TRIUMF

Ab initio nuclear structure & reaction theory: Applications to nuclear astrophysics and tests of fundamental symmetries

Hirschegg 2023 –

Effective field theories for nuclei and nuclear matter

Darmstadter Haus, Hirschegg, Austria, 15-21 January 2023

Petr Navratil

TRIUMF

Kostas Kravvaris, Sofia Quaglioni, Mack Atkinson (LLNL), Guillaume Hupin (IJCLab), Chloe Hebborn (MSU/LLNL), Peter Gysbers (UBC/TRIUMF), Michael Gennari (UVic/TRIUMF)

2023-01-20

Discovery, accelerated

NCSMC applications to capture reactions and β-delayed proton emission

- NCSMC extended to describe exotic ^{11}Be βp emission
- Radiative capture of deuterons on ^{4}He – reaction responsible for the ^{6}Li in BBN
- Radiative capture of protons on ^{7}Be - solar pp chain reaction, solar ^{8}B neutrinos
  - Evaluation with reduced theoretical uncertainties
- NCSMC calculations of ^{8}Be structure and ^{7}Li+p scattering and capture (in progress)
  - X17 anomaly

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]

PHYSICAL REVIEW LETTERS **129,** 042503 (2022)

***Ab Initio* Prediction of the ^{4}He$(d,\gamma)^{6}$Li Big Bang Radiative Capture**

C. Hebborn,[1,2,*] G. Hupin,[3] K. Kravvaris,[2] S. Quaglioni,[2] P. Navrátil,[4] and P. Gysbers[4,5]

Ab initio prediction for the radiative capture of protons on ^{7}Be

K. Kravvaris,[1] P. Navrátil,[2] S. Quaglioni,[1] C. Hebborn,[3,1] and G. Hupin[4]

arXiv: 2202.11759

NCSM(C) applications to tests of fundamental symmetries

- ***Ab initio* calculations of nuclear electric dipole moments (EDMs) and anapole moments in light nuclei**
- *Ab initio* calculations of ^{6}He β-decay electron spectrum including nuclear structure and recoil corrections
- Ongoing calculations of nuclear structure corrections δ_C and δ_{NS} for the extraction of the V_{ud} matrix element from the superallowed Fermi transitions (current focus on ^{10}C→^{10}B)

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

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,*]

Physics Letters B 832 (2022) 137259

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Physics Letters B

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Nuclear *ab initio* calculations of ^{6}He β-decay for beyond the Standard Model studies

Ayala Glick-Magid[a], Christian Forssén[b,*], Daniel Gazda[c], Doron Gazit[a,*], Peter Gysbers[d,e], Petr Navrátil[d]

Calculations performed within the no-core shell model (NCSM); δ_C within NCSM with continuum (NCSMC)

NCSM(C) applications to tests of fundamental symmetries

- ***Ab initio* calculations of nuclear electric dipole moments (EDMs) and anapole moments in light nuclei**
- *Ab initio* calculations of ^{6}He β-decay electron spectrum including nuclear structure and recoil corrections
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PHYSICAL REVIEW C **104**, 025502 (2021)

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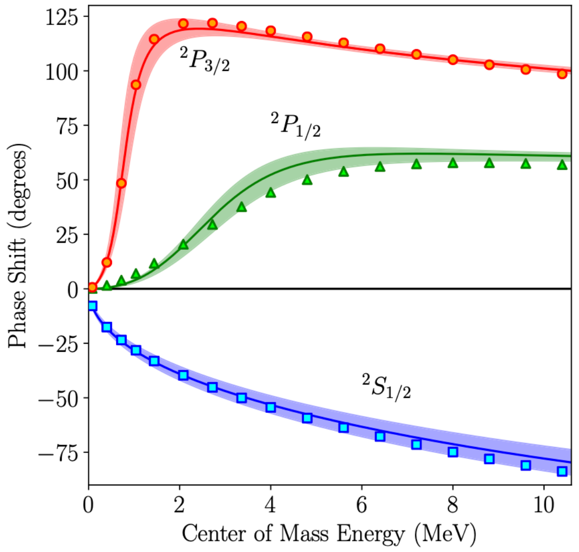
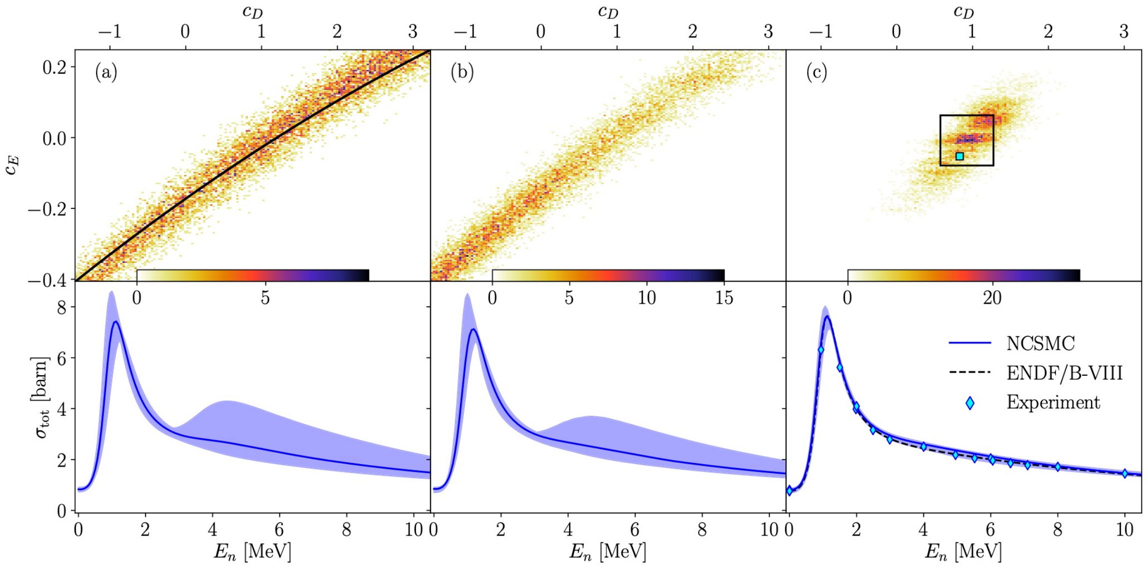
Calculations performed within the no-core shell model (NCSM); δ_C within NCSM with continuum (NCSMC)

Technical connection: Green's functions computed using the Lanczos continued fraction method

NCSMC applications to uncertainty quantifications in n-^{4}He scattering

- Study how the 3N LECs contribute to the overall uncertainty budget of many-body calculations of neutron - ^{4}He elastic scattering
  - Constructed a Gaussian process model that acts as a statistical emulator for the theory





PHYSICAL REVIEW C **102**, 024616 (2020)

Quantifying uncertainties in neutron-α scattering with chiral nucleon-nucleon and three-nucleon forces

Konstantinos Kravvaris,[1,*] Kevin R. Quinlan,[1,†] Sofia Quaglioni,[1] Kyle A. Wendt,[1] and Petr Navrátil[2]

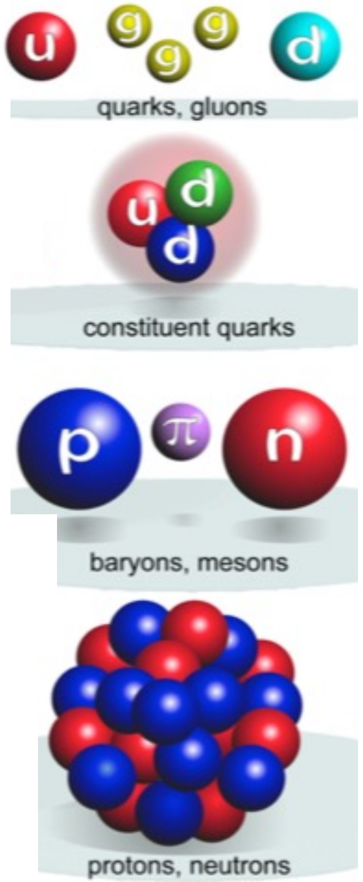
First principles or *ab initio* nuclear theory

Quantum Chromodynamics (QCD)

Chiral Effective Field Theory (parameters fitted to NN data)

Many-nucleon Schroedinger equation

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



Ab Initio Calculations of Structure, Scattering, Reactions

Unified approach to bound & continuum states

No-Core Shell Model with Continuum (NCSMC)

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

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

Ab Initio Calculations of Structure, Scattering, Reactions

Unified approach to bound & continuum states

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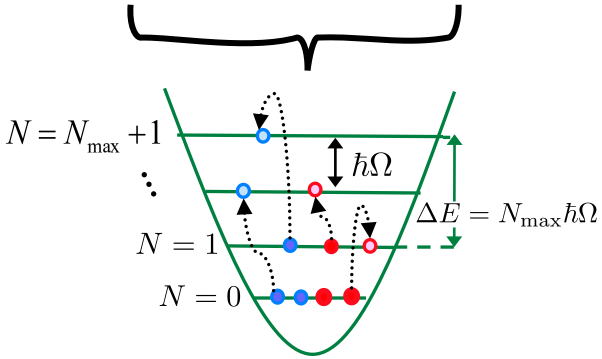

Static solutions for aggregate system,
describe all nucleons close together

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

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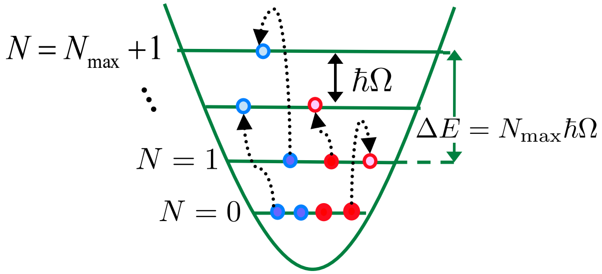


Continuous microscopic cluster states, describe long-range projectile-target

Static solutions for aggregate system, describe all nucleons close together

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

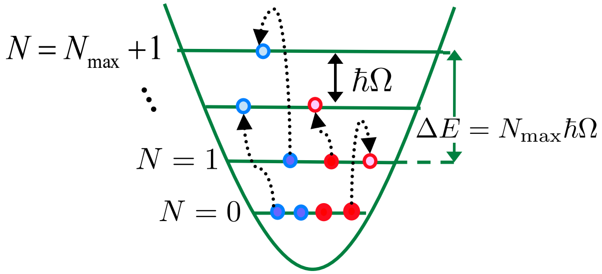
Ab Initio Calculations of Structure, Scattering, Reactions

Unified approach to bound & continuum states

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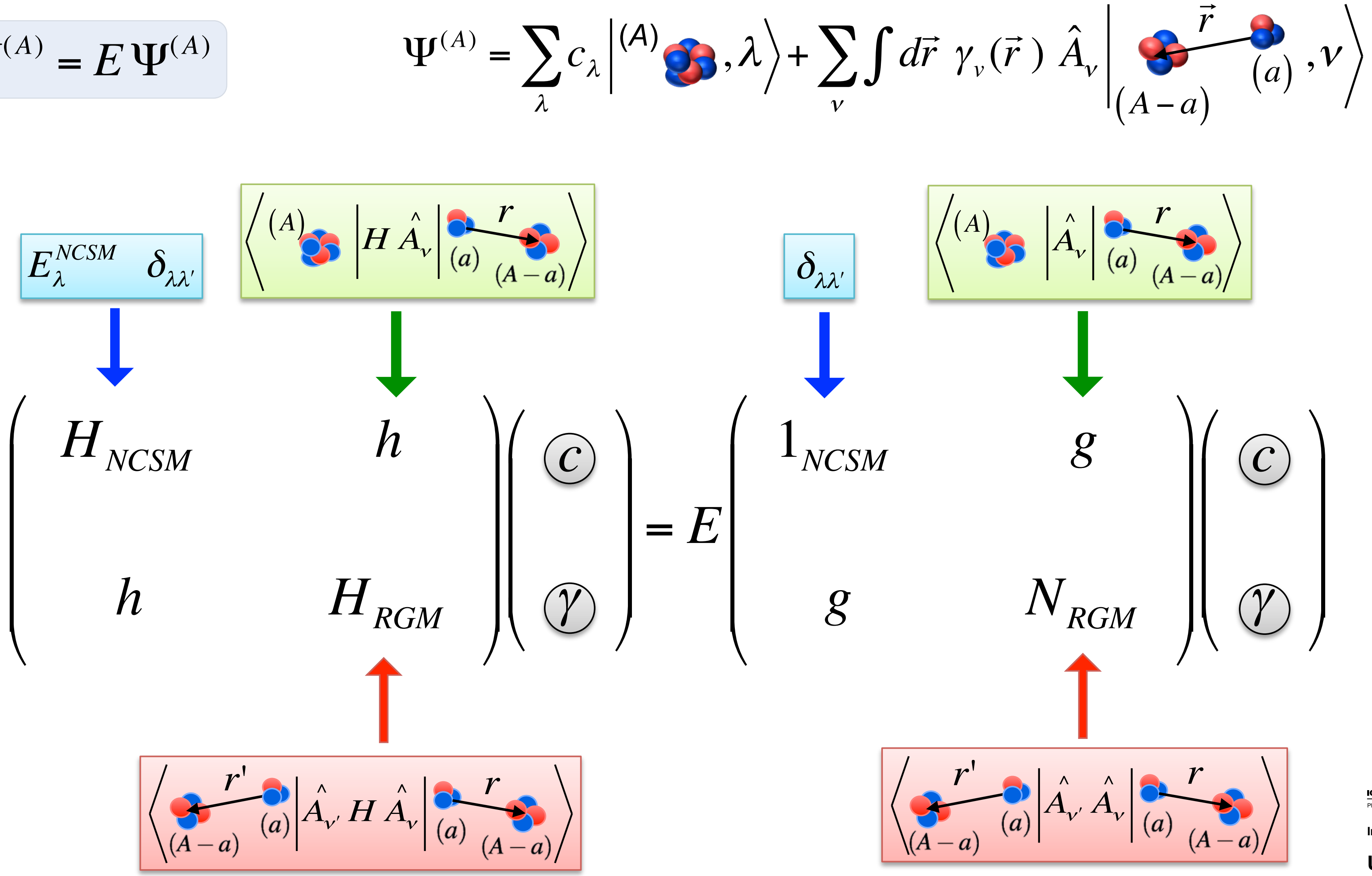
S. Baroni, P. Navratil, and S. Quaglioni, PRL **110**, 022505 (2013); PRC **87**, 034326 (2013).

Coupled NCSMC equations

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

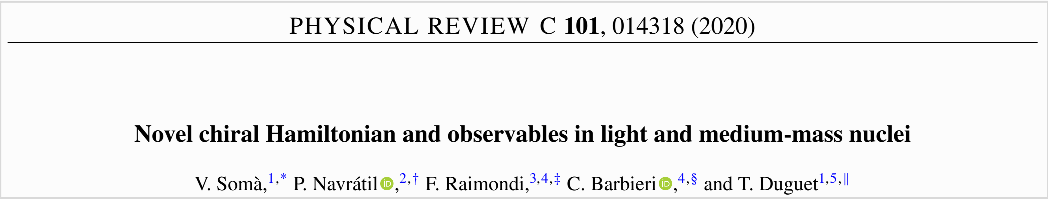



IOP Publishing | Royal Swedish Academy of Sciences Physica Scripta
Phys. Scr. 91 (2016) 053002 (38pp) doi:10.1088/0031-8949/91/5/053002

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]


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

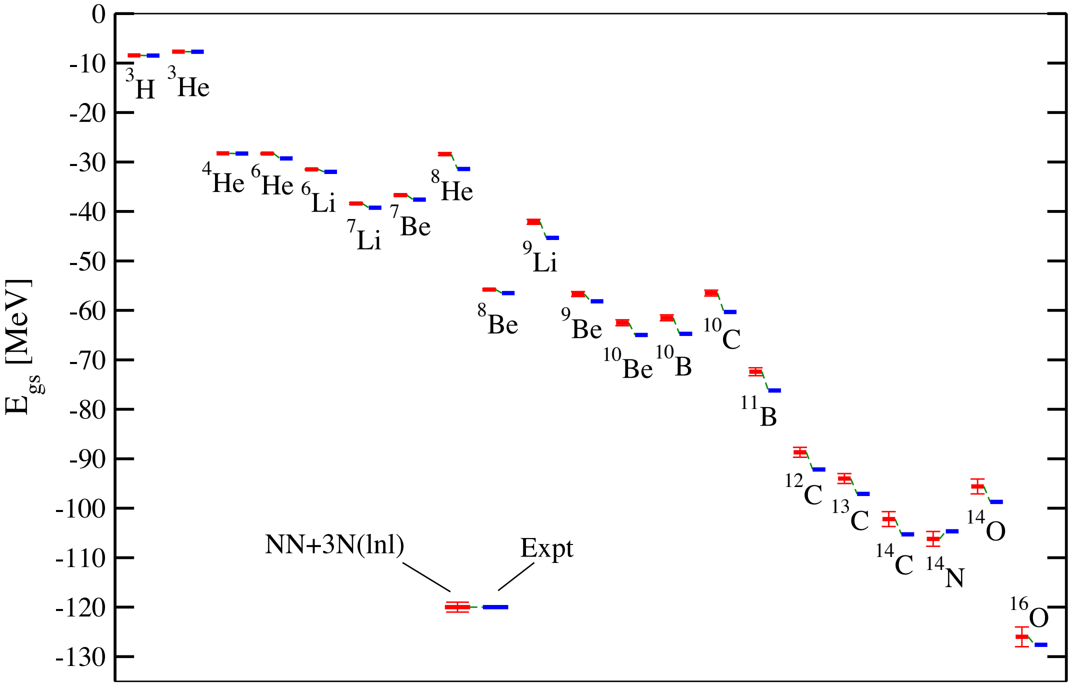
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

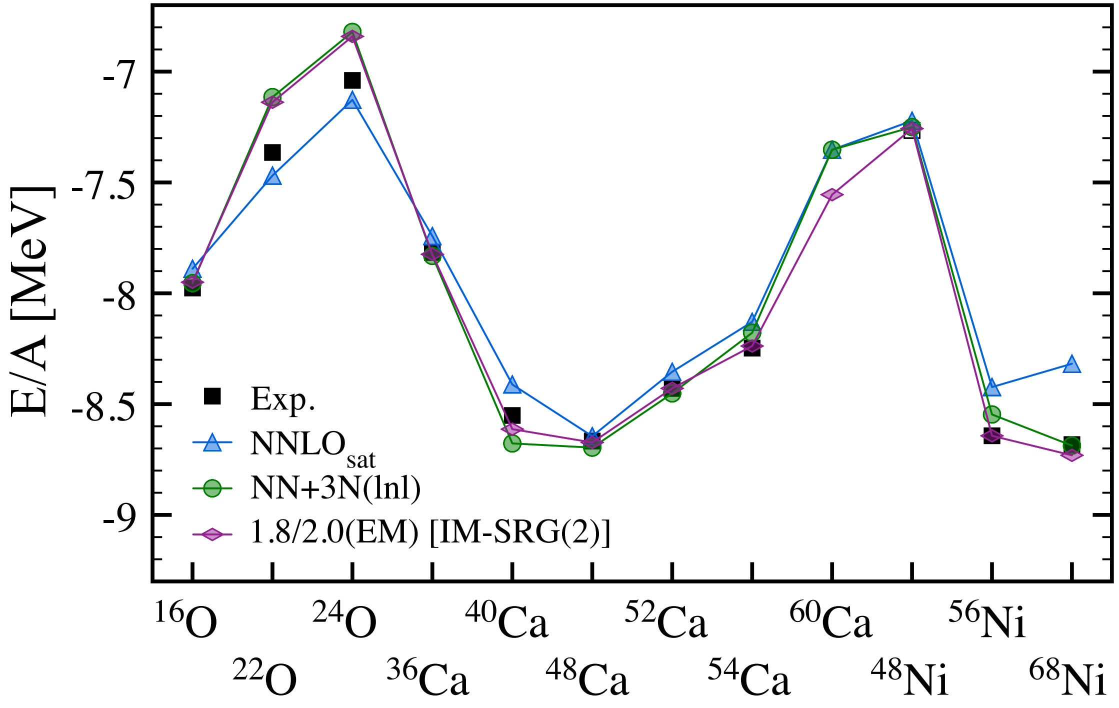
V. Somà,[1,*] P. Navrátil,[2,†] F. Raimondi,[3,4,‡] C. Barbieri,[4,§] and T. Duguet[1,5,‖]

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).

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

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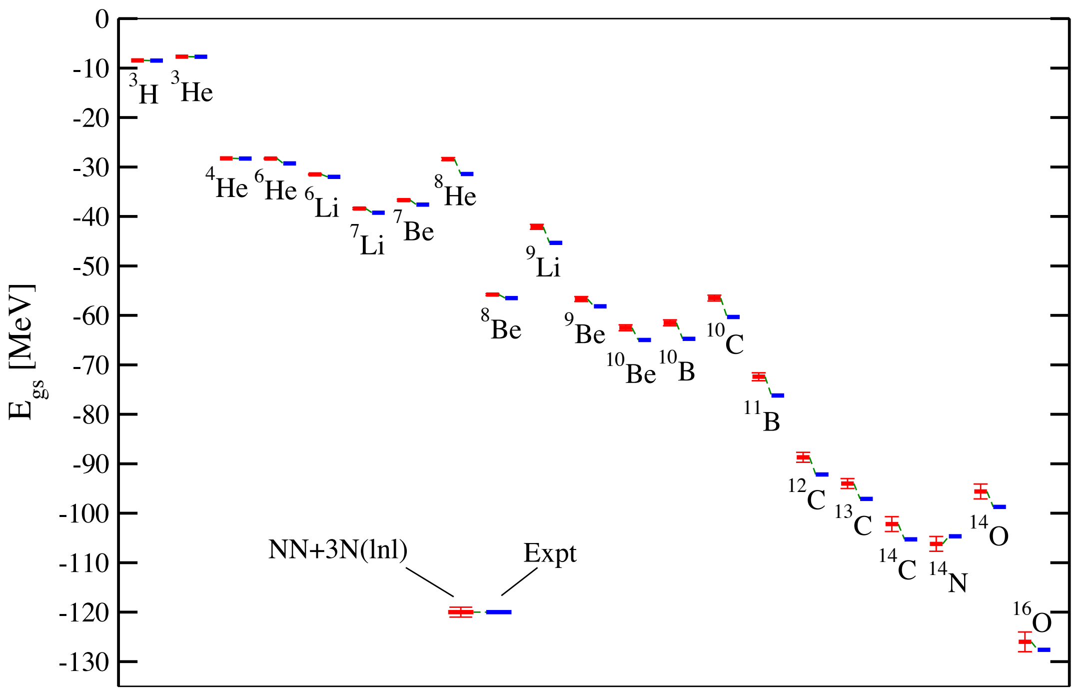
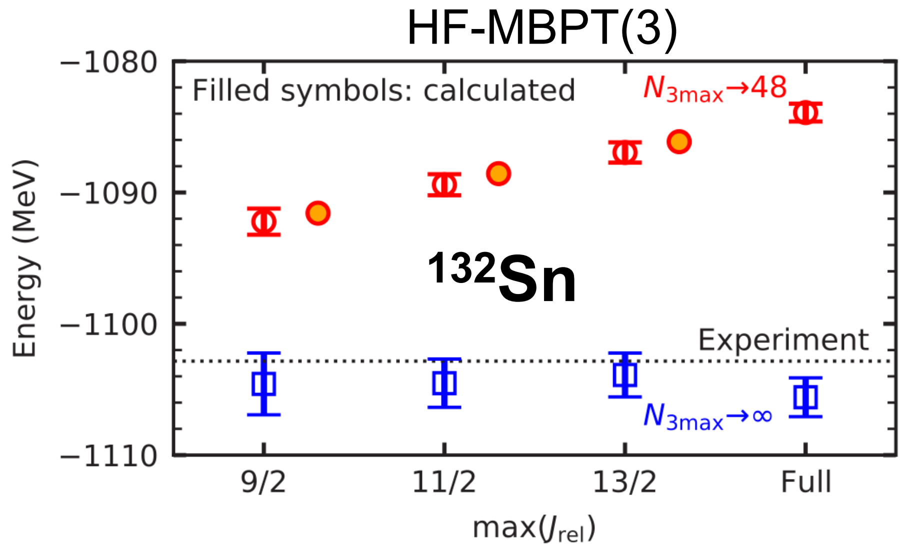
    - Nucleon–nucleon scattering, deuteron properties, ^{3}H and ^{4}He binding energy, ^{3}H half life
  - Light nuclei – NCSM
  - Heavy nuclei – HF-MBPT(3)

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,‖]

β-delayed proton emission in ^{11}Be

Physics Letters B 732 (2014) 305–308

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

^{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 $^{11}\mathrm{Be}(\beta p)^{10}\mathrm{Be}$
- 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:
  1. The neutron decays to an unobserved $p+^{10}\mathrm{Be}$ resonance in $^{11}\mathrm{B}$
  2. There are unobserved dark decay modes

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

β-delayed proton emission in ^{11}Be

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

Editors' Suggestion

Direct Observation of Proton Emission in ^{11}Be

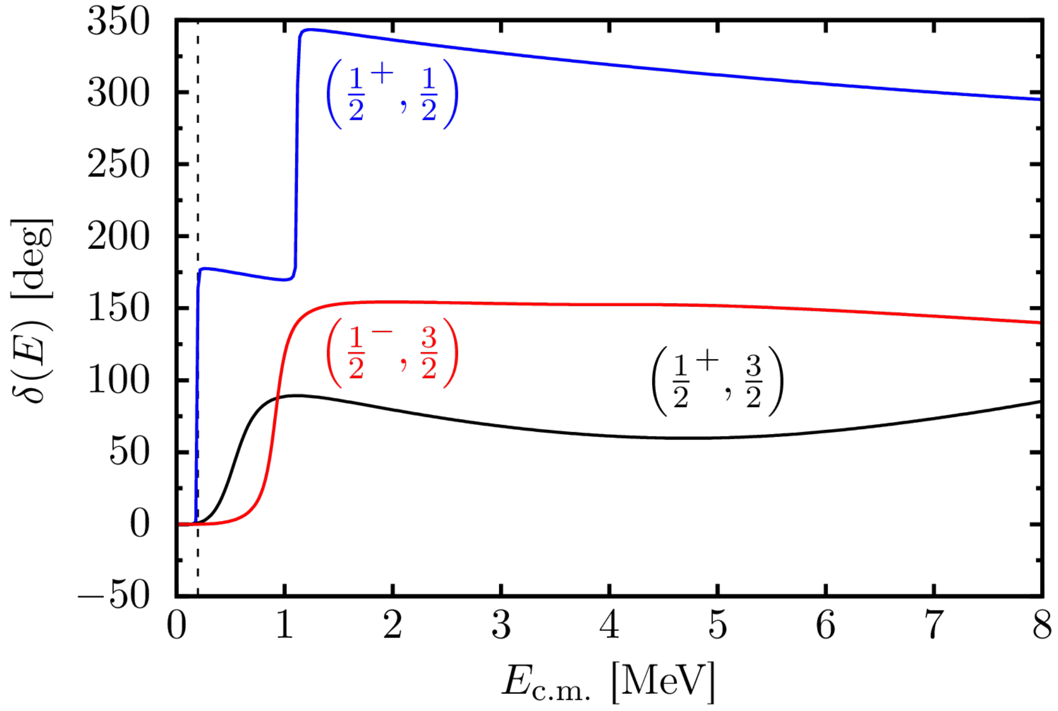
Y. Ayyad,[1,2,*] B. Olaizola,[3] W. Mittig,[2,4] G. Potel,[1] V. Zelevinsky,[1,2,4] M. Horoi,[5] S. Beceiro-Novo,[4] M. Alcorta,[3] C. Andreoiu,[6] T. Ahn,[7] M. Anholm,[3,8] L. Atar,[9] A. Babu,[3] D. Bazin,[2,4] N. Bernier,[3,10] S. S. Bhattacharjee,[3] M. Bowry,[3] R. Caballero-Folch,[3] M. Cortesi,[2] 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 $^{11}\mathrm{Be}(\beta p)^{10}\mathrm{Be}$
- 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, supports large branching ratio due to narrow ½$^+$ resonance

$^{11}\mathrm{Be} \rightarrow (^{10}\mathrm{Be+p}) + \beta^{-} + \bar{\nu}_e$ 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]

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

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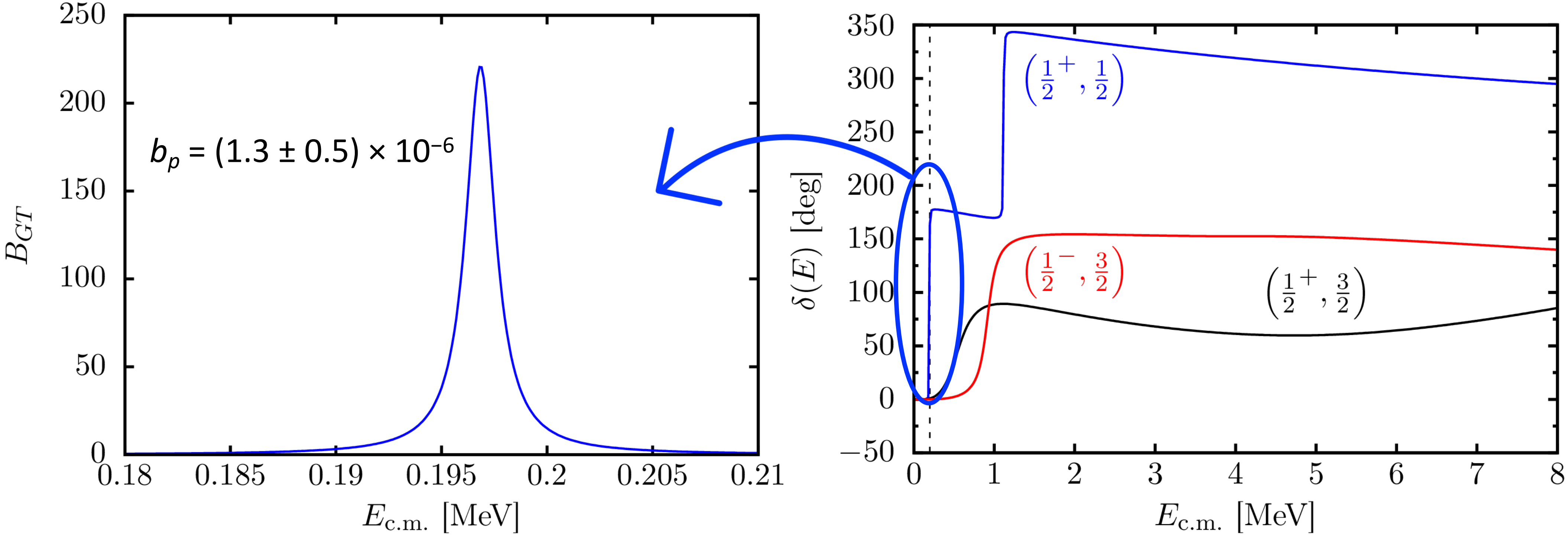
p+^{10}Be Scattering Phase Shifts



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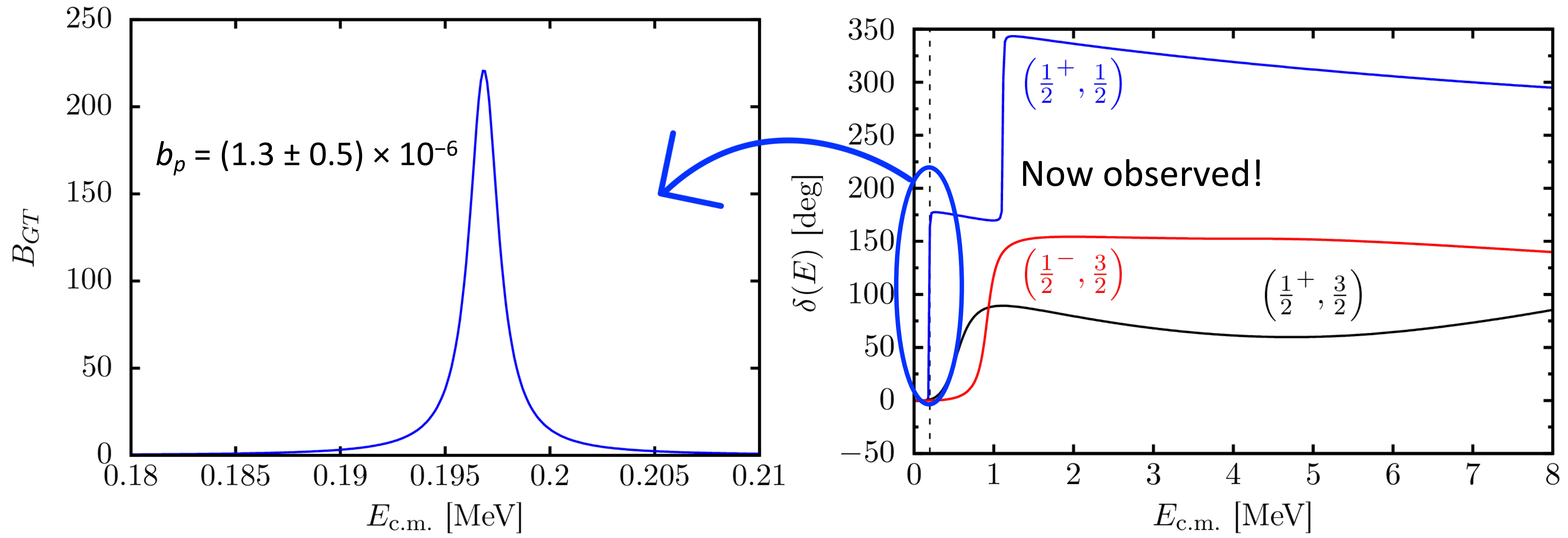


PHYSICAL REVIEW LETTERS **129,** 012502 (2022)

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)

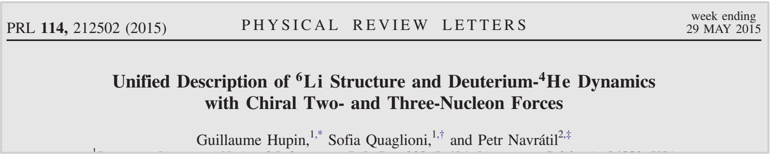
***Ab initio* calculation of the β decay from ^{11}Be to a ^{10}Be + p resonance**

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

Radiative capture of deuterons on ^{4}He

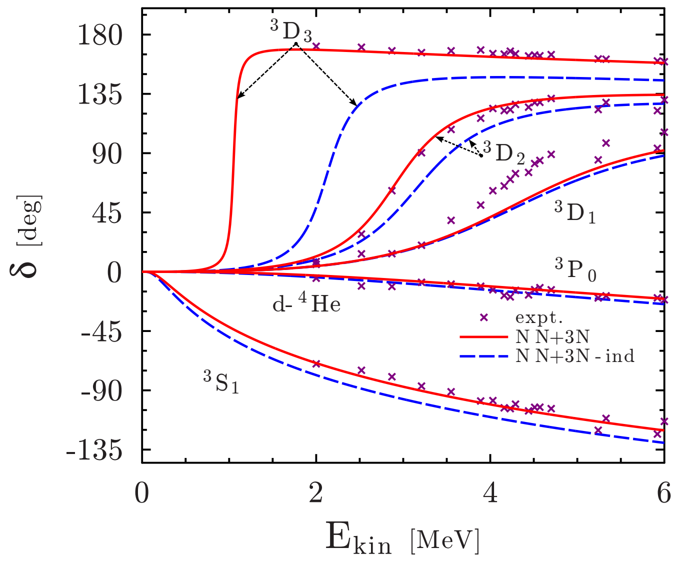
- Reaction ^{4}He(d,γ)^{6}Li responsible for ^{6}Li production in BBN
- Three orders of magnitude discrepancy between BBN predictions and observations
  - Problem with astronomical observations?
  - Problem with our understanding of the reaction rate?
  - New physics?

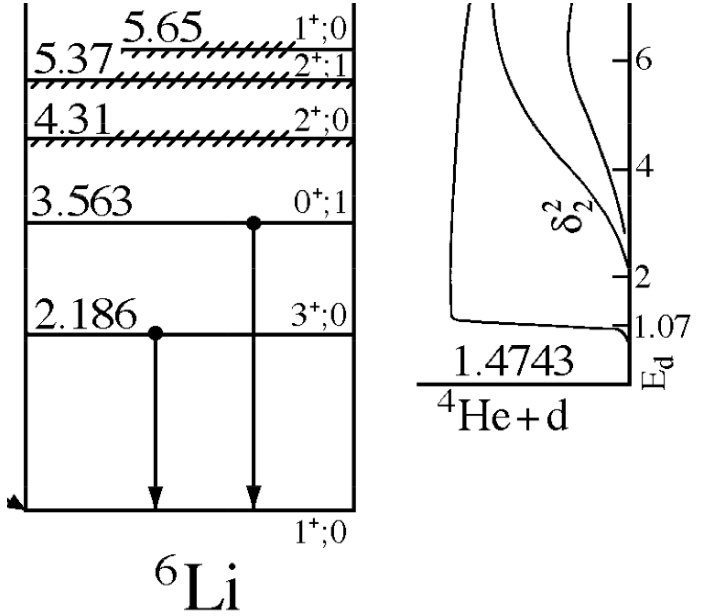
^{6}Li ↔ ^{4}He+d investigated within NCSMC in the past


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

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

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





PHYSICAL REVIEW LETTERS **129,** 042503 (2022)

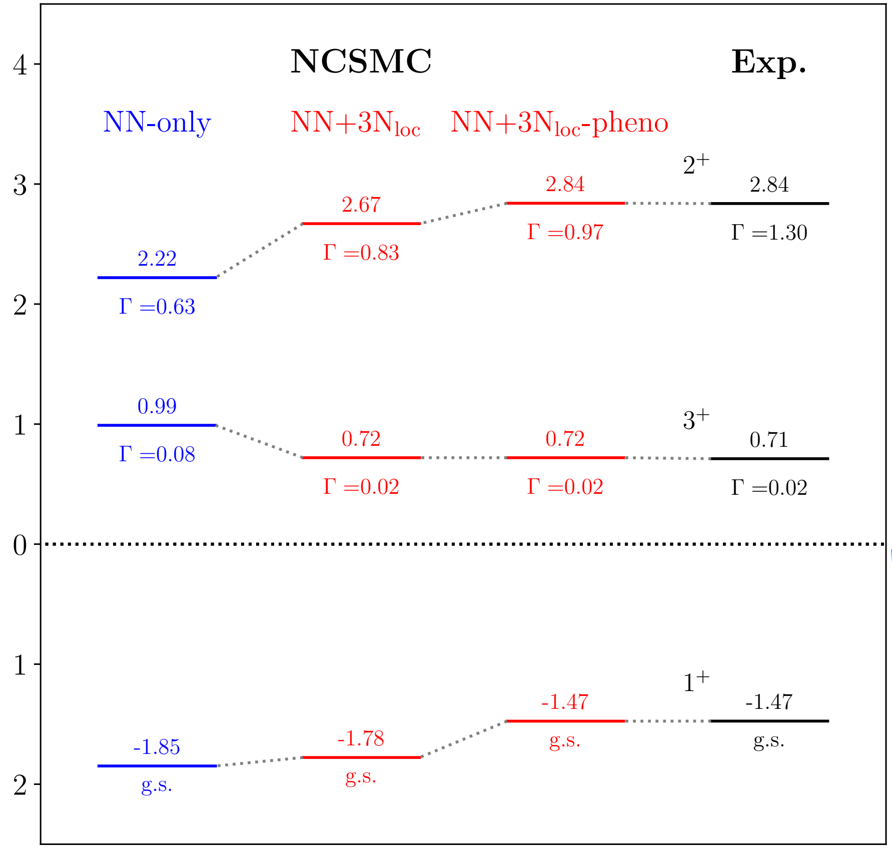
Ab Initio **Prediction of the ^{4}He$(d,\gamma)^{6}$Li Big Bang Radiative Capture**

C. Hebborn,[1,2,*] G. Hupin,[3] K. Kravvaris,[2] S. Quaglioni,[2] P. Navrátil,[4] and P. Gysbers[4,5]

Radiative capture of deuterons on ^{4}He

- NCSMC calculations with chiral NN+3N interaction

Structure of ^{6}Li



^{4}He+d threshold

Ground state properties:
Energy
Asymptotic normalization constants
Magnetic moment

	NN-only	3N$_{loc}$	3N$_{loc}$-pheno	Exp. or Eval.
$E_{g.s.}$	-1.848	-1.778	-1.474	-1.4743
$\mathcal{C}_0$	2.95	2.89	2.62(4)	2.28(7) 2.29(12)
$\mathcal{C}_2$	-0.0369	-0.0642	-0.0554(305)	-0.077(18)
$\mathcal{C}_2/\mathcal{C}_0$	-0.013	-0.022	-0.021(11)	-0.025(6)(10)
μ	0.85	0.84	0.84(1)	0.8220473(6)

PHYSICAL REVIEW LETTERS **129,** 042503 (2022)

***Ab Initio* Prediction of the $^4He(d,\gamma)^6Li$ Big Bang Radiative Capture**

C. Hebborn,[1,2,*] G. Hupin,[3] K. Kravvaris,[2] S. Quaglioni,[2] P. Navrátil,[4] and P. Gysbers[4,5]

Radiative capture of deuterons on ^{4}He

- NCSMC calculations with chiral NN+3N interaction

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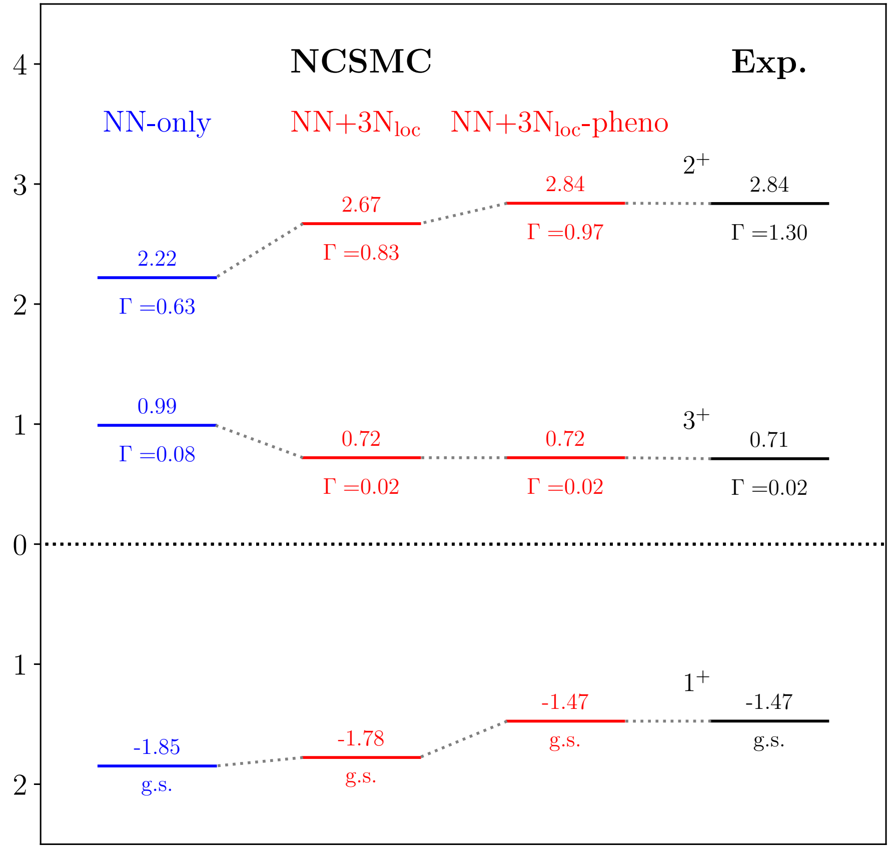
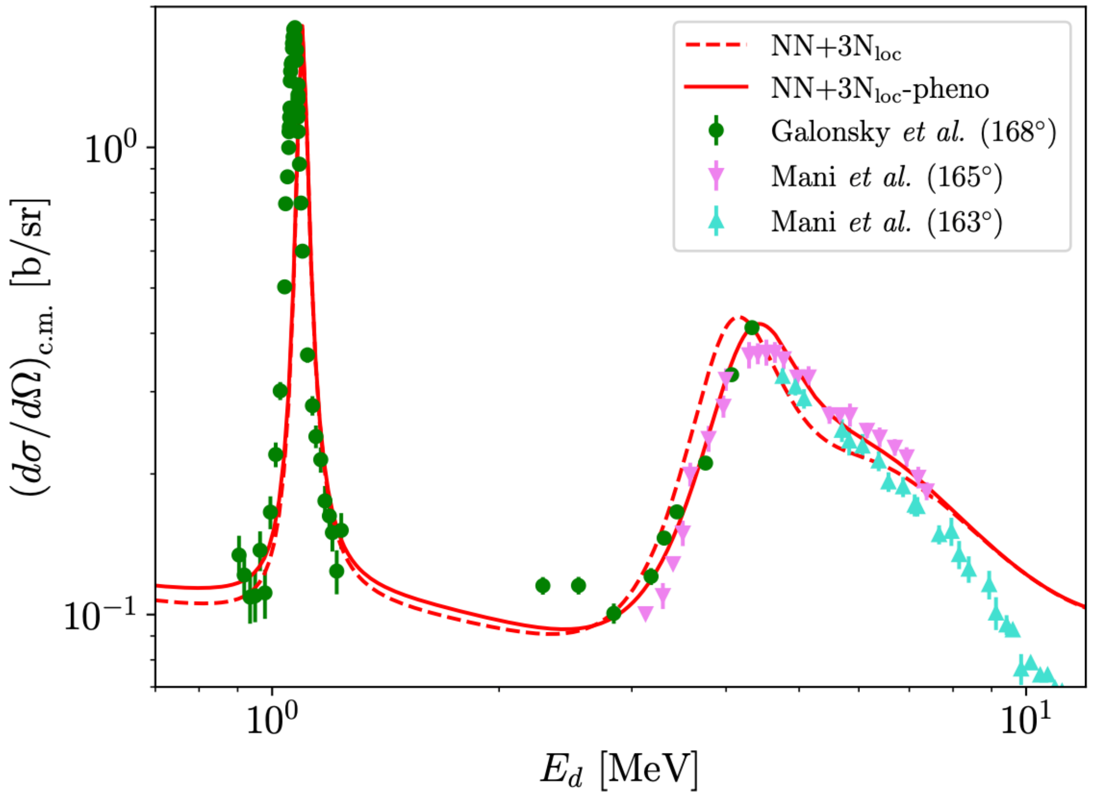
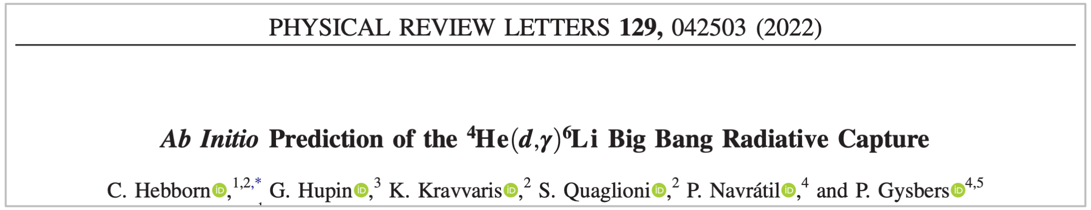


Elastic scattering ^{4}He(d,d)^{4}He cross section at the deuteron back scattered angle 164°





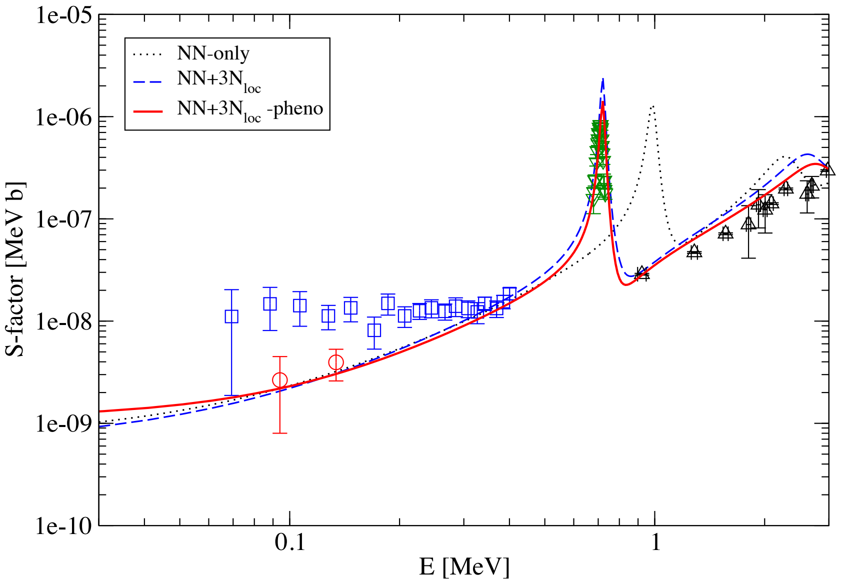
Radiative capture of deuterons on ^{4}He

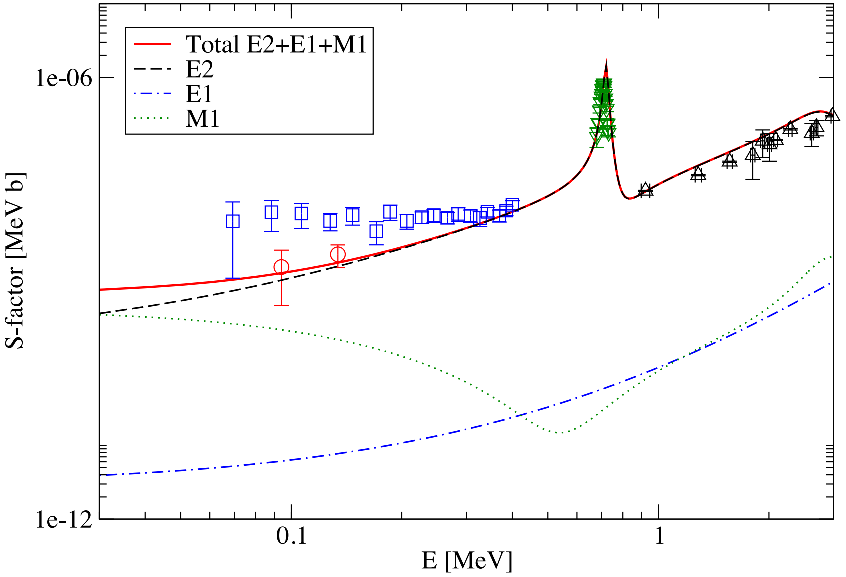
- NCSMC calculations with chiral NN+3N interaction
  - Capture S-factor

Dominated by E2
M1 significant at low energy
E1 negligible – isospin supressed (T=0 → T=0)

$$\mathcal{M}^{E\lambda} = e\sum_{j=1}^{A}\frac{1+\tau_{jz}}{2}[\boldsymbol{r}_j - \boldsymbol{R}_{cm}^{(A)}]^{\lambda}$$

$$\mathcal{M}^{M1} = \frac{\mu_N}{\hbar c}\sqrt{\frac{3}{4\pi}}\sum_{j=1}^{A}(g_{lj}L_j + g_{sj}S_j)$$





Low energy S-factor consistent with LUNA data, below the ^{6}Li Coulomb breakup data

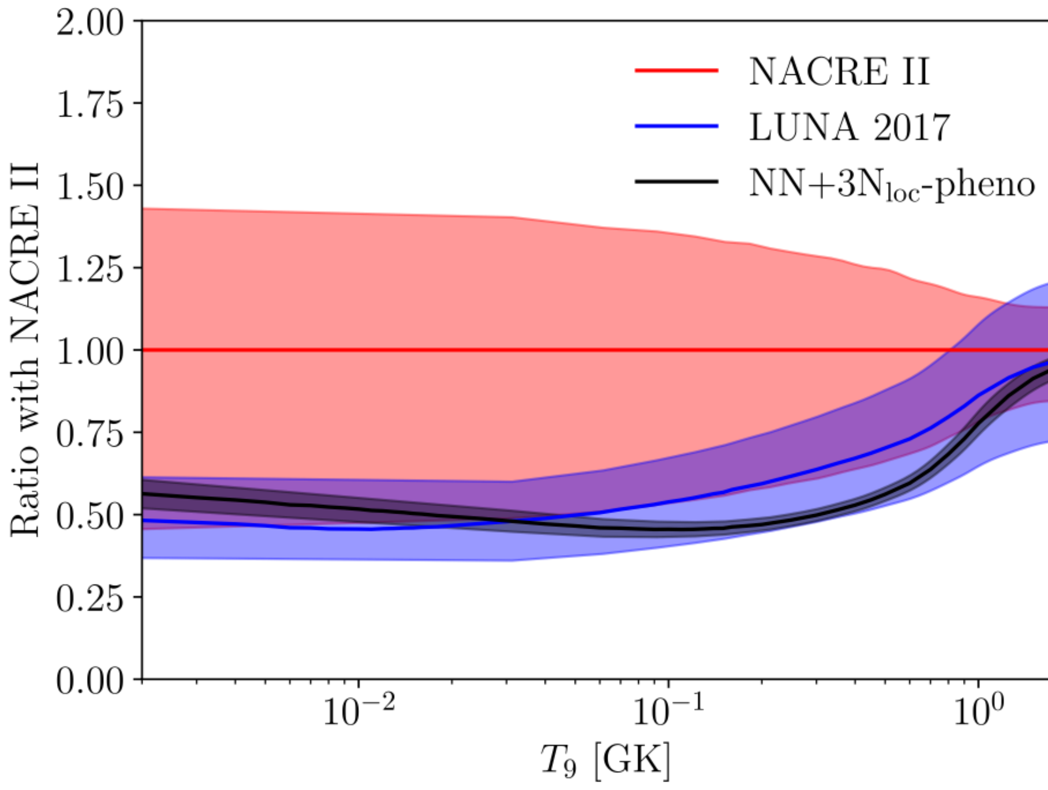
PHYSICAL REVIEW LETTERS 129, 042503 (2022)

***Ab Initio* Prediction of the $^4He(d,\gamma)^6Li$ Big Bang Radiative Capture**

C. Hebborn,[1,2,*] G. Hupin,[3] K. Kravvaris,[2] S. Quaglioni,[2] P. Navrátil,[4] and P. Gysbers[4,5]

Radiative capture of deuterons on ^{4}He

- NCSMC calculations with chiral NN+3N interaction
  - Thermonuclear reaction rate



Thermonuclear reaction rate smaller than NACRE II evaluation, agreement with LUNA result with less uncertainty

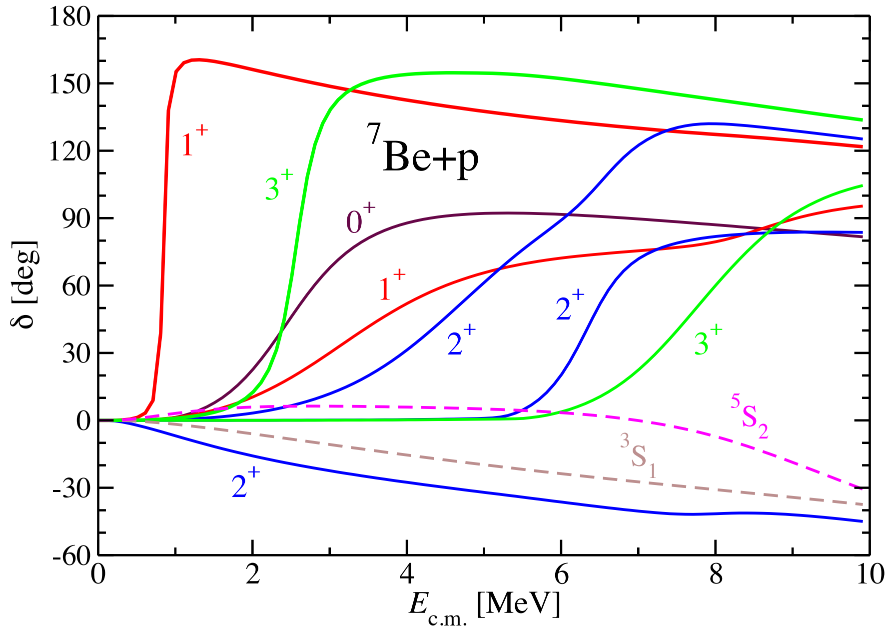
K. Kravvaris,[1] P. Navrátil,[2] S. Quaglioni,[1] C. Hebborn,[3,1] and G. Hupin[4]

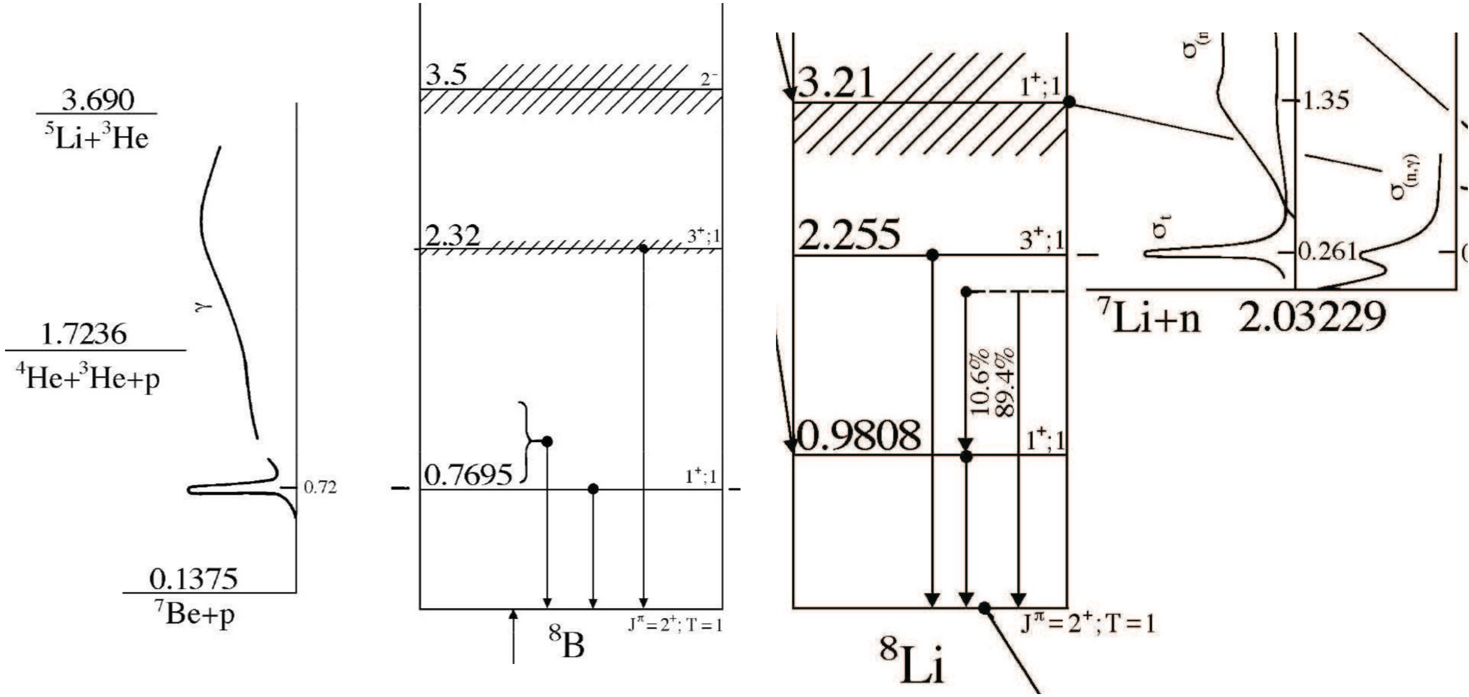
arXiv: 2202.11759

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

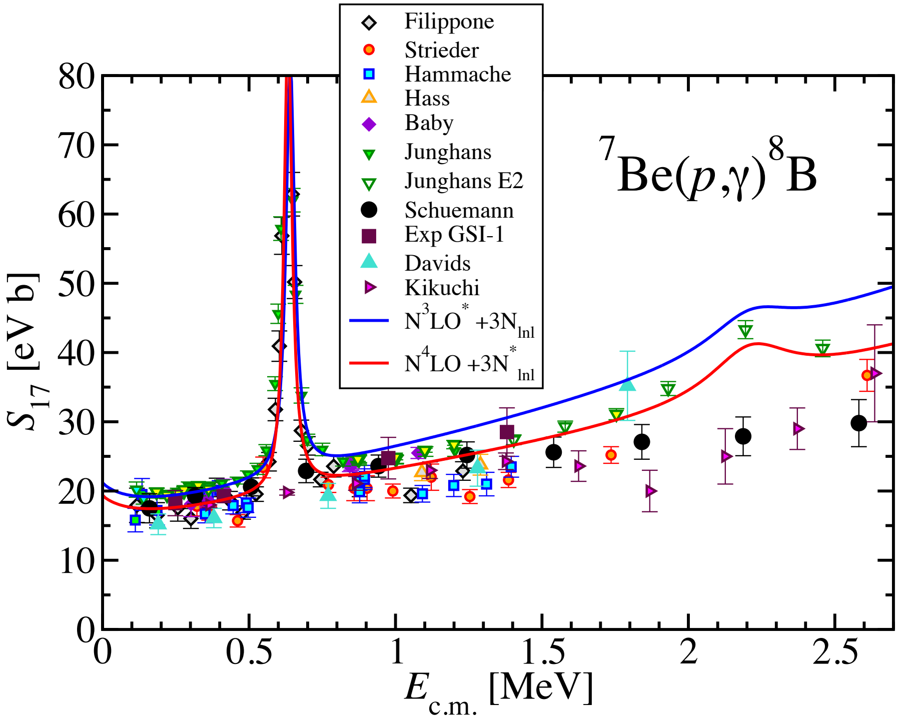


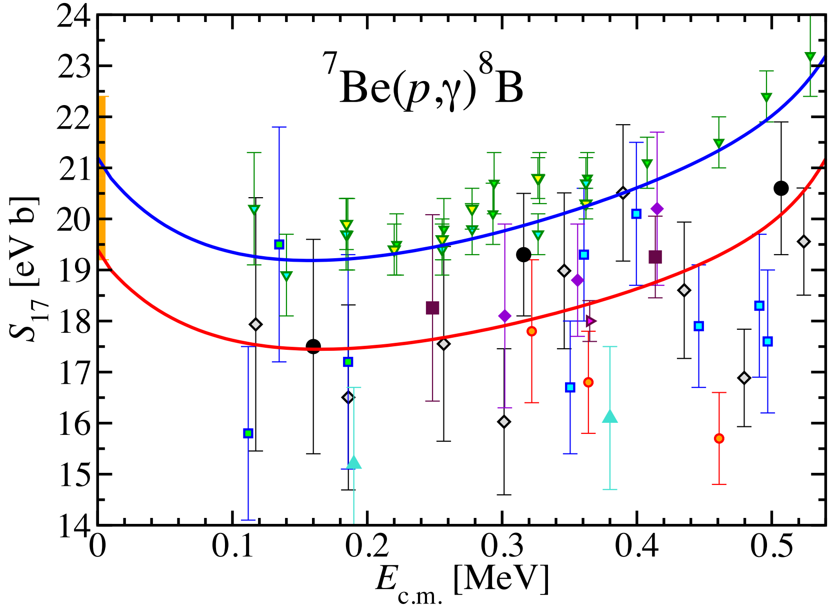


Radiative capture of protons on ^{7}Be

- NCSMC S-factor results

	$C_{p_{1/2}}$	$C_{p_{3/2}}$	a_1	a_2	$S_{17}(0)$
N^{2}LO+3N$_{\rm lnl}$	0.384	0.691	4.4(1)	-0.5(1)	23.9
N^{3}LO+3N$_{\rm lnl}$	0.390	0.678	1.3(1)	-4.7(1)	23.5
N^{4}LO+3N$_{\rm lnl}$	0.354	0.669	1.6(1)	-4.4(1)	22.0
N^{4}LO+3N$^*_{\rm lnl}$	0.343	0.621	1.3(1)	-5.0(1)	19.3
N^{3}LO*+3N$_{\rm lnl}$	0.334	0.663	0.1(1)	-7.7(1)	21.1
N^{3}LO*+3N$_{\rm loc}$	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

Ab initio prediction for the radiative capture of protons on ^{7}Be

K. Kravvaris,[1] P. Navrátil,[2] S. Quaglioni,[1] C. Hebborn,[3,1] and G. Hupin[4]

arXiv: 2202.11759

Radiative capture of protons on ^{7}Be

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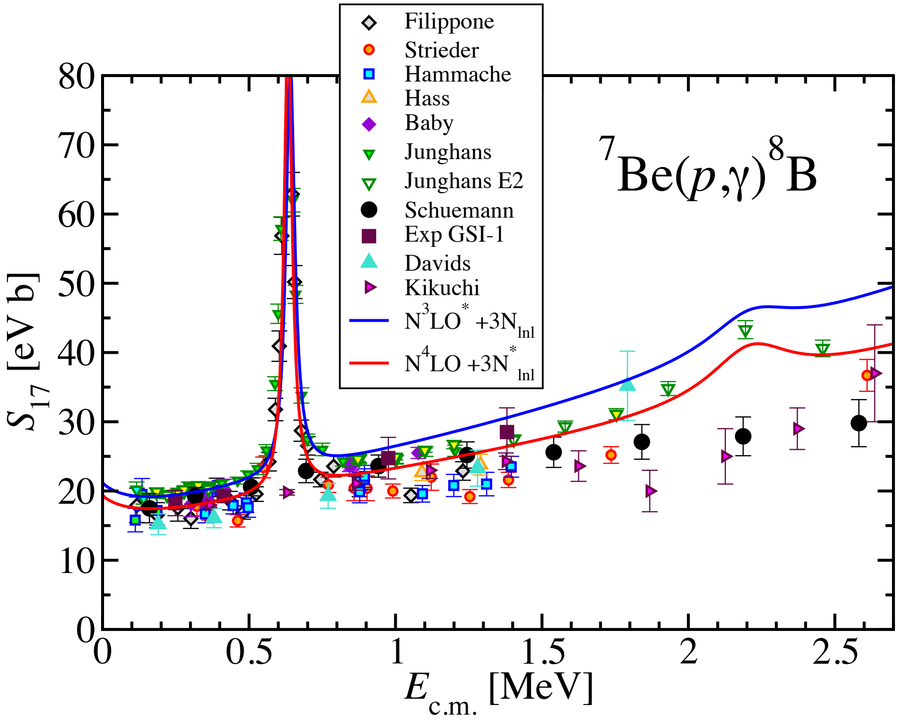

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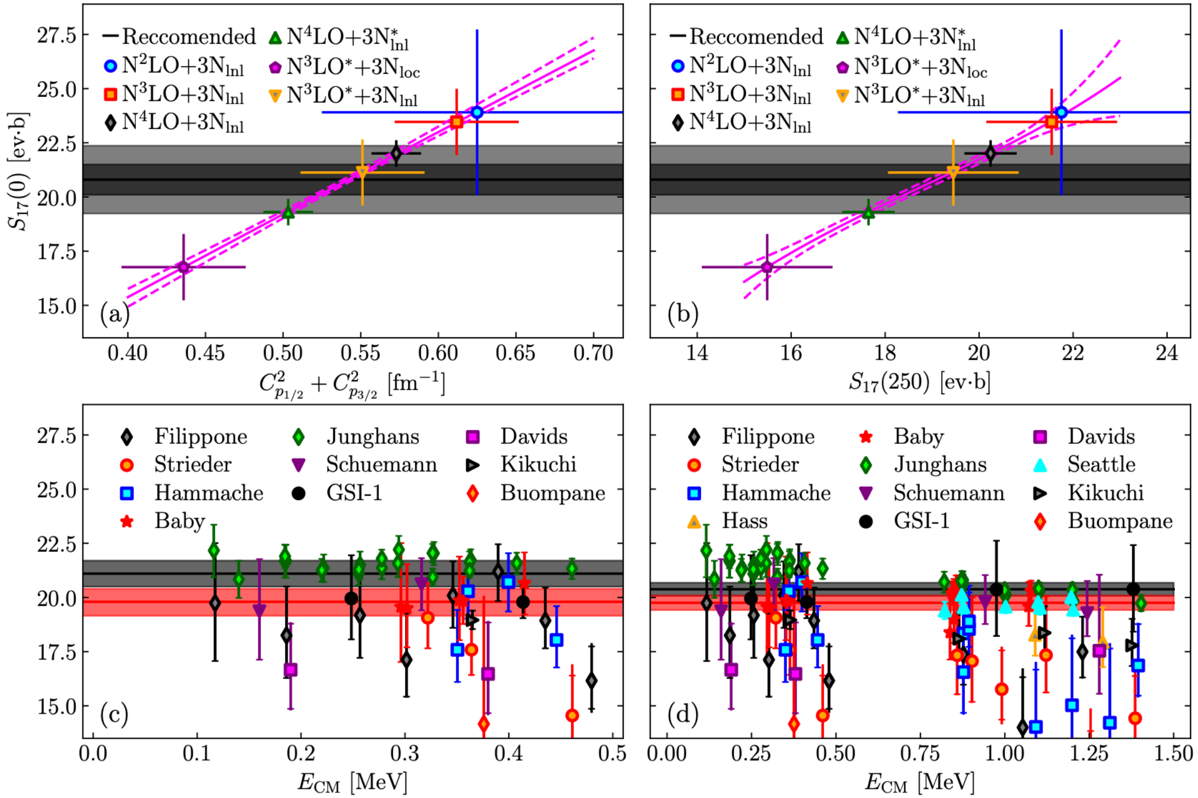

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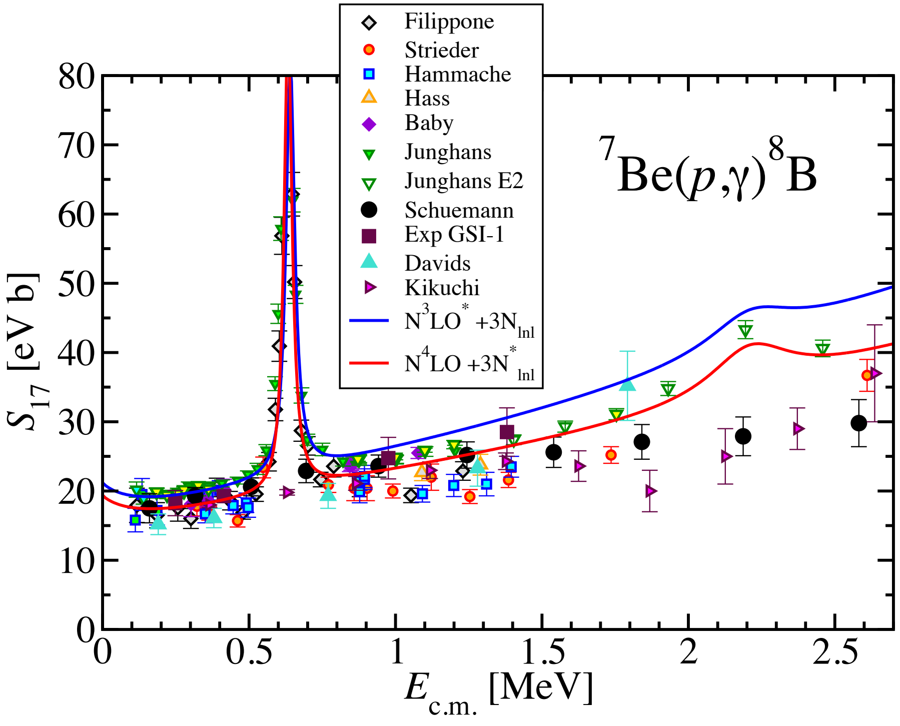
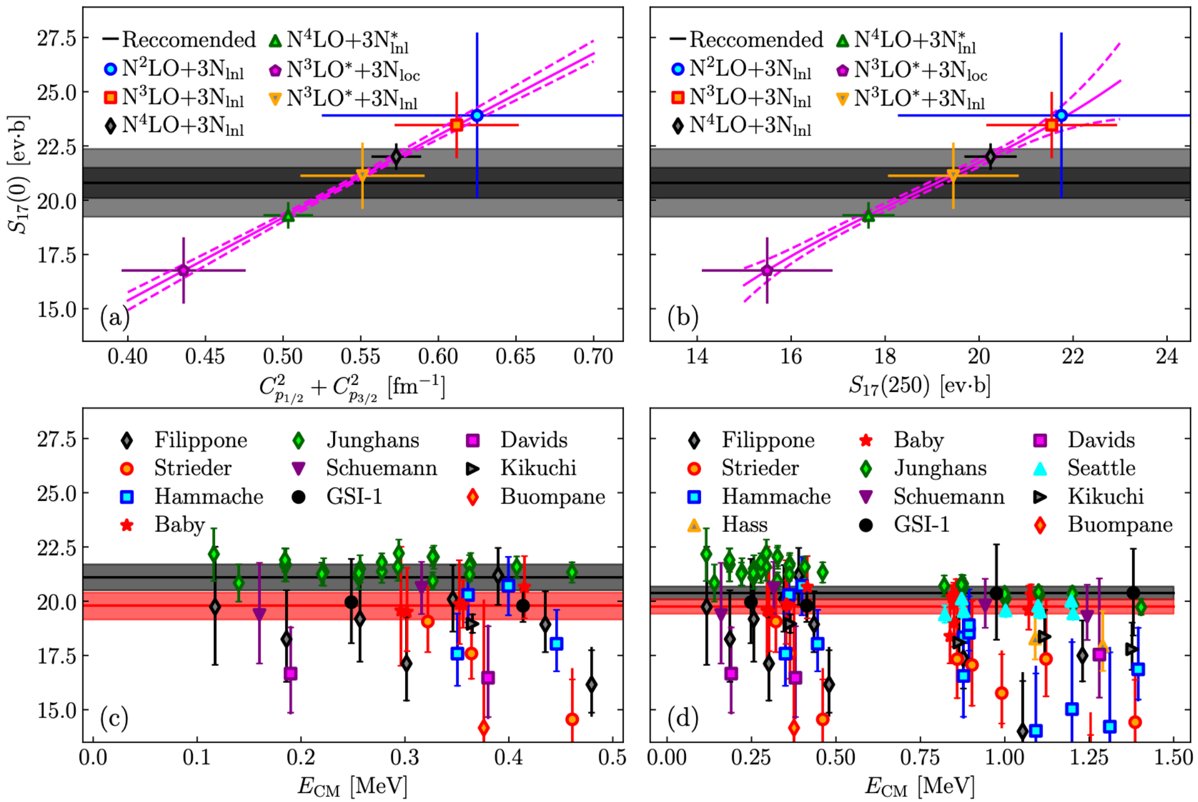
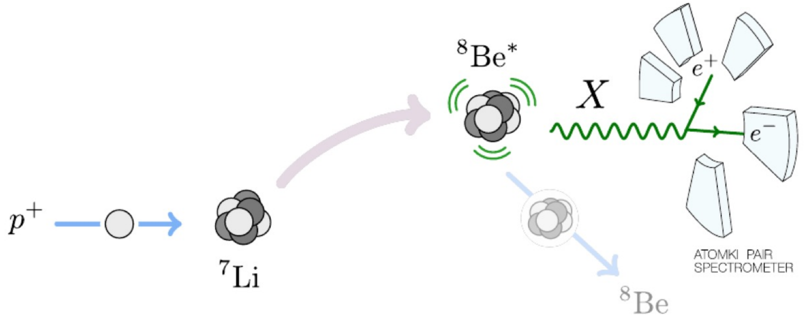




Recommended value $S_{17}(0)$ ~ 19.8(3) eV b

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

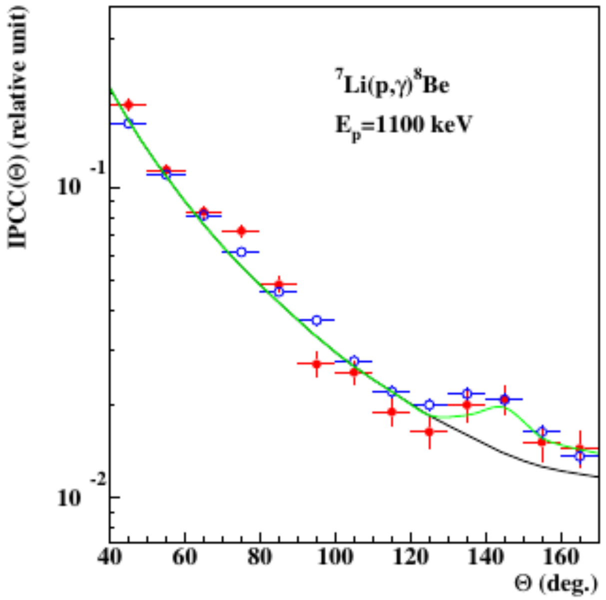
X17 Anomaly

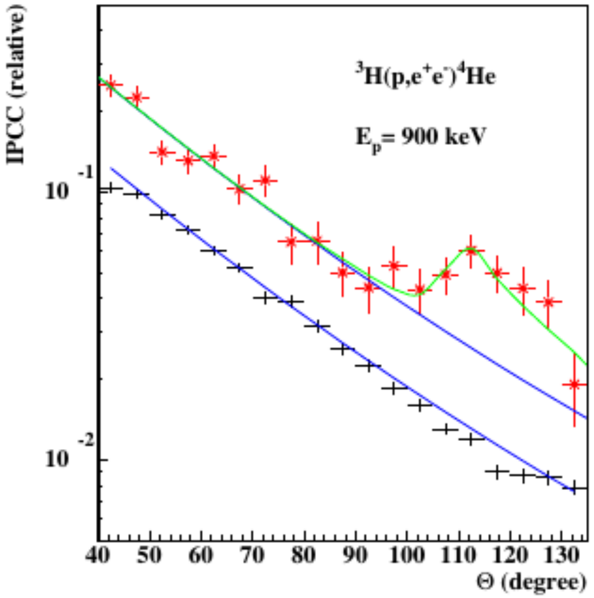


Feng PRD **95**, 035017 (2017)

"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

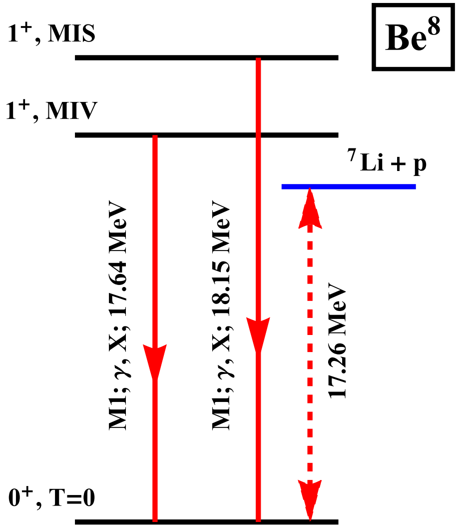


Fig. from PLB 813, 136061 (2021)

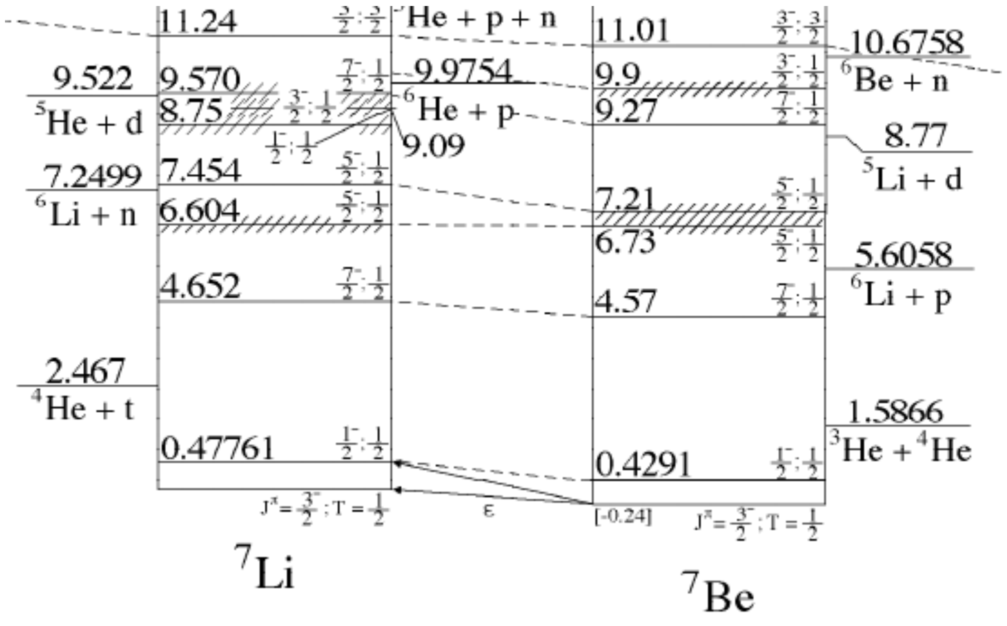
Can *ab initio* nuclear theory help interpret the anomaly?

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



In collaboration with UBC/TRIUMF PhD student Peter Gysbers

TUNL Nuclear Data Evaluation Project

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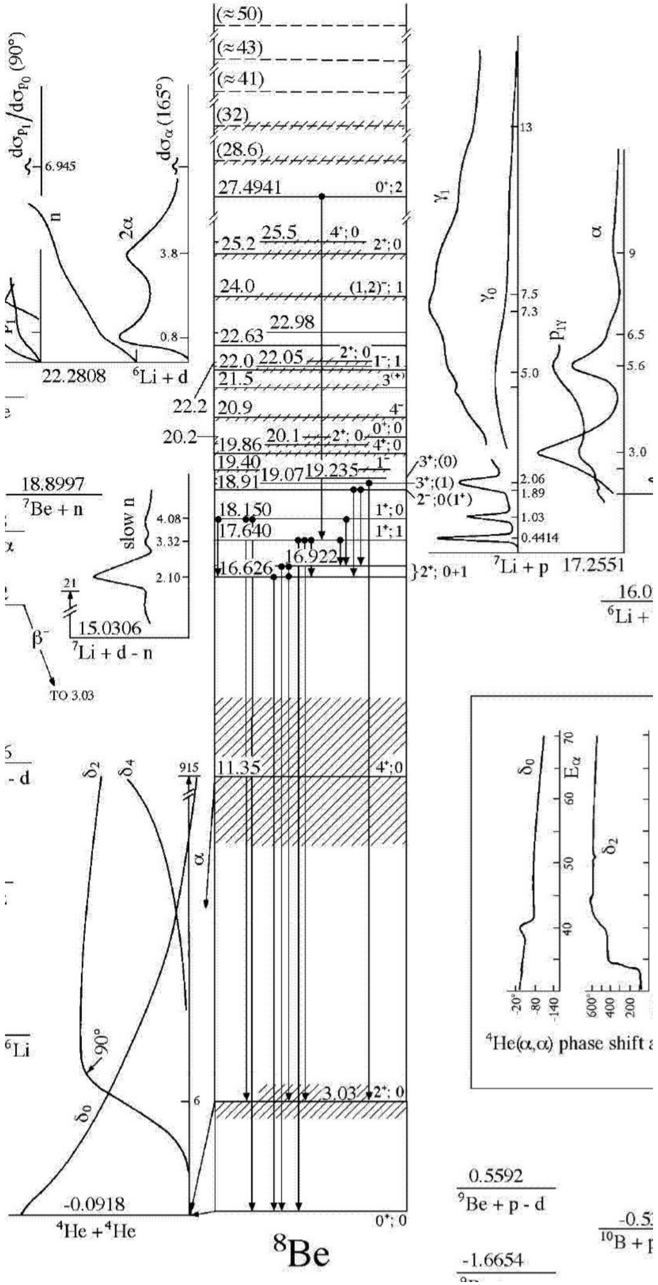
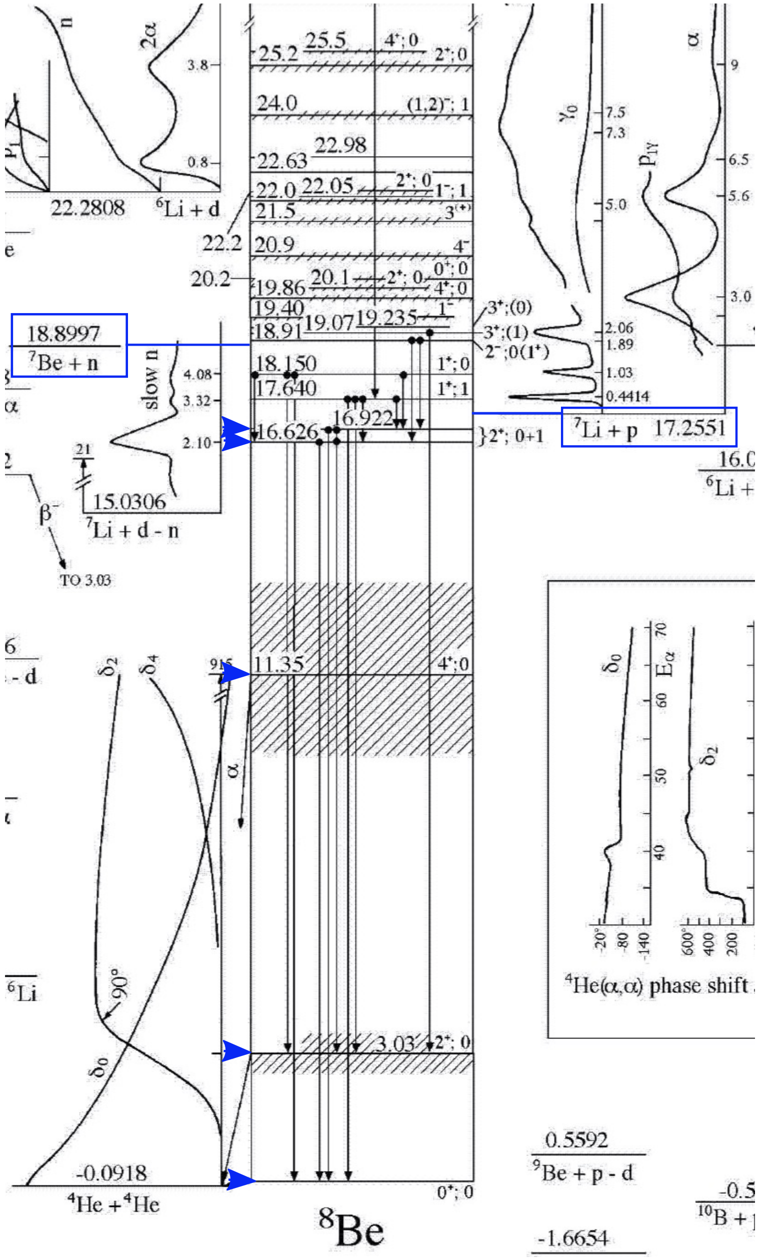


^{8}Be structure

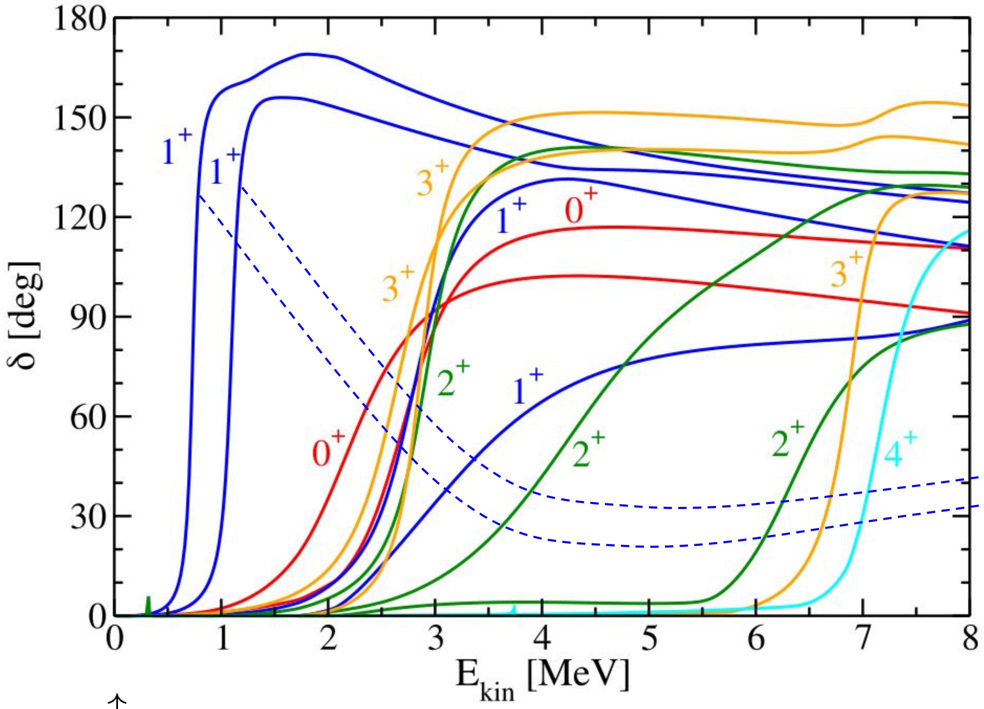
Calculated $^8\mathrm{Be}$ bound states w.r.t. $^7\mathrm{Li} + p$ threshold ($N_{max} = 8/9$)

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

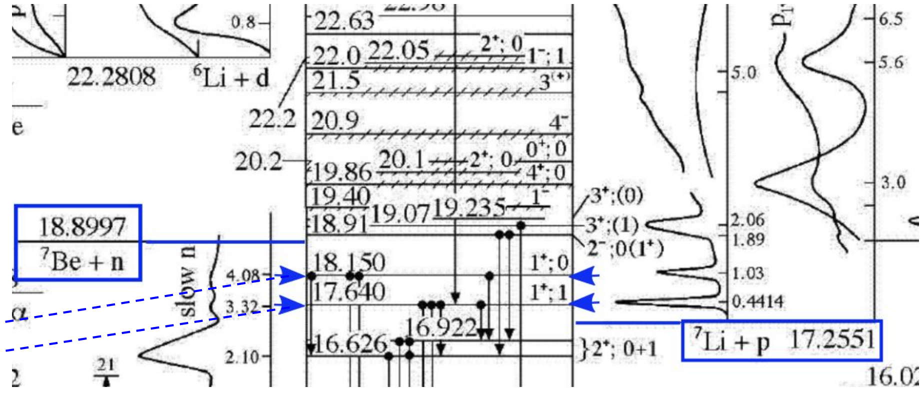
Matches experiment well, except the 3rd 2^+ is slightly above the $^7\mathrm{Li} + p$ threshold.



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



↑
$p + {}^7\mathrm{Li}$ threshold



Additional resonances are seen compared to TUNL data

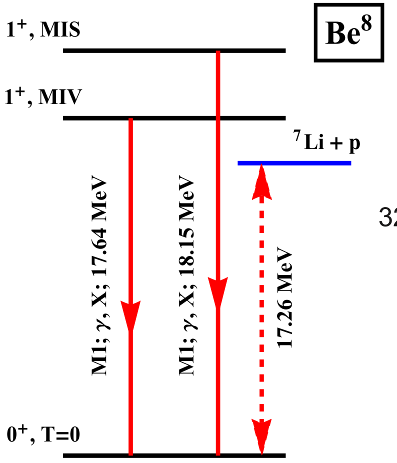


Fig. from PLB 813, 136061 (2021)

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

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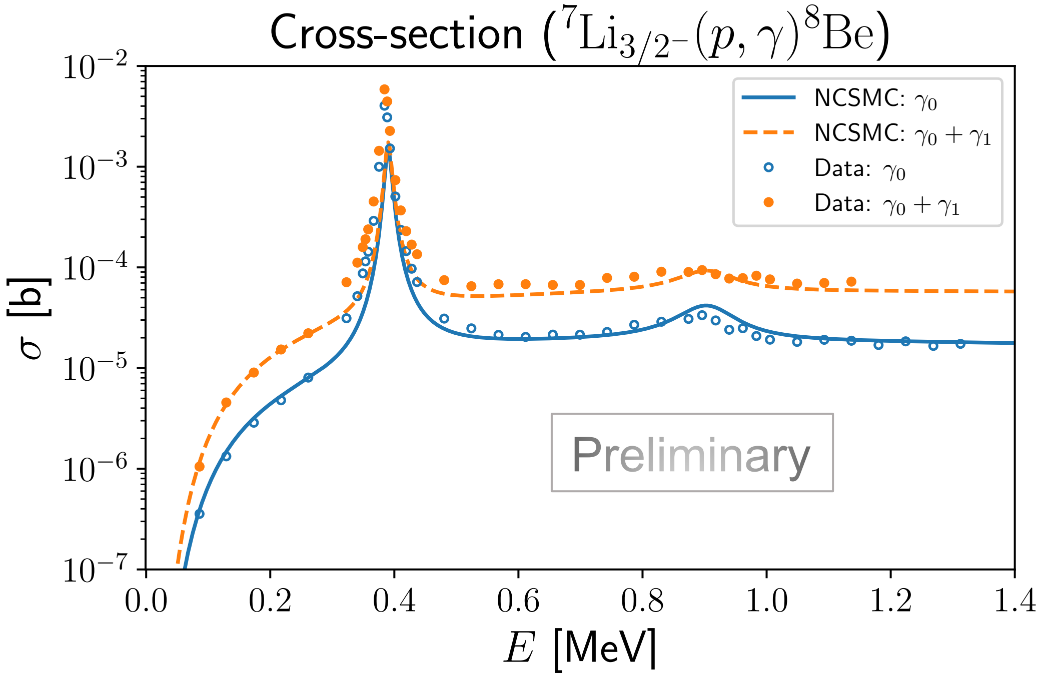

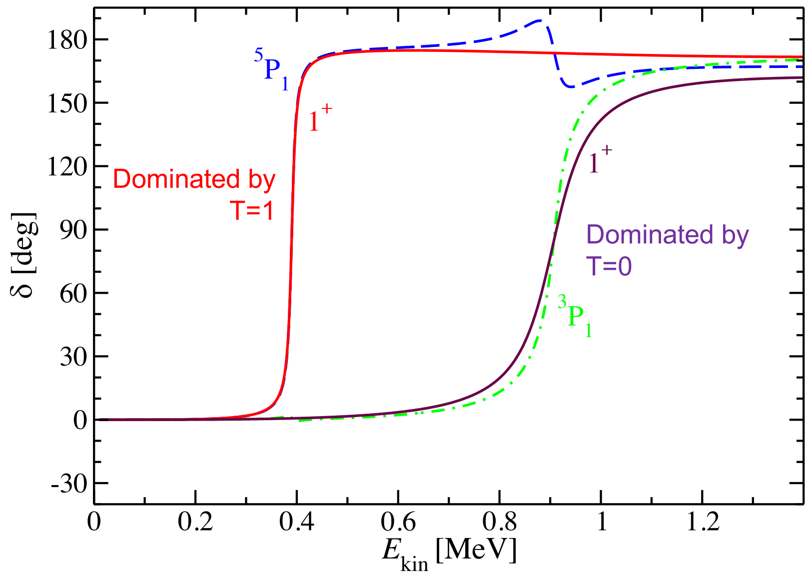

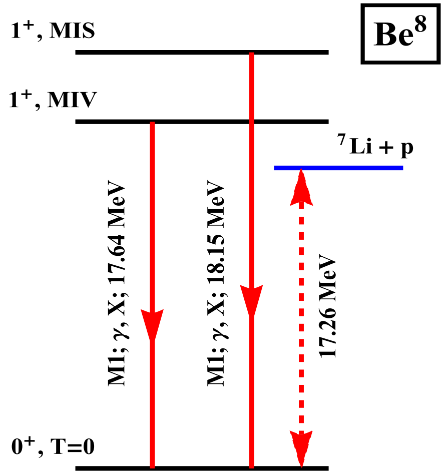

Data: Zahnow *et al.*
Z.Phys.A **351** 229-236 (1995)

γ_0: decay to ground state (0^+)
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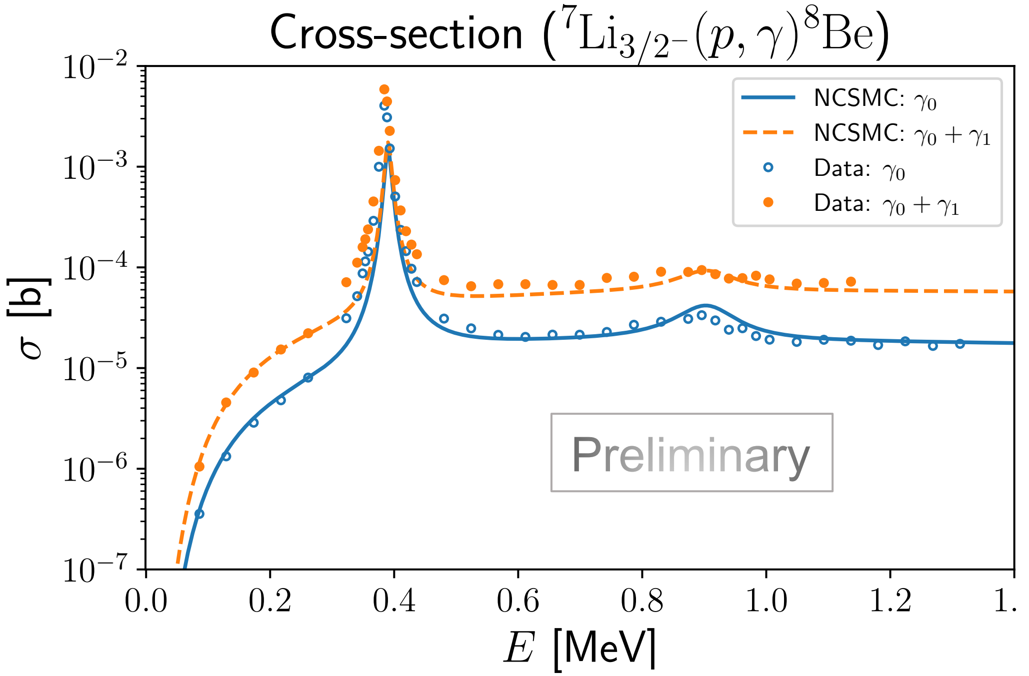

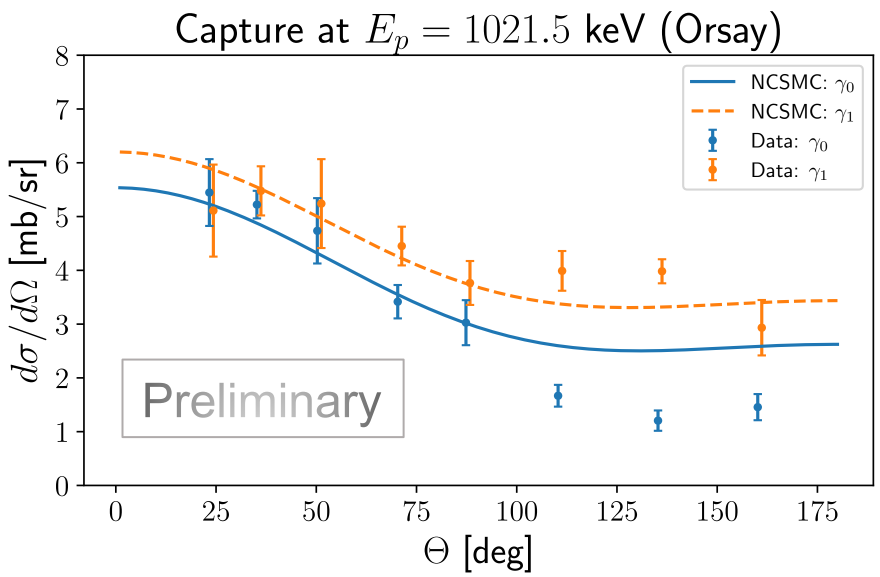

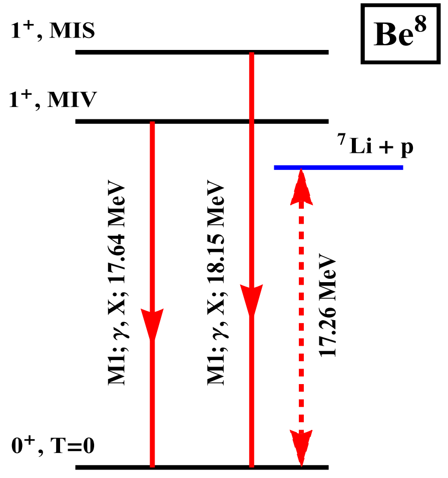

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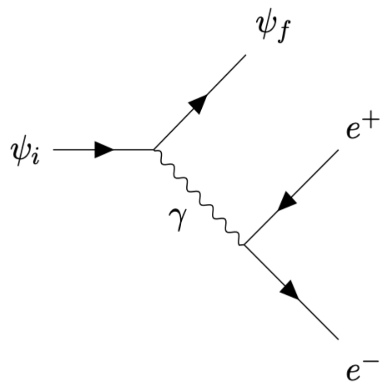
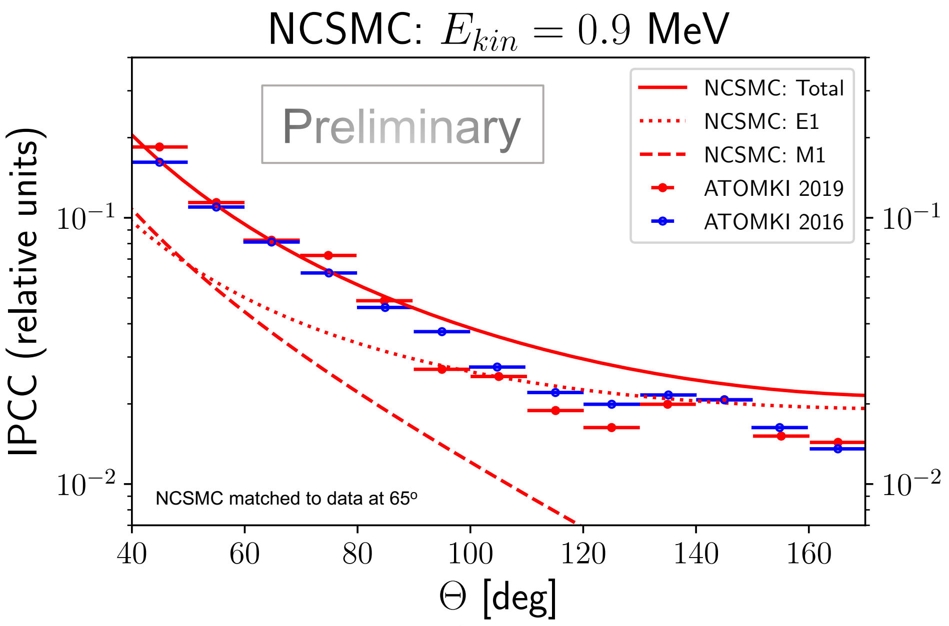
Internal electron-positron pair conversion correlation

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$^+$

NCSMC calculations lead by P. Gysbers (UBC/TRIUMF PhD student)

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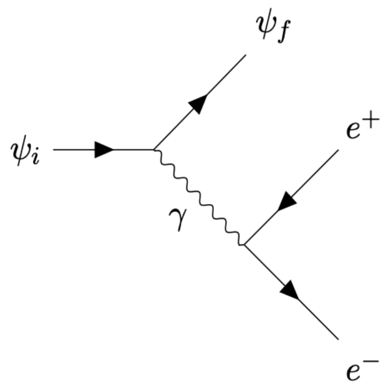

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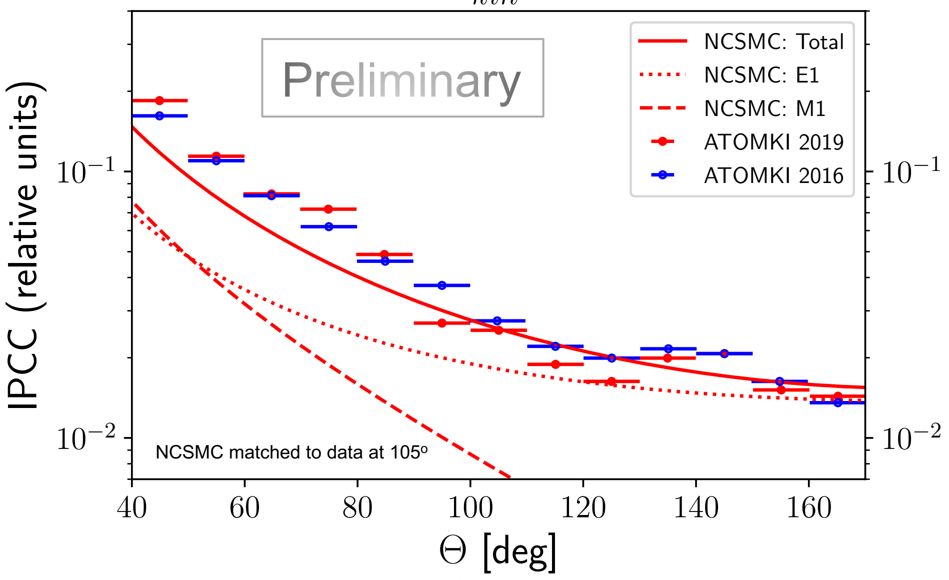
NCSMC: $E_{kin} = 0.9$ MeV



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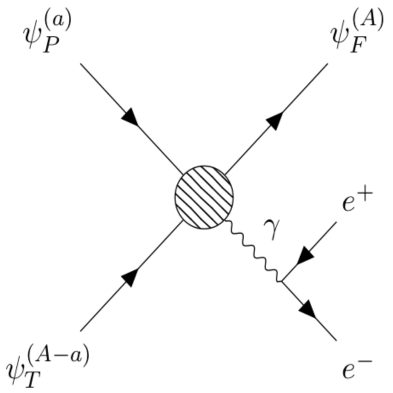
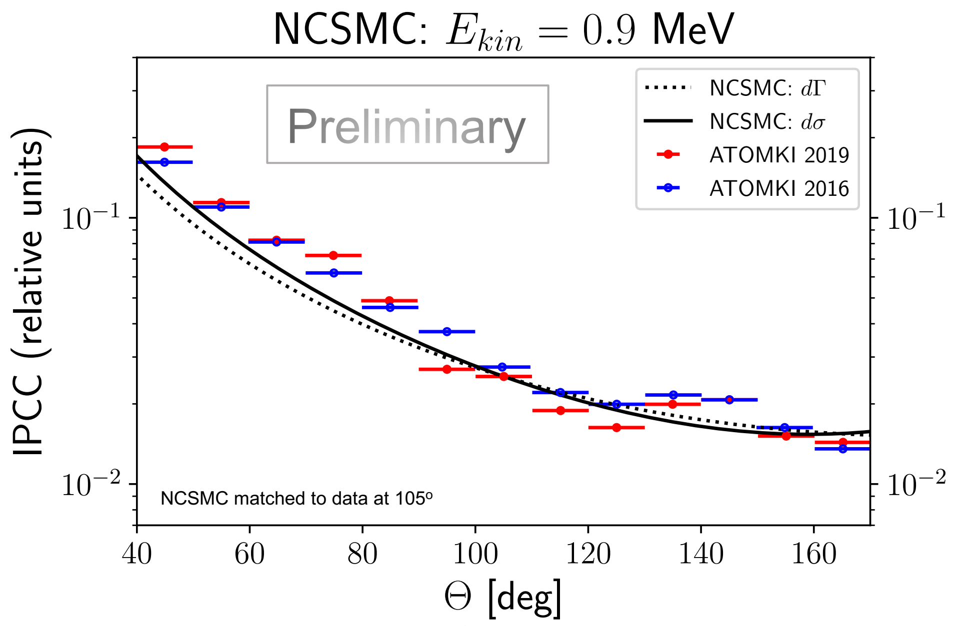
Internal electron-positron pair conversion correlation

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 more in line with ATOMKI data

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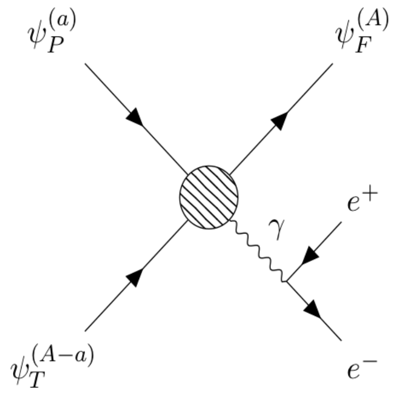
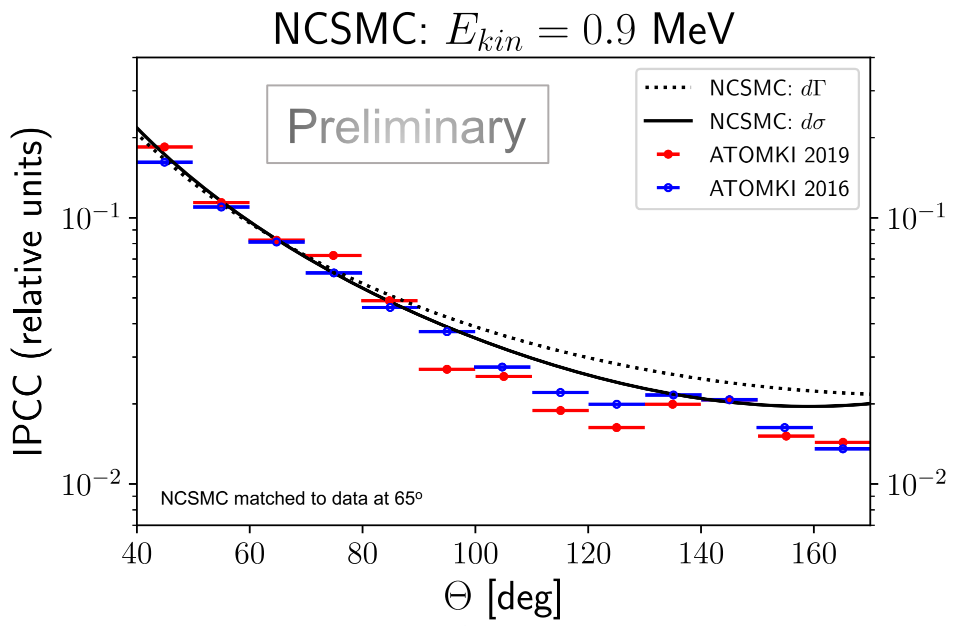
$$\Psi^{(8)}_{\text{NCSMC}} = \sum_\lambda c_\lambda \left|^8\text{Be}, \lambda\right\rangle + \sum_\nu \int \mathrm{d}r \gamma_\nu(r) \hat{A}_\nu \left|^7\text{Li} + p, \nu\right\rangle + \sum_\mu \int \mathrm{d}r \gamma_\mu(r) \hat{A}_\mu \left|^7\text{Be} + n, \mu\right\rangle$$

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 more in line with ATOMKI data

NCSMC calculations lead by P. Gysbers (UBC/TRIUMF PhD student)

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

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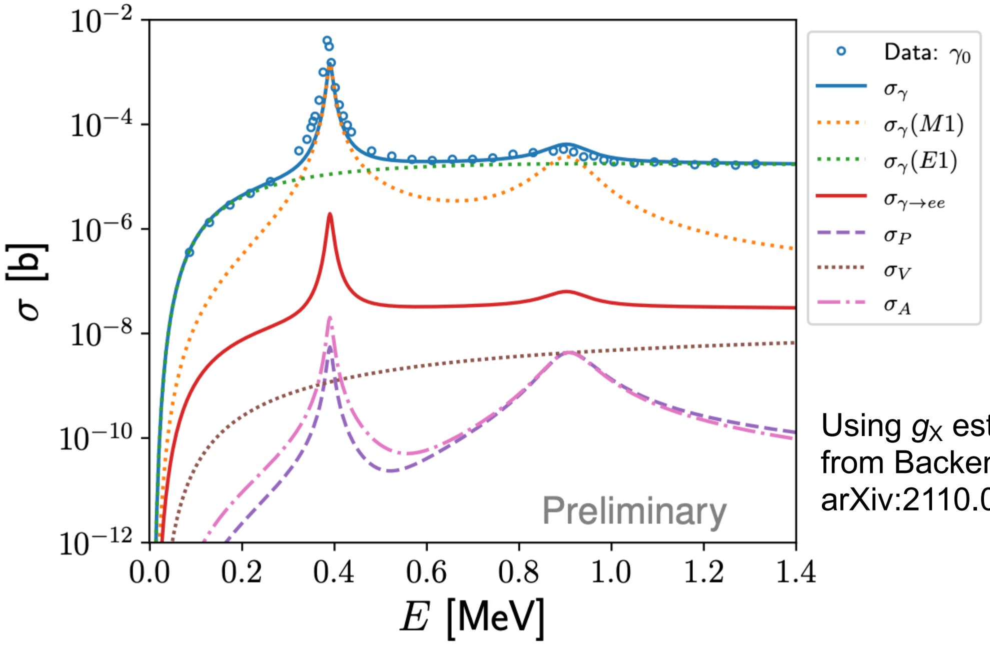
Integrated cross sections



Using g_X estimates from Backens *et al.* arXiv:2110.06055

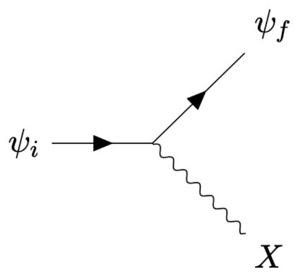
Data: Zahnow *et al.*
Z.Phys.A **351** 229-236 (1995)

X17 Candidate Bosons

($m_X \simeq 17$ MeV, $\Delta E \geq 17.2251$ MeV [$^7\text{Li} + p$], $k_X = \sqrt{\Delta E^2 - m_X^2}$, $k_\gamma = \Delta E$)

Operators for $1^\pm \to 0^+$ decay (in the long-wavelength approximation)

- Pseudo-scalar (0^-):$\langle X_P \rangle \sim \epsilon_P \left\langle \hat{S} \right\rangle k_X$
- Axial-vector (1^+): $\langle X_A \rangle \sim \epsilon_A \left\langle \hat{S} \right\rangle \sqrt{2 + \frac{m_X^2}{\Delta E^2}}$
- Vector (1^-): $\langle X_V \rangle \sim \epsilon_V \langle E1 \rangle \frac{k_X}{k_\gamma}$
- For comparison: γ (E1 (1^-), M1 (1^+), E2 (2^+), etc)
  $\langle E1 \rangle \sim \langle r Y_1 \rangle k_\gamma$
  $\langle M1 \rangle \sim \left(g_l \left\langle \hat{L} \right\rangle + g_s \left\langle \hat{S} \right\rangle \right) k_\gamma$



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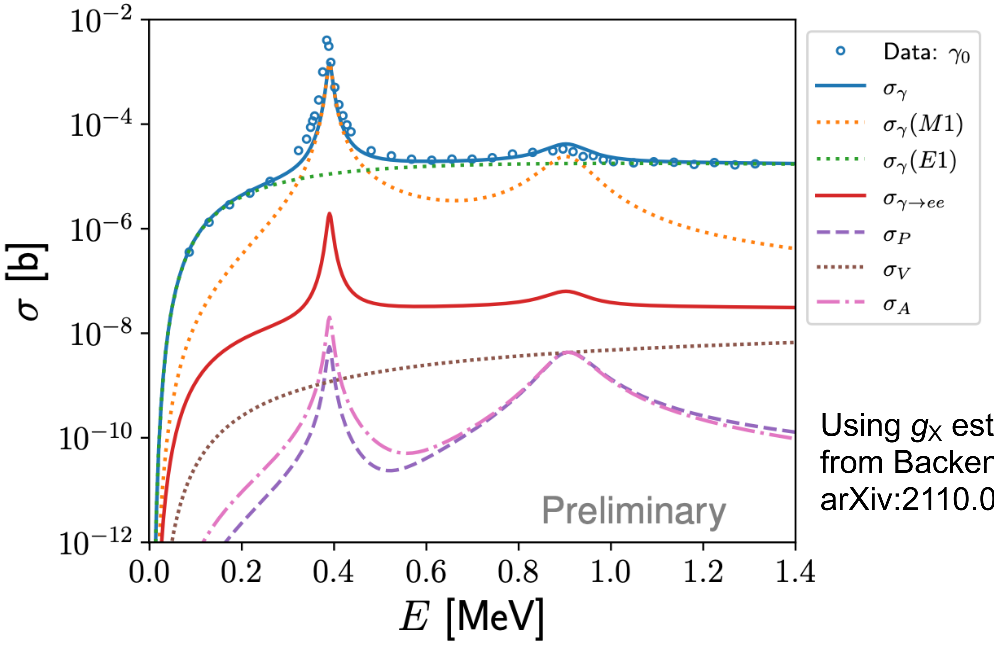
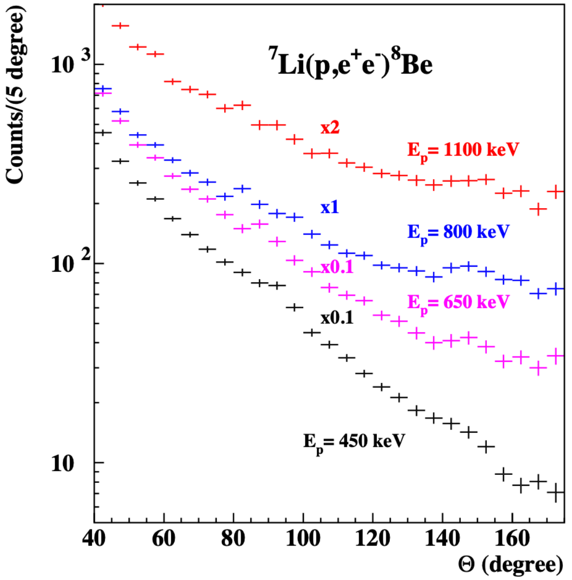
Integrated cross sections



Using g_X estimates from Backens *et al.* arXiv:2110.06055

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

Latest developments (arXiv: 2205.07744):
Anomaly in E1 direct capture – X17 a vector boson



… more calculations to do

NCSMC calculations lead by P. Gysbers (UBC/TRIUMF PhD student)

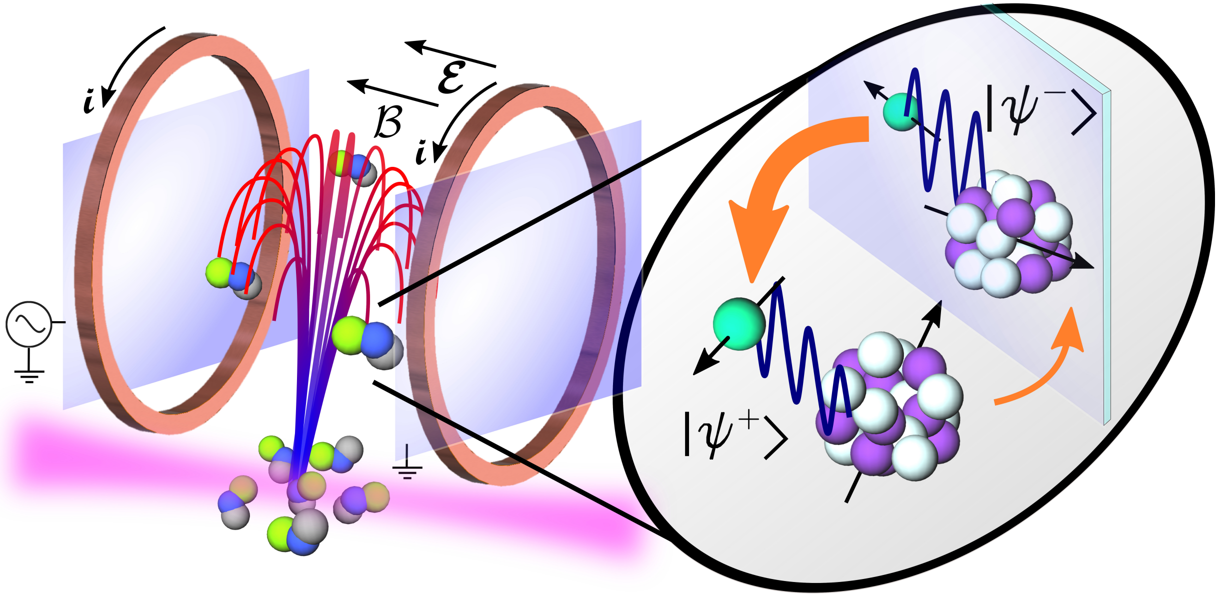
Why investigate the EDM and the anapole moment?

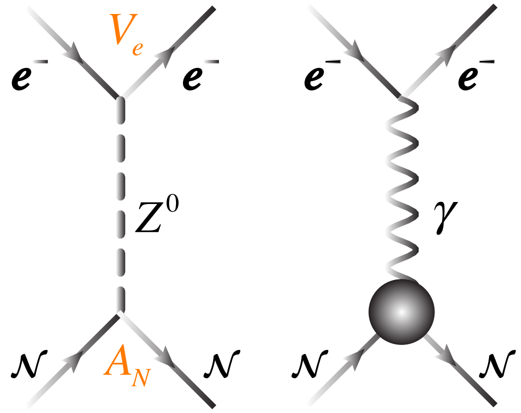
- The EDM is a promising probe for CP violation beyond the standard model as well as CP violating QCD $\bar{\theta}$ parameter
- Nuclear structure can enhance the EDM
- Nuclear EDMs can be measured in storage rings (CERN feasibility study: arXiv:1912.07881)

- 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

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)





(b) (c)

Parity violating nucleon-nucleon interaction

- Meson exchange approach
- Chiral EFT
- Unknown parameters (LECs)
  - DDH (1980) – estimates based on the quark model

ANNALS OF PHYSICS 124, 449–495 (1980)

Unified Treatment of the Parity Violating Nuclear Force

BERTRAND DESPLANQUES*

Institut de Physique Nucleaire, Division de Physique Théorique, 91406 Orsay Cedex—France

JOHN F. DONOGHUE†

Center for Theoretical Physics, Laboratory for Nuclear Science and Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

AND

BARRY R. HOLSTEIN

Physics Division, National Science Foundation, Washington, D. C. 20550

$$
\begin{aligned}
V_{12}^{\mathrm{p.v.}} = {} & \frac{f_\pi g_{\pi NN}}{2^{1/2}}\, i \Big(\frac{\vec\tau_1 \times \vec\tau_2}{2}\Big)^z (\vec\sigma_1 + \vec\sigma_2)\cdot\Big[\frac{\vec p_1 - \vec p_2}{2M}, f_\pi(r)\Big] \\
& - g_\rho \Big(h_\rho^{0}\,\vec\tau_1\cdot\vec\tau_2 + h_\rho^{1}\Big(\frac{\vec\tau_1 + \vec\tau_2}{2}\Big)^z + h_\rho^{2}\,\frac{(3\tau_1^z\tau_2^z - \vec\tau_1\cdot\vec\tau_2)}{2(6)^{1/2}}\Big) \\
& \times \Big((\vec\sigma_1 - \vec\sigma_2)\cdot\Big\{\frac{\vec p_1 - \vec p_2}{2M}, f_\rho(r)\Big\} + i(1+\chi_v)\,\vec\sigma_1\times\vec\sigma_2\cdot\Big[\frac{\vec p_1 - \vec p_2}{2M}, f_\rho(r)\Big] \\
& - g_\omega \Big(h_\omega^{0} + h_\omega^{1}\Big(\frac{\vec\tau_1 + \vec\tau_2}{2}\Big)^z\Big) \\
& \times \Big((\vec\sigma_1 - \vec\sigma_2)\cdot\Big\{\frac{\vec p_1 - \vec p_2}{2M}, f_\omega(r)\Big\} + i(1+\chi_S)\,\vec\sigma_1\times\vec\sigma_2\cdot\Big[\frac{\vec p_1 - \vec p_2}{2M}, f_\omega(r)\Big] \\
& - (g_\omega h_\omega^{1} - g_\rho h_\rho^{1})\Big(\frac{\vec\tau_1 - \vec\tau_2}{2}\Big)^z (\vec\sigma_1 + \vec\sigma_2)\cdot\Big\{\frac{\vec p_1 - \vec p_2}{2M}, f_\rho(r)\Big\} \\
& - g_\rho h_\rho'^{1}\, i\Big(\frac{\vec\tau_1 \times \vec\tau_2}{2}\Big)^z (\vec\sigma_1 + \vec\sigma_2)\cdot\Big[\frac{\vec p_1 - \vec p_2}{2M}, f_\rho(r)\Big],
\end{aligned}
$$

$$f_\pi(r) = \frac{e^{-m_\pi r}}{4\pi r},$$

$$f_\rho(r) = f_\omega(r) = \frac{e^{-m_\rho r}}{4\pi r}.$$

Parity violating nucleon-nucleon interaction

PHYSICAL REVIEW LETTERS **125,** 131803 (2020)

Featured in Physics

First Precision Measurement of the Parity Violating Asymmetry in Cold Neutron Capture on ^{3}He

M. T. Gericke,[1,*] S. Baeßler,[2,3] L. Barrón-Palos,[4] N. Birge,[5] J. D. Bowman,[3] J. Calarco,[6] V. Cianciolo,[3] C. E. Coppola,[5] C. B. Crawford,[7] N. Fomin,[5] I. Garishvili,[5] G. L. Greene,[5,3] G. M. Hale,[8] J. Hamblen,[9] C. Hayes,[5] E. Iverson,[3] M. L. Kabir,[7] M. McCrea,[1,10] E. Plemons,[5] A. Ramírez-Morales,[4] P. E. Mueller,[3] I. Novikov,[11] S. Penttila,[3] E. M. Scott,[5] J. Watts,[9] and C. Wickersham[9]

PHYSICAL REVIEW LETTERS **121,** 242002 (2018)

Editors' Suggestion

First Observation of *P*-odd γ Asymmetry in Polarized Neutron Capture on Hydrogen

D. Blyth,[1,2] J. Fry,[3,4] N. Fomin,[5,6] R. Alarcon,[1] L. Alonzi,[3] E. Askanazi,[3] S. Baeßler,[3,7] S. Balascuta,[8,1] L. Barrón-Palos,[9] A. Barzilov,[10] J. D. Bowman,[7] N. Birge,[5] J. R. Calarco,[11] T. E. Chupp,[12] V. Cianciolo,[7] C. E. Coppola,[5] C. B. Crawford,[13] K. Craycraft,[5,13] D. Evans,[3,4] C. Fieseler,[13] E. Frlež,[3] I. Garishvili,[7,5] M. T. W. Gericke,[14] R. C. Gillis,[7,4] K. B. Grammer,[7,5] G. L. Greene,[5,7] J. Hall,[3] J. Hamblen,[15] C. Hayes,[16,5] E. B. Iverson,[7] M. L. Kabir,[17,13] S. Kucuker,[18,5] B. Lauss,[19] R. Mahurin,[20] M. McCrea,[13,14] M. Maldonado-Velázquez,[9] Y. Masuda,[21] J. Mei,[4] R. Milburn,[13] P. E. Mueller,[7] M. Musgrave,[22,5] H. Nann,[4] I. Novikov,[23] D. Parsons,[15] S. I. Penttilä,[7] D. Počanić,[3] A. Ramirez-Morales,[9] M. Root,[3] A. Salas-Bacci,[3] S. Santra,[24] S. Schröder,[3,25] E. Scott,[5] P.-N. Seo,[3,26] E. I. Sharapov,[27] F. Simmons,[13] W. M. Snow,[4] A. Sprow,[13] J. Stewart,[15] E. Tang,[13,6] Z. Tang,[4,6] X. Tong,[7] D. J. Turkoglu,[28] R. Whitehead,[5] and W. S. Wilburn[6]

(NPDGamma Collaboration)

- Meson exchange approach
- Chiral EFT
- Unknown parameters (LECs)
  - DDH (1980) – estimates based on the quark model
  - Two recent precision experiments constraining the parameters

$$
\begin{aligned}
V_{12}^{\mathrm{p.v.}} = {} & \frac{f_\pi g_{\pi NN}}{2^{1/2}}\, i \left(\frac{\vec{\tau}_1 \times \vec{\tau}_2}{2}\right)^z (\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \left[\frac{\vec{p}_1 - \vec{p}_2}{2M}, f_\pi(r)\right] \\
& - g_\rho \left(h_\rho^{\,0}\,\vec{\tau}_1 \cdot \vec{\tau}_2 + h_\rho^{\,1} \left(\frac{\vec{\tau}_1 + \vec{\tau}_2}{2}\right)^z + h_\rho^{\,2}\, \frac{(3\tau_1^{\,z}\tau_2^{\,z} - \vec{\tau}_1 \cdot \vec{\tau}_2)}{2(6)^{1/2}}\right) \\
& \times \left((\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \left\{\frac{\vec{p}_1 - \vec{p}_2}{2M}, f_\rho(r)\right\} + i(1 + \chi_v)\, \vec{\sigma}_1 \times \vec{\sigma}_2 \cdot \left[\frac{\vec{p}_1 - \vec{p}_2}{2M}, f_\rho(r)\right]\right) \\
& - g_\omega \left(h_\omega^{\,0} + h_\omega^{\,1} \left(\frac{\vec{\tau}_1 + \vec{\tau}_2}{2}\right)^z\right) \\
& \times \left((\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \left\{\frac{\vec{p}_1 - \vec{p}_2}{2M}, f_\omega(r)\right\} + i(1 + \chi_S)\, \vec{\sigma}_1 \times \vec{\sigma}_2 \cdot \left[\frac{\vec{p}_1 - \vec{p}_2}{2M}, f_\omega(r)\right]\right) \\
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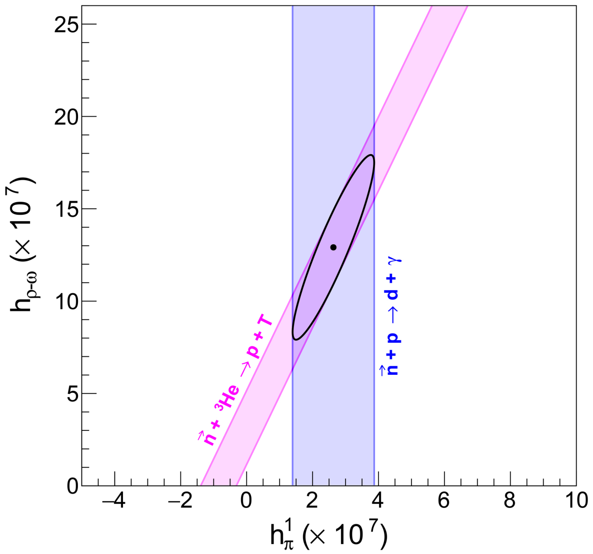
$$f_\rho(r) = f_\omega(r) = \frac{e^{-m_\rho r}}{4\pi r}.$$



$$f_\pi \equiv h_\pi^1;$$

$$h_{\rho-\omega} \equiv h_\omega^1 + 0.46 h_\rho^1 - 0.46 h_\omega^0 - 0.76 h_\rho^0 - 0.02 h_\rho^2$$

Parity and time-reversal violating nucleon-nucleon interaction

Introduced through Hamiltonian H_{PVTV} :

$$
\begin{aligned}
H_{PVTV}(\boldsymbol{r}) = \frac{1}{2m_n} \, & \boldsymbol{\sigma}_- \cdot \nabla \left(-\bar{G}^0_\omega y_\omega(r)\right) \\
& + \boldsymbol{\tau_1} \cdot \boldsymbol{\tau_2} \, \boldsymbol{\sigma}_- \cdot \nabla \left(\bar{G}^0_\pi y_\pi(r) - \bar{G}^0_\rho y_\rho(r)\right) \\
& + \frac{\tau^z_+}{2} \boldsymbol{\sigma}_- \cdot \nabla \left(\bar{G}^1_\pi y_\pi(r) - \bar{G}^1_\rho y_\rho(r) - \bar{G}^1_\omega y_\omega(r)\right) \\
& + \frac{\tau^z_-}{2} \boldsymbol{\sigma}_+ \cdot \nabla \left(\bar{G}^1_\pi y_\pi(r) + \bar{G}^1_\rho y_\rho(r) - \bar{G}^1_\omega y_\omega(r)\right) \\
& + (3\tau^z_1 \tau^z_2 - \boldsymbol{\tau_1} \cdot \boldsymbol{\tau_2}) \boldsymbol{\sigma}_- \cdot \nabla \left(\bar{G}^2_\pi y_\pi(r) - \bar{G}^2_\rho y_\rho(r)\right)
\end{aligned}
$$

- Based on one meson exchange model
- $y_x(r) = e^{-m_x r}/(4\pi r)$

$$\sigma_\pm = \sigma_1 \pm \sigma_2$$

$$\tau^z_\pm = \tau^z_1 \pm \tau^z_2$$

Parity and time-reversal violating nucleon-nucleon interaction

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& + \boldsymbol{\tau_1} \cdot \boldsymbol{\tau_2}\, \boldsymbol{\sigma}_- \cdot \nabla \left(\bar{G}^0_\pi y_\pi(r) - \bar{G}^0_\rho y_\rho(r)\right) \\
& + \frac{\tau^z_+}{2} \boldsymbol{\sigma}_- \cdot \nabla \left(\bar{G}^1_\pi y_\pi(r) - \bar{G}^1_\rho y_\rho(r) - \bar{G}^1_\omega y_\omega(r)\right) \\
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& + (3\tau^z_1\tau^z_2 - \boldsymbol{\tau_1} \cdot \boldsymbol{\tau_2}) \boldsymbol{\sigma}_- \cdot \nabla \left(\bar{G}^2_\pi y_\pi(r) - \bar{G}^2_\rho y_\rho(r)\right)
\end{aligned}
$$

- Based on one meson exchange model
- $y_x(r) = e^{-m_x r}/(4\pi r)$
- Coupling constants

$$\sigma_\pm = \sigma_1 \pm \sigma_2$$

$$\tau^z_\pm = \tau^z_1 \pm \tau^z_2$$

Parity and time-reversal violating nucleon-nucleon interaction and nuclear EDM

H_{PVTV} introduces parity admixture in the ground state (perturbation theory):

$$|0\rangle \longrightarrow |0\rangle + |\tilde{0}\rangle$$

$$|\tilde{0}\rangle = \sum_{n\neq 0} \frac{1}{E_0 - E_n} |n\rangle\langle n|H_{PVTV}|0\rangle$$

Nuclear EDM is dominated by polarization contribution:

$$D^{(pol)} = \langle 0|\hat{D}_z|\tilde{0}\rangle + c.c.$$

$$\hat{D}_z = \frac{e}{2}\sum_{i=1}^{A} (1+\tau_i^z)\, z_i$$

Parity and time-reversal violating nucleon-nucleon interaction and nuclear EDM

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$$|\tilde{0}\rangle = \sum_{n\neq 0} \frac{1}{E_0 - E_n} |n\rangle\langle n|H_{PVTV}|0\rangle$$

Low lying states of opposite parity can lead to enhancement!

Nuclear EDM is dominated by polarization contribution:

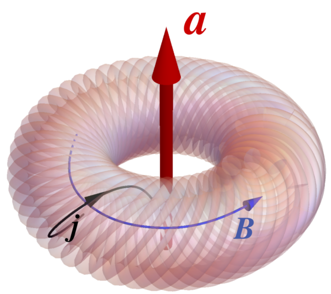
$$D^{(pol)} = \langle 0|\hat{D}_z|\tilde{0}\rangle + c.c. \qquad \hat{D}_z = \frac{e}{2}\sum_{i=1}^{A}(1+\tau_i^z)\, z_i$$

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:

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

How to calculate the sum of intermediate unnatural parity states?

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

- Solving Schroedinger equation with inhomogeneous term

$$(E_{\rm gs} - H)|\psi_{\rm gs}\ I\rangle = V_{\rm NN}^{\rm PNC}|\psi_{\rm gs}\ I^{\pi}\rangle$$

- To invert this equation, we apply the Lanczos algorithm

How to calculate the sum of intermediate unnatural parity states?

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

- Solving Schroedinger equation with inhomogeneous term

$$(E_{\rm gs} - H)|\psi_{\rm gs}\ I\rangle = V_{\rm NN}^{\rm PNC}|\psi_{\rm gs}\ I^{\pi}\rangle$$

- To invert this equation, we apply the Lanczos algorithm

$$|\mathbf{v}_1\rangle = V_{\rm NN}^{\rm PNC}|\psi_{\rm gs}\ I^{\pi}\rangle$$

$$|\psi_{\rm gs}\ I\rangle \approx \sum_k g_k(E_0)|\mathbf{v}_k\rangle$$

$$\hat{g}_1(\omega) = \cfrac{1}{\omega - \alpha_1 - \cfrac{\beta_1^2}{\omega - \alpha_2 - \cfrac{\beta_2^2}{\omega - \alpha_3 - \beta_3^2}}}$$

$$\ddots$$

Few-Body Systems 33, 259–276 (2003)
DOI 10.1007/s00601-003-0017-z

Few-Body Systems
Printed in Austria

Efficient Method for Lorentz Integral Transforms of Reaction Cross Sections

M. A. Marchisio[1], N. Barnea[2], W. Leidemann[1], and G. Orlandini[1]

Lanczos continued fraction method

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

Ab initio calculations of electric dipole moments of light nuclei

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

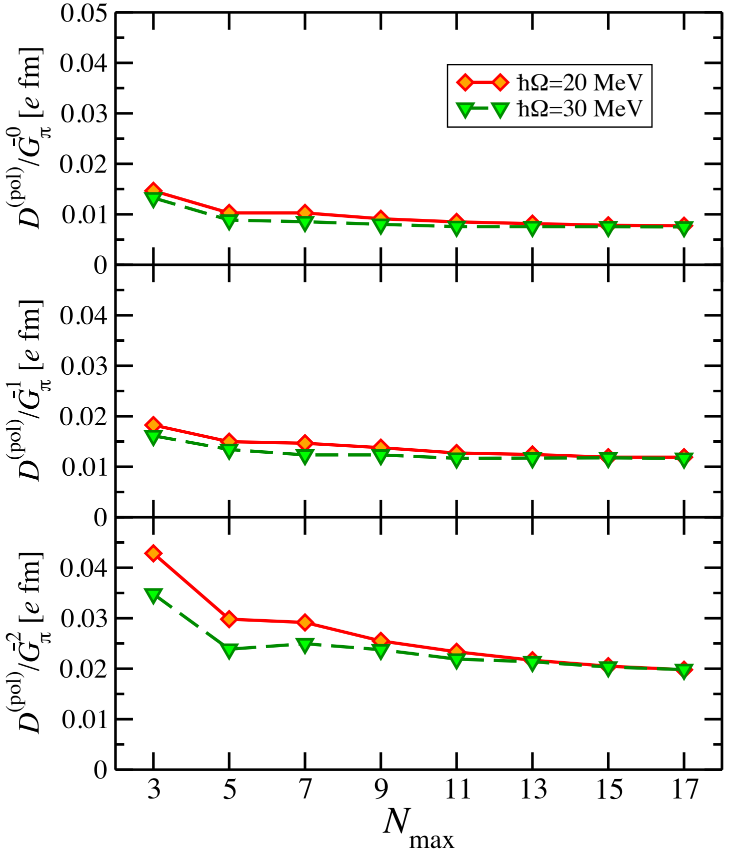
^{3}He EDM Benchmark Calculation

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^3LO NN



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

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

Calculated EDMs of selected stable nuclei

Ab initio calculations of electric dipole moments of light nuclei

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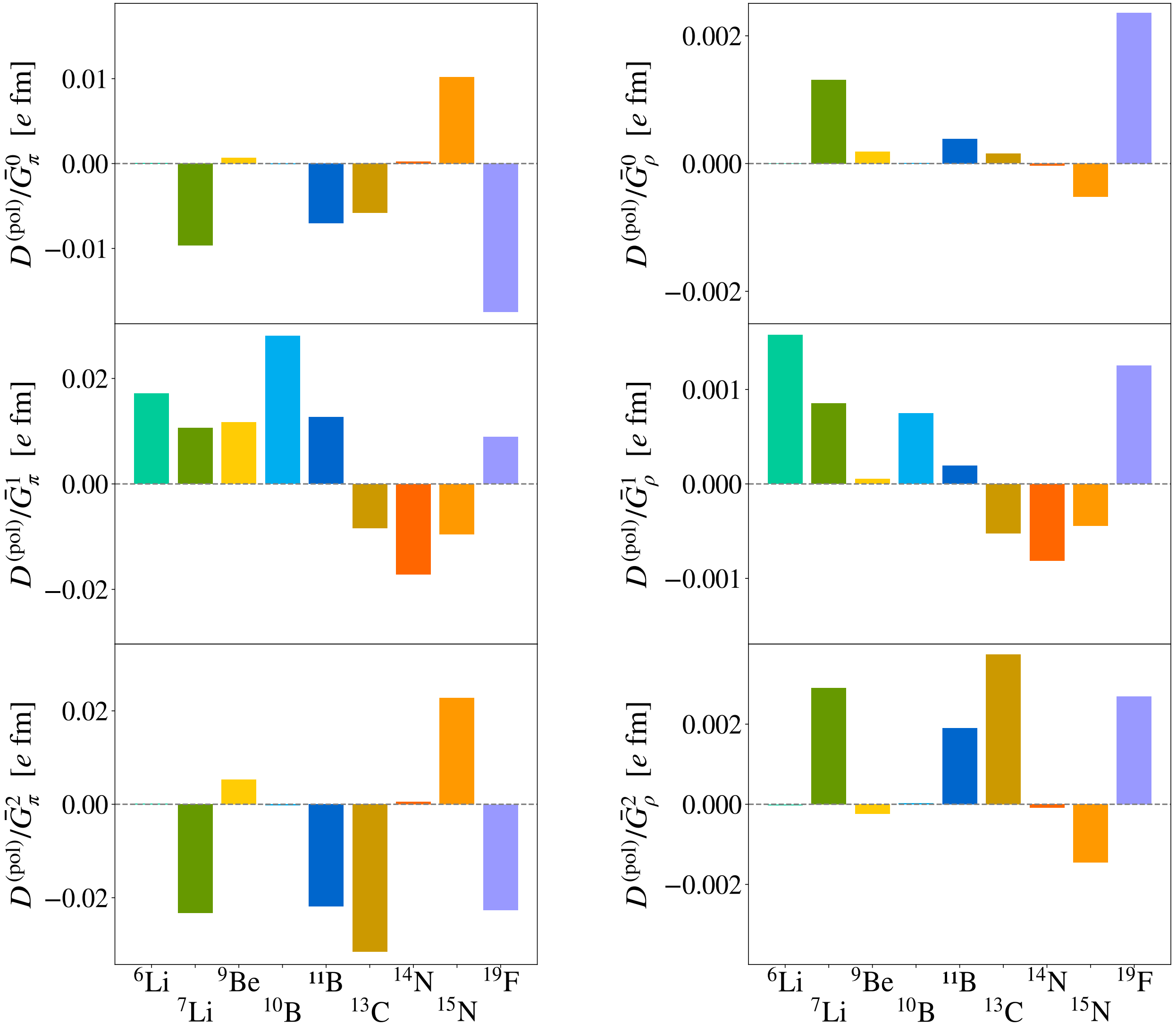
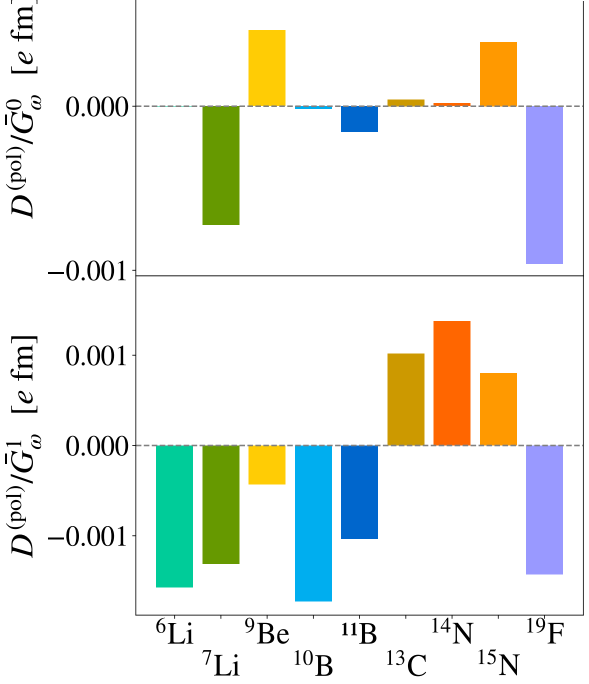
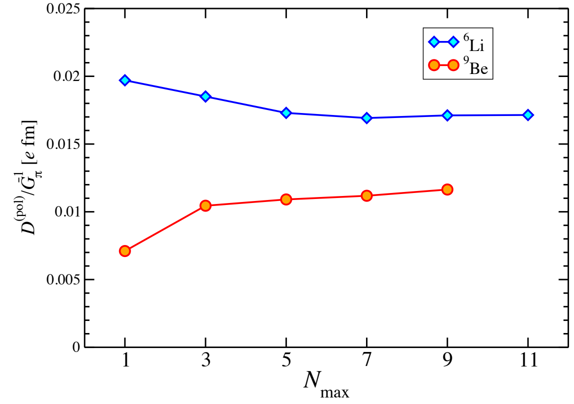




Examples of N_{max} convergence



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

Editors' Suggestion

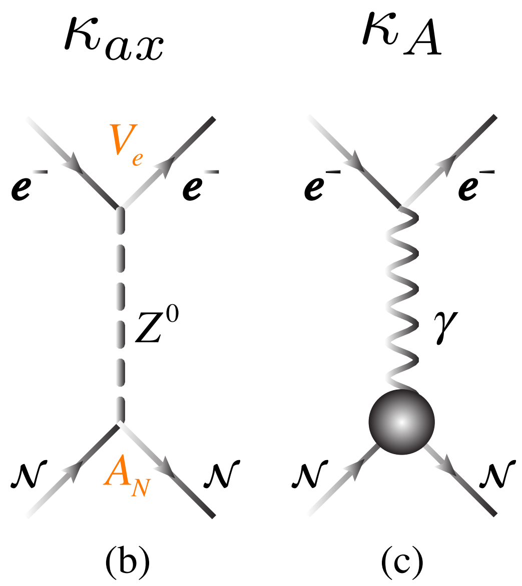
Nuclear spin-dependent parity-violating effects in light polyatomic molecules

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



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

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

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

Applications of *ab initio* nuclear theory to tests of fundamental symmetries

- Precision measurements of β-decay observables offer the possibility to search for deviations from the Standard Model
- Discovering such small deviations demands high-precision theoretical calculations
- Theoretical analysis of β-decay observables of the pure Gamow-Teller (GT) transition $^6\mathrm{He}(0^+) \rightarrow {}^6\mathrm{Li}(1^+)$ using *ab initio* NCSM nuclear structure calculations in combination with the chiral effective field theory (χEFT)
- Four experiments investigating ^{6}He β decay at present
- We find up to 1% correction for the β spectrum and up to 2% correction for the angular correlation
- Propagating nuclear structure and χEFT uncertainties results in an overall uncertainty of 10^{-4}
  - Comparable to the precision of current experiments

Non-zero Fierz interference term due to nuclear structure corrections

$$b_{\mathrm{F}}^{1^+\beta^-} = \delta_b^{1^+\beta^-} = -1.52\,(18)\cdot 10^{-3}$$

Note that new physics at TeV scale implies

$$b^{\mathrm{BSM}}_{\mathrm{Fierz}} = \frac{C_T + C_T'}{C_A} \sim 10^{-3}$$

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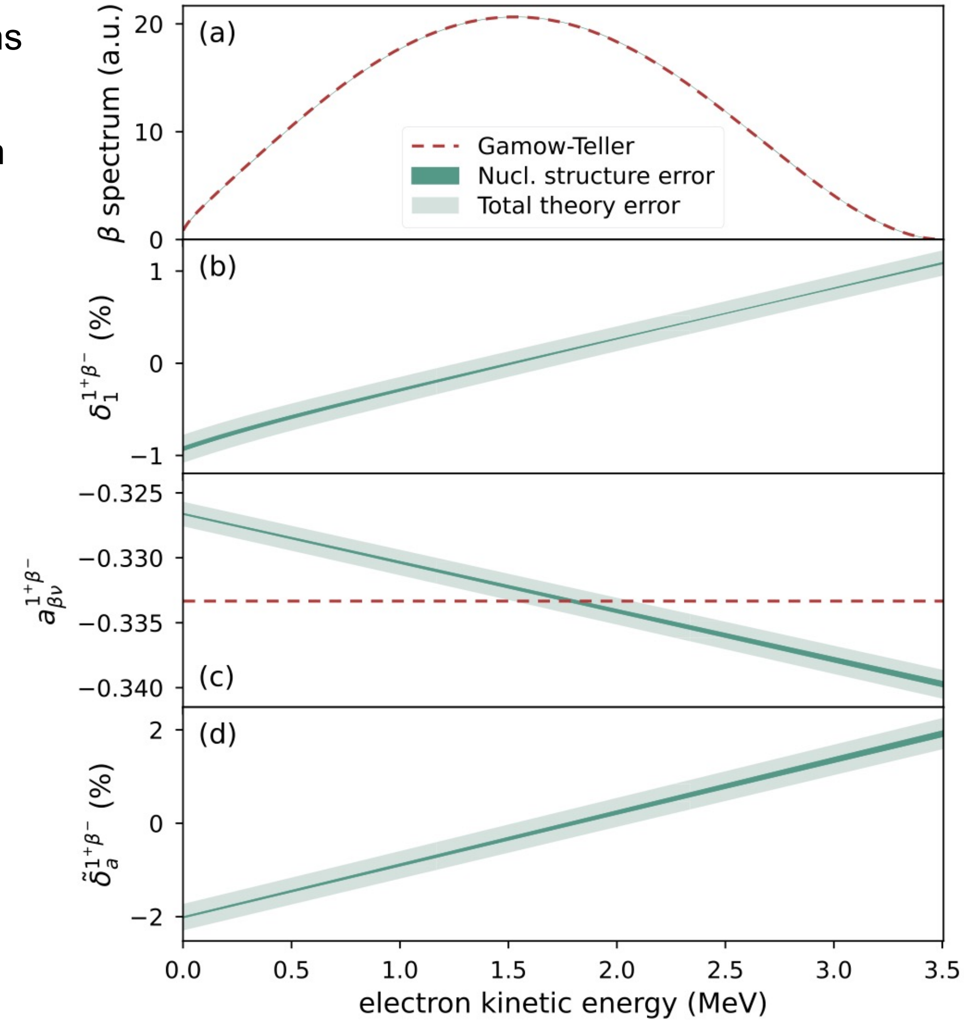
Nuclear *ab initio* calculations of ^{6}He β-decay for beyond the Standard Model studies

Ayala Glick-Magid [a], Christian Forssén [b,*], Daniel Gazda [c], Doron Gazit [a,*], Peter Gysbers [d,e], Petr Navrátil [d]

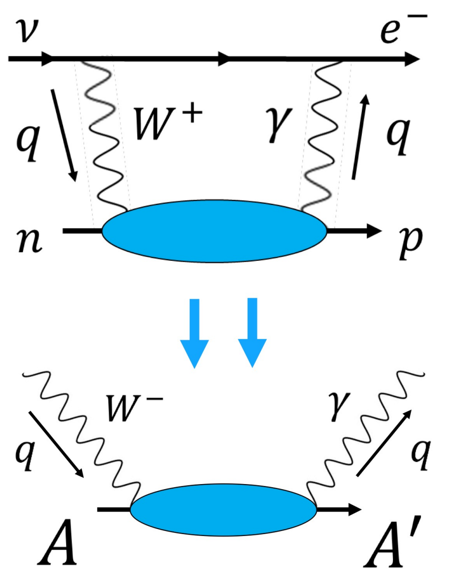


Structure corrections for the extraction of the V_{ud} matrix element from the $^{10}C \rightarrow {}^{10}B$ Fermi transition

- CKM unitarity sensitive probe of BSM physics
  - V_{ud} element from super-allowed Fermi transitions

$$|V_{ud}|^2 = \frac{\hbar^7}{G_F^2 m_e^5 c^4} \frac{\pi^3 \ln(2)}{\mathcal{F}t} \qquad \mathcal{F}t = \frac{K}{G_V^2 |M_{F0}|^2 (1+\Delta_R^V)}$$

$$\mathcal{F}t(1+\Delta_R^V) = ft(1+\delta'_R)\underline{(1-\delta_C+\delta_{NS})}$$



  - δ_{NS} parametrizes correction to free γW box $\delta_{NS} = 2[\Box_{\gamma W}^{VA,\mathrm{nuc.}} - \Box_{\gamma W}^{VA,\mathrm{free\ n}}]$
  - Apply NCSM and calculate

$$T_3(q_0,Q^2) = -4\pi i \frac{q_0}{q}\sqrt{M_i M_f}\sum_{J=1}^{\infty}(2J+1)$$
$$\times \langle A\lambda_f J_f M_f | \Big[T_{J0}^{mag}(q)\, G(M_f+q_0+i\epsilon)\, T_{J0}^{5,el}(q) + T_{J0}^{el}(q)\, G(M_f+q_0+i\epsilon)\, T_{J0}^{5,mag}(q)$$
$$+ T_{J0}^{5,mag}(q)\, G(M_i-q_0+i\epsilon)\, T_{J0}^{el}(q) + T_{J0}^{5,el}(q)\, G(M_i-q_0+i\epsilon)\, T_{J0}^{mag}(q) \Big] | A\lambda_i J_i M_i \rangle$$

In collaboration with
C.-Y. Seng & M. Gorchtein
See talk by Chien-Yeah Seng

  - δ_C isospin symmetry breaking correction
  - Apply NCSMC: $^{10}C \rightarrow {}^{9}B+p$; $^{10}B \rightarrow {}^{9}Be+p$, $^{9}B+n$

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

Work in progress…

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* NCSMC to
  - ^{11}Be β decay with the proton emission
  - Radiative capture of protons on ^{7}Be and deuteron capture on ^{4}He
  - Proton capture on ^{7}Li - internal pair conversion and the X17 boson claim

- *Ab initio* NCSM capable to calculate accurately nuclear structure effects needed for analysis of parity-violation and time-reversal violation experiments in atoms and molecules
  - First results available; 10% precision within the reach
  - Different nuclei can be used to probe different terms of the parity & time-reversal violating interaction

- NCSM applied to analyze the nuclear-structure corrections to ^{6}He β-decay observables

- NCSM and NCSMC calculations of structure corrections for the extraction of the V_{ud} matrix element from Fermi transitions

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