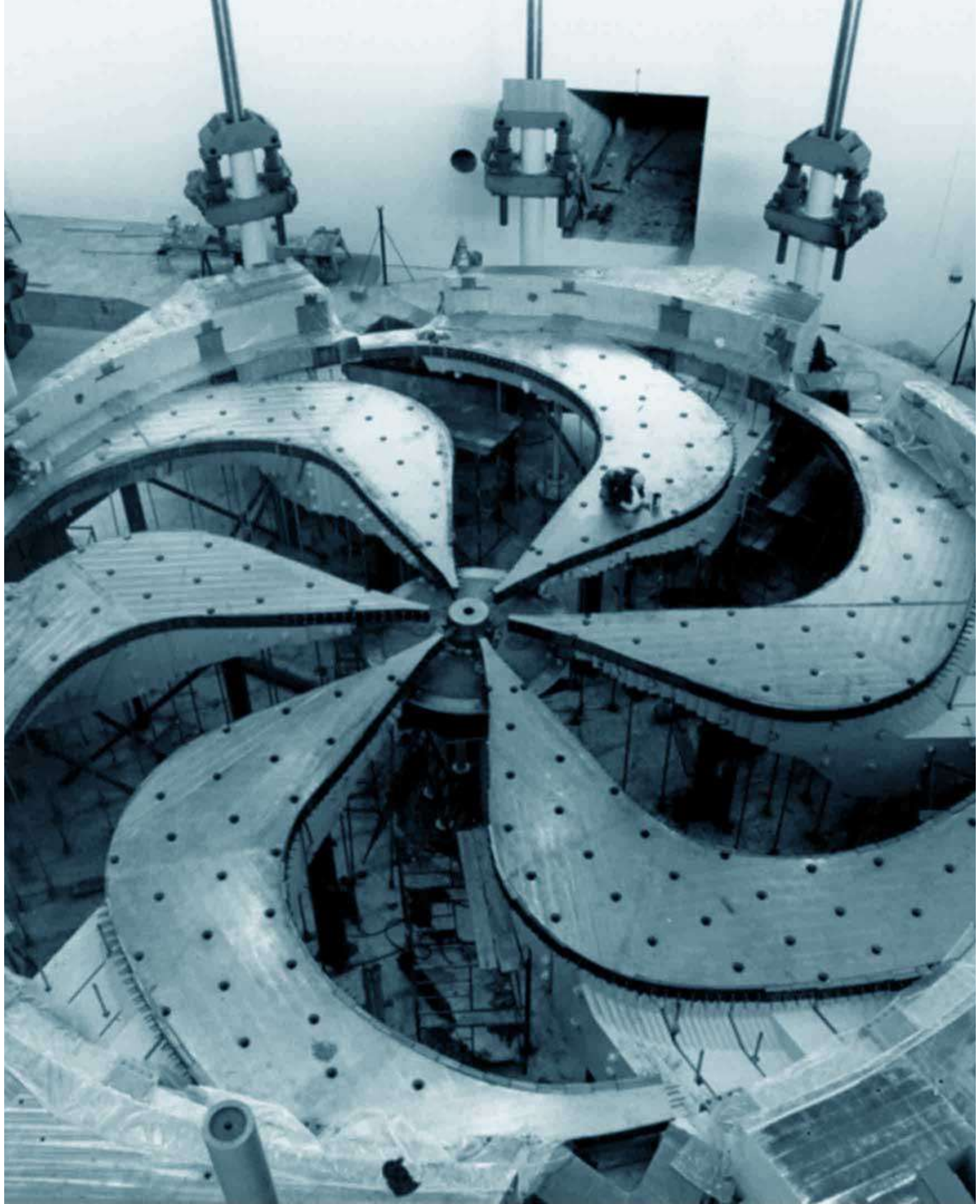
From *ab initio* no-core shell model to a unified approach to nuclear structure and reactions

The 80th Jubilee of Professor James P. Vary
Institute of Modern Physics, Chinese Academy of Sciences in Lanzhou, China (online)

5th June 2023

Petr Navratil

TRIUMF



Discovery, accelerated

Outline

- Introduction to *ab initio* no-core shell model (NCSM)
- Parity-violating moments within *ab initio* NCSM
- Unified description of bound and unbound states – *ab initio* NCSM with Continuum
- ^{7}Li(p,e^+e^-)^{8}Be pair production & the X17 boson within NCSMC

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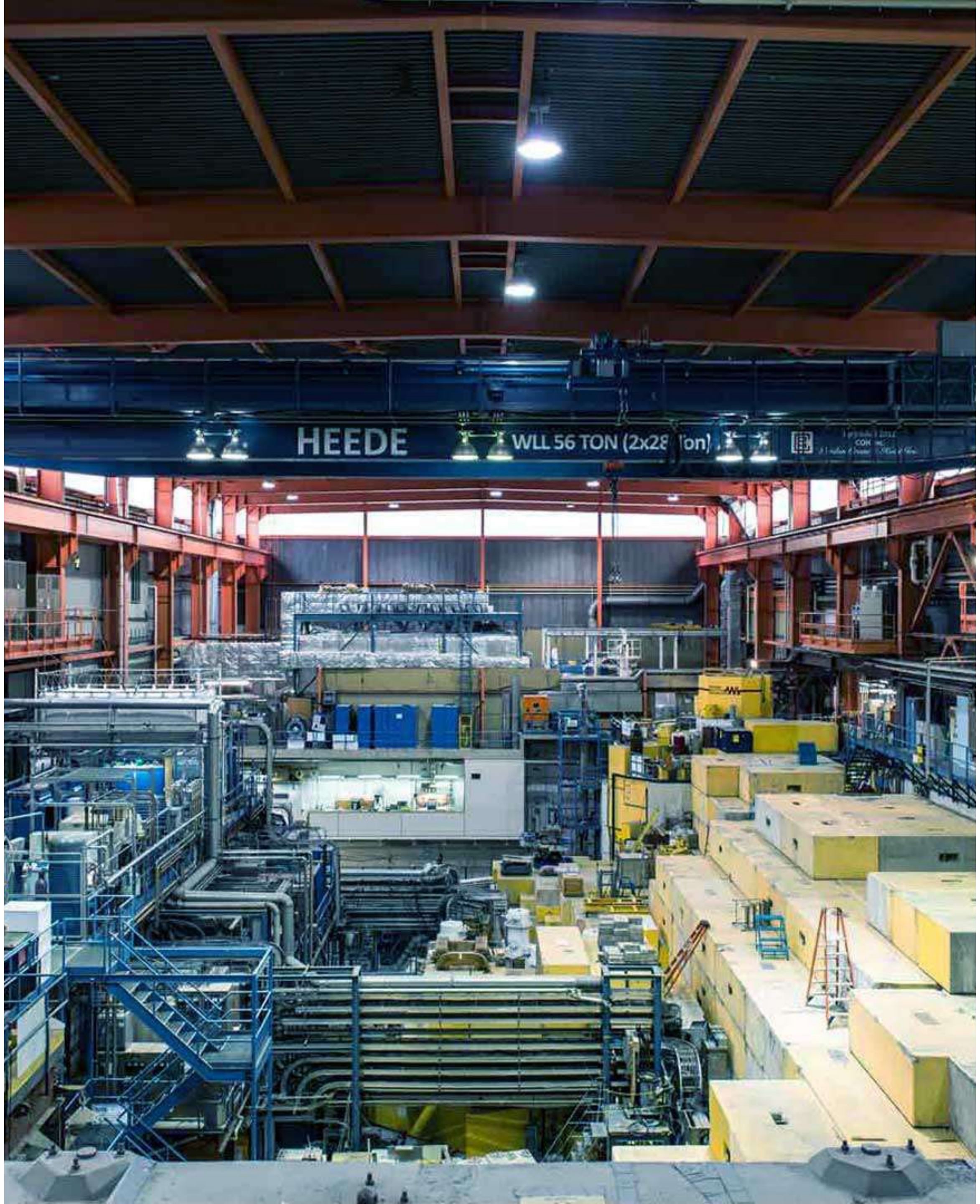
Ab initio no-core shell model (NCSM)



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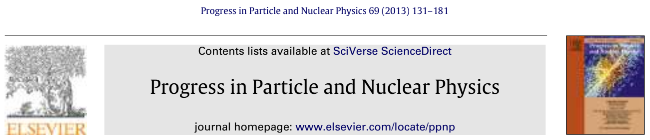
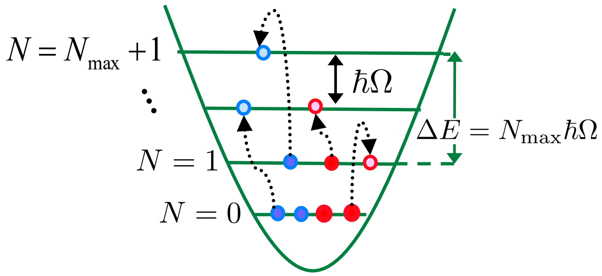
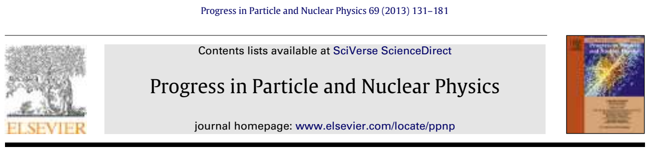

Progress in Particle and Nuclear Physics 69 (2013) 131–181
Contents lists available at SciVerse ScienceDirect
Progress in Particle and Nuclear Physics
journal homepage: www.elsevier.com/locate/ppnp
Review
Ab initio no core shell model
Bruce R. Barrett[a], Petr Navrátil[b], James P. Vary[c,*]

Ab Initio No-Core Shell Model (NCSM)

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-coordinate and Slater determinant basis
- Short- and medium range correlations
- Bound-states, narrow resonances

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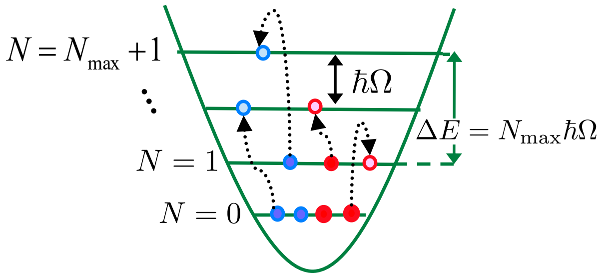
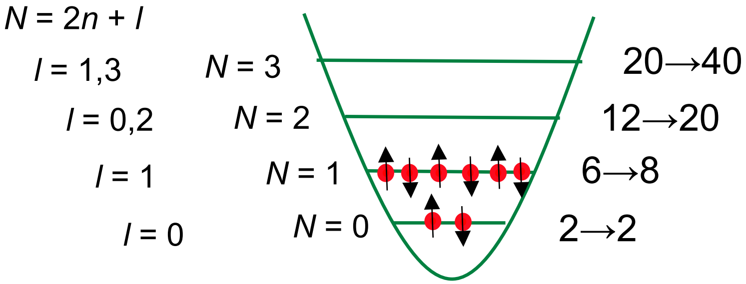
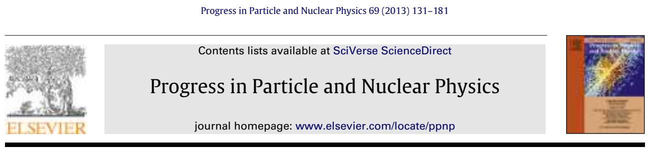




$$E = (2n + l + \tfrac{3}{2})\hbar\Omega$$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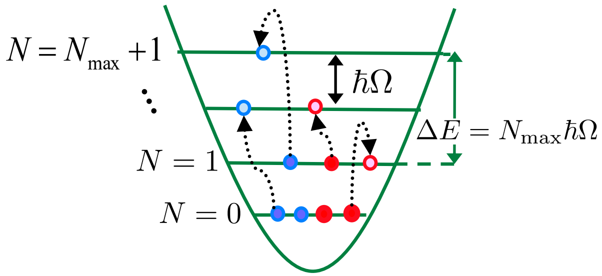
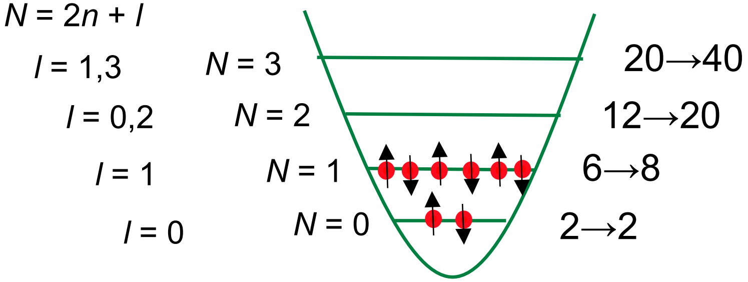


$$\Psi^A = \sum_{N=0}^{N_{\max}} \sum_i c_{Ni} \Phi_{Ni}^{HO}(\vec{\eta}_1, \vec{\eta}_2, \ldots, \vec{\eta}_{A-1})$$

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



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

Ab Initio No-Core Shell Model (NCSM) early development – personal notes

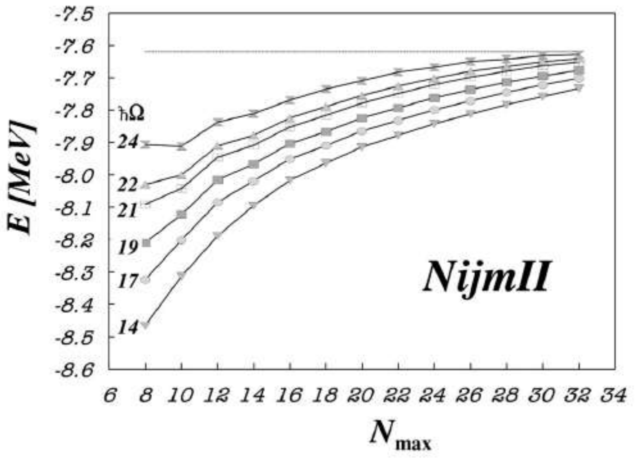
- For myself, a key development was the confirmation that NCSM calculations of the ^{3}H gs energy reproduce Faddeev method results
- Later, the NCSM ^{4}He gs energy prediction with the CD-Bonn potential was confirmed by Faddeev-Yakubovsky calculations

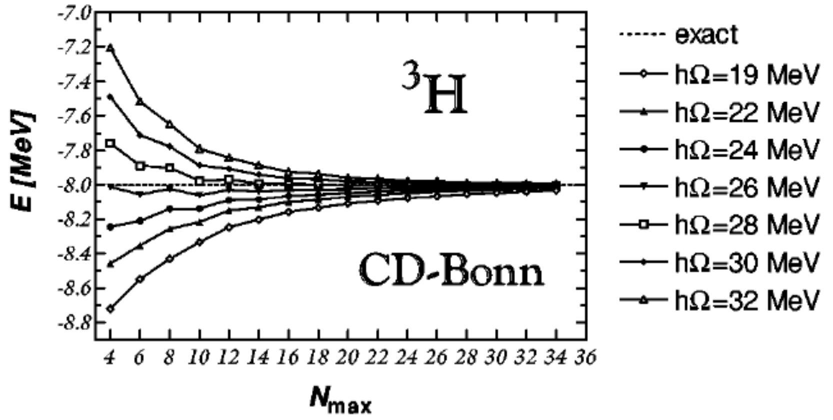
  - Jacobi-coordinate HO basis
  - Okubo-Lee-Suzuki effective interaction

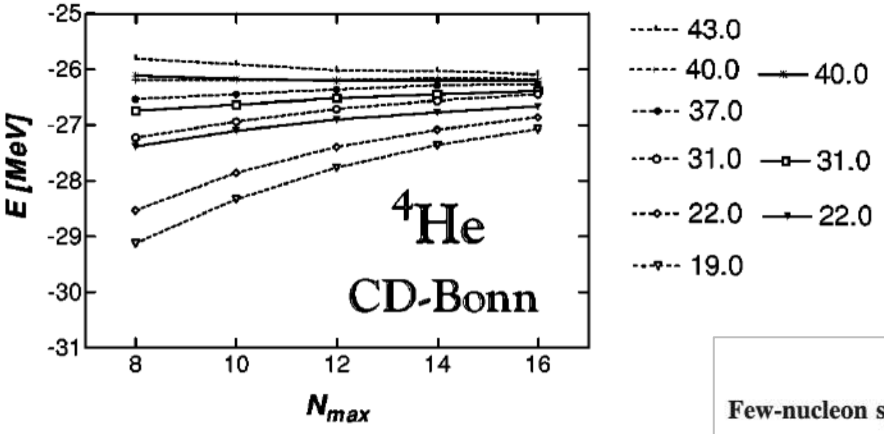
PHYSICAL REVIEW C VOLUME 57, NUMBER 2 FEBRUARY 1998

Shell-model calculations for the three-nucleon system

P. Navrátil* and B. R. Barrett
Department of Physics, University of Arizona, Tucson, Arizona 85721
(Received 21 May 1997)







NCSM is an *ab initio* method

PHYSICAL REVIEW C, VOLUME 61, 044001

Few-nucleon systems in a translationally invariant harmonic oscillator basis

P. Navrátil,[1,2] G. P. Kamuntavičius,[1,3,4] and B. R. Barrett[1]

Ab Initio No-Core Shell Model (NCSM) early development – personal notes

- Breakthrough paper on the structure of ^{12}C
  - Energies of states and other properties of a complex nucleus can be predicted from an *ab initio* approach
  - Slater-Determinant HO basis
  - Okubo-Lee-Suzuki effective interaction

VOLUME 84, NUMBER 25 PHYSICAL REVIEW LETTERS 19 JUNE 2000

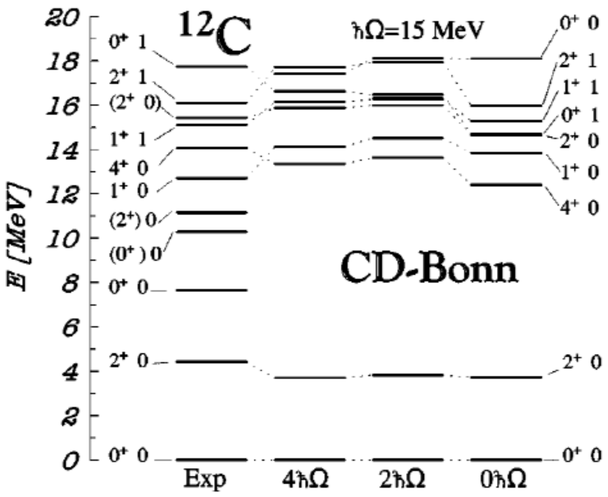
Properties of ^{12}C in the *Ab Initio* Nuclear Shell Model

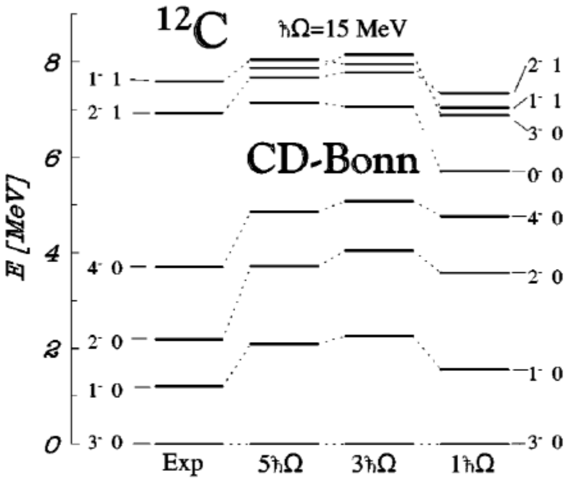
P. Navrátil,[1,2] J.P. Vary,[3] and B.R. Barrett[1]

PHYSICAL REVIEW C, VOLUME 62, 054311

Large-basis *ab initio* no-core shell model and its application to ^{12}C

P. Navrátil,[1,2,*] J. P. Vary,[3] and B. R. Barrett[1]

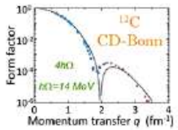




Physical Review C 50[th] Anniversary Milestones

PHYSICAL REVIEW C

This year, 2020, is the 50[th] anniversary of *Physical Review C*, which evolved from a section of its parent journal, *The Physical Review*, to one of the most read and trusted journals for nuclear physics. As part of the anniversary celebration, we are putting together a collection of milestone papers that remain central to developments in the field of nuclear physics. These papers announce major discoveries or open up new avenues of research. They would not have come to our journal, had the community not trusted and upheld the top-shelf quality of what PRC has traditionally published and intends to publish in the future.



Large-basis *ab initio* no-core shell model and its application to ^{12}C

Coupled-cluster and configuration-interaction shell model methods originated decades ago. Today, by employing high-precision interactions, new conceptual tools, and powerful computers, these *ab initio* methods have shown the ability to compute energies and other observables, such as electron scattering form factors, for a wide range of atomic nuclei without adjustable parameters. These two papers were early demonstrations of the power of the revitalized methods.

Large-basis *ab initio* no-core shell model and its application to ^{12}C
P. Navrátil, J. P. Vary, and B. R. Barrett
Phys. Rev. C **62**, 054311 (2000)

Ab Initio No-Core Shell Model (NCSM) early development – personal notes

- Other notable early papers
  - 0^+ and 2^+ intruder states in ^{8}Be – not 100% confirmed but a significant experimental evidence
  - Impact of a genuine 3N force on electroweak transitions in ^{12}C, spectra of ^{10,11}B, ^{13}C & on the ^{14}C lifetime

RAPID COMMUNICATIONS

PHYSICAL REVIEW C, VOLUME 64, 051301(R)

Intruder states in ^{8}Be

E. Caurier,[1] P. Navrátil,[2] W. E. Ormand,[2] and J. P. Vary[3]

VOLUME 91, NUMBER 1 PHYSICAL REVIEW LETTERS week ending 4 JULY 2003

Neutrino-^{12}C Scattering in the *Ab Initio* Shell Model with a Realistic Three-Body Interaction

A. C. Hayes,[1] P. Navrátil,[2] and J. P. Vary[3]

PRL 99, 042501 (2007) PHYSICAL REVIEW LETTERS week ending 27 JULY 2007

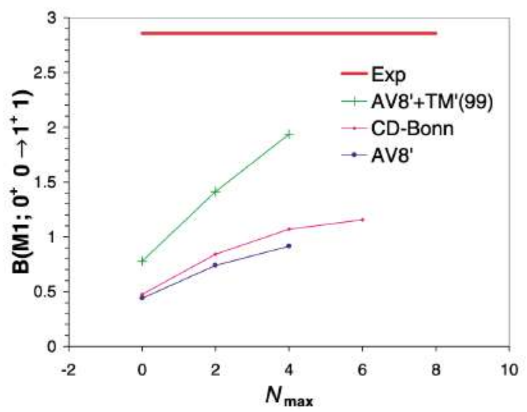
Structure of $A = 10$–13 Nuclei with Two- Plus Three-Nucleon Interactions from Chiral Effective Field Theory

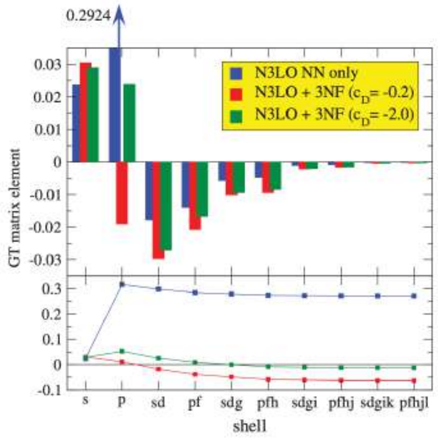
P. Navrátil,[1] V. G. Gueorguiev,[1,*] J. P. Vary,[1,2] W. E. Ormand,[1] and A. Nogga[3]

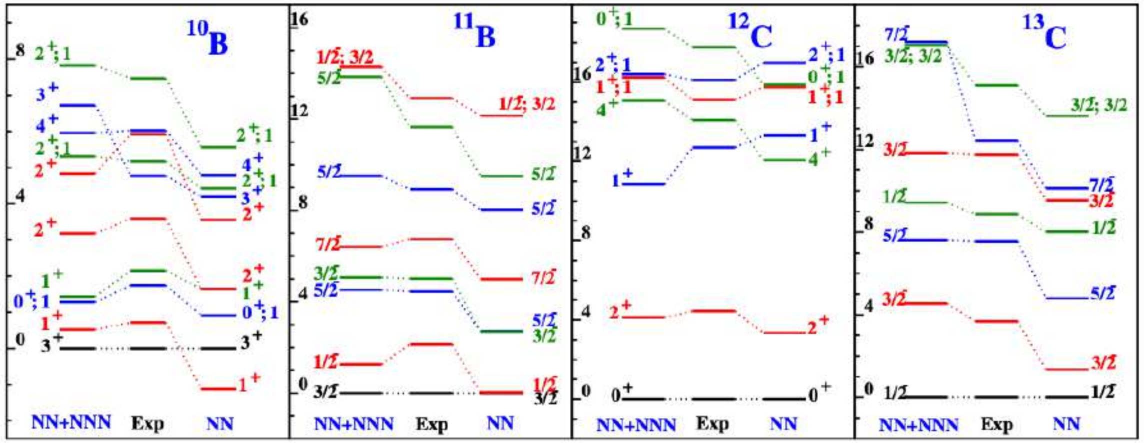
PRL 106, 202502 (2011) PHYSICAL REVIEW LETTERS week ending 20 MAY 2011

Origin of the Anomalous Long Lifetime of ^{14}C

P. Maris,[1] J. P. Vary,[1] P. Navrátil,[2,3] W. E. Ormand,[3,4] H. Nam,[5] and D. J. Dean[5]







PHYSICAL REVIEW C **101**, 014318 (2020)

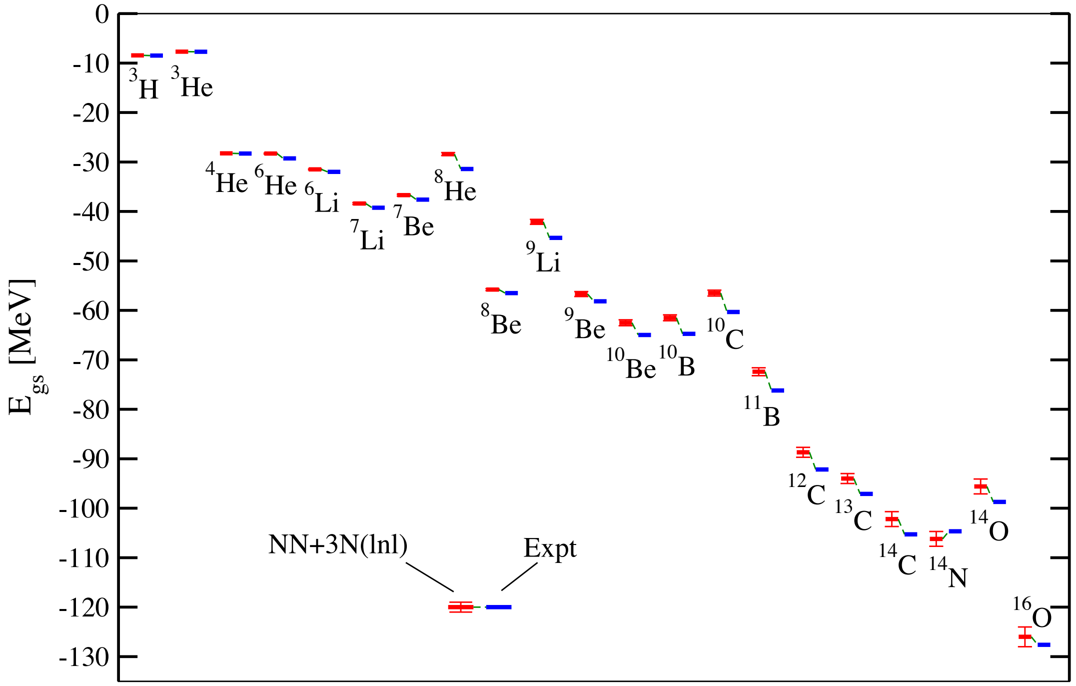
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

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

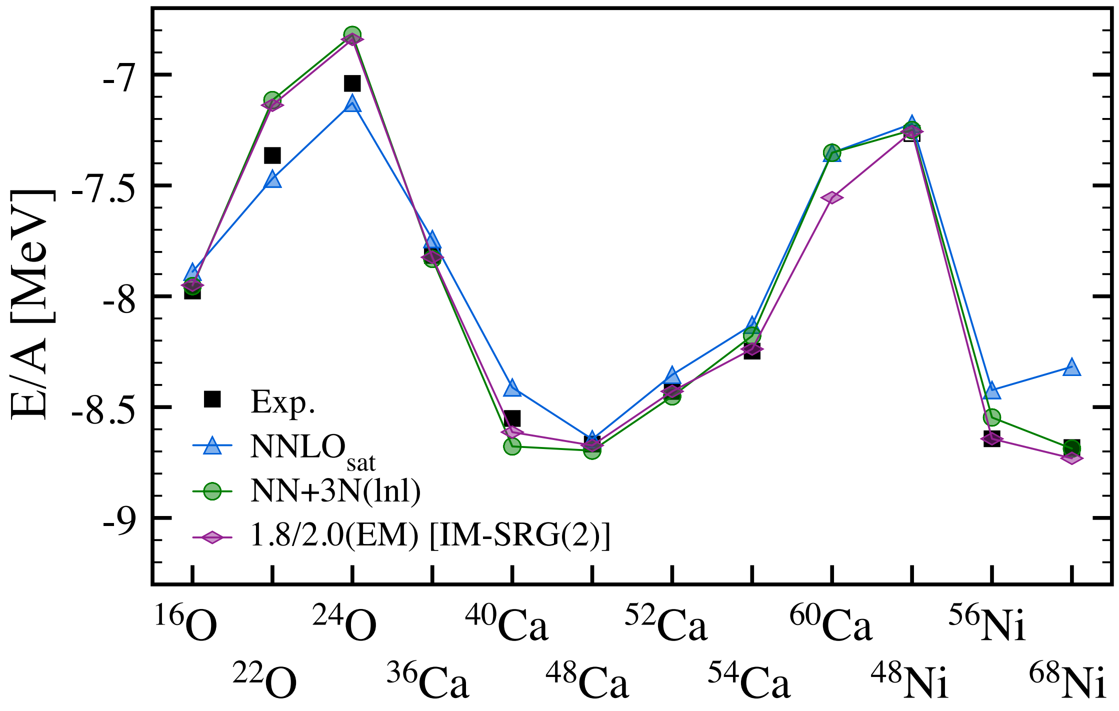
Input for *ab initio* calculations: Nuclear forces from chiral Effective Field Theory

- 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



SRG renormalization - 3N-induced interaction



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).

PHYSICAL REVIEW C **101**, 014318 (2020)

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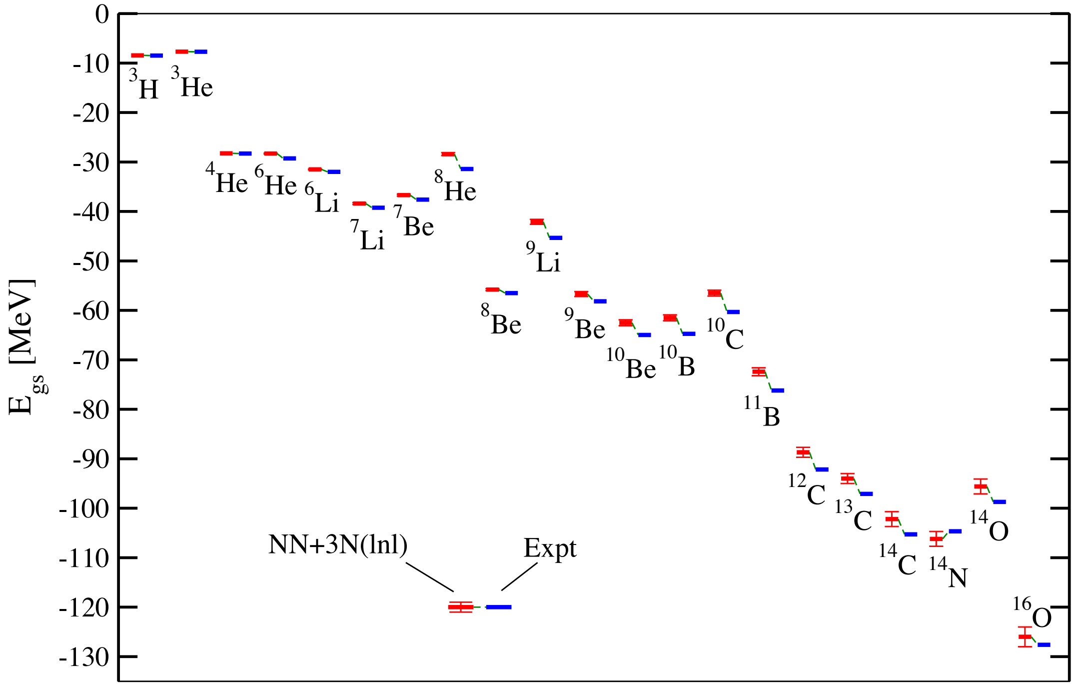
  - Light nuclei – NCSM
  - Heavy nuclei – HF-MBPT(3)

NN N³LO (Entem-Machleidt 2003)
3N N²LO w local/non-local regulator



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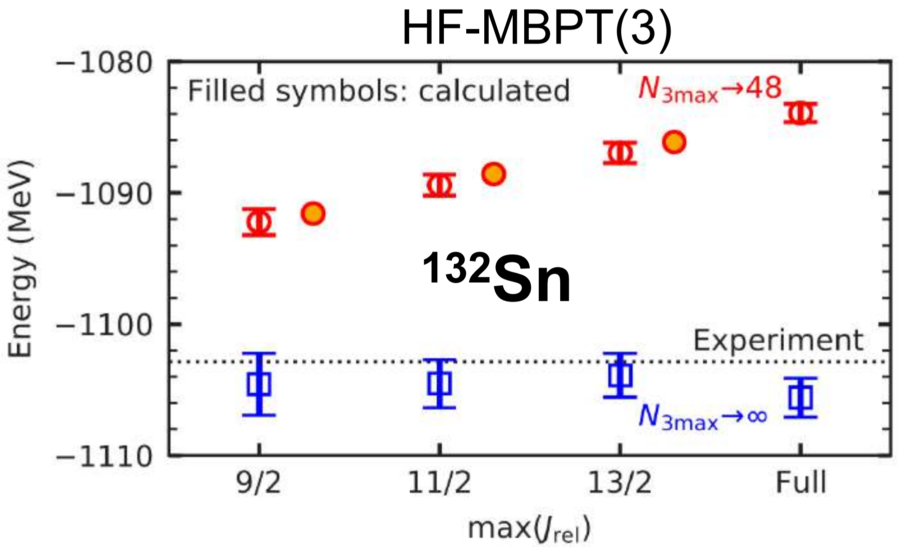
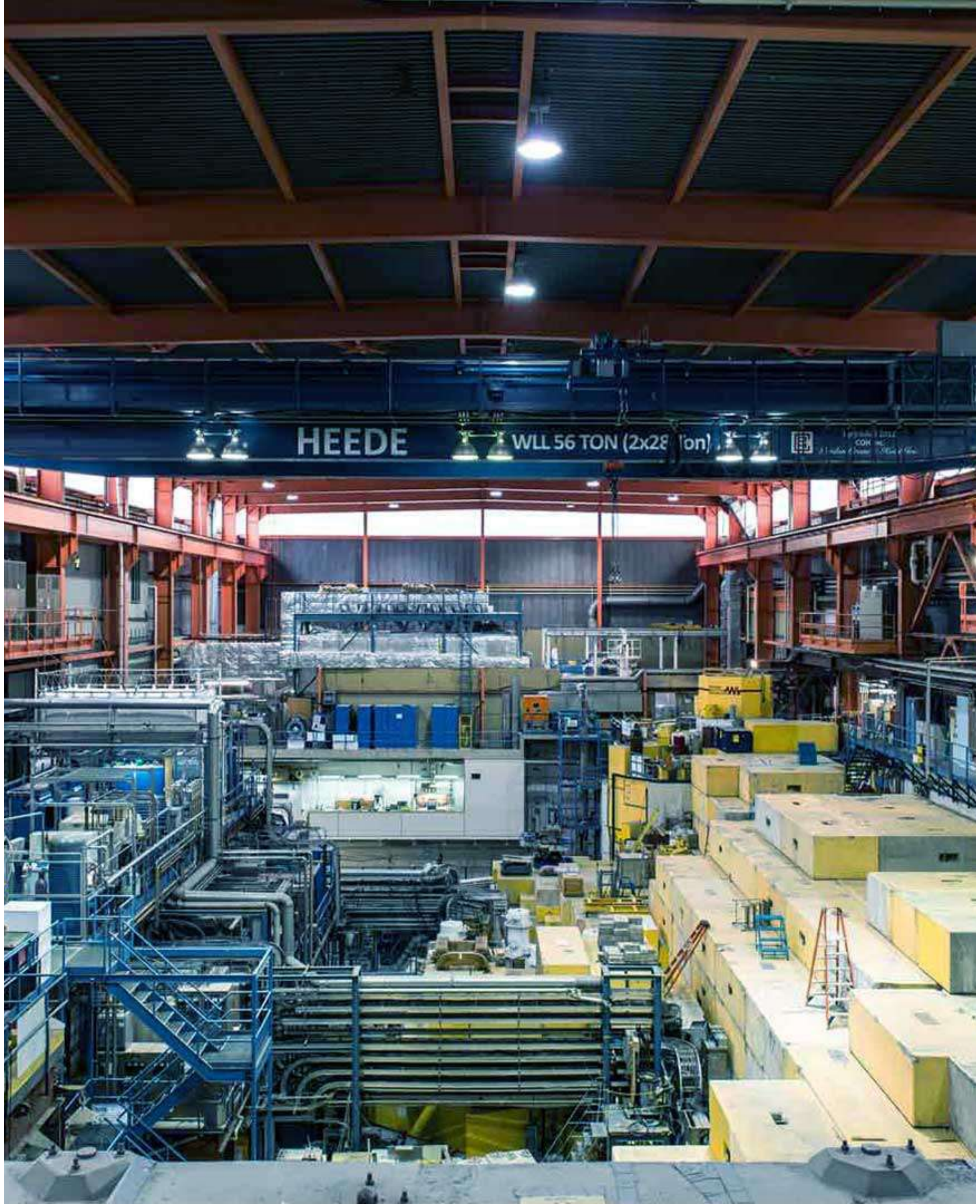


PHYSICAL REVIEW C **105**, 014302 (2022)

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,‖]

Parity-violating moments within *ab initio* NCSM

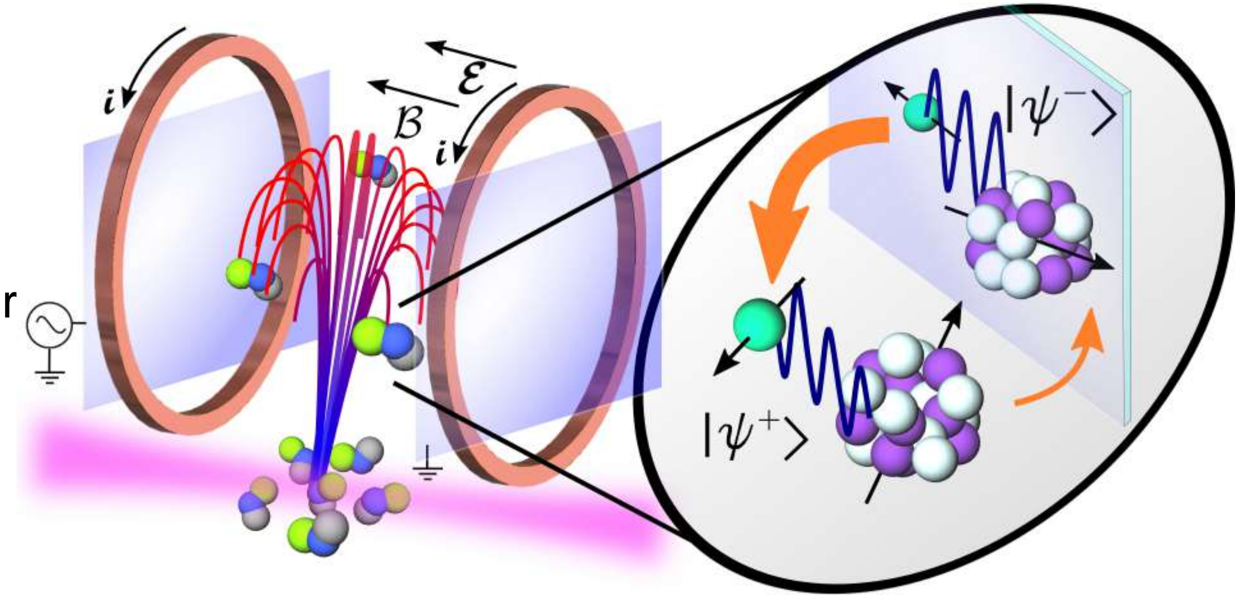


Why to investigate the parity violating moments - the anapole moment and the electric dipole moment (EDM)?

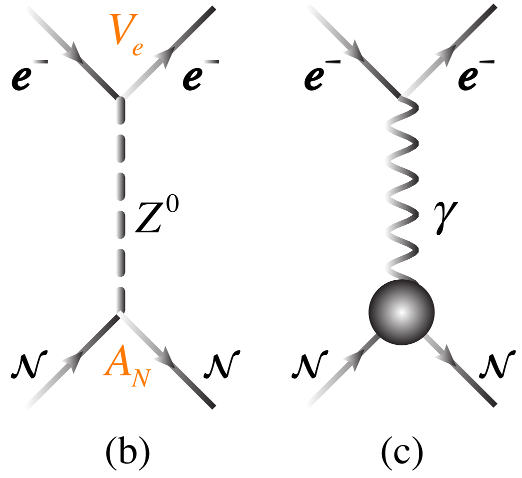
- Parity violation in atomic and molecular systems sensitive to a variety of “new physics”
  - Probes electron-quark electroweak interaction
  - Best limits on the Z’ boson parity violating interaction with electrons and nucleons

- The EDM is a promising probe for CP violation beyond the standard model as well as CP violating QCD $\bar{\theta}$ parameter
  - Nuclear structure can enhance the EDM
  - Nuclear EDMs can be measured in storage rings (CERN feasibility study: arXiv:1912.07881)

Nuclear spin dependent parity violating effects in light polyatomic molecules



- Experiments proposed for ^{9}BeNC, ^{25}MgNC
- To extract the underlying physics, atomic, molecular and **nuclear** structure effects must be understood
  - *Ab initio* calculations
- Spin dependent PV
  - Z-boson exchange between nucleon axial-vector and electron-vector currents (b)
  - Electromagnetic interaction of atomic electrons with the nuclear anapole moment (c)

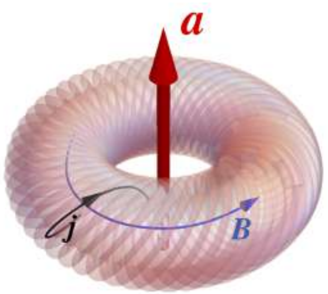


Parity violating nucleon-nucleon interaction and the nuclear anapole moment

- Parity violating (non-conserving) V_{NN}^{PNC} interaction
  - Conserves total angular momentum *I*
  - Mixes opposite parities
  - Has isoscalar, isovector and isotensor components
  - Admixes unnatural parity states in the ground state

$$|\psi_{\rm gs}\; I\rangle = |\psi_{\rm gs}\; I^{\pi}\rangle + \sum_j |\psi_j\; I^{-\pi}\rangle$$
$$\times \frac{1}{E_{\rm gs}-E_j}\langle\psi_j\; I^{-\pi}|V_{\rm NN}^{\rm PNC}|\psi_{\rm gs}\; I^{\pi}\rangle$$

- Anapole moment operator dominated by spin contribution



$$\boldsymbol{a} = -\pi \int d^3r\, r^2\, \boldsymbol{j}(\boldsymbol{r})$$

$$\hat{\boldsymbol{a}}_s = \frac{\pi e}{m}\sum_{i=1}^{A}\mu_i(\boldsymbol{r}_i \times \boldsymbol{\sigma}_i)$$

$$\mu_i{=}\mu_p(1/2{+}t_{z,i}) + \mu_n(1/2{-}t_{z,i})$$

$$a_s = \langle\psi_{\rm gs}\; I\; I_z{=}I|\hat{a}^{(1)}_{s,0}|\psi_{\rm gs}\; I\; I_z{=}I\rangle$$

- Here is what we want to calculate:

$$\kappa_A = \frac{\sqrt{2}e}{G_F}a_s \qquad \kappa_A = -i4\pi\frac{e^2}{G_F}\frac{\hbar}{mc}\frac{(II10|II)}{\sqrt{2I+1}}\sum_j\langle\psi_{\rm gs}\; I^{\pi}||\sqrt{4\pi/3}\sum_{i=1}^{A}\mu_i r_i[Y_1(\hat{r}_i)\sigma_i]^{(1)}||\psi_j\; I^{-\pi}\rangle\frac{1}{E_{\rm gs}-E_j}\langle\psi_j\; I^{-\pi}|V_{\rm NN}^{\rm PNC}|\psi_{\rm gs}\; I^{\pi}\rangle$$

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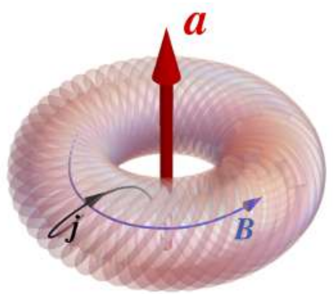
Lanczos continued fraction method to compute nuclear Green's function

- Anapole moment operator dominated by spin contribution



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PHYSICAL REVIEW C **104**, 025502 (2021)

Ab initio **calculations of electric dipole moments of light nuclei**

Paul Froese*
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada
and Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada

Petr Navrátil†
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada

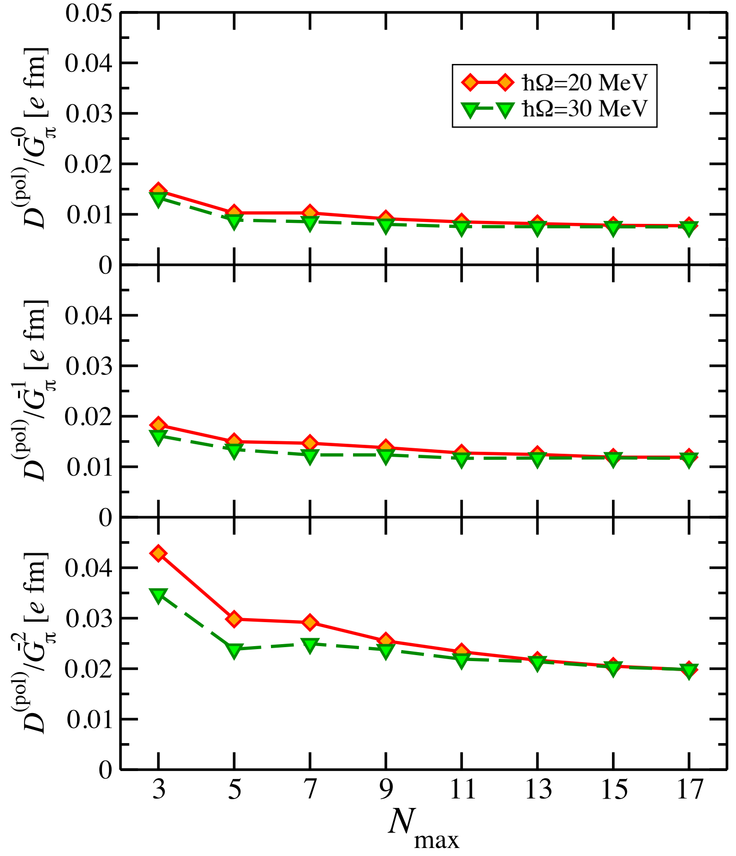
^{3}He EDM Benchmark Calculation

Discrepancy between calculations?

	PLB 665:165-172 (2008) (NN EFT)	PRC 87:015501 (2013)	PRC 91:054005 (2015)	Our calculation (NN EFT)
$\bar{G}_\pi^0$	0.015	(x 1/2)	(x 1/2)	0.0073 (x 1/2)
$\bar{G}_\pi^1$	0.023	(x 1/2)	(x 1/2)	0.011 (x 1/2)
$\bar{G}_\pi^2$	0.037	(x 1/5)	(x 1/2)	0.019 (x 1/2)
$\bar{G}_\rho^0$	-0.0012	(x 1/2)	(x 1/2)	-0.00062 (x 1/2)
$\bar{G}_\rho^1$	0.0013	(x 1/2)	(x 1/2)	0.00063 (x 1/2)
$\bar{G}_\rho^2$	-0.0028	(x 1/5)	(x 1/2)	-0.0014 (x 1/2)
$\bar{G}_\omega^0$	0.0009	(x 1/2)	(x 1/2)	0.00042 (x 1/2)
$\bar{G}_\omega^1$	-0.0017	(x 1/2)	(x 1/2)	-0.00086 (x 1/2)

N_{max} convergence for ^{3}He

N^{3}LO NN



Our results confirm those of Yamanaka and Hiyama, PRC 91:054005 (2015)

PHYSICAL REVIEW A **102**, 052828 (2020)

Editors' Suggestion

Nuclear spin-dependent parity-violating effects in light polyatomic molecules

Yongliang Hao,[1] Petr Navrátil,[2] Eric B. Norrgard,[3] Miroslav Iliaš,[4] Ephraim Eliav,[5] Rob G. E. Timmermans,[1] Victor V. Flambaum,[6] and Anastasia Borschevsky[1,*]

Nuclear spin-dependent parity-violating effects from NCSM

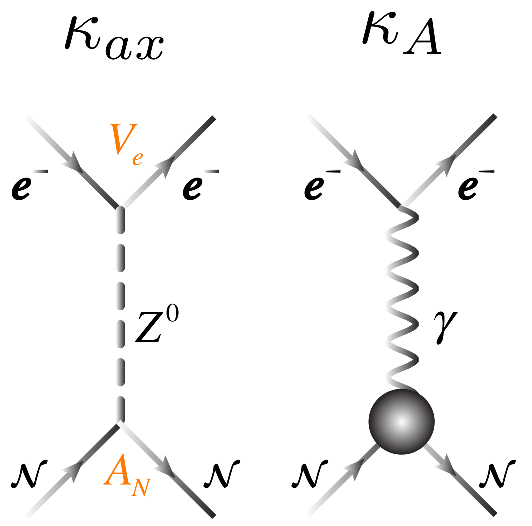
- Contributions from nucleon axial-vector and the anapole moment

	^{9}Be	^{13}C	^{14}N	^{15}N	^{25}Mg
I^{π}	$3/2^{-}$	$1/2^{-}$	1^{+}	$1/2^{-}$	$5/2^{+}$
$\mu^{\text{exp.}}$	−1.177[a]	0.702[b]	0.404[c]	−0.283[d]	−0.855[e]
			NCSM calculations		
μ	−1.05	0.44	0.37	−0.25	−0.50
κ_{A}	0.016	−0.028	0.036	0.088	0.035
$\langle s_{p,z}\rangle$	0.009	−0.049	−0.183	−0.148	0.06
$\langle s_{n,z}\rangle$	0.360	−0.141	−0.1815	0.004	0.30
κ_{ax}	0.035	−0.009	0.0002	0.015	0.024
κ	0.050	−0.037	0.037	0.103	0.057

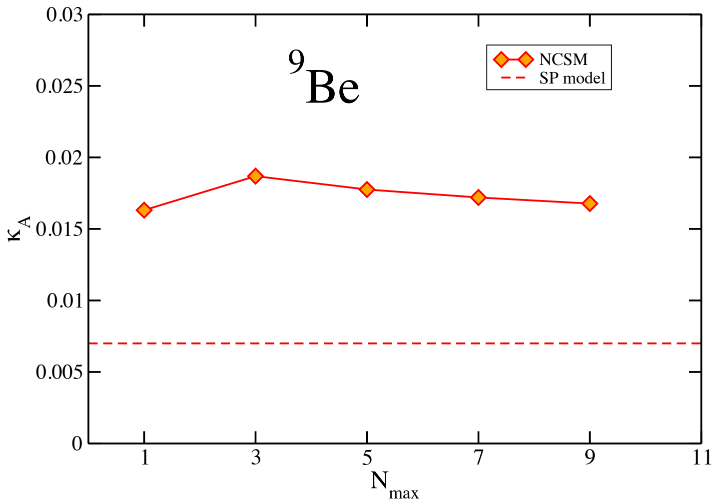
$$\kappa_{ax} \simeq -2C_{2p}\langle s_{p,z}\rangle - 2C_{2n}\langle s_{n,z}\rangle \simeq -0.1\langle s_{p,z}\rangle + 0.1\langle s_{n,z}\rangle$$

$$\langle s_{\nu,z}\rangle \equiv \langle \psi_{\mathrm{gs}}\; I^{\pi} I_z{=}I | \hat{s}_{\nu,z} | \psi_{\mathrm{gs}}\; I^{\pi} I_z{=}I\rangle$$

$$C_{2\mathrm{p}} = -C_{2\mathrm{n}} = g_A(1 - 4\sin^2\theta_W)/2 \simeq 0.05$$



(b) (c)



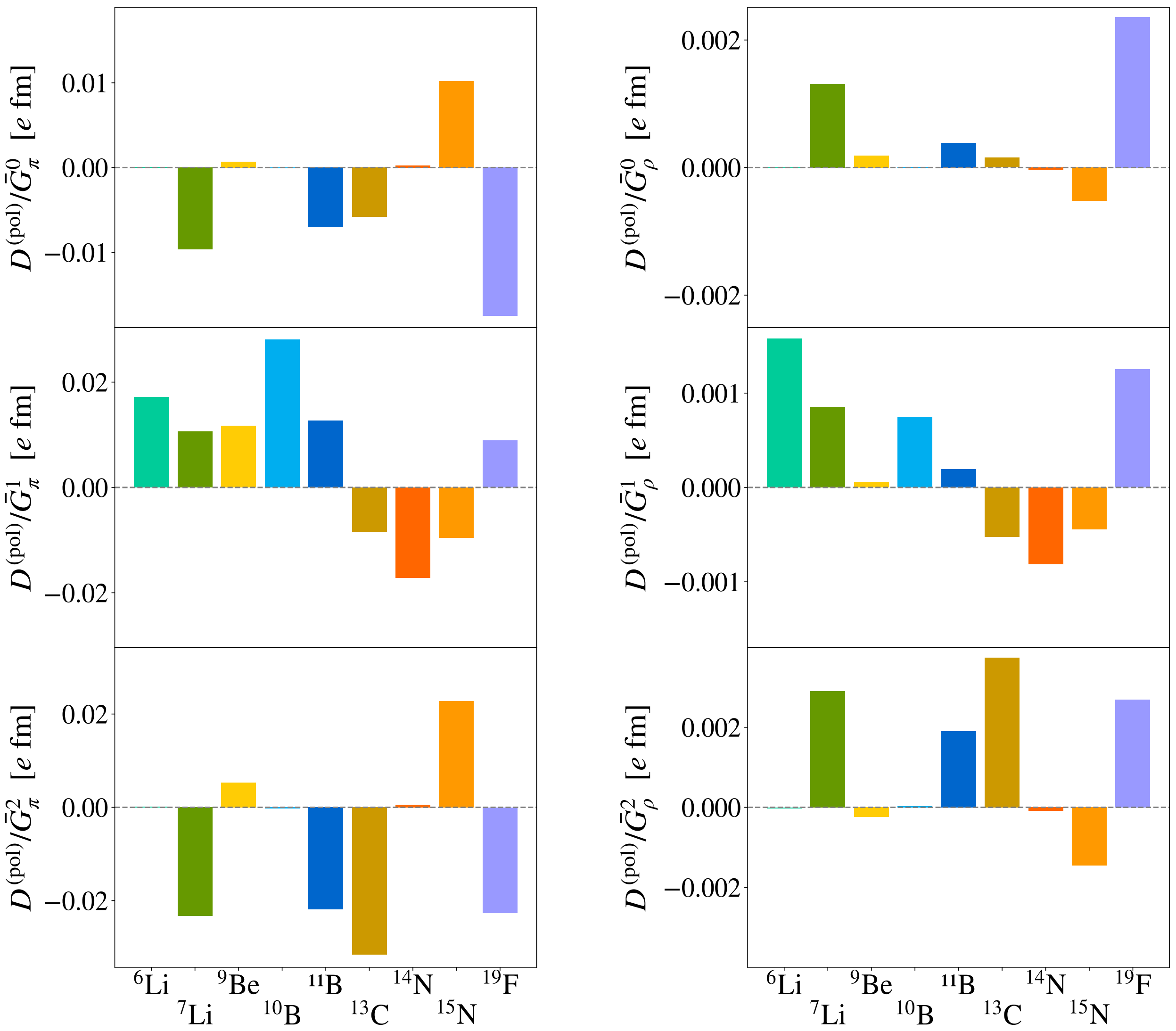
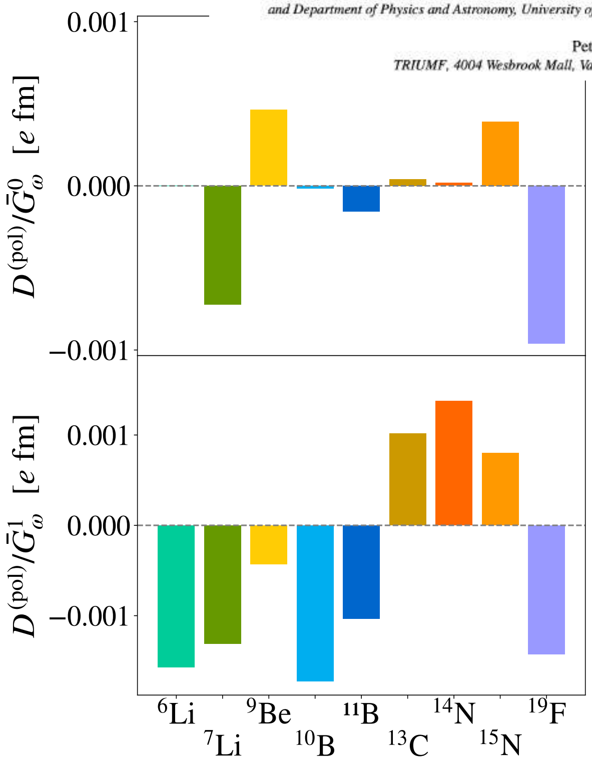
PHYSICAL REVIEW C **104**, 025502 (2021)

Calculated EDMs of selected stable nuclei

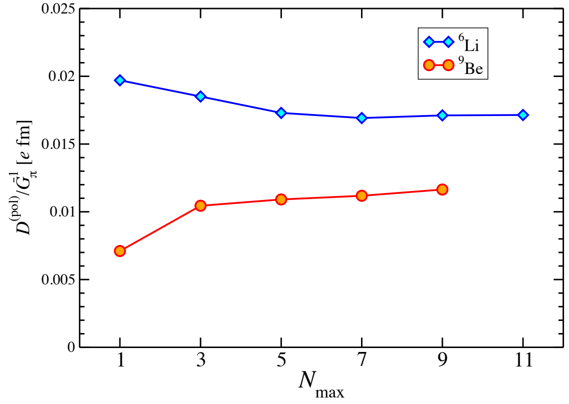
Ab initio **calculations of electric dipole moments of light nuclei**

Paul Froese*
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada
and Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada

Petr Navrátil†
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada

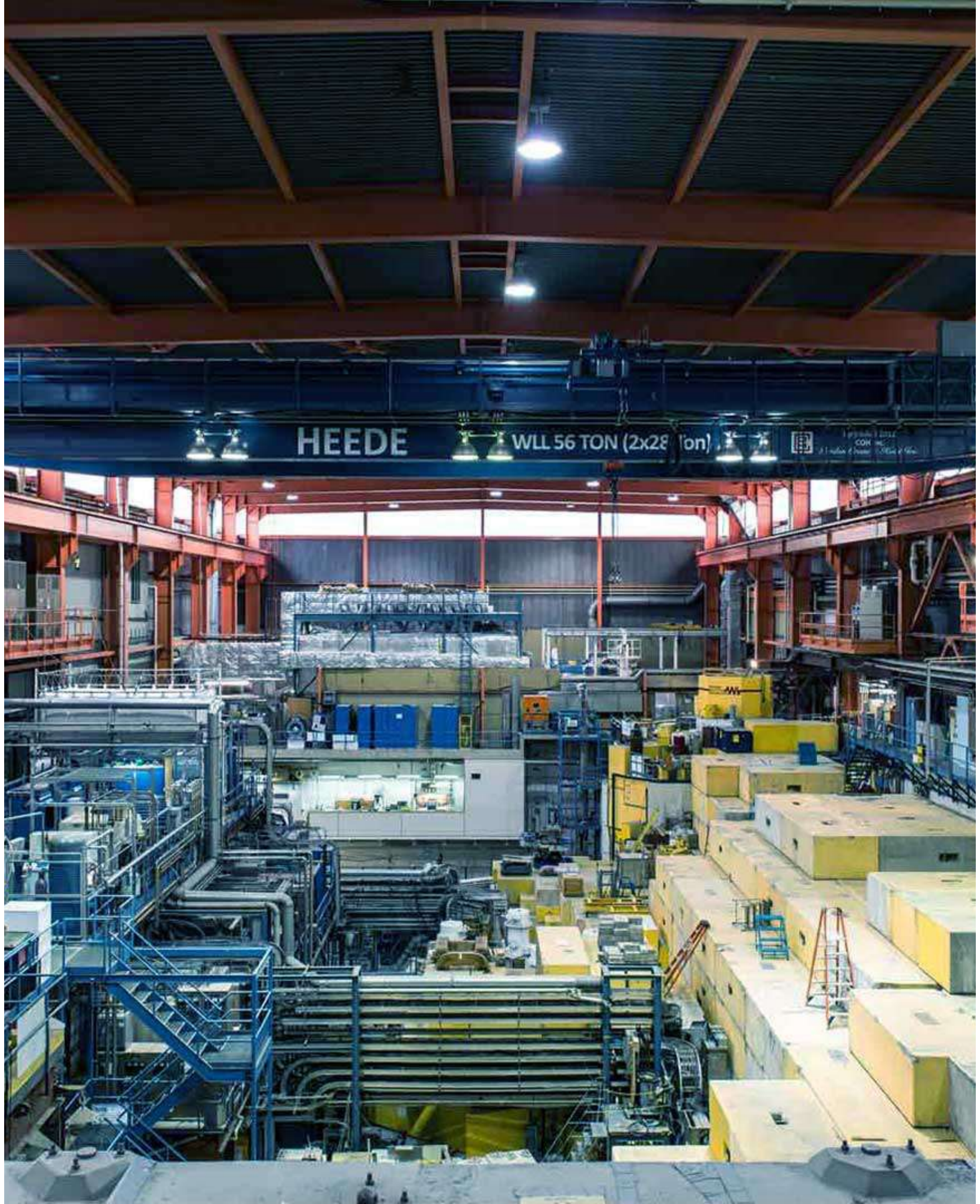



Examples of N_{max} convergence



TRIUMF

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



Discovery, accelerated

Ab Initio Calculations of Structure, Scattering, Reactions

Unified approach to bound & continuum states

No-Core Shell Model with Continuum (NCSMC)

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

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

Ab Initio Calculations of Structure, Scattering, Reactions

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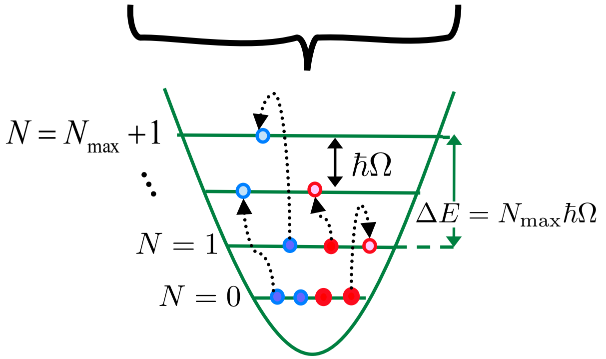

Static solutions for aggregate system,
describe all nucleons close together

S. Baroni, P. Navratil, and S. Quaglioni,
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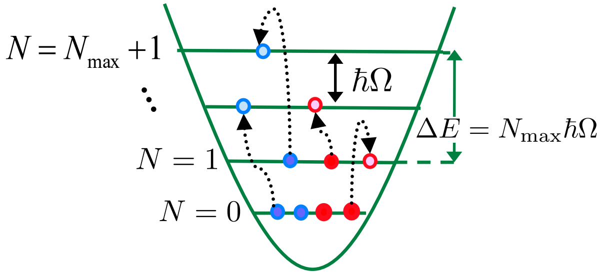

Static solutions for aggregate system, describe all nucleons close together

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

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

Ab Initio Calculations of Structure, Scattering, Reactions

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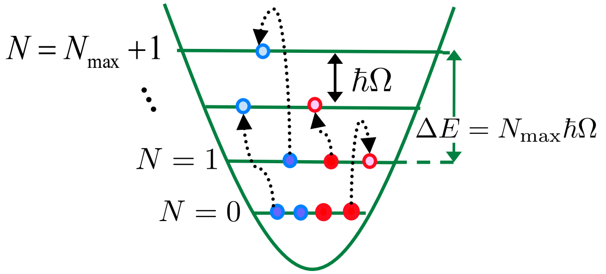
No-Core Shell Model with Continuum (NCSMC)

Unknowns

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



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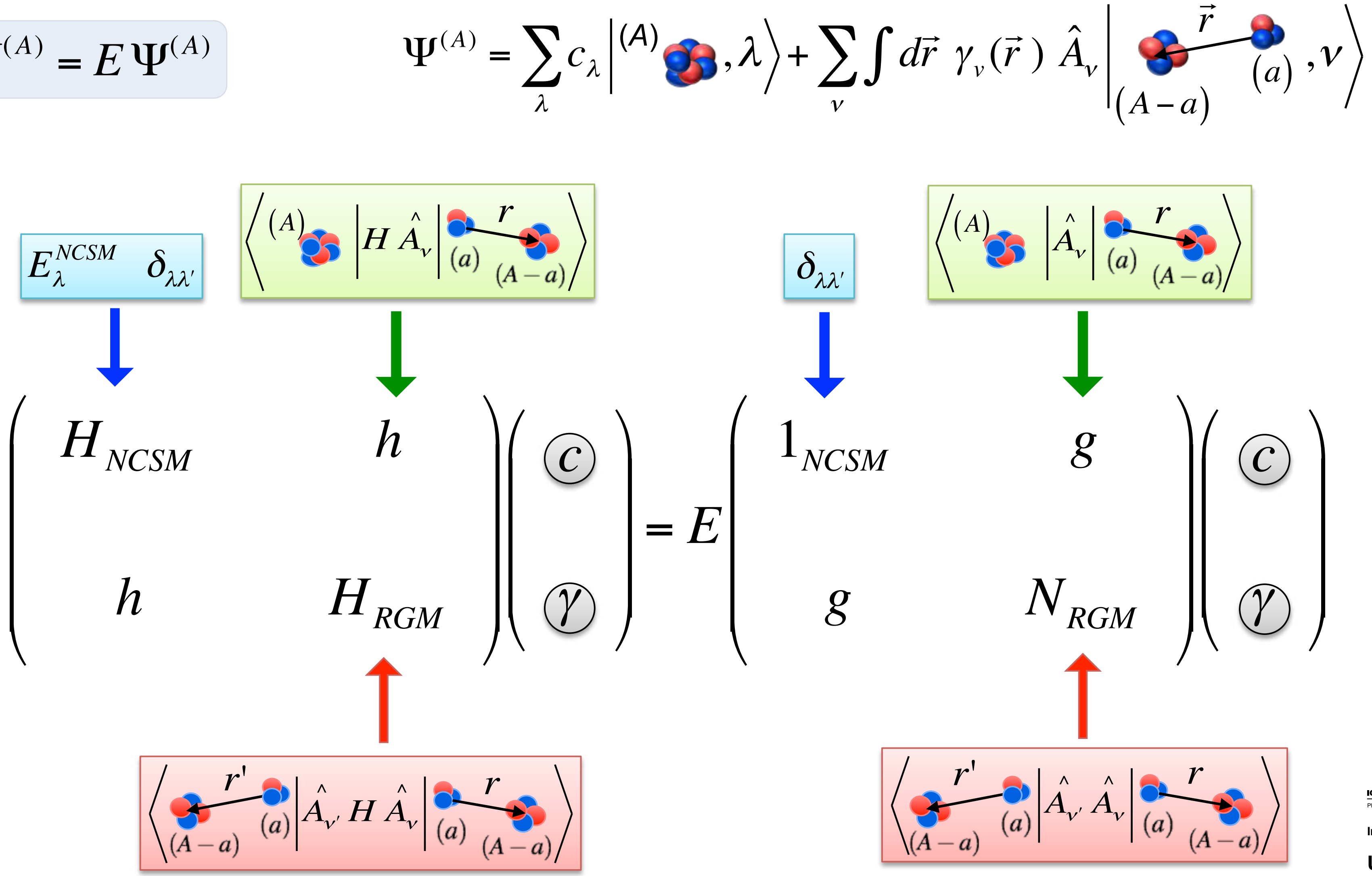
S. Baroni, P. Navratil, and S. Quaglioni,
PRL **110**, 022505 (2013); PRC **87**, 034326 (2013).

Coupled NCSMC equations

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



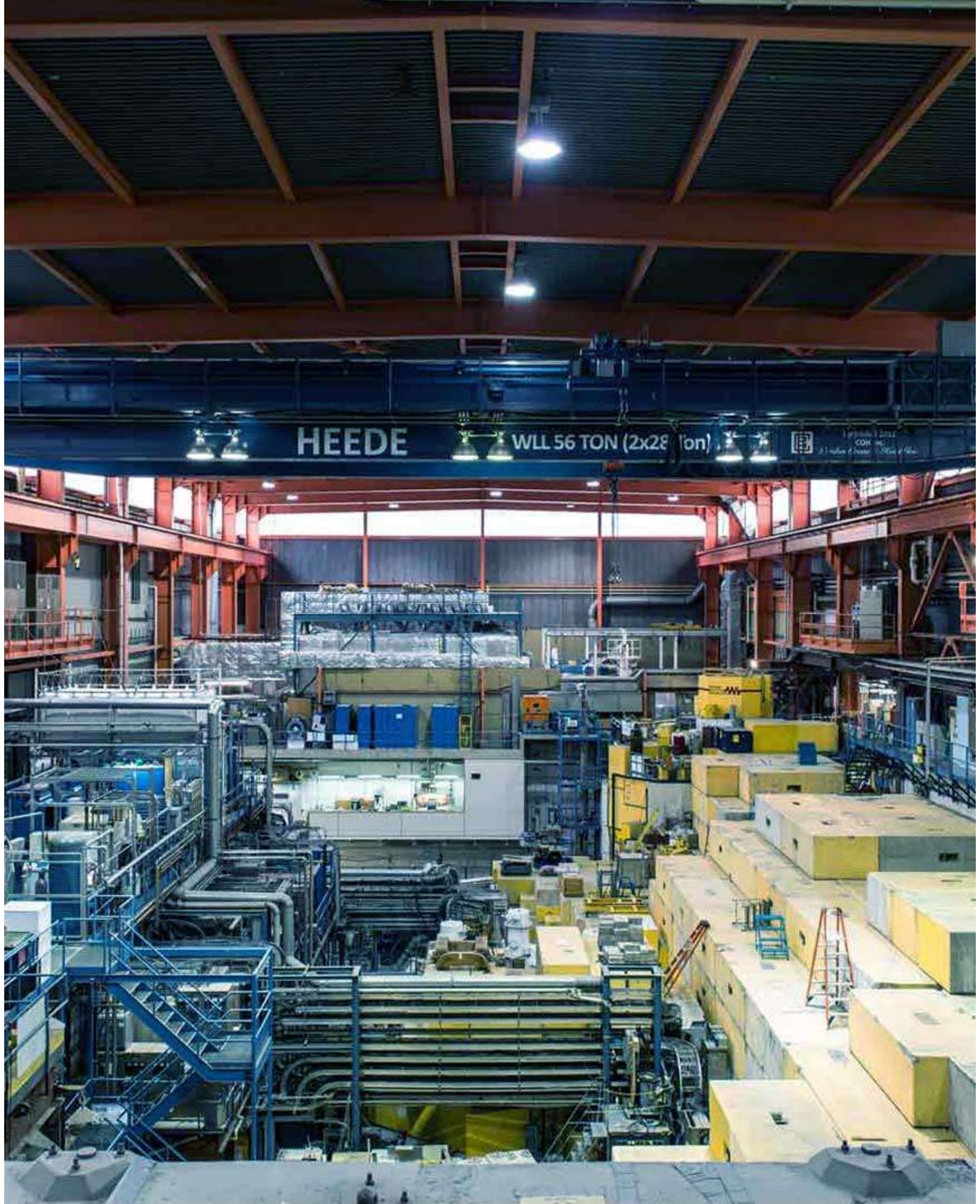

IOP Publishing | Royal Swedish Academy of Sciences Physica Scripta
Phys. Scr. **91** (2016) 053002 (38pp) doi:10.1088/0031-8949/91/5/053002

Invited Comment

Unified *ab initio* approaches to nuclear structure and reactions

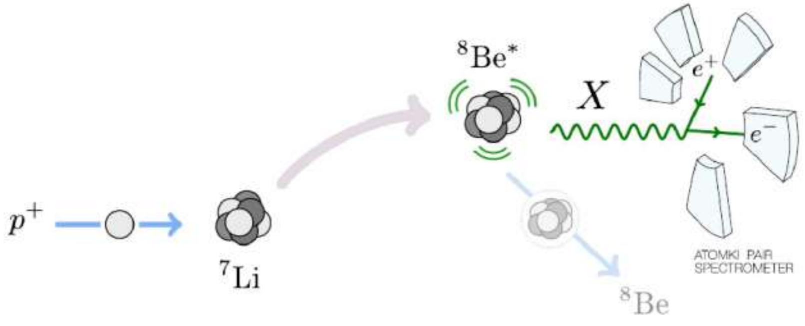
Petr Navrátil[1], Sofia Quaglioni[2], Guillaume Hupin[3,4], Carolina Romero-Redondo[2] and Angelo Calci[1]

^{7}Li(p,e^{+}e^{-})^{8}Be pair production & X17 boson within NCSMC



X17 Anomaly

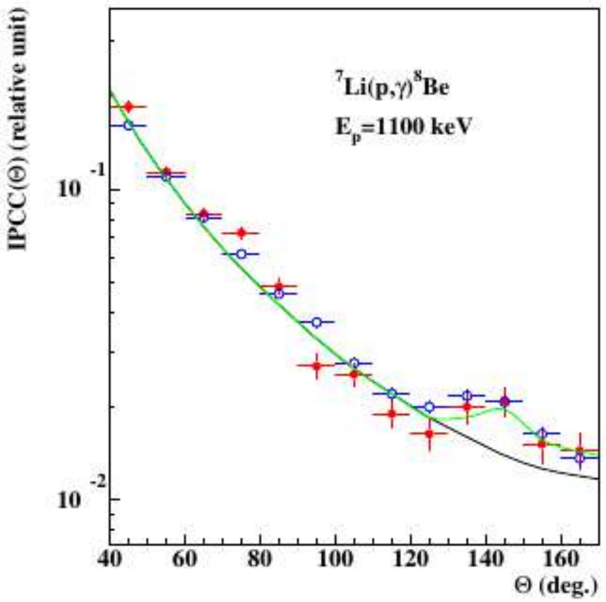
Phys. Rev. Lett. **116**, 042501 (2016) – ^{7}Li+p -> ^{8}Be
Phys. Rev. C **104**, 044003 (2021) – ^{3}H+p -> ^{4}He
Phys. Rev. C **106**, L061601 (2022) – ^{11}B+p ->^{12}C

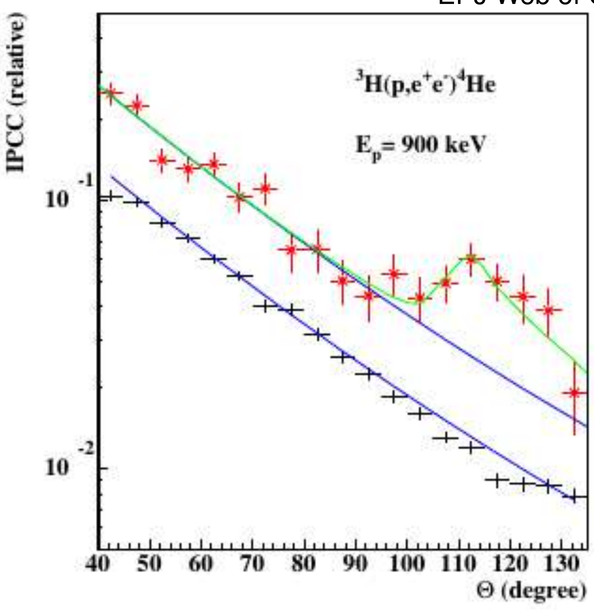


Feng PRD **95**, 035017 (2017)

"An anomaly in the internal pair creation on the M1 transition depopulating the 18.15 MeV isoscalar 1^{+} state on $^{8}\mathrm{Be}$ was observed. This could be explained by the creation and subsequent decay of a new boson .. mass 17.01(16) MeV"

Firak, Krasznahorkay, et al
EPJ Web of Conferences **232 04005 (2020)**





Angle between e$^-$ and e$^+$

IPCC:
Internal Pair Creation
Angular Correlation

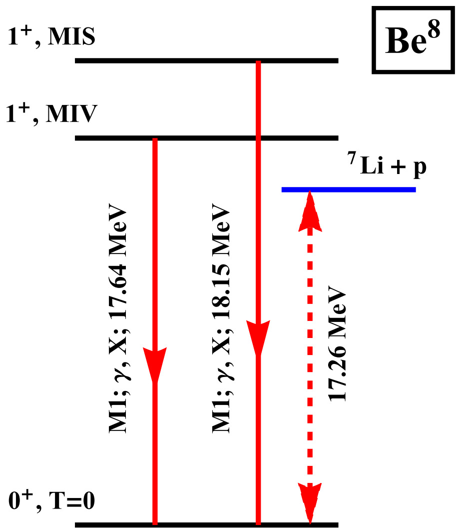


Fig. from PLB 813, 136061 (2021)

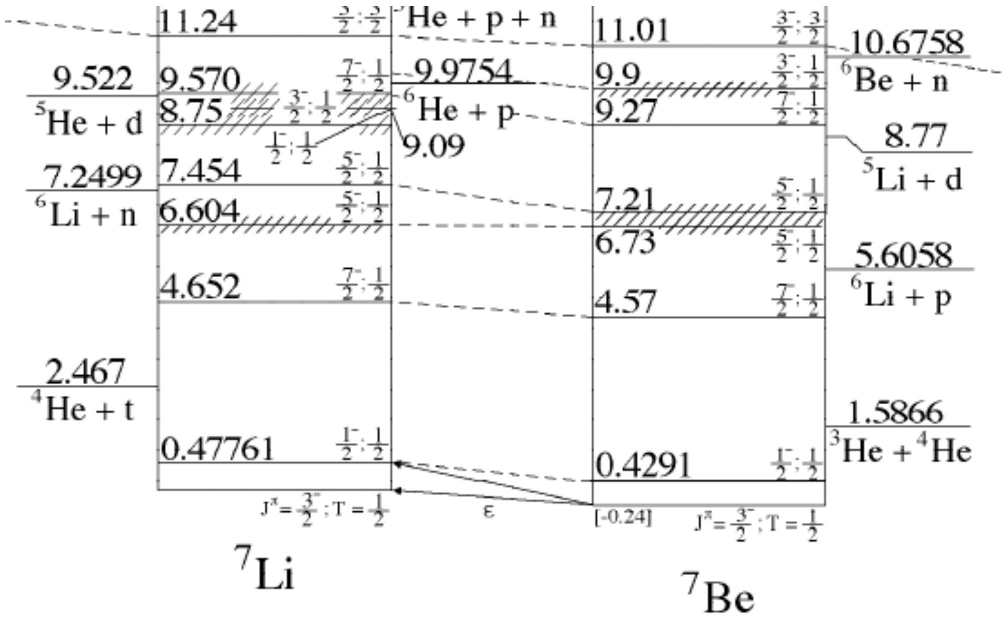
Can *ab initio* nuclear theory help interpret the anomaly?

NCSMC calculations of ^{8}Be structure and ^{7}Li+p scattering and capture

- Wave function ansatz

$$\Psi^{(8)}_{\text{NCSMC}} = \sum_{\lambda} c_\lambda \left|^8\text{Be}, \lambda\right\rangle + \sum_{\nu} \int \mathrm{d}r \gamma_\nu(r) \hat{A}_\nu \left|^7\text{Li} + p, \nu\right\rangle + \sum_{\mu} \int \mathrm{d}r \gamma_\mu(r) \hat{A}_\mu \left|^7\text{Be} + n, \mu\right\rangle$$

- $3/2^-$, $1/2^-$, $7/2^-$, $5/2^-$, $5/2^-$ ^{7}Li and ^{7}Be states in cluster basis
- 15 positive and 15 negative parity states in ^{8}Be composite state basis



TUNL Nuclear Data Evaluation Project

NCSMC calculations of ^{8}Be structure and ^{7}Li+p scattering and capture

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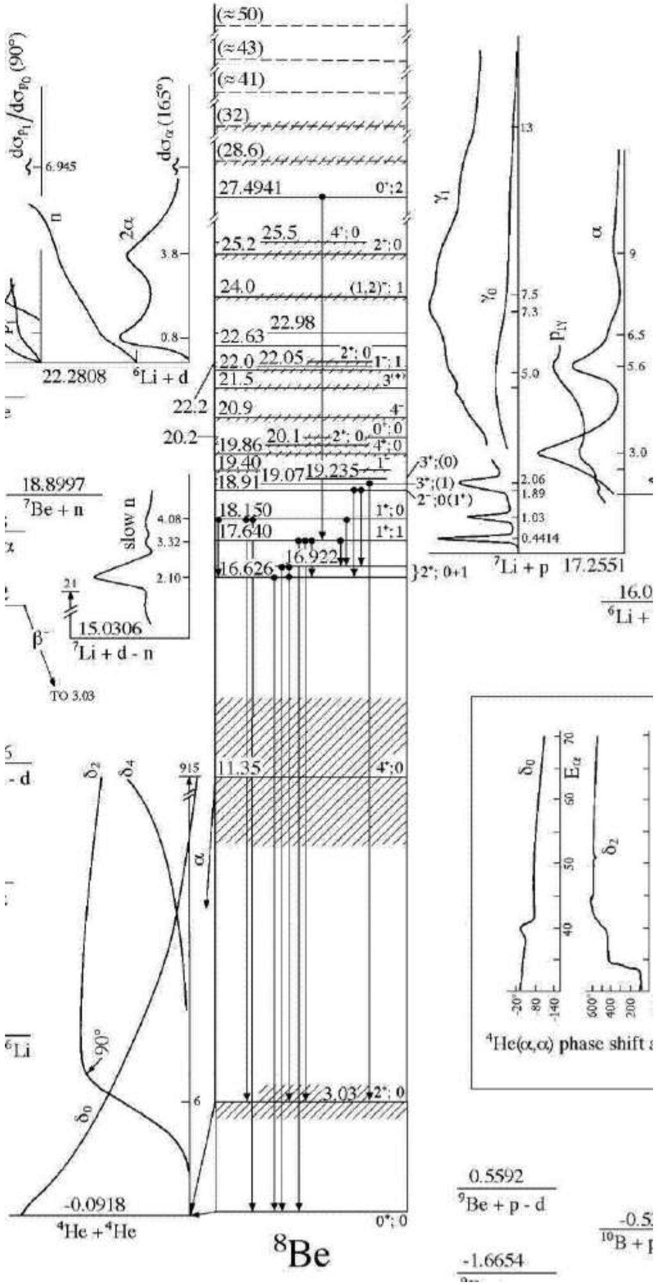


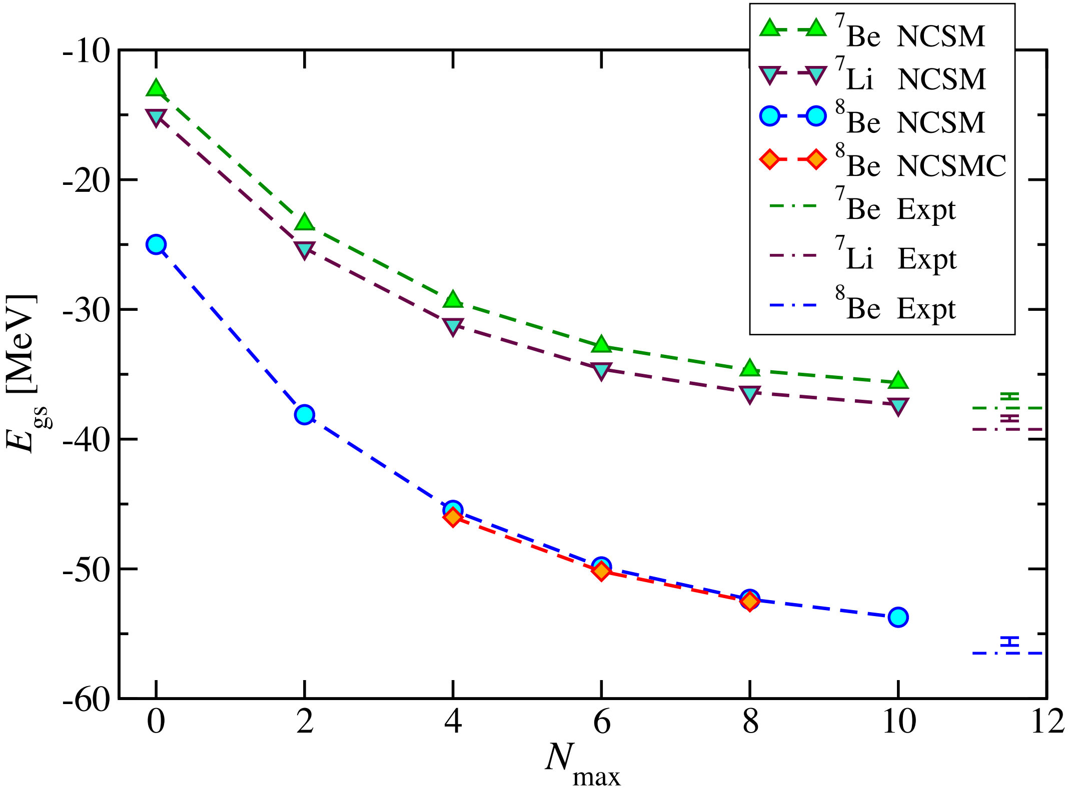
PHYSICAL REVIEW C **101**, 014318 (2020)

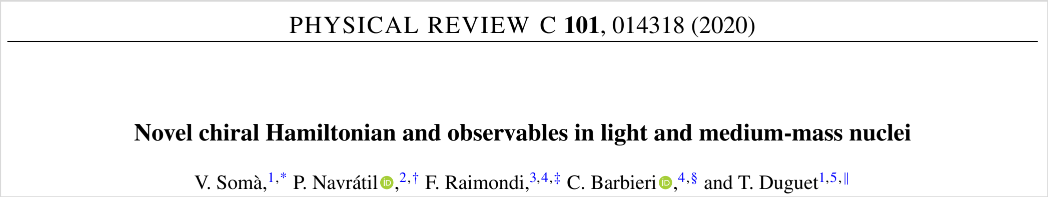
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

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

Convergence of ground-state energies of ^{7}Li, ^{7}Be, ^{8}Be

Chiral EFT NN+3N interaction from PRC **101**, 014318 (2020)
Low-energy constants determined in *A*=2,3,4 systems

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Convergence of NCSM excitation energies of ^{7}Li, ^{7}Be, ^{8}Be

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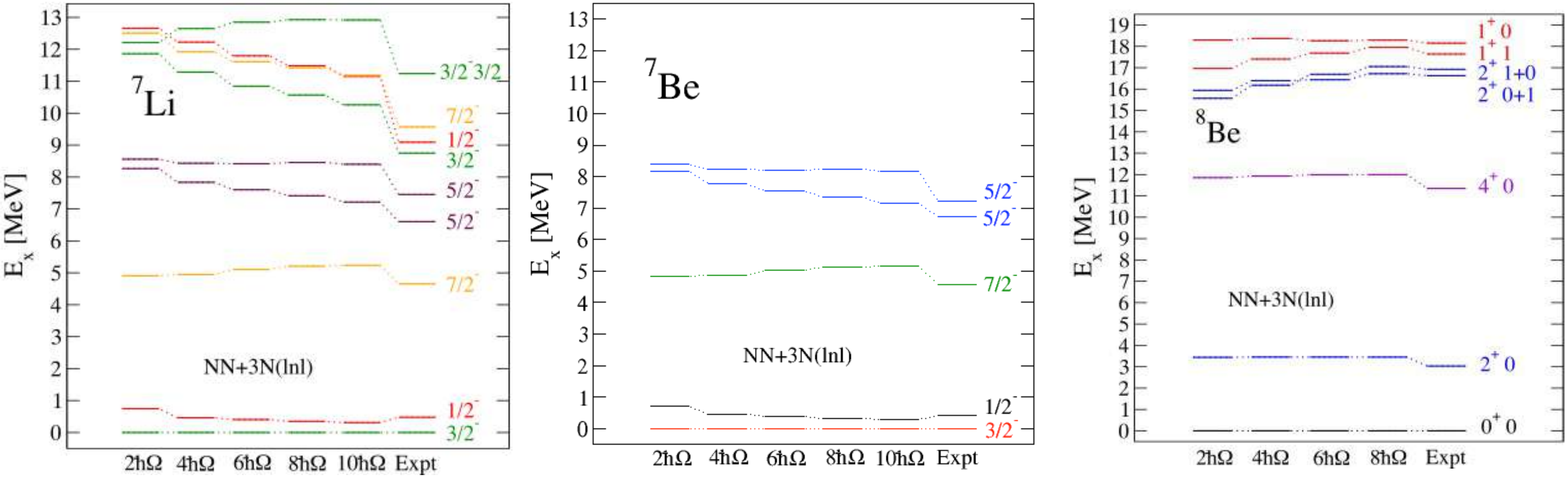
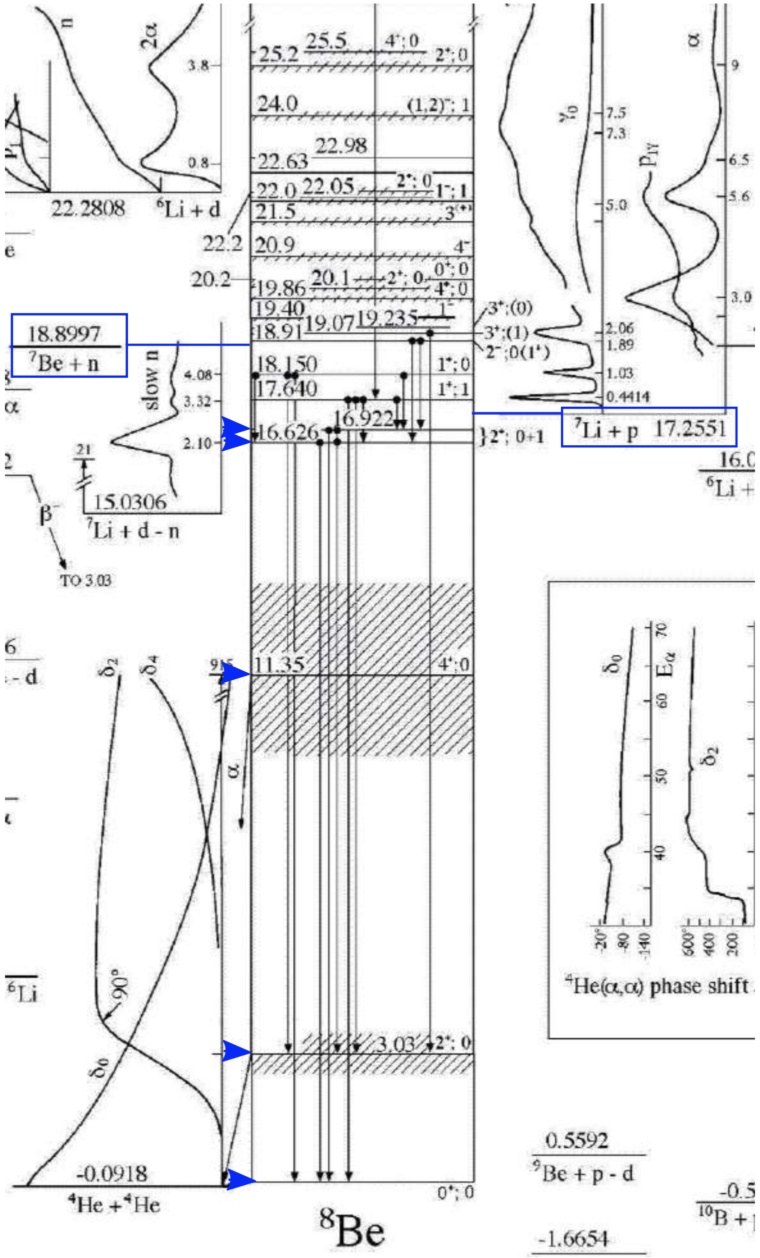


^{8}Be structure

Calculated $^8\mathrm{Be}$ bound states w.r.t. $^7\mathrm{Li}+p$ threshold ($N_{max}=8/9$)

State	Energy [MeV]		Excitation Energy [MeV]	
	NCSMC	Expt.	NCSMC	Expt.
0^+	-16.13	-17.25	0.00	0.00
2^+	-12.72	-14.23	3.41	3.03
4^+	-4.31	-5.91	11.82	11.35
2^+	-0.10	-0.63	16.03	16.63
2^+	+0.31	-0.33	16.44	16.92

Matches experiment well, except the 3rd 2^+ is slightly above the $^7\mathrm{Li}+p$ threshold.



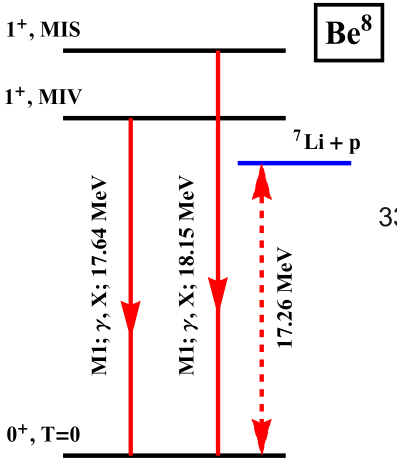
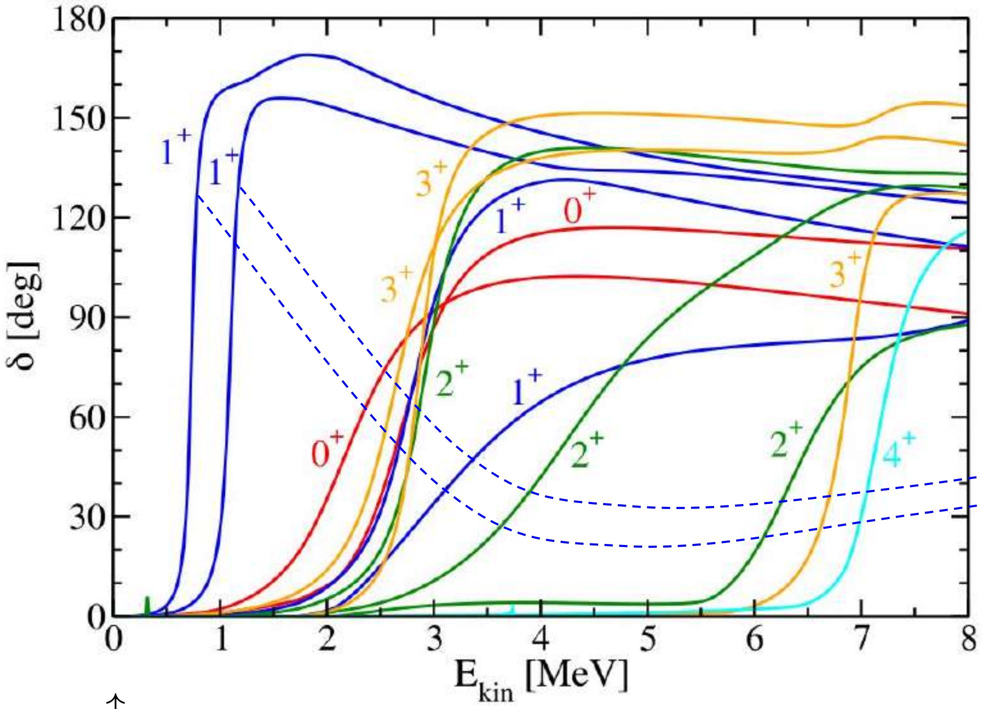
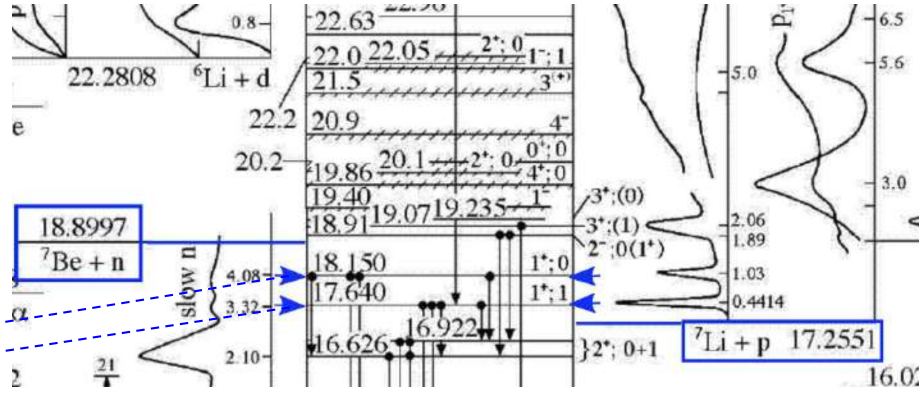


Fig. from PLB 813, 136061 (2021)

^{8}Be structure – calculated positive-parity eigenphase shifts



↑
$p + {}^7\mathrm{Li}$ threshold



Additional resonances are seen compared to TUNL data

Ab initio calculations of ^{7}Li(p,γ)^{8}Be radiative capture, ^{7}Li(p,e$^+$e$^-$)^{8}Be pair production & the X17 boson

- Motivated by ATOMKI experiments (Firak, Krasznahorkay *et al.*, EPJ Web of Conferences **232**, 04005 (2020))
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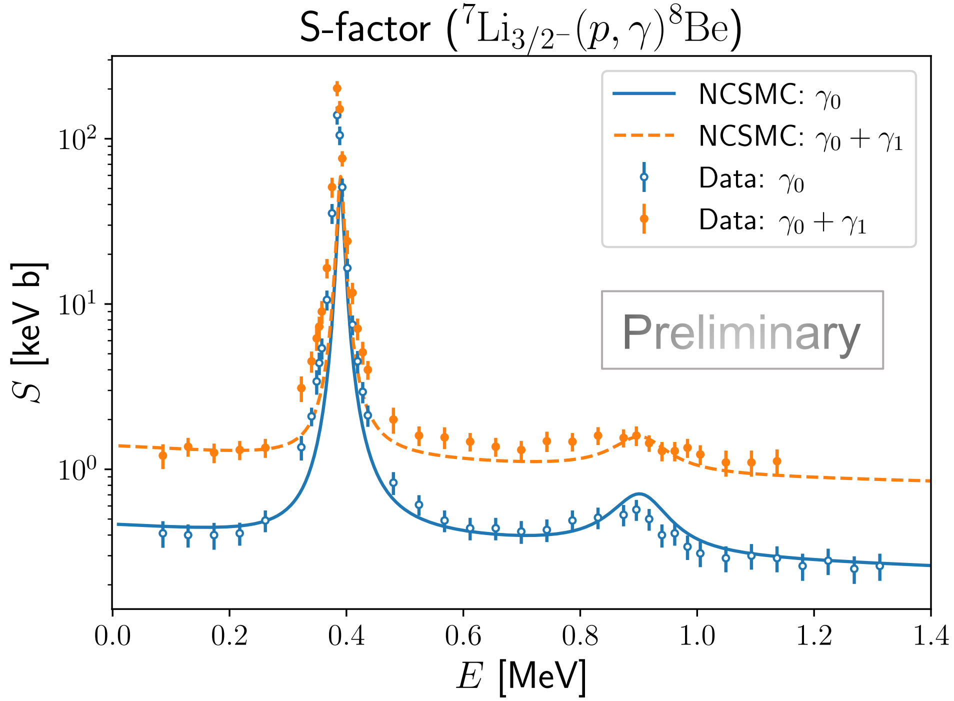

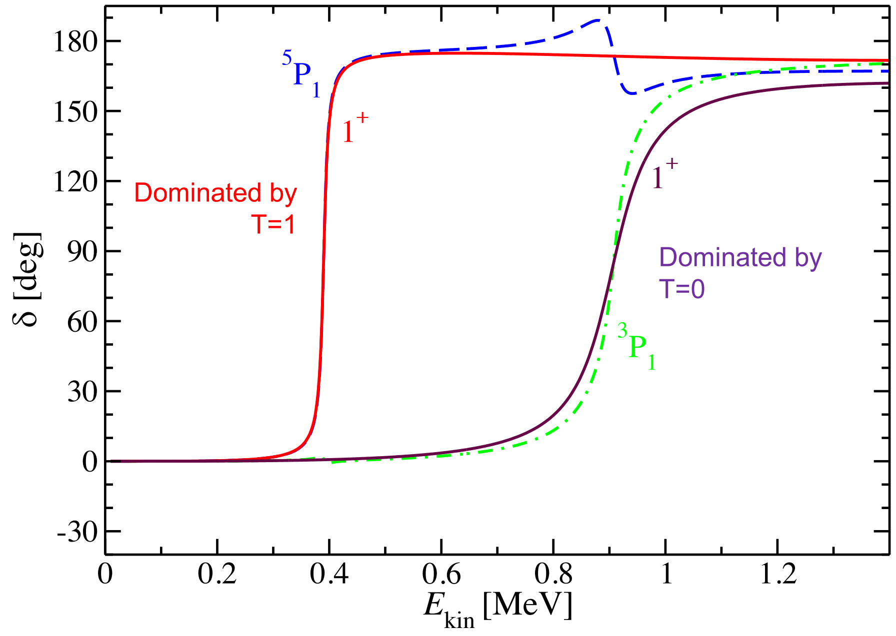

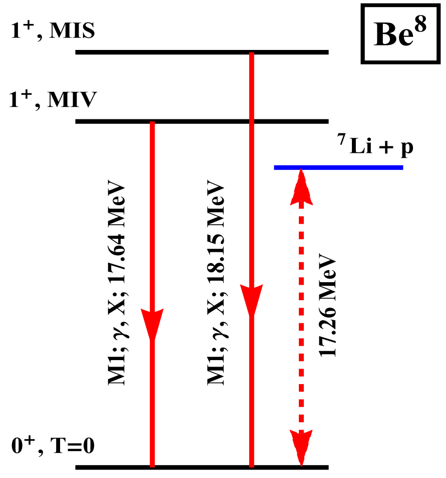

Data: Zahnow *et al.*
Z.Phys.A **351** 229-236 (1995)

γ_0: decay to ground state (0^+)
γ_1: decay to first excited (2^+)

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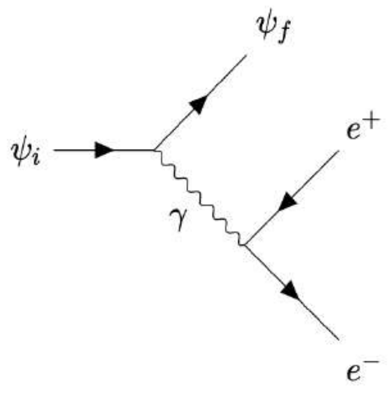
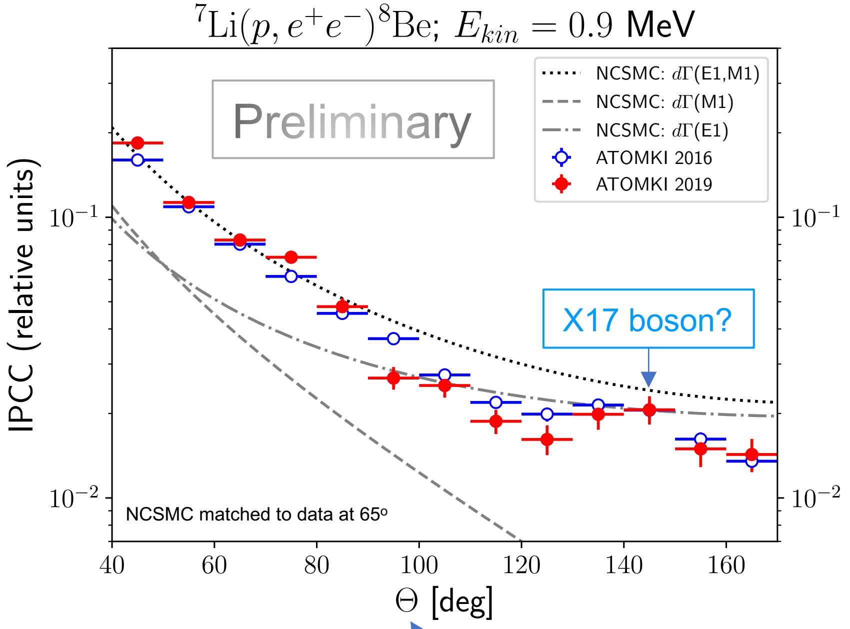
Internal electron-positron pair conversion correlation

Assuming J=1 → 0$^+$ bound-to-bound like decay rate



NCSMC IPCC results consistent with LANL R-matrix phenomenology
arXiv: 2106.06834; Phys. Rev. C **105**, 055502 (2022)



Angle between e$^-$ and e$^+$

P. Navratil. K. Kravvaris, P. Gysbers *et al.*, arXiv: 2212.00160; P. Gysbers, PhD Thesis; P. Gysbers *et al.,* in preparation

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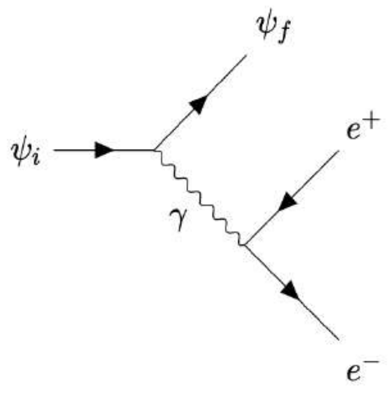

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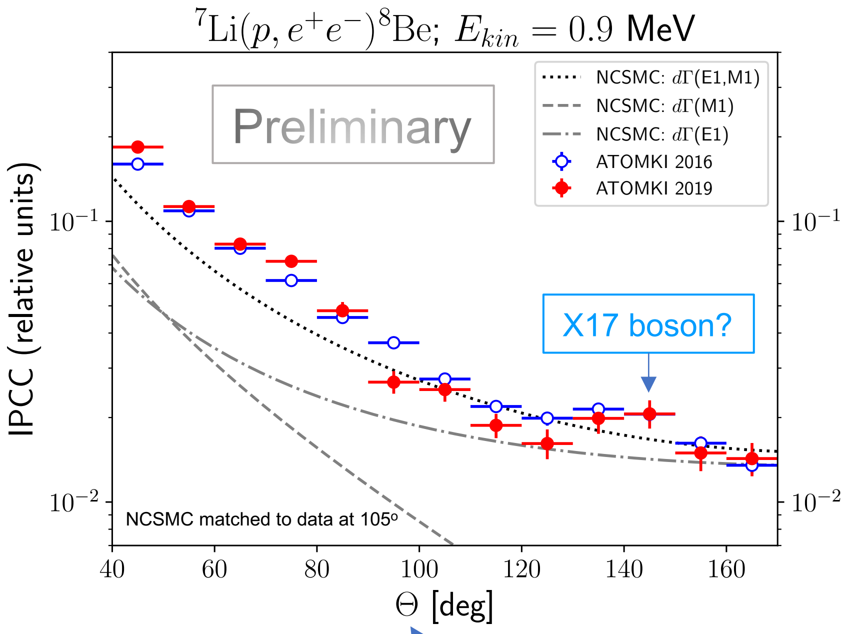

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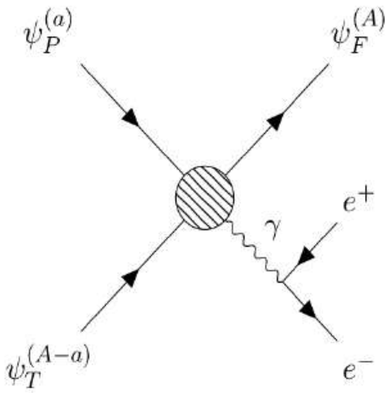
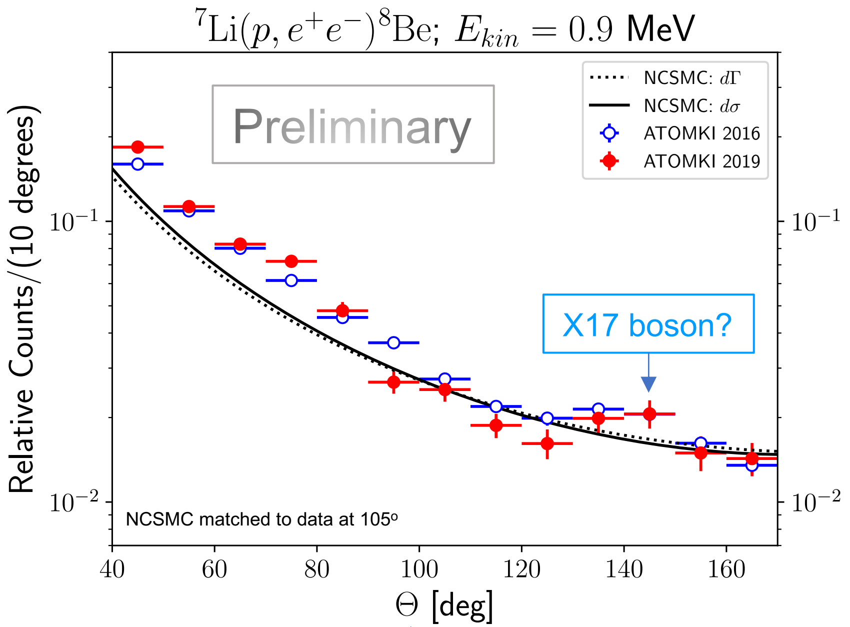
Internal electron-positron pair conversion correlation

Calculating properly the pair production cross section with the interference of different multipoles



Following formalism by Viviani *et al.* Phys. Rev. C **105**, 014001 (2022)



Angle between e$^-$ and e$^+$

NCSMC pair production cross section slightly closer to ATOMKI SM background data

P. Navratil. K. Kravvaris, P. Gysbers *et al.*, arXiv: 2212.00160; P. Gysbers, PhD Thesis; P. Gysbers *et al.*, in preparation

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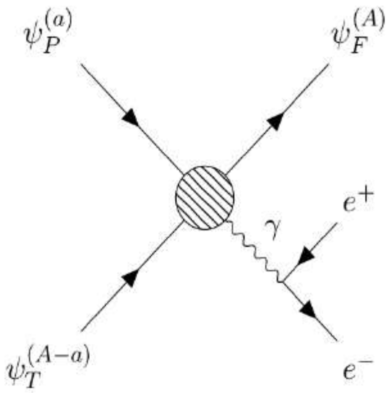
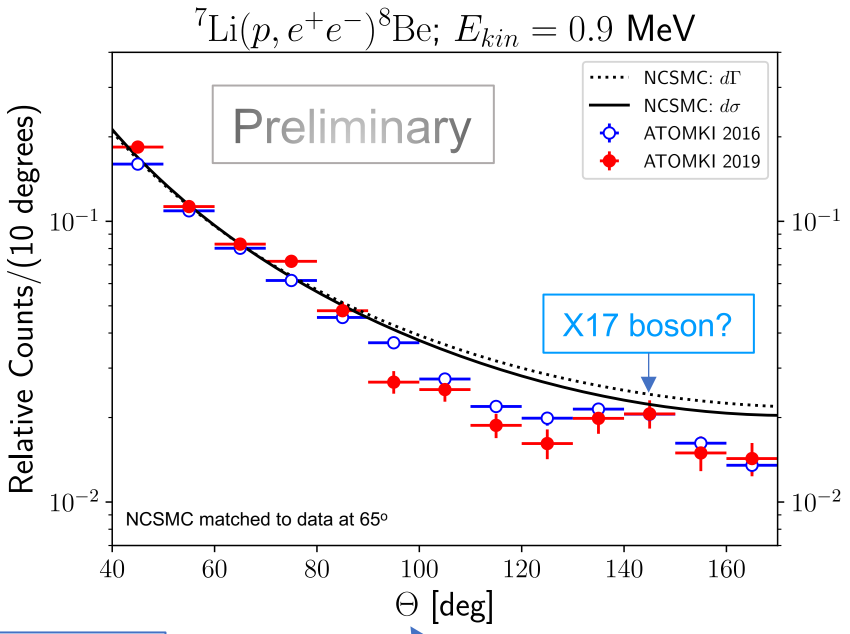


Following formalism by Viviani *et al.* Phys. Rev. C **105**, 014001 (2022)



Angle between e$^-$ and e$^+$

NCSMC pair production cross section slightly closer to ATOMKI SM background data

P. Navratil. K. Kravvaris, P. Gysbers *et al.*, arXiv: 2212.00160; P. Gysbers, PhD Thesis; P. Gysbers *et al.*, in preparation

Conclusions and outlook

- *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

- *Ab initio* no-core shell model is one of the pioneering methods with impact beyond light nuclei

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

TRIUMF

Congratulations, James!

Recent NCSM and NCSMC collaborators:

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P. Gysbers (TRIUMF)

Thank you!

Discovery, accelerated