TRIUMF

Weakly bound states and near-threshold resonances from *ab initio* nuclear theory

Critical stability of few-body quantum systems

ECT* Trento, October 23 - 27, 2023

Petr Navratil

TRIUMF

Kostas Kravvaris, Sofia Quaglioni, Mack Atkinson (LLNL), Guillaume Hupin (IJCLab), Chloe Hebborn (MSU/LLNL), Peter Gysbers (TRIUMF), Michael Gennari (UVic/TRIUMF), Matteo Vorabbi (Surrey), Jakub Herko (UND)

2023-10-26

Discovery, accelerated

Outline

- *Ab initio* nuclear theory
  - No-core shell model (NCSM) and NCSM with continuum (NCSMC)
    - Input chiral NN+3N interactions
- Applications to weakly-bound states and near threshold resonances
  - DT fusion
  - *S*-wave resonance close to the ^{6}He+p threshold in ^{7}Li
  - Parity inversion in ^{11}Be ground state
  - β-delayed proton emission in ^{11}Be
  - Two-neutron Borromean halo nucleus ^{6}He

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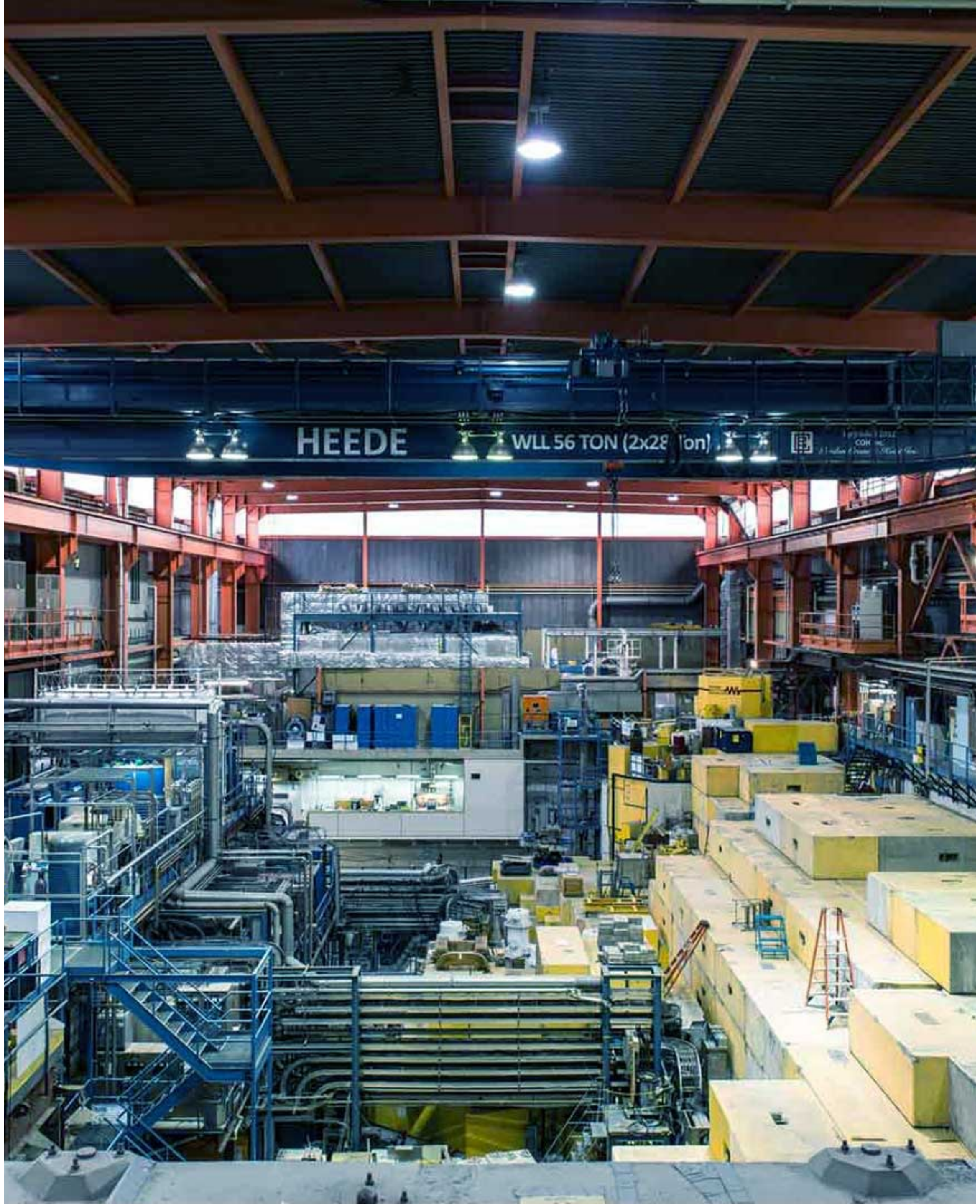
Ab initio nuclear theory



Discovery, accelerated

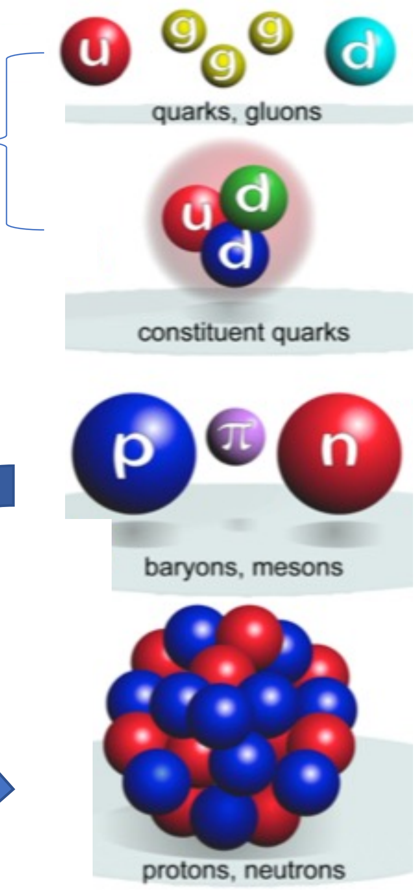
First principles or *ab initio* nuclear theory – what we do at present

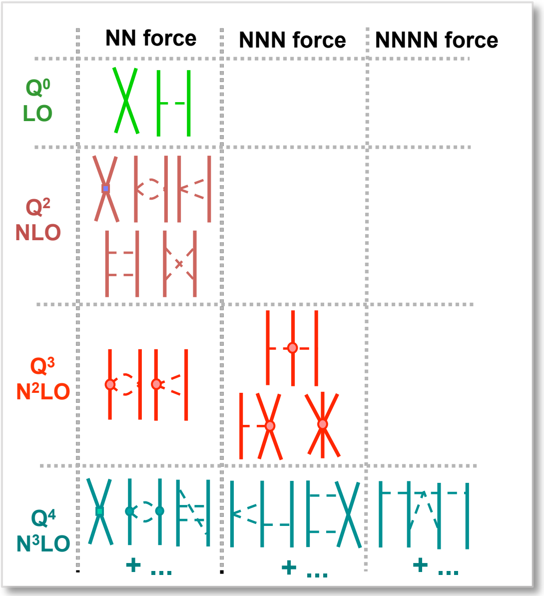
Quantum Chromodynamics (QCD)

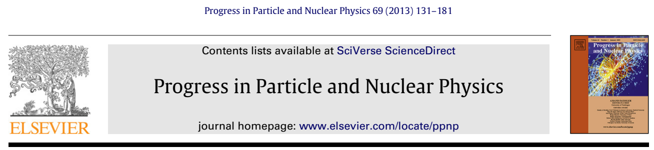
Chiral Effective Field Theory (parameters fitted to NN data)

Current *ab initio* nuclear theory

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



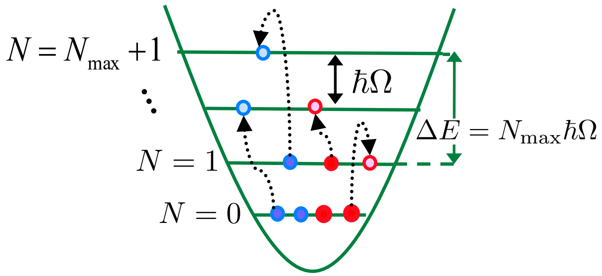


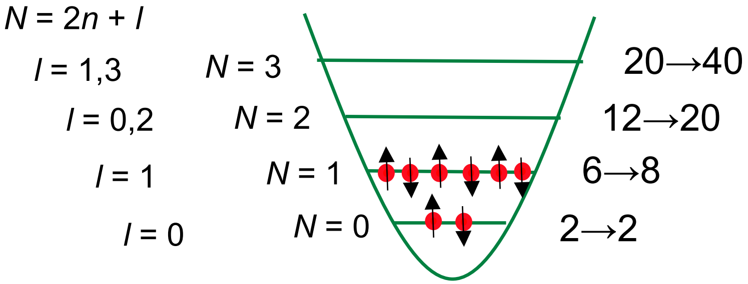

Progress in Particle and Nuclear Physics 69 (2013) 131–181
Contents lists available at SciVerse ScienceDirect
Progress in Particle and Nuclear Physics
journal homepage: www.elsevier.com/locate/ppnp
Review
Ab initio no core shell model
Bruce R. Barrett[a], Petr Navrátil[b], James P. Vary[c,*]

Ab initio No-Core Shell Model (NCSM)

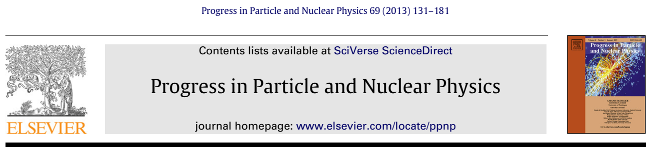
- Basis expansion method
  - Harmonic oscillator (HO) basis truncated in a particular way (N_{max})
  - Why HO basis?
    - Lowest filled HO shells match magic numbers of light nuclei (2, 8, 20 – ^{4}He, ^{16}O, ^{40}Ca)
    - Equivalent description in relative(Jacobi)-coordinate and Slater determinant (SD) basis
- Short- and medium range correlations
- Bound-states, narrow resonances

NCSM





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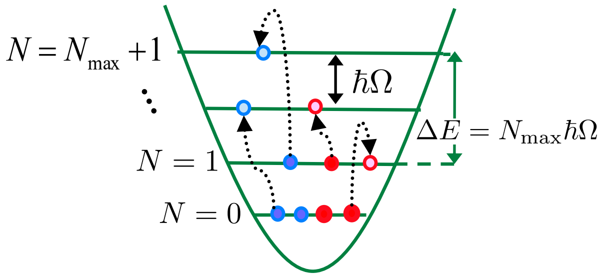
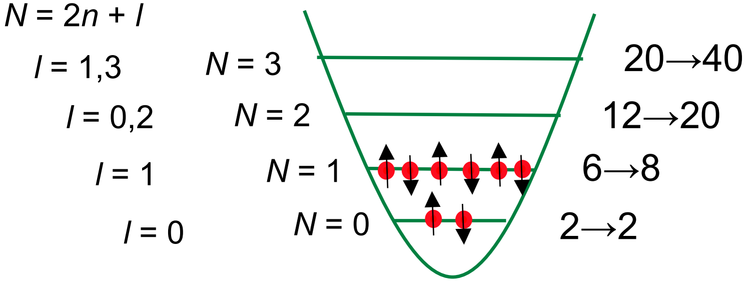


$$\Psi^A = \sum_{N=0}^{N_{max}} \sum_i c_{Ni} \Phi_{Ni}^{HO}(\vec{\eta}_1, \vec{\eta}_2, \ldots, \vec{\eta}_{A-1})$$



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

$$\Psi_{SD}^A = \sum_{N=0}^{N_{max}} \sum_j c_{Nj}^{SD} \Phi_{SD\,Nj}^{HO}(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) = \Psi^A \varphi_{000}(\vec{R}_{CM})$$

Ab Initio Calculations of Structure, Scattering, Reactions

Unified approach to bound & continuum states

No-Core Shell Model with Continuum (NCSMC)

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

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

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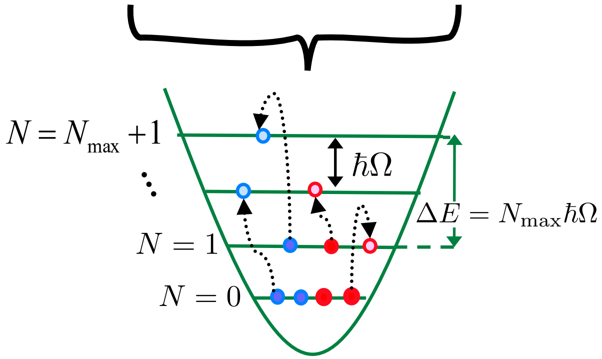

Static solutions for aggregate system, describe all nucleons close together

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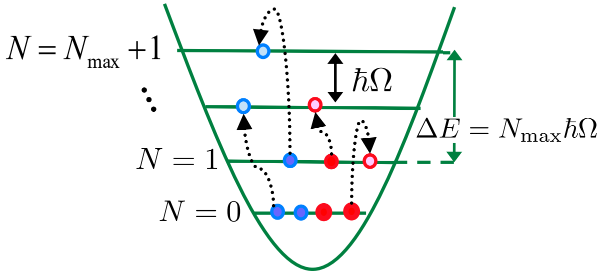

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Continuous microscopic cluster states, describe long-range projectile-target

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Ab Initio Calculations of Structure, Scattering, Reactions

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No-Core Shell Model with Continuum (NCSMC)

Unknowns

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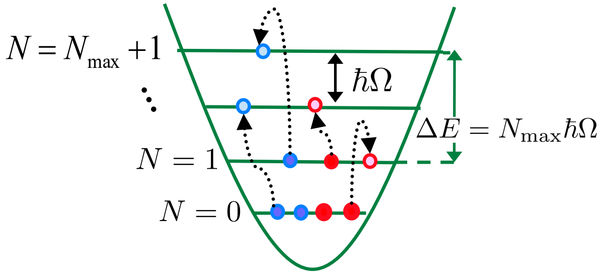

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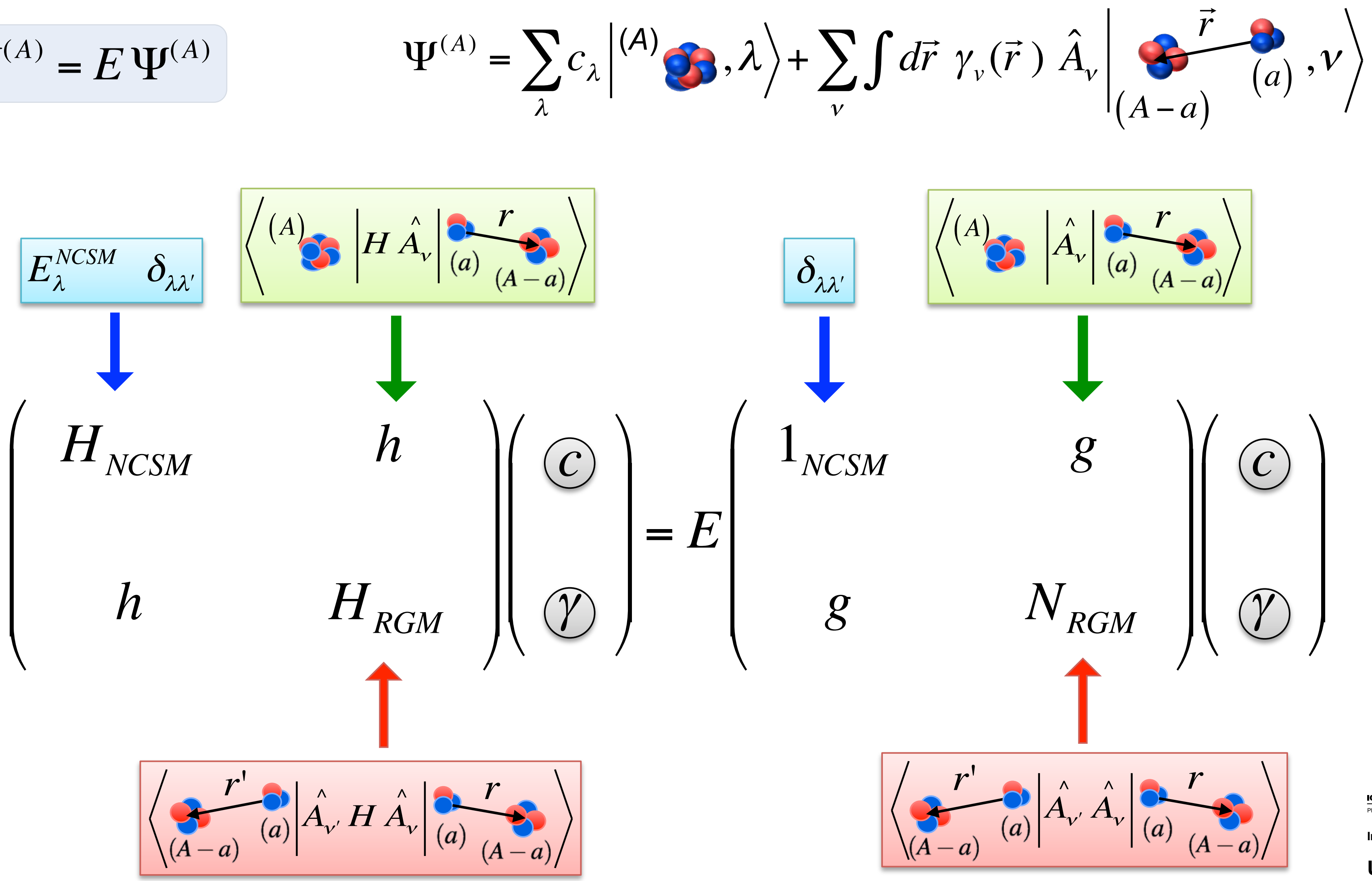
Coupled NCSMC equations

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

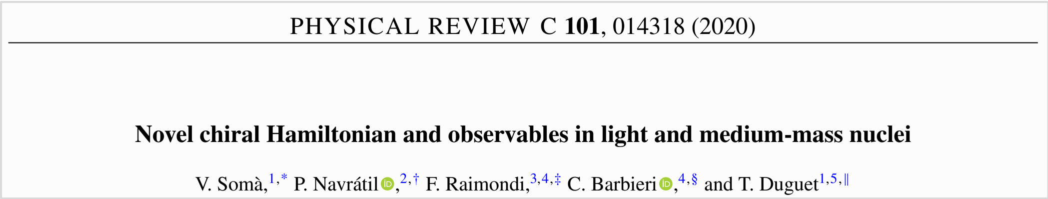


IOP Publishing | Royal Swedish Academy of Sciences Physica Scripta
Phys. Scr. 91 (2016) 053002 (38pp) doi:10.1088/0031-8949/91/5/053002

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 **101**, 014318 (2020)

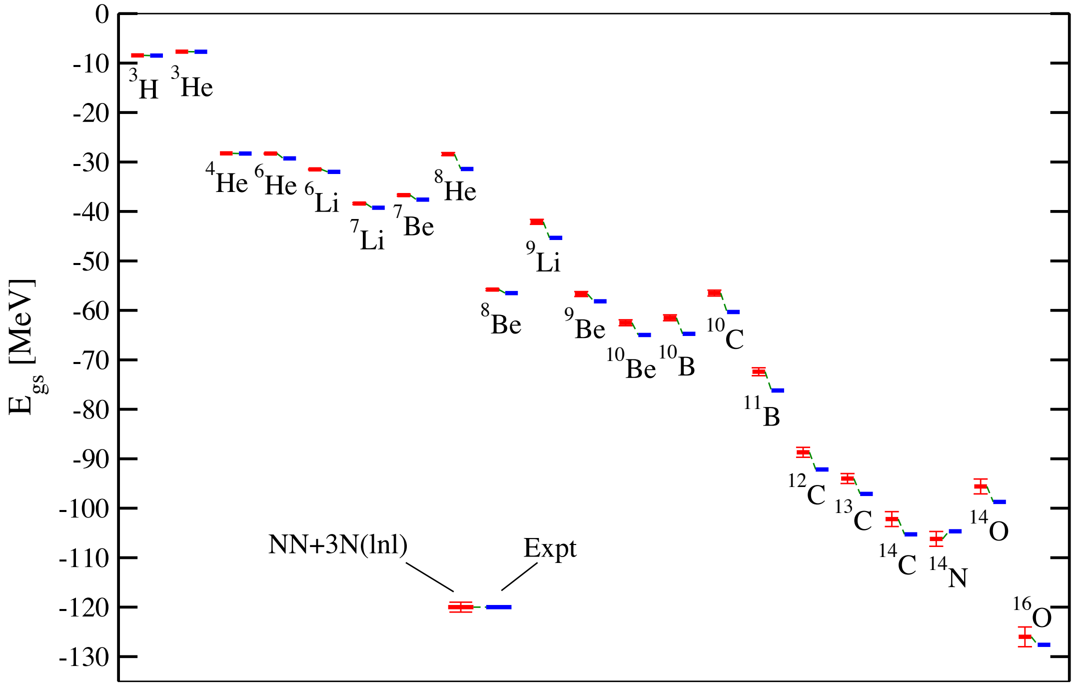
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

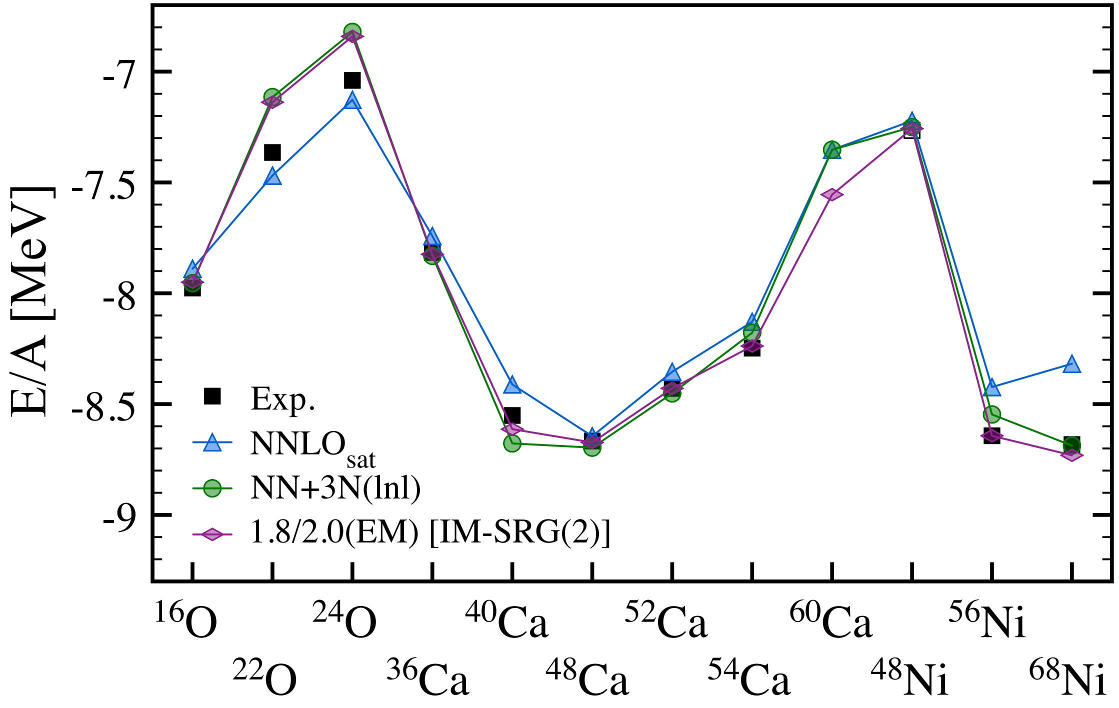
V. Somà,[1,*] P. Navrátil,[2,†] F. Raimondi,[3,4,‡] C. Barbieri,[4,§] and T. Duguet[1,5,‖]

Input for NCSMC calculations: Nuclear forces from chiral Effective Field Theory

- Quite reasonable description of binding energies across the nuclear charts becomes feasible
  - **The Hamiltonian fully determined in *A*=2 and *A*=3,4 systems**
    - Nucleon–nucleon scattering, deuteron properties, ^{3}H and ^{4}He binding energy, ^{3}H half life
  - Light nuclei – NCSM
  - Medium mass nuclei – Self-Consistent Green's Function method

NN N^{3}LO (Entem-Machleidt 2003)
3N N^{2}LO w local/non-local regulator





1.8/2.0 (EM) results: J. Simonis, S. R. Stroberg, K. Hebeler, J. D. Holt, and A. Schwenk, Phys. Rev. C 96, 014303 (2017).

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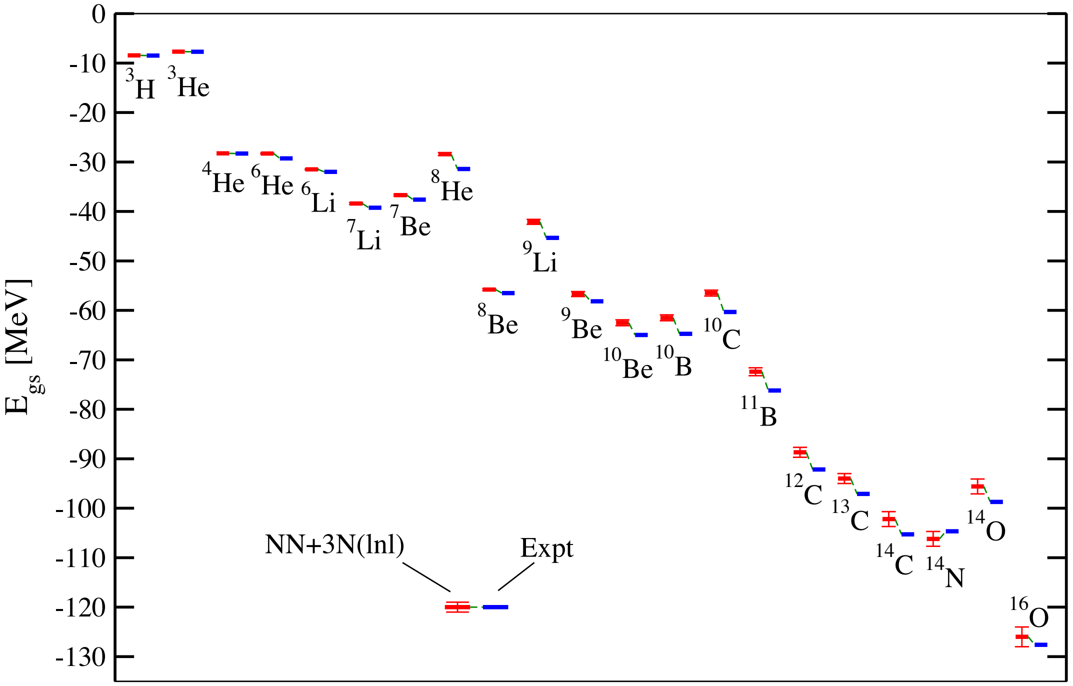
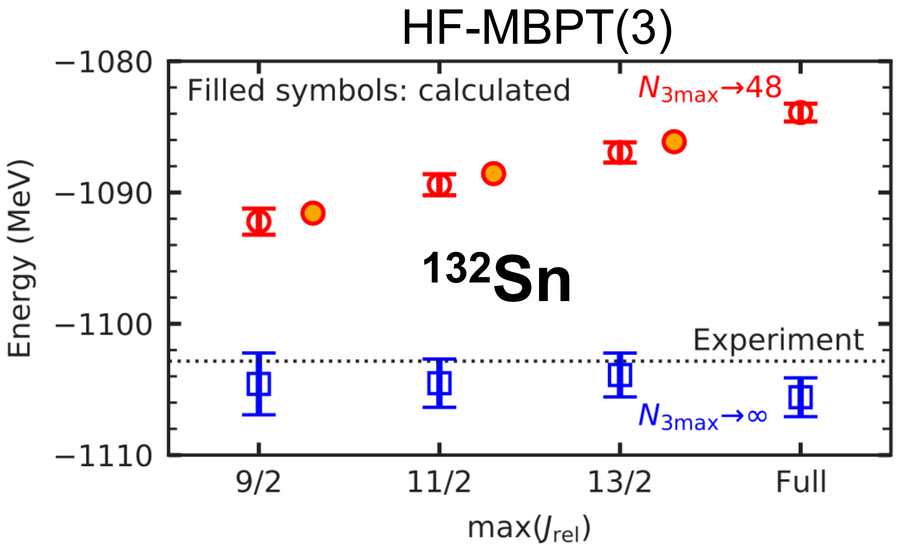
  - Light nuclei – NCSM
  - Heavy nuclei – HF-MBPT(3)

NN N^{3}LO (Entem-Machleidt 2003)
3N N^{2}LO w local/non-local regulator



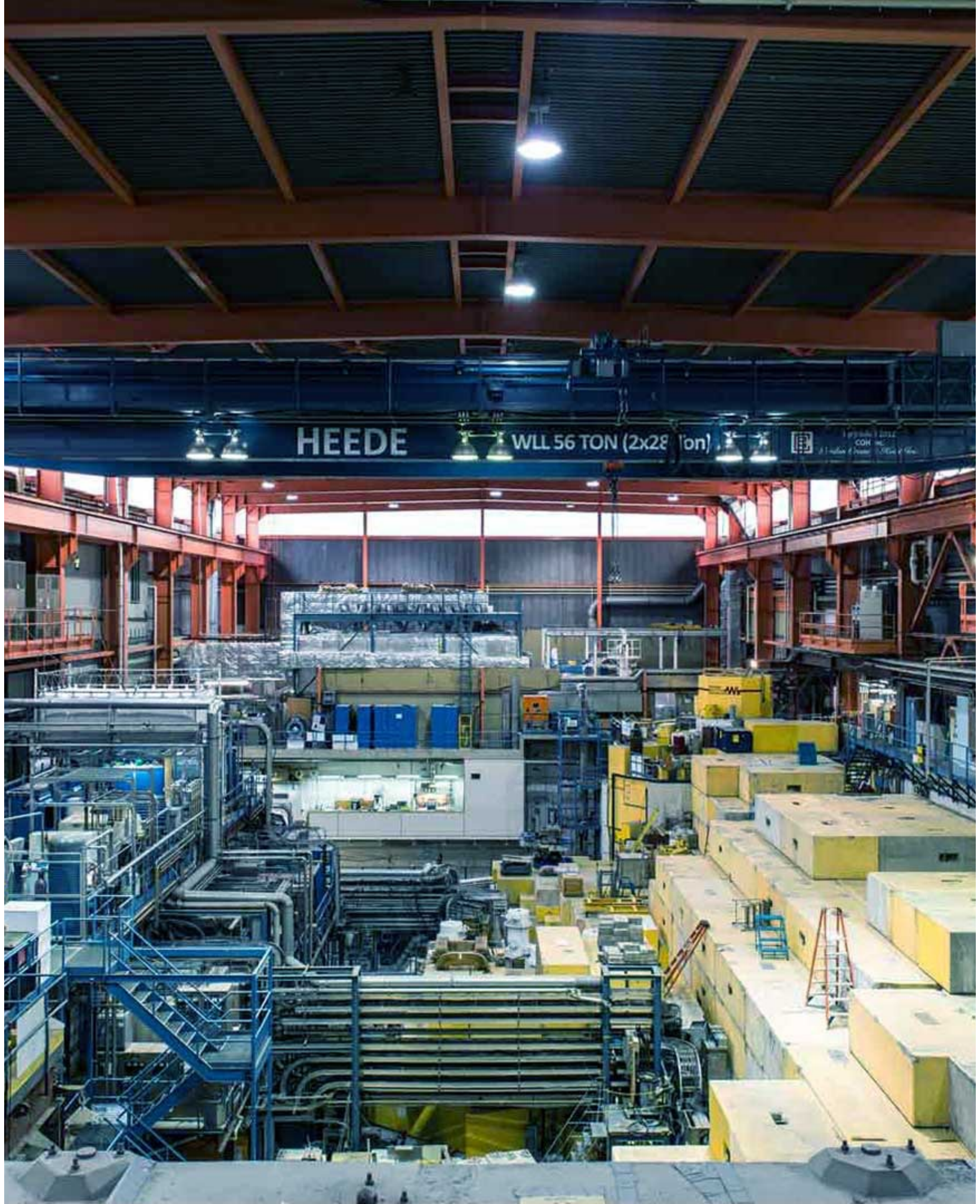


PHYSICAL REVIEW C **105**, 014302 (2022)

Converged *ab initio* calculations of heavy nuclei

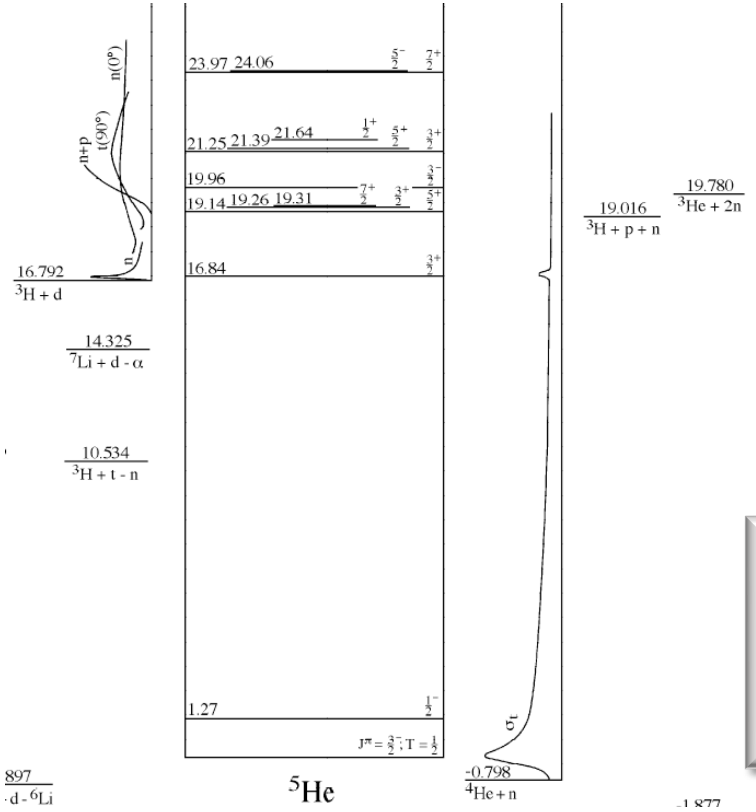
T. Miyagi,[1,*] S. R. Stroberg,[2,†] P. Navrátil,[1,‡] K. Hebeler,[3,4,5,§] and J. D. Holt[1,6,‖]

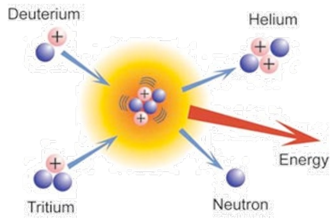
DT fusion

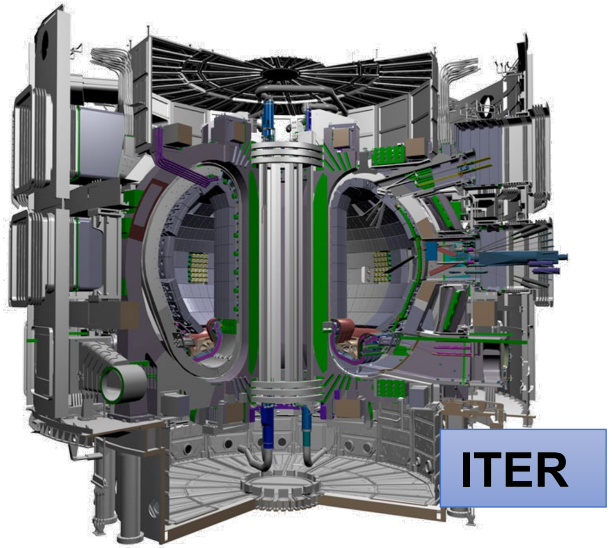


Deuterium-Tritium fusion

- The d+^{3}H$\rightarrow$$n$+^{4}He reaction
  - The most promising to produce fusion energy in the near future
  - Used to achieve inertial-confinement (laser-induced) fusion at NIF, and magnetic-confinement fusion at ITER
  - With its mirror reaction, ^{3}He(d,p)^{4}He, important for Big Bang nucleosynthesis



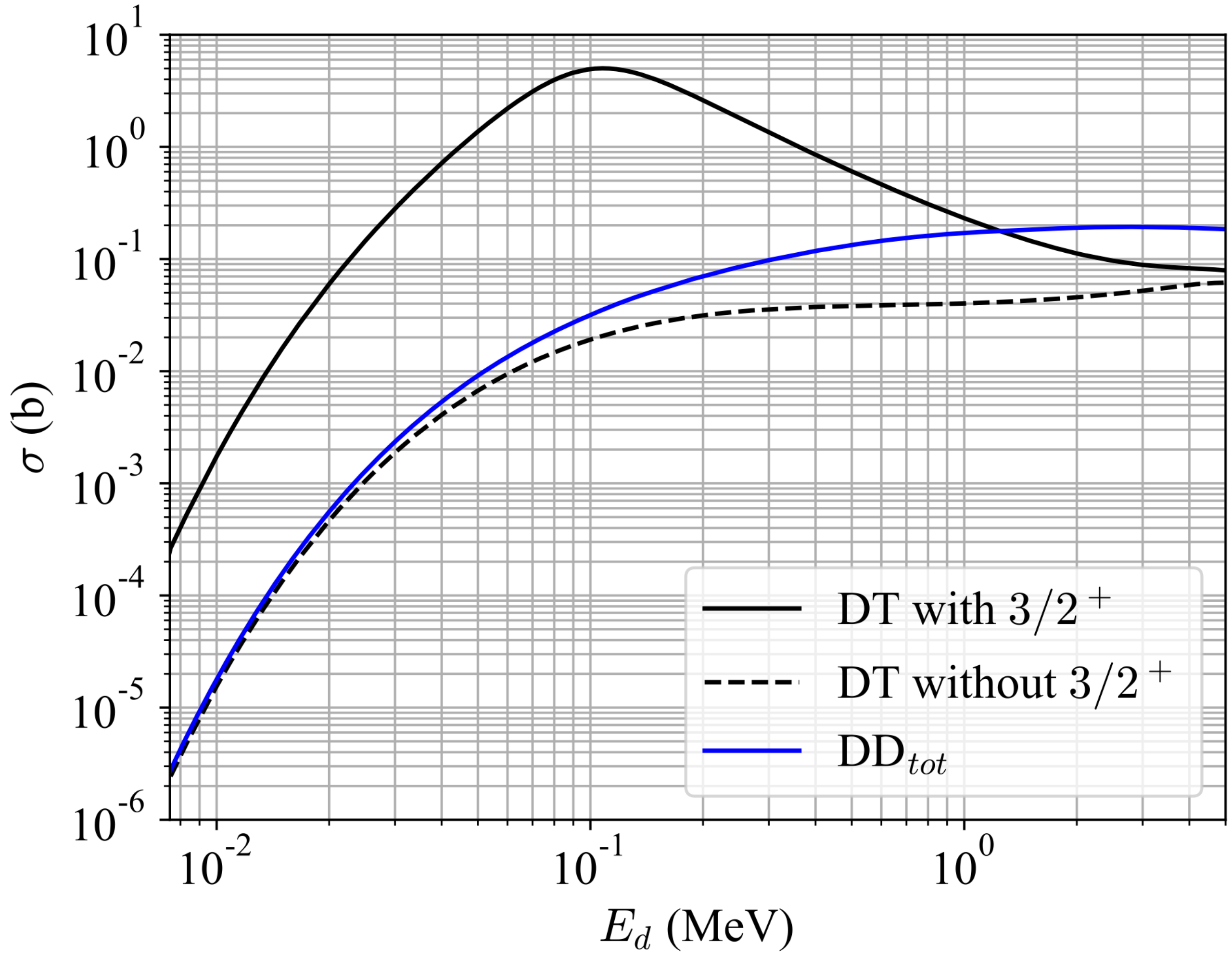




Resonance at E_{cm} =48 keV (E_d=105 keV) in the J=3/2$^+$ channel
Cross section at the peak: 4.88 b

17.64 MeV energy released:
14.1 MeV neutron and 3.5 MeV alpha

DT cross section would be 100x smaller, like DD, without the 3/2⁺ resonance

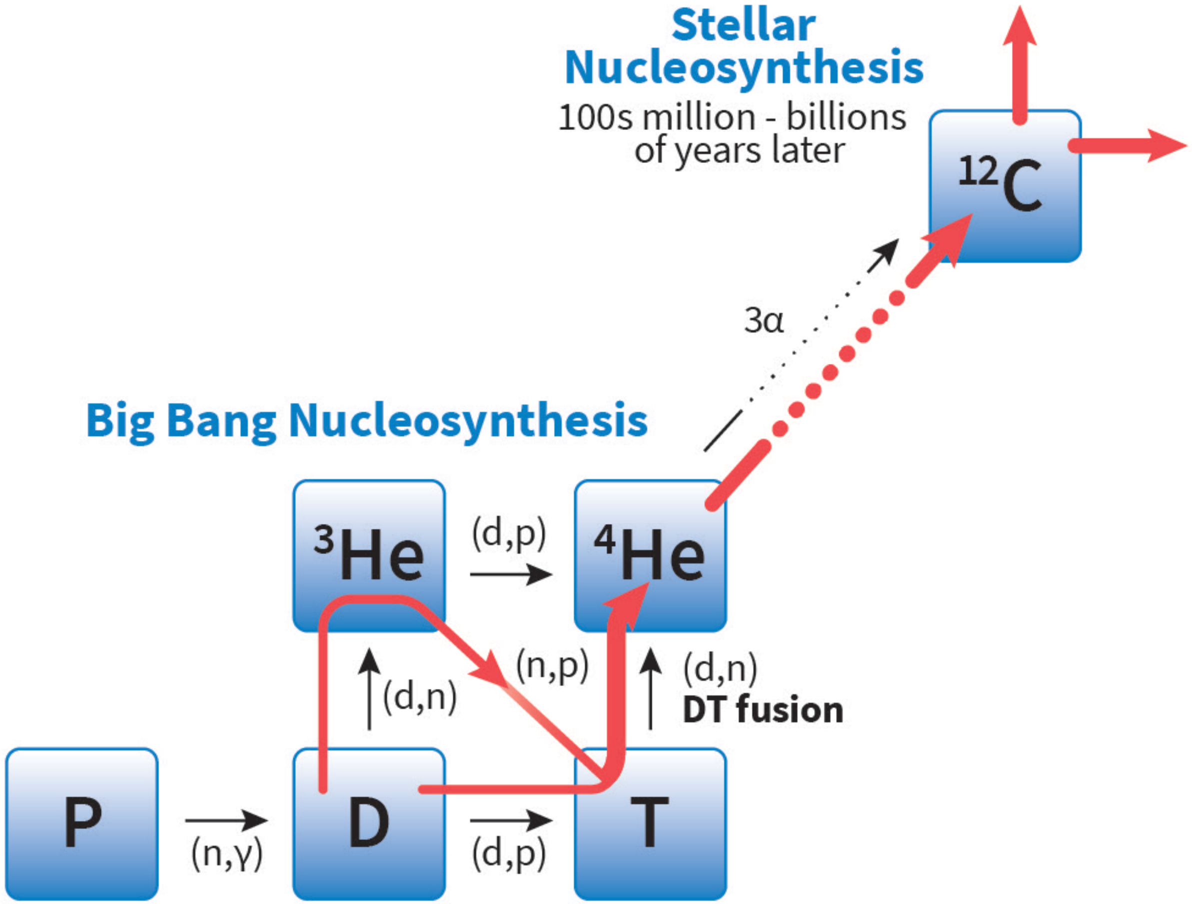


Mark Paris
LANL

M.B. Chadwick *et al.*, arXiv:2305.00647

Big bang Nucleosynthesis and DT fusion

- D(T,n)α, enhanced by the $3/2^+$ resonance, is responsible for 99% of primordial ^{4}He
- The remaining 1% of primordial ^{4}He came from the D(^{3}He,p)^{4}He reaction, which benefits from the same mirror $3/2^+$ resonance but is suppressed because of the larger Coulomb repulsion between D and ^{3}He
- This helium became a source for the subsequent creation of ≥25% of the carbon and other heavier elements and, thus, a substantial fraction of our human bodies



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NCSMC calculation of the DT fusion

$$|\Psi\rangle = \sum_{\lambda} c_{\lambda} \left| {}^{5}\mathrm{He}, \lambda \right\rangle + \int d\vec{r}\, u_{\nu_{DT}}(\vec{r}) \hat{A}_{DT} \left| \mathrm{T} \overset{\vec{r}}{\leftarrow} D, \nu_{DT} \right\rangle + \int d\vec{r}\, u_{\nu_{n\alpha}}(\vec{r}) \hat{A}_{n\alpha} \left| \alpha \overset{\vec{r}}{\leftarrow} n, \nu_{n\alpha} \right\rangle$$

- 2x7 static ^{5}He eigenstates computed with the NCSM
- Continuous D-T(g.s.) cluster states (entrance channel)
  - Including positive-energy eigenstates of D to account for distortion
- Continuous n-^{4}He(g.s.) cluster states (exit channel)
- Chiral NN+3N(500) interaction


nature COMMUNICATIONS

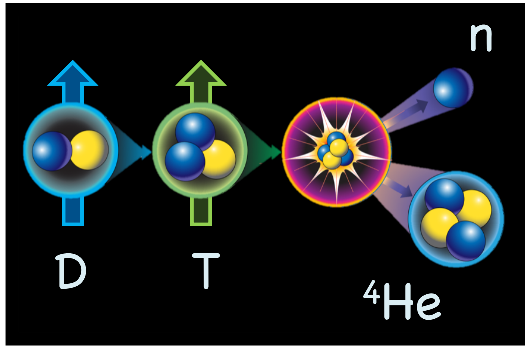
ARTICLE

https://doi.org/10.1038/s41467-018-08052-6 OPEN

Ab initio predictions for polarized deuterium-tritium thermonuclear fusion

Guillaume Hupin[1,2,3], Sofia Quaglioni[3] & Petr Navrátil[4]

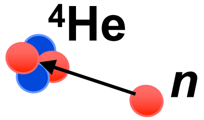
n-^{4}He scattering and ^{3}H+d fusion within NCSMC

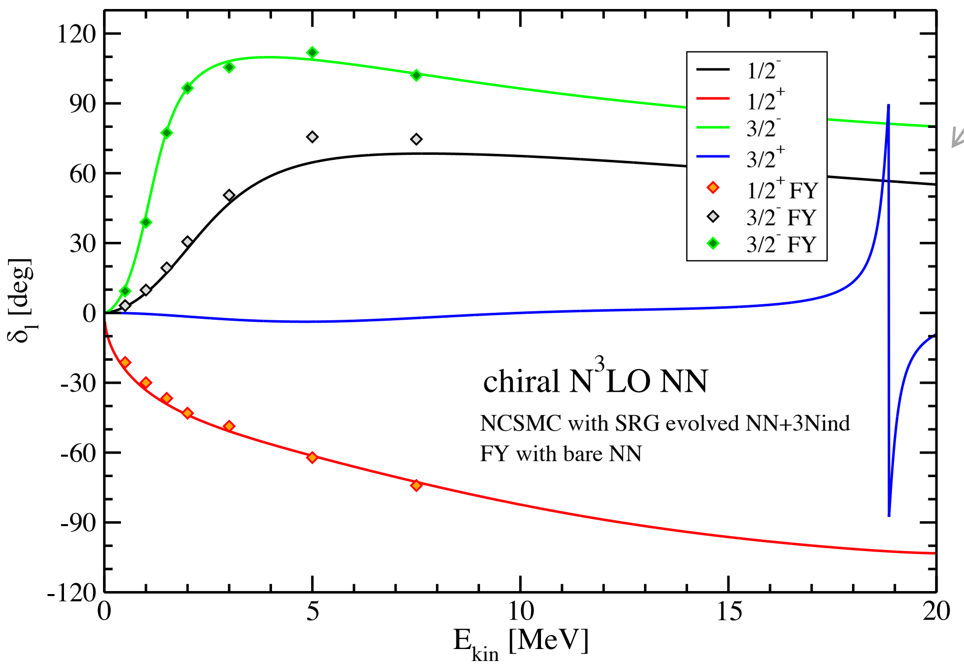


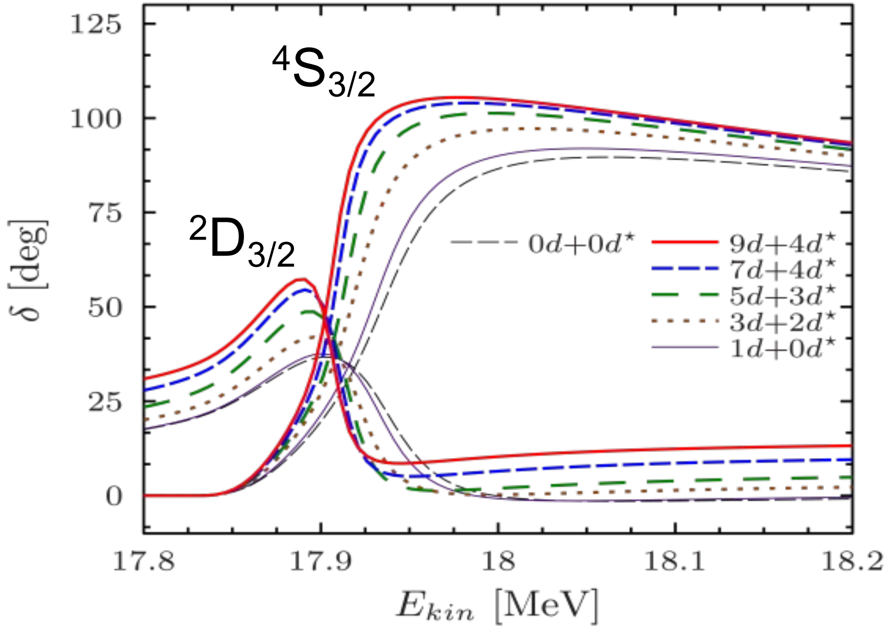
^{4}He+n -> ^{3}H+d

n-^{4}He and *d*+^{3}H scattering phase-shifts

^{4}He+n



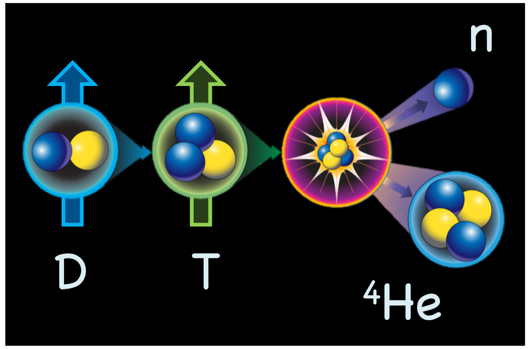




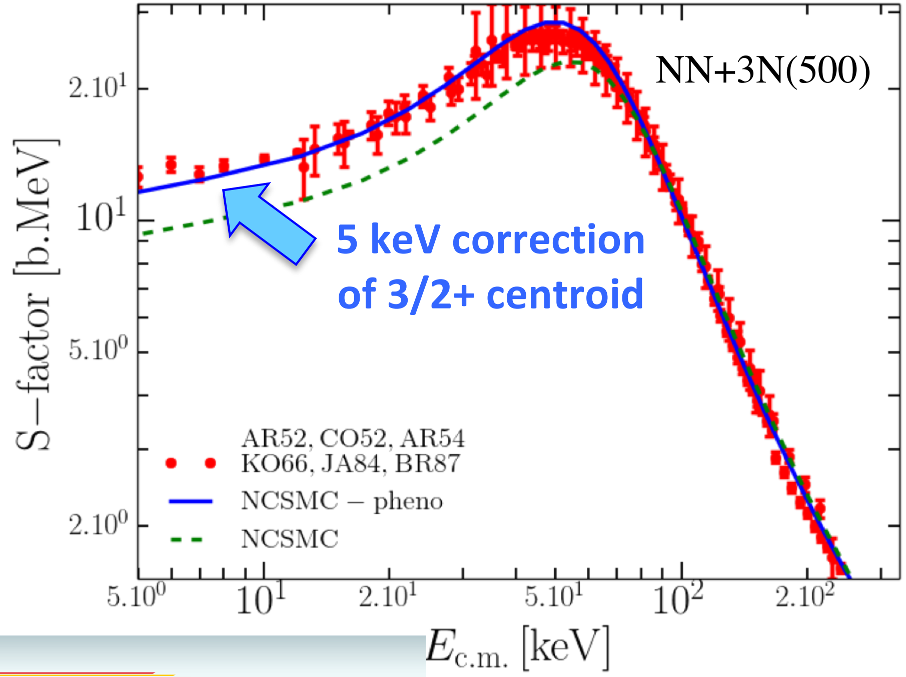
FY: Faddeev-Yakubovsky method - Rimantas Lazauskas

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

$^3H(d,n)^4He$ with chiral NN+3N(500) interaction



Astrophysical S-factor



Fusion cross section

Astrophysical S-factor: nuclear contribution

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

'Coulomb' Contribution (tunneling)

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-018-08052-6 OPEN

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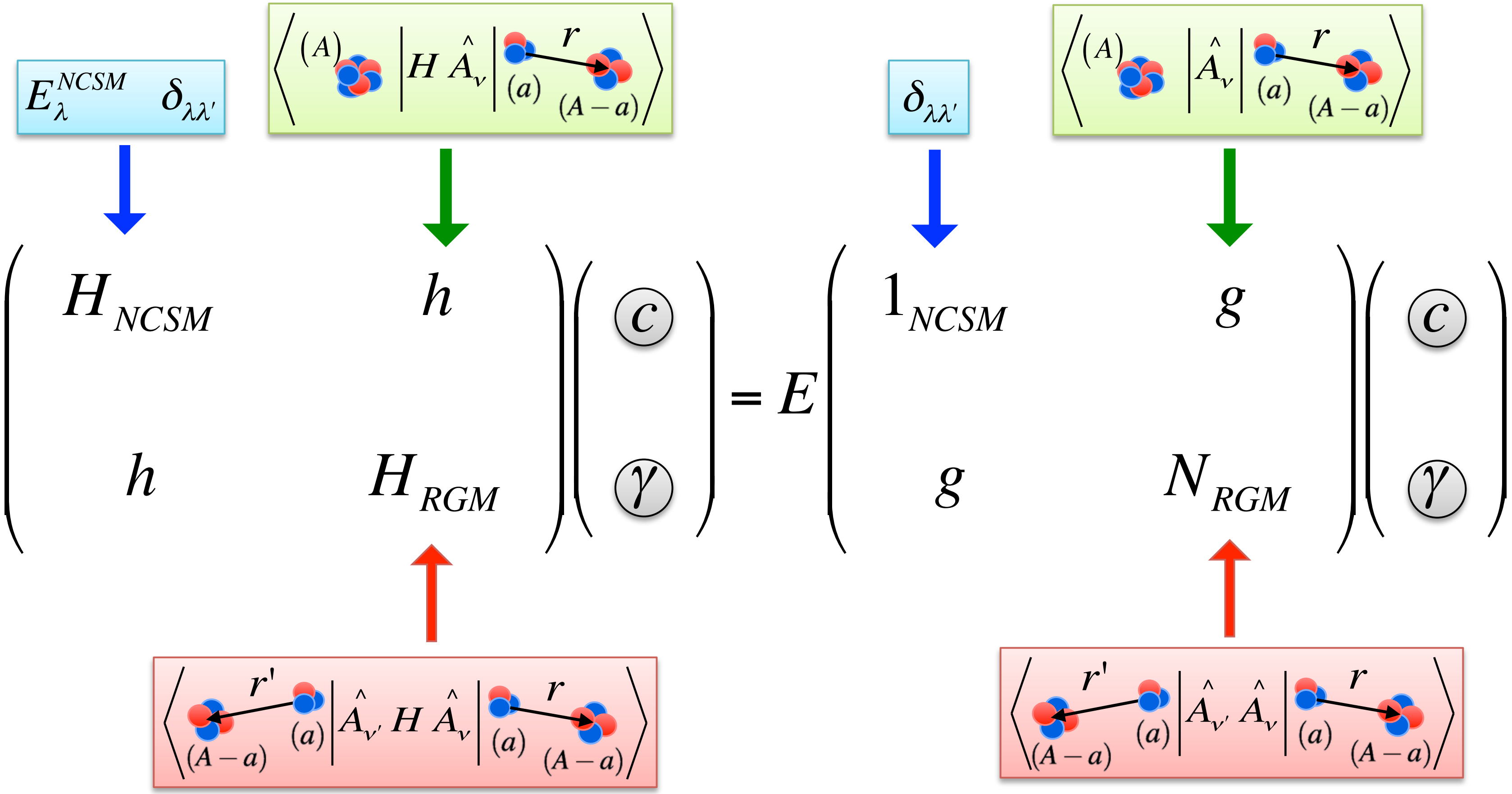
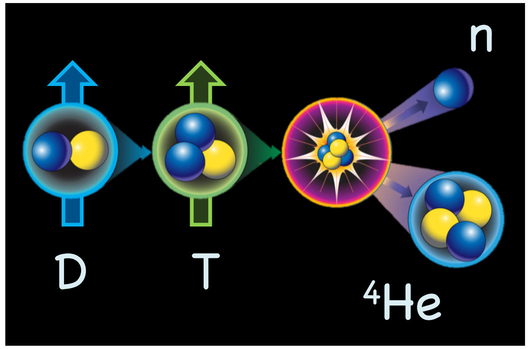
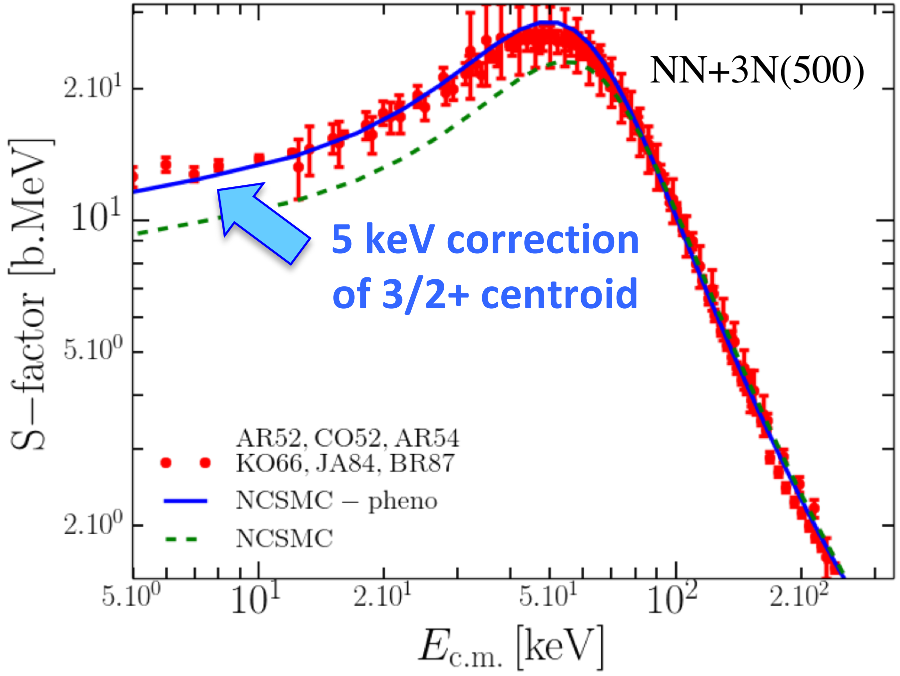


E_λ^{NCSM} energies treated as adjustable parameters

$^3H(d,n)^4He$ with chiral NN+3N(500) interaction



Astrophysical S-factor



Astrophysical S-factor: nuclear contribution

Fusion cross section

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'Coulomb' Contribution (tunneling)

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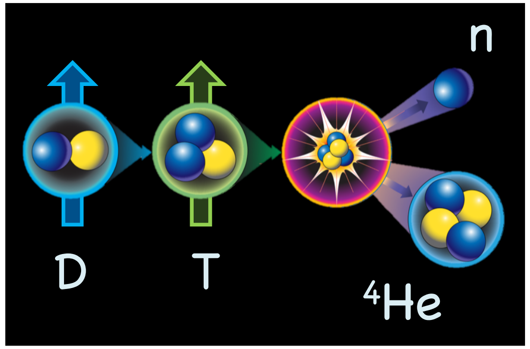

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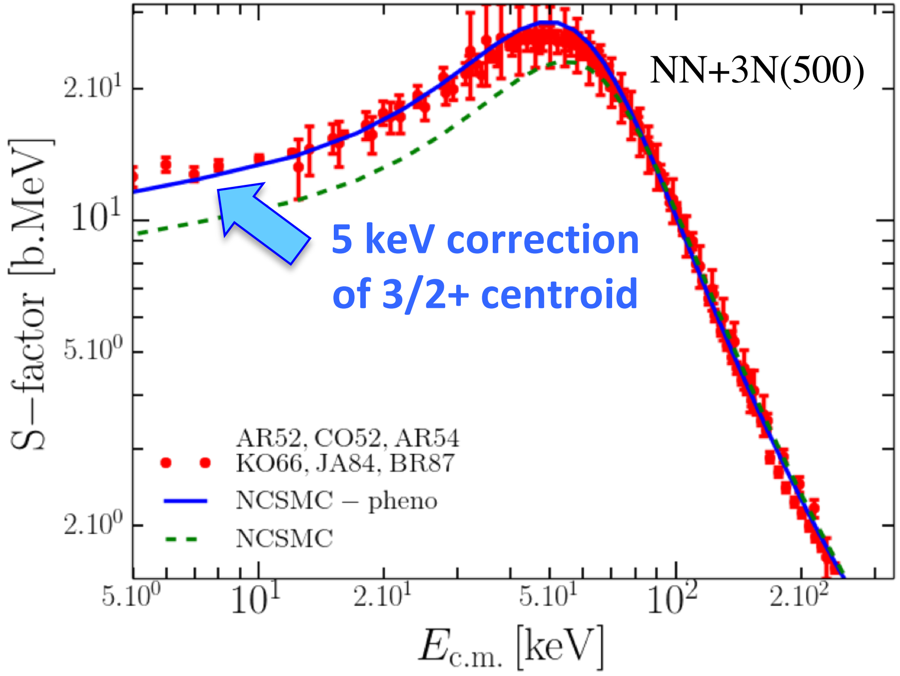


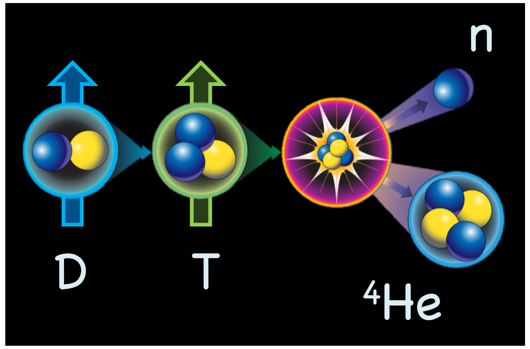
- While the DT fusion rate has been measured extensively, a fundamental understanding of the process is still missing
- Very little is known experimentally of how the polarization of the reactants' spins affects the reaction

$$\sigma_{unpol} = \sum_J \frac{2J+1}{(2I_D+1)(2I_T+1)} \sigma_J$$
$$\approx \frac{1}{3}\sigma_{\frac{1}{2}} + \frac{2}{3}\sigma_{\frac{3}{2}}$$

$$\sigma_{pol} \approx 1.5\ \sigma_{unpol}$$

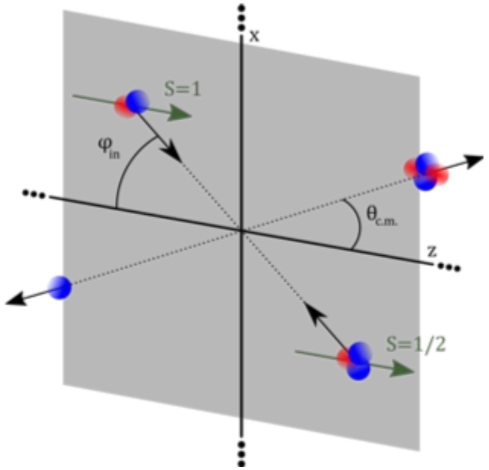
Assuming the fusion proceeds only in S-wave
with spins of D and T completely aligned:
Polarized cross section 50% higher than unpolarized

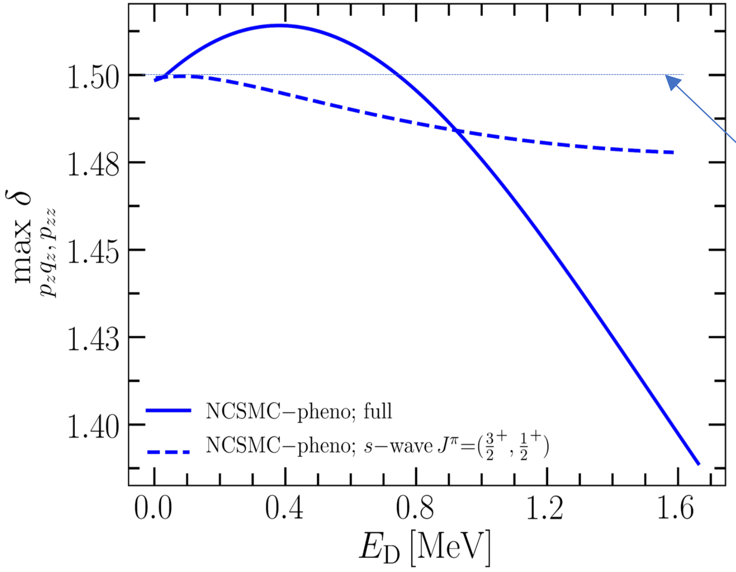
^{3}H(d,n)^{4}He with chiral NN+3N(500) interaction



Polarized fusion

$$\frac{\partial\sigma_{pol}}{\partial\Omega_{c.m.}}(\theta_{\text{c.m.}}) = \frac{\partial\sigma_{unpol}}{\partial\Omega_{c.m.}}(\theta_{\text{c.m.}})\left(1+\frac{1}{2}p_{zz}A_{zz}^{(b)}(\theta_{\text{c.m.}})+\frac{3}{2}p_z q_z C_{z,z}(\theta_{\text{c.m.}})\right)$$





$$\sigma_{unpol} = \sum_J \frac{2J+1}{(2I_D+1)(2I_T+1)}\sigma_J$$

$$\approx \frac{1}{3}\sigma_{\frac{1}{2}} + \frac{2}{3}\sigma_{\frac{3}{2}}$$

$$\sigma_{pol} \approx 1.5\,\sigma_{unpol}$$

nature COMMUNICATIONS

ARTICLE

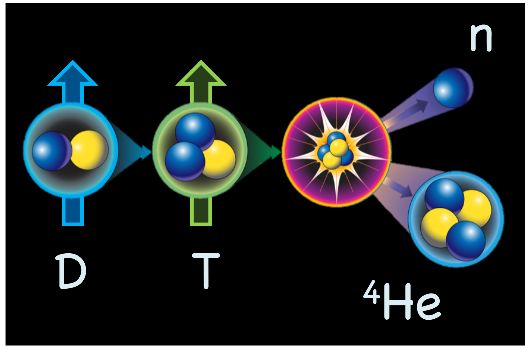
https://doi.org/10.1038/s41467-018-08052-6 OPEN

Ab initio predictions for polarized deuterium-tritium thermonuclear fusion

Guillaume Hupin[1,2,3], Sofia Quaglioni[3] & Petr Navrátil[4]

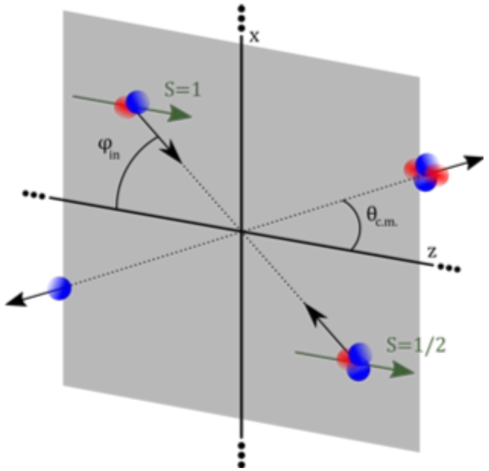
NCSMC calculation demonstrates impact of partial waves with l > 0
as well as the contribution of l = 0 J^π = ½$^+$ channel

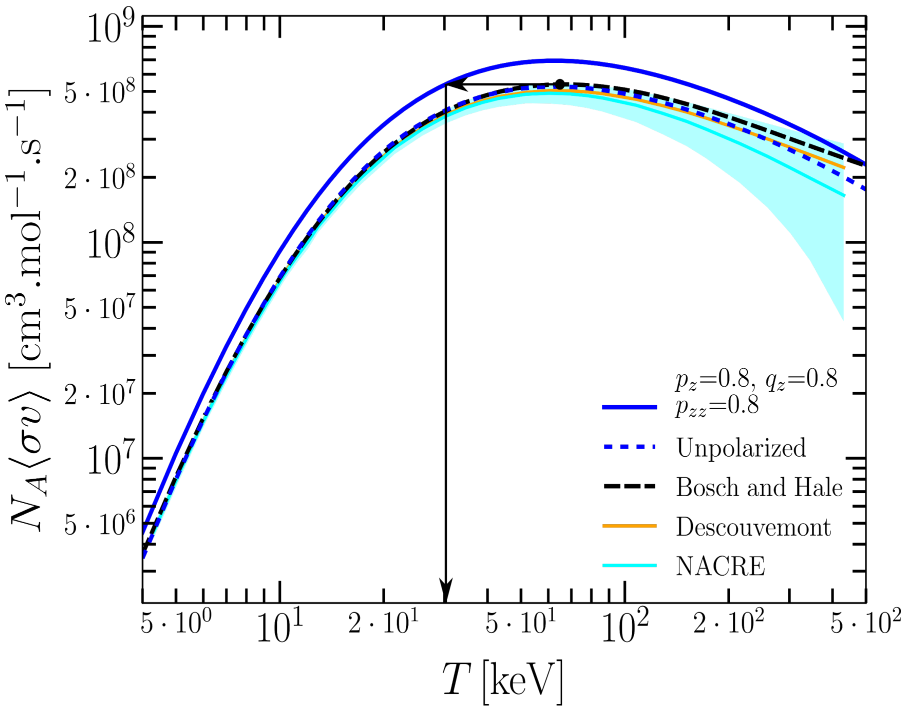
^{3}H(d,n)^{4}He with chiral NN+3N(500) interaction



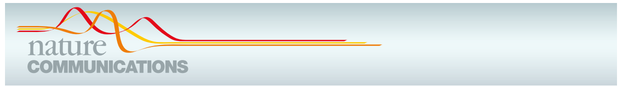
Polarized fusion

$$\frac{\partial \sigma_{pol}}{\partial \Omega_{c.m.}}(\theta_{\text{c.m.}}) = \frac{\partial \sigma_{unpol}}{\partial \Omega_{c.m.}}(\theta_{\text{c.m.}}) \left(1 + \frac{1}{2} p_{zz} A_{zz}^{(b)}(\theta_{\text{c.m.}}) + \frac{3}{2} p_z q_z C_{z,z}(\theta_{\text{c.m.}})\right)$$





$$\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\mu(k_bT)^3}} \int_0^\infty S(E)\, exp\left(-\frac{E}{k_bT} - \sqrt{\frac{E_g}{E}}\right) dE,$$



ARTICLE

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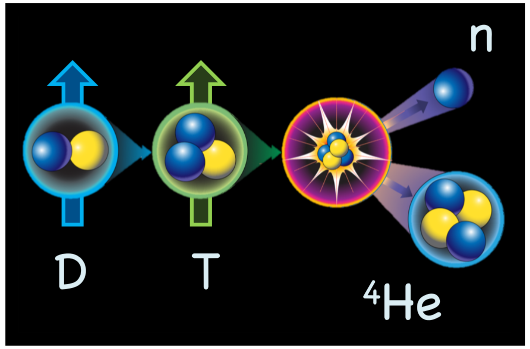
Ab initio predictions for polarized deuterium-tritium thermonuclear fusion

Guillaume Hupin[1,2,3], Sofia Quaglioni[3] & Petr Navrátil[4]

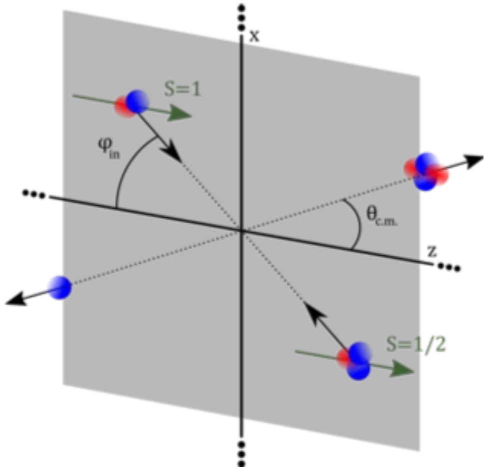
For a realistic 80% polarization, reaction rate increases by ~32% or the same rate at ~45% lower temperature

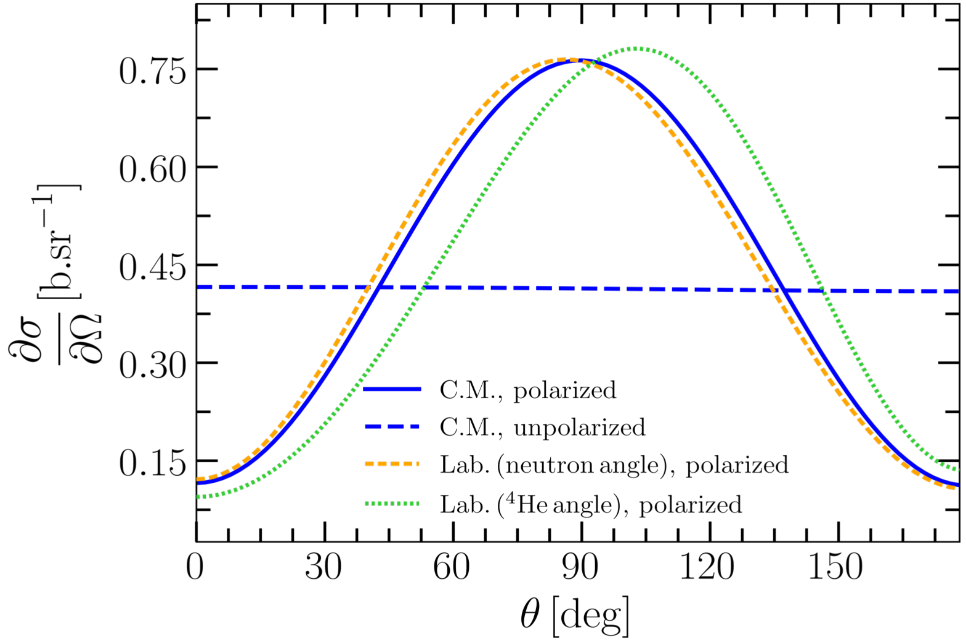


^{3}H(d,n)^{4}He with chiral NN+3N(500) interaction

Polarized fusion

$$\frac{\partial\sigma_{pol}}{\partial\Omega_{c.m.}}(\theta_{\text{c.m.}}) = \frac{\partial\sigma_{unpol}}{\partial\Omega_{c.m.}}(\theta_{\text{c.m.}})\left(1+\frac{1}{2}p_{zz}A^{(b)}_{zz}(\theta_{\text{c.m.}})+\frac{3}{2}p_z q_z C_{z,z}(\theta_{\text{c.m.}})\right)$$





For a realistic 80% polarization, outgoing neutrons and alphas emitted dominantly in the perpendicular direction to the magnetic field

nature COMMUNICATIONS

ARTICLE

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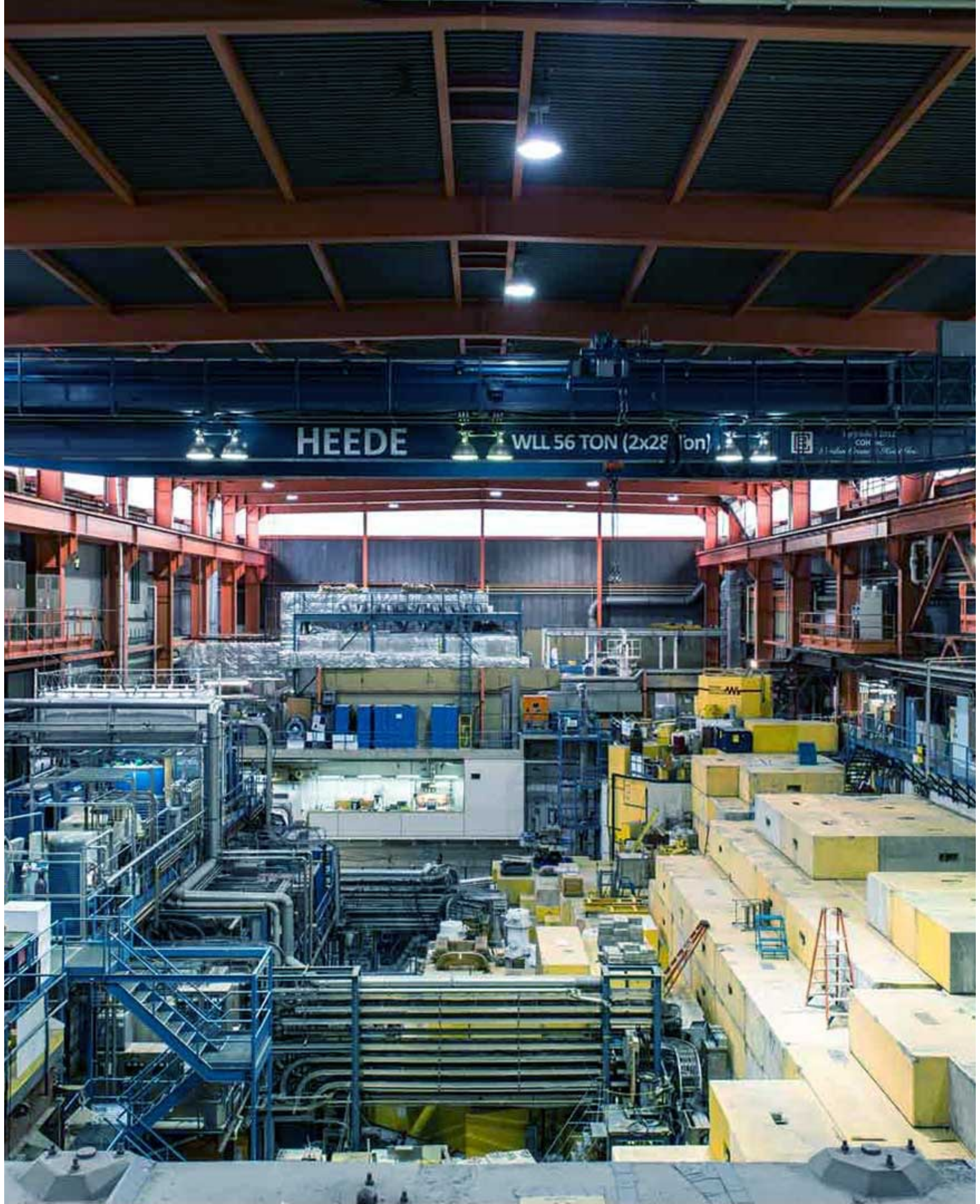
Ab initio predictions for polarized deuterium-tritium thermonuclear fusion

Guillaume Hupin[1,2,3], Sofia Quaglioni[3] & Petr Navrátil[4]

TRIUMF

S-wave resonance close to the ^{6}He+p threshold in ^{7}Li



Discovery, accelerated

PHYSICAL REVIEW C **100**, 024304 (2019)

^{7}Be and ^{7}Li nuclei within the no-core shell model with continuum

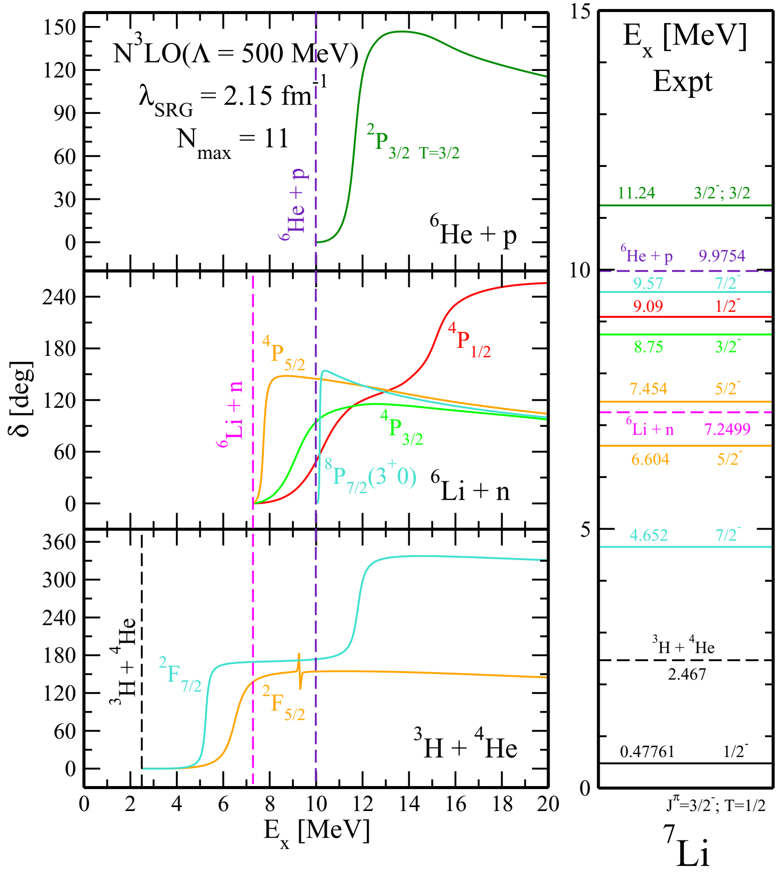
Matteo Vorabbi* and Petr Navrátil†
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada

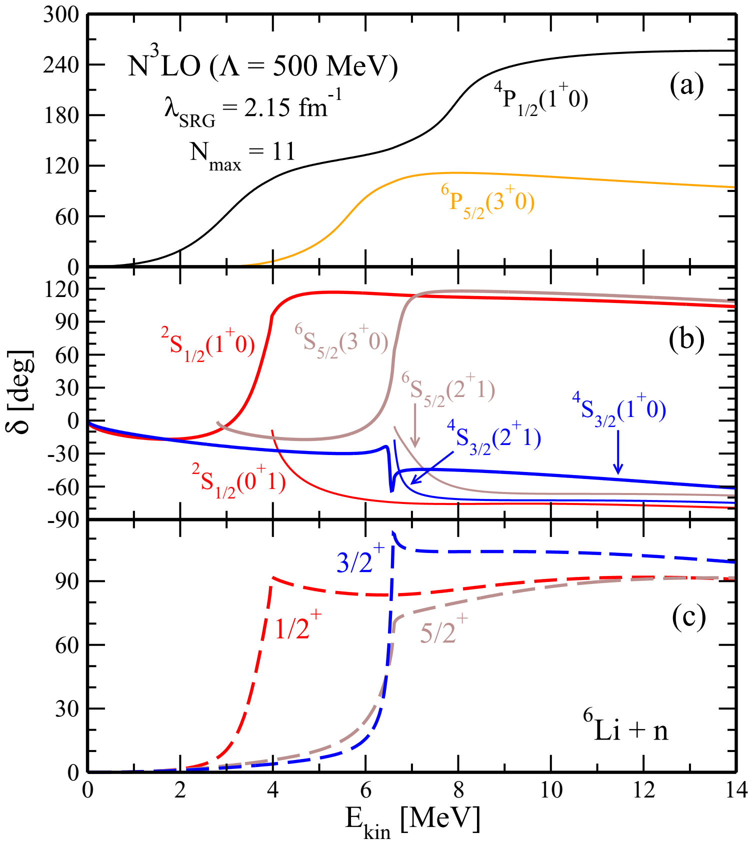
Sofia Quaglioni
Lawrence Livermore National Laboratory, P. O. Box 808, L-414, Livermore, California 94551, USA

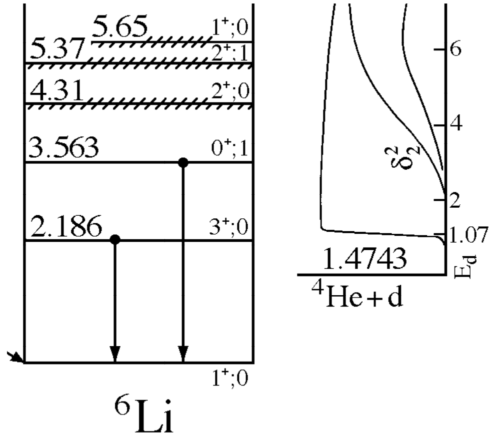
Guillaume Hupin
Institut de Physique Nucléaire, CNRS/IN2P3, Université Paris-Sud, Université Paris-Saclay, F-91406, Orsay, France

S-wave resonance close to the threshold of ^{6}He+p?

- NCSMC study of ^{7}Li and ^{7}Be nuclei using all binary mass partitions
  - Known resonances reproduced
  - Prediction of several new resonances of both parities







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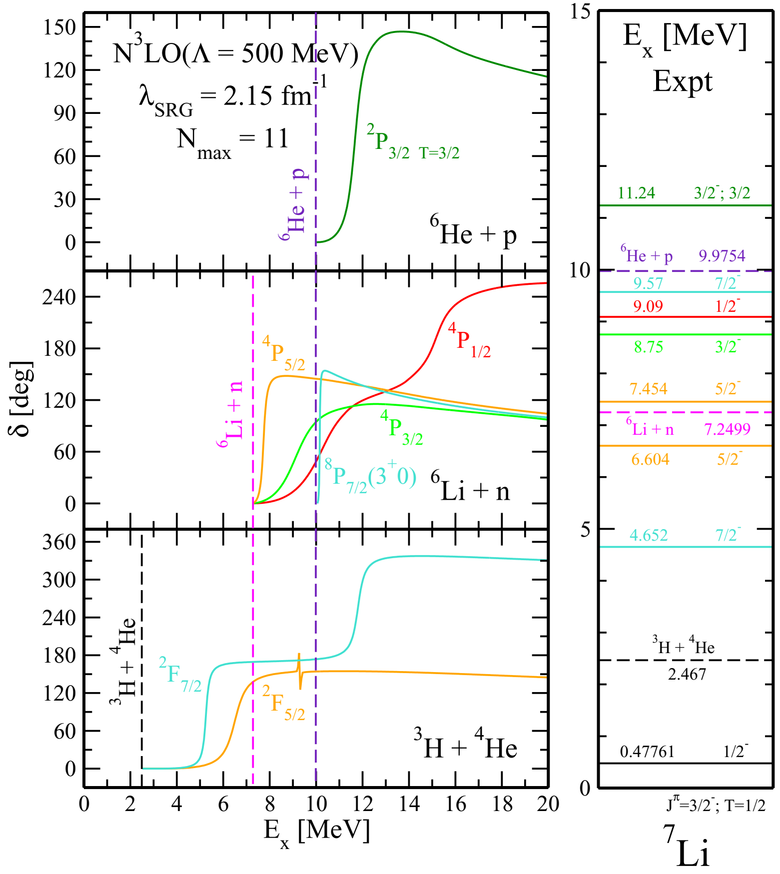
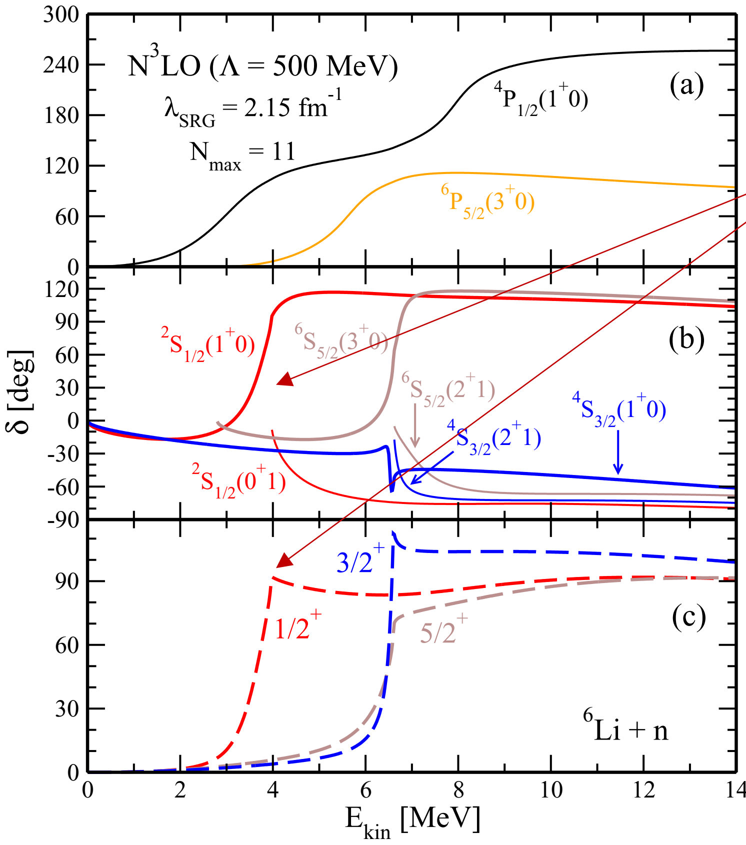
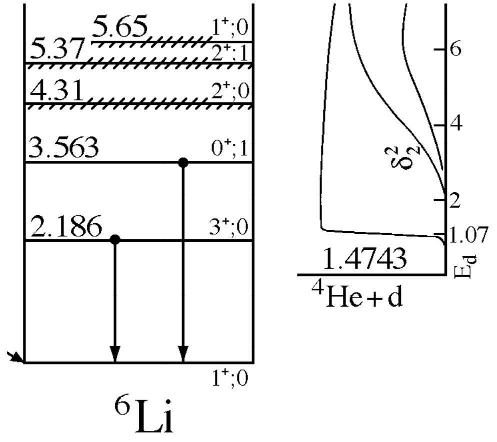




S-wave resonance



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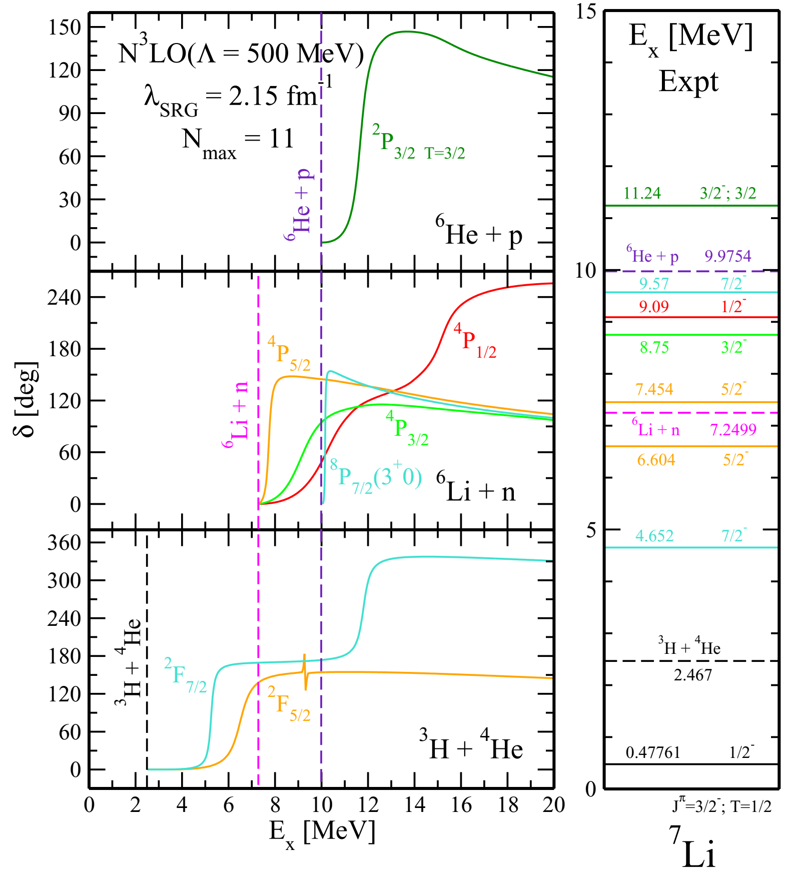

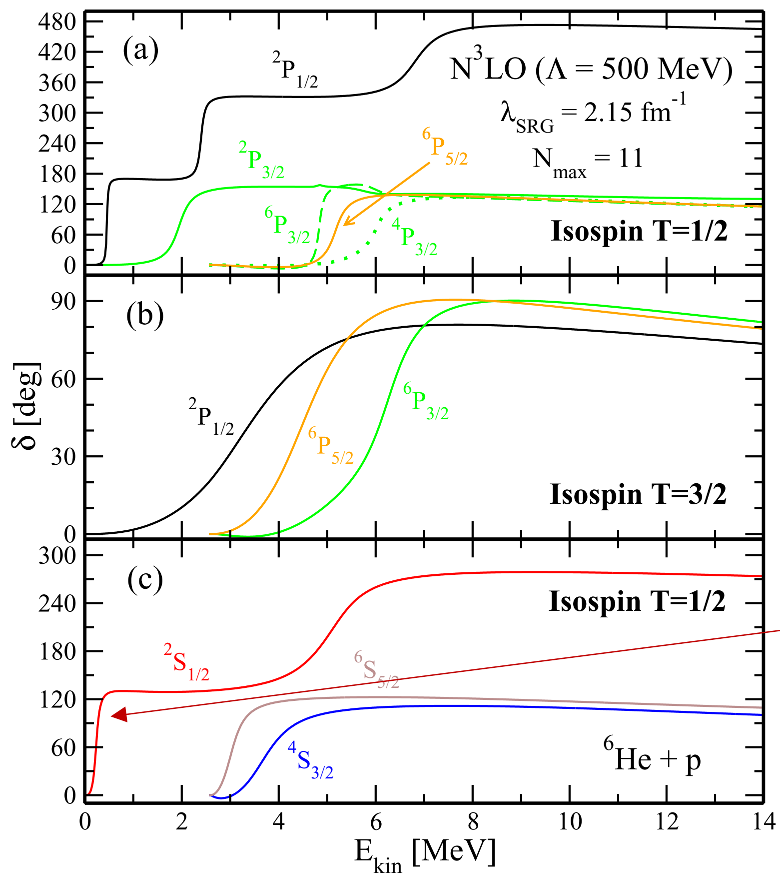

S-wave resonance predicted at low energy in ^{6}He+p scattering with possible astrophysics implications.

S-wave resonance

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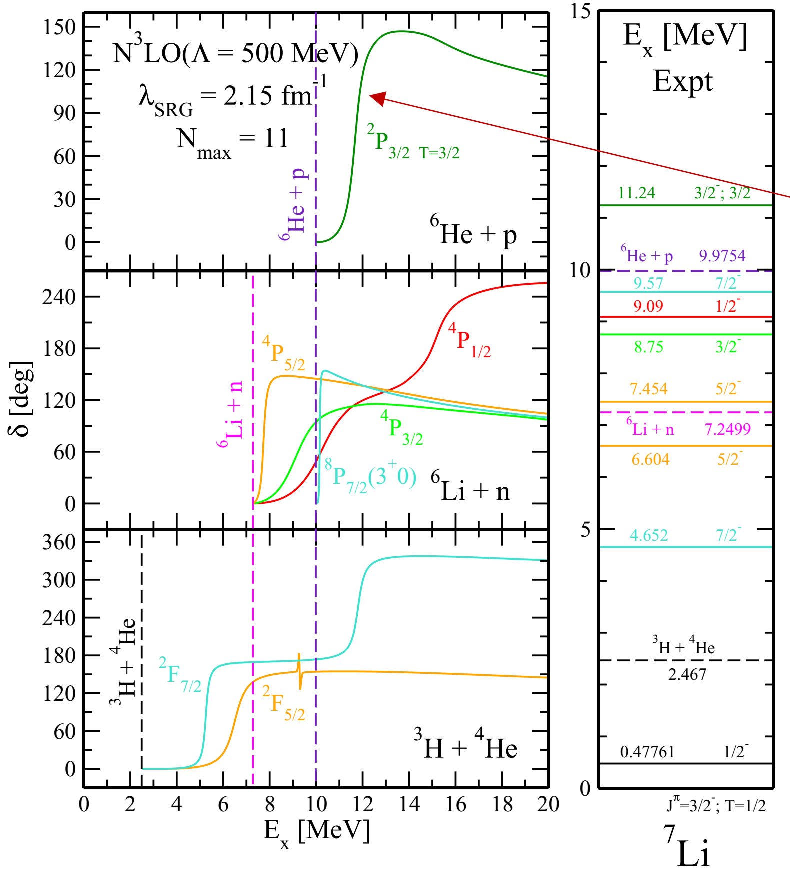
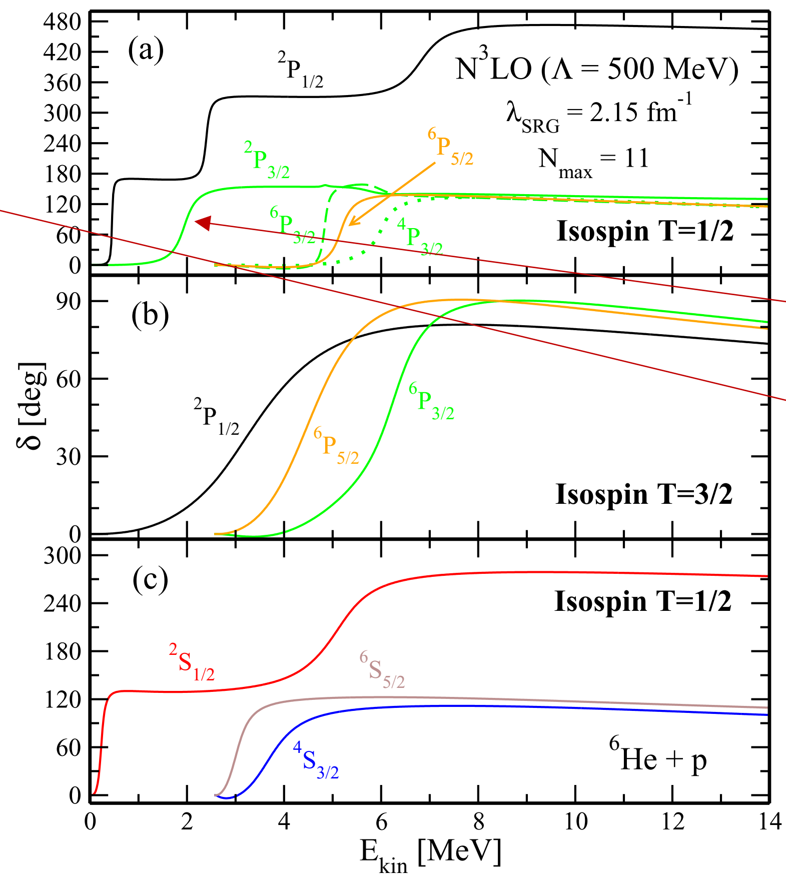




^{6}He(d,n)^{7}Li* → ^{6}He+p experiment at Texas A&M University Cyclotron Institute

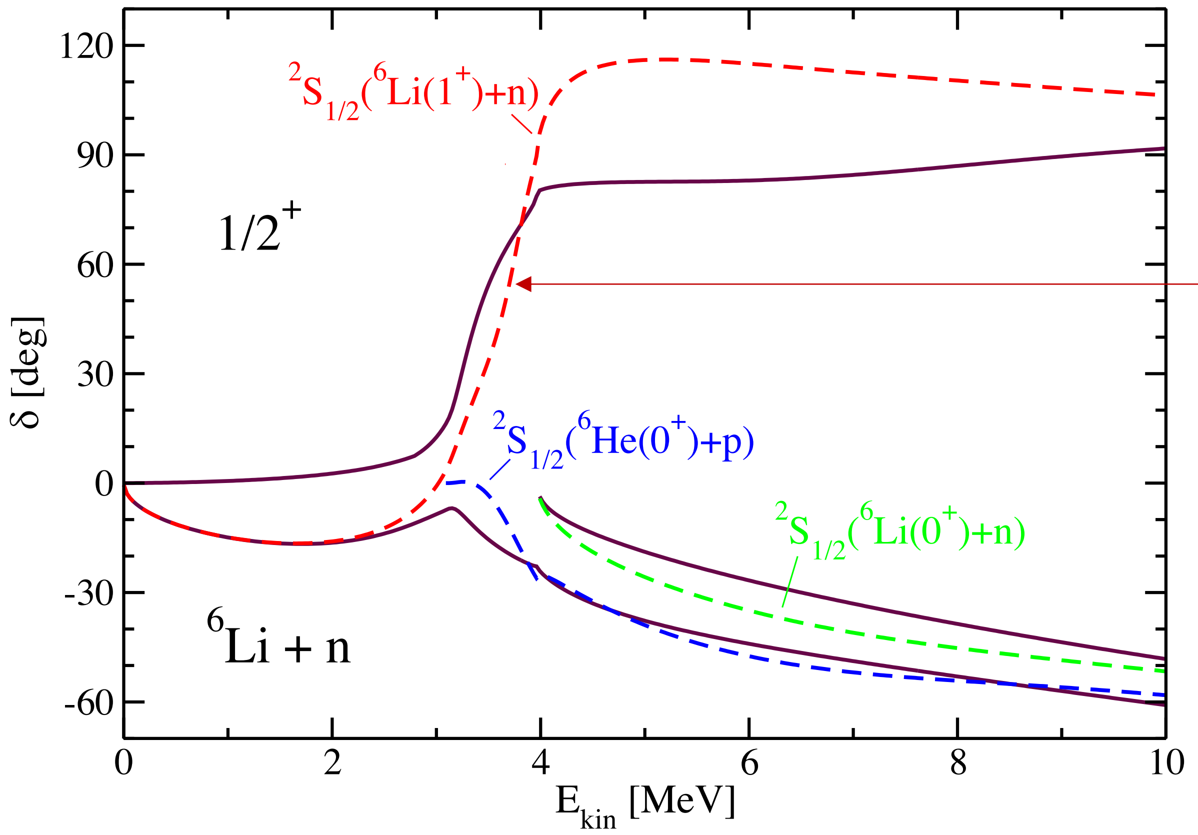
Near threshold resonance not found

3/2- T=1/2 anti-analog resonance observed just above 3/2- T=3/2

Weakness of the calculation - **mass partitions not coupled**:
The resonance appears in both ^{6}Li+n and ^{6}He+p. Might be below the ^{6}He+p threshold or might decay by charge exchange ^{6}He(p,n)^{6}Li(gs) …or might be dissolved in d+n+^{4}He continuum (not included)

^{7}Li structure: Coupling of different mass partitions in NCSMC in progress

- ^{6}Li+n and ^{6}He+p coupled calculations



***S*-wave resonance just above the ^{6}He+p threshold**. However, it is in the **^{6}Li(1$^+$)+n** channel; the ^{6}He(0$^+$)+p *S*-wave phase shift decreasing similarly as ^{6}Li(0$^+$)+n.

Explains non-observation in the ^{6}He(d,n)^{7}Li* → ^{6}He+p Texas A&M experiment

PHYSICAL REVIEW C **107**, L061303 (2023)

Letter

Search for an *s*-wave resonance in ^{7}Li just above the proton-decay threshold

N. Dronchi,[1,*] J. Berkman,[2] R. J. Charity,[2] J. M. Elson,[2] L. G. Sobotka,[1,2] A. G. Thomas,[2]
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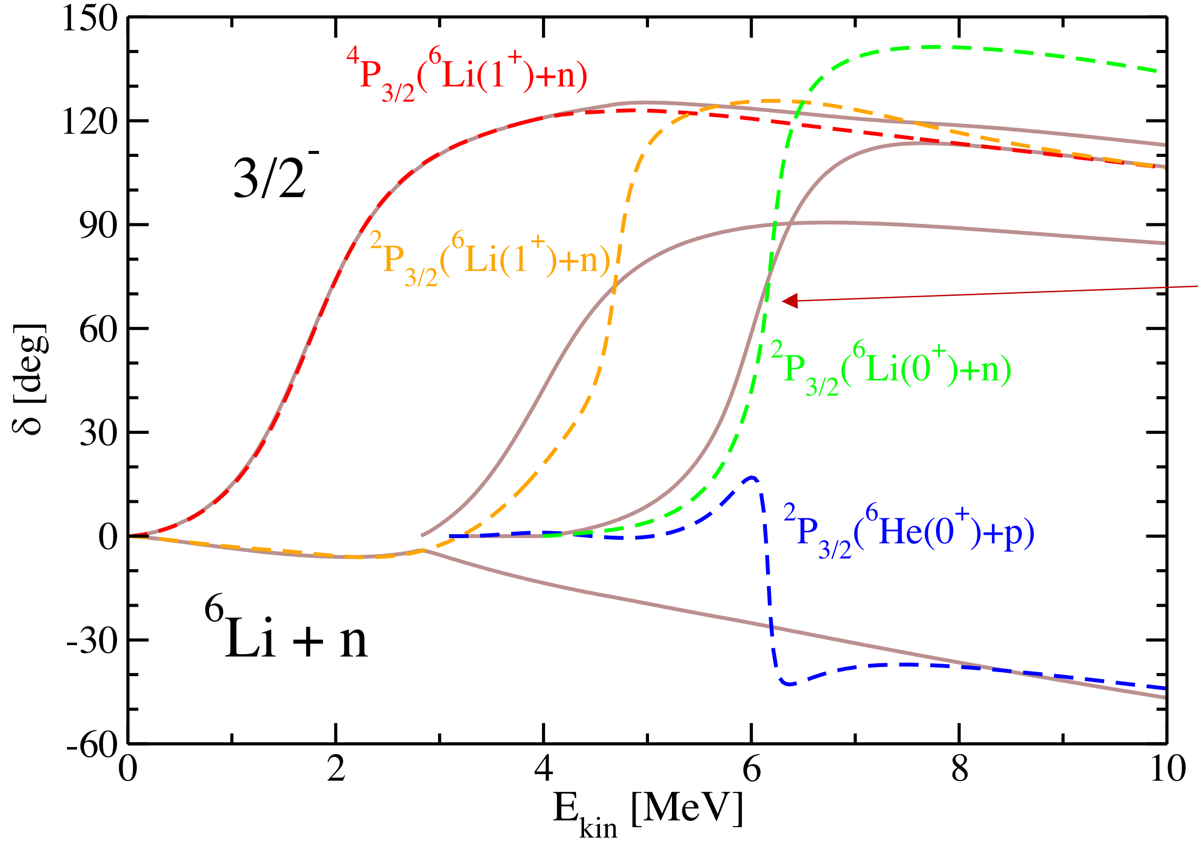
D. P. Scriven,[3,4] S. T. Marley,[6] and R. M. Shaffer[6]

^{7}Li structure: Coupling of different mass partitions in NCSMC in progress

- ^{6}Li+n and ^{6}He+p coupled calculations



$3/2^-$ T=1/2 anti-analog resonance with contributions from both the **^{6}Li(0^+)+n** and the **^{6}He(0^+)+p** *P*-waves.

Consistent with the observation in the ^{6}He(d,n)^{7}Li* → ^{6}He+p Texas A&M experiment

PHYSICAL REVIEW C **107**, L061303 (2023)

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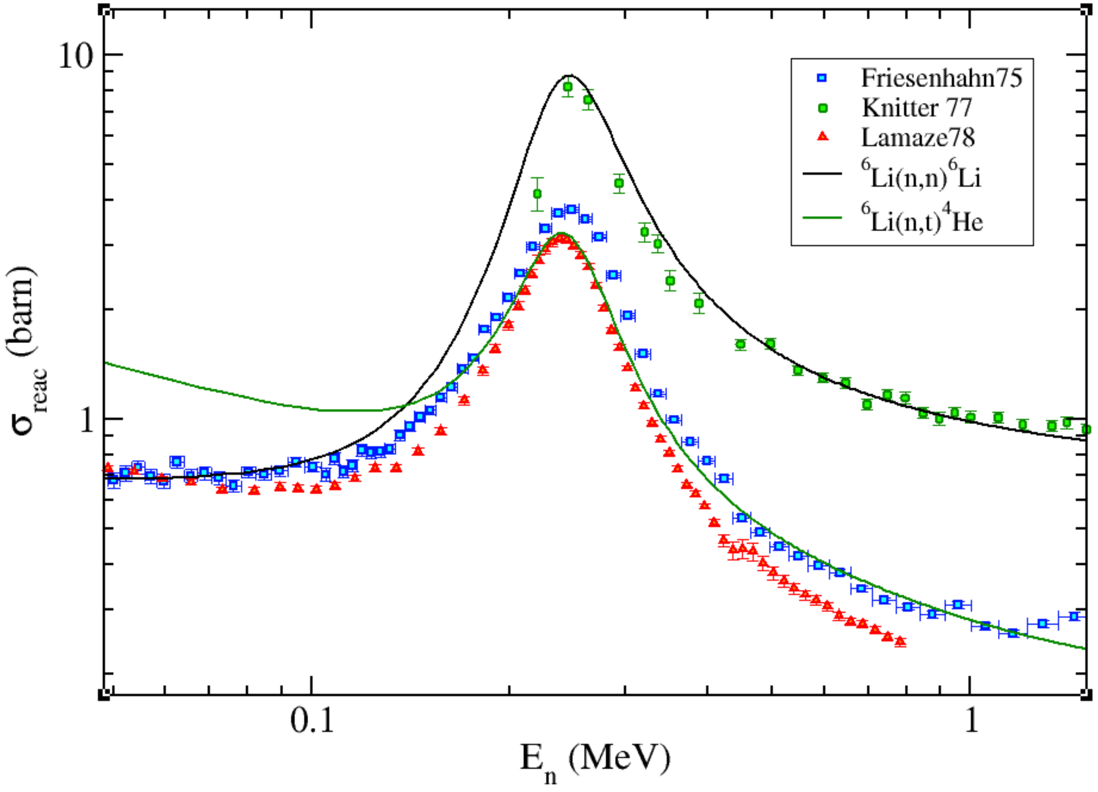
^{7}Li structure: Coupling of different mass partitions in NCSMC in progress

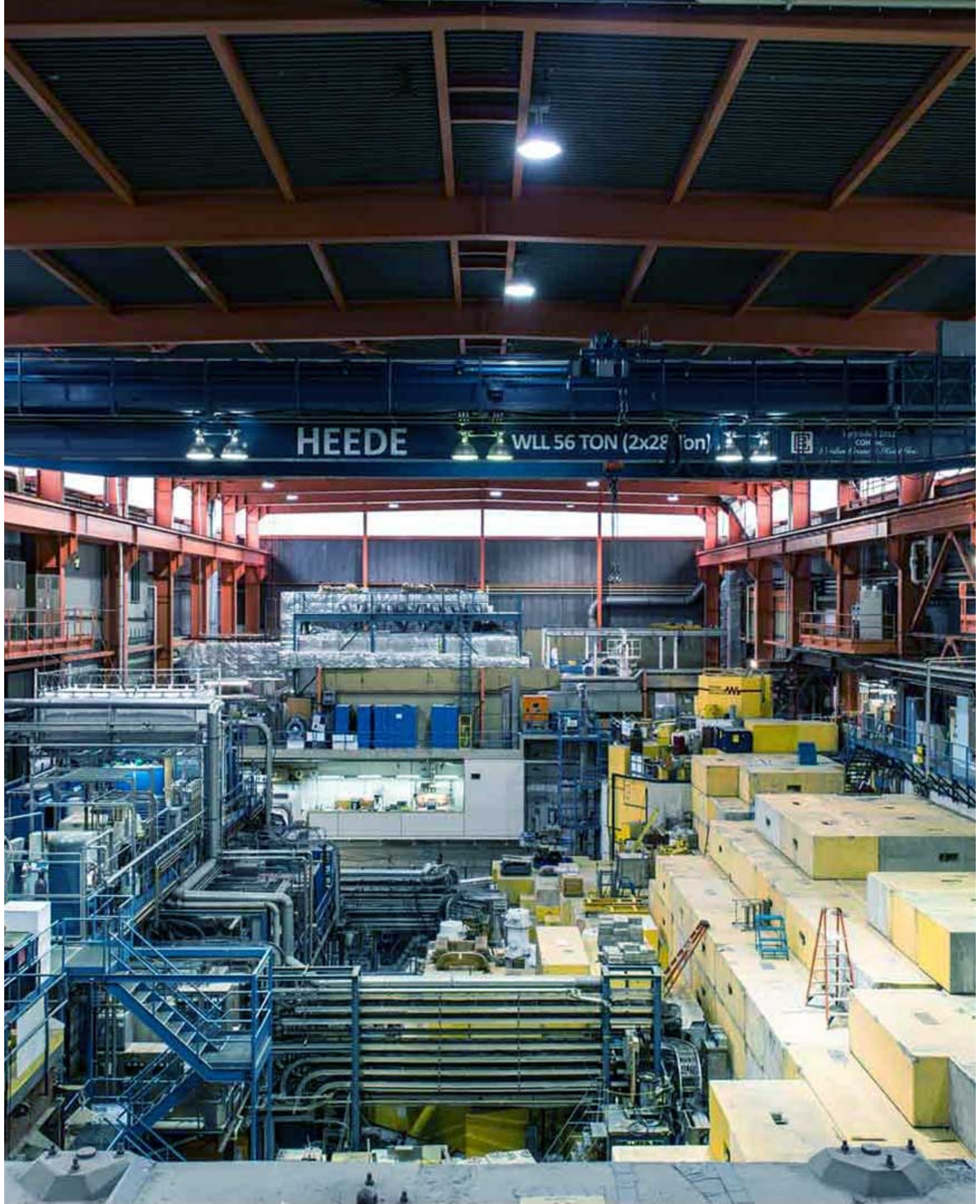
- ^{4}He+^{3}H and ^{6}Li+n coupled calculations
- First results for ^{6}Li(n,t)^{4}He



Next to do: ^{4}He+^{3}H and ^{6}Li+n and ^{6}He+p coupled calculations

TRIUMF

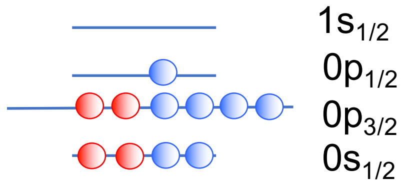
Parity inversion in ^{11}Be ground state

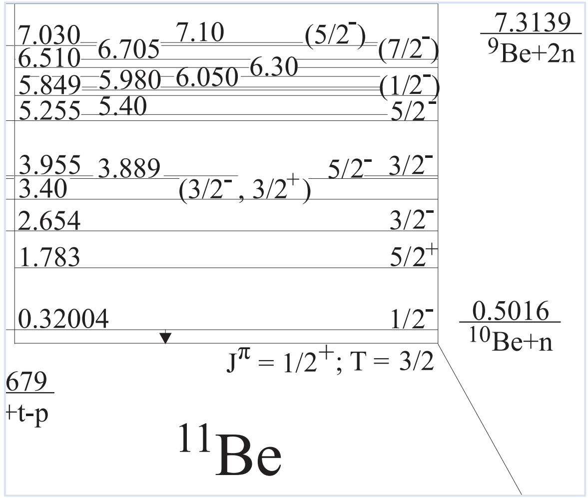


Discovery, accelerated

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 **$J^{\pi}=1/2^{+}$** - 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

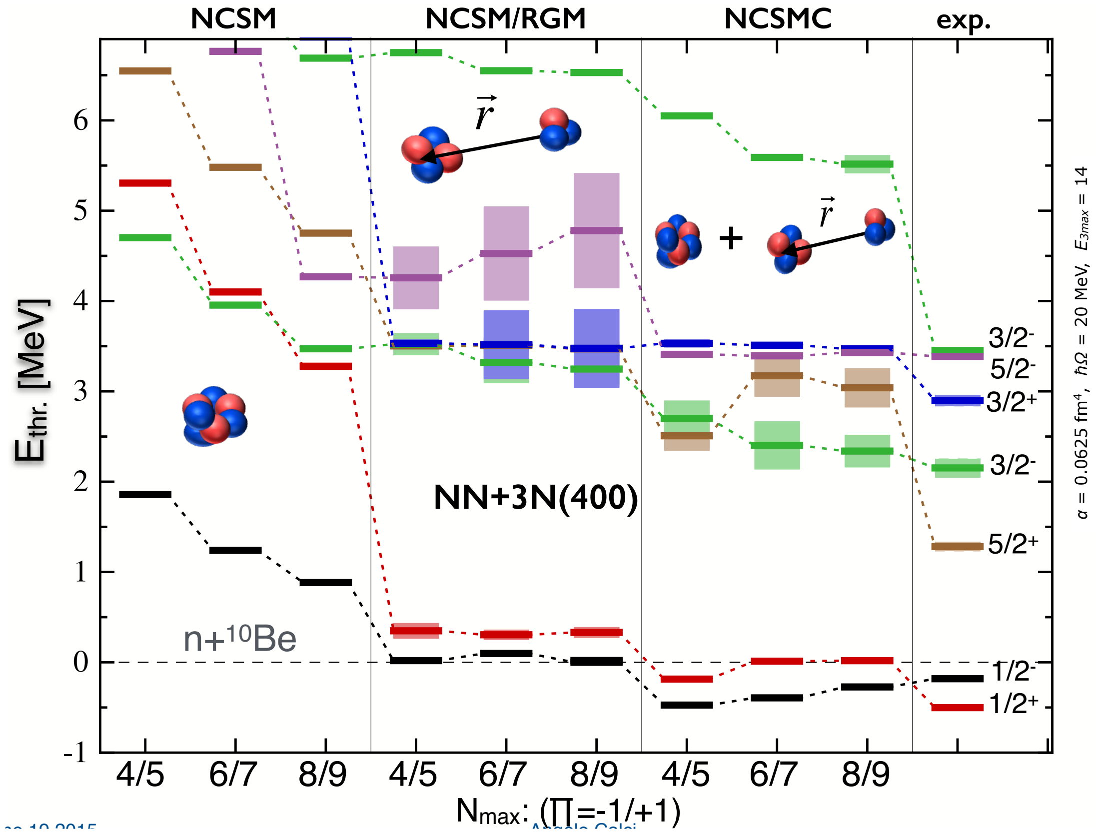


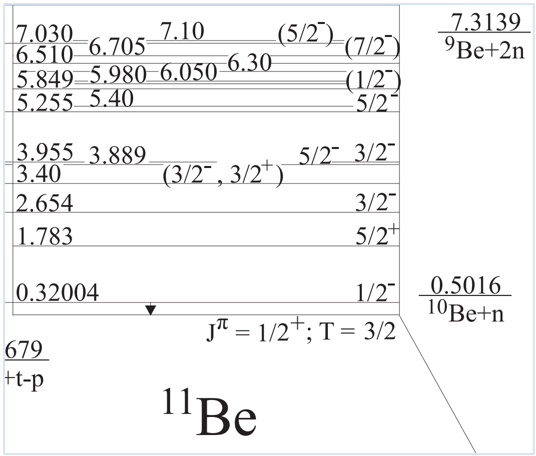


- Can we describe ^{11}Be in *ab initio* calculations?
  - Continuum must be included
  - Does the 3N interaction play a role in the parity inversion?

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

- NCSMC calculations **including chiral 3N** (NN N^3LO+N^2LO 3N(400), N^2LO_{sat}, NN N^4LO+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



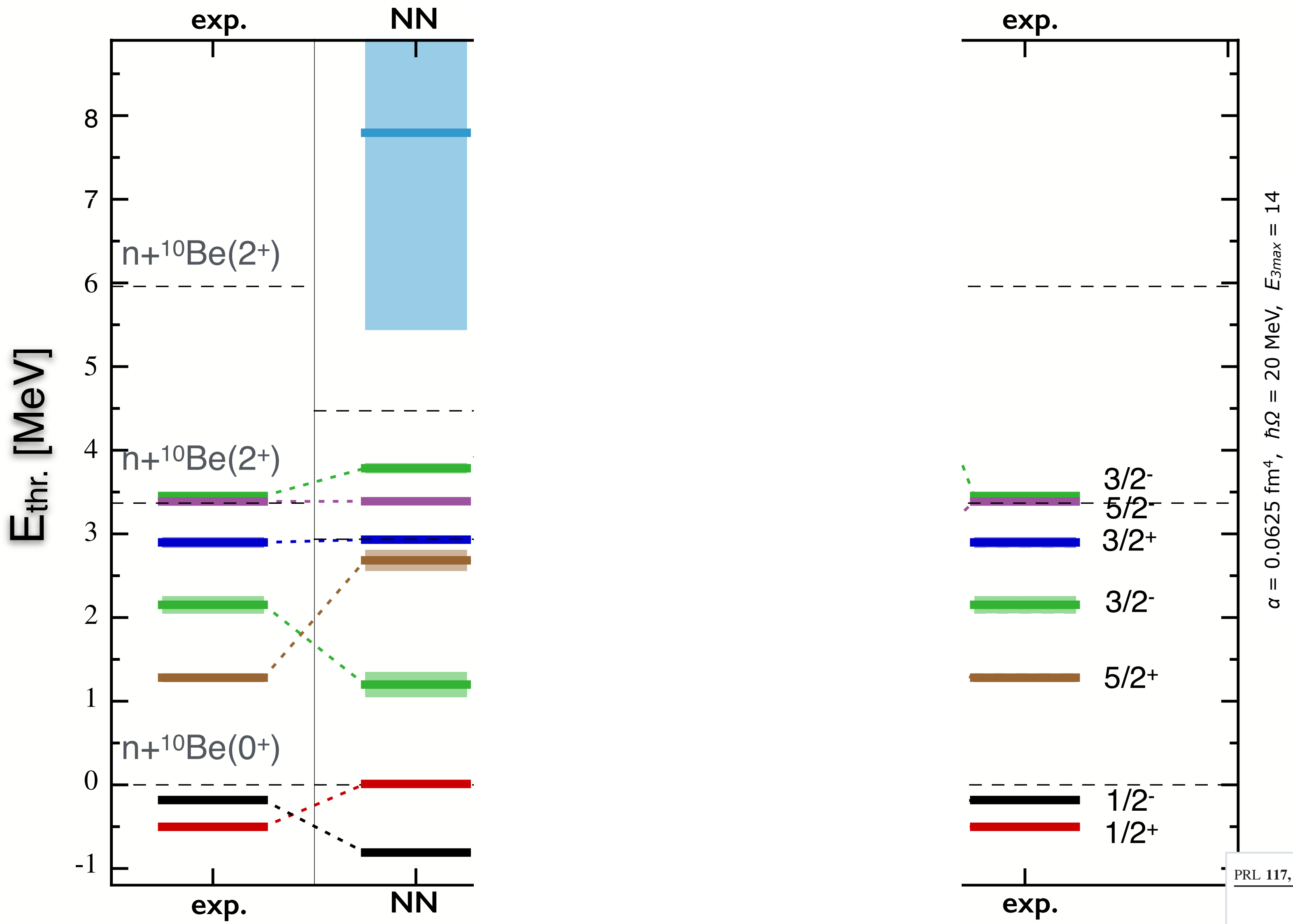


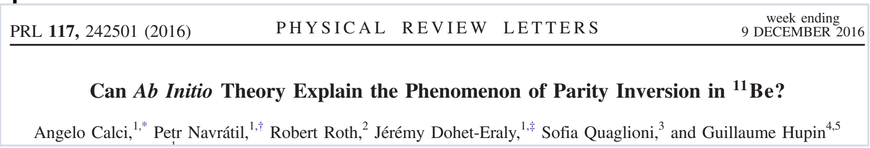
PRL 117, 242501 (2016) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2016

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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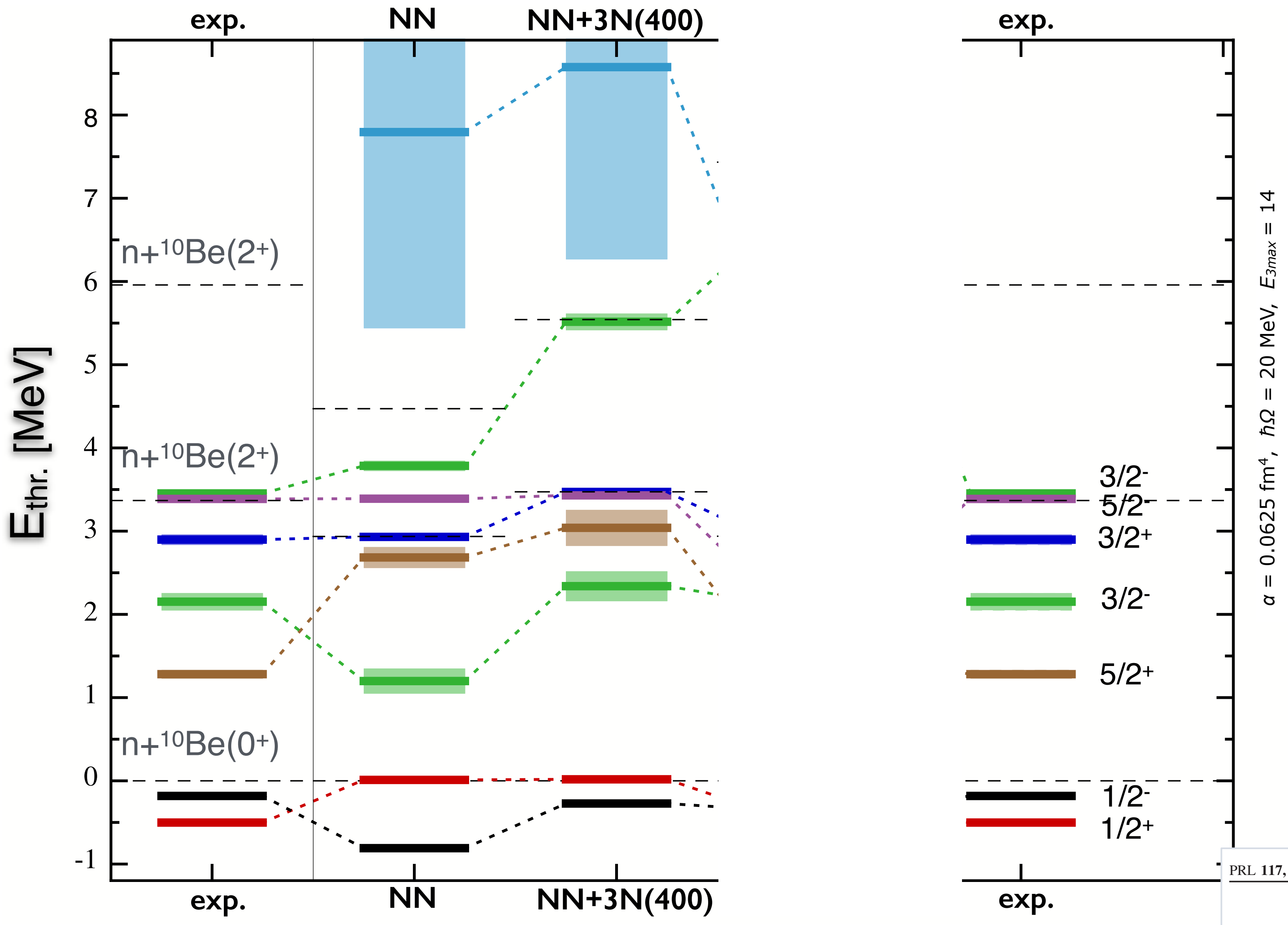

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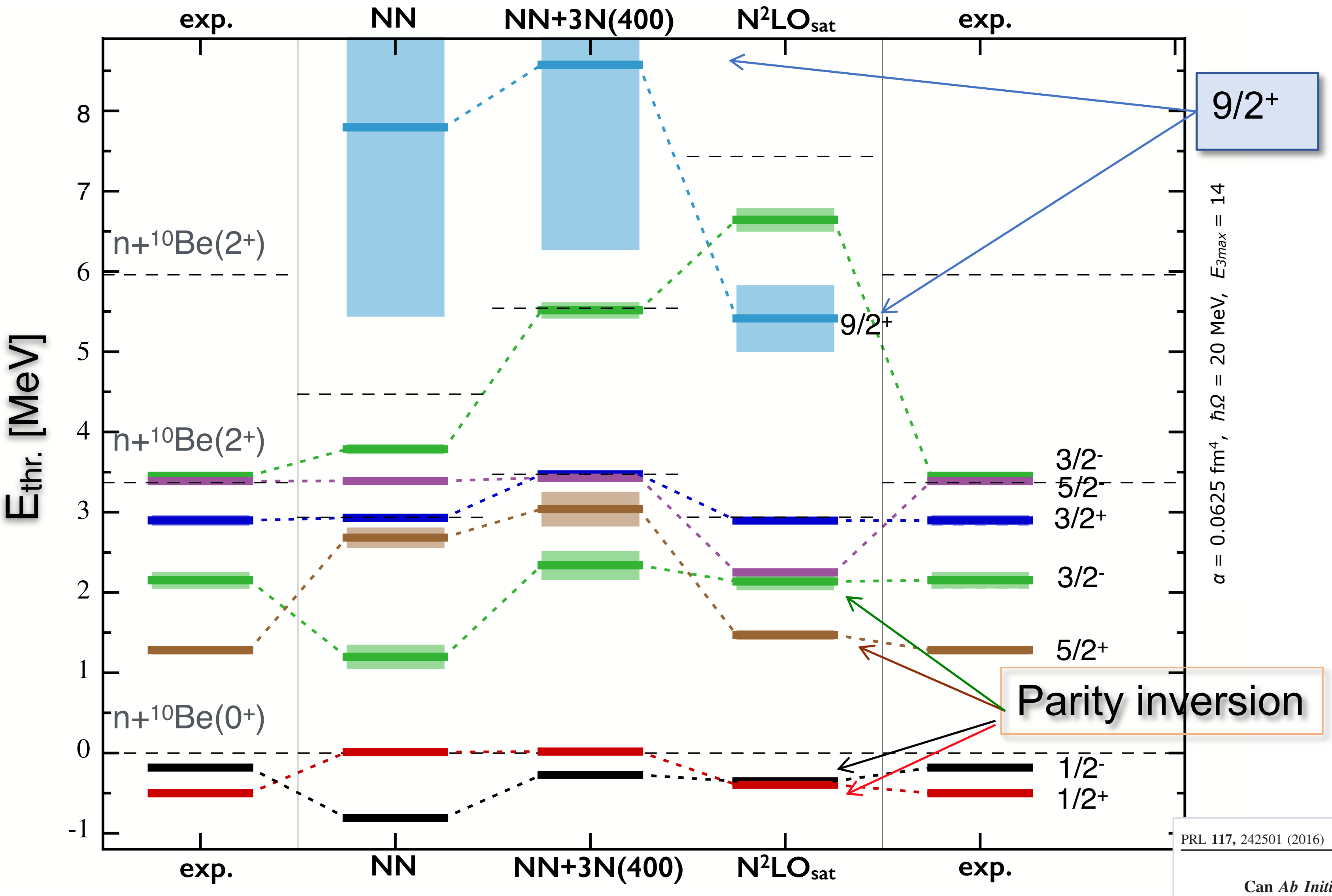

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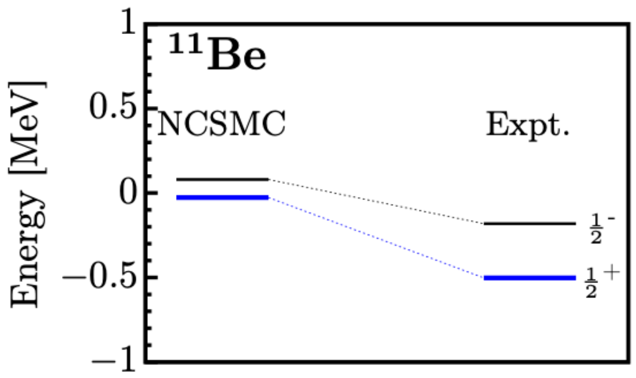
New calculations with NN N^{4}LO500+3N$_{lnl}$

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

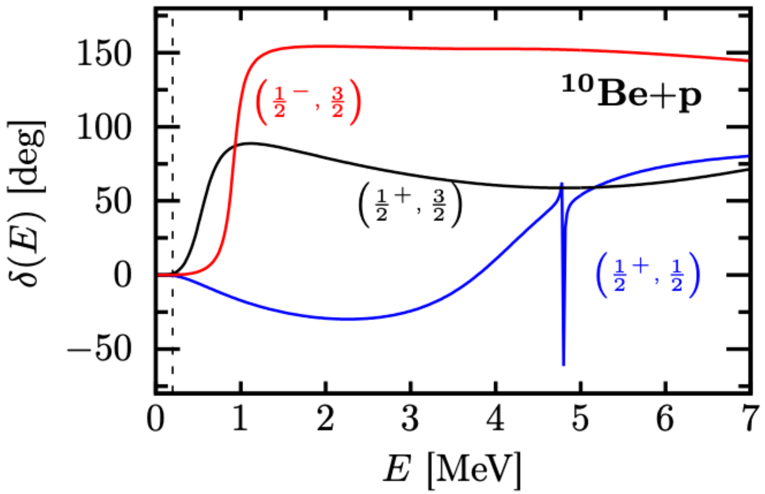
***Ab initio* calculation of the β decay from ^{11}Be to a ^{10}Be + p resonance**

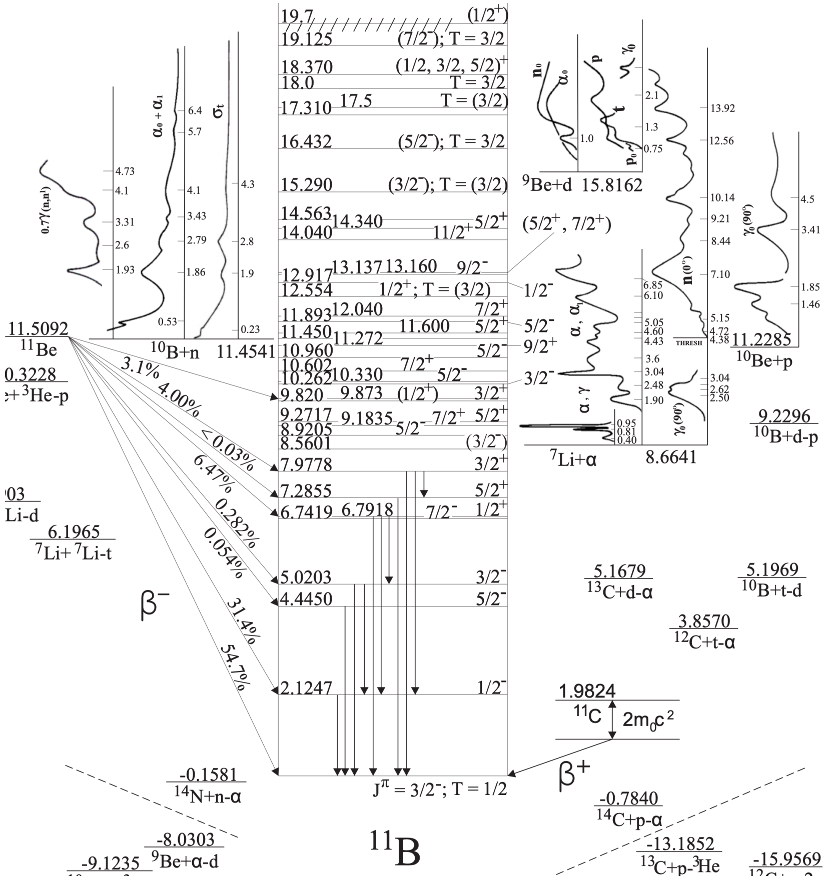
M. C. Atkinson,[1] P. Navrátil,[1] G. Hupin,[2] K. Kravvaris,[3] and S. Quaglioni[3]

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



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



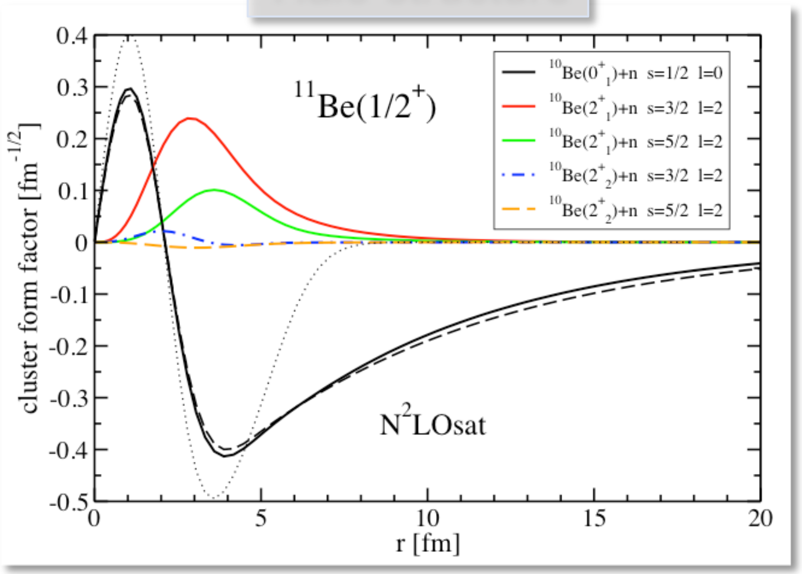


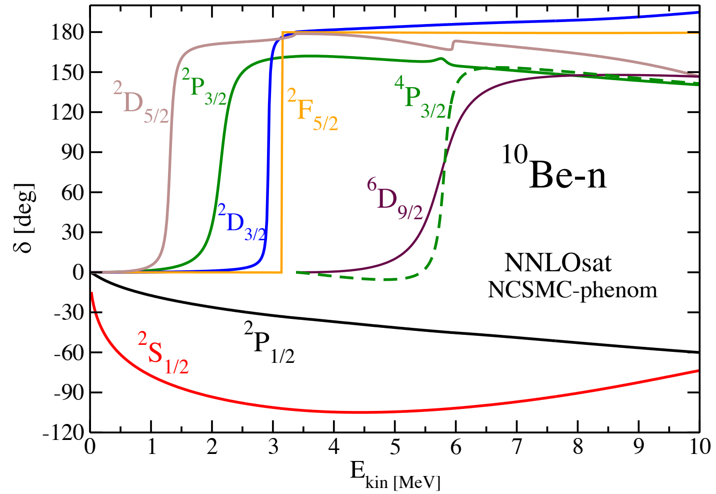
Parity inversion reproduced

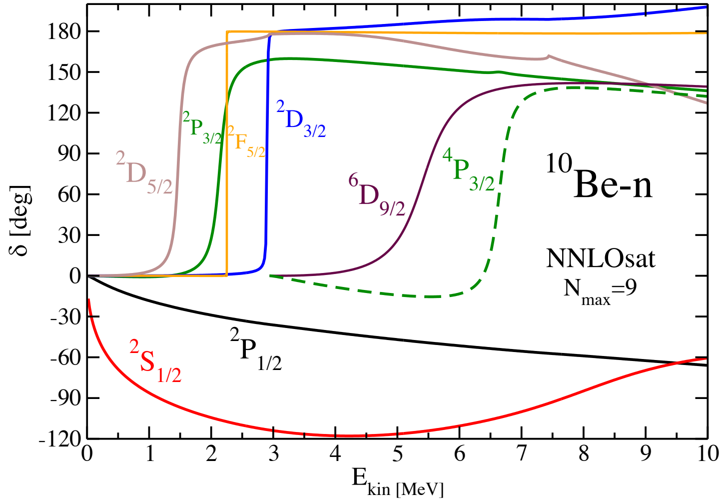
Photo-disassociation of ^{11}Be

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

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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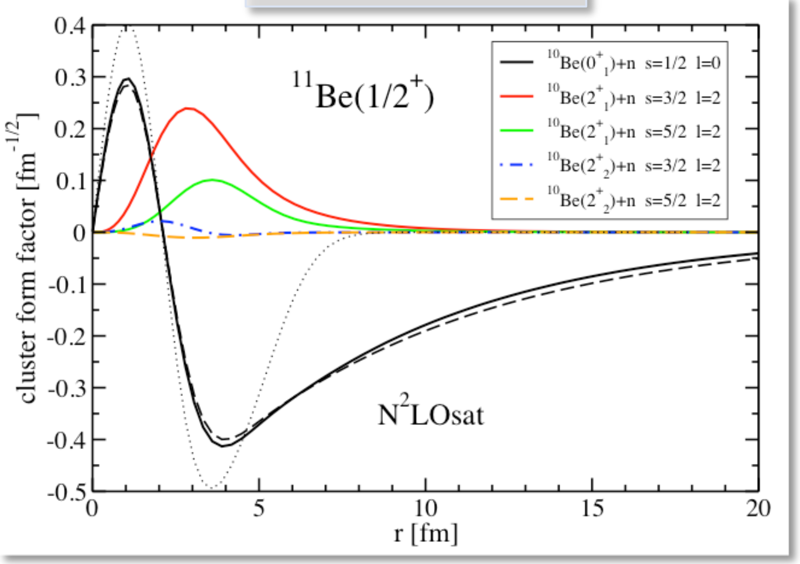


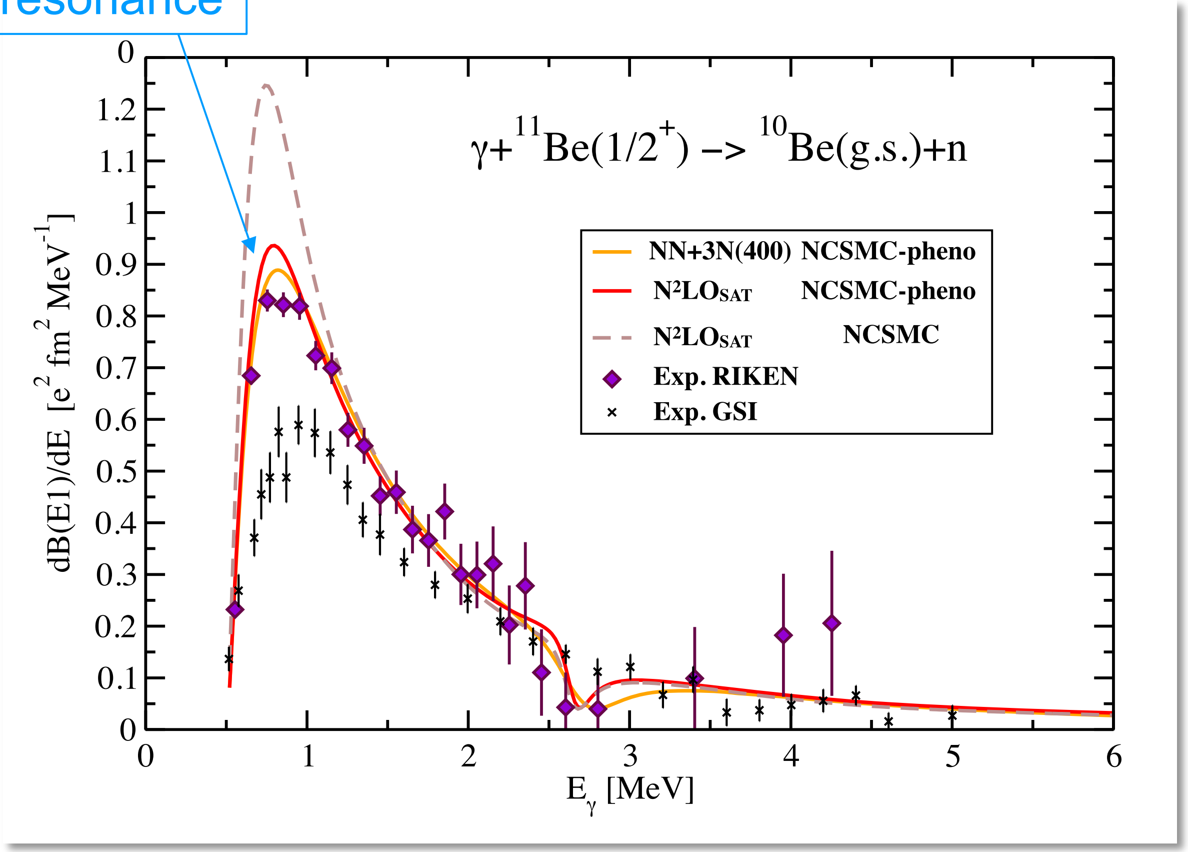
cluster form factor

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

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

Bound to continuum

Not a resonance



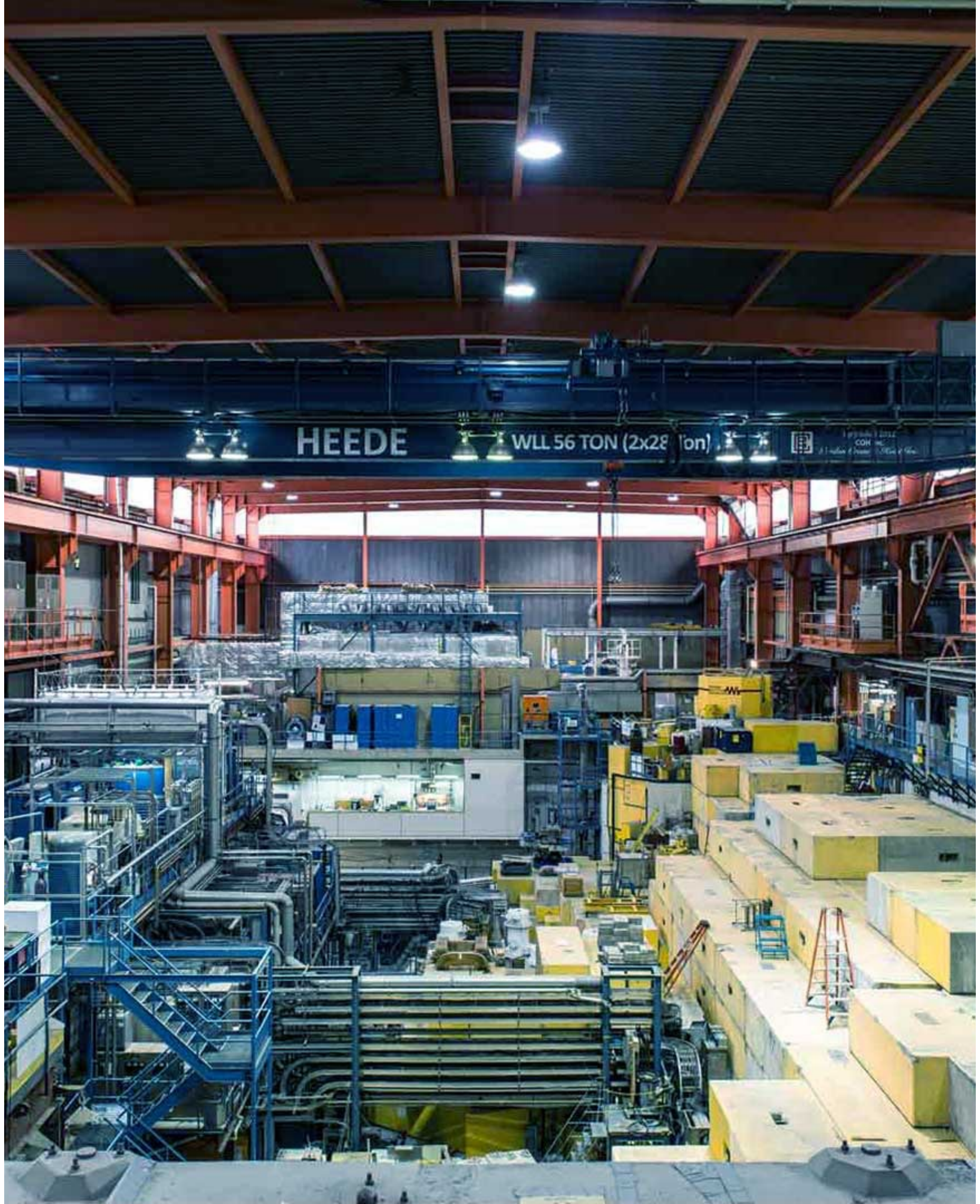
PRL 117, 242501 (2016) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2016

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]

TRIUMF

β-delayed proton emission in ^{11}Be



Discovery,
accelerated

β-delayed proton emission in ^{11}Be

Physics Letters B 732 (2014) 305–308

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Physics Letters B

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^{11}Be(βp), a quasi-free neutron decay?

K. Riisager[a,*], O. Forstner[b,c], M.J.G. Borge[d,e], J.A. Briz[e], M. Carmona-Gallardo[e], L.M. Fraile[f], H.O.U. Fynbo[a], T. Giles[g], A. Gottberg[e,g], A. Heinz[h], J.G. Johansen[a,1], B. Jonson[h], J. Kurcewicz[d], M.V. Lund[a], T. Nilsson[h], G. Nyman[h], E. Rapisarda[d], P. Steier[b], O. Tengblad[e], R. Thies[h], S.R. Winkler[b]

- Indirectly observed $^{11}\text{Be}(\beta p)^{10}\text{Be}$
- Measured an extremely high branching ratio $b_p = 8.3 \pm 0.9 \times 10^{-6}$
  - Orders of magnitude larger than theoretical predictions (*e.g.* 3.0×10^{-8})
- Two proposed explanations:

D. Baye and E.M. Tursunov, PLB **696**, 4, 464-467 (2011)

1. The neutron decays to an unobserved $p+^{10}\text{Be}$ resonance in ^{11}B
2. There are unobserved dark decay modes

β-delayed proton emission in ^{11}Be

Eur. Phys. J. A (2020) 56:100
https://doi.org/10.1140/epja/s10050-020-00110-2

THE EUROPEAN PHYSICAL JOURNAL A

Check for updates

Regular Article - Experimental Physics

Search for beta-delayed proton emission from ^{11}Be

K. Riisager[1,a], M. J. G. Borge[2,3], J. A. Briz[3], M. Carmona-Gallardo[4], O. Forstner[5], L. M. Fraile[4], H. O. U. Fynbo[1], A. Garzon Camacho[3], J. G. Johansen[1], B. Jonson[6], M. V. Lund[1], J. Lachner[5], M. Madurga[2], S. Merchel[7], E. Nacher[3], T. Nilsson[6], P. Steier[5], O. Tengblad[3], V. Vedia[4]

- New Accelerator Mass Spectrometry experiment that supersedes the 2014 measurement
  - Branching ratio b_p ~ 2.2 x 10^{-6}
    - Upper limit, possible contamination by BeH molecular ions

β-delayed proton emission in ^{11}Be

PHYSICAL REVIEW LETTERS **123**, 082501 (2019)

Editors' Suggestion

Direct Observation of Proton Emission in ^{11}Be

Y. Ayyad,[1,2,*] B. Olaizola,[3] W. Mittig,[2,4] G. Potel,[1] V. Zelevinsky,[1,2,4] M. Horoi,[5] S. Beceiro-Novo,[4] M. Alcorta,[3] C. Andreoiu,[6] T. Ahn,[7] M. Anholm,[3,8] L. Atar,[9] A. Babu,[3] D. Bazin,[2,4] N. Bernier,[3,10] S. S. Bhattacharjee,[3] M. Bowry,[3] R. Caballero-Folch,[3] M. Cortesi,[2] C. Dalitz,[11] E. Dunling,[3,12] A. B. Garnsworthy,[3] M. Holl,[3,13] B. Kootte,[3,8] K. G. Leach,[14] J. S. Randhawa,[2] Y. Saito,[3,10] C. Santamaria,[15] P. Šiurytė,[3,16] C. E. Svensson,[9] R. Umashankar,[3] N. Watwood,[2] and D. Yates[3,10]

- Directly observed the protons from $^{11}\text{Be}(\beta p)^{10}\text{Be}$
- Measured consistent branching ratio $b_p = 1.3(3) \times 10^{-5}$
  - Still orders of magnitude larger than theoretical predictions
- Predict the proton resonance at 11.425(20) MeV from the proton energy distribution
  - Predicted to be either $\frac{1}{2}^+$ or $\frac{3}{2}^+$
  - Corresponds to excitation energy of 197 keV

NCSMC extended to describe exotic ^{11}Be βp emission

^{11}Be or ^{11}B

$$\left|\Psi_A^{J^\pi T}\right\rangle = \sum_\lambda c_\lambda^{J^\pi T} |A\lambda J^\pi T\rangle + \sum_\nu \int dr r^2 \frac{\gamma_\nu^{J^\pi T}(r)}{r} \hat{\mathcal{A}}_\nu \left|\Phi_{\nu r}^{J^\pi T}\right\rangle$$

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

n for ^{11}Be or p for ^{11}B

Including 0^+_{gs} and 2^+_1 states of ^{10}Be

$$B(\mathrm{GT}) = \frac{1}{2}\left|\left\langle \Psi_{^{11}B}^{\frac{1}{2}^+\frac{1}{2}} \right\| \hat{\mathrm{GT}} \left\| \Psi_{^{11}\mathrm{Be}}^{\frac{1}{2}^+\frac{3}{2}} \right\rangle\right|^2$$

Input chiral interaction

NN N^{4}LO(500) + 3N(lnl)

Entem-Machleidt-Nosyk 2017

3N N^{2}LO w local/non-local regulator

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]

Gamow-Teller and Fermi β-decay in NCSMC

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]

- Compute GT and Fermi matrix element in NCSMC

$$M_F = \left\langle \Psi^{J^\pi T_f M_{T_f}} \middle| T_+ \middle| \Psi^{J^\pi T_i M_{T_i}} \right\rangle$$

- Total isospin (or GT) operator $T_+ = T_+^{(1)} + T_+^{(2)}$ for partitioned system

$$M_F \sim \langle A\lambda_f J_f T_f M_{T_f} | T_+ | A\lambda J_i T_i M_{T_i} \rangle + \langle A\lambda J_f T_f M_{T_f} | T_+ \mathcal{A}_{\nu i} | \Phi_{\nu r}^{J_i T_i M_{T_i}} \rangle$$
$$+ \langle \Phi_{\nu r}^{J_f T_f M_{T_f}} | \mathcal{A}_{\nu f} T_+ | A\lambda_i J_i T_i M_{T_i} \rangle + \langle \Phi_{\nu r}^{J_f T_f M_{T_f}} | \mathcal{A}_{\nu f} T_+ \mathcal{A}_{\nu i} | \Phi_{\nu r}^{J_i T_i M_{T_i}} \rangle$$

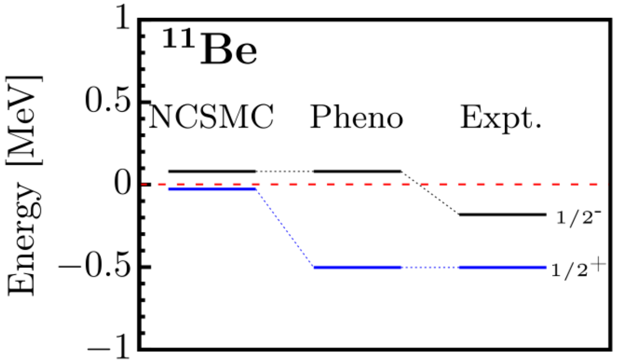
NCSM matrix element

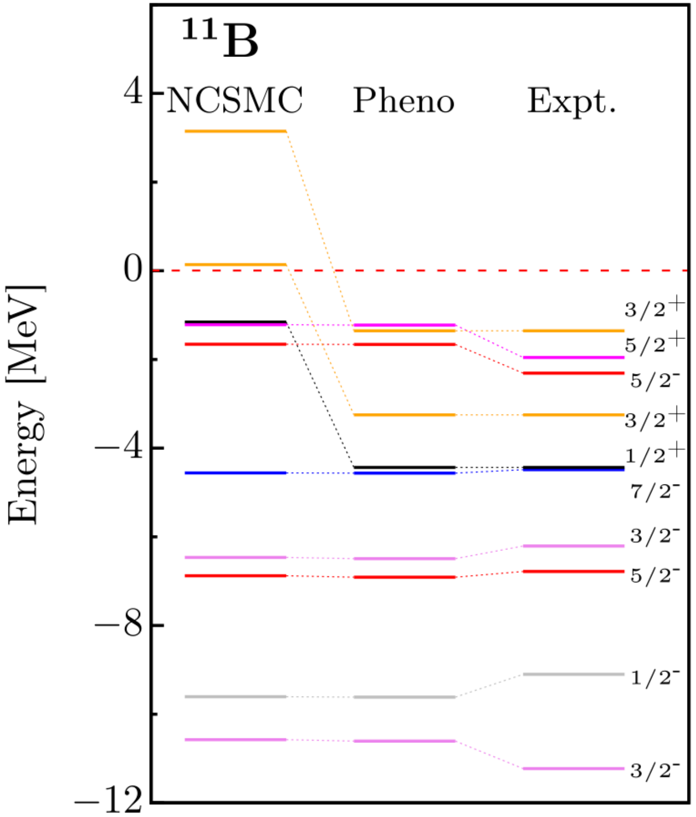
NCSM-Cluster matrix elements

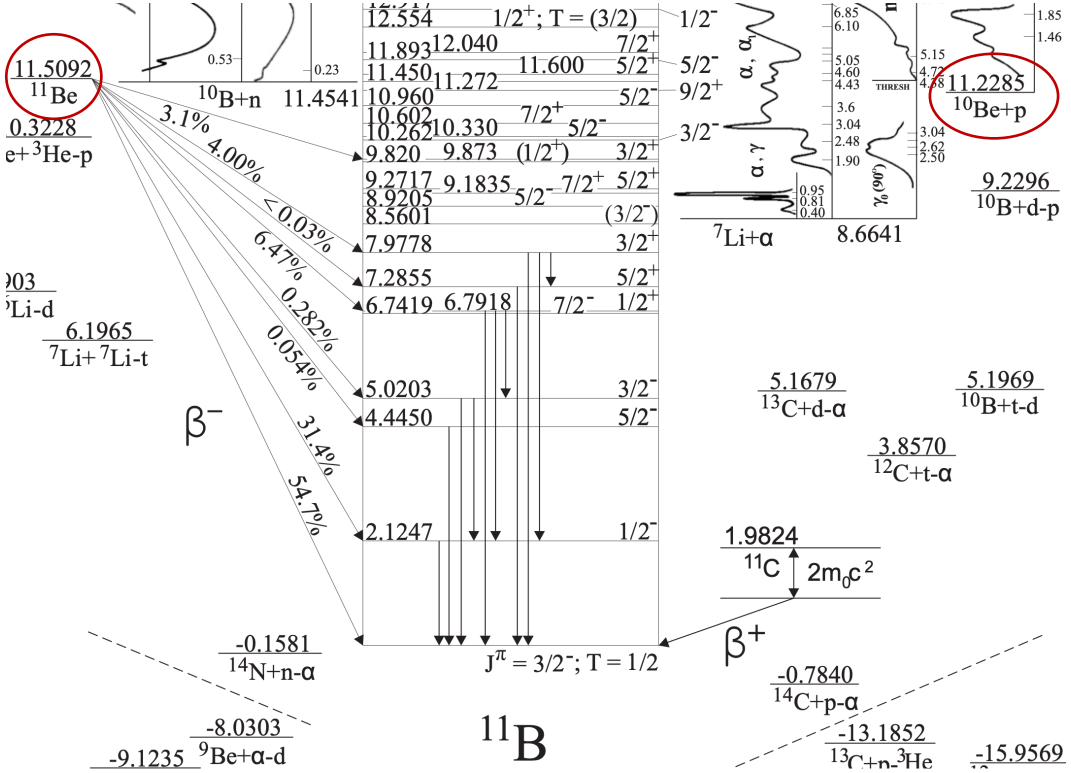
Continuum (cluster) matrix element

^{11}Be and ^{11}B nuclear structure results

- Bound states wrt ^{10}Be+N thresholds

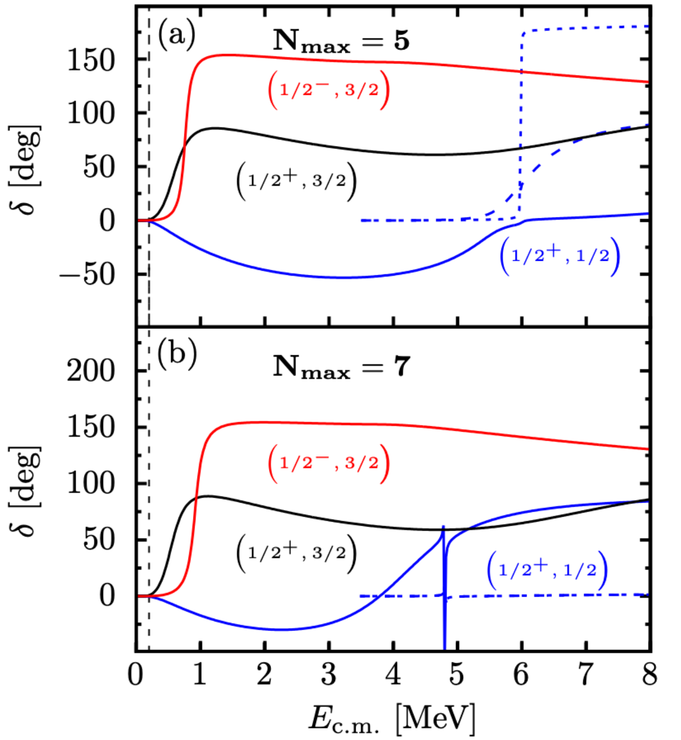




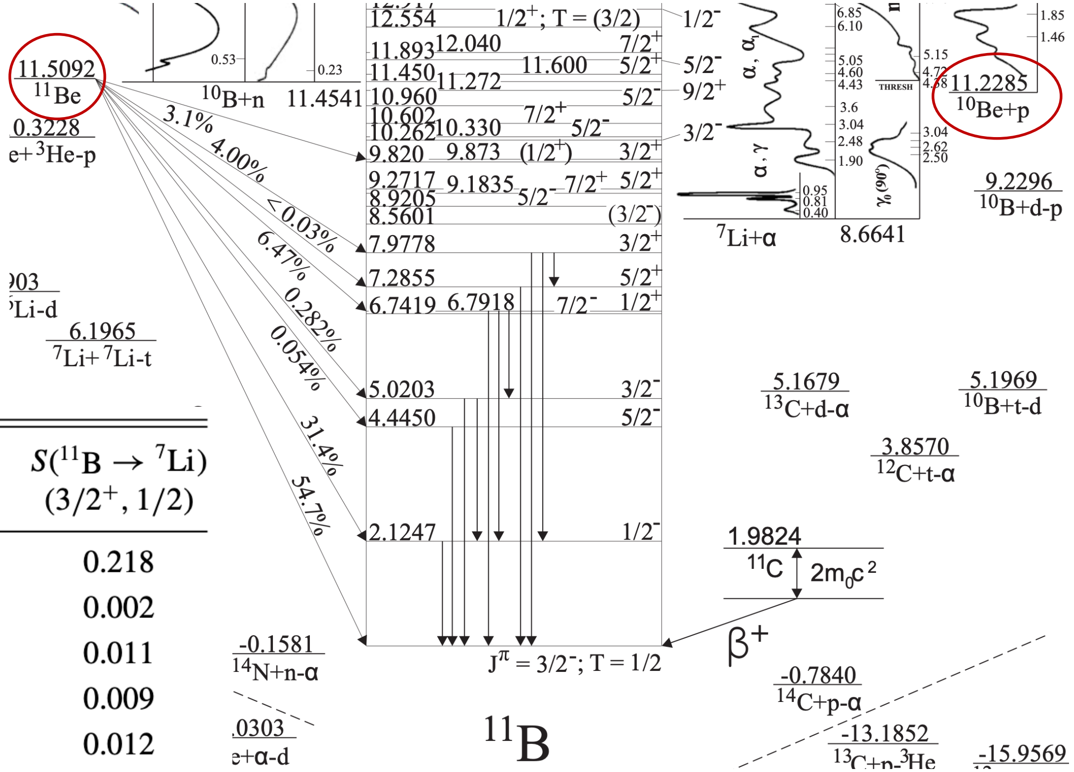


^{11}Be and ^{11}B nuclear structure results

- ^{11}B resonances above ^{10}Be+p threshold



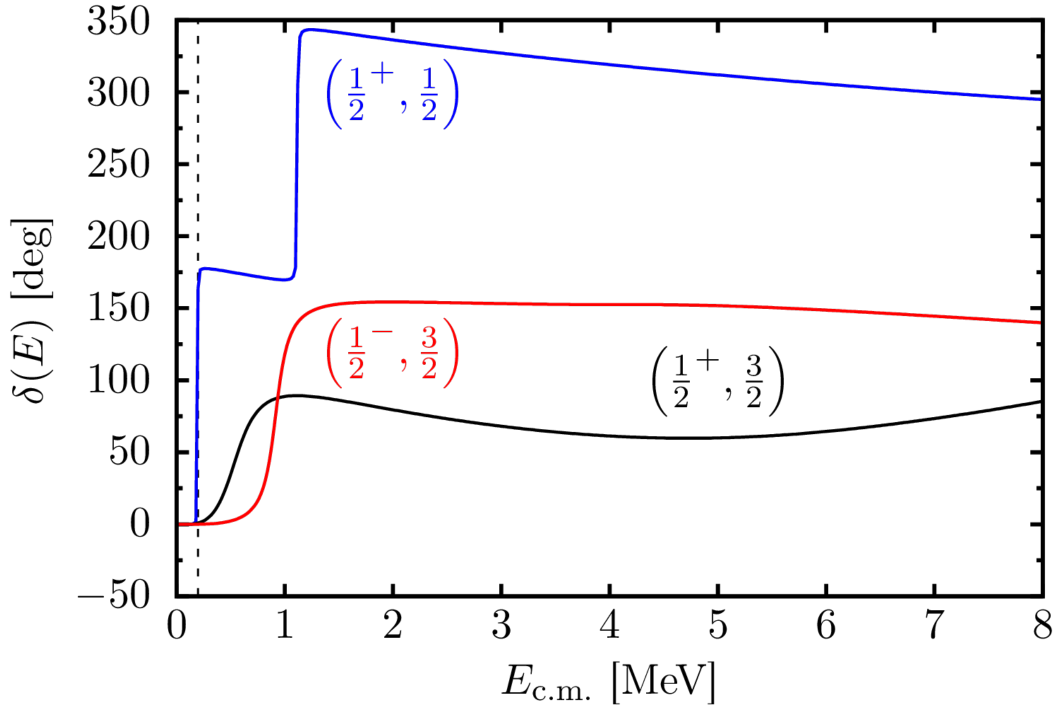
J^π	$S(^{11}B \rightarrow {}^{10}Be)$ $(0^+, 1)$	$S(^{11}B \rightarrow {}^{10}B)$ $(1_1^+, 0)$	$(1_2^+, 0)$	$S(^{11}B \rightarrow {}^{7}Li)$ $(3/2^+, 1/2)$
$1/2_1^+$	0.276	0.250	2×10^{-4}	0.218
$1/2_2^+$	0.0525	0.171	0.562	0.002
$1/2_3^+$	0.067	0.231	0.188	0.011
$3/2_1^+$	0.079	6×10^{-4}	0.215	0.009
$3/2_2^+$	4×10^{-4}	0.581	0.002	0.012
$3/2_3^+$	6×10^{-4}	0.011	0.006	0.021
$3/2_4^+$	0.067	0.034	0.35	0.006



NCSMC extended to describe exotic ^{11}Be βp emission, supports large branching ratio due to narrow ½⁺ resonance

$^{11}\text{Be} \rightarrow (^{10}\text{Be+p}) + \beta^{-} + \bar{\nu}_e$ GT transition

p+^{10}Be Scattering Phase Shifts



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]

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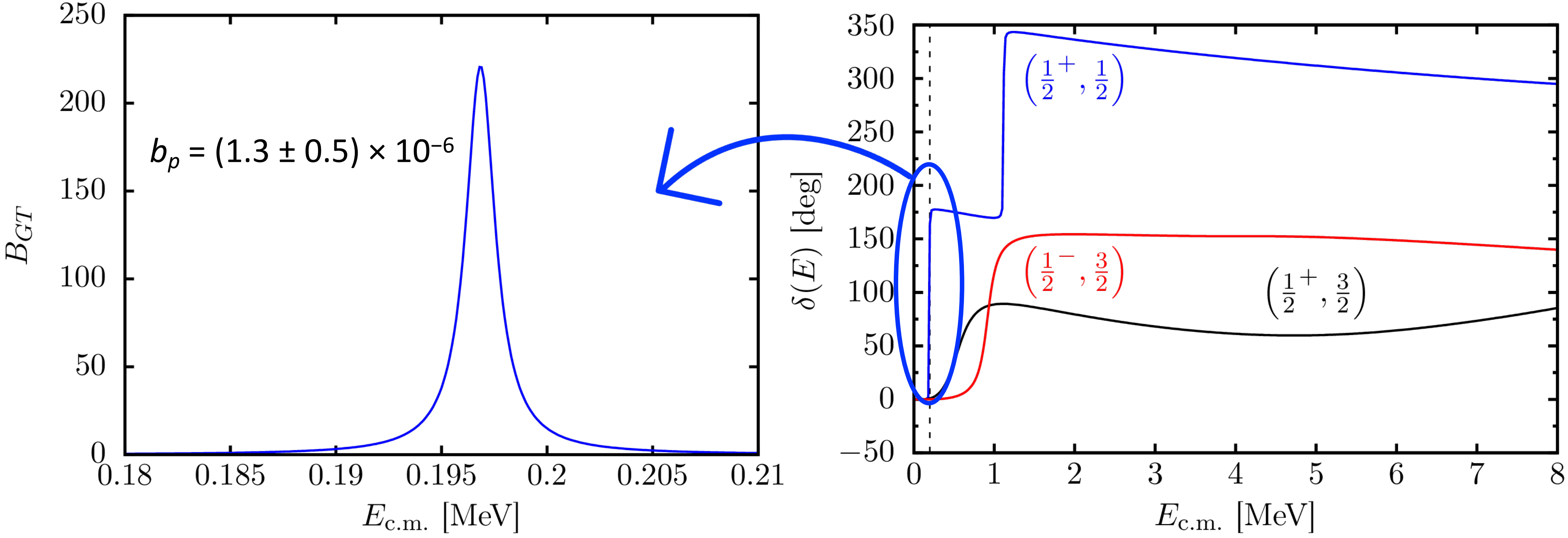

PHYSICAL REVIEW C **105**, 054316 (2022)

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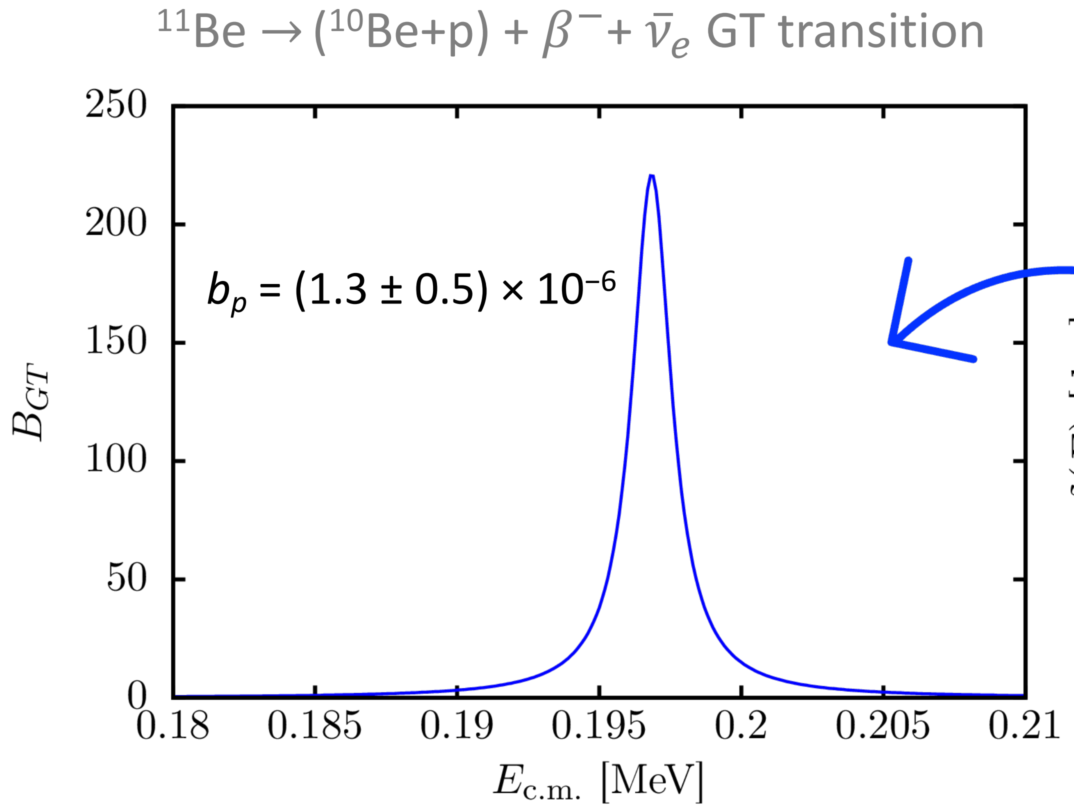
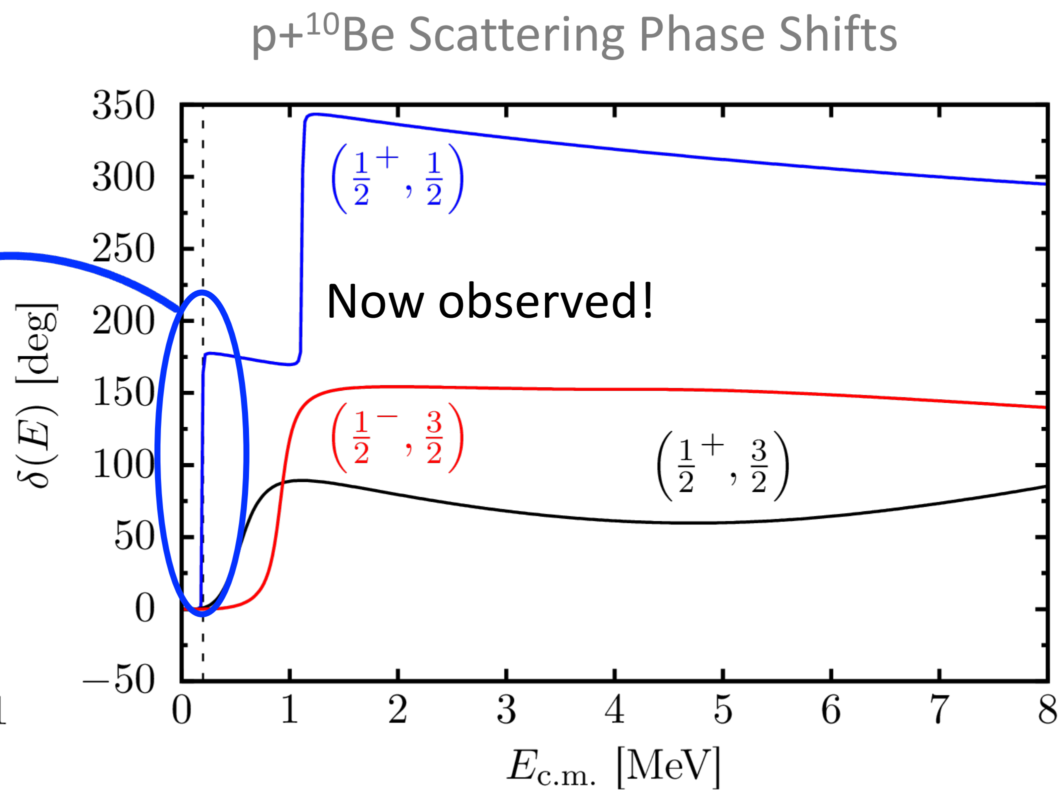




PHYSICAL REVIEW LETTERS **129**, 012502 (2022)

Observation of a Near-Threshold Proton Resonance in ^{11}B

E. Lopez-Saavedra,[1,*] S. Almaraz-Calderon,[1,†] B. W. Asher,[1] L. T. Baby,[1] N. Gerken,[1] K. Hanselman,[1] K. W. Kemper,[1] A. N. Kuchera,[2] A. B. Morelock,[1] J. F. Perello,[1] E. S. Temanson,[1] A. Volya,[1] and I. Wiedenhöver[1]

PHYSICAL REVIEW LETTERS **129**, 012501 (2022)

Evidence of a Near-Threshold Resonance in ^{11}B Relevant to the β-Delayed Proton Emission of ^{11}Be

Y. Ayyad,[1,2,*] W. Mittig,[2,3] T. Tang,[2] B. Olaizola,[4] G. Potel,[5] N. Rijal,[2] N. Watwood,[2] H. Alvarez-Pol,[1] D. Bazin,[2,3] M. Caamaño,[1] J. Chen,[6] M. Cortesi,[2] B. Fernández-Domínguez,[1] S. Giraud,[2] P. Gueye,[2,3] S. Heinitz,[7] R. Jain,[2,3] B. P. Kay,[6] E. A. Maugeri,[7] B. Monteagudo,[2] F. Ndayisabye,[2,3] S. N. Paneru,[2] J. Pereira,[2] E. Rubino,[2] C. Santamaria,[2] D. Schumann,[7] J. Surbrook,[2,3] L. Wagner,[2] J. C. Zamora,[2] and V. Zelevinsky[2,3]

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]

β-delayed proton emission in ^{11}Be

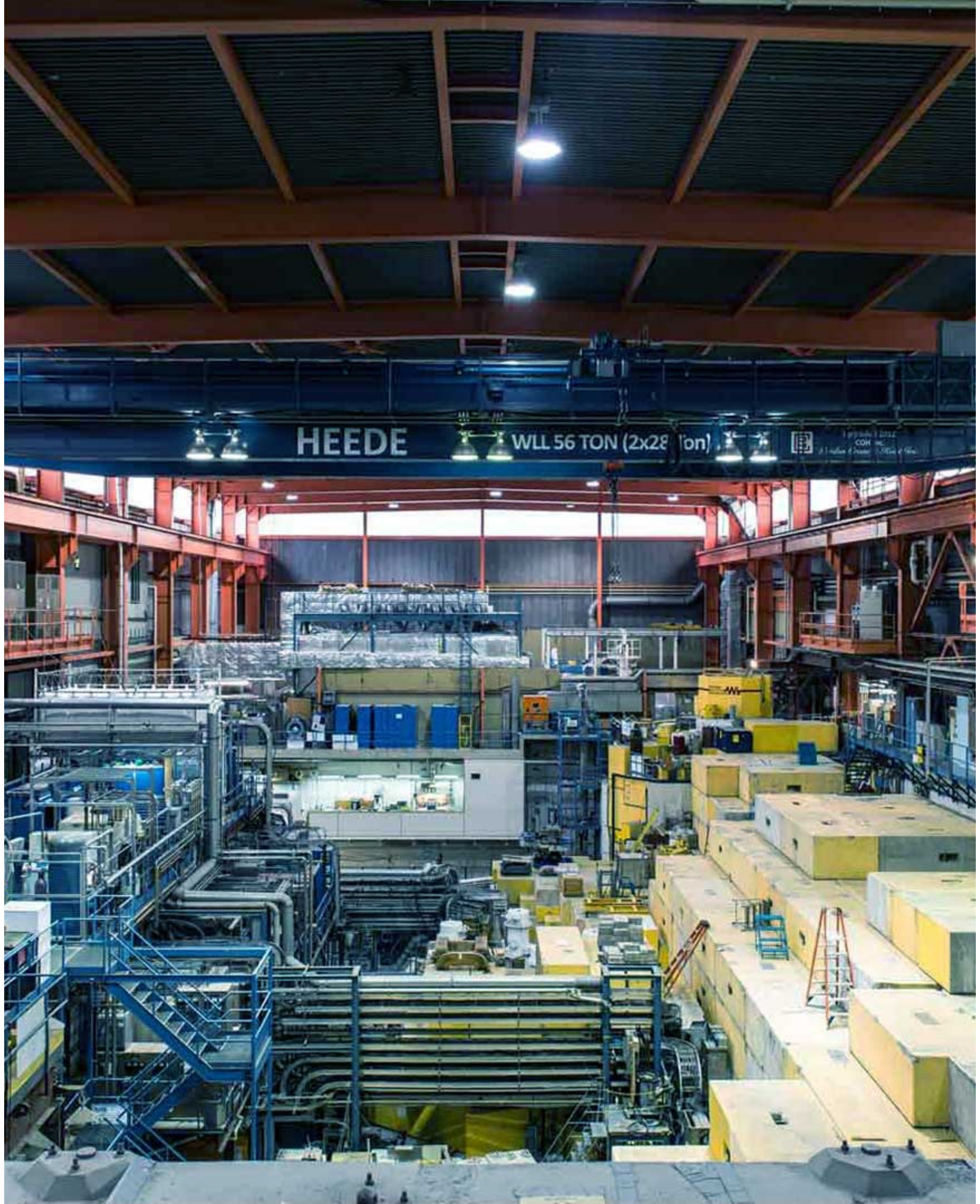
- New FRIB experiment measuring proton emission led by Jason Surbrook reports branching ratio $b_p \sim 8(4) \times 10^{-6}$
  - Lower but still consistent with Ayyad TRIUMF experiment

- More experiments planned!

- NCSMC calculations will be extended by **including the ^{7}Li+α** mass partition

TRIUMF

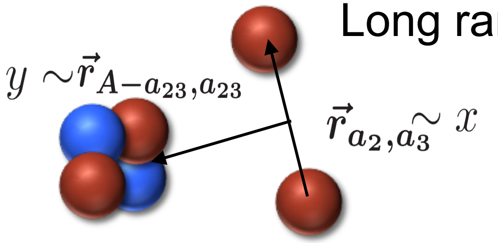
Two-neutron Borromean halo nucleus ^{6}He



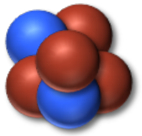
Discovery, accelerated

NCSMC for three-body clusters

NCSM/RGM-3B
Long range description

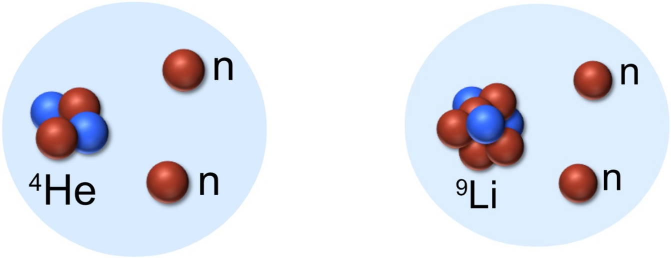


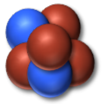
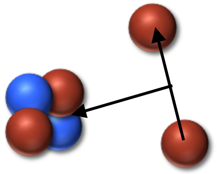
NCSM
Short range description



+

Two-neutron Borromean
halo nuclei



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

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

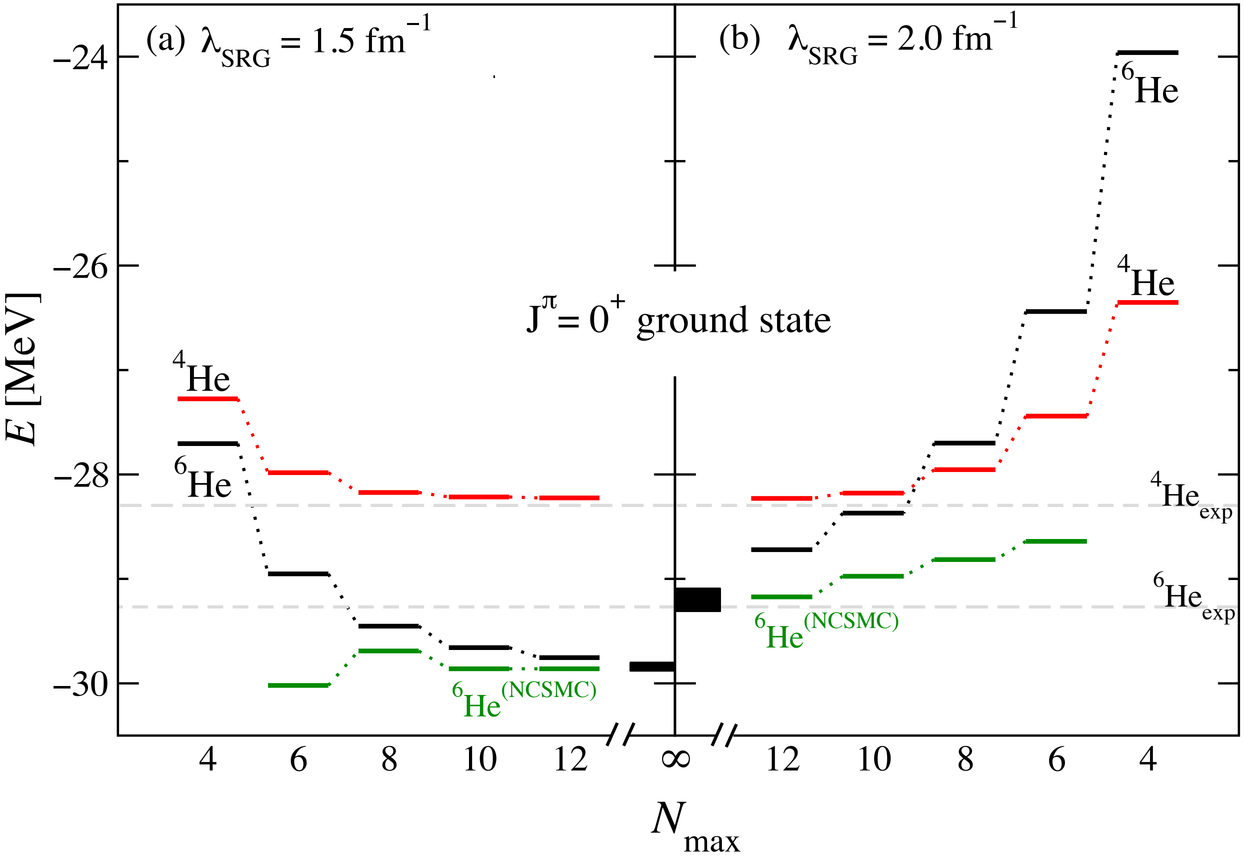
Sofia Quaglioni,[1,*] Carolina Romero-Redondo,[1,†] Petr Navrátil,[2,‡] and Guillaume Hupin[3,§]

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

How Many-Body Correlations and α Clustering Shape ^{6}He

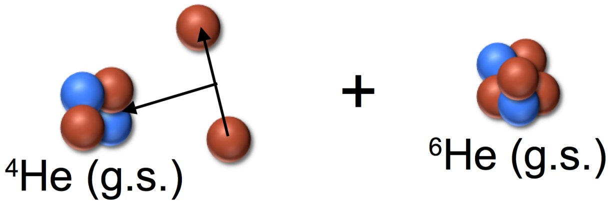
Carolina Romero-Redondo,[1,*] Sofia Quaglioni,[1,†] Petr Navrátil,[2,‡] and Guillaume Hupin[3,§]

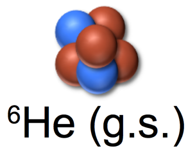
NCSMC for three-body clusters: ^{6}He ~ ^{4}He+n+n



SRG N^{3}LO NN potential

NCSMC vs. NCSM





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PHYSICAL REVIEW C 97, 034332 (2018)

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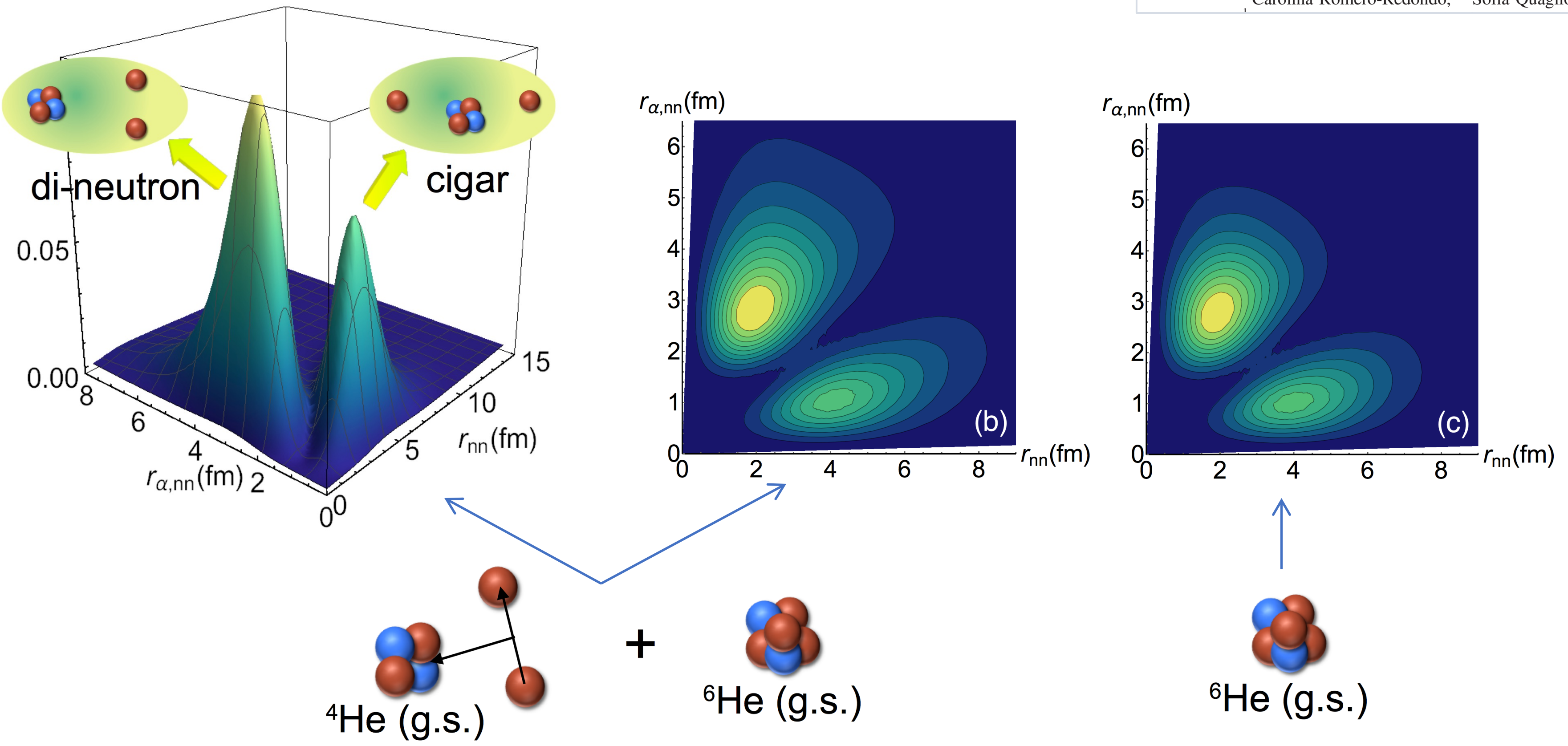
PRL 117, 222501 (2016) PHYSICAL REVIEW LETTERS week ending 25 NOVEMBER 2016

How Many-Body Correlations and α Clustering Shape ^{6}He

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



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

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

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

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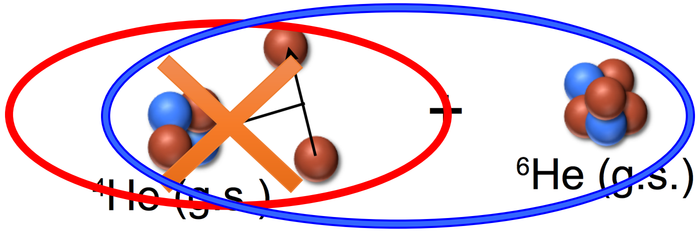
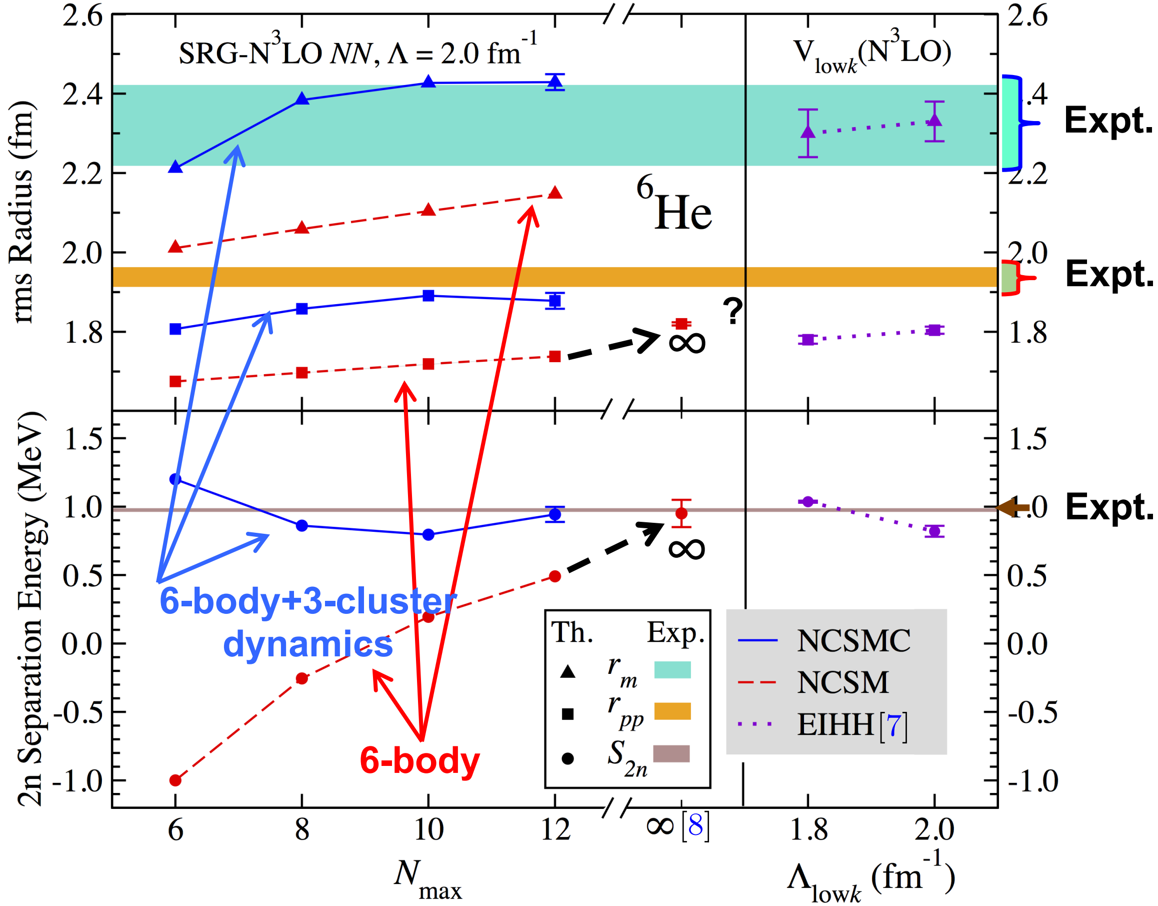
NCSMC for three-body clusters: ^{6}He ~ ^{4}He+n+n





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

Conclusions

- *Ab initio* nuclear theory
  - Makes connections between the low-energy QCD and many-nucleon systems
  - Applicable to nuclear structure, reactions including those relevant for astrophysics, electroweak processes, tests of fundamental symmetries
  - Very recently reach extended to heavy nuclei

- Applications of *ab initio* no-core shell model with continuum to nuclear structure and reactions
  - DT fusion - near threshold $3/2^+$ *S*-wave resonance
  - $1/2^+$ *S*-wave resonance close to the ^{6}He+p threshold in ^{7}Li
  - Parity inversion in ^{11}Be ground state – weakly bound halo state
  - β-delayed proton emission in ^{11}Be - near threshold $1/2^+$ *S*-wave resonance
  - Two-neutron Borromean halo nucleus ^{6}He - di-neutron and cigar configurations in the ground state

In synergy with experiments, *ab initio* nuclear theory is the right approach to understand low-energy properties of atomic nuclei

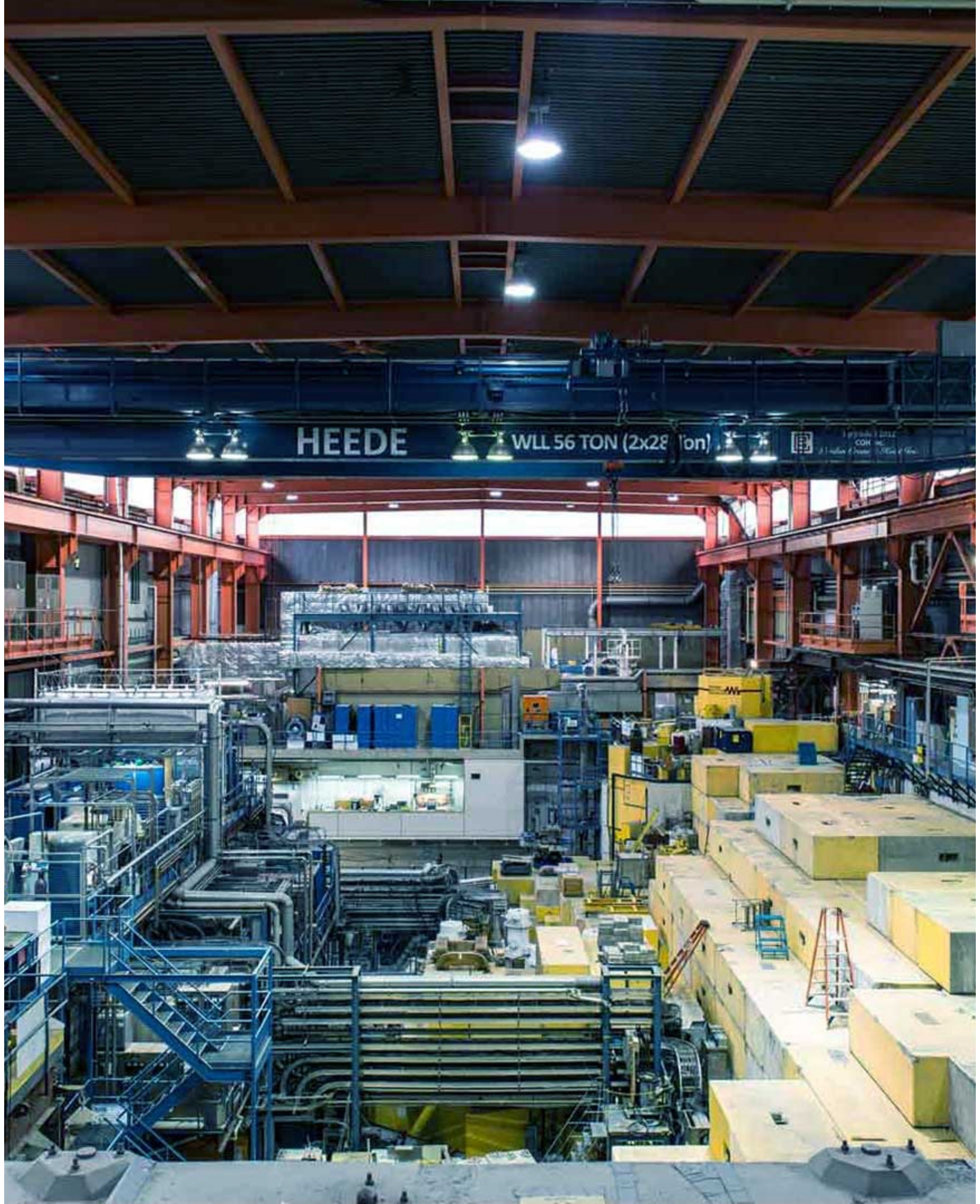
TRIUMF

Thank you!
Merci!
Grazie!

Discovery,
accelerated

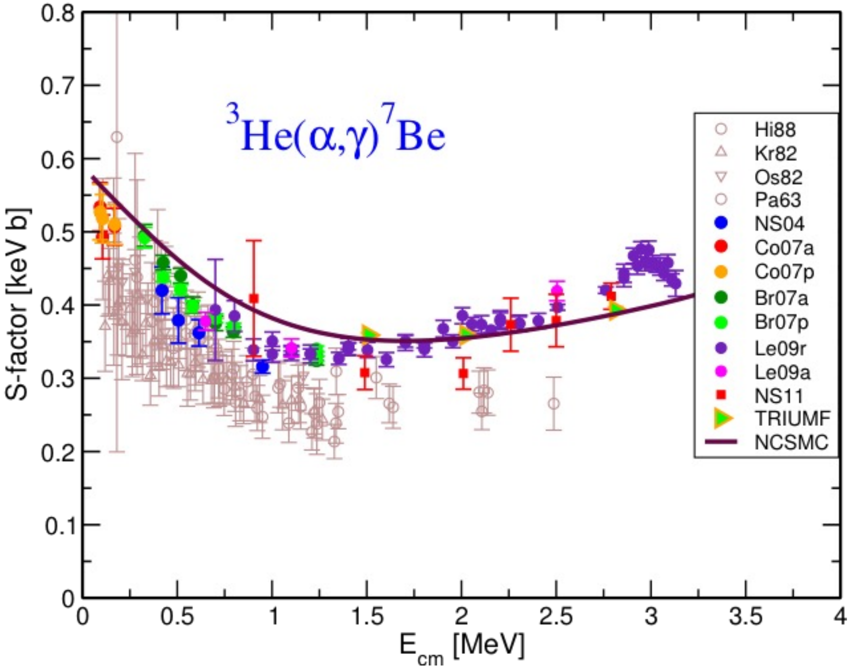
TRIUMF

Backup slides



Discovery,
accelerated

^{7}Be structure and capture reactions important for astrophysics



Physics Letters B 757 (2016) 430–436

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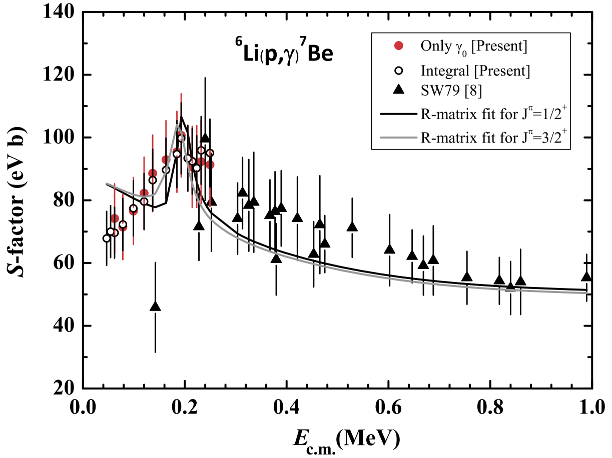
^{3}He$(\alpha,\gamma)^7$Be and ^{3}H$(\alpha,\gamma)^7$Li astrophysical S factors from the no-core shell model with continuum

Jérémy Dohet-Eraly [a,*], Petr Navrátil [a], Sofia Quaglioni [b], Wataru Horiuchi [c], Guillaume Hupin [b,d,1], Francesco Raimondi [a,2]



Physics Letters B 725 (2013) 287–291

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Physics Letters B

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A drop in the ^{6}Li$(p,\gamma)^7$Be reaction at low energies

J.J. He [a,*], S.Z. Chen [a,b], C.E. Rolfs [c,a], S.W. Xu [a], J. Hu [a], X.W. Ma [a], M. Wiescher [d], R.J. deBoer [d], T. Kajino [e,f], M. Kusakabe [g], L.Y. Zhang [a,b], S.Q. Hou [a,b], X.Q. Yu [a], N.T. Zhang [a], G. Lian [h], Y.H. Zhang [a], X.H. Zhou [a], H.S. Xu [a], G.Q. Xiao [a], W.L. Zhan [a]

What resonances do we find in ^{7}Be within NCSMC?

PHYSICAL REVIEW C **100**, 024304 (2019)

^{7}Be and ^{7}Li nuclei within the no-core shell model with continuum

Matteo Vorabbi [*] and Petr Navrátil [†]
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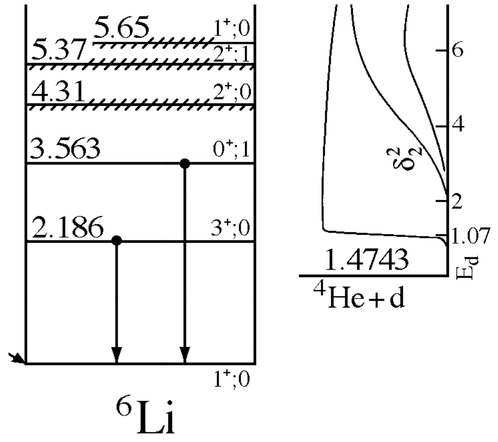
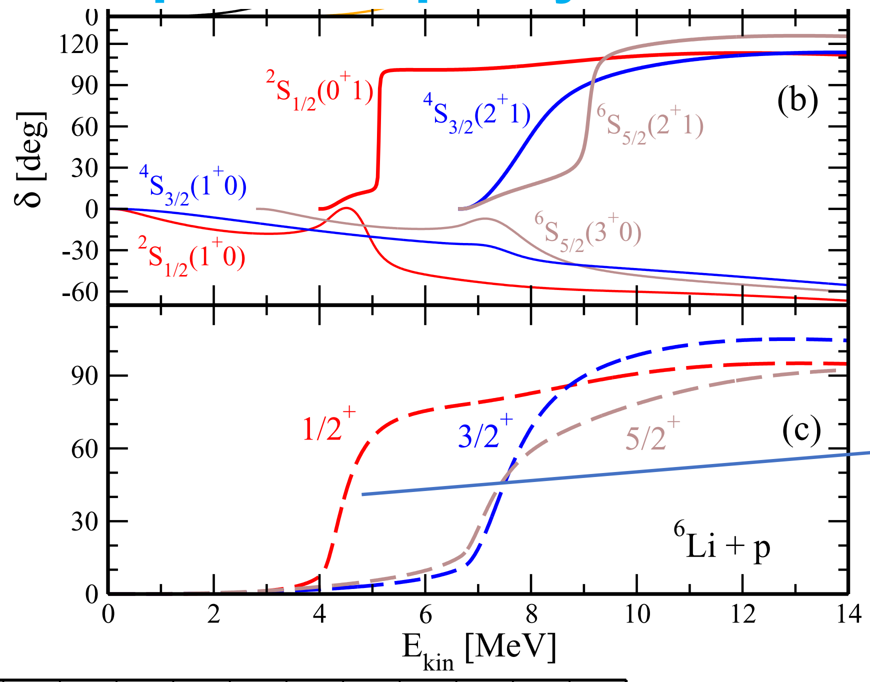
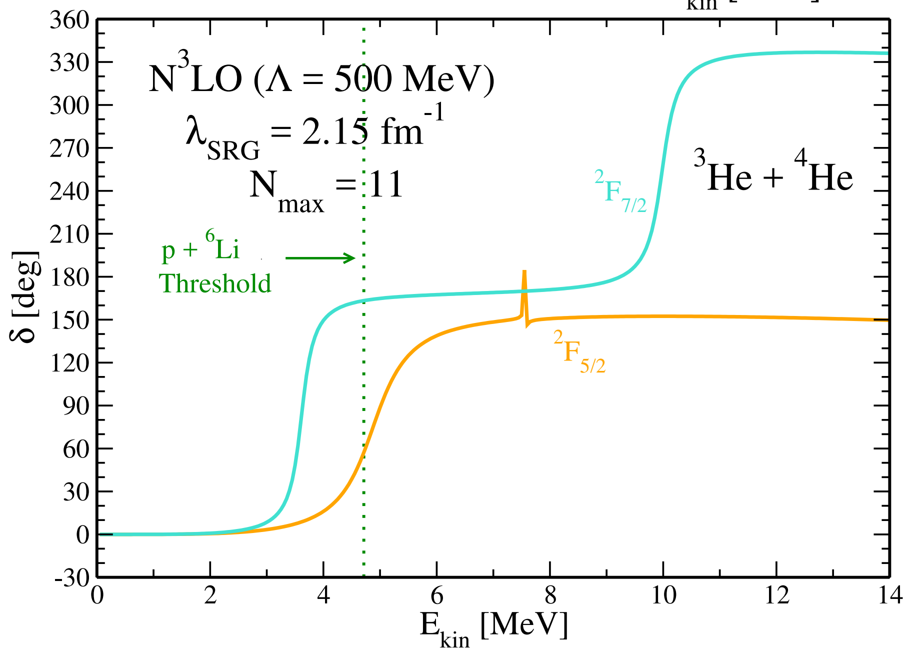
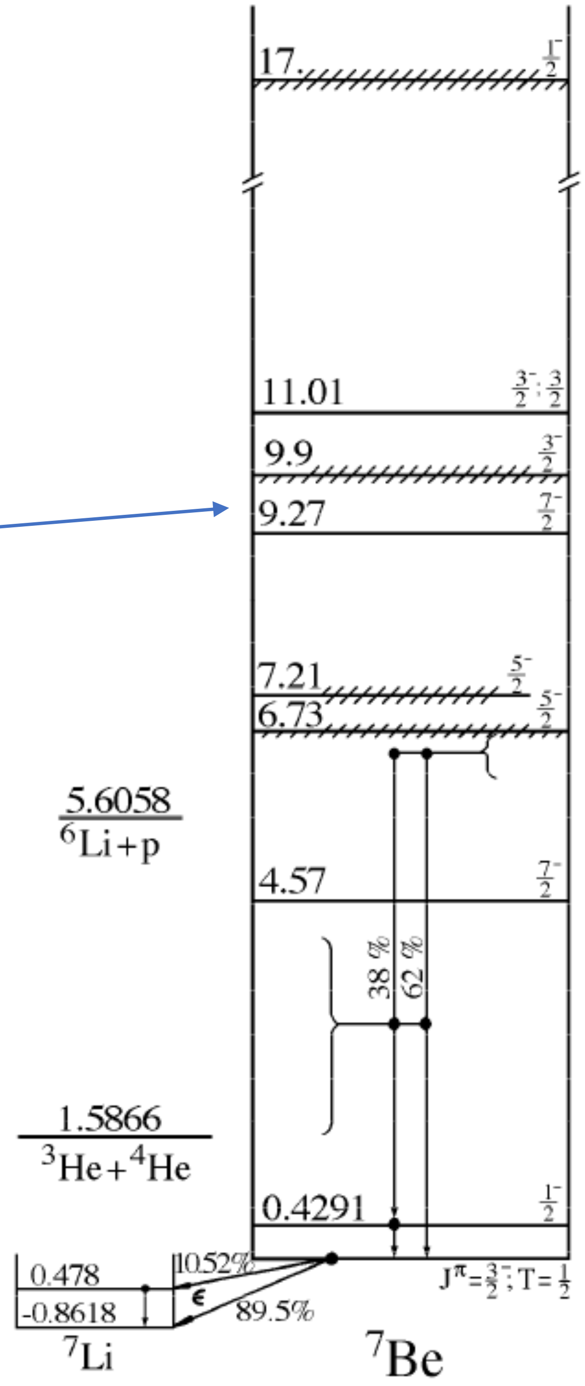
^{7}Be – New positive-parity states









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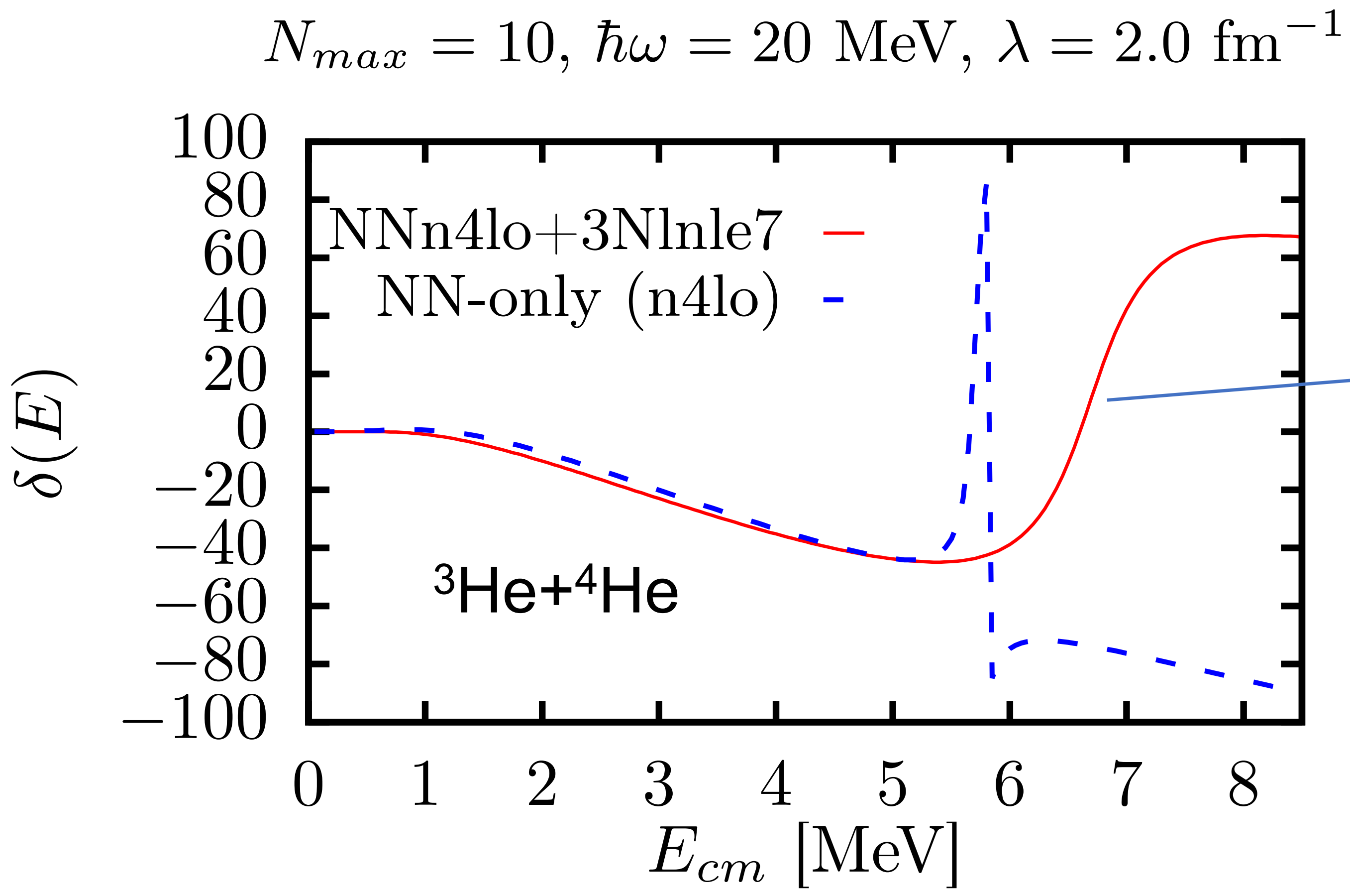
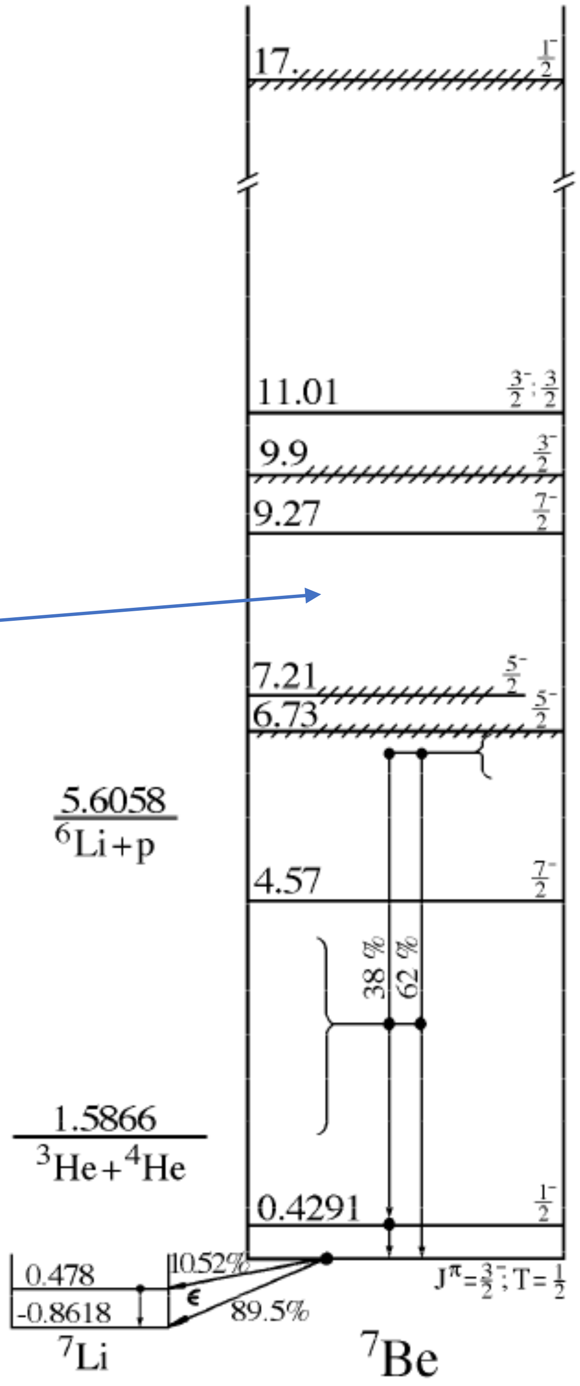
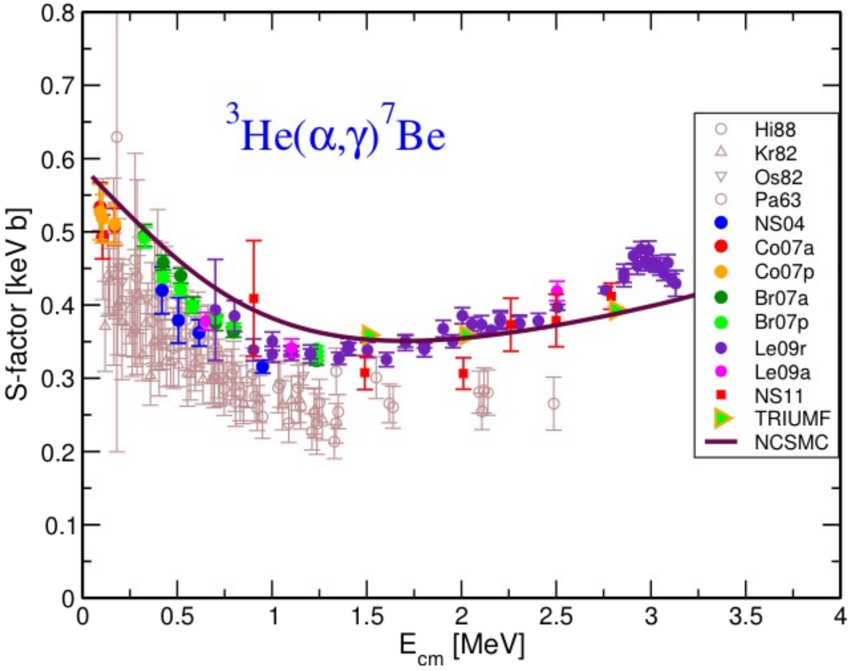




Preliminary – in progress

S-factor for $^3He(\alpha,\gamma)^7Be$ and $^6Li(p,\gamma)^7Be$ reaction



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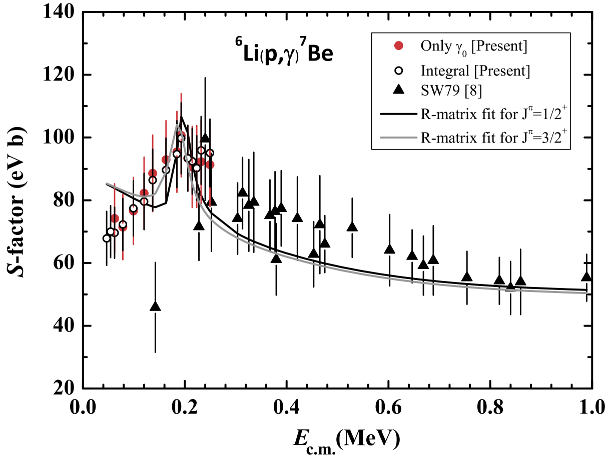
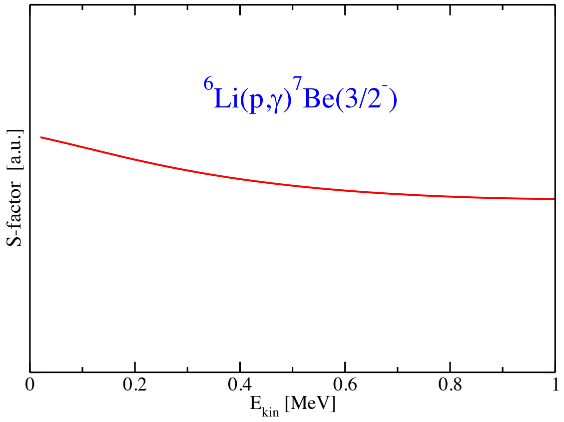
$^3He(\alpha,\gamma)^7Be$ and $^3H(\alpha,\gamma)^7Li$ astrophysical S factors from the no-core shell model with continuum

CrossMark

Jérémy Dohet-Eraly[a,*], Petr Navrátil[a], Sofia Quaglioni[b], Wataru Horiuchi[c], Guillaume Hupin[b,d,1], Francesco Raimondi[a,2]





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A drop in the $^6Li(p,\gamma)^7Be$ reaction at low energies

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J.J. He[a,*], S.Z. Chen[a,b], C.E. Rolfs[c,a], S.W. Xu[a], J. Hu[a], X.W. Ma[a], M. Wiescher[d], R.J. deBoer[d], T. Kajino[e,f], M. Kusakabe[g], L.Y. Zhang[a,b], S.Q. Hou[a,b], X.Q. Yu[a], N.T. Zhang[a], G. Lian[h], Y.H. Zhang[a], X.H. Zhou[a], H.S. Xu[a], G.Q. Xiao[a], W.L. Zhan[a]

No resonance in ^7Be close to ^6Li+p threshold contrary to claim in Lanzhou experiment

Still, we predict a ½$^+$ resonance at ~ 3 MeV above ^6Li+p threshold

Need to couple all mass partitions to get a reliable prediction of its properties