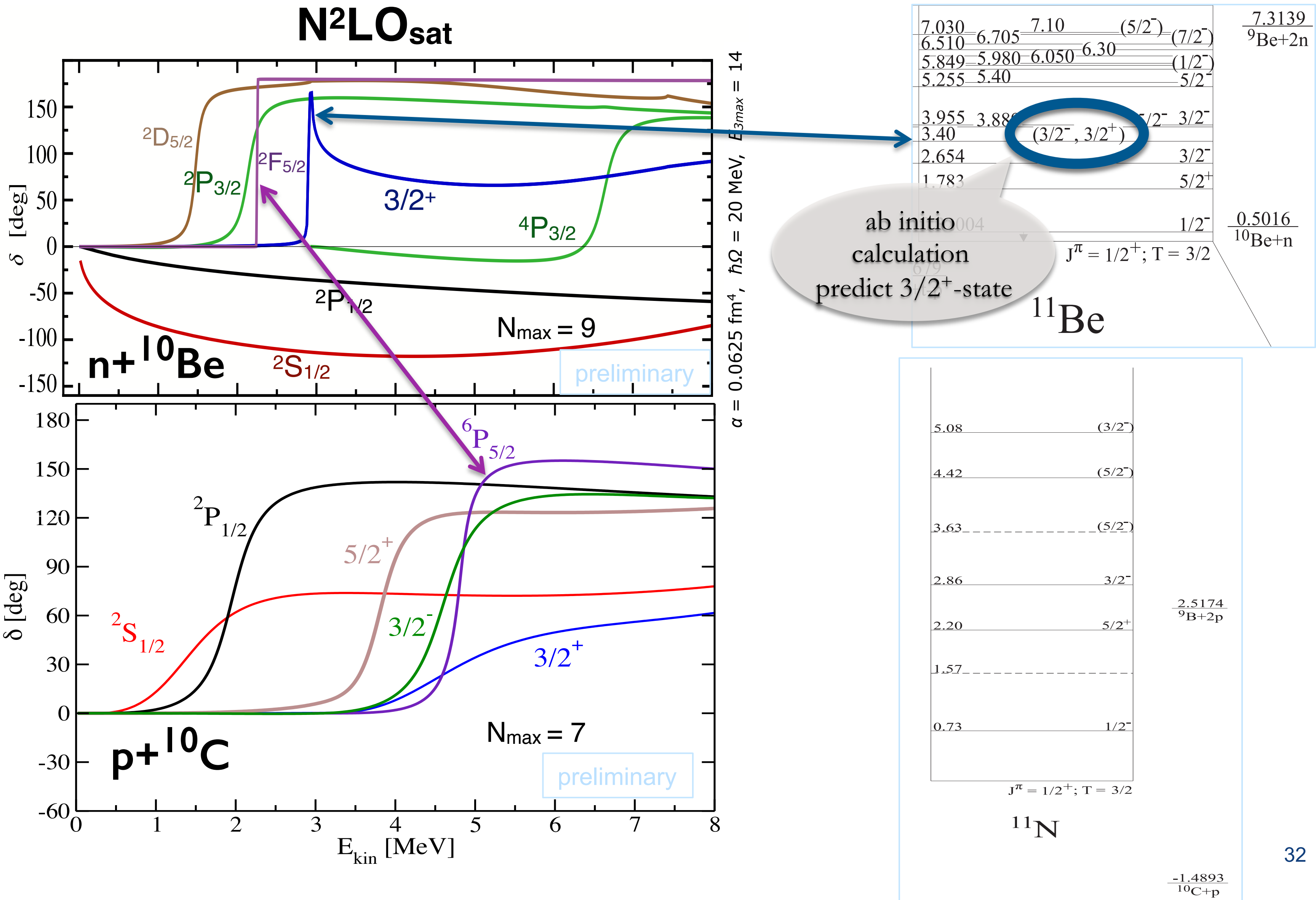


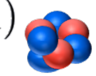

A. Calci, P. Navratil, G. Hupin, S. Quaglioni, R. Roth *et al* with IRIS collaboration, in preparation

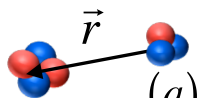
# Mirror nuclei $^{11}$Be and $^{11}$N



# NCSMC wave function

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| (A) \, , \lambda \right\rangle + \sum_{\nu} \int d\vec{r} \; \gamma_{\nu}(\vec{r}\,) \; \hat{A}_{\nu} \left| \underset{(A-a)}{} \; \vec{r} \; (a) \, , \nu \right\rangle$$






$$\left|\Psi_A^{J^\pi T}\right\rangle = \sum_{\lambda} |A\lambda J^\pi T\rangle \left[ \sum_{\lambda'} (N^{-\frac{1}{2}})^{\lambda\lambda'} \bar{c}_{\lambda'} + \sum_{\nu'} \int dr' \, r'^2 (N^{-\frac{1}{2}})^{\lambda}_{\nu' r'} \frac{\bar{\chi}_{\nu'}(r')}{r'} \right]$$

$$+ \sum_{\nu\nu'} \int dr \, r^2 \int dr' \, r'^2 \hat{\mathcal{A}}_{\nu} \left|\Phi^{J^\pi T}_{\nu r}\right\rangle \mathcal{N}^{-\frac{1}{2}}_{\nu\nu'}(r,r') \left[ \sum_{\lambda'} (N^{-\frac{1}{2}})^{\lambda'}_{\nu' r'} \bar{c}_{\lambda'} + \sum_{\nu''} \int dr'' \, r''^2 (N^{-\frac{1}{2}})_{\nu' r' \nu'' r''} \frac{\bar{\chi}_{\nu''}(r'')}{r''} \right].$$

Asymptotic behavior $r \rightarrow \infty$ :

$$\bar{\chi}_{\nu}(r) \sim C_{\nu} W(k_{\nu} r) \qquad \bar{\chi}_{\nu}(r) \sim \mathrm{v}_{\nu}^{-\frac{1}{2}} \left[ \delta_{\nu i} I_{\nu}(k_{\nu} r) - U_{\nu i} O_{\nu}(k_{\nu} r) \right]$$

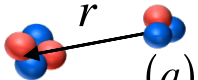
Bound state

Scattering state

Scattering matrix

# E1 transitions in NCSMC

$$\Psi^{(A)} = \sum_\lambda c_\lambda \left|^{(A)}\ ,\lambda\right\rangle + \sum_\nu \int d\vec r\ \gamma_\nu(\vec r\,)\ \hat A_\nu \left|_{(A-a)}\ \vec r\ (a)\ ,\nu\right\rangle$$




$$\begin{aligned}\vec E1 &= e\sum_{i=1}^{A-a}\frac{1+\tau_i^{(3)}}{2}\left(\vec r_i - \vec R^{(A-a)}_{\rm c.m.}\right)\\ &+ e\sum_{j=A-a+1}^{A}\frac{1+\tau_j^{(3)}}{2}\left(\vec r_i - \vec R^{(a)}_{\rm c.m.}\right)\\ &+ e\frac{Z_{(A-a)}a - Z_{(a)}(A-a)}{A}\vec r_{A-a,a}\,.\end{aligned}$$

$$\mathcal{M}^E_{1\mu} = e\sum_{j=1}^{A}\frac{1+\tau_j^{(3)}}{2}\left|\vec r_j - \vec R^{(A)}_{\rm c.m.}\right| Y_{1\mu}(\widehat{r_j - R^{(A)}_{\rm c.m.}})$$

$$\begin{aligned}\mathcal{B}^{E1}_{fi} = &\sum_{\lambda\lambda'} c^{*f}_{\lambda'}\langle A\lambda' J_f^{\pi_f}T_f||\mathcal{M}^E_1||A\lambda J_i^{\pi_i}T_i\rangle\, c^i_\lambda\\ &+\sum_{\lambda'\nu}\int drr^2\, c^{*f}_{\lambda'}\langle A\lambda' J_f^{\pi_f}T_f||\mathcal{M}^E_1\hat{\mathcal{A}}_\nu||\Phi^i_{\nu r}\rangle\,\frac{\gamma^i_\nu(r)}{r}\\ &+\sum_{\lambda\nu'}\int dr'r'^2\,\frac{\gamma^{*f}_{\nu'}(r')}{r'}\langle\Phi^f_{\nu'r'}||\hat{\mathcal{A}}_{\nu'}\mathcal{M}^E_1||A\lambda J_i^{\pi_i}T_i\rangle\, c^i_\lambda\\ &+\sum_{\nu\nu'}\int dr'r'^2\int drr^2\,\frac{\gamma^{*f}_{\nu'}(r')}{r'}\langle\Phi^f_{\nu'r'}||\hat{\mathcal{A}}_{\nu'}\mathcal{M}^E_1\hat{\mathcal{A}}_\nu||\Phi^i_{\nu r}\rangle\,\frac{\gamma^i_\nu(r)}{r}\end{aligned}$$

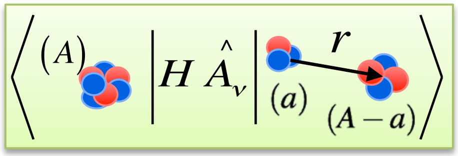
TRIUMF

# Photo-disassociation of $^{11}$Be

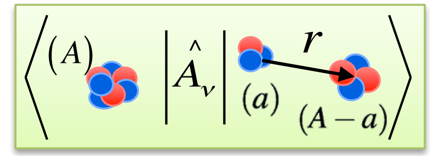
| Bound to bound | NCSM | NCSMC-phenom | Expt. |
|---|---|---|---|
| B(E1; $1/2^+ \rightarrow 1/2^-$) [$e^2$ $fm^2$] | $5\times10^{-6}$ | 0.118 | 0.102(2) |

# NCSMC phenomenology

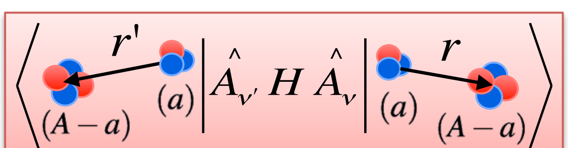
$E_\lambda^{NCSM}\,\delta_{\lambda\lambda'}$

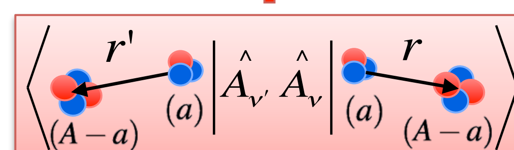



$\delta_{\lambda\lambda'}$




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



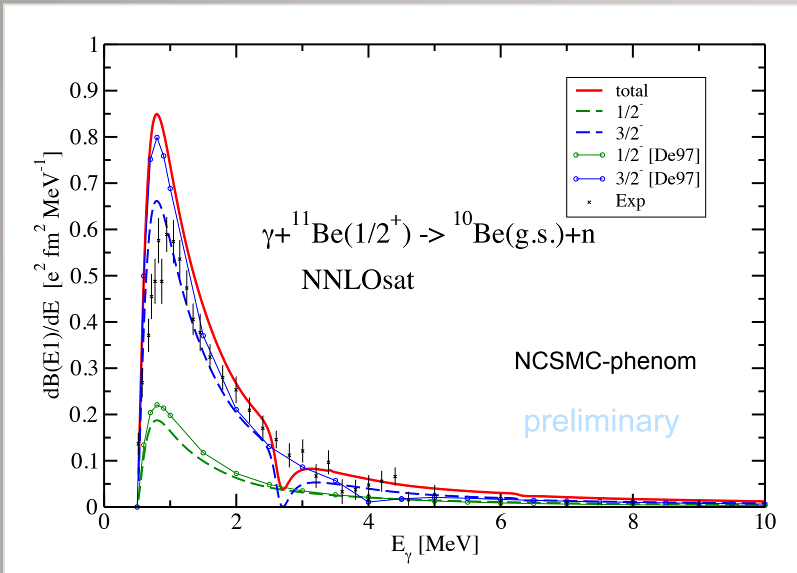




$E_\lambda^{NCSM}$ energies treated as adjustable parameters

Cluster excitation energies set to experimental values

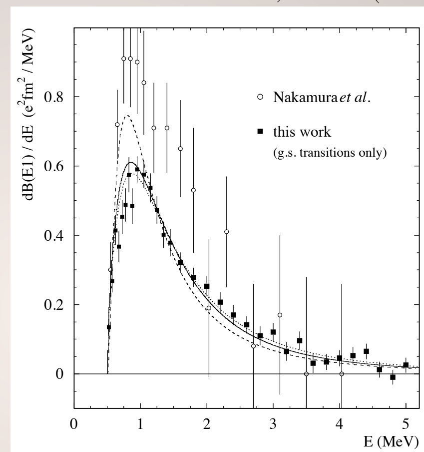
# Photo-disassociation of $^{11}$Be

## Bound to continuum

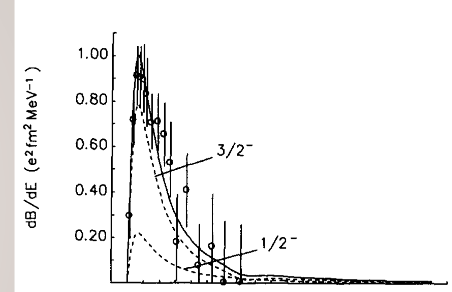


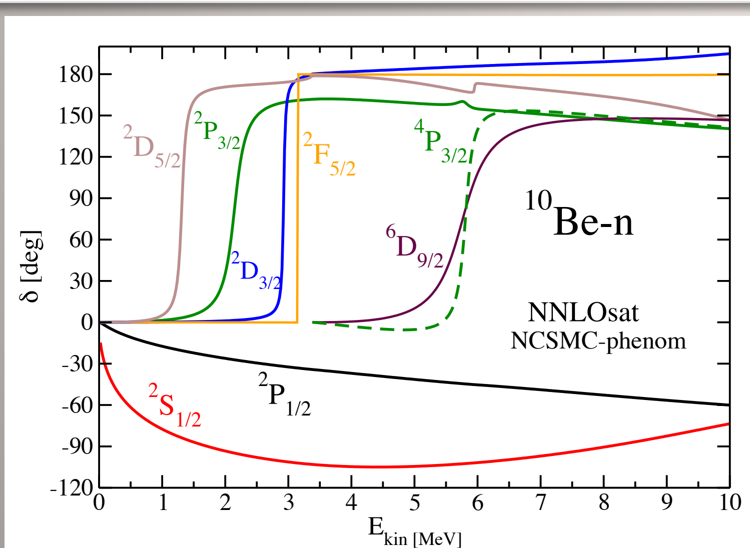

| Bound to bound | NCSM | NCSMC-phenom | Expt. |
|---|---|---|---|
| B(E1; $1/2^+ \rightarrow 1/2^-$) [$e^2$ $fm^2$] | $5\times10^{-6}$ | 0.118 | 0.102(2) |

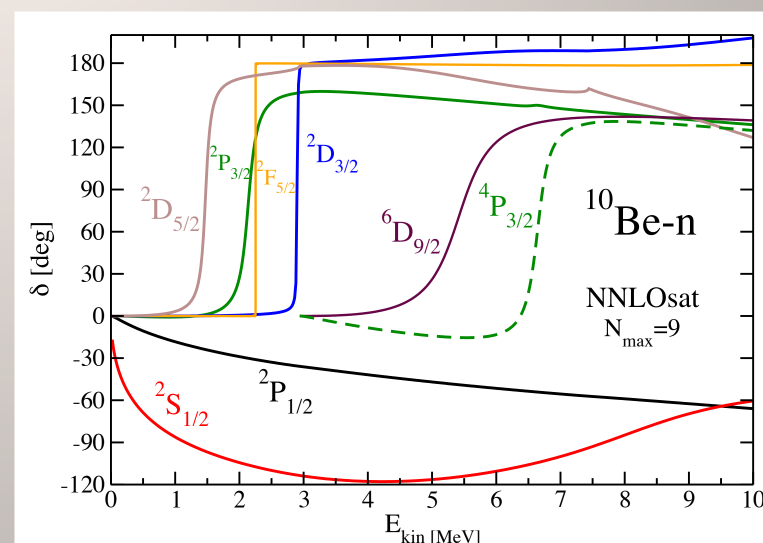
PHYSICAL REVIEW C **68**, 034318 (2003)



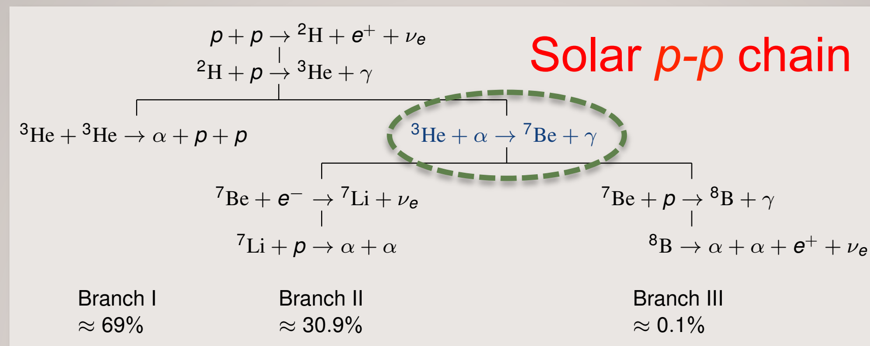

*P. Descouvemont/Nuclear Physics A 615 (1997) 261–276*

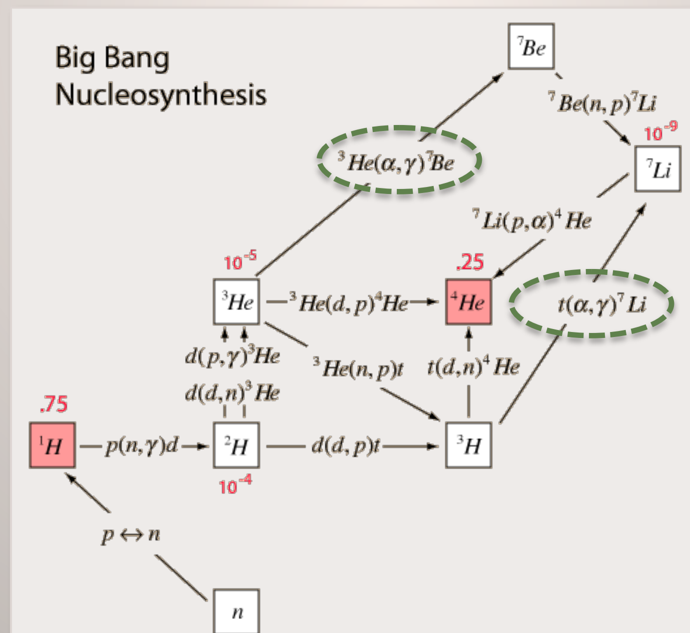


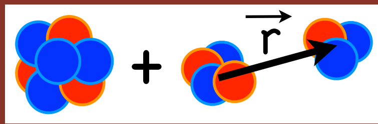



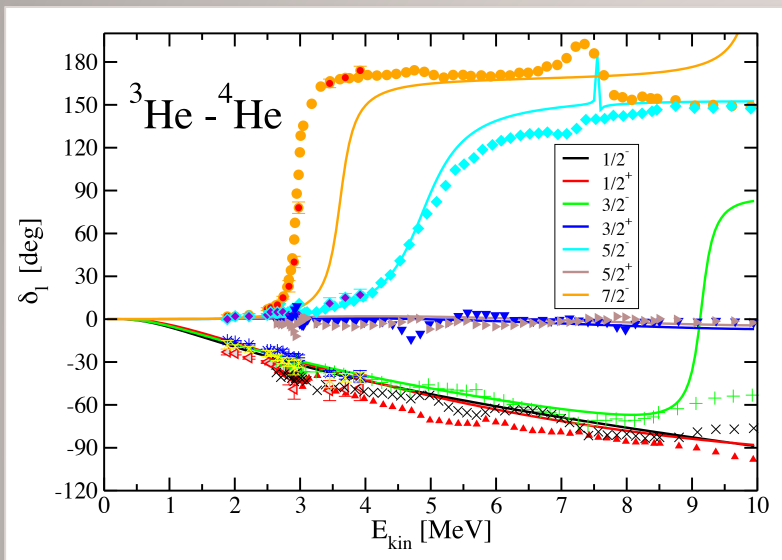
# Capture reactions important for astrophysics






# $^3He$-$^4He$ and $^3H$-$^4He$ scattering




| | $^7Be$ | | $^7Li$ | |
|---|---|---|---|---|
| | NCSMC | Expt. | NCSMC | Expt. |
| $E_{3/2^-}$ [MeV] | -1.52 | -1.586 | -2.43 | -2.467 |
| $E_{1/2^-}$ [MeV] | -1.26 | -1.157 | -2.15 | -1.989 |
| $r_{ch}$ [fm] | 2.62 | 2.647(17) | 2.42 | 2.390(30) |
| Q [e fm$^2$] | -6.14 | | -3.72 | -4.00(3) |
| $\mu$ [$\mu_N$] | -1.16 | -1.3995(5) | +3.02 | +3.256 |

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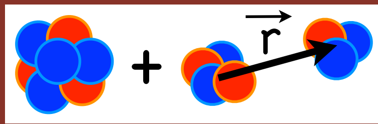
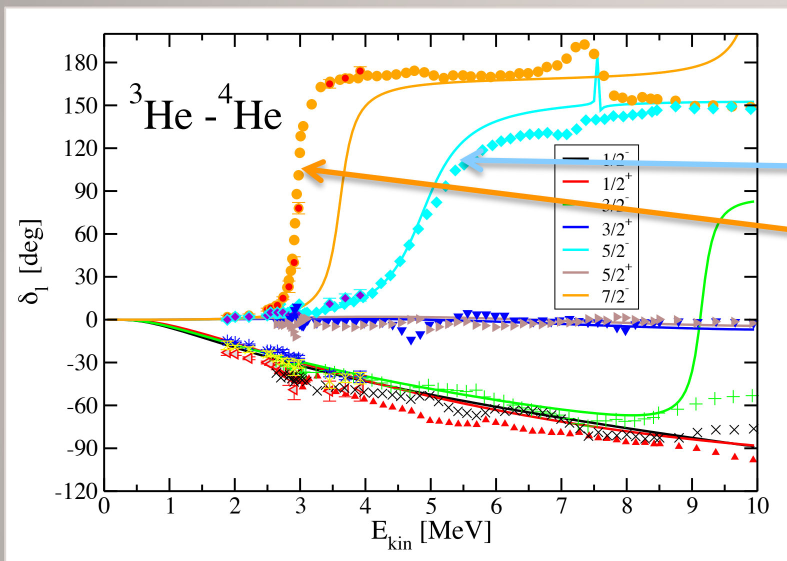
NCSMC calculations with chiral SRG-N$^3$LO *NN* potential (λ=2.15 fm$^{-1}$)

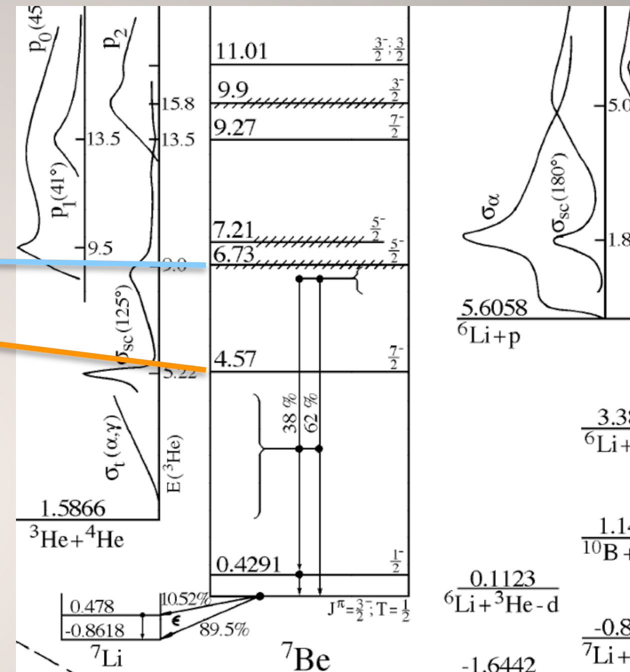
$^3$He, $^3$H, $^4$He ground state, 8(π-) + 6(π+) eigenstates of $^7$Be and $^7$Li

Preliminary: $N_{max}$=12, hΩ=20 MeV



# $^3$He-$^4$He and $^3$H-$^4$He scattering

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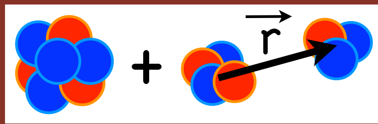
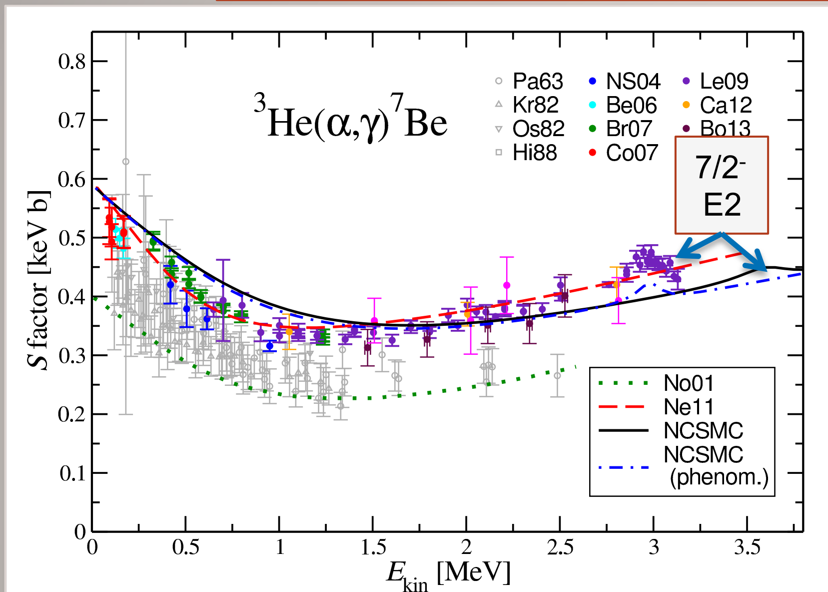
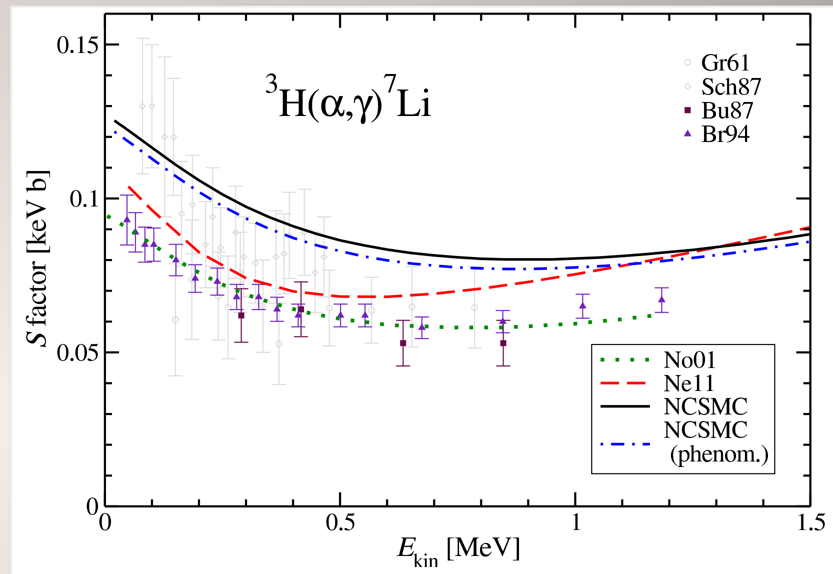
TRIUMF



# $^3$He-$^4$He and $^3$H-$^4$He capture

E1 radiative capture with small E2 contribution at $7/2^-$ resonance

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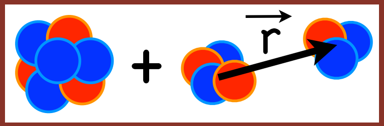
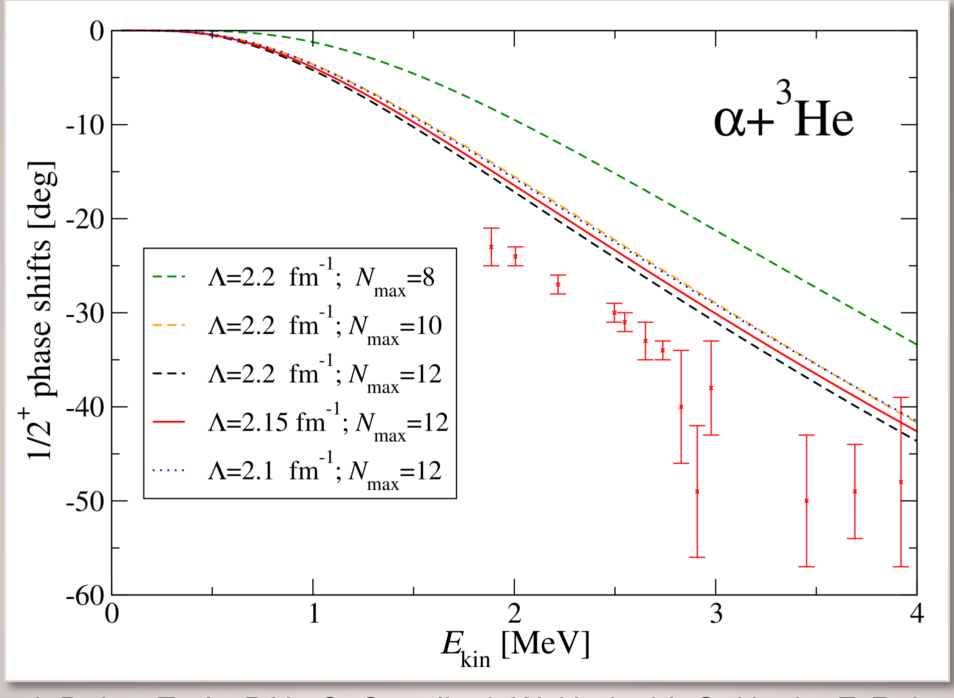
Preliminary: $N_{max}$=12, hΩ=20 MeV

**Theoretical calculations suggest that the most recent and precise $^7$Be and $^7$Li data are inconsistent**

# $^3$He-$^4$He S-wave phase shifts



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TRIUMF

# Conclusions and Outlook

- *Ab initio* calculations of nuclear structure and reactions is a dynamic field with significant advances

- We developed a new unified approach to nuclear bound and unbound states
  - Merging of the NCSM and the NCSM/RGM = **NCSMC**
  - Inclusion of three-nucleon interactions in reaction calculations for $A$>5 systems
  - Extension to three-body clusters ($^{6}$He ~ $^{4}$He+$n$+$n$): NCSMC in progress

- Ongoing projects:
  - Transfer reactions
  - Sensitivity analysis of nuclear interactions for halo $^{11}$Be and exotic $^{11}$N
  - Applications to capture reactions important for astrophysics
  - Bremsstrahlung

- Outlook
  - Alpha-clustering ($^{4}$He projectile)
    - $^{12}$C and Hoyle state: $^{8}$Be+$^{4}$He
    - $^{16}$O: $^{12}$C+$^{4}$He