Halo nuclei
from *ab initio* nuclear theory

International Symposium Commemorating the 40th Anniversary of the Halo Nuclei (HALO-40)

Beijing, October 12-18, 2025

Petr Navratil

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Collaborators:

Sofia Quaglioni (LLNL), Kostas Kravvaris (LLNL), Guillaume Hupin (IJCLab), Michael Gennari (Mainz),

2025-10-24

Discovery, accelerated

Outline

- Introduction – *Ab initio* nuclear theory – no-core shell model with continuum (NCSMC)
- Parity inversion in ^{11}Be ground state
- Halo ground state of ^{15}C
- *P*-wave halo ground state of ^{8}B & radiative capture of protons on ^{7}Be
- NCSMC for three-body cluster – ^{6}He ~ ^{4}He + n + n
- ^{11}Li within NCSM (prerequisite for ^{11}Li ~ ^{9}Li + n + n)
- Conclusions

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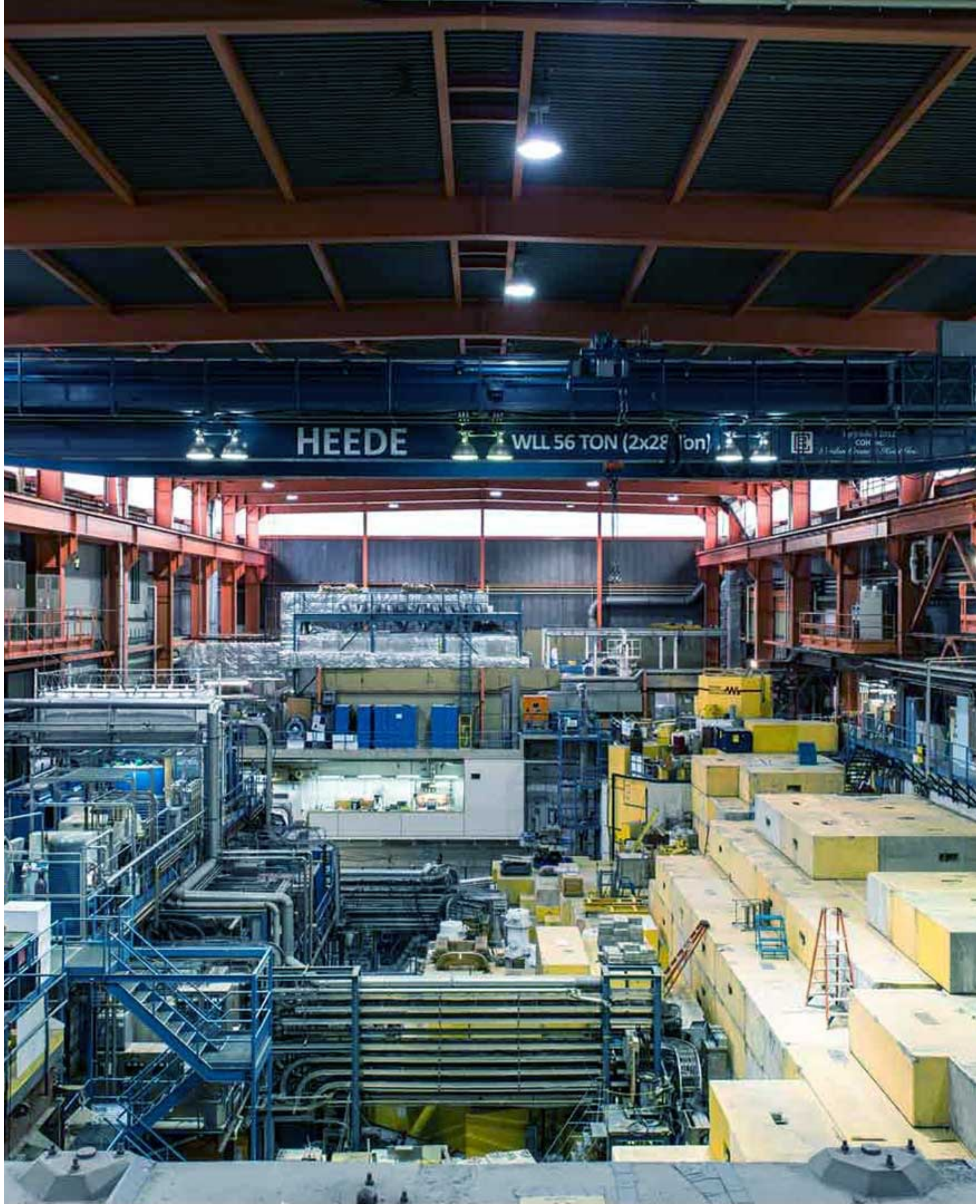
Ab initio nuclear theory - no-core shell model with continuum (NCSMC)



Discovery, accelerated

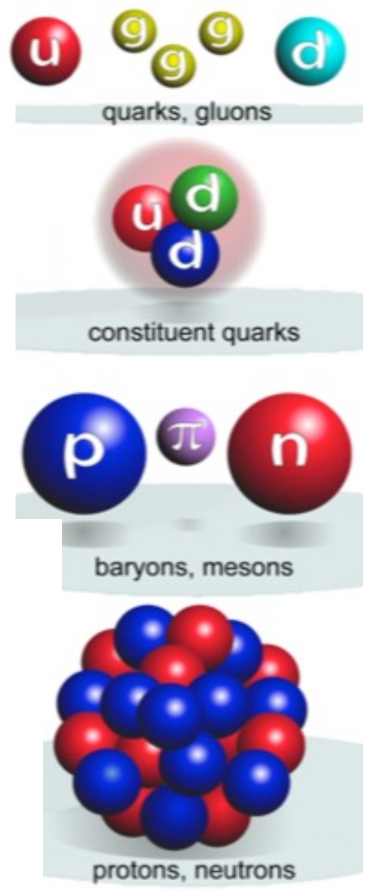
First principles or *ab initio* nuclear theory

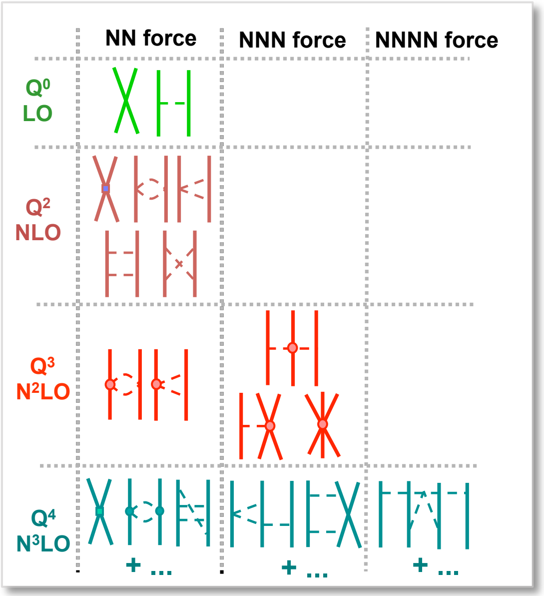
Quantum Chromodynamics (QCD)

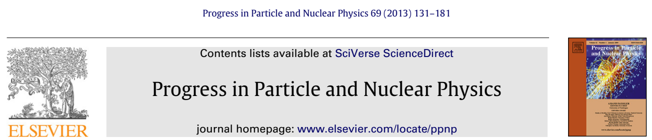
Chiral Effective Field Theory (parameters fitted to NN data)

Many-body *ab initio* nuclear theory

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

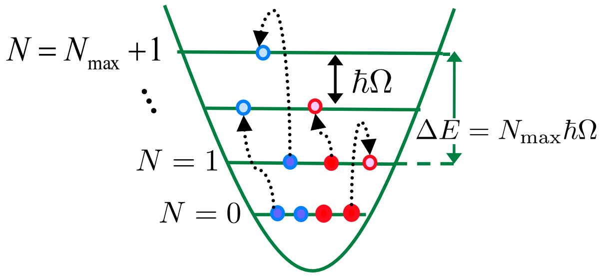


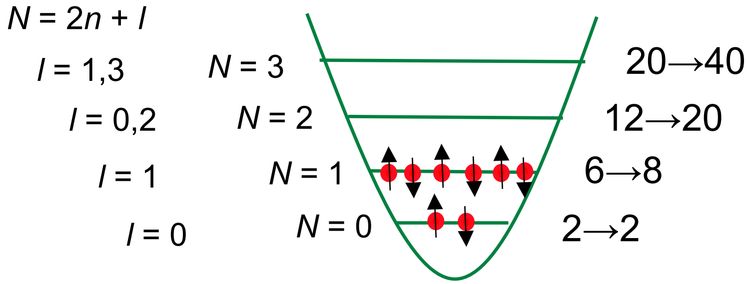



Progress in Particle and Nuclear Physics 69 (2013) 131–181
Contents lists available at SciVerse ScienceDirect
Progress in Particle and Nuclear Physics
journal homepage: www.elsevier.com/locate/ppnp
Review
Ab initio no core shell model
Bruce R. Barrett [a], Petr Navrátil [b], James P. Vary [c,*]

Conceptually simplest *ab initio* method: No-Core Shell Model (NCSM)

- Basis expansion method (CI)
  - Harmonic oscillator (HO) basis truncated in a particular way ($N_{\max}$)
  - Why HO basis?
    - Lowest filled HO shells match magic numbers of light nuclei (2, 8, 20 – ^{4}He, ^{16}O, ^{40}Ca)
    - Equivalent description in relative(Jacobi)-coordinate and Slater determinant basis – nuclei self-bound, $[H,P_{CM}]=0$
      - Exact factorization of CM and intrinsic eigenfunctions at each $N_{\max}$
- Good for well-bound states, approximation of weakly-bound states and narrow resonances





$$E = (2n + l + \tfrac{3}{2})\hbar\Omega$$

Ab initio calculations of structure including weakly bound halo states, scattering, reactions

Unified approach to bound & continuum states

No-Core Shell Model with Continuum (NCSMC)

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

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

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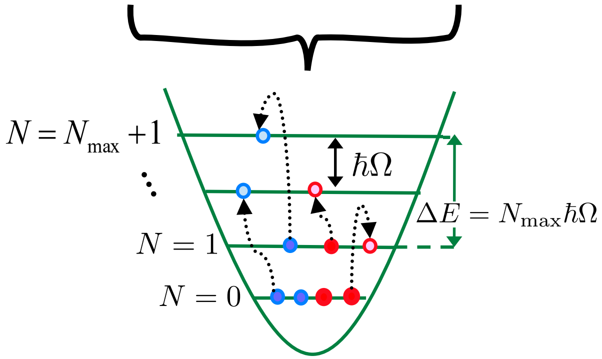

Static solutions for aggregate system,
describe all nucleons close together

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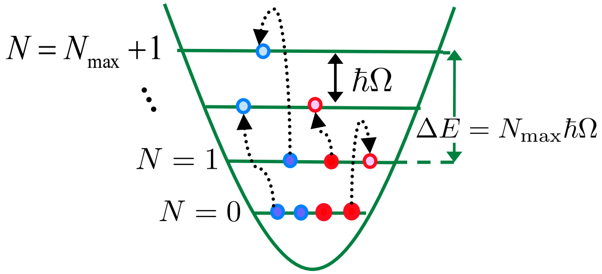

Static solutions for aggregate system,
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Continuous microscopic cluster states,
describe long-range projectile-target

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NCSM NCSM

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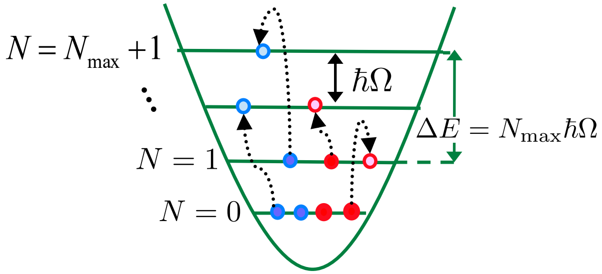

Continuous microscopic cluster states, describe long-range projectile-target

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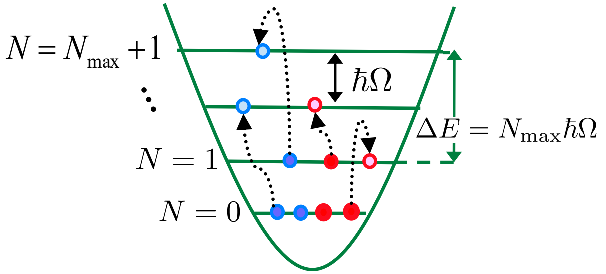
Ab initio calculations of structure including weakly bound halo states, scattering, reactions

Unified approach to bound & continuum states

No-Core Shell Model with Continuum (NCSMC)

Unknowns

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



Continuous microscopic cluster states, describe long-range projectile-target

Static solutions for aggregate system, describe all nucleons close together

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Coupled NCSMC equations

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

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

$$E_\lambda^{NCSM}\,\delta_{\lambda\lambda'} \qquad \left\langle (A) \middle| H\,\hat{A}_\nu \middle| r, (a), (A-a) \right\rangle \qquad \delta_{\lambda\lambda'} \qquad \left\langle (A) \middle| \hat{A}_\nu \middle| r, (a), (A-a) \right\rangle$$

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

$$\left\langle r', (A-a), (a) \middle| \hat{A}_{\nu'}\, H\, \hat{A}_\nu \middle| r, (a), (A-a) \right\rangle \qquad \left\langle r', (A-a), (a) \middle| \hat{A}_{\nu'}\, \hat{A}_\nu \middle| r, (a), (A-a) \right\rangle$$


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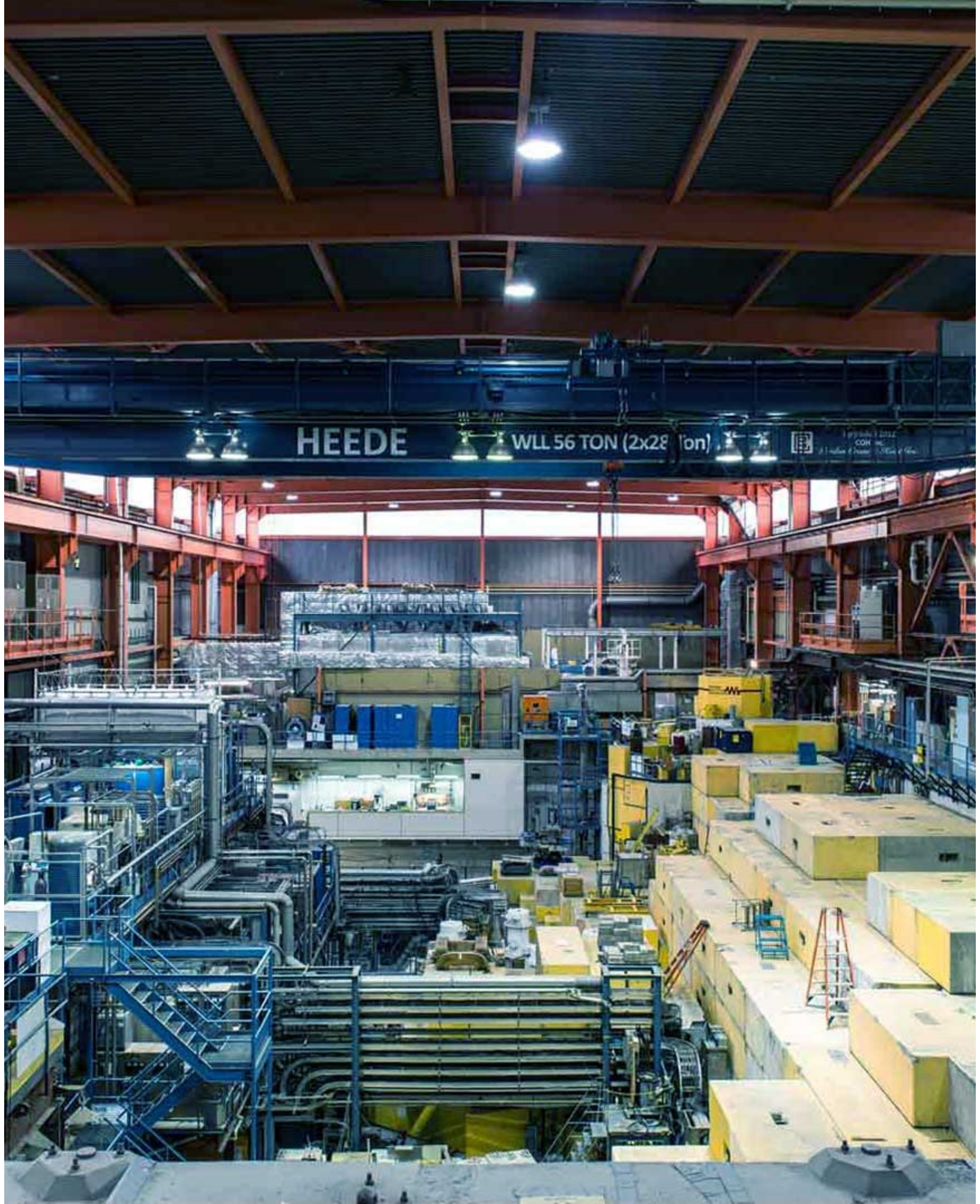
Invited Comment

Unified *ab initio* approaches to nuclear structure and reactions

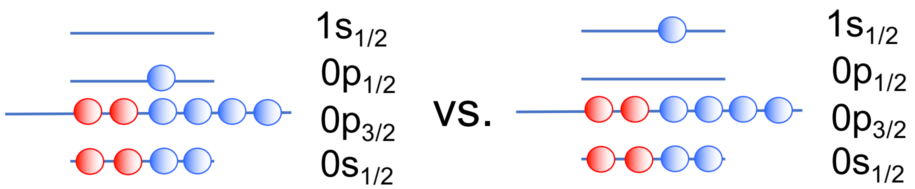
Petr Navrátil[1], Sofia Quaglioni[2], Guillaume Hupin[3,4], Carolina Romero-Redondo[2] and Angelo Calci[1]

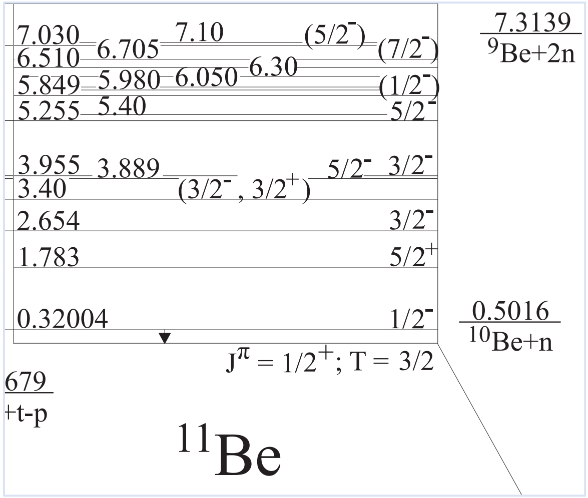
Parity inversion in ^{11}Be ground state



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

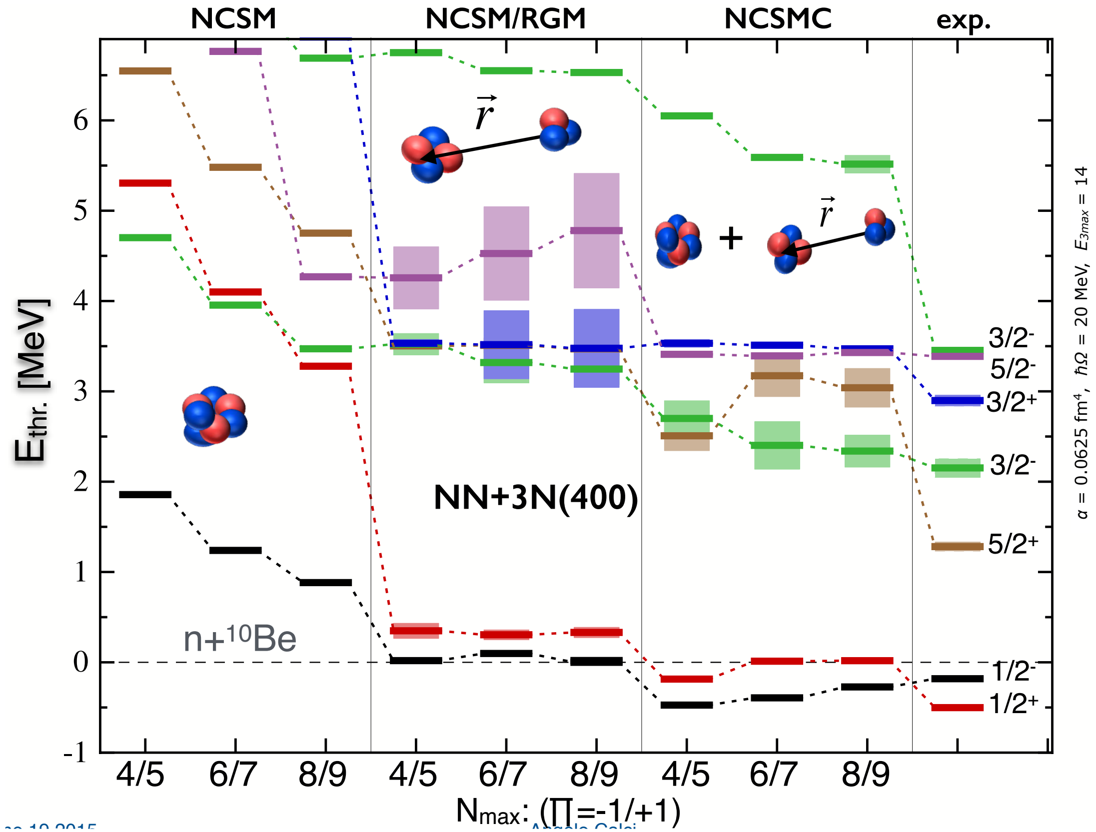


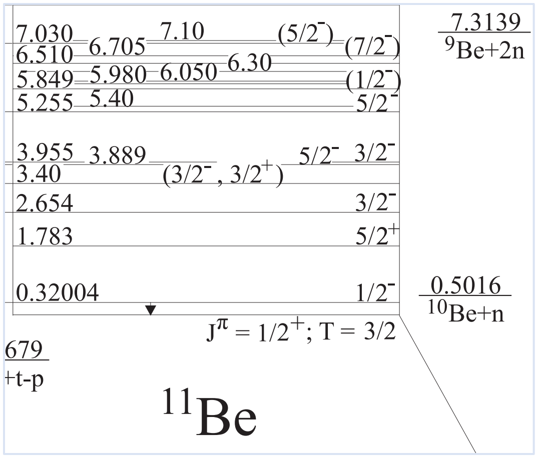


- Can we describe ^{11}Be in *ab initio* calculations?
  - Continuum must be included
  - Does the 3N interaction play a role in the parity inversion?

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

- NCSMC calculations **including chiral 3N** (NN N^{3}LO+N^{2}LO 3N(400), N^{2}LO$_{sat}$, NN N^{4}LO+3N$_{lnl}$)
  - n-^{10}Be + ^{11}Be
    - ^{10}Be: 0$^+$, 2$^+$, 2$^+$ NCSM eigenstates
    - ^{11}Be: ≥6 π = -1 and ≥3 π = +1 NCSM eigenstates



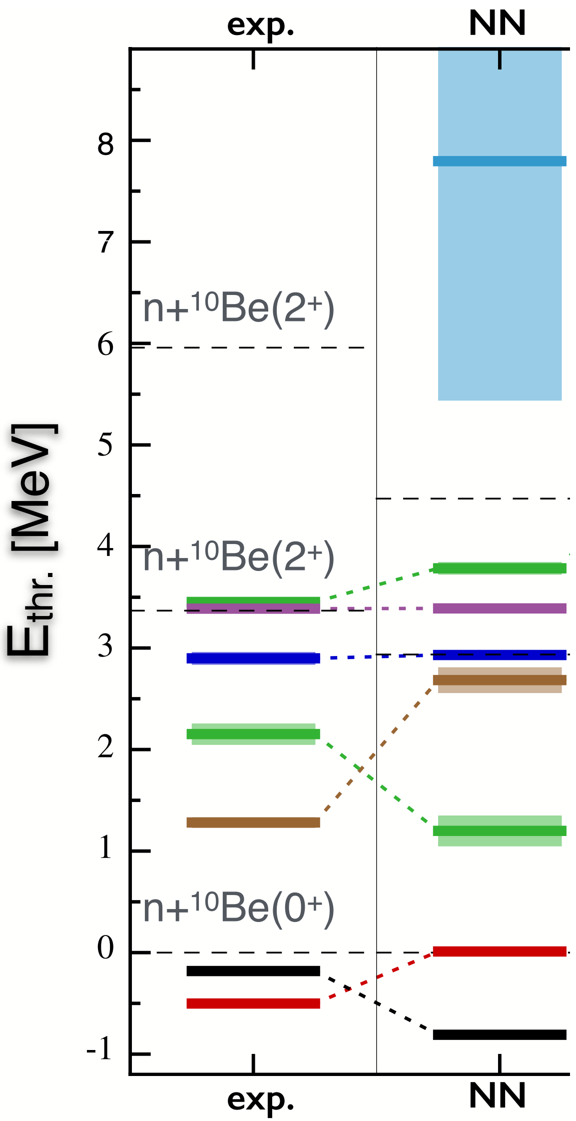


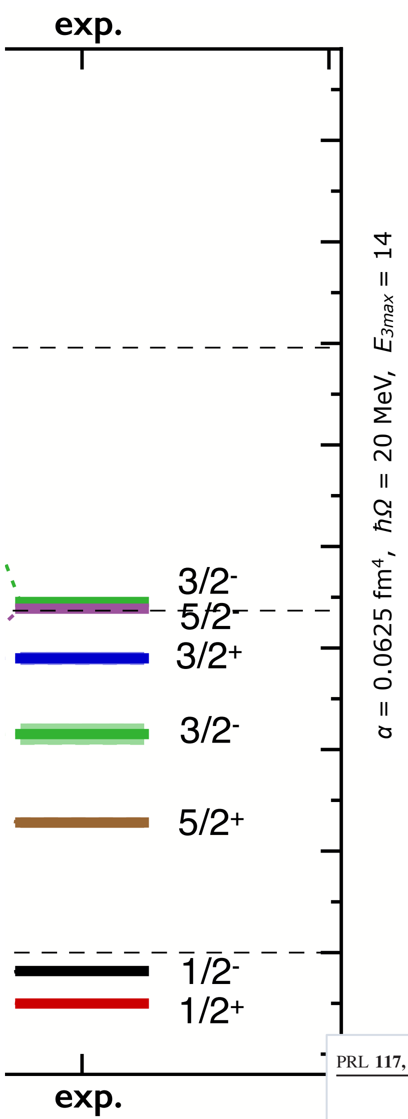
PRL **117,** 242501 (2016) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2016

Can *Ab Initio* Theory Explain the Phenomenon of Parity Inversion in ^{11}Be?

Angelo Calci,[1,*] Petr Navrátil,[1,†] Robert Roth,[2] Jérémy Dohet-Eraly,[1,‡] Sofia Quaglioni,[3] and Guillaume Hupin[4,5]

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





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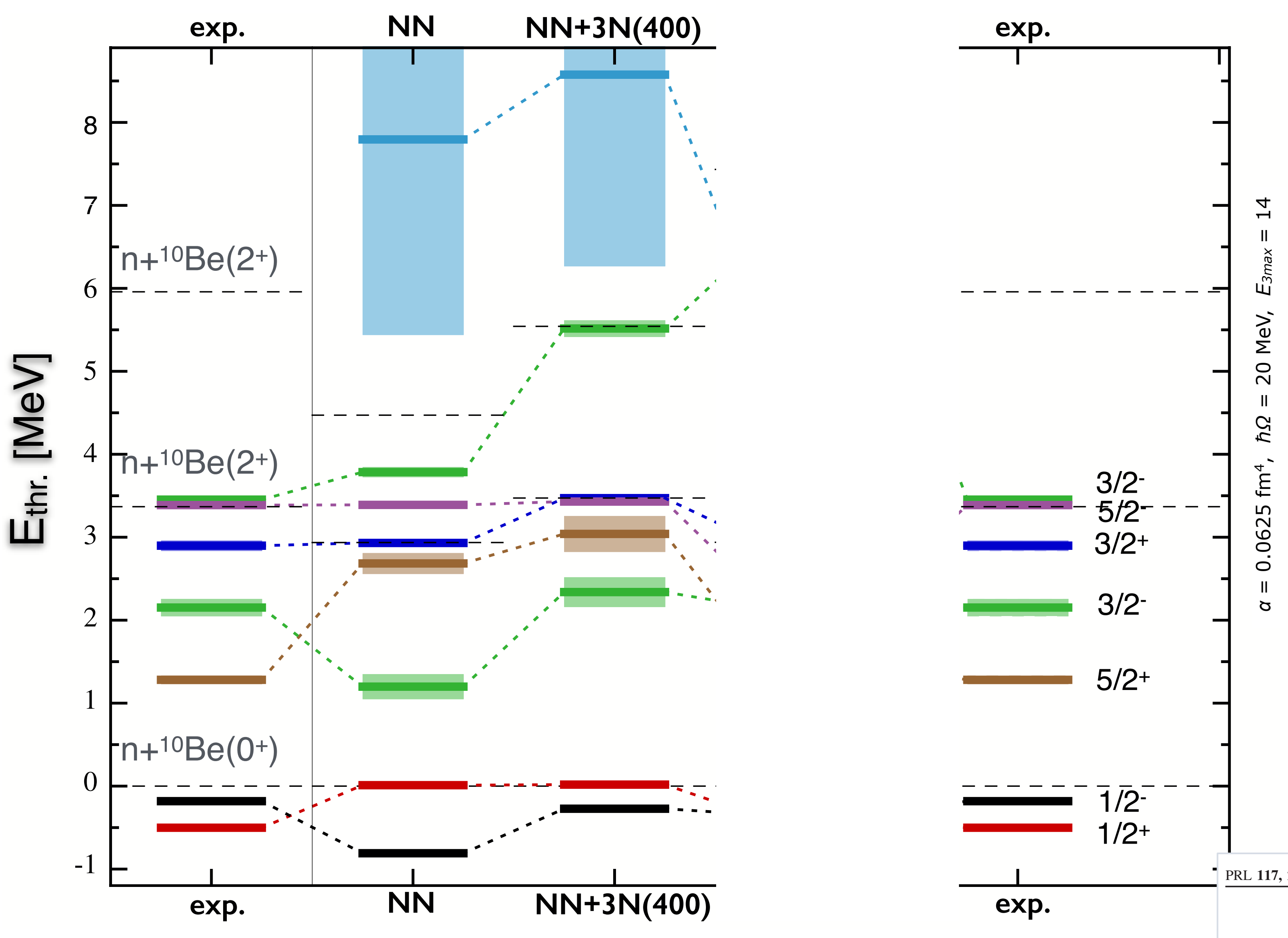

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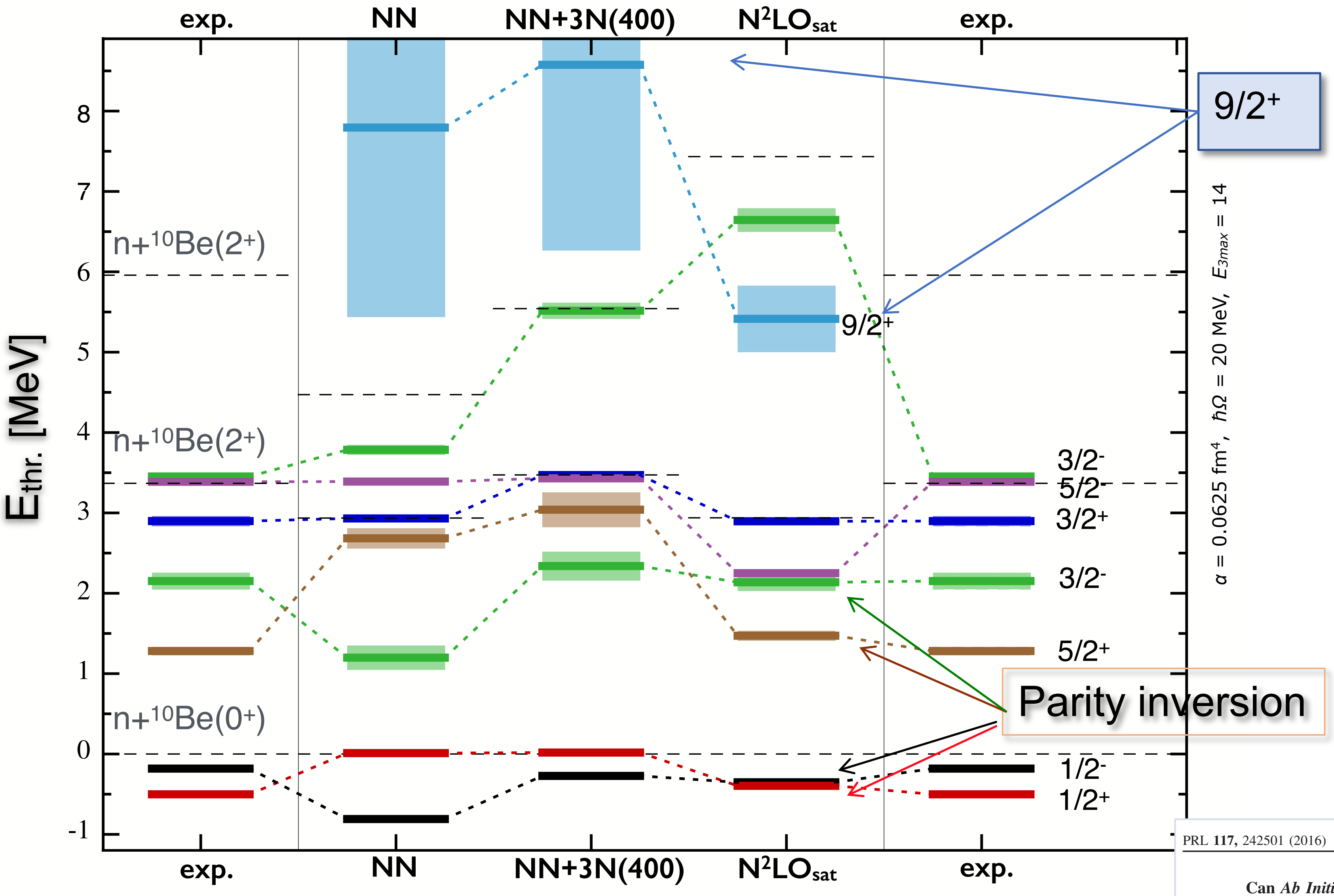

Tensor force included in NN interaction

Core excitation also included

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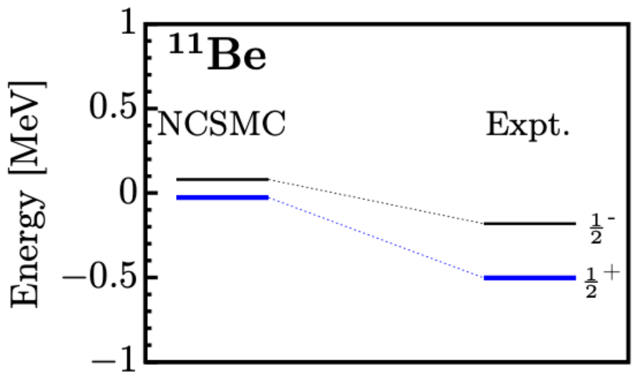
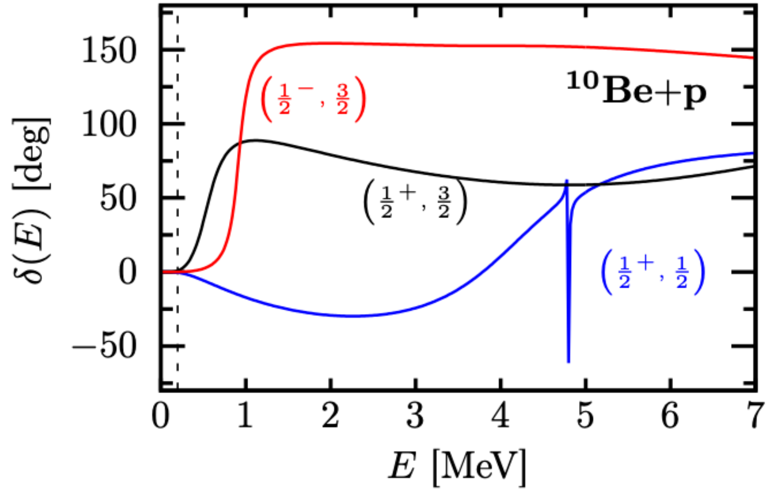
^{11}Be within NCSMC: Discrimination among chiral nuclear forces

New calculations with NN $N^4LO500+3N_{lnl}$

^{11}Be -> ^{10}Be+n



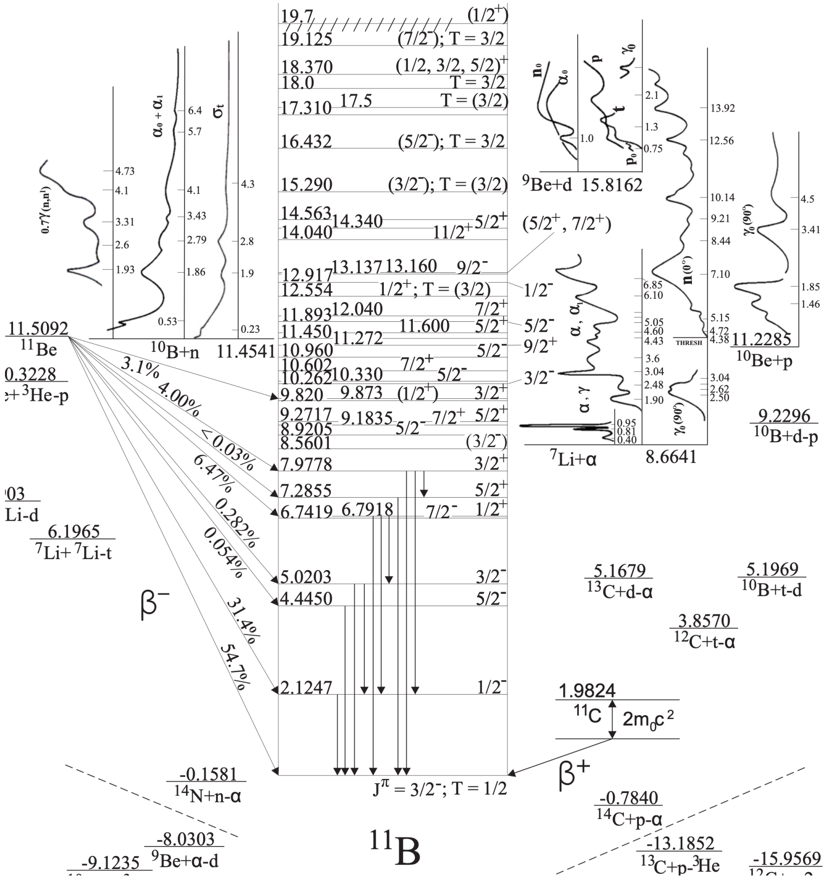
^{11}B -> ^{10}Be+p



PHYSICAL REVIEW C **105**, 054316 (2022)

Ab initio **calculation of the *β* decay from ^{11}Be to a ^{10}Be + *p* resonance**

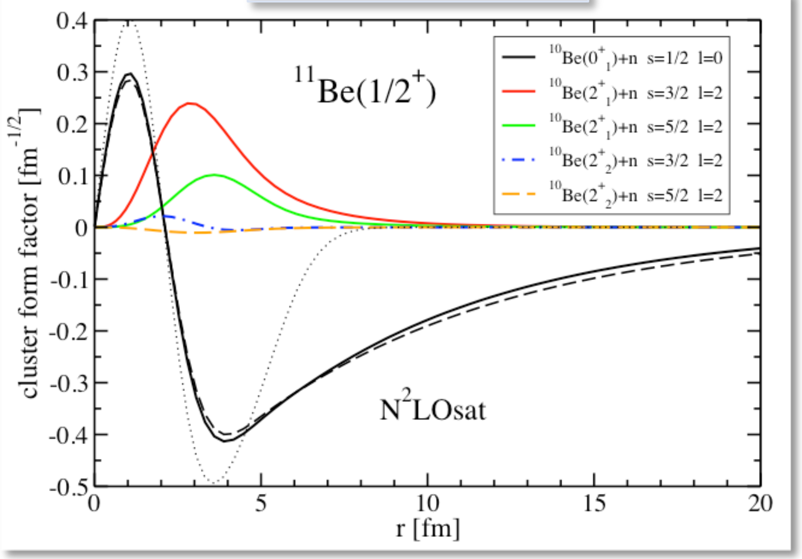
M. C. Atkinson,[1] P. Navrátil,[1] G. Hupin,[2] K. Kravvaris,[3] and S. Quaglioni[3]



Parity inversion reproduced

Photo-disassociation of ^{11}Be

Halo structure



cluster form factor

$$= r \left\langle \Phi^{J^\pi T}_{\nu r} \middle| \hat{A}_\nu \middle| \psi^{J^\pi T} \right\rangle$$

$$\left|\Phi^{J^\pi T}_{\nu r}\right\rangle = \left[\left(\left| {}^{10}\mathrm{Be}\ \alpha_1 I_1^{\pi_1} T_1 \right\rangle \left| n\, \tfrac{1}{2}^+ \tfrac{1}{2} \right\rangle \right)^{(sT)} Y_\ell(\hat{r}_{10,1}) \right]^{(J^\pi T)} \frac{\delta(r - r_{10,1})}{r r_{10,1}}$$

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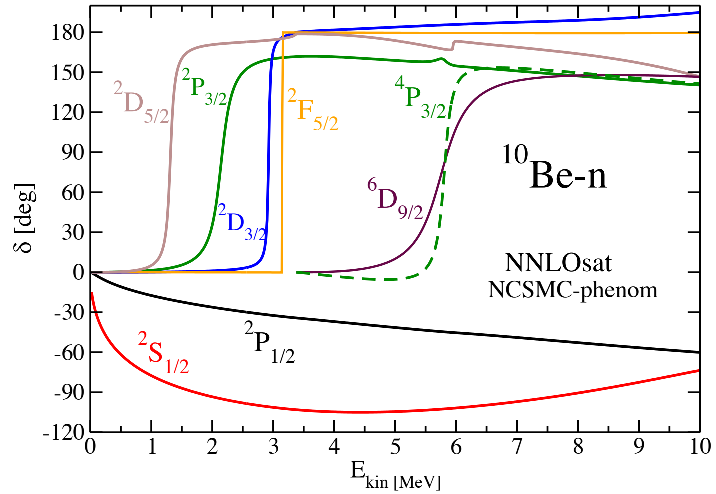
Bound to bound	NCSM	NCSMC-phenom	Expt.
B(E1; 1/2$^+$→1/2$^-$) [e^2 fm^2]	0.0005	0.117	0.102(2)



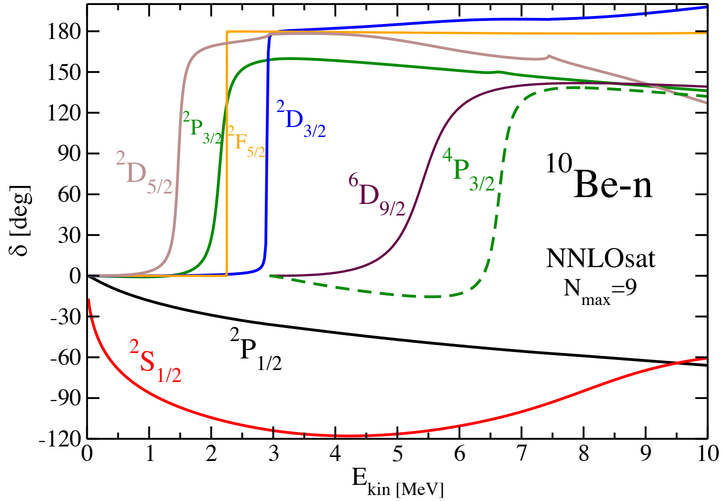


Photo-disassociation of ^{11}Be

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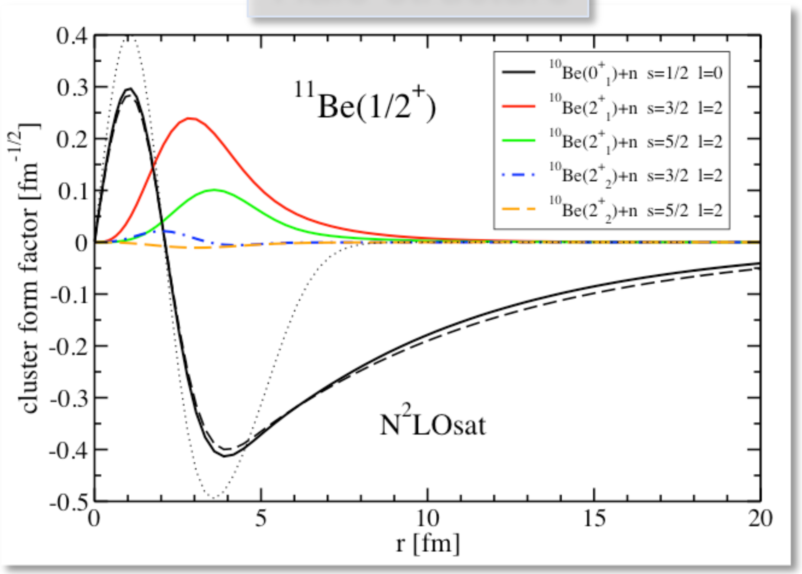

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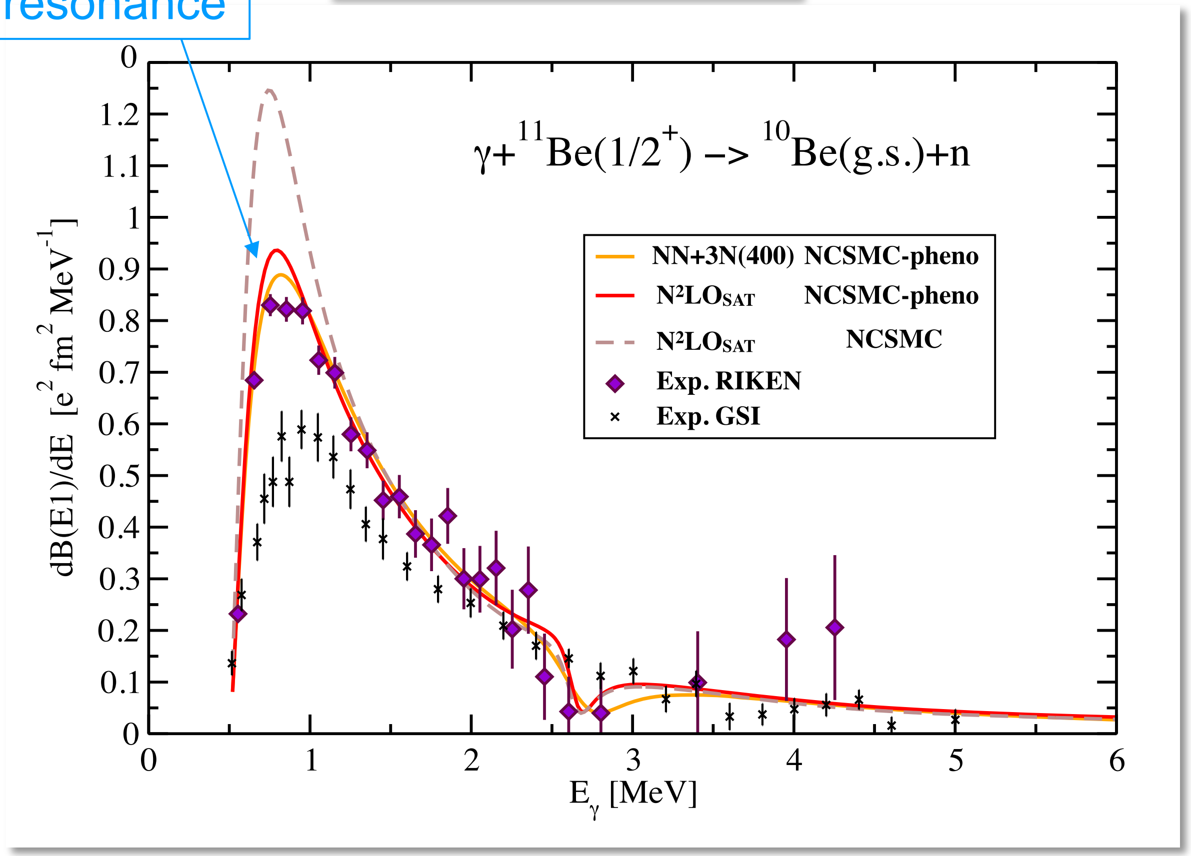
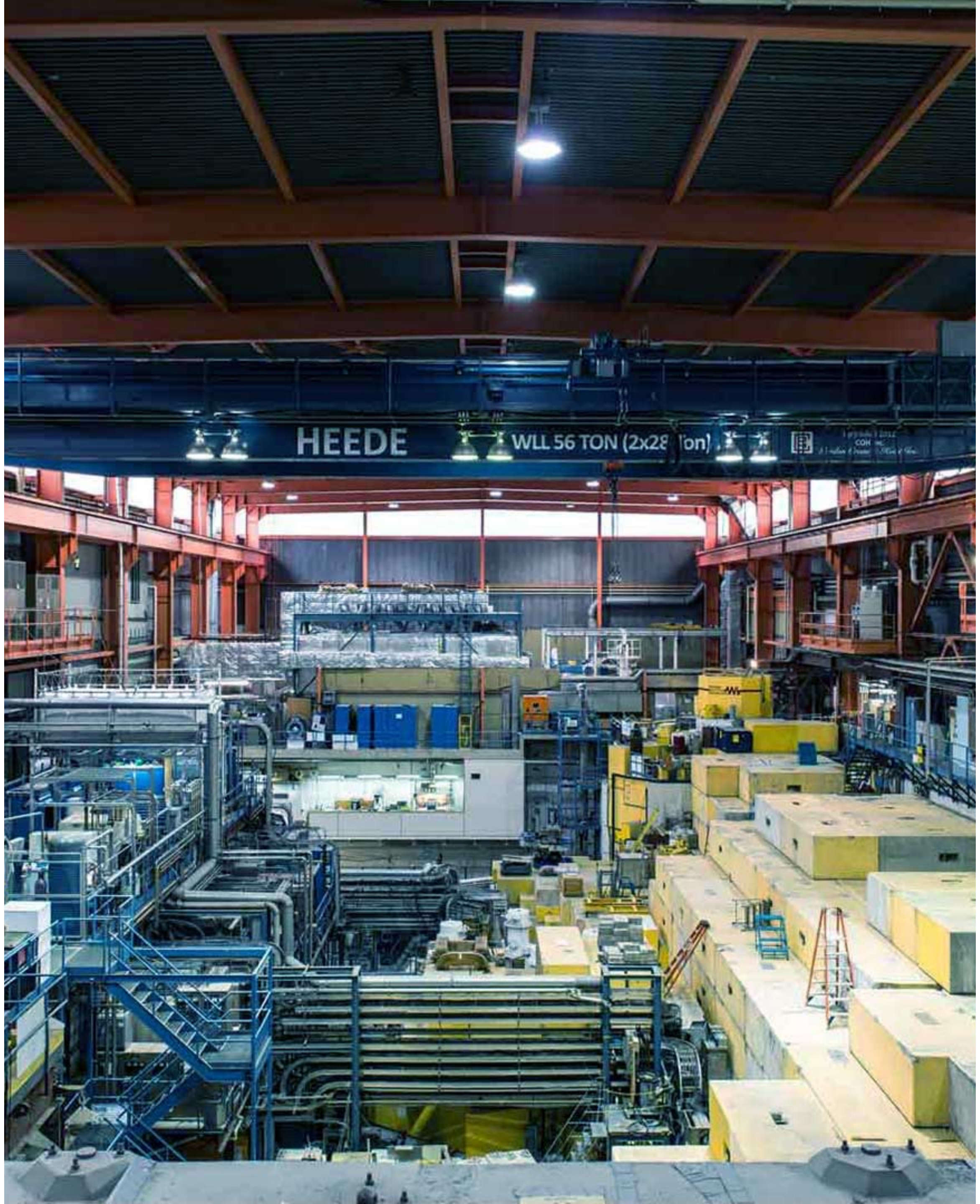
Not a resonance

Bound to continuum

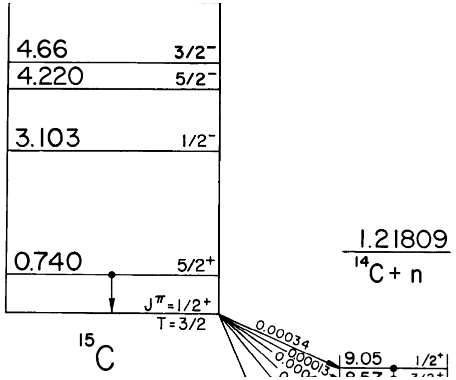


Halo ground state of ^{15}C

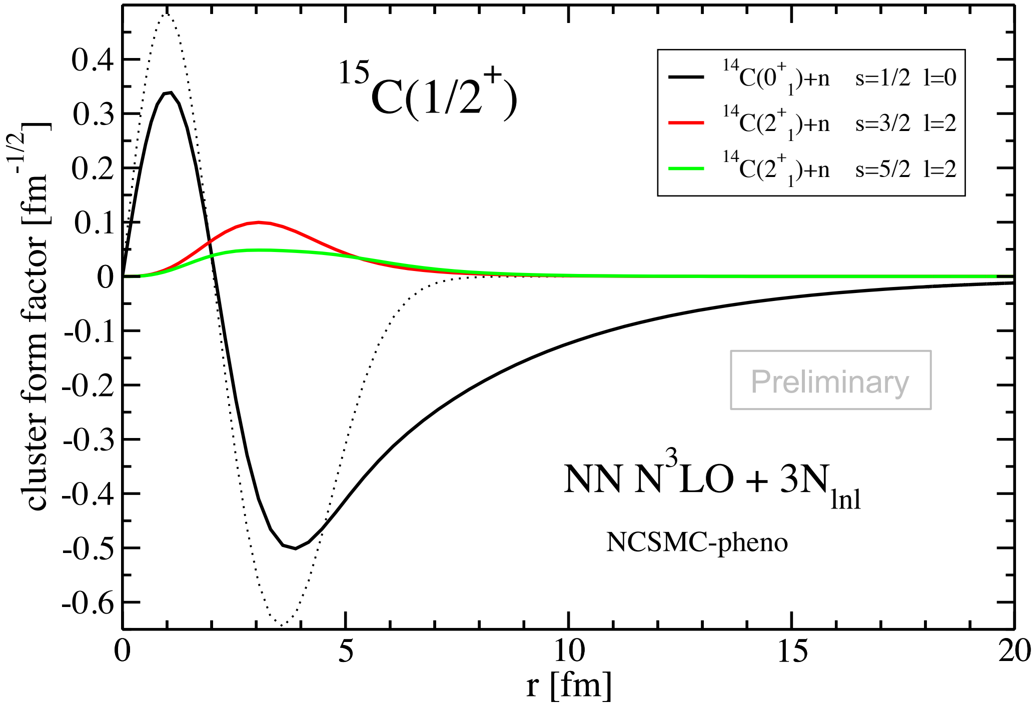


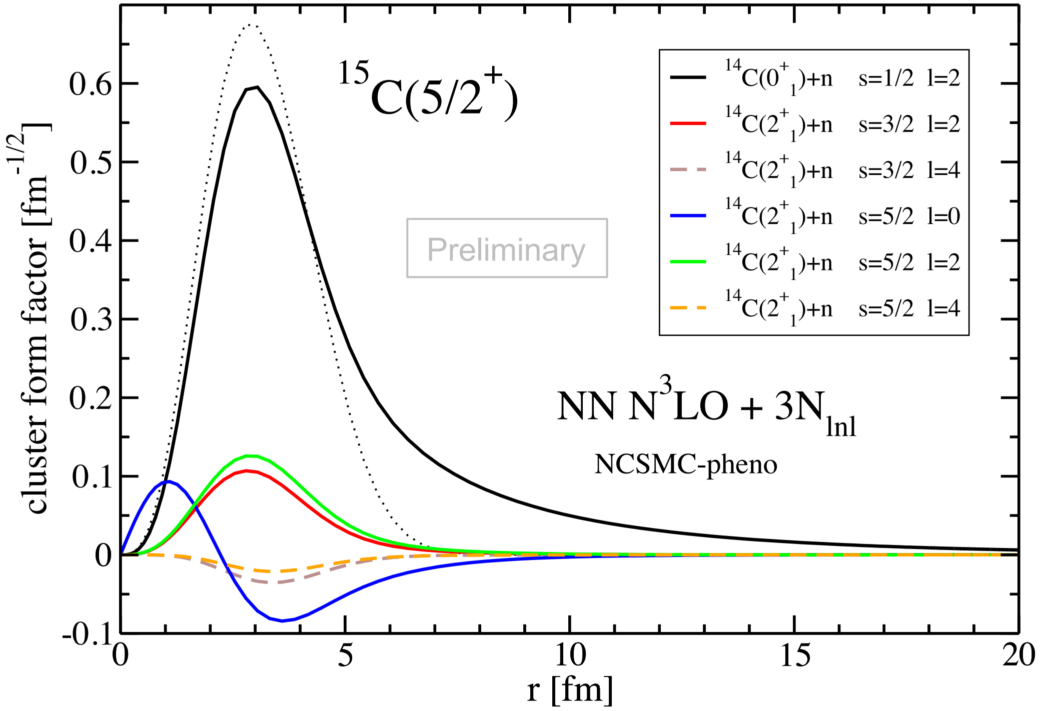
Discovery, accelerated

NCSMC application to $^{15}C \sim {}^{14}C + n$ – cluster form factor calculations



- $1/2^+$ *S*-wave and $5/2^+$ *D*-wave Asymptotic Normalization Coefficients
  - $C_{1/2+} = 1.282\ \mathrm{fm}^{-1/2}$ - compare to Moschini & Capel inferred from transfer data: $1.26(2)\ \mathrm{fm}^{-1/2}$
  - $C_{5/2+} = 0.048\ \mathrm{fm}^{-1/2}$ $0.056(1)\ \mathrm{fm}^{-1/2}$
  - Spectroscopic factors: 0.96 for $1/2^+$ and 0.90 for $5/2^+$ - experiments 0.95(5) and 0.69, resp.





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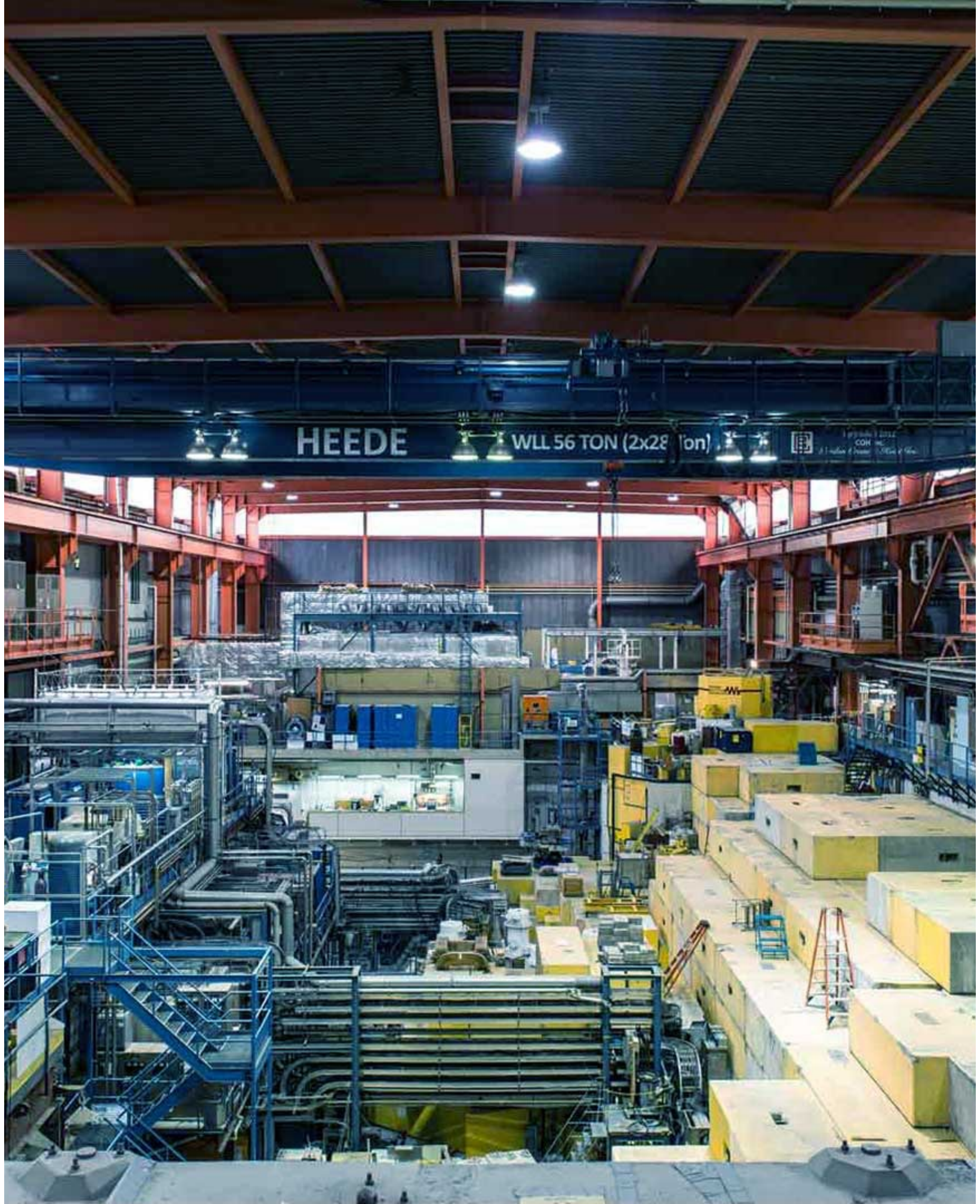
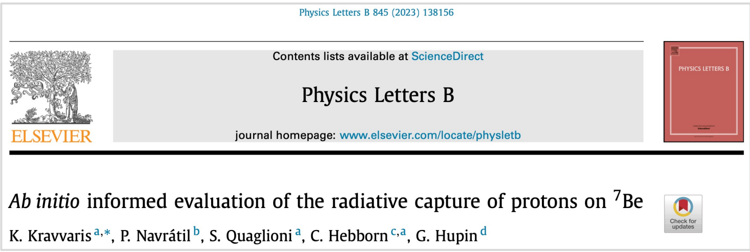
P-wave halo ground state of ^{8}B

&

radiative capture of protons on ^{7}Be



Discovery, accelerated


Physics Letters B 845 (2023) 138156
Contents lists available at ScienceDirect
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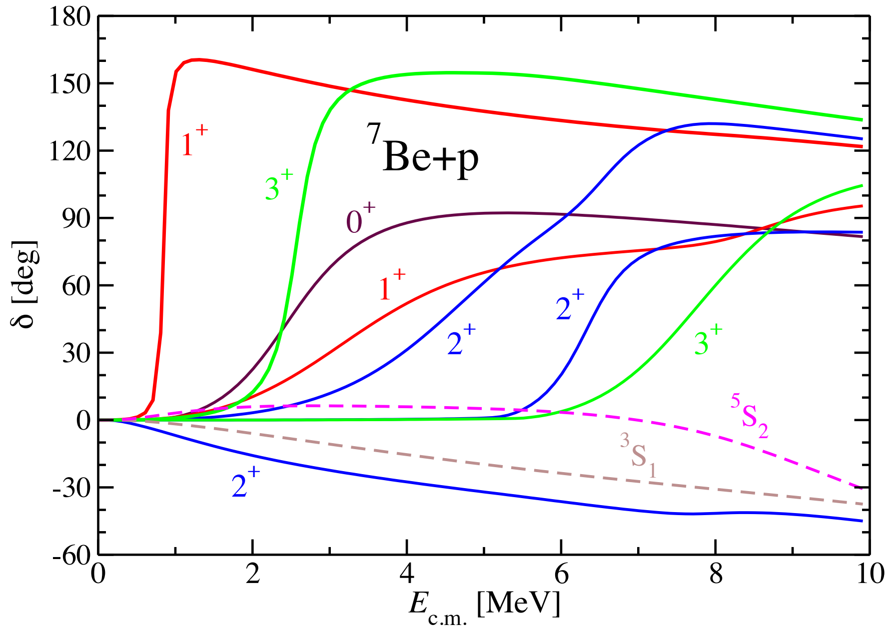
Ab initio informed evaluation of the radiative capture of protons on ^{7}Be

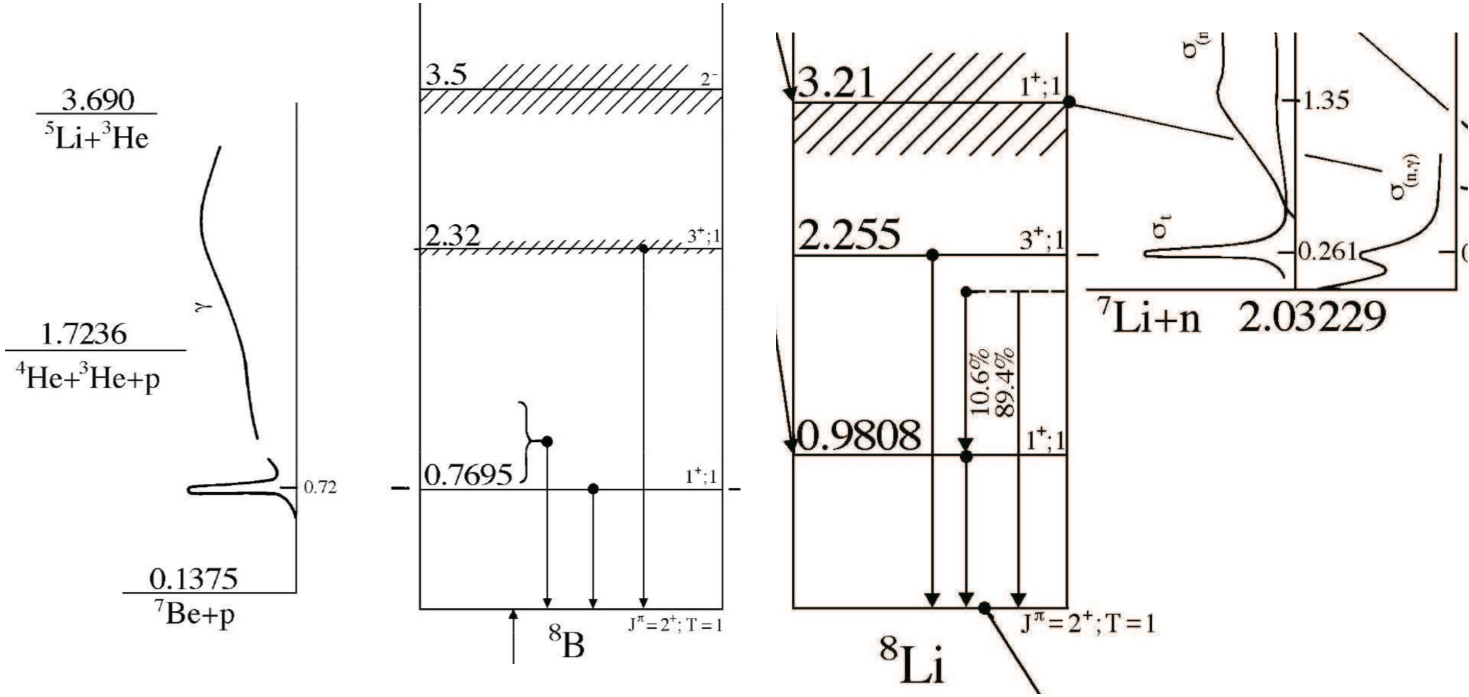
K. Kravvaris[a,*], P. Navrátil[b], S. Quaglioni[a], C. Hebborn[c,a], G. Hupin[d]

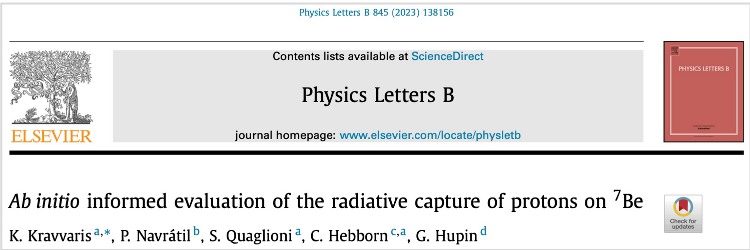
Radiative capture of protons on ^{7}Be

- Solar pp chain reaction, solar ^{8}B neutrinos
- NCSMC calculations with a set of chiral NN+3N interactions as input

- Example of ^{8}B structure results



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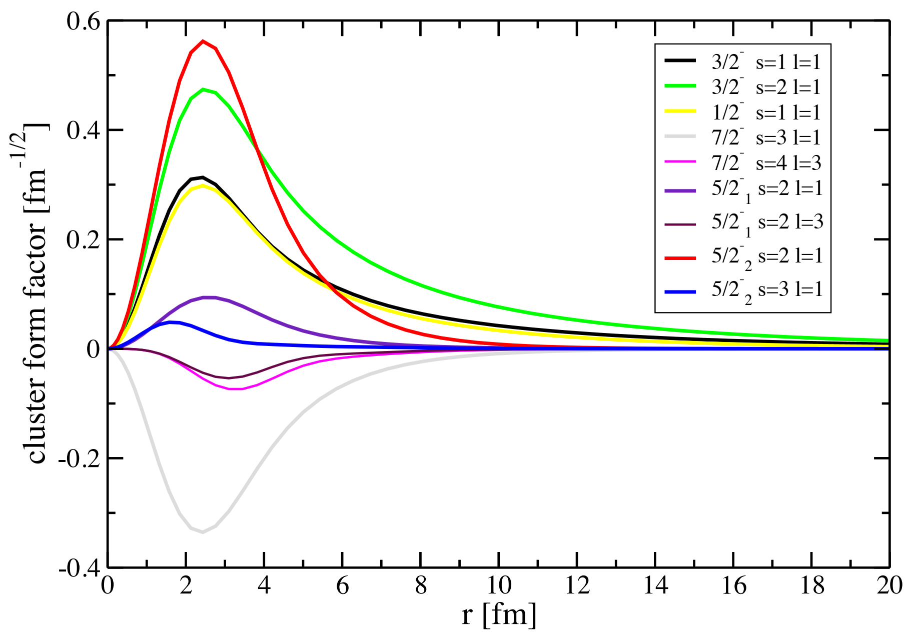
Ab initio informed evaluation of the radiative capture of protons on ^{7}Be

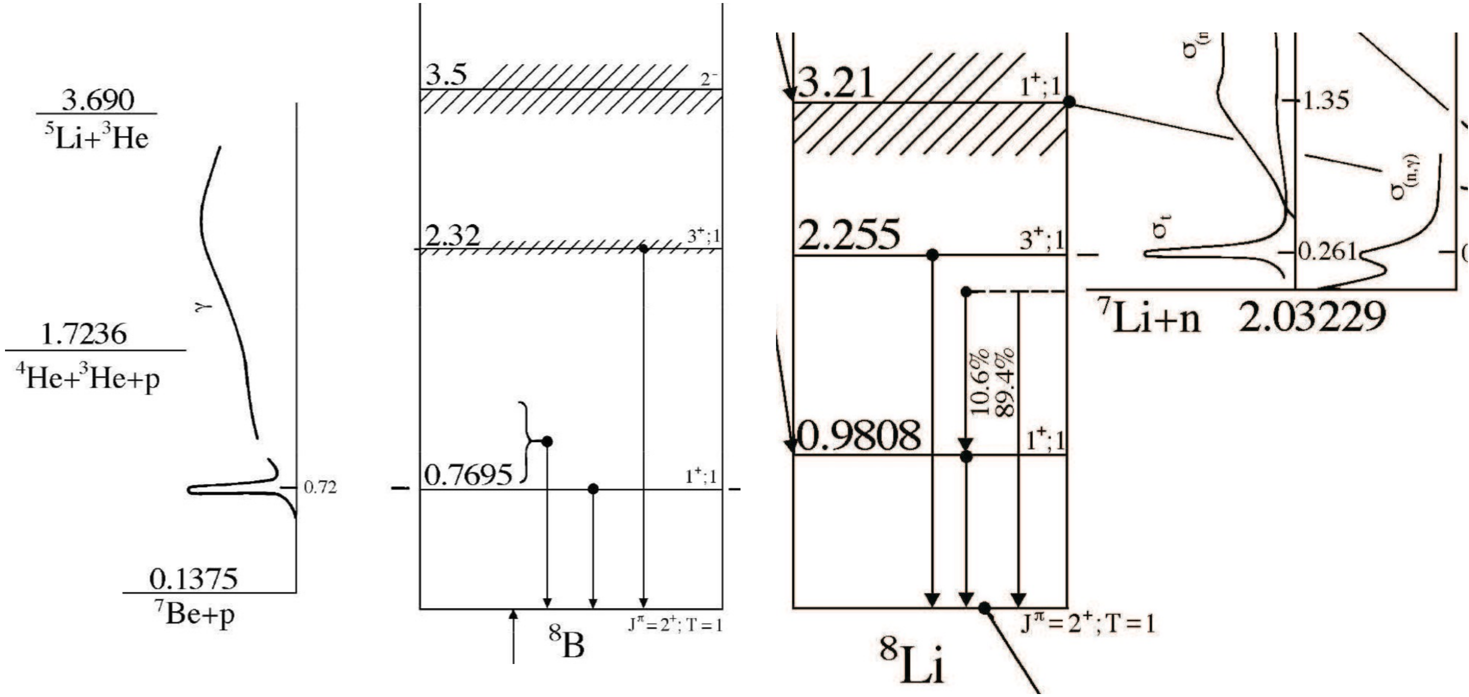
K. Kravvaris[a,*], P. Navrátil[b], S. Quaglioni[a], C. Hebborn[c,a], G. Hupin[d]

Radiative capture of protons on ^{7}Be

- Solar pp chain reaction, solar ^{8}B neutrinos
- NCSMC calculations with a set of chiral NN+3N interactions as input

- Example of ^{8}B structure results

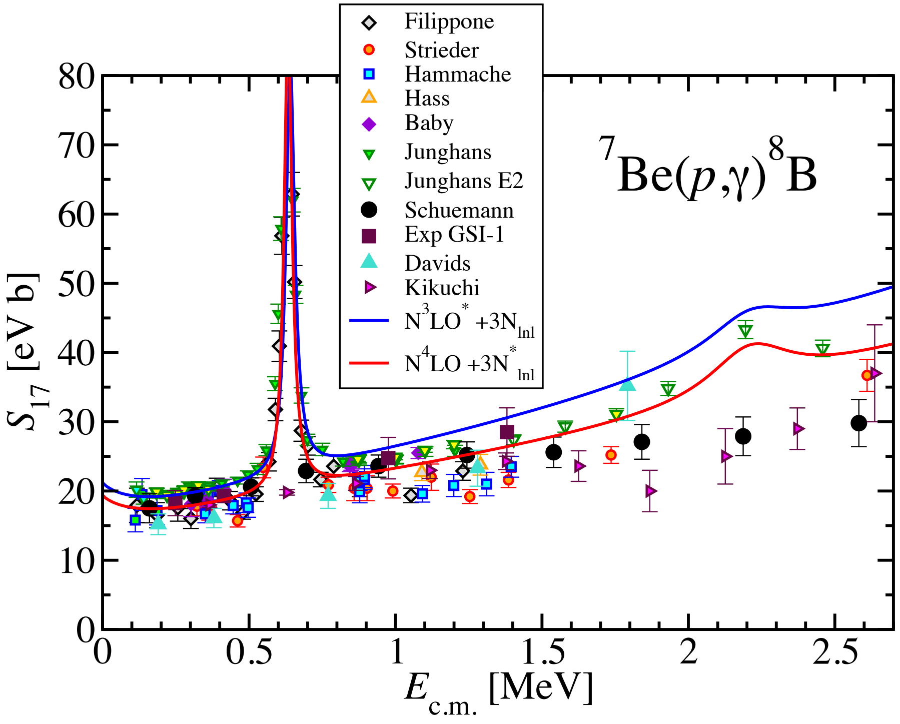


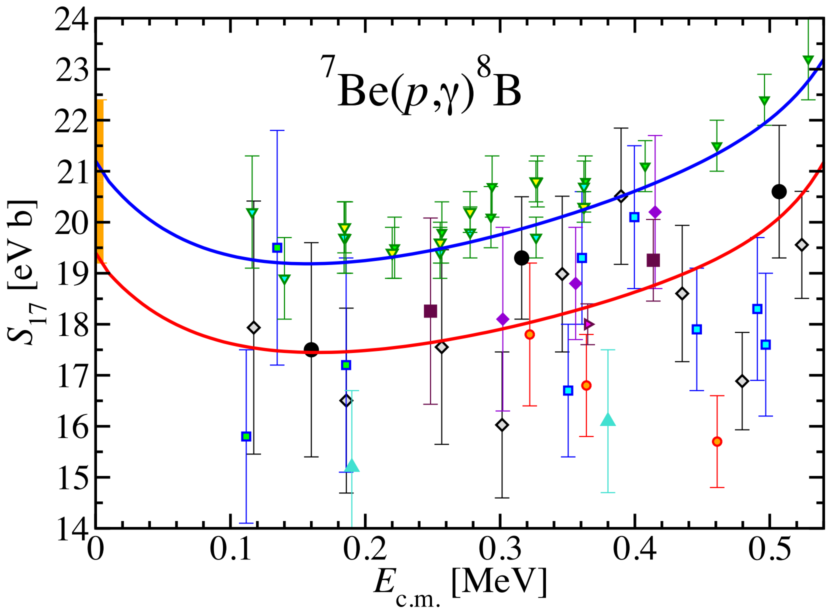


Radiative capture of protons on ^{7}Be

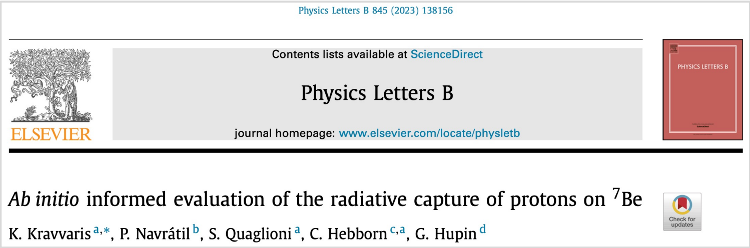
- NCSMC S-factor results

	$C_{p_{1/2}}$	$C_{p_{3/2}}$	a_1	a_2	$S_{17}(0)$
N^{2}LO+3N$_{\text{lnl}}$	0.384	0.691	4.4(1)	-0.5(1)	23.9
N^{3}LO+3N$_{\text{lnl}}$	0.390	0.678	1.3(1)	-4.7(1)	23.5
N^{4}LO+3N$_{\text{lnl}}$	0.354	0.669	1.6(1)	-4.4(1)	22.0
N^{4}LO+3N$^*_{\text{lnl}}$	0.343	0.621	1.3(1)	-5.0(1)	19.3
N^{3}LO*+3N$_{\text{lnl}}$	0.334	0.663	0.1(1)	-7.7(1)	21.1
N^{3}LO*+3N$_{\text{loc}}$	0.308	0.584	2.5(1)	-3.6(2)	16.8
Ref. [41]	0.315(9)	0.66(2)	$17.34^{+1.11}_{-1.33}$	$-3.18^{+0.55}_{-0.50}$	





E1 non-resonant, M1/E2 at 1$^+$ and 3$^+$ resonances


Physics Letters B 845 (2023) 138156
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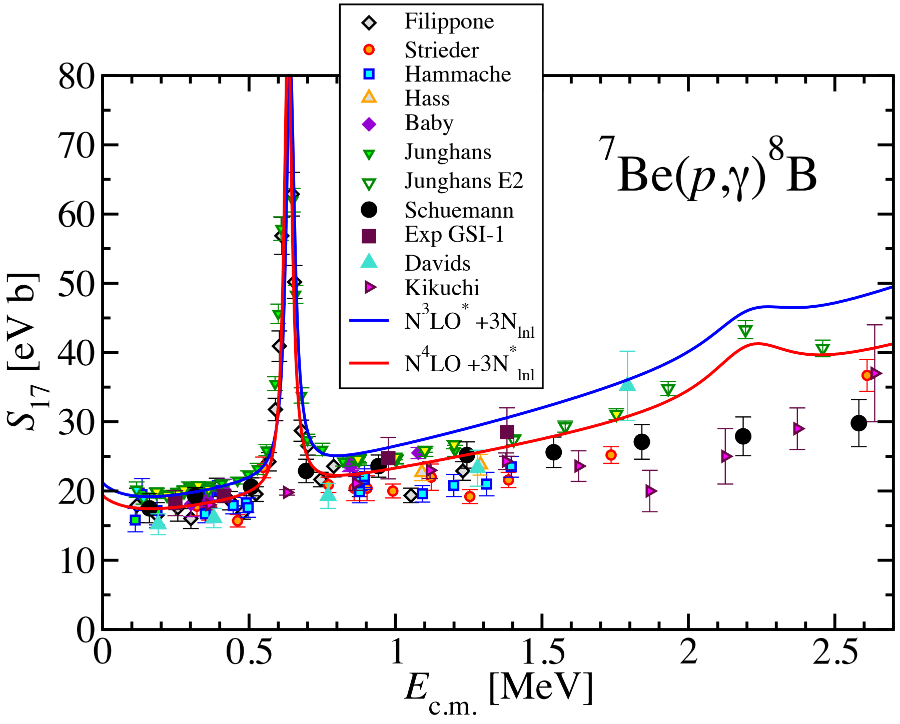

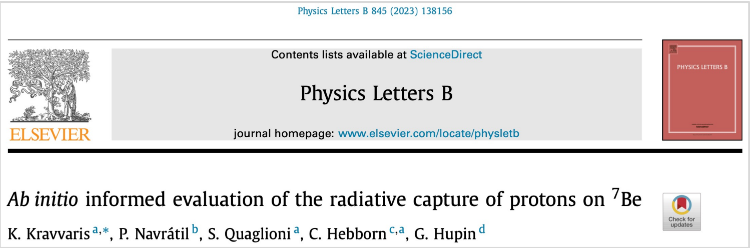

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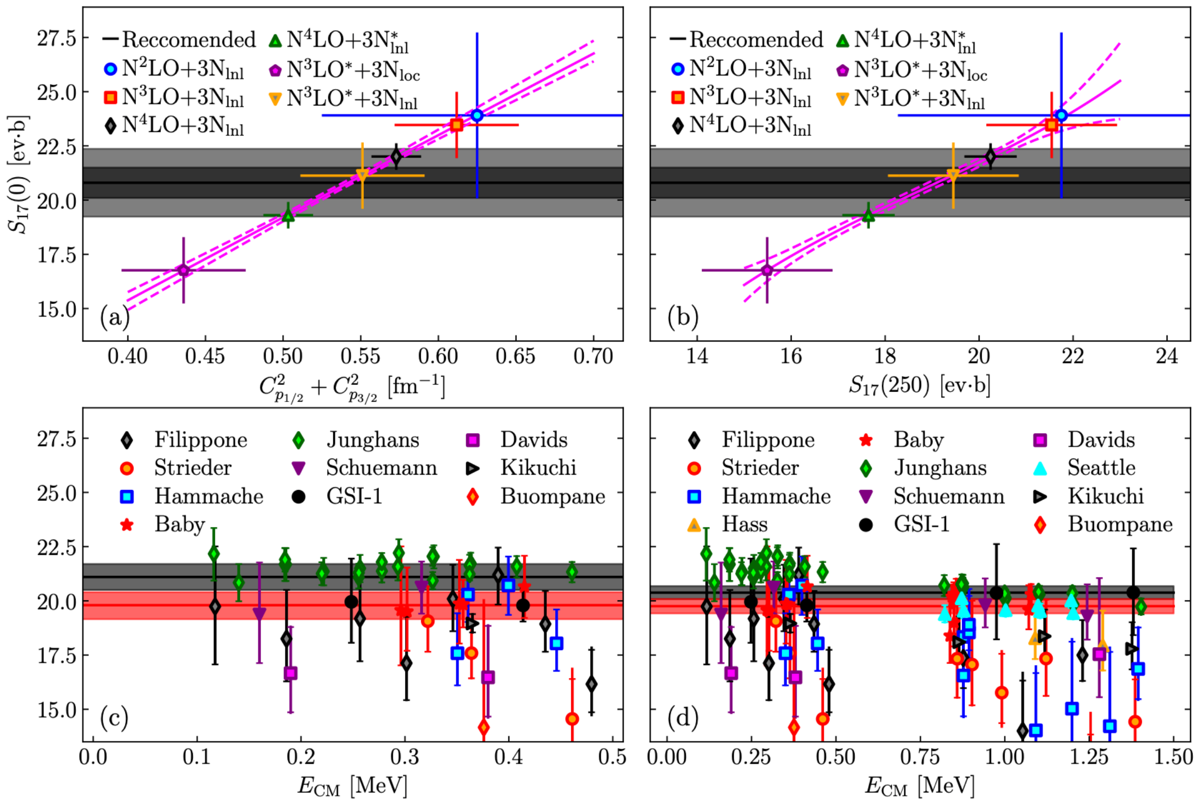

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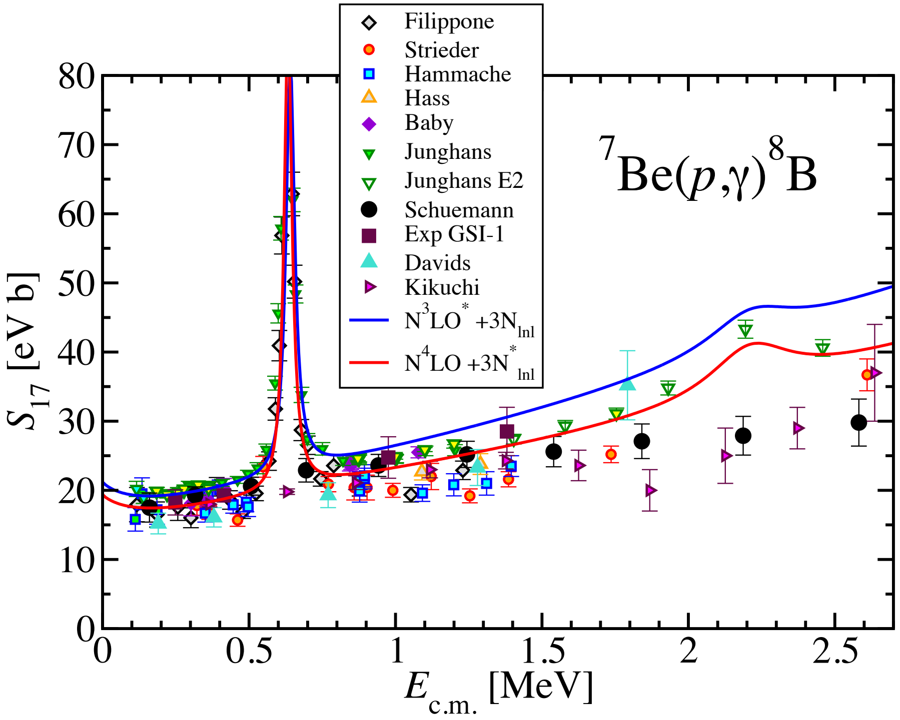

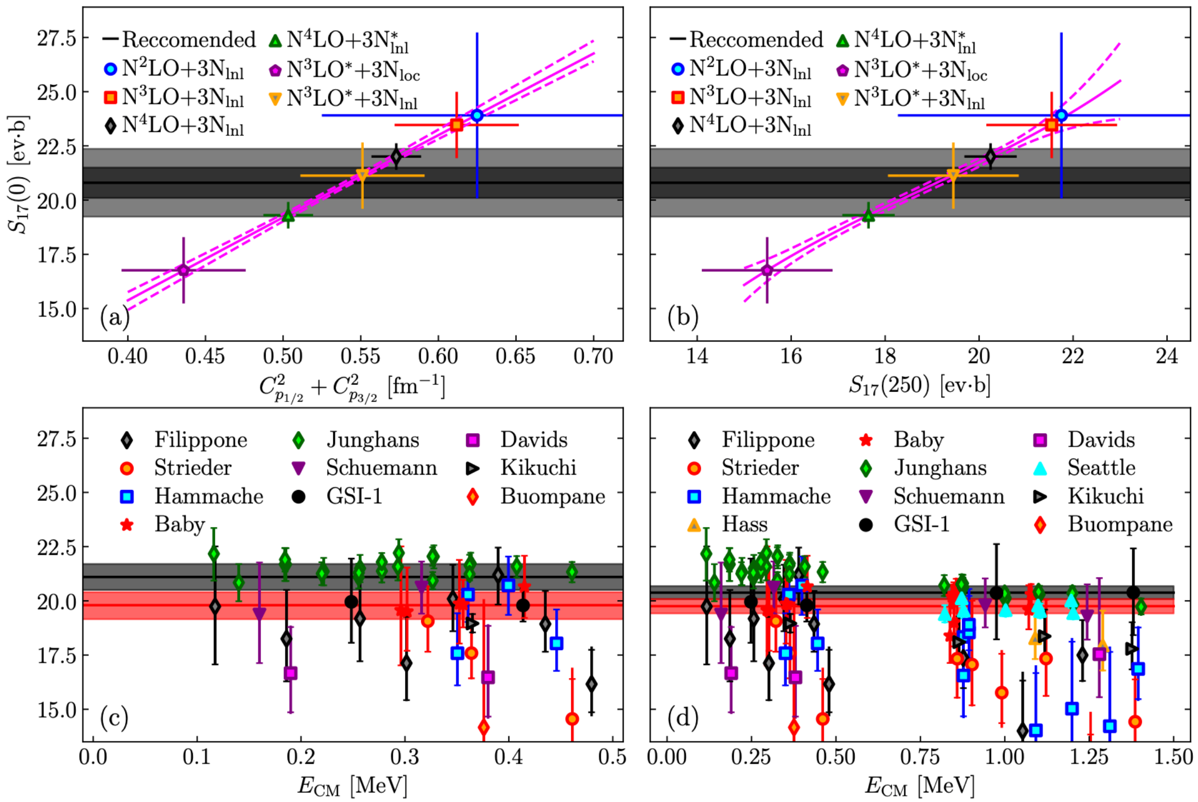

Recommended value $S_{17}(0) \sim 19.8(3)$ eV b

2011 evaluation in *Rev. Mod. Phys.* **83**,195–245 (2011):
$S_{17}(0) = 20.8 \pm 0.7(\mathrm{expt}) \pm 1.4(\mathrm{theory})$ eV b

Radiative capture of protons on ^{7}Be

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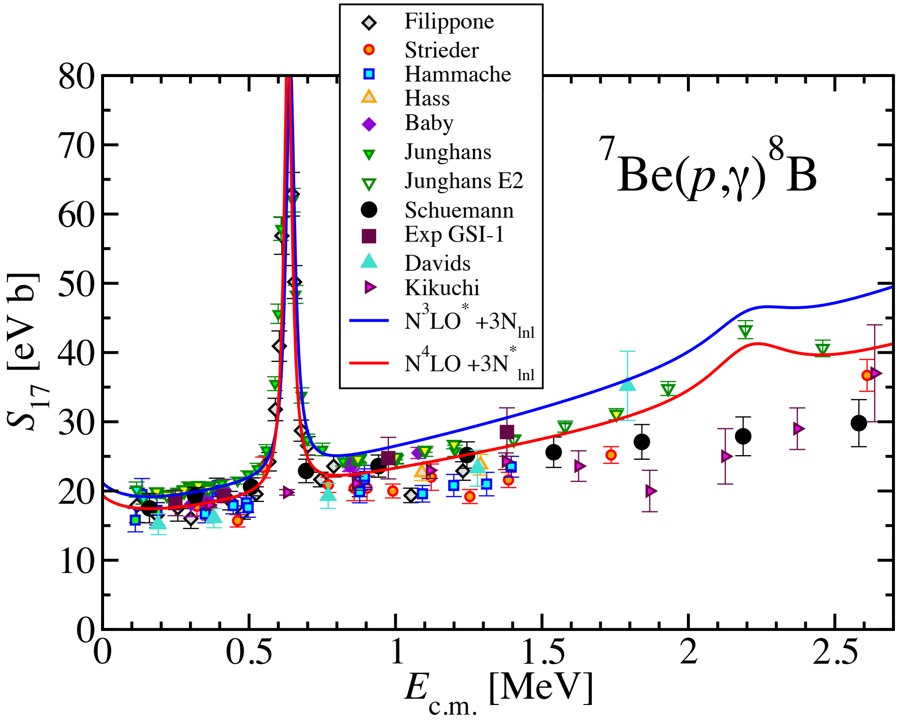

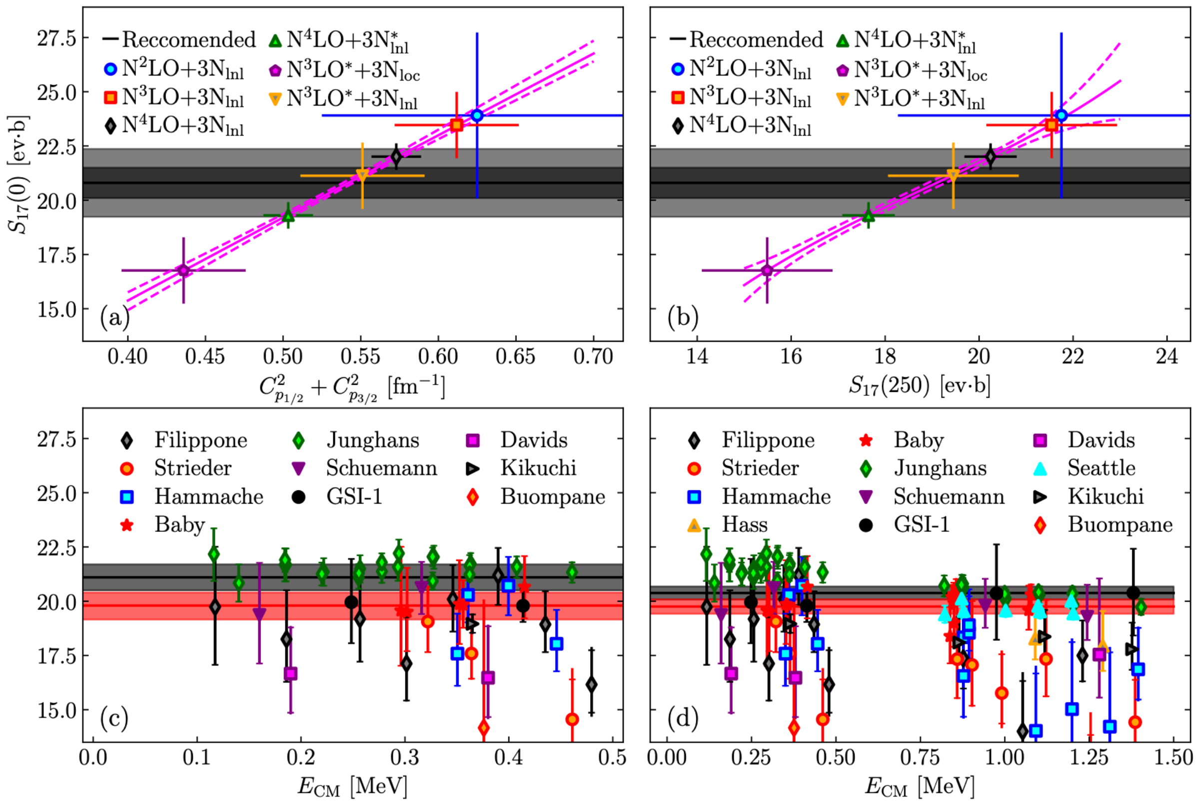

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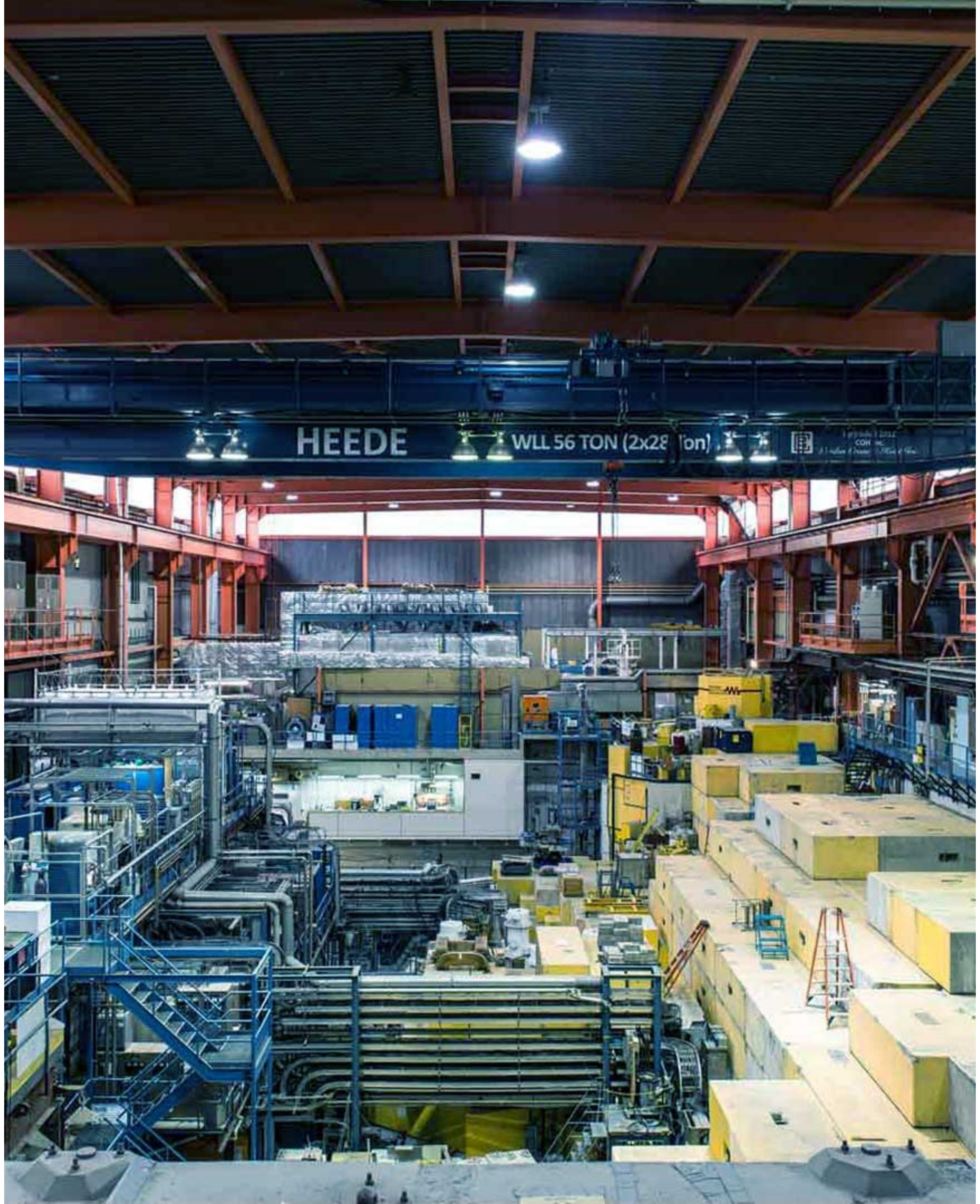
New evaluation in *Rev. Mod. Phys.* **97,** 035002 (2025):
$S_{17}(0) = 20.5 \pm 0.7$ eV b

TRIUMF

NCSMC for three-body cluster

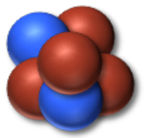
$^{6}He \sim {}^{4}He + n + n$



Discovery, accelerated

NCSMC for three-body clusters

NCSM
Short range description



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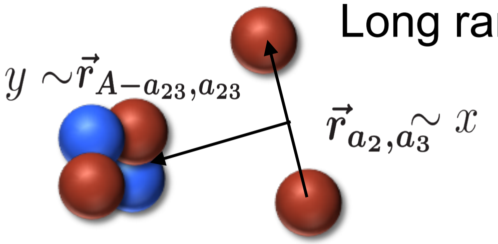
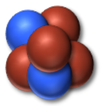
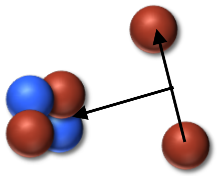


NCSM/RGM-3B
Long range description

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \Big|$$  $$,\lambda\Big\rangle + \sum_{\nu} \int d\vec{x}\, d\vec{y}\, \gamma_{\nu}(\vec{x},\vec{y})\, \hat{A}_{\nu} \Big|$$  $$,\nu\Big\rangle$$

Unknowns

PHYSICAL REVIEW C **97**, 034332 (2018)

Three-cluster dynamics within the *ab initio* no-core shell model with continuum: How many-body correlations and α clustering shape ^{6}He

Sofia Quaglioni,[1,*] Carolina Romero-Redondo,[1,†] Petr Navrátil,[2,‡] and Guillaume Hupin[3,§]

PRL **117**, 222501 (2016) PHYSICAL REVIEW LETTERS week ending 25 NOVEMBER 2016

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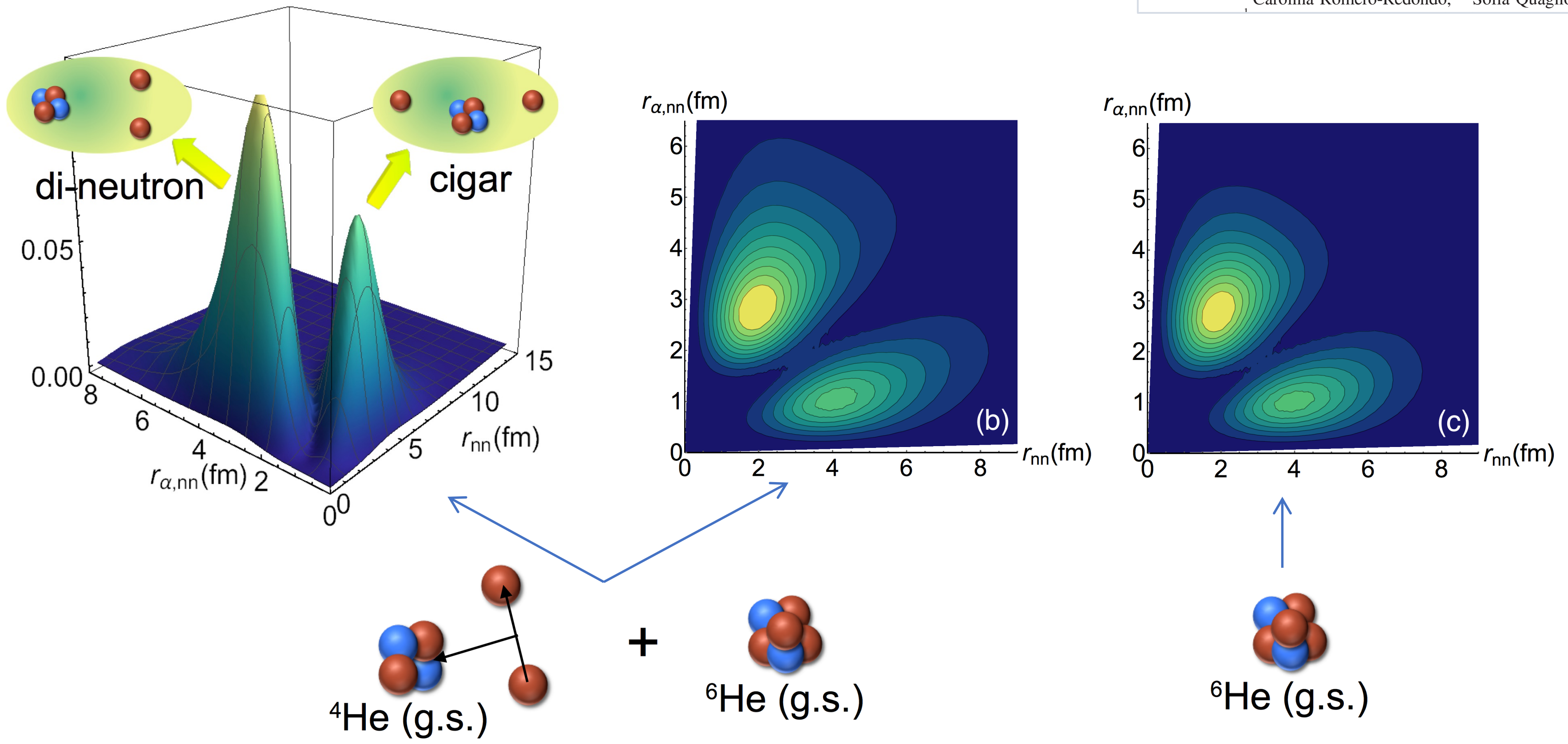
Carolina Romero-Redondo,[1,*] Sofia Quaglioni,[1,†] Petr Navrátil,[2,‡] and Guillaume Hupin[3,§]

NCSMC for three-body clusters: ^{6}He ~ ^{4}He+n+n



The probability distribution of the ^{6}He ground state presents two peaks corresponding to the di-neutron and cigar configurations

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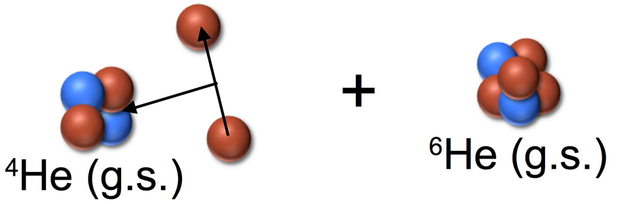

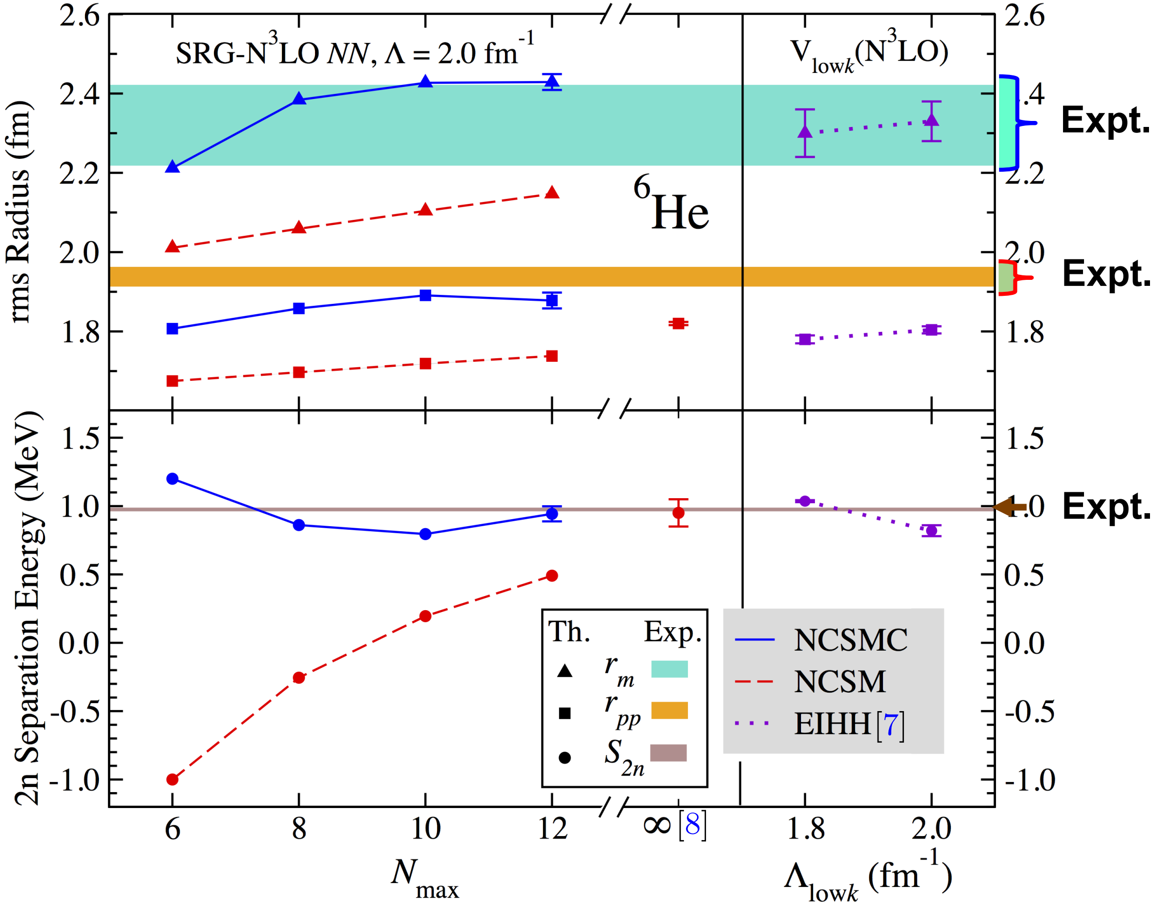

Separation energy, point proton and matter radius simultaneously consistent with experiment

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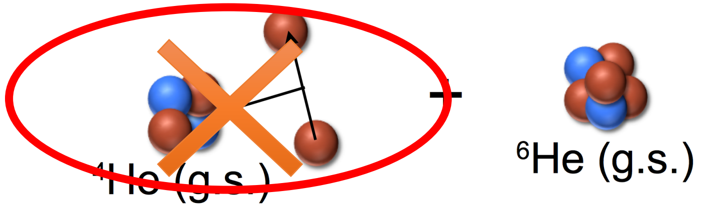

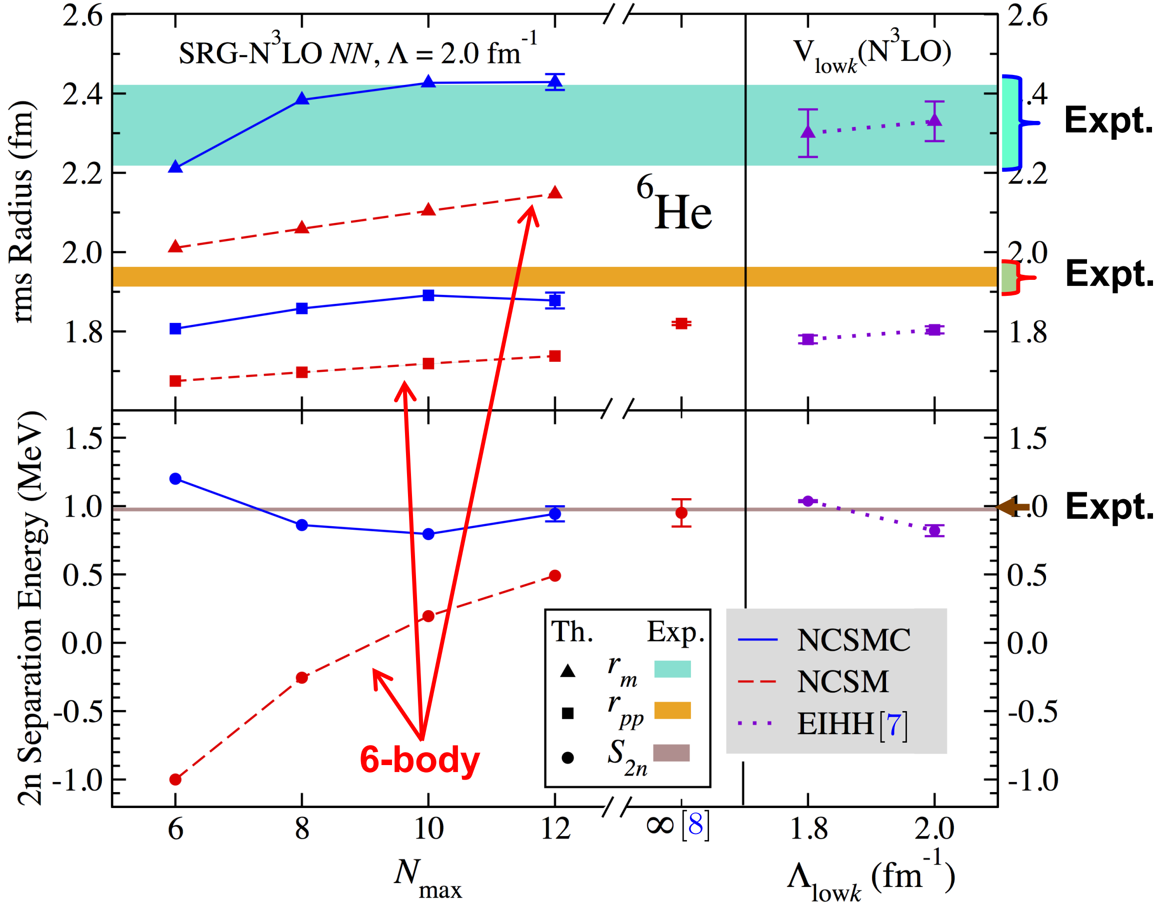

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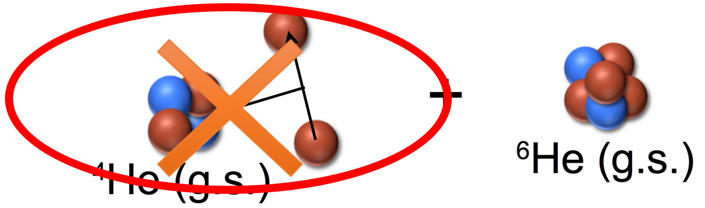

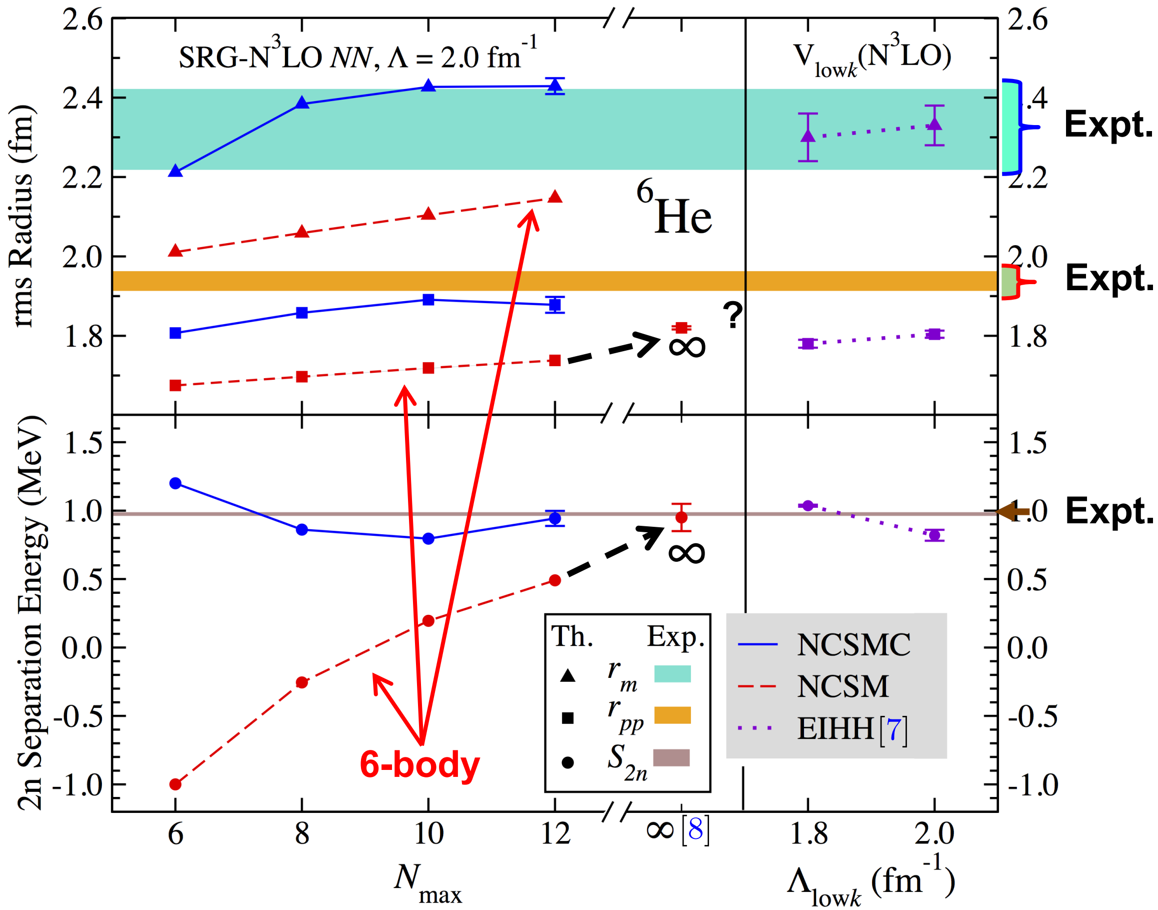

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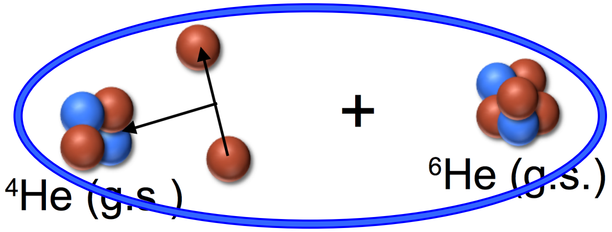

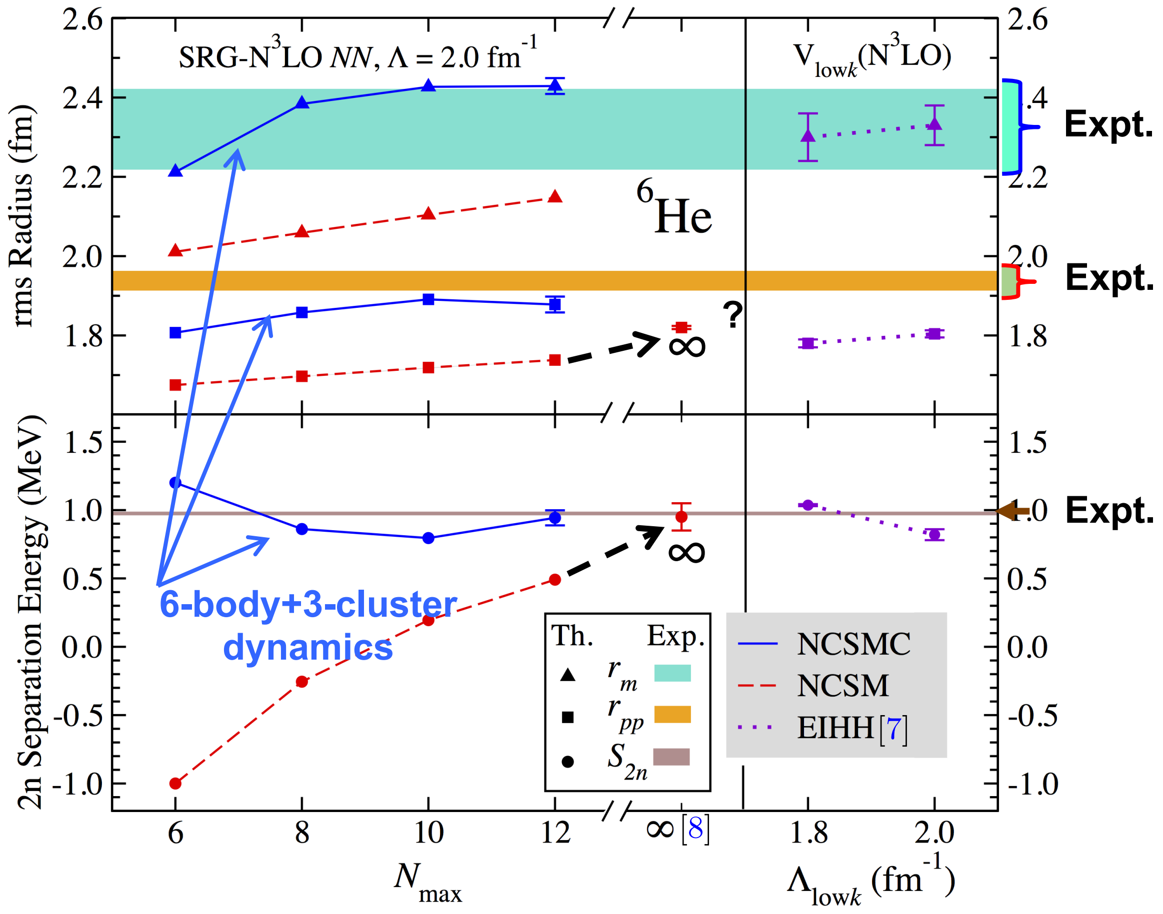

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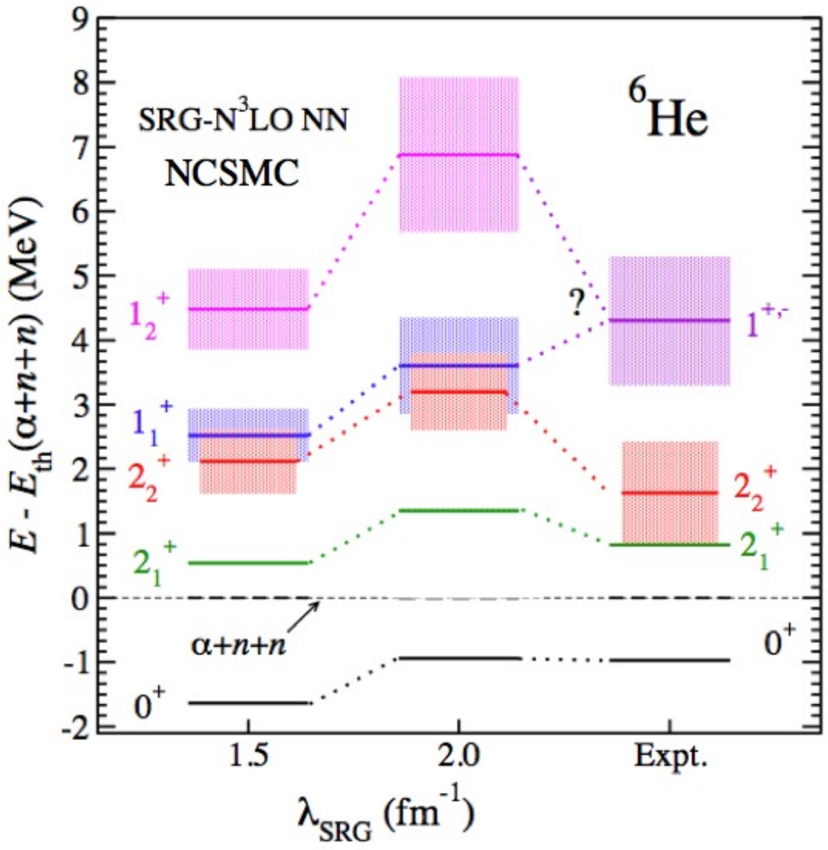

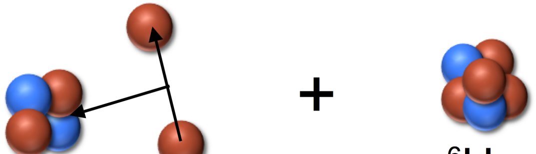

^{4}He (g.s.) + ^{6}He

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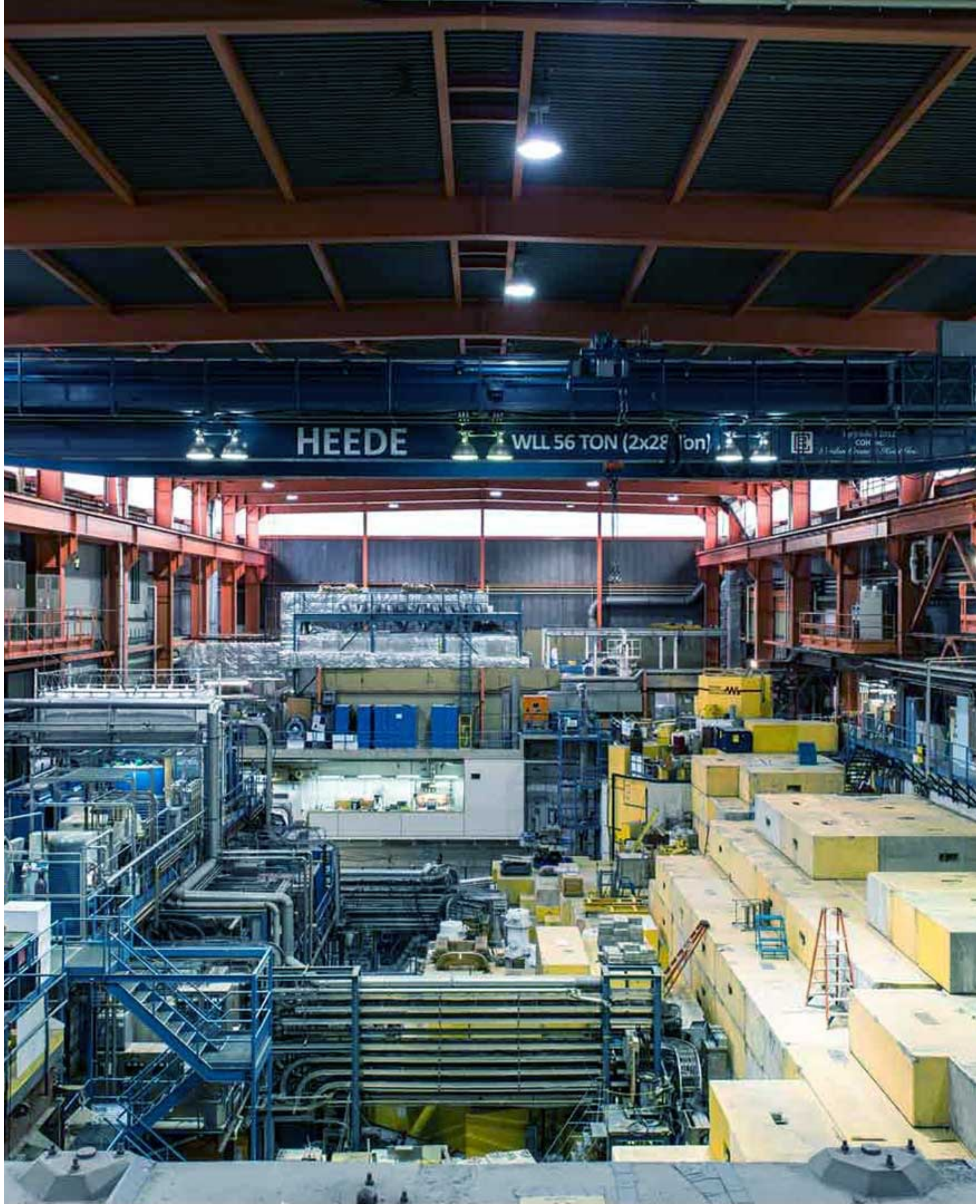
Quantitative comparison still requires inclusion of 3N forces

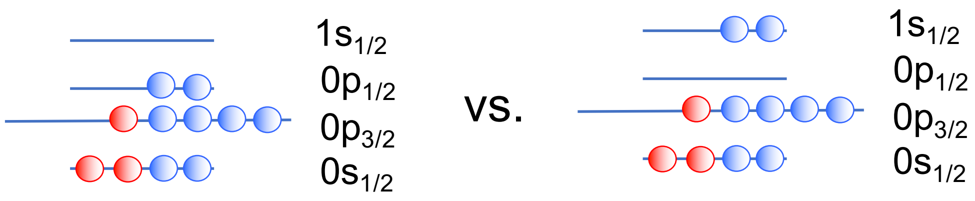
^{11}Li within NCSM

(prerequisite for ^{11}Li ~ ^{9}Li + n + n)

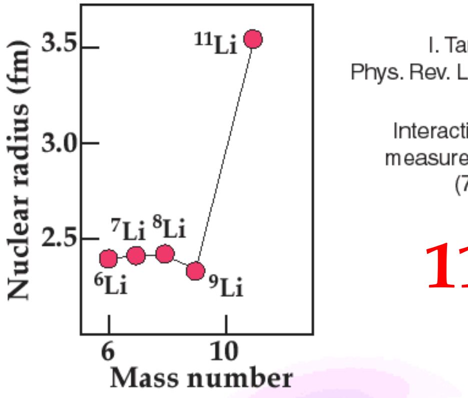


Discovery, accelerated

Borromean halo nucleus ^{11}Li



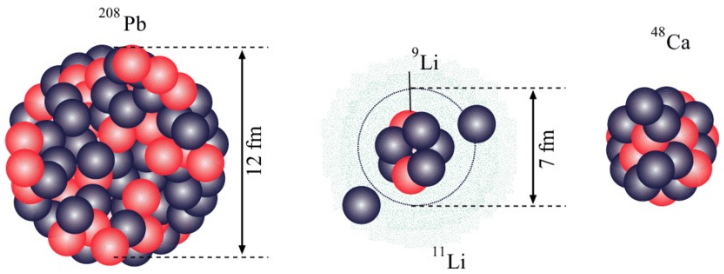
- Z=3, N=8
  - Very weakly bound: E_{th}=-0.3 MeV
    - Halo state – dominated by ^{9}Li+n+n in the *S*-wave
    - Configuration mixing, ^{9}Li ½- excited state plays a role
- Can we describe ^{11}Li in *ab initio* calculations?
  - Continuum must be included
  - What role does the 3N interaction play in the configuration mixing?
  - NCSMC needs to be applied – very challenging
  - The first step – large-scale NCSM



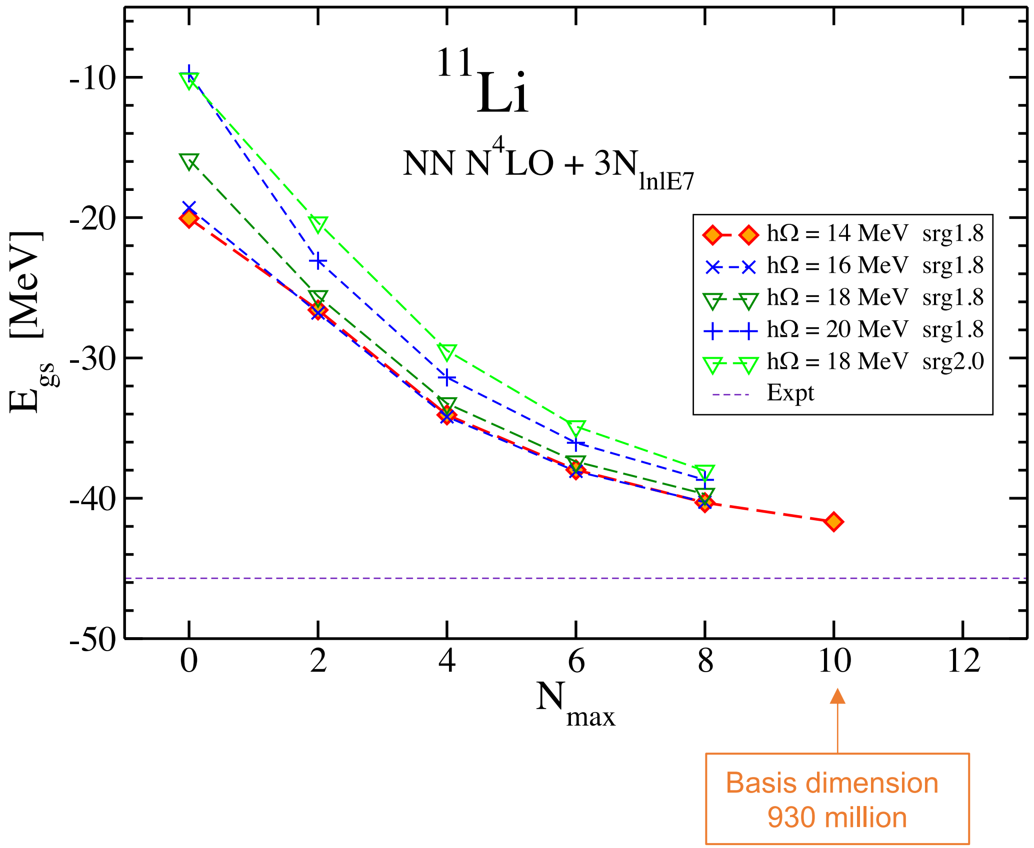
I. Tanihata et al.
Phys. Rev. Lett. 55, 2676 (1985)

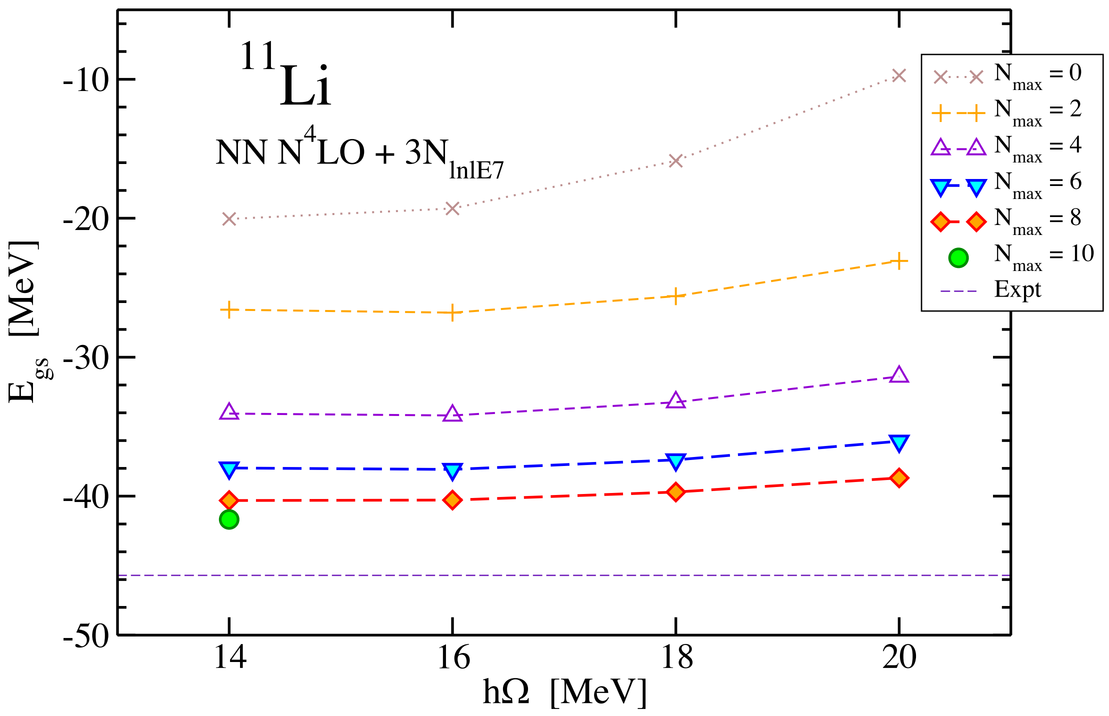
Interaction cross section measurements at Bevalac (790 MeV/u)

^{11}Li



Large-scale NCSM calculations of ^{11}Li





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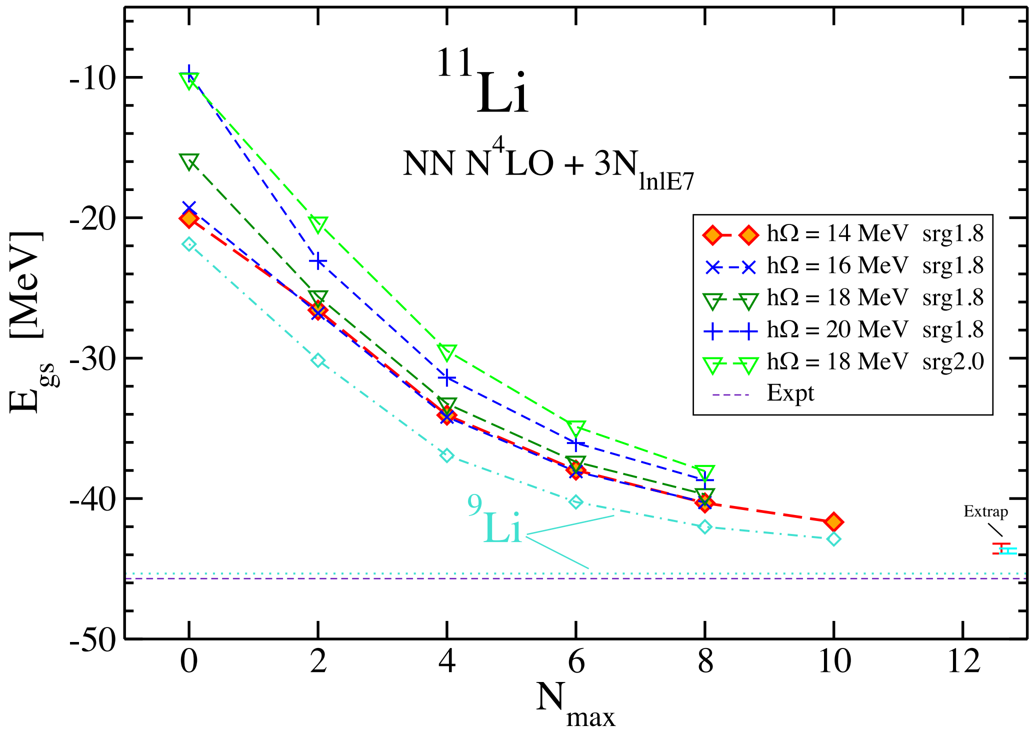

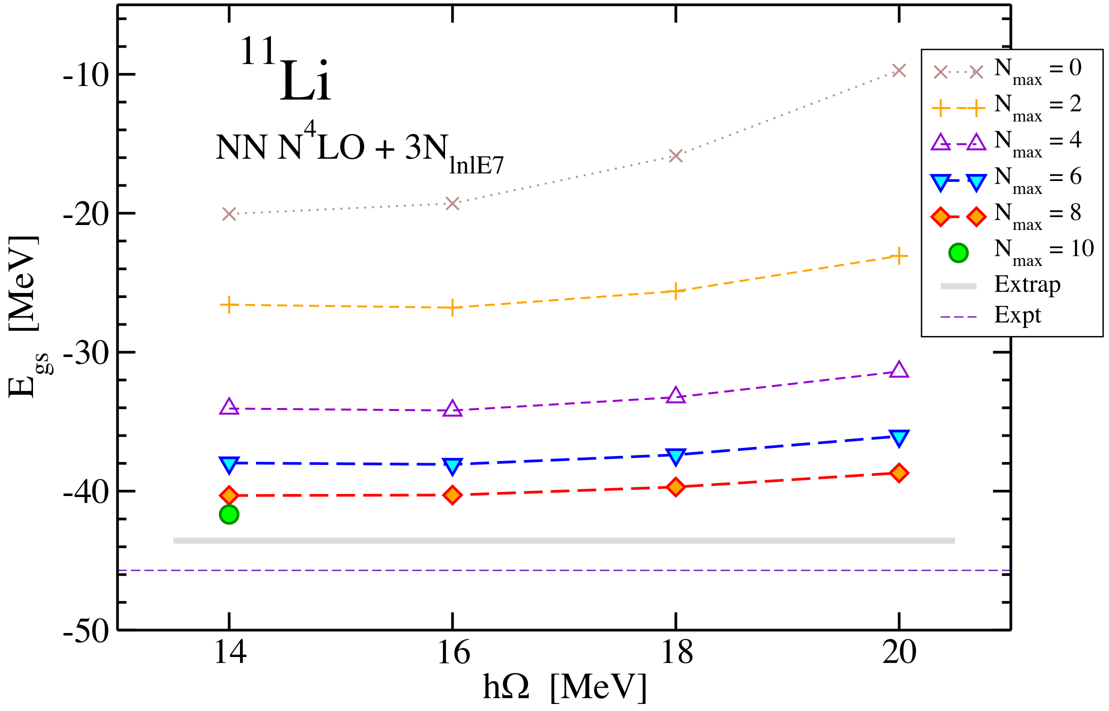

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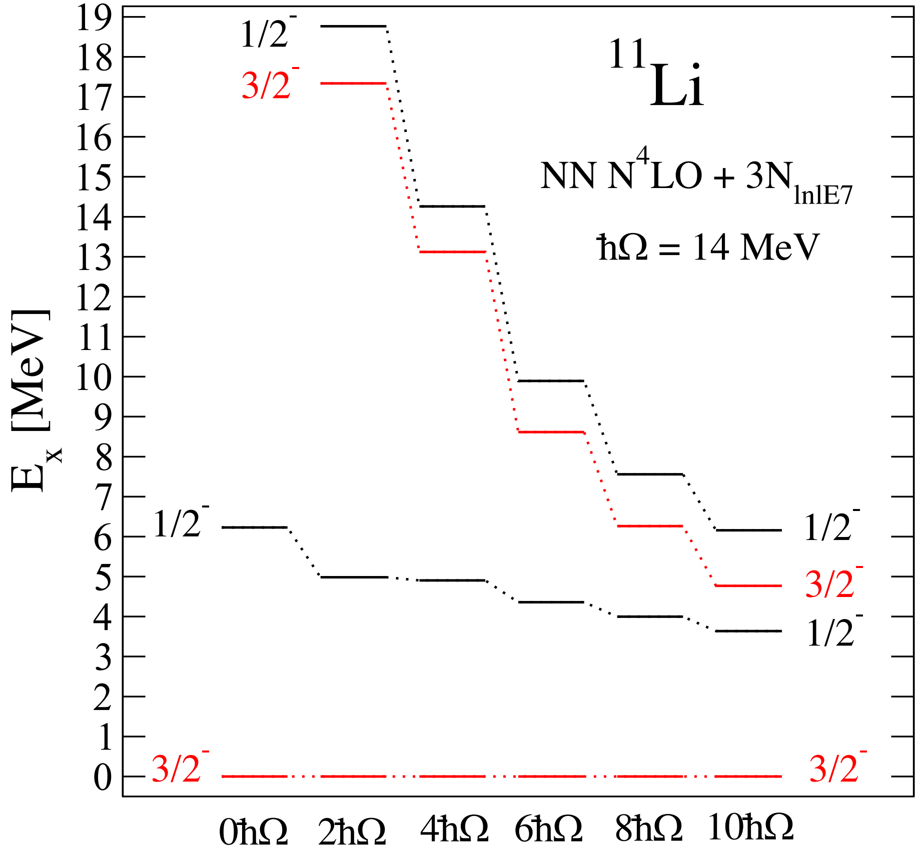
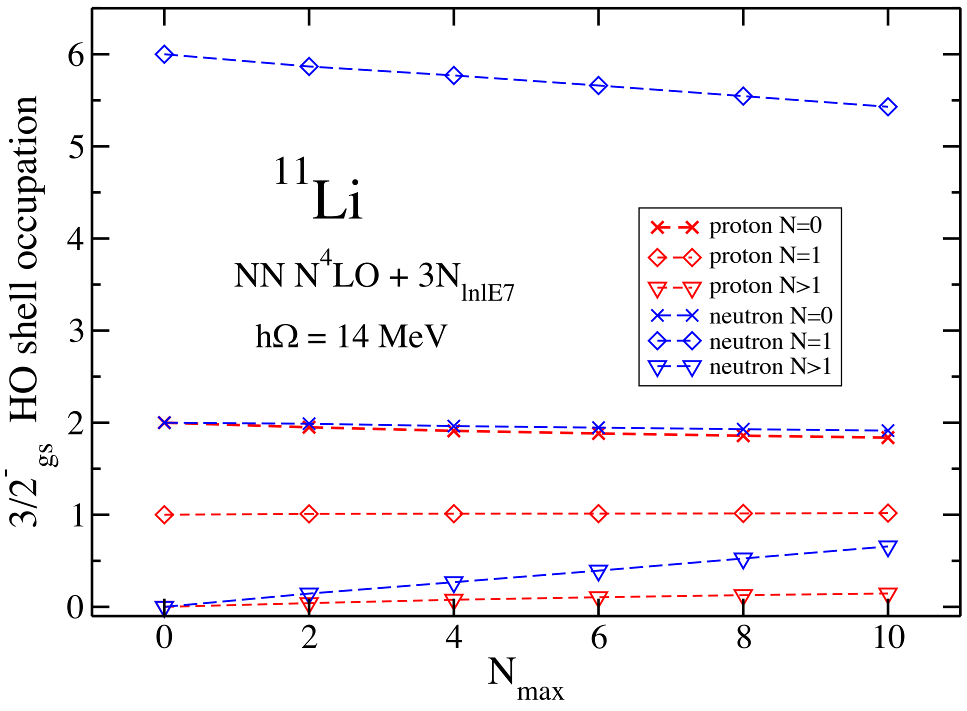


Preliminary



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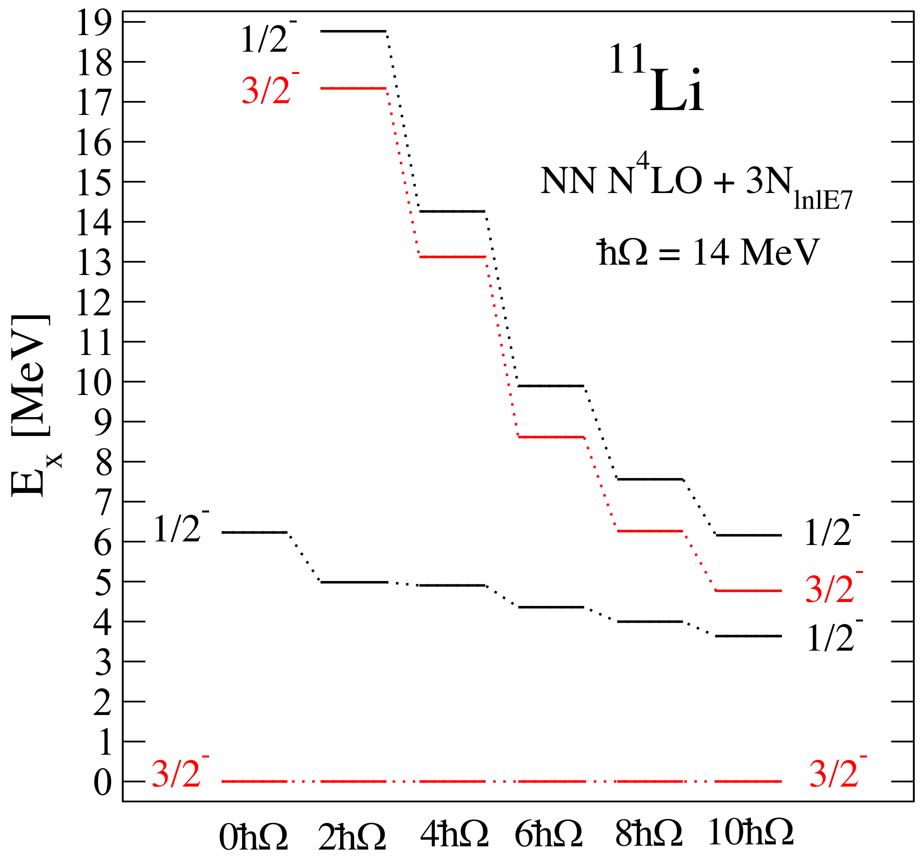
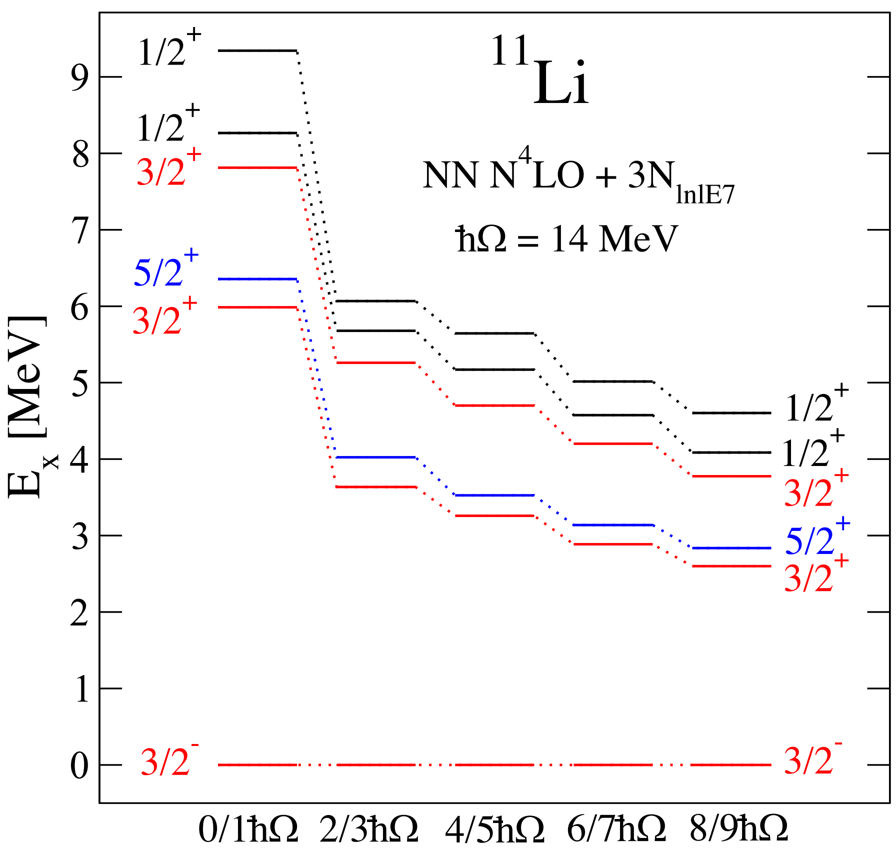
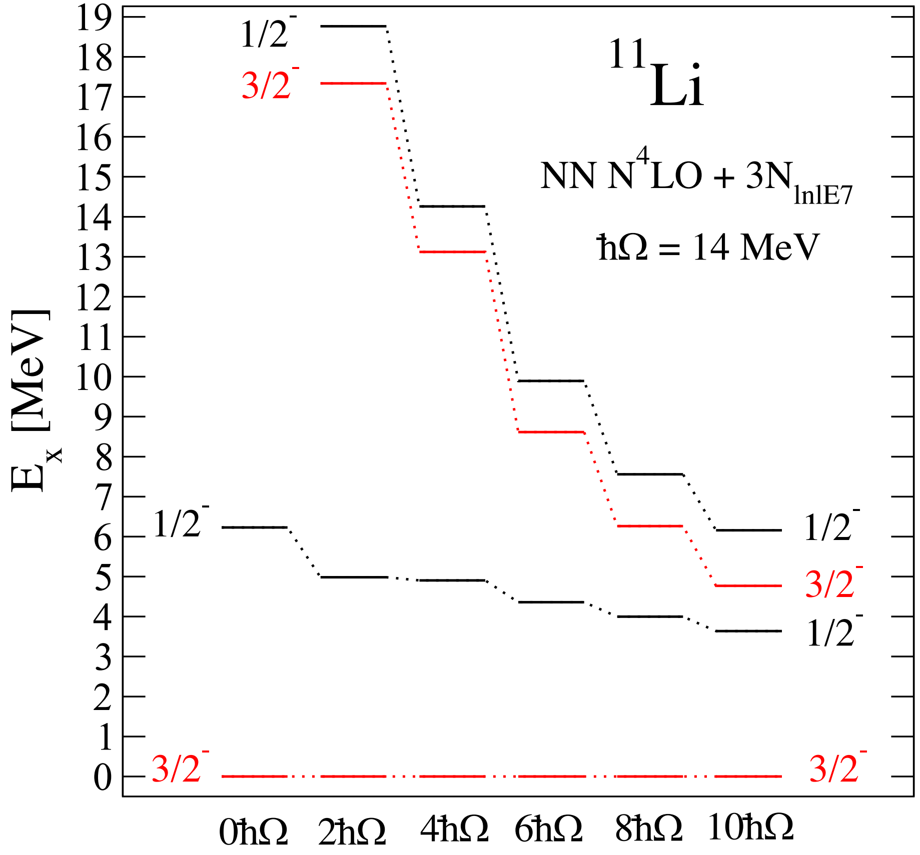
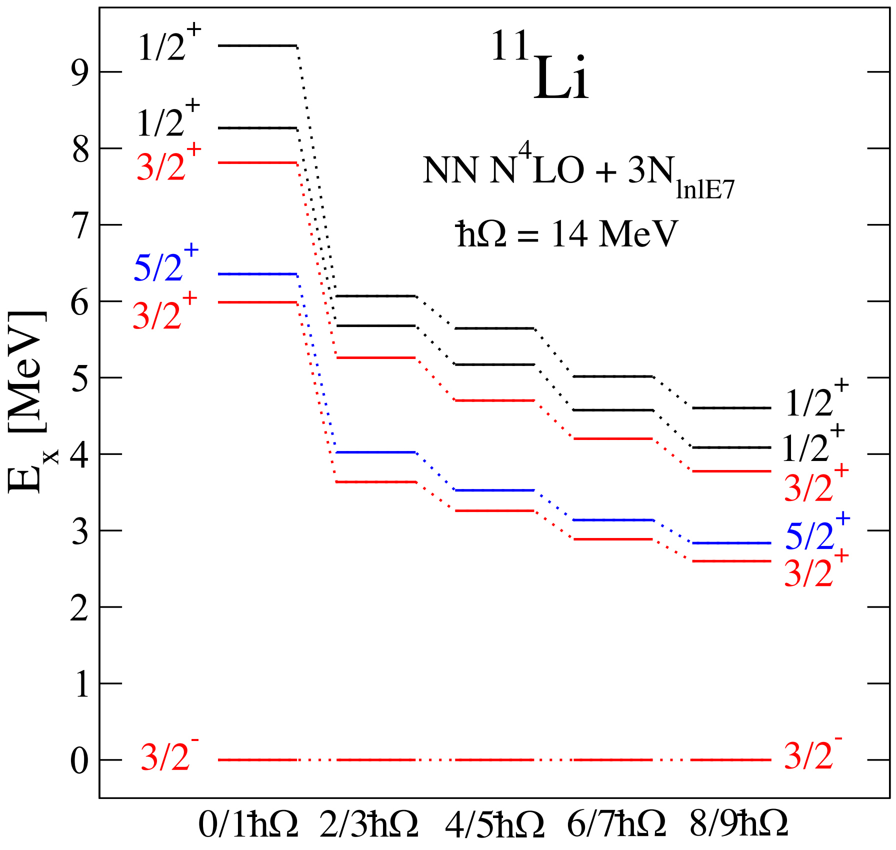




Large-scale NCSM calculations of ^{11}Li





Next step – including continuum via NCSMC – ^{11}Li ~ ^{9}Li + n + n

Conclusions

- *Ab initio* nuclear theory
  - Makes connections between the low-energy QCD and many-nucleon systems
- No-core shell model with continuum capable of describing halo nuclei from first principles
  - Successful reproduction of ^{11}Be parity inversion – three-nucleon interaction important
  - Ground-state halo of ^{8}B significantly impacts the proton capture on ^{7}Be
  - Three-body cluster NCSMC applied to the Borromean halo nucleus ^{6}He
- Next frontier – *ab initio* NCSMC description of ^{11}Li as a three-cluster ^{9}Li + n + n system