TRIUMF

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

FRIB-TA Topical Program: Theoretical Justifications and Motivations for Early High-Profile FRIB Experiments

FRIB, MSU, May 20, 2023

Petr Navratil

TRIUMF

Collaborators:
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Chien Yeah Seng (INT), Misha Gorshteyn (U Mainz), Sofia Quaglioni (LLNL),
Matteo Vorabbi (Surrey)

2023-05-19

Discovery, accelerated

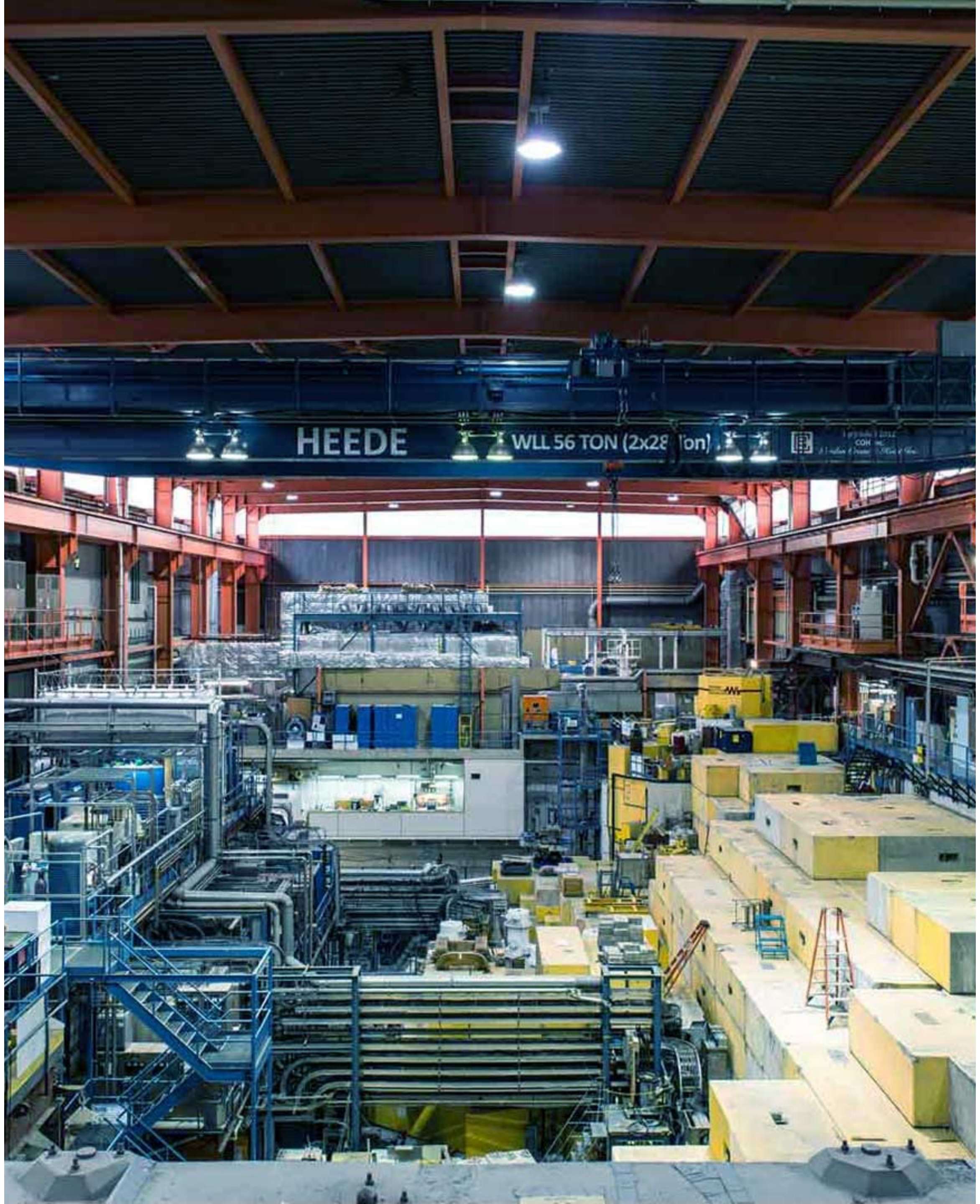
Outline

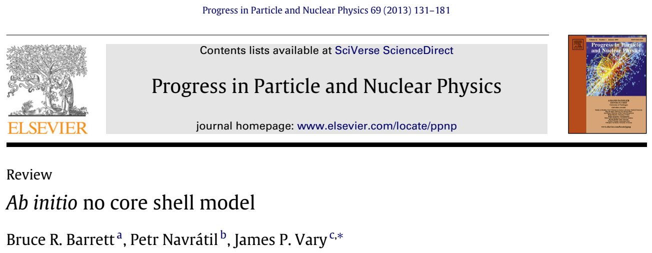
- Theory method
  - *Ab initio* no-core shell model (NCSM) and NCSM with continuum (NCSMC)
    - Input chiral NN+3N interactions
    - Continued fraction Lanczos method for Green's functions
- Fundamental symmetries
  - Calculations of β-decay electron spectrum
    - ^{6}He, ^{16}N – reach to light *sd*-shell, e.g., ^{19}Ne
  - Nuclear structure corrections for the extraction of the V_{ud} from the superallowed Fermi transition
    - δ_C and δ_{NS} for $^{10}C\rightarrow^{10}B$ – reach to $^{14}O \rightarrow {}^{14}N$ and possibly $^{18}Ne \rightarrow {}^{18}F$, $^{22}Mg \rightarrow {}^{22}Na$
  - Parity-violating and time-reversal violating nuclear moments
    - Anapole and electric dipole moments of light nuclei
  - Proton capture on ^{7}Li and the hypothetical X17 boson

Outline

- Nuclear structure
    - Resonances close to threshold – reach to light *sd*-shell
        - DT fusion, ^{6}He+p, ^{10}Be+p – ^{11}Be β-decay to continuum
    - Halo nuclei
        - ^{11}Be – photodissociation, ANC
        - ^{15}C – ANCs, narrow resonances in the ^{15}F mirror
    - Radii of weakly bound nuclei within the NCSMC – much superior to NCSM (HO basis)
- Nuclear astrophysics
    - Capture reactions – reach to light *sd*-shell
        - $^{4}\mathrm{He}(d,\gamma)^{6}\mathrm{Li}$, $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$, $^{11}\mathrm{C}(p,\gamma)^{12}\mathrm{N}$, $^{8}\mathrm{Li}(n,\gamma)^{9}\mathrm{Li}$, $^{14}\mathrm{C}(n,\gamma)^{15}\mathrm{C}$

Ab initio NCSM and NCSMC




Progress in Particle and Nuclear Physics 69 (2013) 131–181

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Progress in Particle and Nuclear Physics

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Ab initio no core shell model

Bruce R. Barrett[a], Petr Navrátil[b], James P. Vary[c,*]

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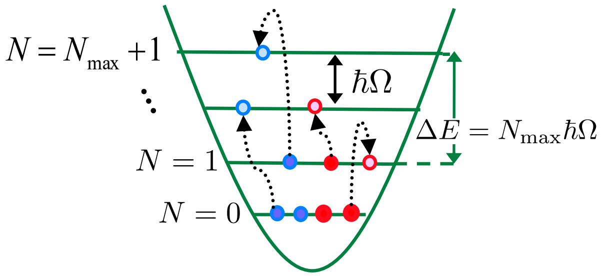
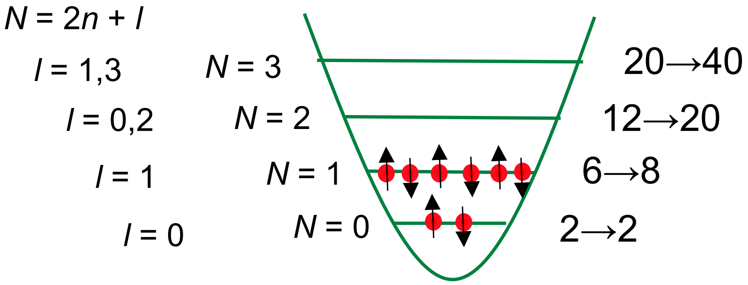
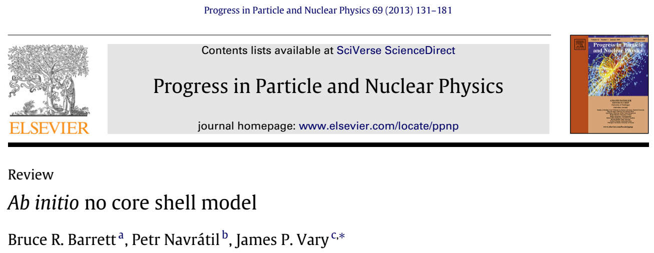
- Basis expansion method
  - Harmonic oscillator (HO) basis truncated in a particular way (N_{max})
  - Why HO basis?
    - Lowest filled HO shells match magic numbers of light nuclei (2, 8, 20 – ^{4}He, ^{16}O, ^{40}Ca)
    - Equivalent description in relative(Jacobi)-coordinate and Slater determinant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

NCSM





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



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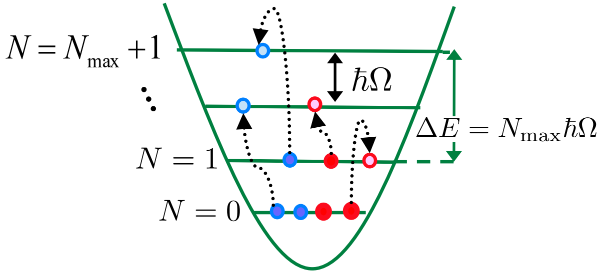
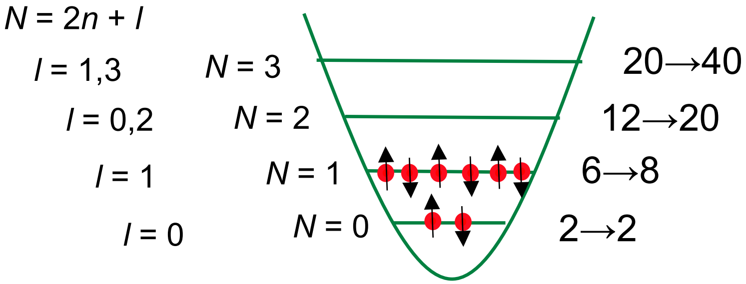


$$\Psi^A = \sum_{N=0}^{N_{\max}} \sum_{i} c_{Ni}\, \Phi^{HO}_{Ni}(\vec{\eta}_1, \vec{\eta}_2, \ldots, \vec{\eta}_{A-1})$$

$$\Psi^A_{\mathrm{SD}} = \sum_{N=0}^{N_{\max}} \sum_{j} c^{\mathrm{SD}}_{Nj}\, \Phi^{HO}_{\mathrm{SD}\,Nj}(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) = \Psi^A\, \varphi_{000}(\vec{R}_{CM})$$



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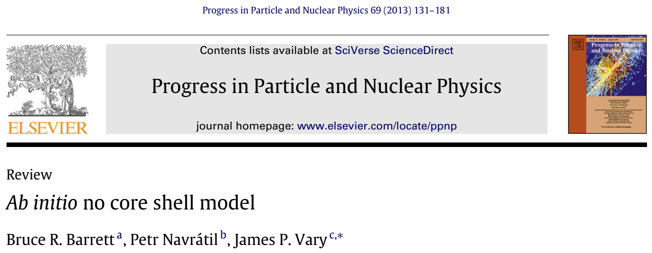
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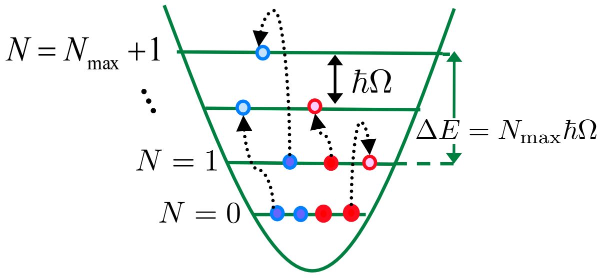
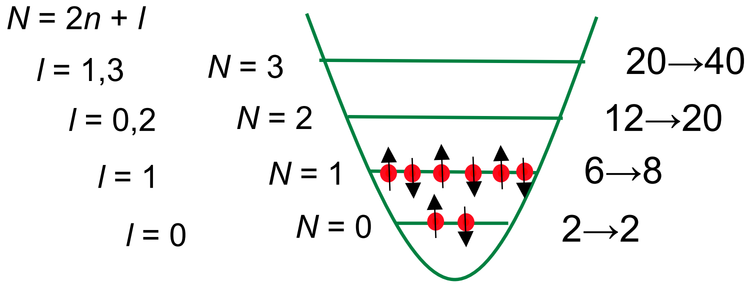


For *A*>4 nuclei we use the SD basis



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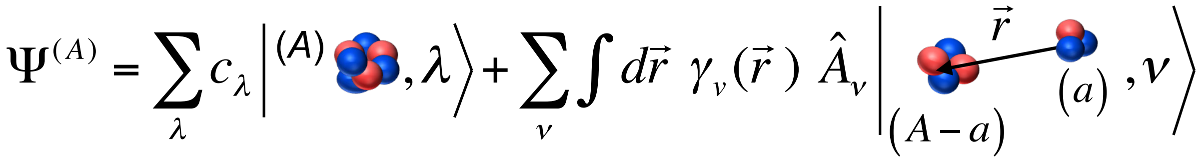
Ab Initio Calculations of Structure, Scattering, Reactions
Unified approach to bound & continuum states

No-Core Shell Model with Continuum (NCSMC)



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

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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]

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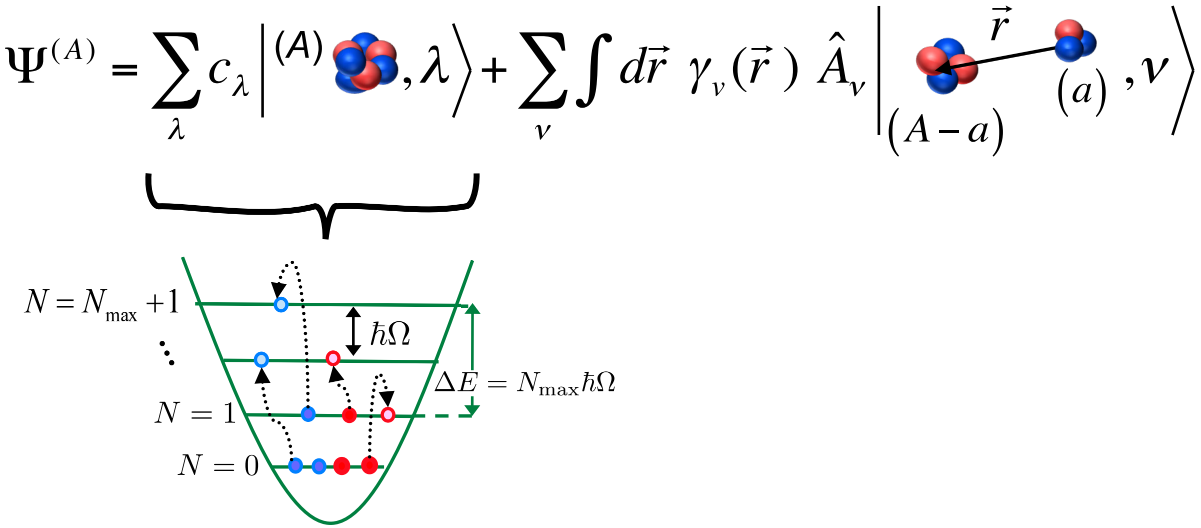

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Static solutions for aggregate system,
describe all nucleons close together

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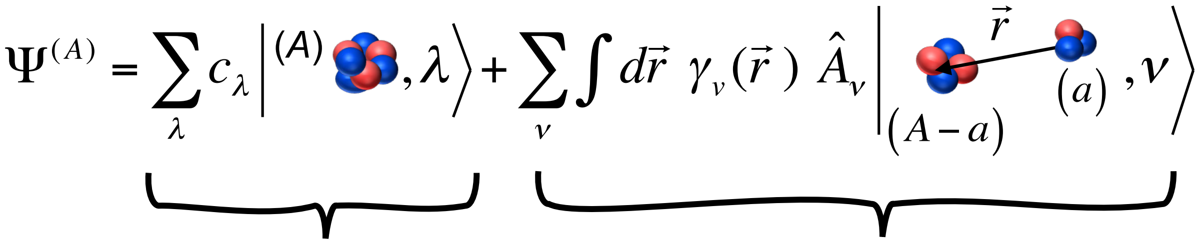

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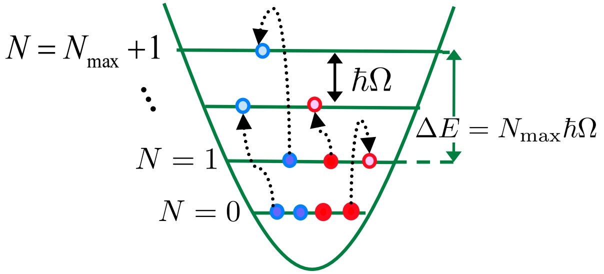

Continuous microscopic cluster states, describe long-range projectile-target

Static solutions for aggregate system, describe all nucleons close together

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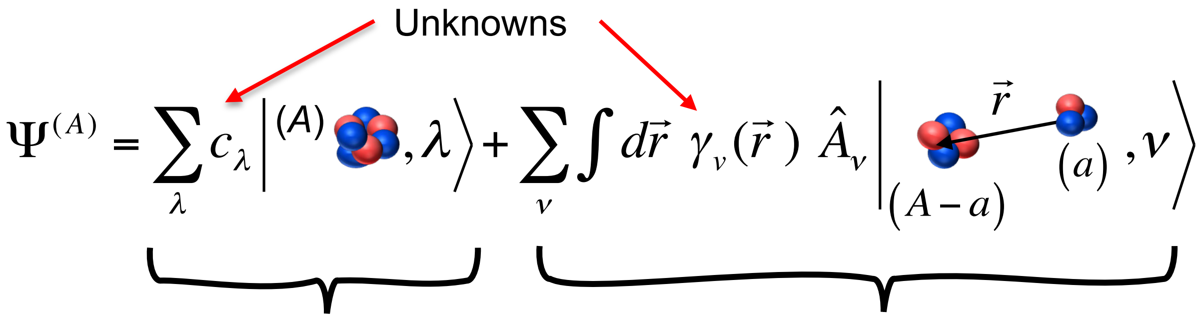
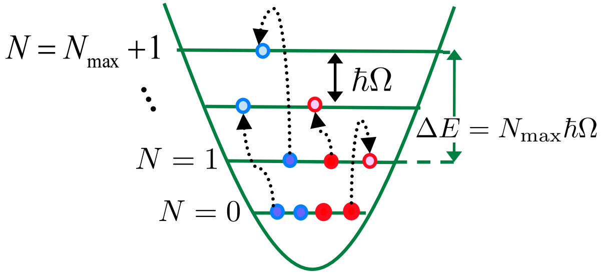


$$\Psi^{(A)} = \underbrace{\sum_{\lambda} c_{\lambda} \left| {}^{(A)}\ ,\lambda \right\rangle}_{} + \underbrace{\sum_{\nu} \int d\vec{r}\ \gamma_{\nu}(\vec{r}\,)\ \hat{A}_{\nu} \left|_{(A-a)}\ \vec{r}\ (a)\ ,\nu \right\rangle}_{}$$



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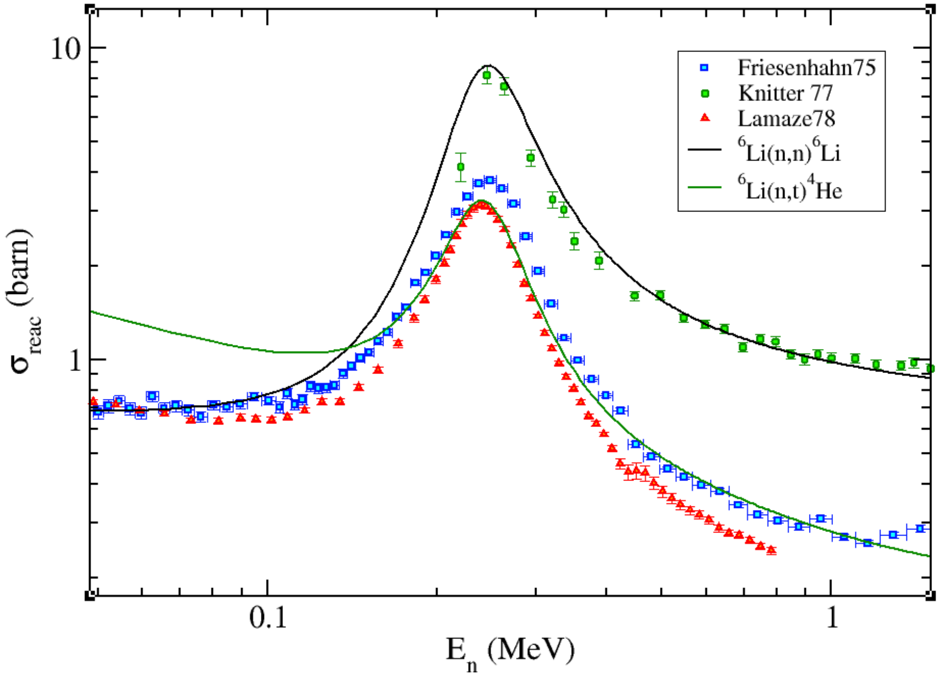
NCSM & NCSMC

- What are the observables that will have the most impact?
  - Input – chiral NN+3N interactions
    - NN well constrained by the nucleon-nucleon scattering data
    - 3N is not well constrained
      - Need to measure **three-nucleon scattering**

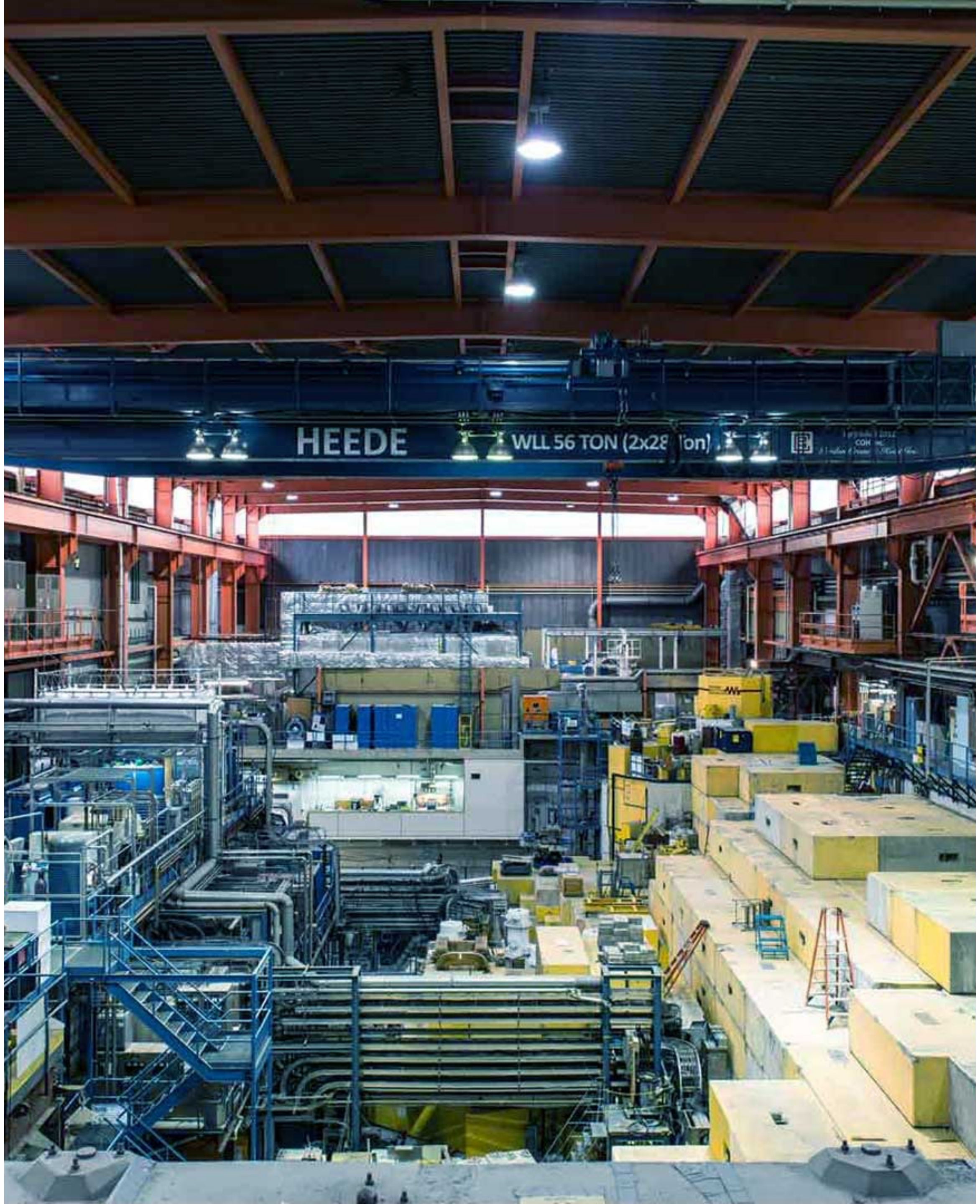
NCSM & NCSMC

- What theoretical advances are required?
    - Coupling of different mass partitions

Moving in that direction:
First example ^{6}Li(n,t)^{4}He



^{6}He and ^{16}N β-decay



Precise measurements of β decays to search for Physics Beyond the Standard Model

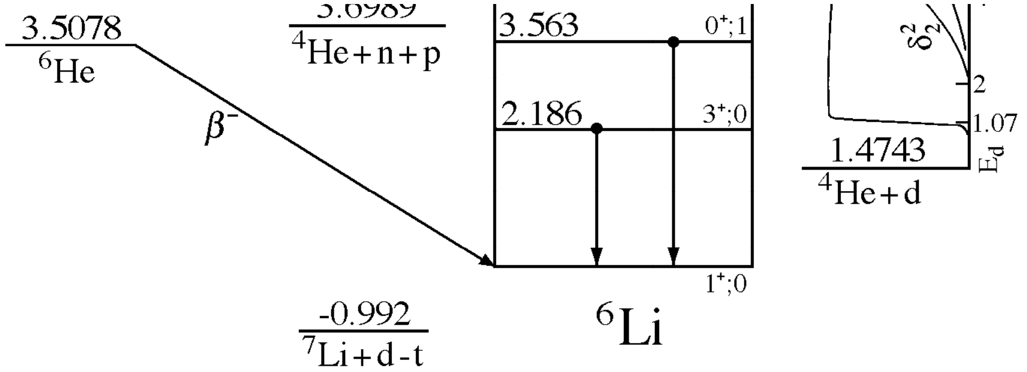
- Precision measurements of β-decay observables offer the possibility to search for deviations from the Standard Model
    - β-decay observables are sensitive to interference of currents of SM particles and hypothetical BSM physics
    - Discovering such small deviations from the SM predictions demands also high-precision theoretical calculations
        - ⇒ Nuclear structure calculations with quantified uncertainties

^{6}He β-decay

- Decay rate proportional to

$$d\omega \propto 1 + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu} + b_{\mathrm{F}}\frac{m_e}{E} \qquad \vec{\beta} = \frac{\vec{k}}{E} \qquad \vec{\nu} = \nu\hat{\nu}$$

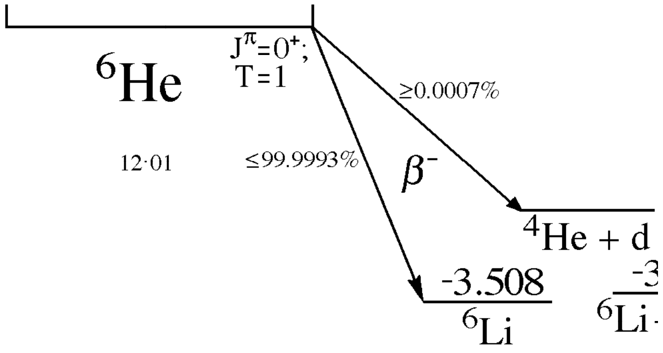
$a_{\beta\nu}$	angular correlation coefficient between the emitted electron and the antineutrino
b_{F}	Fierz interference term that can be extracted from electron energy spectrum measurements



- The *V-A* structure of the weak interaction in the Standard Model implies for a Gamow-Teller transition

$$a_{\beta\nu} = -\frac{1}{3}$$

$$b_{\mathrm{F}} = 0$$



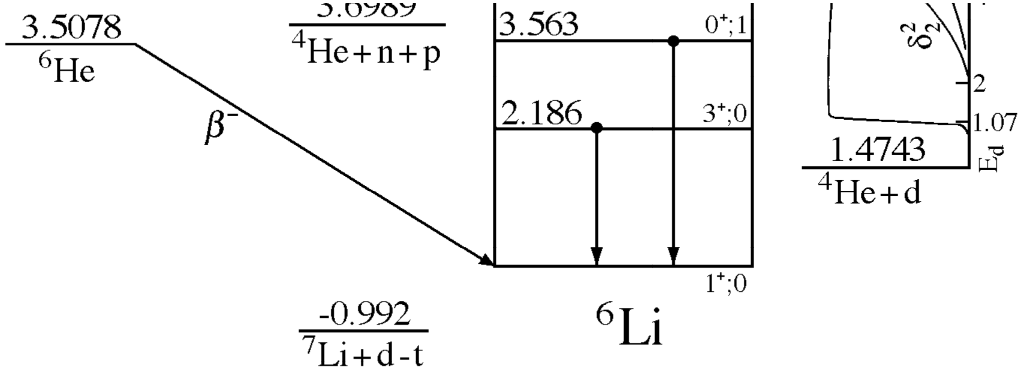
Precise measurements of β decays to search for Physics Beyond the Standard Model

- In the presence of Beyond the Standard Model interactions

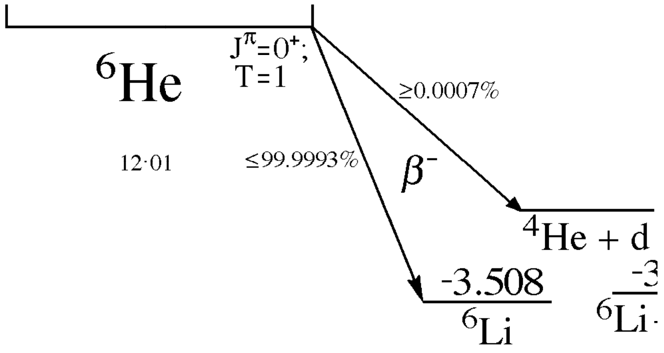
$$a_{\beta\nu}^{\mathrm{BSM}} = -\frac{1}{3}\left(1 - \frac{|C_T|^2+\left|C'_T\right|^2}{2|C_A|^2}\right)$$

$$b_{\mathrm{Fierz}}^{\mathrm{BSM}} = \frac{C_T+C'_T}{C_A}$$

  - with tensor and pseudo-tensor contributions



- However, deviations also within the Standard Model caused by the finite momentum transfer, higher-order transition operators, and nuclear structure effects
  - Detailed, accurate, and precise calculations required



Precise measurements of β decays to search for Physics Beyond the Standard Model

- Higher-order Standard Model recoil and shape corrections

$$a_{\beta\nu}^{1^+\beta^-} = -\frac{1}{3}\left(1+\tilde{\delta}_a^{1^+\beta^-}\right)$$

$$b_{\mathrm{F}}^{1^+\beta^-} = \delta_b^{1^+\beta^-}$$

$$\delta_1^{1^+\beta^-} \equiv \frac{2}{3}\mathfrak{Re}\left[-E_0\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}+\sqrt{2}\,(E_0-2E)\,\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right] - \frac{4}{7}ER\alpha Z_f - \frac{233}{630}\left(\alpha Z_f\right)^2,$$

$$\tilde{\delta}_a^{1^+\beta^-} \equiv \frac{4}{3}\mathfrak{Re}\left[2E_0\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}+\sqrt{2}\,(E_0-2E)\,\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right] + \frac{4}{7}ER\alpha Z_f - \frac{2}{5}E_0R\alpha Z_f,$$

$$\delta_b^{1^+\beta^-} \equiv \frac{2}{3}m_e\mathfrak{Re}\left[\frac{\langle\|\hat{C}_1^A/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}+\sqrt{2}\frac{\langle\|\hat{M}_1^V/q\|\rangle}{\langle\|\hat{L}_1^A\|\rangle}\right],$$

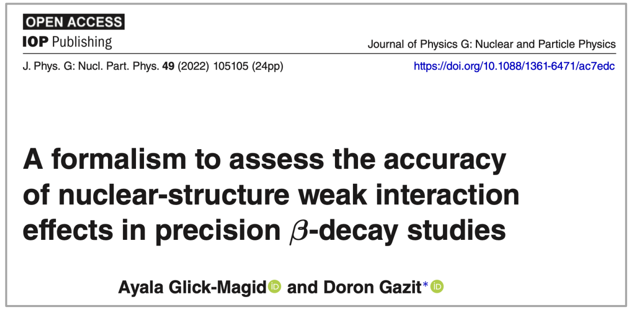
$\vec{q} = \vec{k} + \vec{\nu}$ momentum transfer

$\hat{C}_1^A$ axial charge

$\hat{M}_1^V$ vector magnetic or weak magnetism

$\hat{L}_1^A \propto 1$ Gamow-Teller leading order

$\hat{C}_1^A$ $\hat{M}_1^V$ NLO recoil corrections, order q/m_N



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A formalism to assess the accuracy of nuclear-structure weak interaction effects in precision β-decay studies

Ayala Glick-Magid and Doron Gazit*

Precise measurements of β decays to search for Physics Beyond the Standard Model

- Higher-order Standard Model recoil and shape corrections

$$\frac{\hat{C}^A_{JM_J}}{q} = \sum_{j=1}^{A} \frac{i}{m_N}\Big[g_A \hat{\Omega}'_{JM_J}(q\vec{r}_j) - \frac{1}{2}\frac{\tilde{g}_P}{2m_N}(E_0+\Delta E_c)\,\hat{\Sigma}''_{JM_J}(q\vec{r}_j)\Big]\tau_j^+,$$

$$\hat{L}^A_{JM_J} = \sum_{j=1}^{A} i\left(g_A + \frac{\tilde{g}_P}{(2m_N)^2}q^2\right)\hat{\Sigma}''_{JM_J}(q\vec{r}_j)\,\tau_j^+,$$

$$\frac{\hat{M}^V_{JM_J}}{q} = \sum_{j=1}^{A} \frac{-i}{m_N}\left[g_V\,\hat{\Delta}_{JM_J}(q\vec{r}_j) - \frac{1}{2}\mu\hat{\Sigma}'_{JM_J}(q\vec{r}_j)\right]\tau_j^+$$

$$\hat{\Sigma}''_{JM_J}(q\vec{r}_j) = \left[\frac{1}{q}\vec{\nabla}_{\vec{r}_j} M_{JM_J}(q\vec{r}_j)\right]\cdot\vec{\sigma}(j),$$

$$\hat{\Omega}'_{JM_J}(q\vec{r}_j) = M_{JM_J}(q\vec{r}_j)\,\vec{\sigma}(j)\cdot\vec{\nabla}_{\vec{r}_j} + \frac{1}{2}\hat{\Sigma}''_{JM_J}(q\vec{r}_j),$$

$$\hat{\Delta}_{JM_J}(q\vec{r}_j) = \vec{M}_{JJM_J}(q\vec{r}_j)\cdot\frac{1}{q}\vec{\nabla}_{\vec{r}_j},$$

$$\hat{\Sigma}'_{JM_J}(q\vec{r}_j) = -i\left[\frac{1}{q}\vec{\nabla}_{\vec{r}_j}\times\vec{M}_{JJM_J}(q\vec{r}_j)\right]\cdot\vec{\sigma}(j),$$

$$M_{JM_J}(q\vec{r}_j) = j_J(qr_j)Y_{JM_J}(\hat{r}_j)$$

$$\vec{M}_{JLM_J}(q\vec{r}_j) = j_L(qr_j)\vec{Y}_{JLM_J}(\hat{r}_j)$$

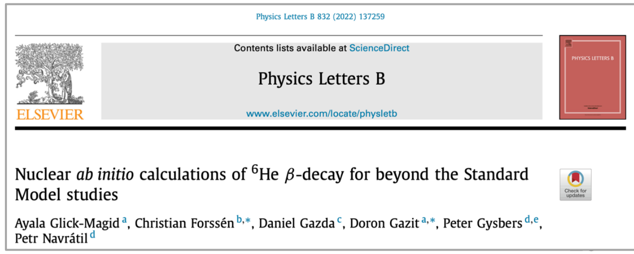
Hadronic vector, axial vector and pseudo-scalar charges

$g_V = 1$ $\quad g_A = -1.2756(13)$ $\quad \tilde{g}_P = -\frac{(2m_N)^2}{m_\pi^2 - q^2}g_A$

$\mu \approx 4.706$ is the nucleon isovector magnetic moment

$$\Delta E_c \equiv \langle {}^6\mathrm{Li}\ 1^+_{\mathrm{gs}}|V_c|{}^6\mathrm{Li}\ 1^+_{\mathrm{gs}}\rangle - \langle {}^6\mathrm{He}\ 0^+_{\mathrm{gs}}|V_c|{}^6\mathrm{He}\ 0^+_{\mathrm{gs}}\rangle$$

Ultimately, we need to calculate
^{6}He(0^+ 1) → ^{6}Li(1^+ 0) matrix elements
of these “one-body” operators



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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]

Apply *ab initio* No-Core Shell Model to calculate the ^{6}Li and ^{6}He wave functions and the operator matrix elements

NCSM

- Matrix elements of the relevant operators

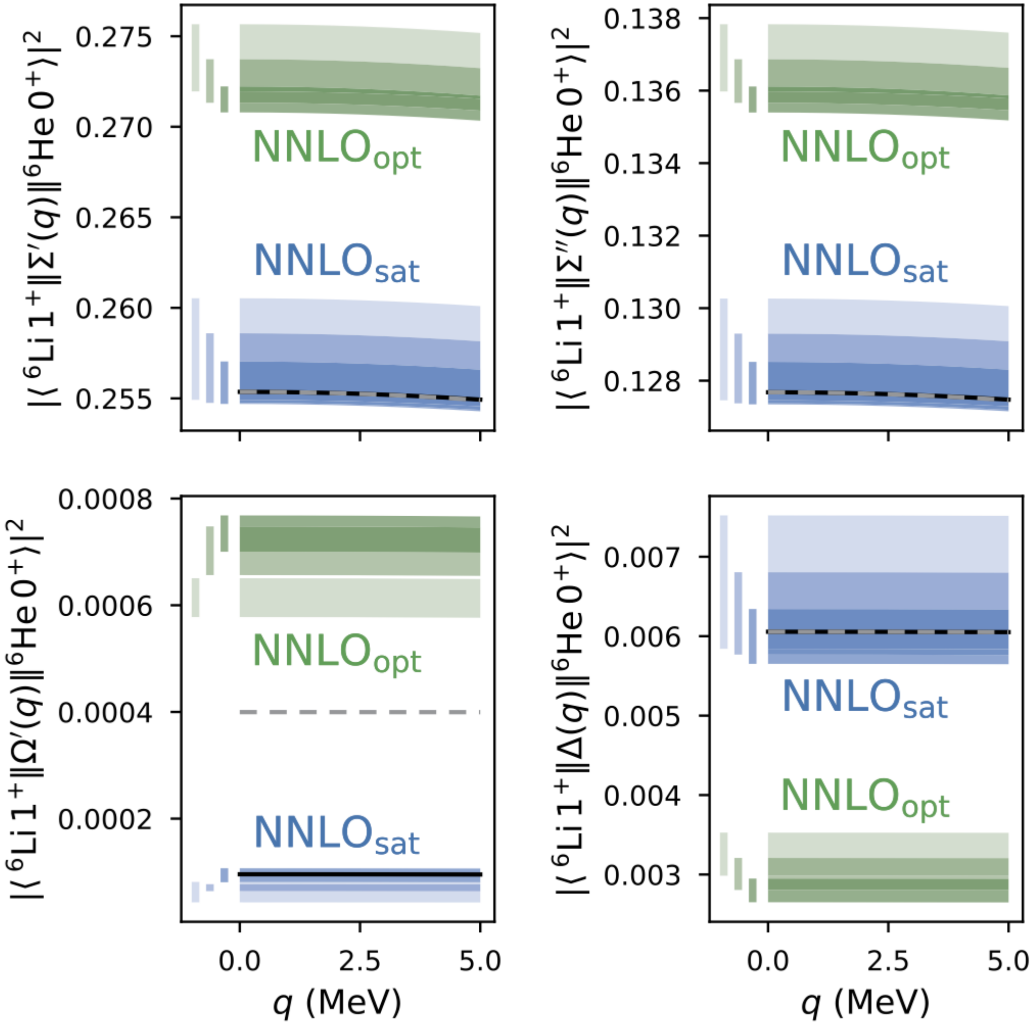
$$\hat{\Sigma}''_{JM_J}(q\vec{r}_j) = \left[\frac{1}{q}\vec{\nabla}_{\vec{r}_j} M_{JM_J}(q\vec{r}_j)\right]\cdot\vec{\sigma}(j),$$

$$\hat{\Omega}'_{JM_J}(q\vec{r}_j) = M_{JM_J}(q\vec{r}_j)\,\vec{\sigma}(j)\cdot\vec{\nabla}_{\vec{r}_j} + \frac{1}{2}\hat{\Sigma}''_{JM_J}(q\vec{r}_j),$$

$$\hat{\Delta}_{JM_J}(q\vec{r}_j) = \vec{M}_{JJM_J}(q\vec{r}_j)\cdot\frac{1}{q}\vec{\nabla}_{\vec{r}_j},$$

$$\hat{\Sigma}'_{JM_J}(q\vec{r}_j) = -i\left[\frac{1}{q}\vec{\nabla}_{\vec{r}_j}\times\vec{M}_{JJM_J}(q\vec{r}_j)\right]\cdot\vec{\sigma}(j),$$

- Convergence investigation
  - Variation of HO frequency
    - $h\Omega$ = 16 - 24 MeV
  - Variation of basis size
    - N_{max}= 0 - 14 for NNLO$_{\text{opt}}$
    - N_{max}= 0 - 12 for NNLO$_{\text{sat}}$



Overall results for ^{6}He(0^{+} 1) → ^{6}Li(1^{+} 0) + e^{-} + $\overline{\nu}$

- 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

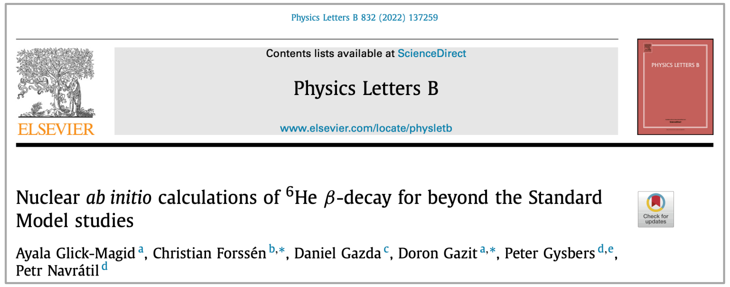
$$b_{\mathrm{F}}^{1^{+}\beta^{-}} = \delta_{b}^{1^{+}\beta^{-}} = -1.52\,(18)\cdot 10^{-3}$$

$$\left\langle \tilde{\delta}_{a}^{1^{+}\beta^{-}} \right\rangle = -2.54\,(68)\cdot 10^{-3}$$

Non-zero Fierz interference term due to nuclear structure corrections

Note that new physics at TeV scale implies

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


Physics Letters B 832 (2022) 137259

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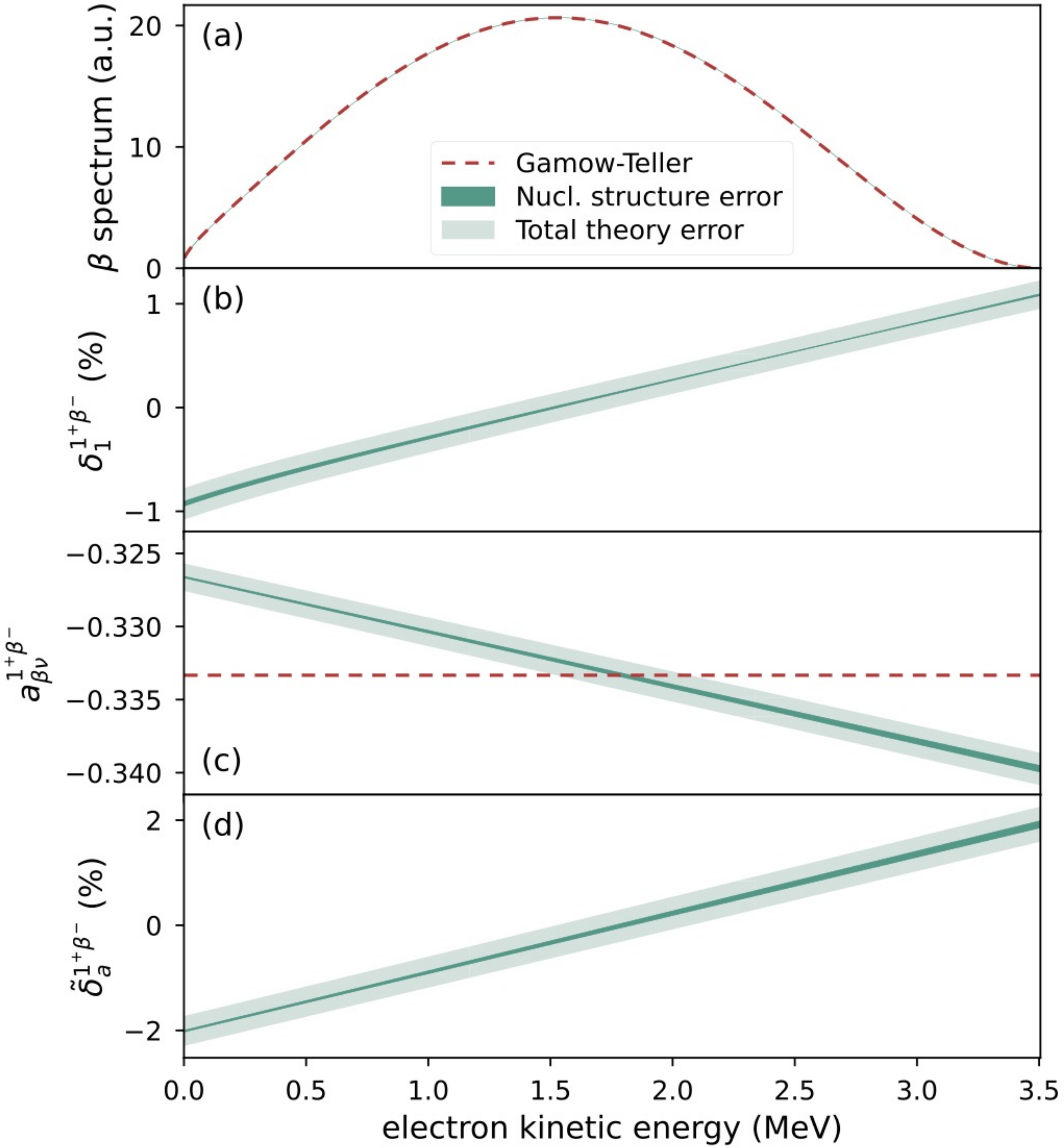
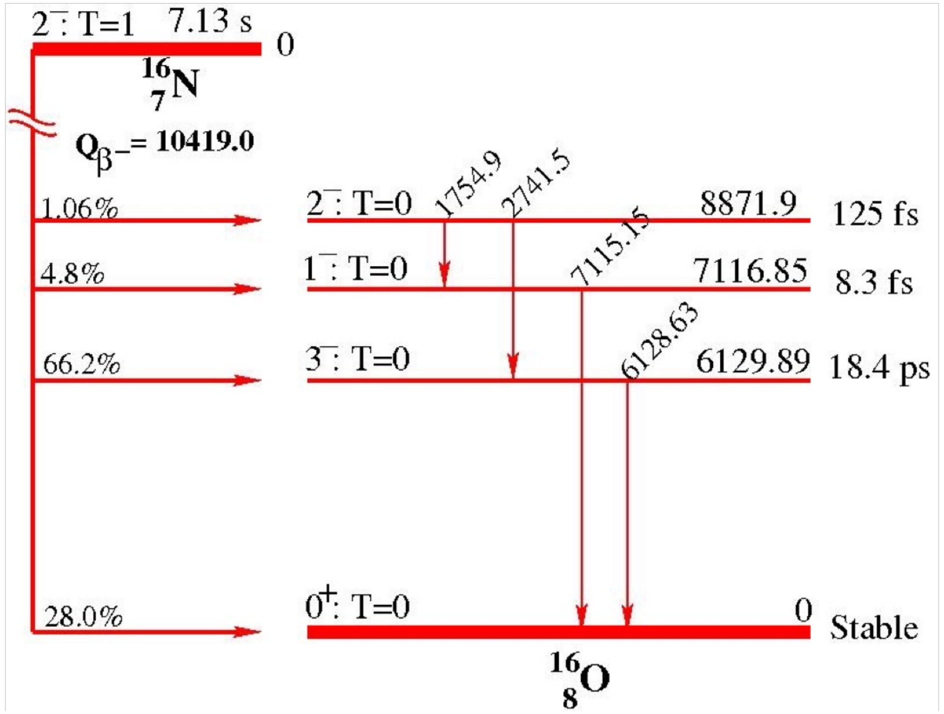
Nuclear *ab initio* calculations of ^{6}He β-decay for beyond the Standard Model studies

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

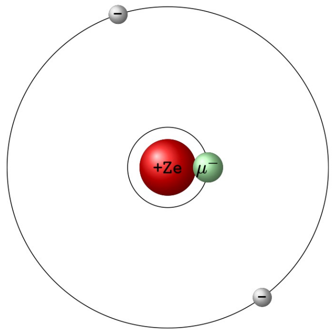


Unique first-forbidden beta decay $^{16}N(2^-) \rightarrow {}^{16}O(0^+)$

- The unique first-forbidden transition, $J^{\Delta\pi} = 2^-$, is of great interest for BSM searches
  - Energy spectrum of emitted electrons sensitive to the symmetries of the weak interaction, gives constraints both in the case of right and left couplings of the new beyond standard model currents
  - Ayala Glick-Magid *et al*., PLB 767 (2017) 285
- Ongoing experiment at SARAF, Israel



Ordinary muon capture on ^{16}O within the NCSM



$$^{16}\mathrm{O}(0^+_{\mathrm{gs}}) + \mu^- \rightarrow \; ^{16}\mathrm{N}(2^-_{\mathrm{gs}}) + \nu_\mu$$

- Investigated using three sets of chiral EFT NN+3N interactions:
  - NN(N^{4}LO)+3N(N^{2}LO,lnl)

    Entem, Machleidt, Nosyk, Phys. Rev. C 96, 024004 (2017) (NN)

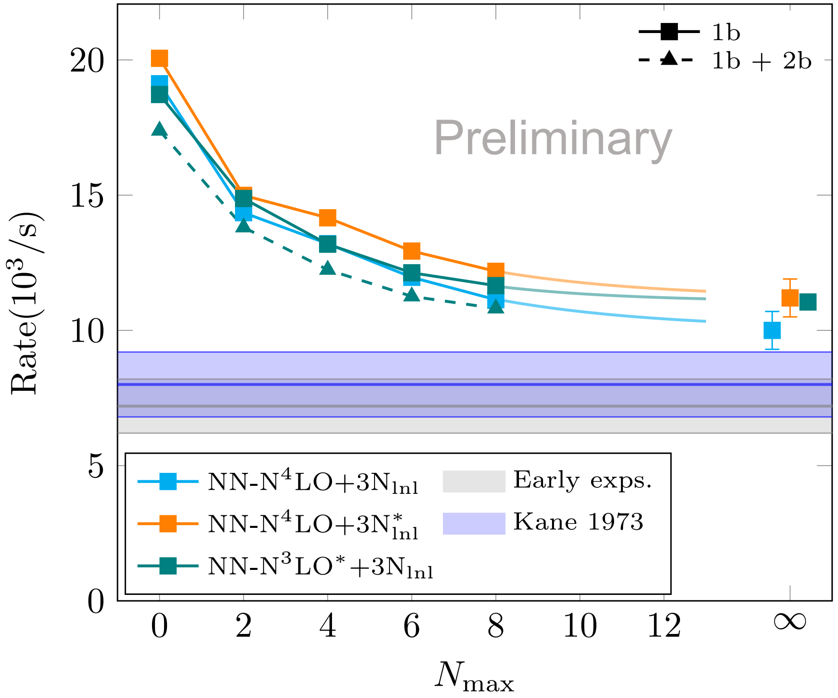
    Gysbers *et al.*, Nature Phys. 15, 428 (2019) (3N)
  - NN(N^{4}LO)+3N(N^{2}LO,lnl,E7)

    Girlanda, Kievsky, Viviani, Phys. Rev. C 84, 014001 (2011) (E7)
  - NN(N^{3}LO)+3N(N^{2}LO,lnl)

    Entem, Machleidt, Phys. Rev. C 68, 041001 (2003) (NN)

    Soma, Navratil *et al.*, Phys. Rev. C 101, 014318 (2020) (3N)

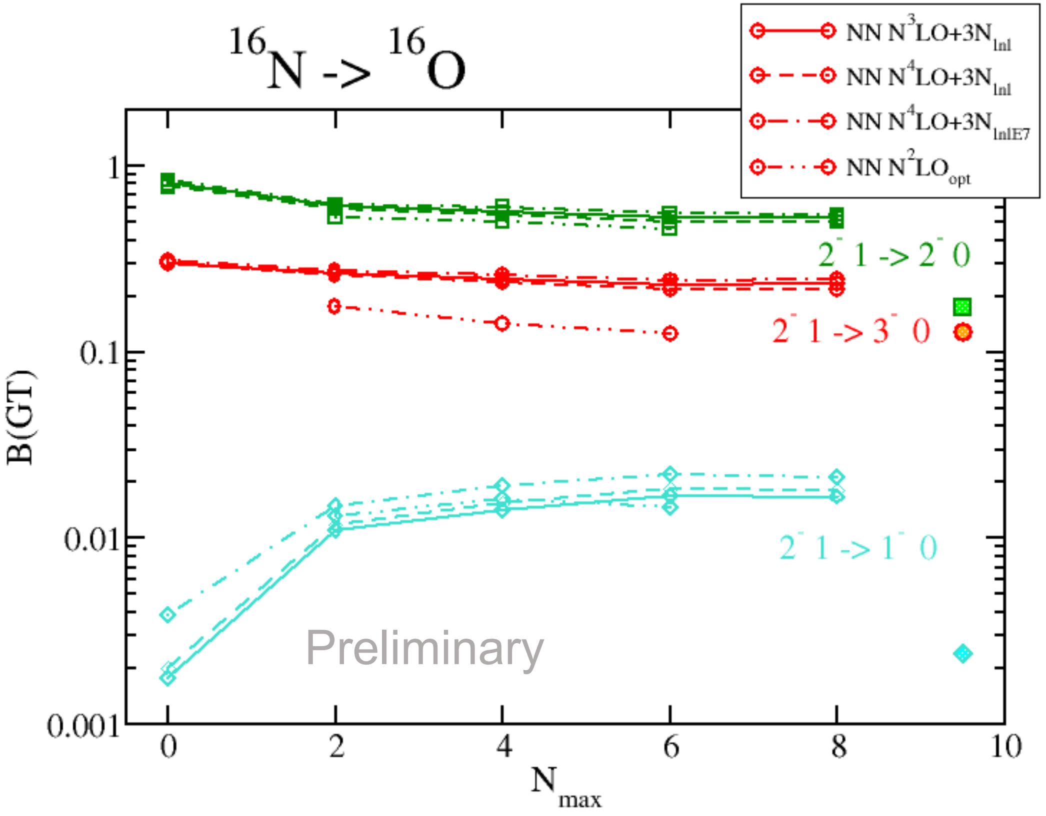
- Results quite encouraging
  - NCSM describes well the complex systems ^{16}O and ^{16}N
  - → Feasible to apply NCSM to the ^{16}N beta decay

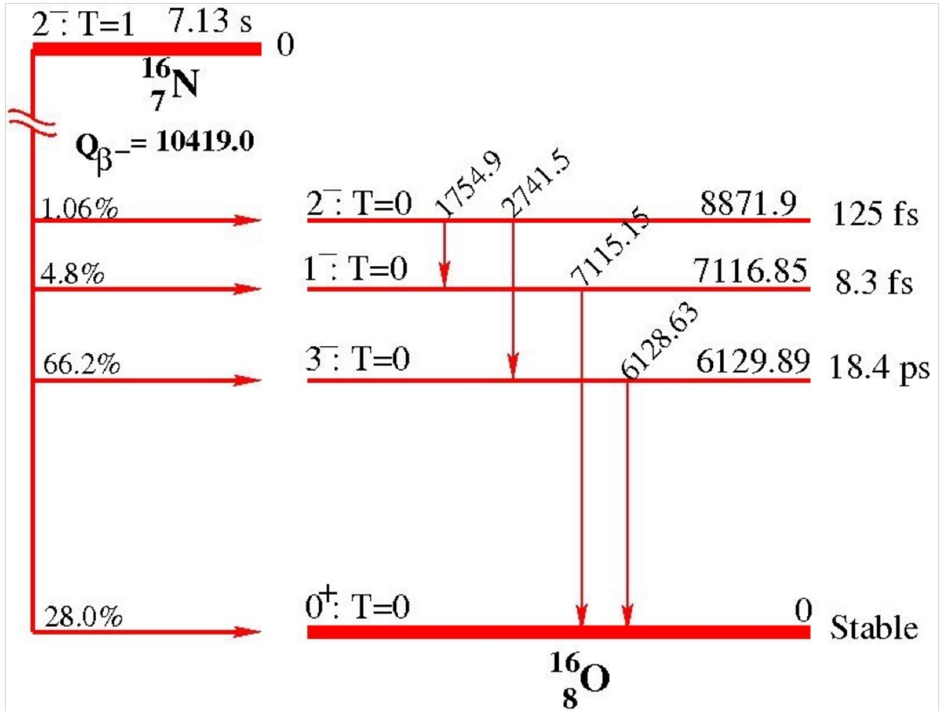


Lotta Jokiniemi, PN, Kotila, and Kravvaris, in progress

^{16}N(2$^-$) Gamow-Teller transitions to the negative parity excited states of ^{16}O

- Tests of NCSM wave functions
  - B(GT)s overestimated – operator SRG, 2BC need to be included, continuum
  - Correct hierarchy of transitions

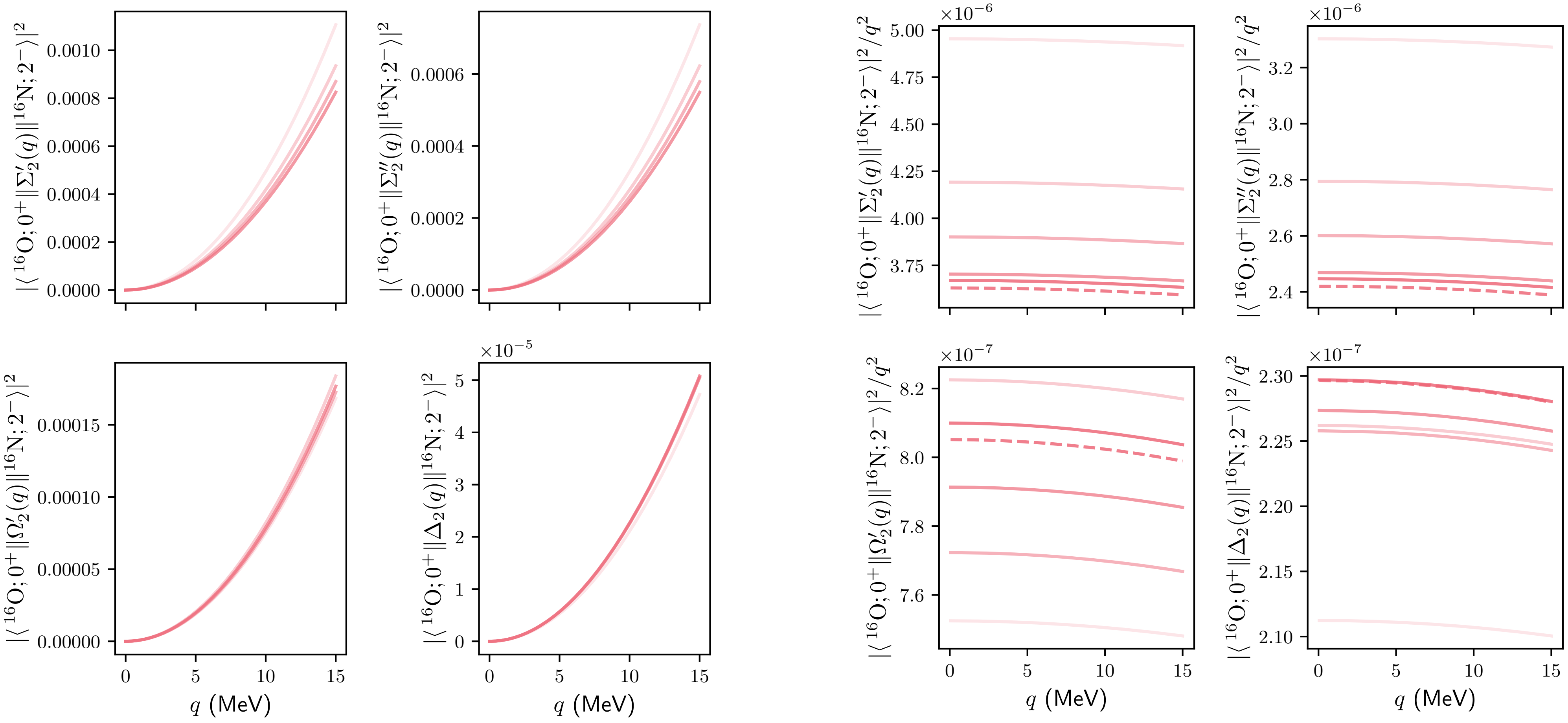




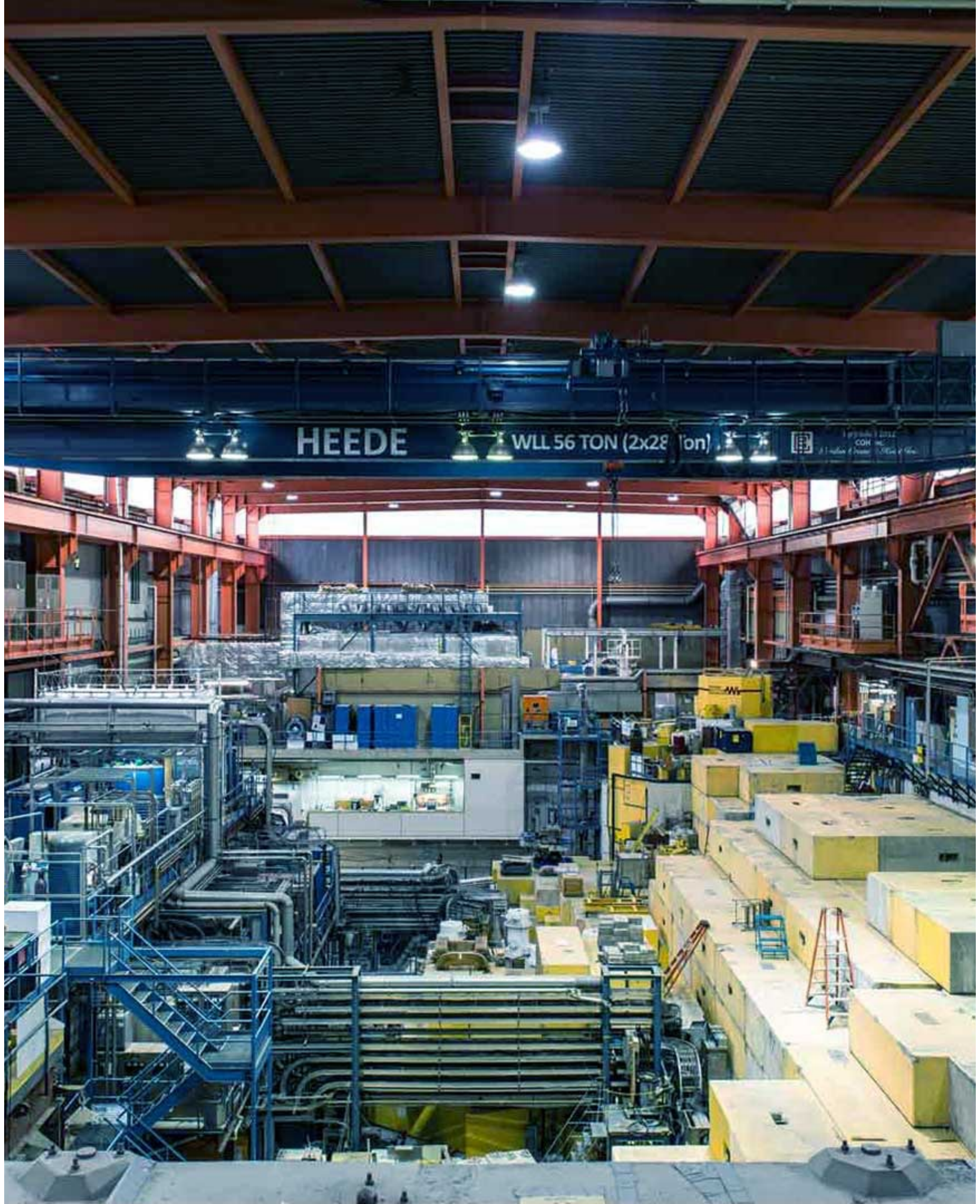
Unique first-forbidden beta decay $^{16}N(2^{-}) \rightarrow {}^{16}O(0^{+})$

- Basic operator matrix elements
  - NN-N^{3}LO+3N$_{\mathrm{lnl}}$ - N_{max} dependence, COM effect

Preliminary



Electroweak radiative corrections δ_{NS} and δ_C



V_{ud} element of CKM matrix

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}(\bar{u}_L, \bar{c}_L, \bar{t}_L)\gamma^\mu W_\mu^+ \boxed{V_{CKM}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + h.c.$$

- Precise V_{ud} from superallowed Fermi transitions

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

G_F ≡ Fermi coupling constant
determined from muon β decay

  - hadronic matrix elements modified by nuclear environment
  - Fermi matrix element renormalized by isospin non–conserving forces

$$\mathcal{F}t = ft(1+\delta_R')\underline{(1-\delta_C+\delta_{NS})}$$

$$\mathcal{F}t = \frac{K}{G_V^2 |M_{F0}|^2 (1+\Delta_R^V)}$$

Δ_R^V and δ_{NS}

Leptonic current

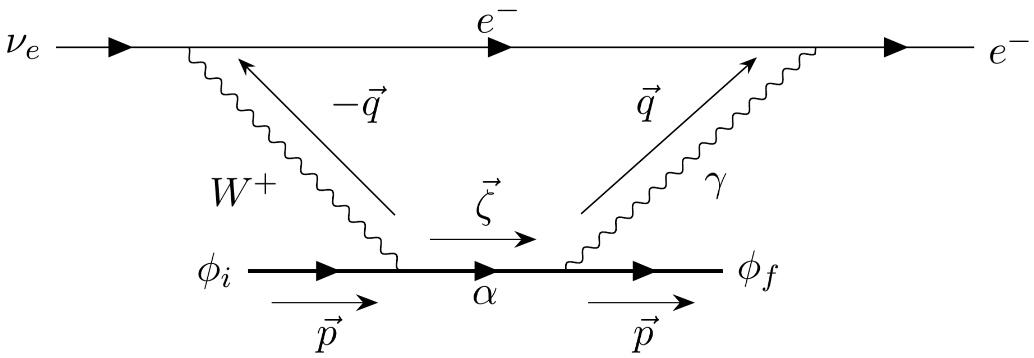
NME of charged weak current

- Tree level beta decay amplitude

$$M_{tree} = -\frac{G_F}{\sqrt{2}} L_\lambda F^\lambda(p', p)$$

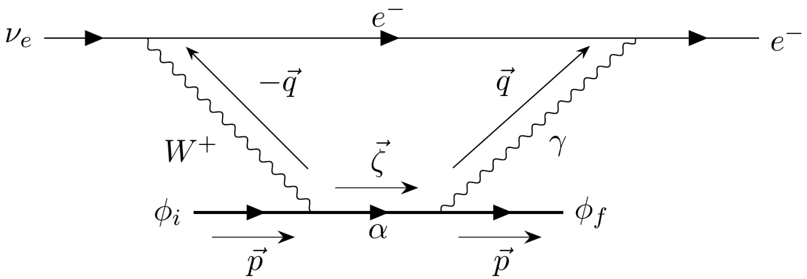
- Hadronic correction in forward scattering limit

$$\delta M = \Box_{\gamma W}(E_e) M_{tree}$$



$$\boxed{\Box^b_{\gamma W}(E_e) = \frac{e^2}{M}\int \frac{d^4q}{(2\pi)^4}\frac{M_W^2}{M_W^2 - q^2}\frac{1}{q^2 + i\epsilon}\frac{1}{(p_e - q)^2 + i\epsilon'}\frac{M\nu\left(\frac{p_e\cdot q}{p\cdot p_e}\right) - q^2}{\nu}\frac{T_3(\nu, |\vec{q}|)}{f_+(0)}}$$

Nonrelativistic Compton amplitude

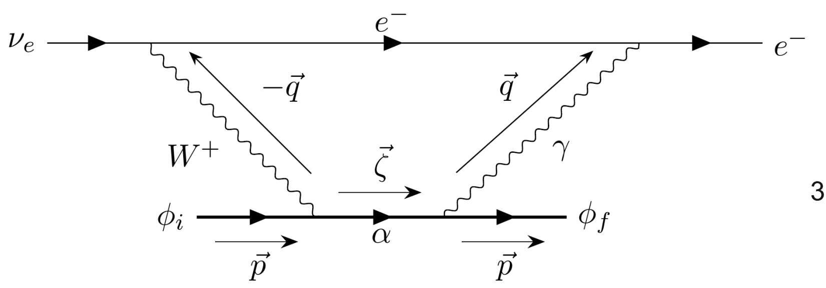


- **Goal**: Non-relativistic currents in momentum space
- Rewrite currents with A-body propagators
- Fourier transform currents into momentum space
- General multipole expansion of currents

$$T_3(\nu,|\vec{q}\,|) = 4\pi i \frac{\nu}{|\vec{q}\,|}\sqrt{M_i M_f}\sum_{J=1}^{\infty}(2J+1)\,\langle\Psi_f|\Big\{T^{\rm mag}_{J0}\,G(\nu+M_f+i\epsilon)\,T^{5,\rm el}_{J0} + T^{\rm el}_{J0}\,G(\nu+M_f+i\epsilon)\,T^{5,\rm mag}_{J0}$$
$$+\,T^{5,\rm mag}_{J0}\,G(-\nu+M_i+i\epsilon)\,T^{\rm el}_{J0} + T^{5,\rm el}_{J0}\,G(-\nu+M_i+i\epsilon)T^{\rm mag}_{J0}\Big\}(|\vec{q}\,|)\,|\Psi_i\rangle$$

NCSM calculations led by M. Gennari (UVic/TRIUMF PhD student)

Nonrelativistic Compton amplitude



- **Goal**: Non-relativistic currents in momentum space
- Rewrite currents with A-body propagators
- Fourier transform currents into momentum space
- General multipole expansion of currents

Lanczos continued fraction method to compute nuclear Green's functions

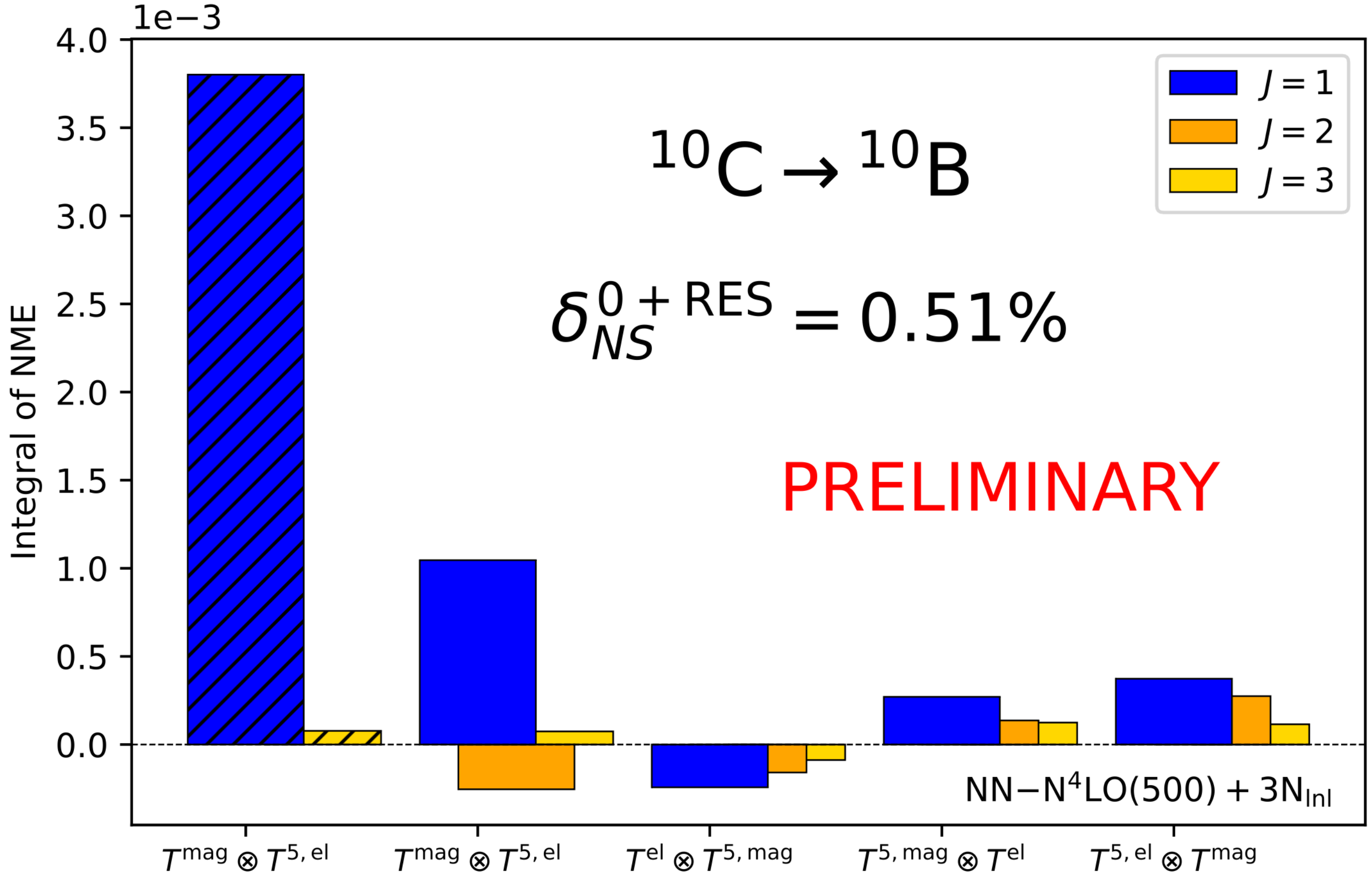
$$T_3(\nu,|\vec{q}\,|) = 4\pi i \frac{\nu}{|\vec{q}\,|}\sqrt{M_i M_f}\sum_{J=1}^{\infty}(2J+1)\langle\Psi_f|\Big\{T^{\mathrm{mag}}_{J0}\boxed{G(\nu+M_f+i\epsilon)}T^{5,\mathrm{el}}_{J0}+T^{\mathrm{el}}_{J0}\boxed{G(\nu+M_f+i\epsilon)}T^{5,\mathrm{mag}}_{J0}$$
$$+T^{5,\mathrm{mag}}_{J0}\boxed{G(-\nu+M_i+i\epsilon)}T^{\mathrm{el}}_{J0}+T^{5,\mathrm{el}}_{J0}\boxed{G(-\nu+M_i+i\epsilon)}T^{\mathrm{mag}}_{J0}\Big\}(|\vec{q}\,|)|\Psi_i\rangle$$

NCSM calculations led by M. Gennari (UVic/TRIUMF PhD student)

Preliminary δ_{NS} result at $N_{\max}$=3 and $N_{\max}$=5 still being double checked

Feasible to reach $N_{\max}$=11

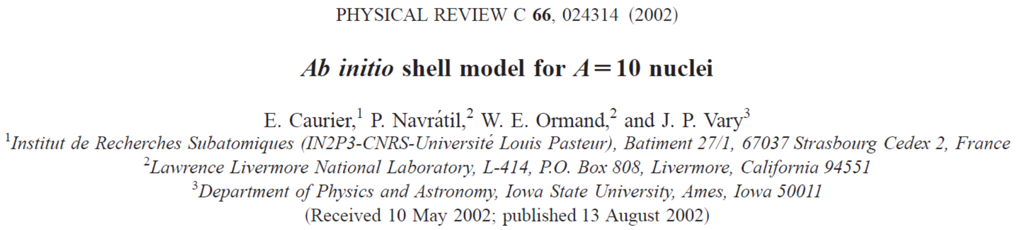
Towner & Hardy used δ_{NS} = -0.4



NCSM calculations led by M. Gennari (UVic/TRIUMF PhD student)

The pathway to δ_C

- δ_C in *ab initio* NCSM over 20 years ago

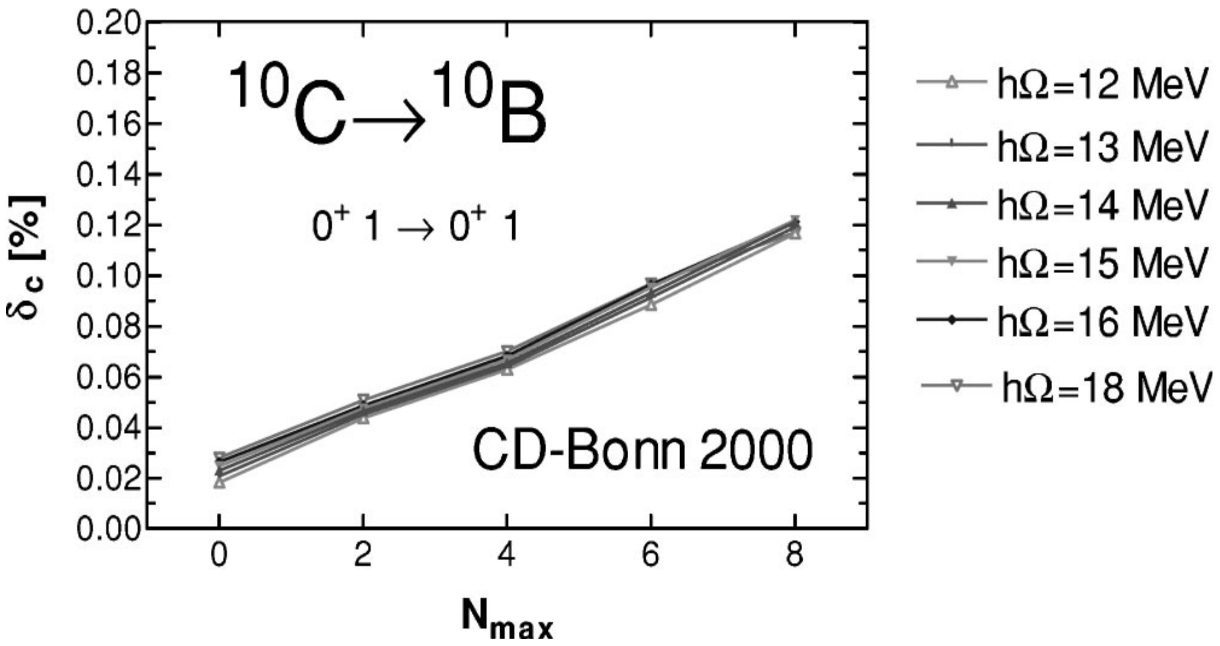


PHYSICAL REVIEW C **66**, 024314 (2002)

***Ab initio* shell model for $A=10$ nuclei**

E. Caurier,[1] P. Navrátil,[2] W. E. Ormand,[2] and J. P. Vary[3]
[1]*Institut de Recherches Subatomiques (IN2P3-CNRS-Université Louis Pasteur), Batiment 27/1, 67037 Strasbourg Cedex 2, France*
[2]*Lawrence Livermore National Laboratory, L-414, P.O. Box 808, Livermore, California 94551*
[3]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011*

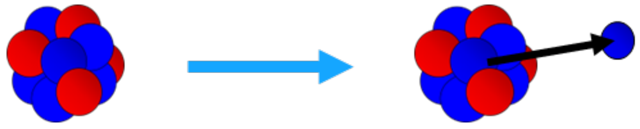
(Received 10 May 2002; published 13 August 2002)



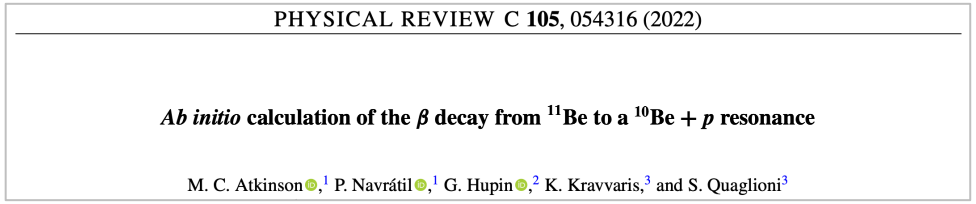
HO expansion incompatible with reaction theory

i. imprecise asymptotics
ii. missing correlations in excited states
iii. description of scattering not feasible

Combine NCSM with resonating group method (RGM)



δ_C 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 Fermi matrix element in NCSMC

$$M_F = \left\langle \Psi^{J^\pi T_f M_{T_f}} \middle| T_+ \middle| \Psi^{J^\pi T_i M_{T_i}} \right\rangle \xrightarrow{\qquad\qquad} |M_F|^2 = |M_{F0}|^2(1-\delta_C)$$

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

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

NCSM matrix element

NCSM-Cluster matrix elements

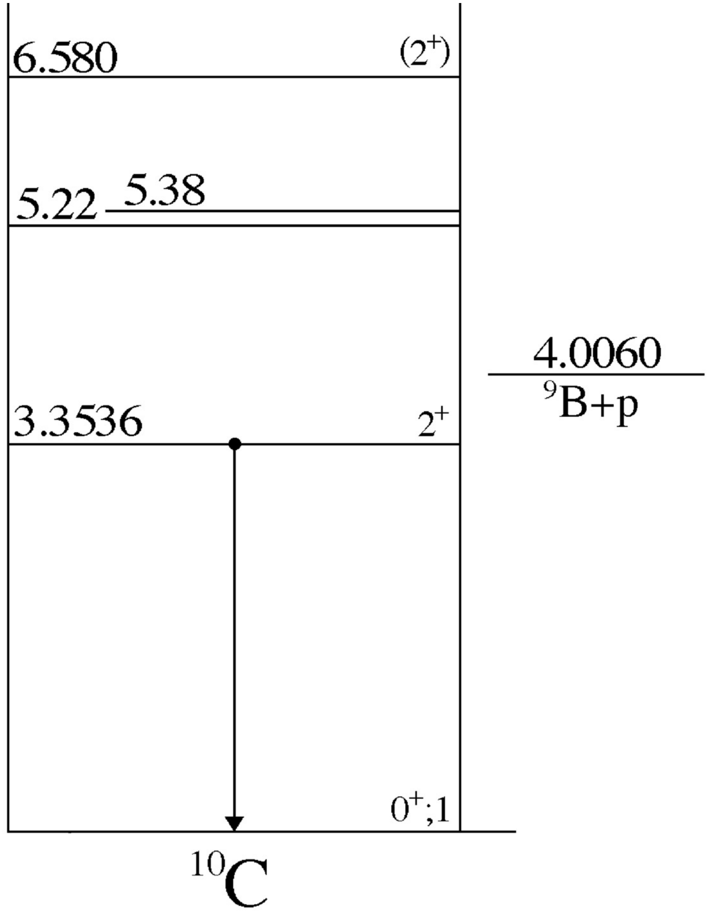
Continuum (cluster) matrix element

^{10}C structure from chiral EFT NN(N^{4}LO)+3N(N^{2}LO,lnl) interaction ($N_{max} = 9$)

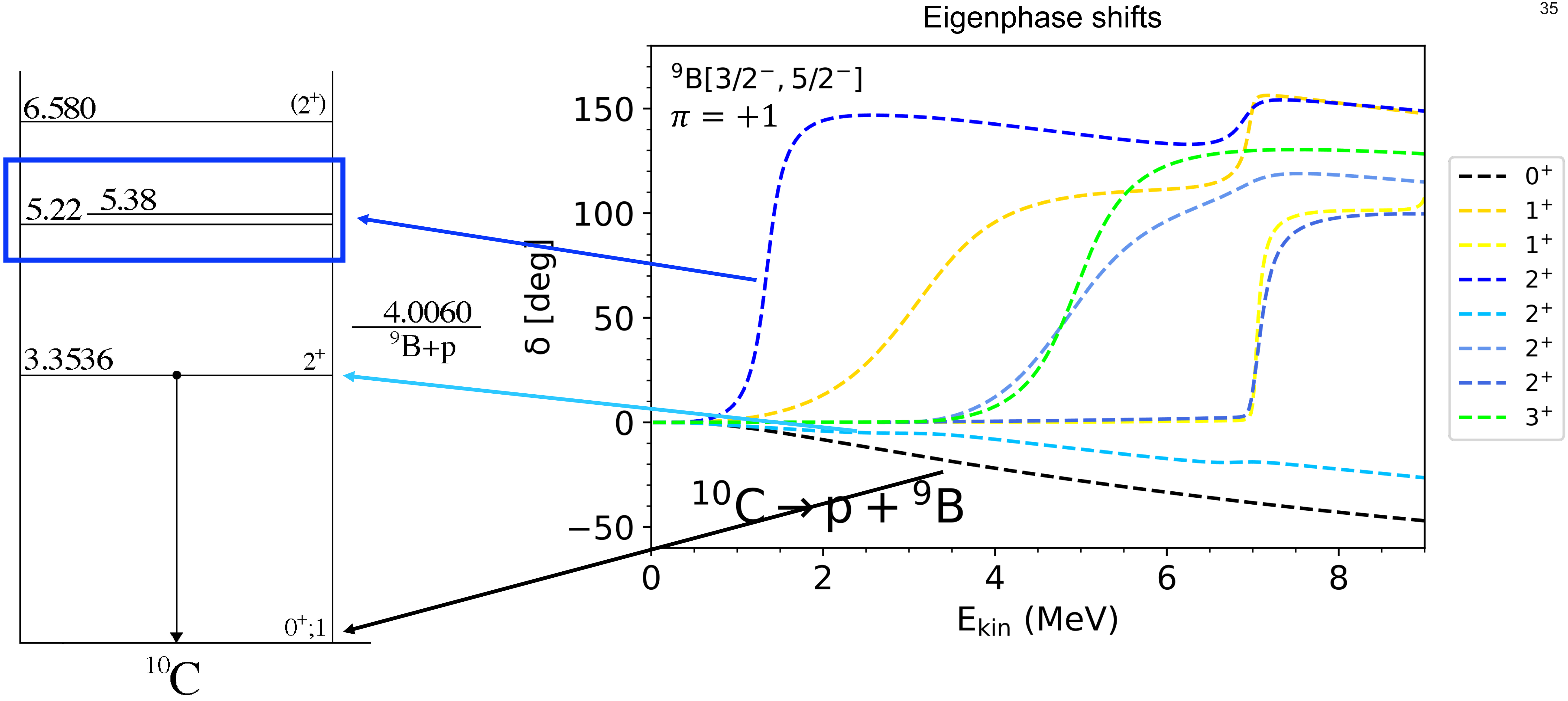
$$\left|{}^{10}\mathrm{C}\right\rangle = \sum_{\alpha} c_\alpha \left|{}^{10}\mathrm{C},\alpha\right\rangle_{\mathrm{NCSM}} + \sum_{\nu} \int dr\, \gamma_{\nu}^{J^\pi T}(r) \mathcal{A}_\nu \left|{}^{9}\mathrm{B}+\mathrm{p},\nu\right\rangle$$

- Treat as mass partition of proton plus ^{9}B
- Use $3/2^-$ and $5/2^-$ states of ^{9}B
- Known bound states captured by NCSMC

State	E_{NCSM} (MeV)	E (MeV)	E_{exp} (MeV)
0^+	-3.09	-3.46	-4.006
2^+	$+0.40$	-0.03	-0.652

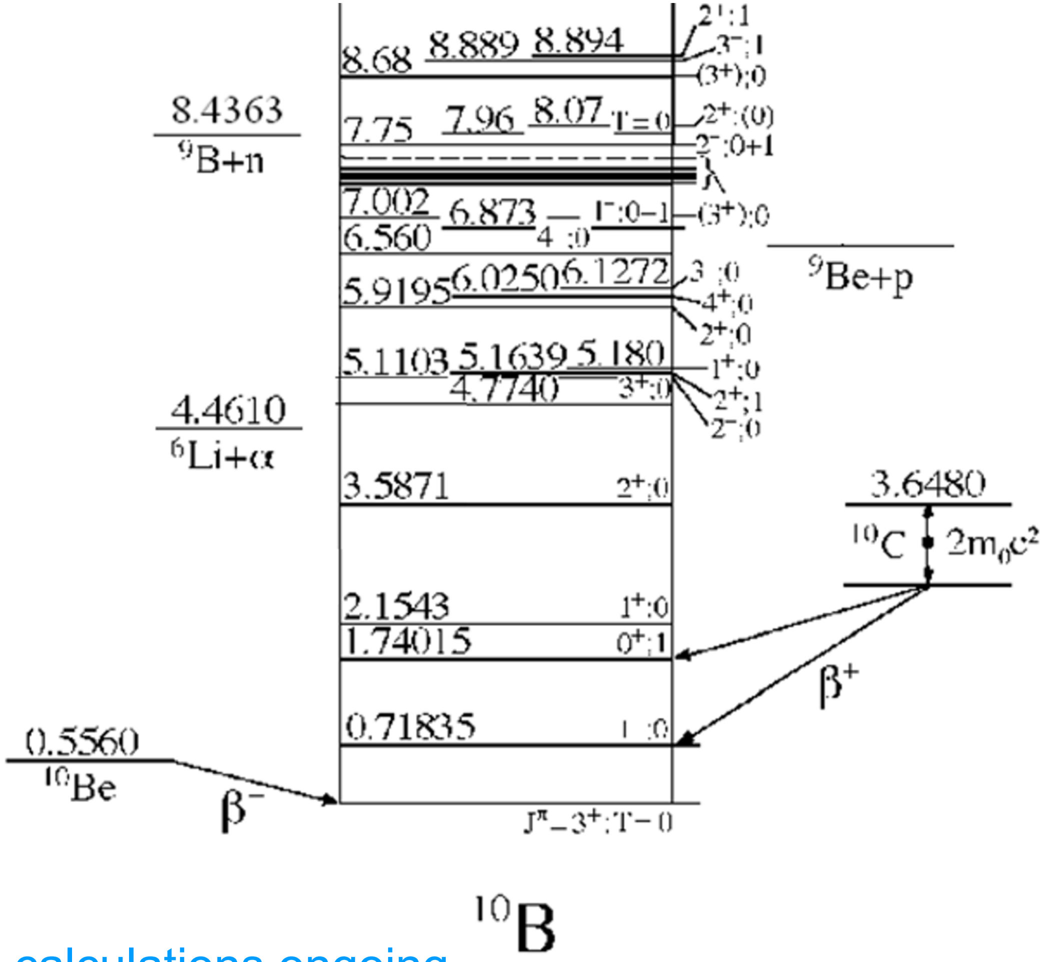


^{10}C structure from chiral EFT NN(N^{4}LO)+3N(N^{2}LO,lnl) interaction ($N_{max} = 9$)



^{10}B structure from chiral EFT NN(N^{4}LO)+3N(N^{2}LO,lnl) interaction ($N_{max} = 9$)

$$|^{10}\mathrm{B}\rangle = \sum_{\alpha} c_\alpha \,|^{10}\mathrm{B}, \alpha\rangle_{\mathrm{NCSM}} + \sum_{\nu} \int dr\, \gamma_\nu(r) \mathcal{A}_\nu \,|^{9}\mathrm{Be} + p, \nu\rangle + \sum_{\mu} \int dr\, \gamma_\mu(r) \mathcal{A}_\mu \,|^{9}\mathrm{B} + n, \mu\rangle$$

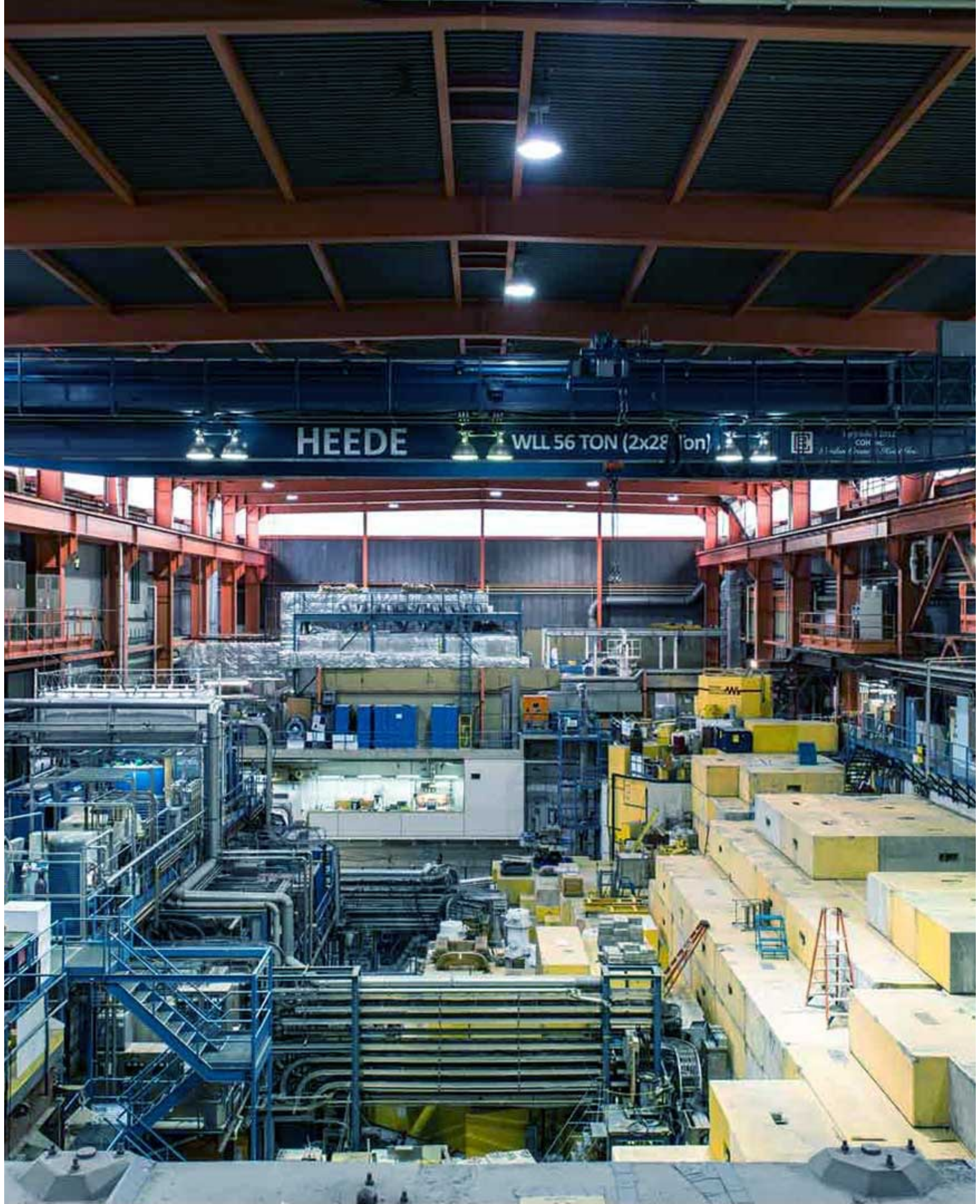


- Use $3/2^{-}$ and $5/2^{-}$ states of ^{9}B and ^{9}Be
- Eight of twelve bound states predicted

State	E (MeV)	E_{exp} (MeV)
3^+	-5.75	-6.5859
1^+	-5.33	-5.8676
0^+	-4.30	-4.8458
1^+	-4.26	-4.4316
2^+	-2.69	-2.9988
2^+	-0.93	-1.4220
2^+	-0.70	-0.6664
4^+	-0.19	-0.5609

δ_C calculations ongoing …

Parity-violating and time-reversal violating nuclear moments



Why investigate the anapole moment and the 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

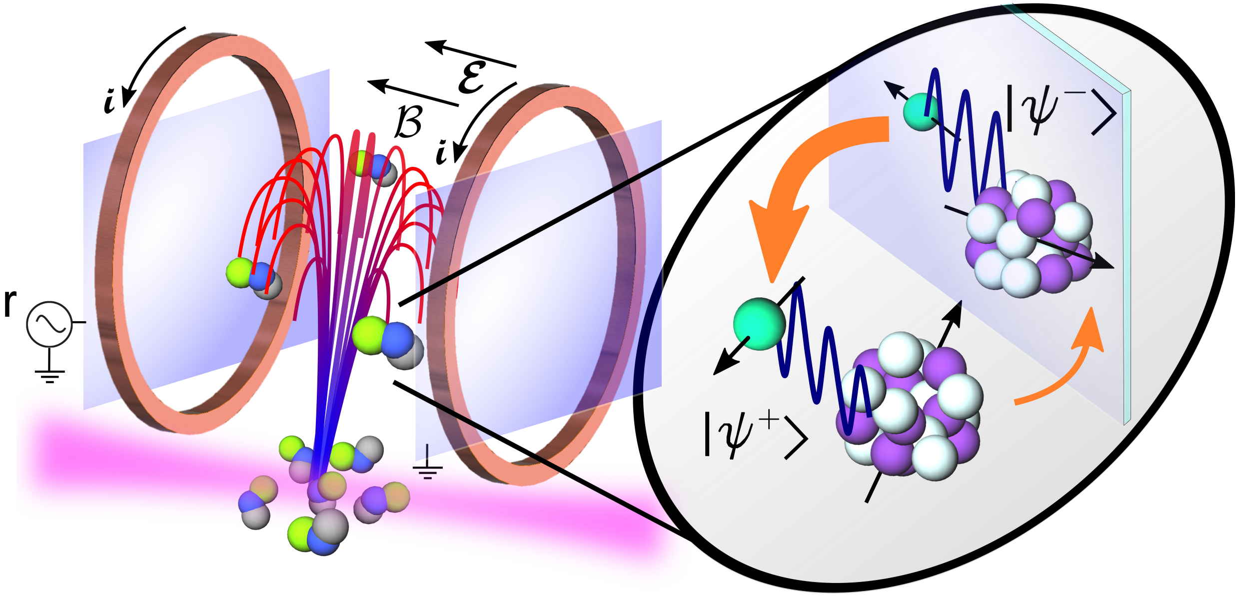
- The EDM is a promising probe for CP violation beyond the standard model as well as CP violating QCD $\bar{\theta}$ parameter
  - Nuclear structure can enhance the EDM
  - Nuclear EDMs can be measured in storage rings (CERN feasibility study: arXiv:1912.07881)

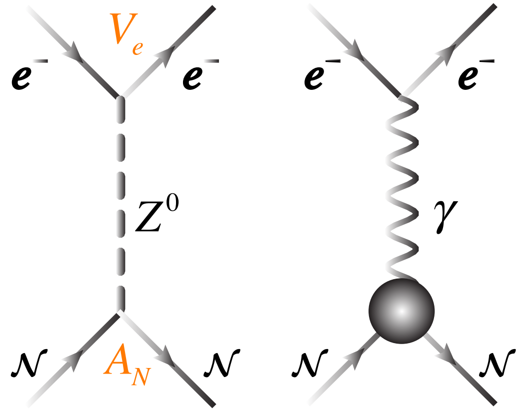
Nuclear spin dependent parity violating effects in light polyatomic molecules

- 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)





(b) (c)

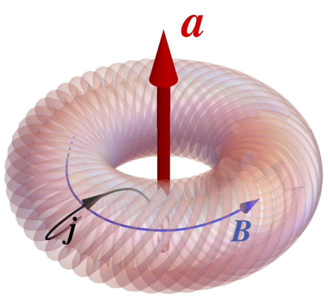
Parity violating nucleon-nucleon interaction and the nuclear anapole moment

- 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

$$|\psi_{\mathrm{gs}}\ I\rangle = |\psi_{\mathrm{gs}}\ I^{\pi}\rangle + \sum_j |\psi_j\ I^{-\pi}\rangle$$

$$\times \frac{1}{E_{\mathrm{gs}} - E_j}\langle\psi_j\ I^{-\pi}|V_{\mathrm{NN}}^{\mathrm{PNC}}|\psi_{\mathrm{gs}}\ I^{\pi}\rangle$$

- Anapole moment operator dominated by spin contribution



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

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

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

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

- Here is what we want to calculate:

$$\kappa_A = \frac{\sqrt{2}e}{G_F}a_s$$

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

Parity violating nucleon-nucleon interaction and the nuclear anapole moment

- Parity violating (non-conserving) V_{NN}^{PNC} interaction
  - Conserves total angular momentum *I*
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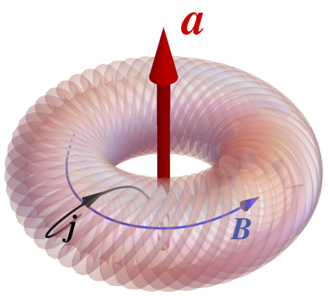
$$\times \frac{1}{E_{\rm gs}-E_j}\langle\psi_j\ I^{-\pi}|V_{\rm NN}^{\rm PNC}|\psi_{\rm gs}\ I^{\pi}\rangle$$

Lanczos continued fraction method to compute nuclear Green's function

- Anapole moment operator dominated by spin contribution



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

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

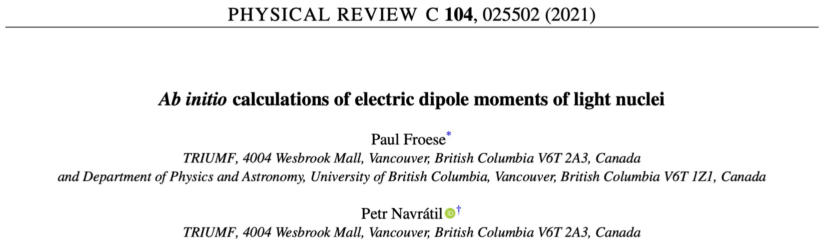
$$\mu_i{=}\mu_p(1/2{+}t_{z,i}) + \mu_n(1/2{-}t_{z,i})$$

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

- Here is what we want to calculate:

$$\kappa_A = \frac{\sqrt{2}e}{G_F}a_s$$

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


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

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

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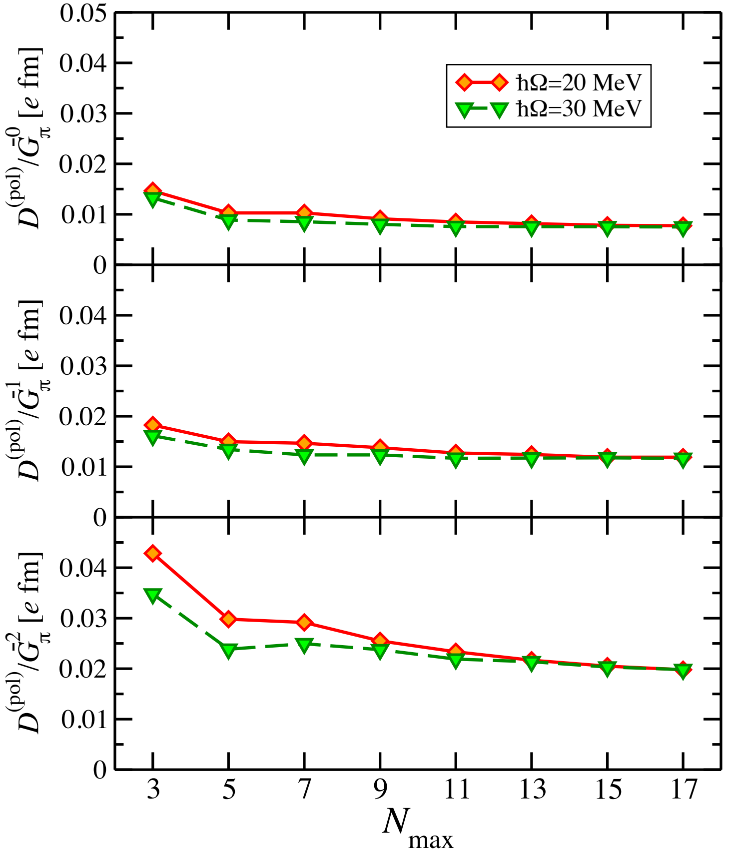
^{3}He EDM Benchmark Calculation

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 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

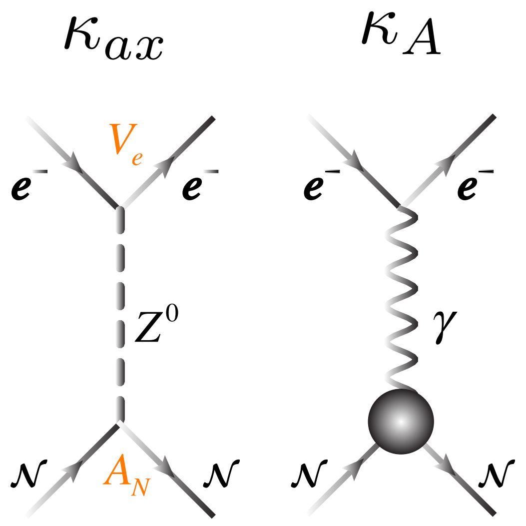
- Contributions from nucleon axial-vector and the anapole moment

	^{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

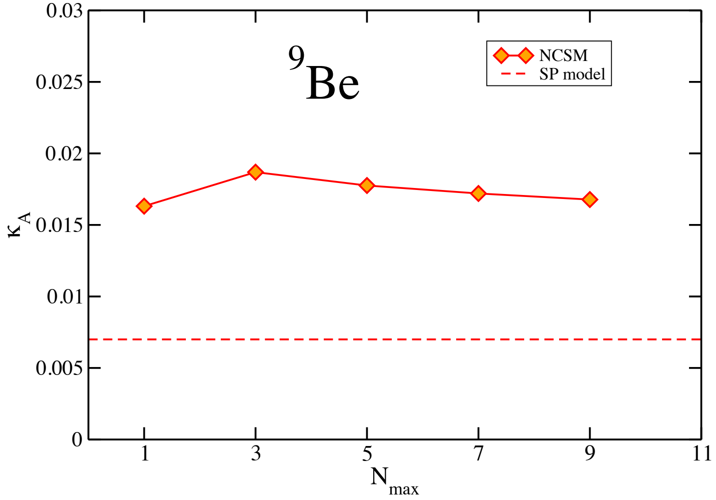
$$\kappa_{ax} \simeq -2C_{2p}\langle s_{p,z}\rangle - 2C_{2n}\langle s_{n,z}\rangle \simeq -0.1\langle s_{p,z}\rangle + 0.1\langle s_{n,z}\rangle$$

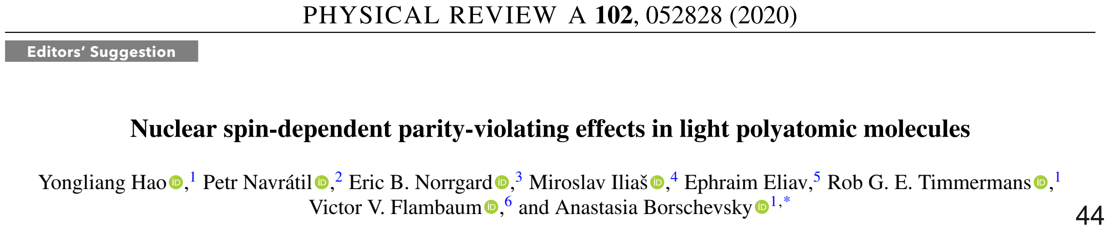
$$\langle s_{\nu,z}\rangle \equiv \langle \psi_{\text{gs}}\ I^\pi I_z{=}I|\hat{s}_{\nu,z}|\psi_{\text{gs}}\ I^\pi I_z{=}I\rangle$$

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



(b) (c)





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

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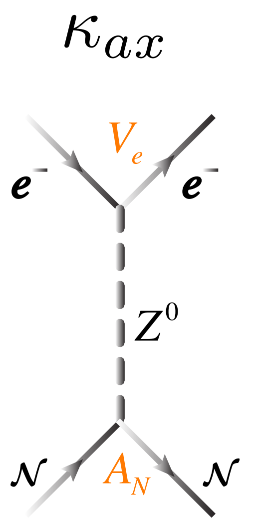
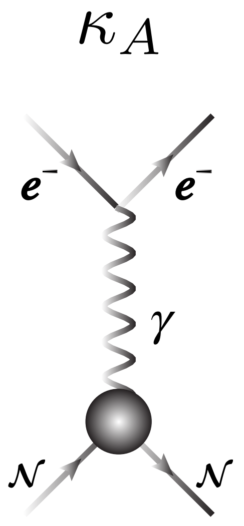
κ_{ax}	0.035	-0.009	0.0002	0.015	0.024
κ	0.050	-0.037	0.037	0.103	0.057

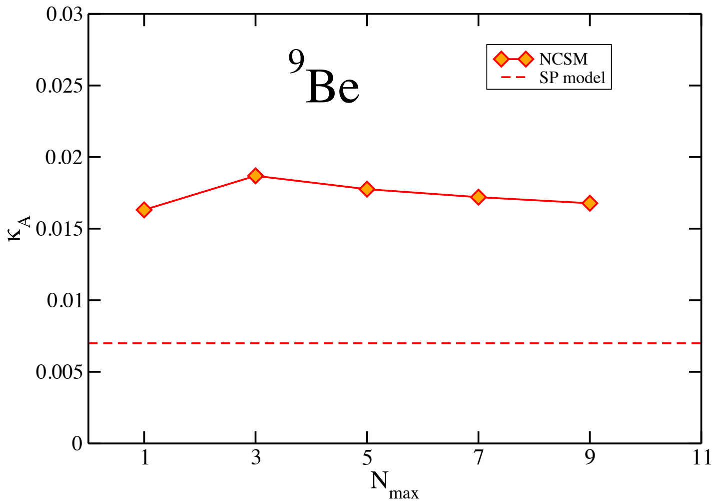
Expecting a significant enhancement of the anapole moment for ^{11}Be



(b)



(c)



Calculated EDMs of selected stable nuclei

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

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

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and Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada

Petr Navrátil[†]
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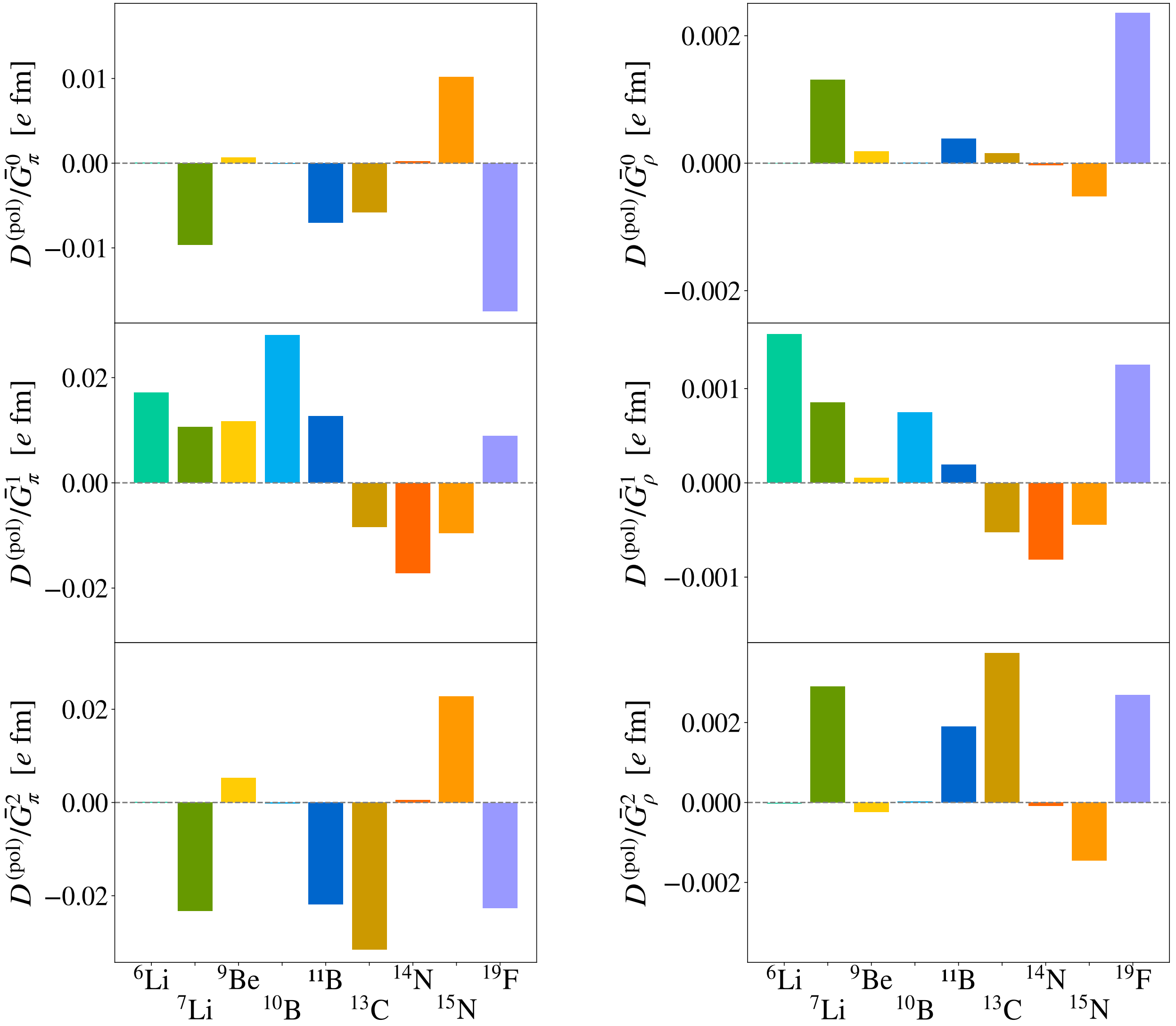
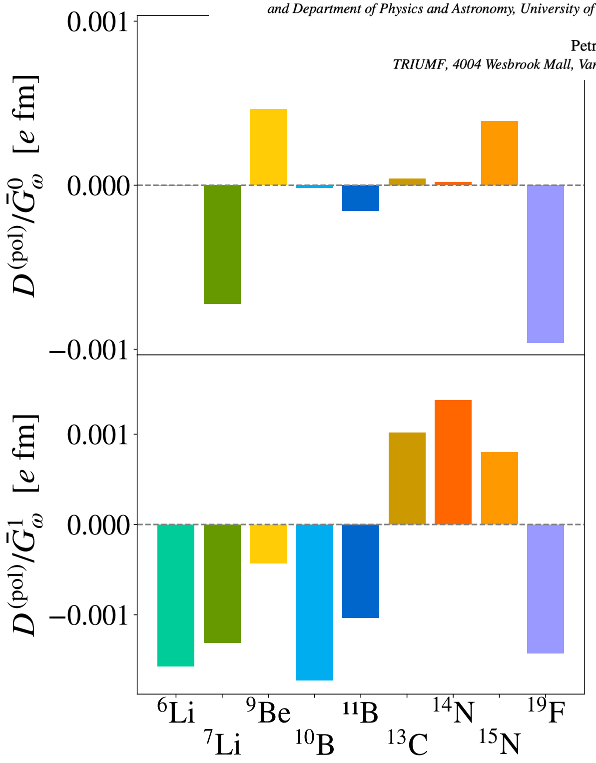
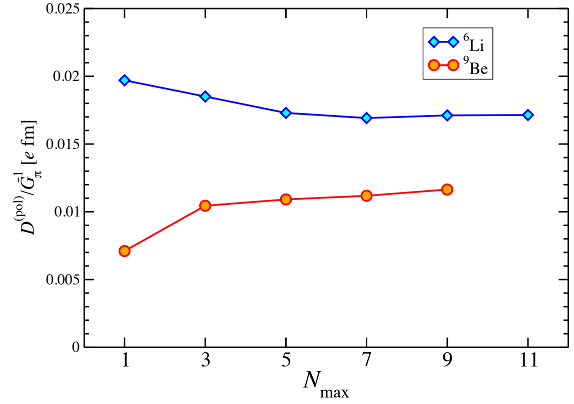
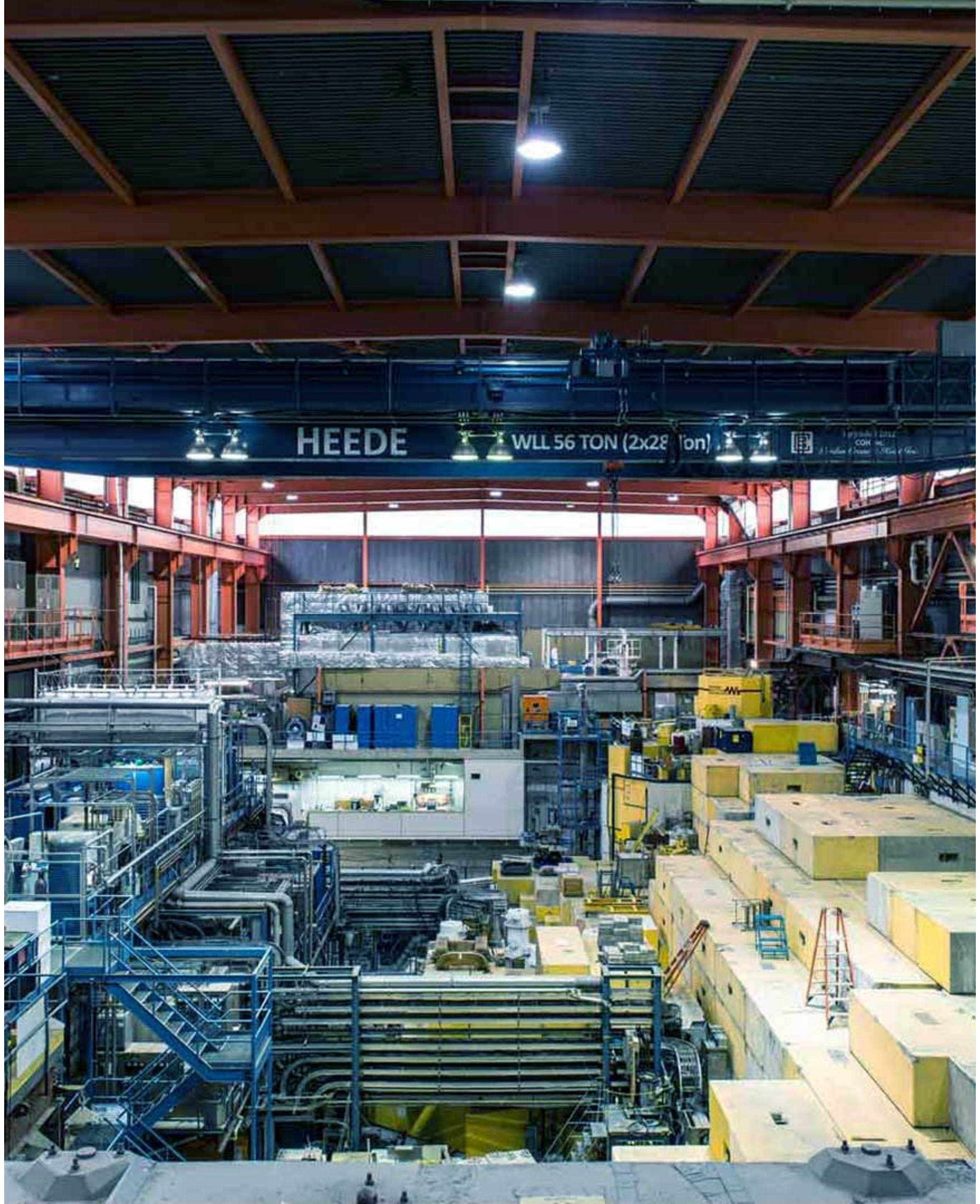



Examples of N$_{max}$ convergence

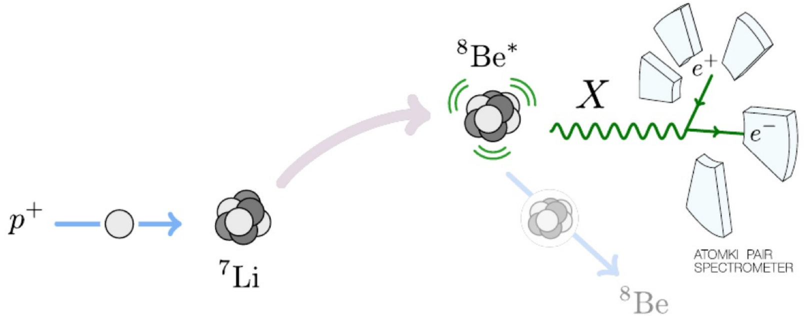


Proton capture on ^{7}Li and the hypothetical X17 boson



X17 Anomaly

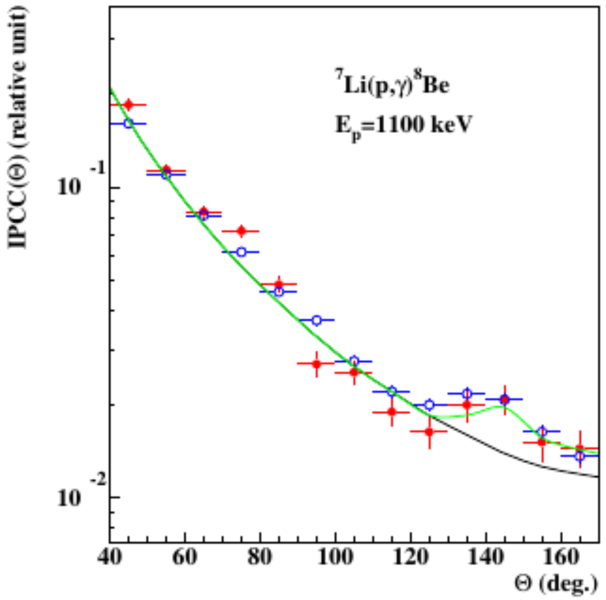
Phys. Rev. Lett. **116**, 042501 (2016) – ^{7}Li+p -> ^{8}Be
Phys. Rev. C **104**, 044003 (2021) – ^{3}H+p -> ^{4}He
Phys. Rev. C **106**, L061601 (2022) – ^{11}B+p ->^{12}C

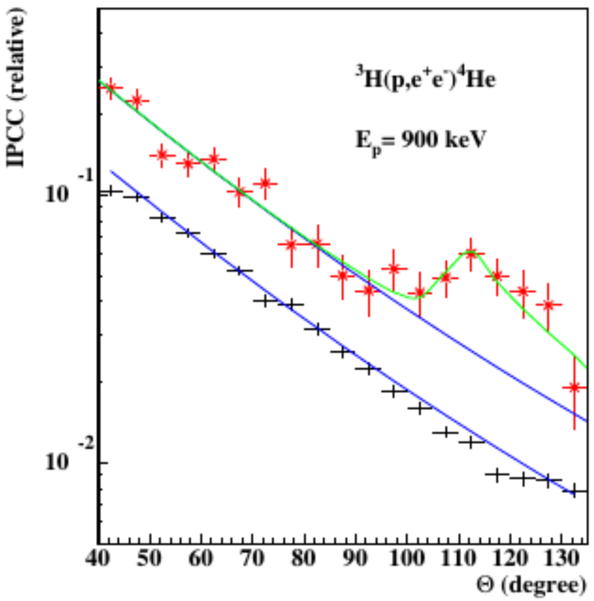


Feng PRD **95**, 035017 (2017)

"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

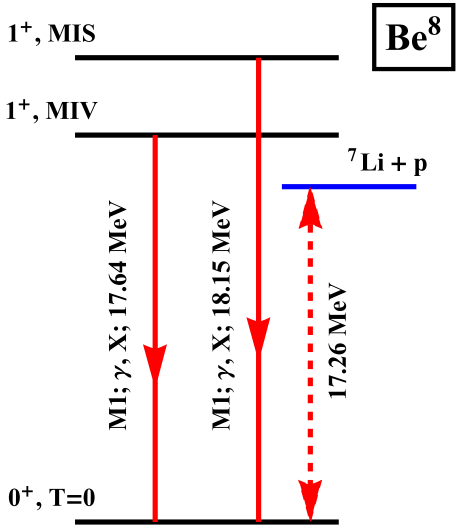


Fig. from PLB 813, 136061 (2021)

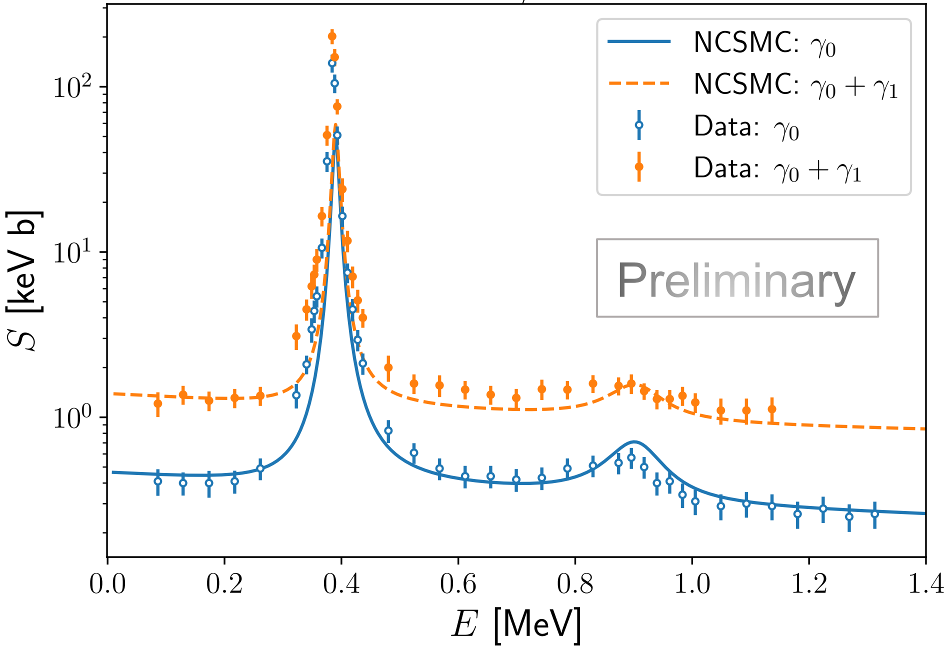
Can *ab initio* nuclear theory help interpret the anomaly?

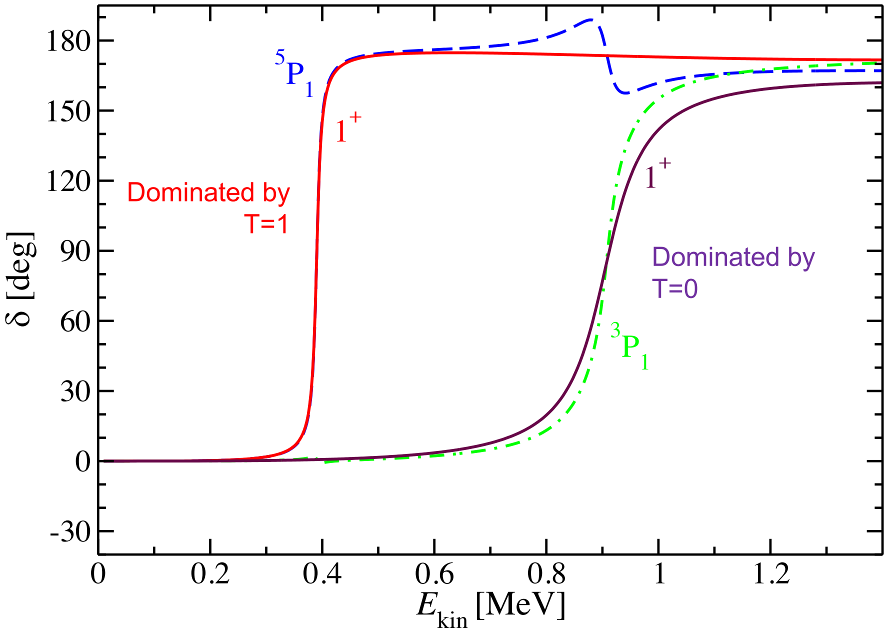
Ab initio calculations of ^{7}Li(p,γ)^{8}Be radiative capture, ^{7}Li(p,e$^+$e$^-$)^{8}Be pair production & X17 boson

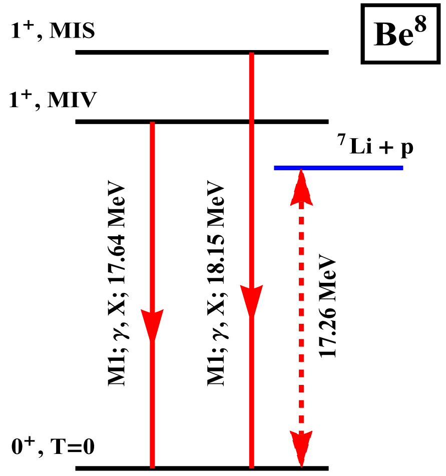
- Motivated by ATOMKI experiments (Firak, Krasznahorkay *et al.*, EPJ Web of Conferences **232**, 04005 (2020))
- No-core shell model with continuum (NCSMC) with wave function ansatz

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

S-factor $({}^7\text{Li}_{3/2^-}(p,\gamma)^8\text{Be})$







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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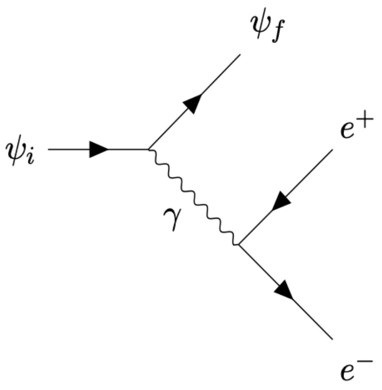
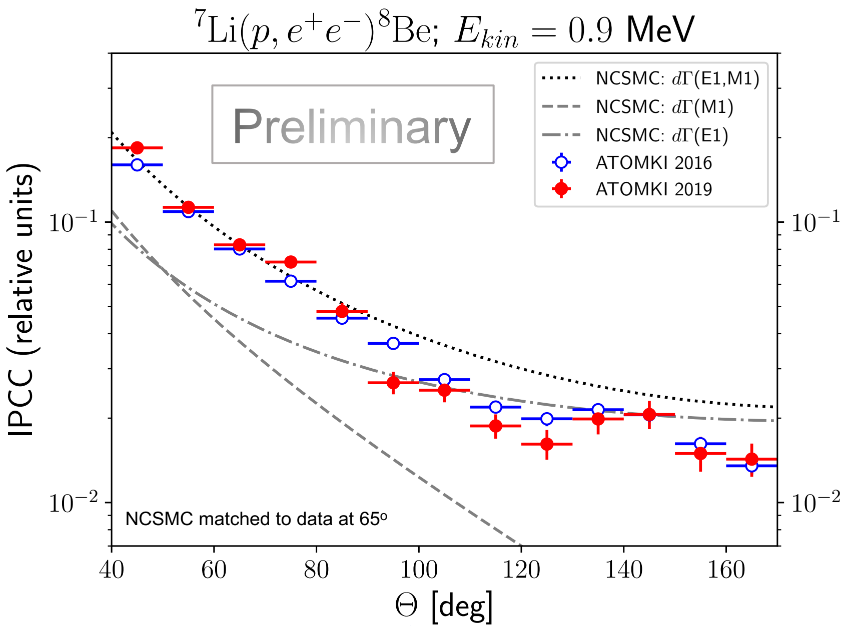
Internal electron-positron pair conversion correlation

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$^+$

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

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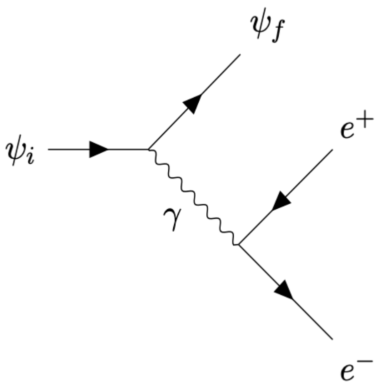

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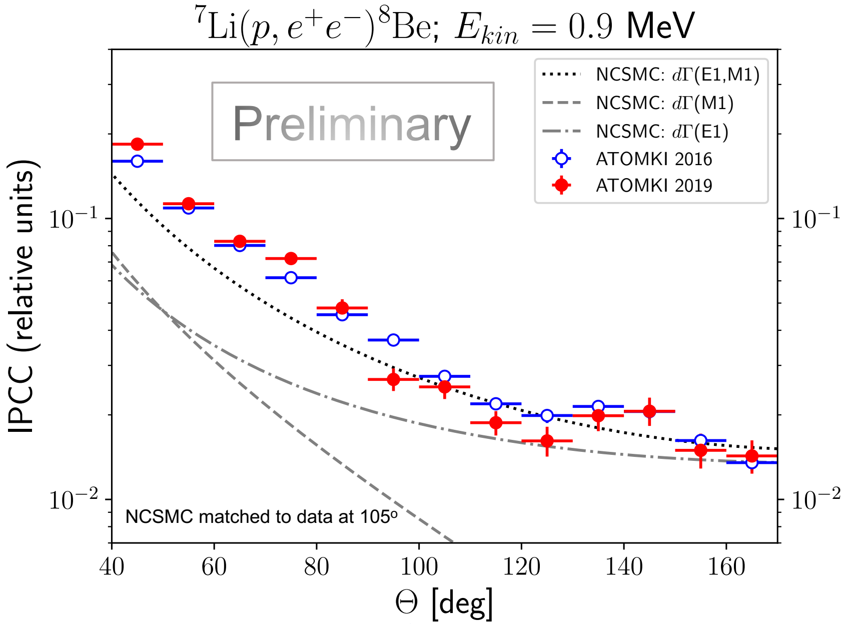

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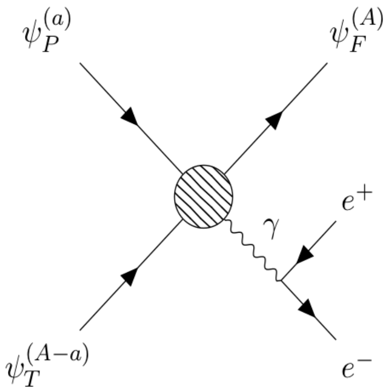
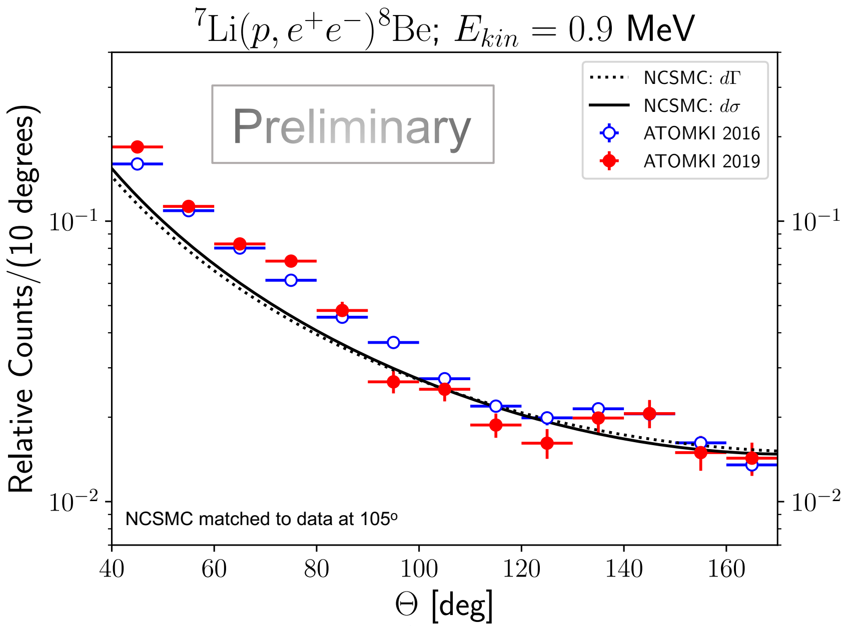
Internal electron-positron pair conversion correlation

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

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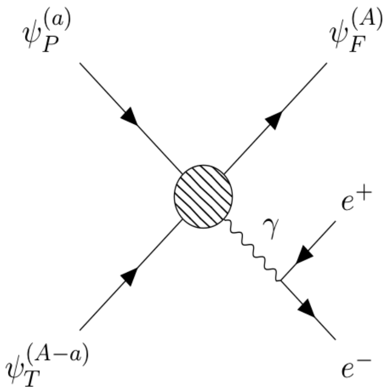

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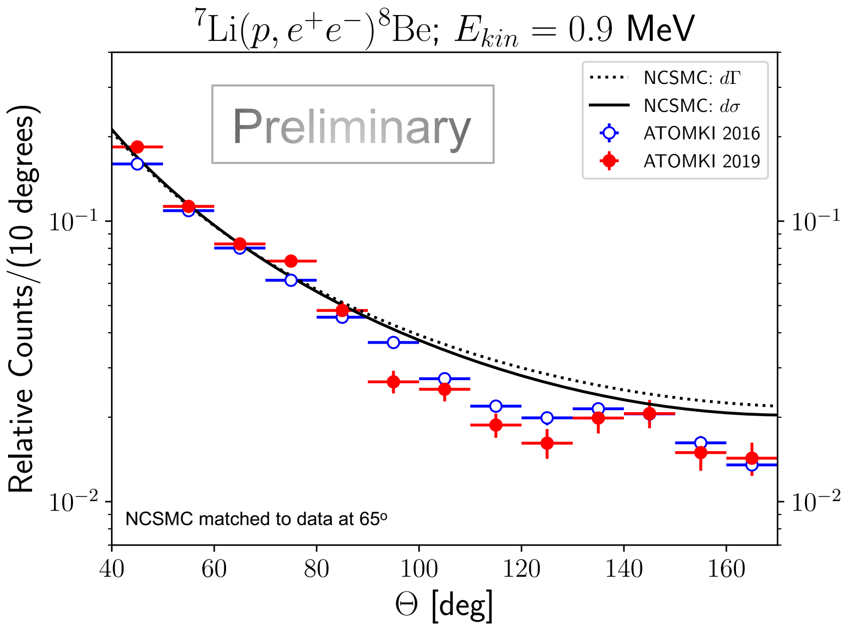

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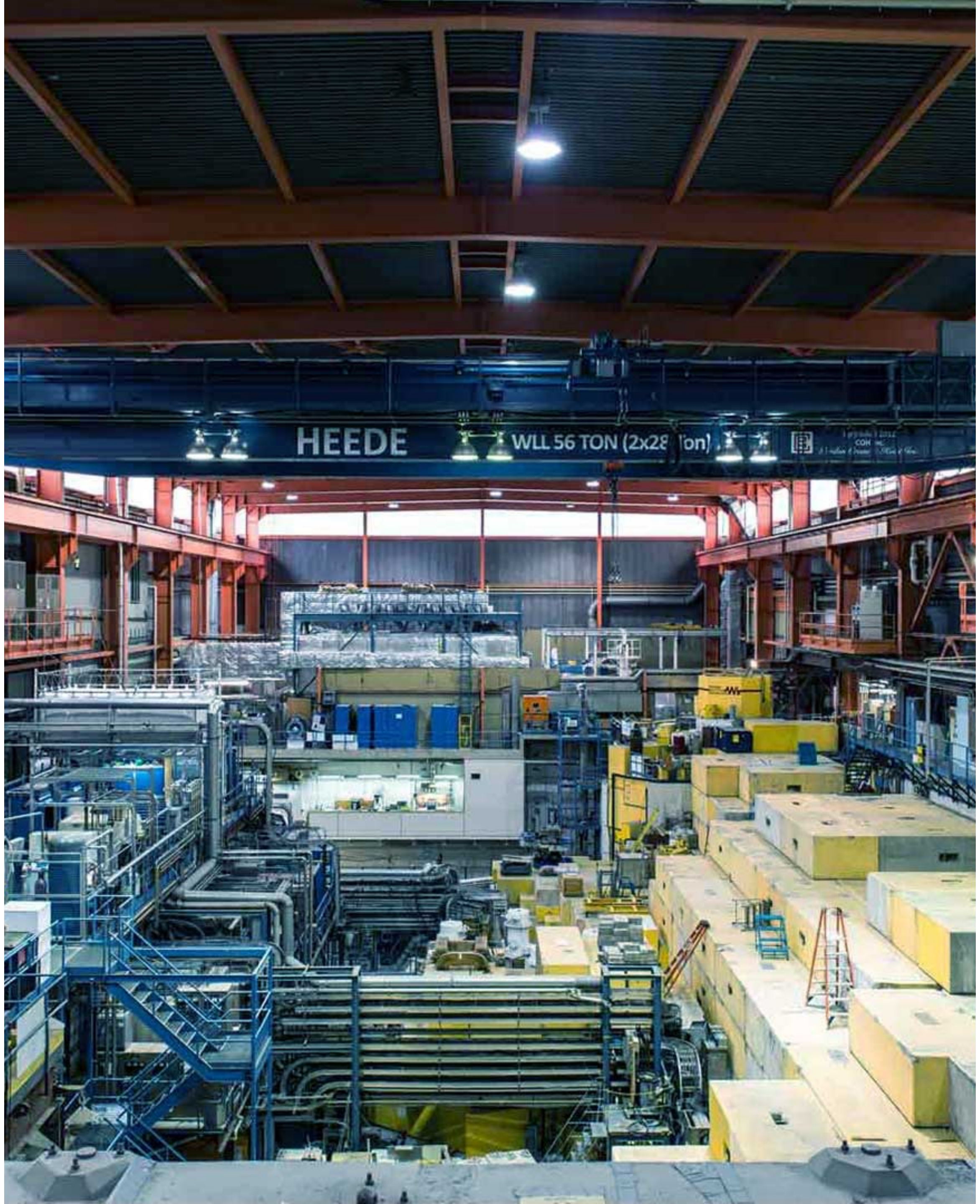
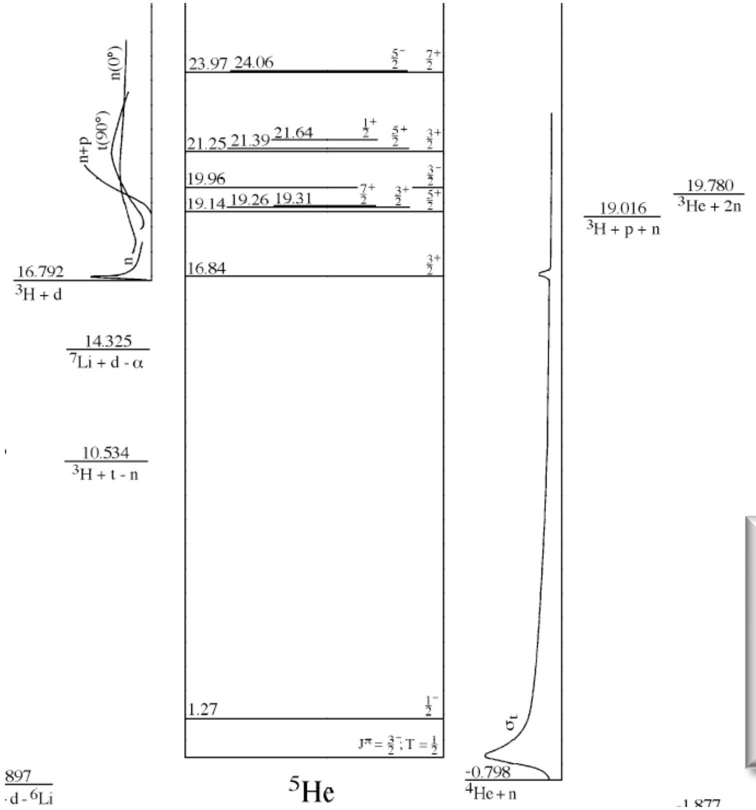
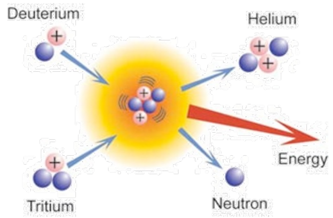
Nuclear structure:
Resonances close to threshold

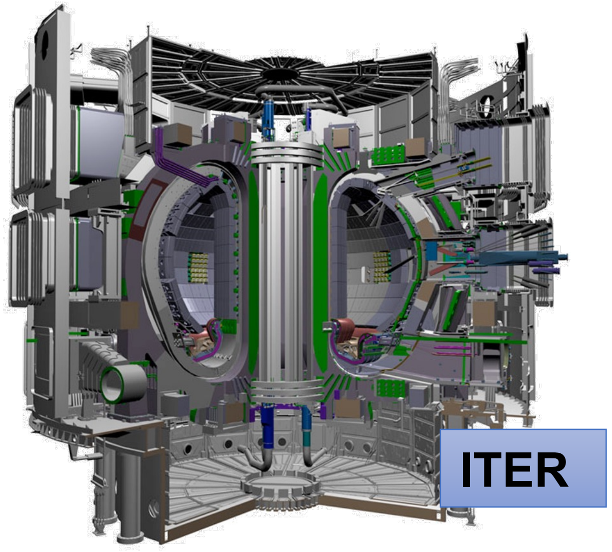


Deuterium-Tritium fusion

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





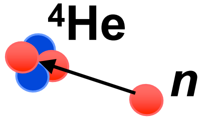


Resonance at E_{cm} =48 keV (E_d=105 keV) in the J=3/2$^+$ channel
Cross section at the peak: 4.88 b

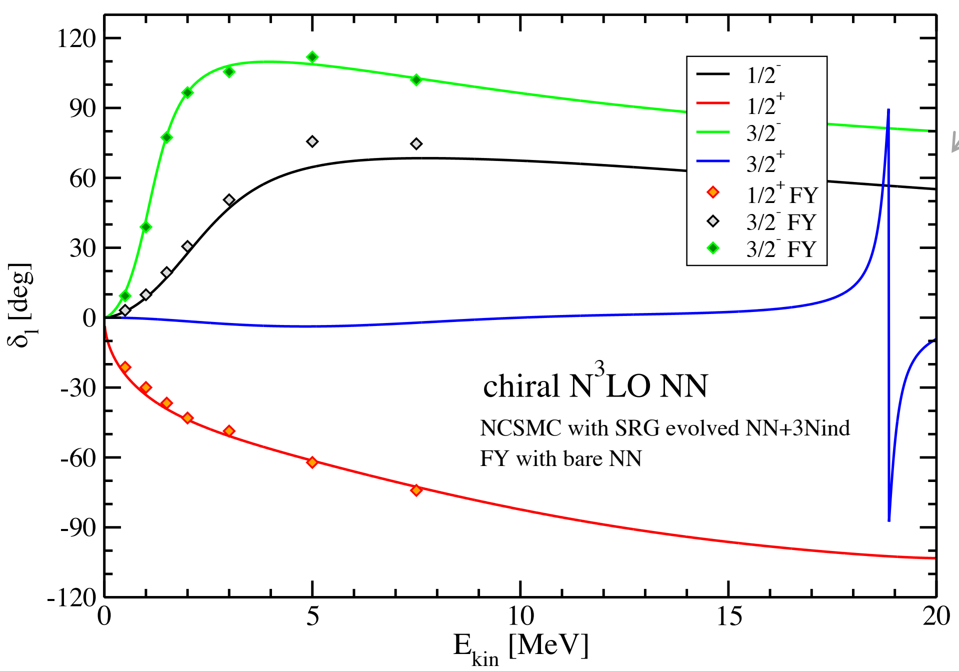
17.64 MeV energy released:
14.1 MeV neutron and 3.5 MeV alpha

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

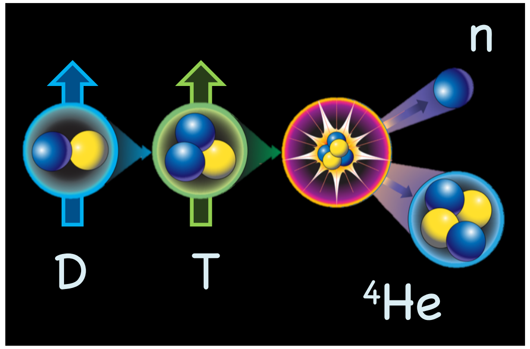
n-^{4}He and *d*+^{3}H scattering phase-shifts



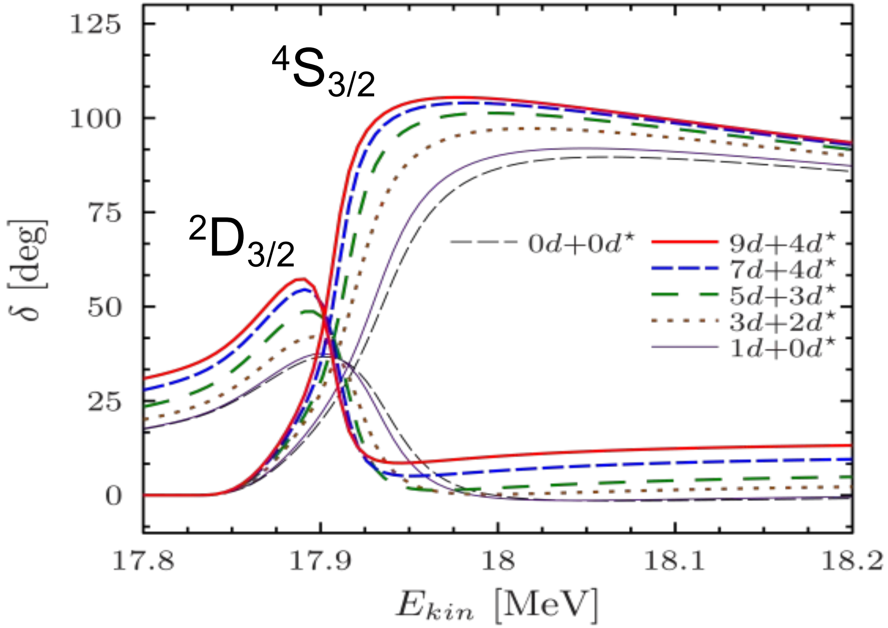
^{4}He+n



FY: Faddeev-Yakubovsky method - Rimantas Lazauskas

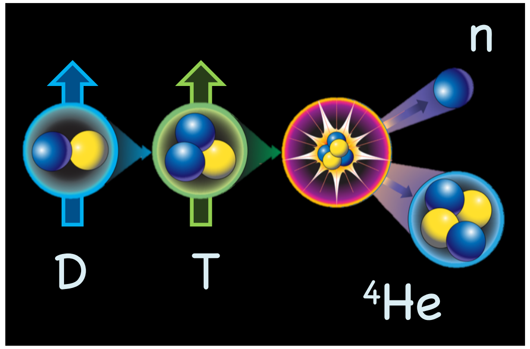


^{4}He+n -> ^{3}H+d

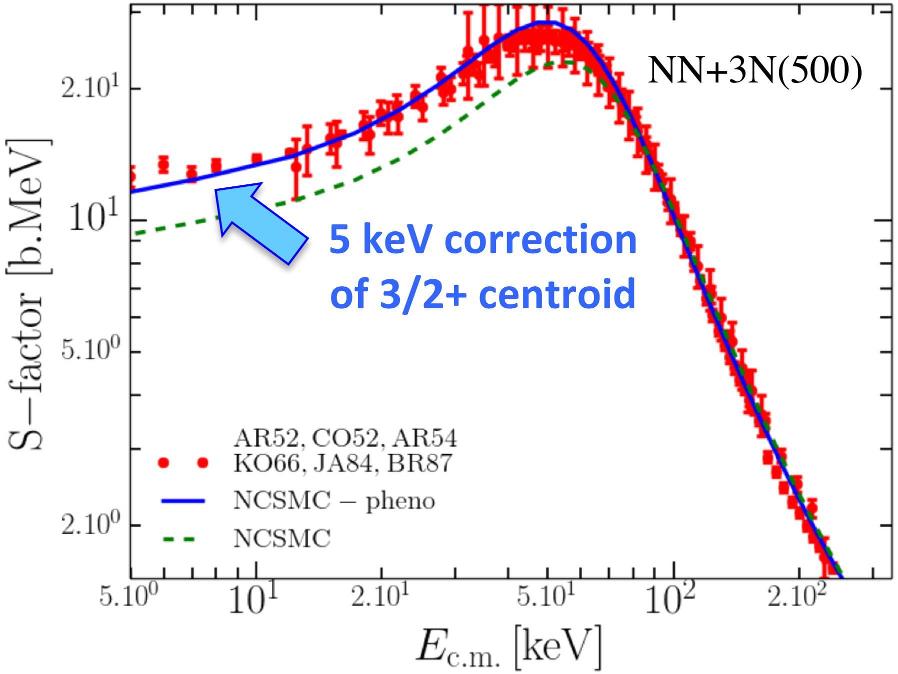


The *d*-^{3}H fusion takes place through a transition of *d*+^{3}H is *S*-wave to *n*+^{4}He in *D*-wave: Importance of the **tensor and 3N force**

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



Astrophysical S-factor



5 keV correction of 3/2+ centroid

Fusion cross section

Astrophysical S-factor: nuclear contribution

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

'Coulomb' Contribution (tunneling)

nature COMMUNICATIONS

ARTICLE

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

Ab initio predictions for polarized deuterium-tritium thermonuclear fusion

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

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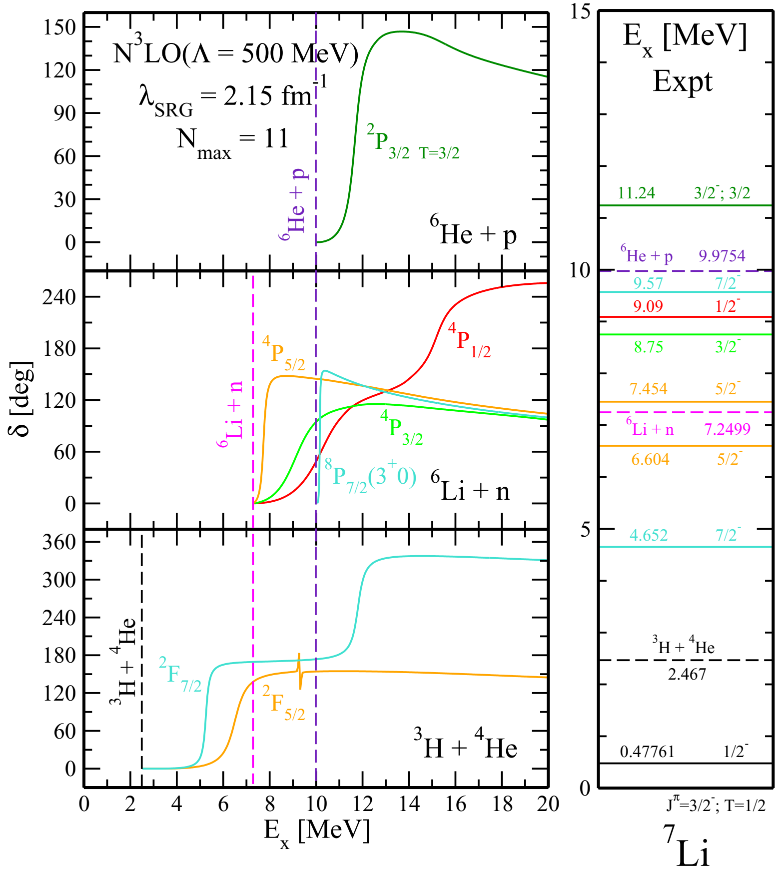
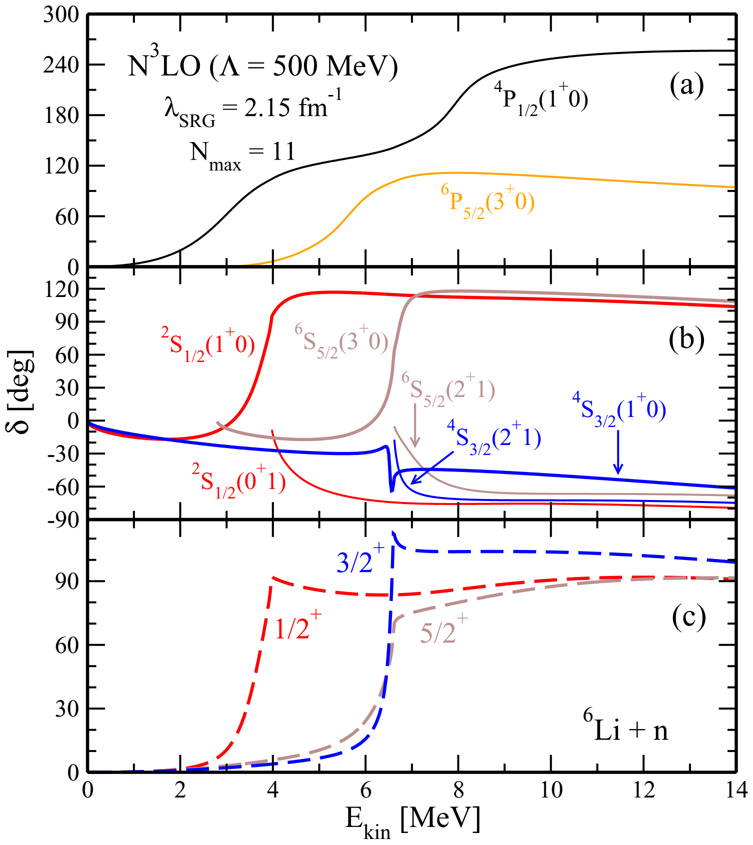
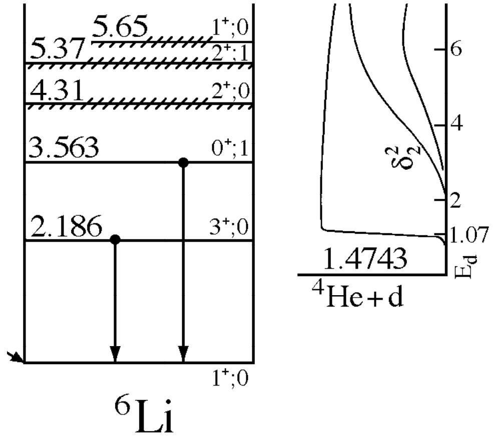
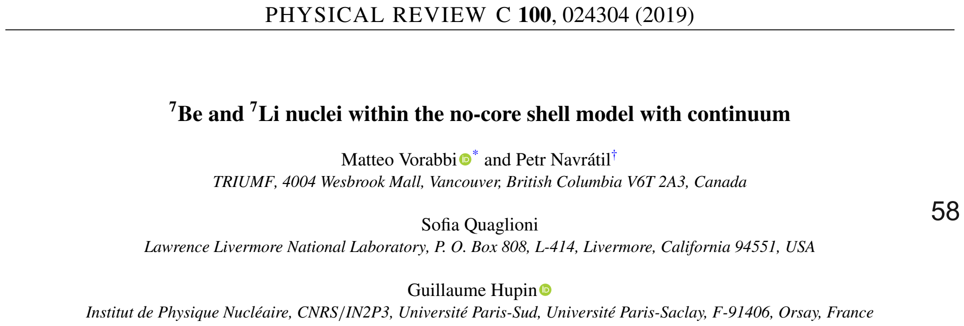
S-wave resonance close to the threshold of ^{6}He+p?

- 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








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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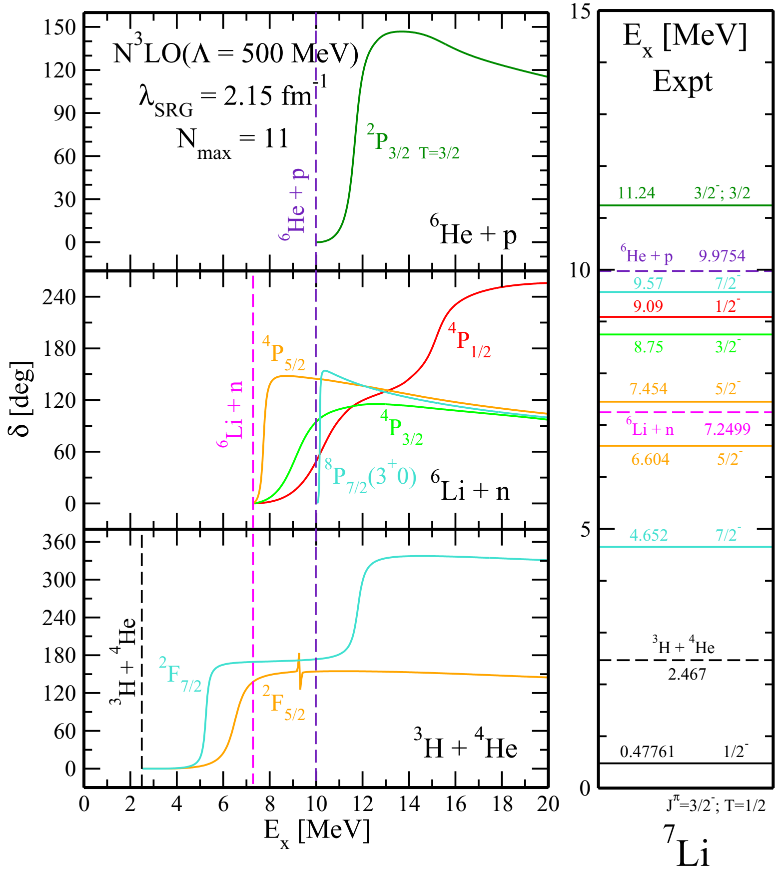
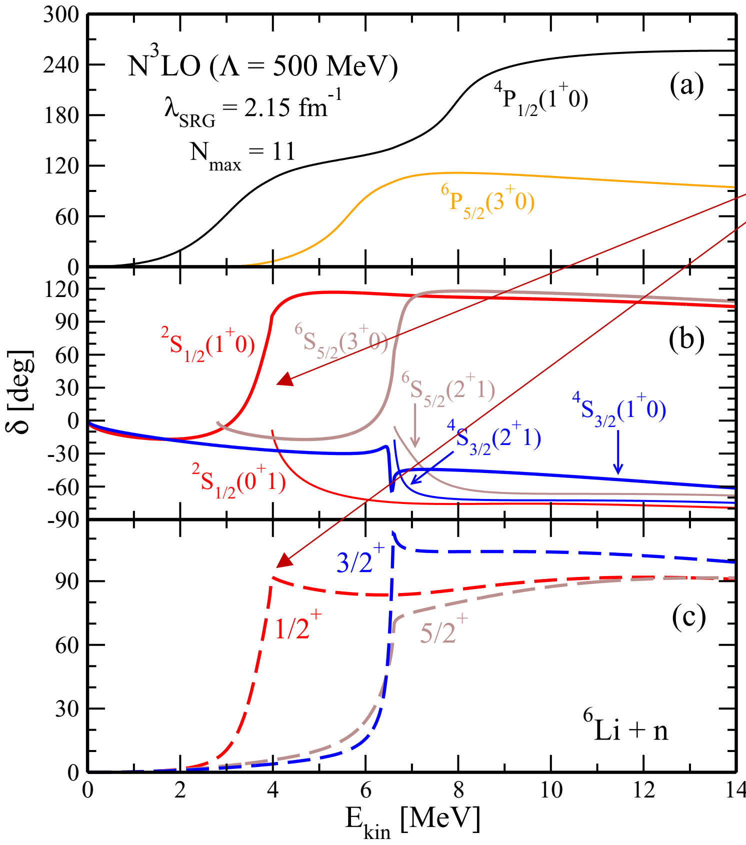
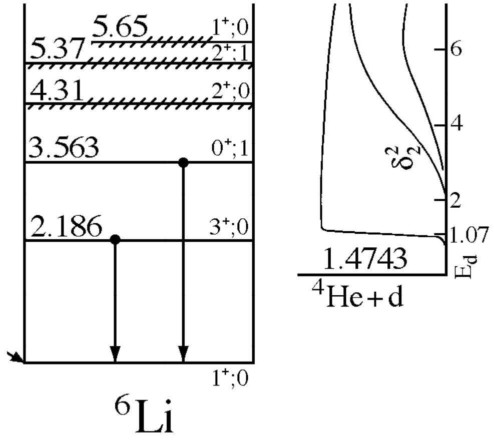




S-wave resonance



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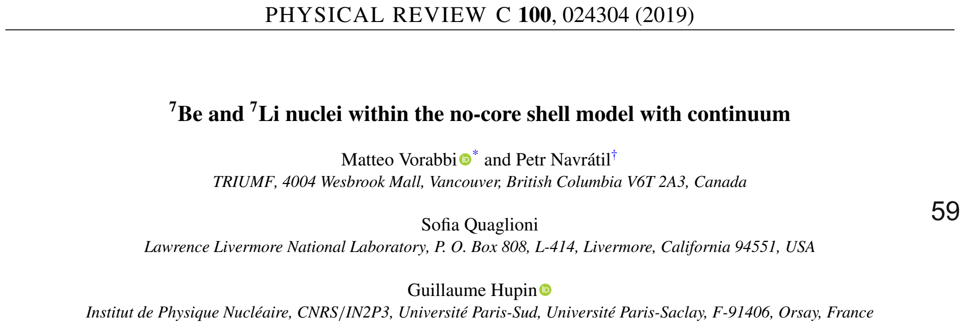
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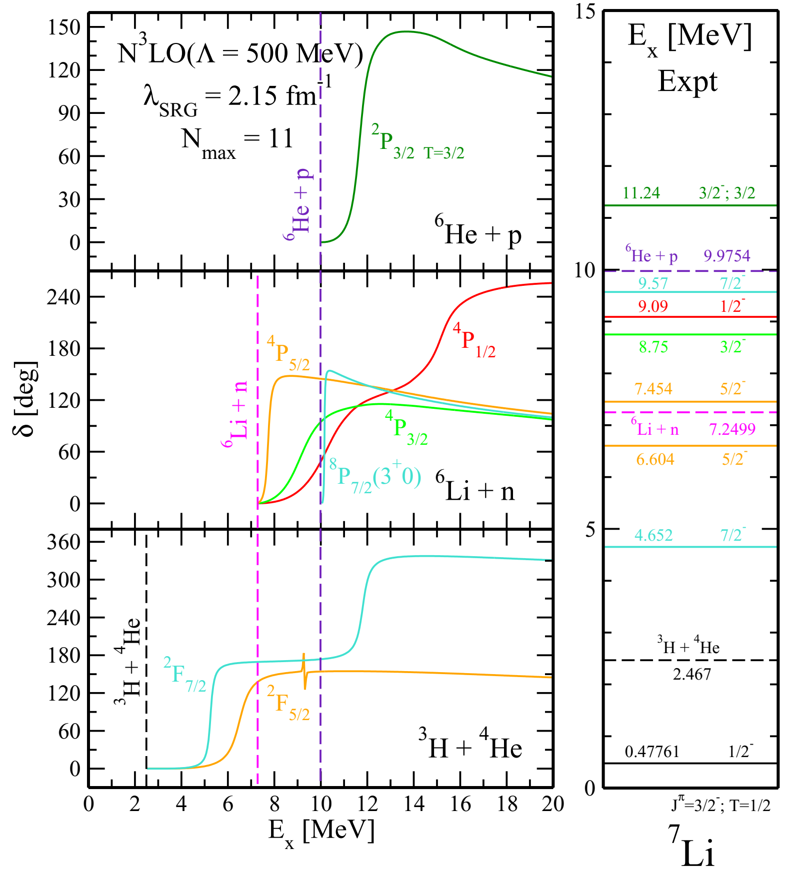
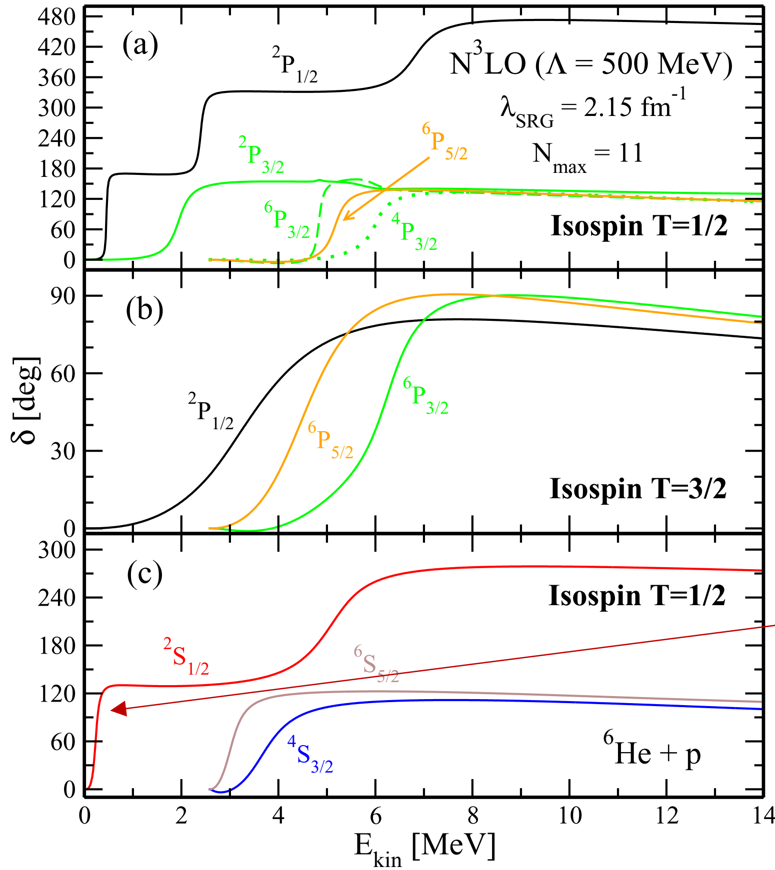
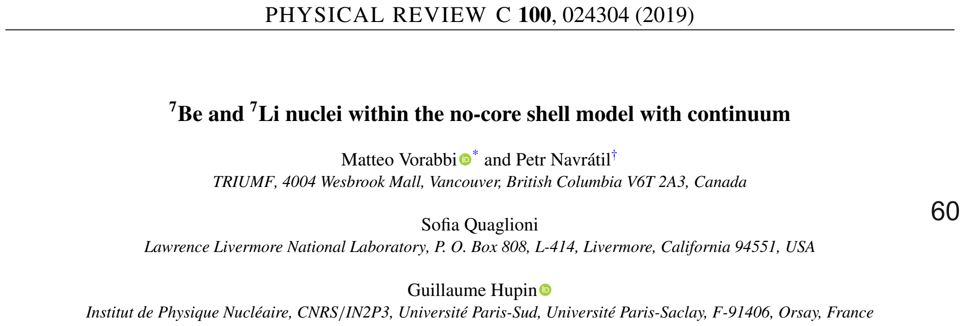




S-wave resonance predicted at low energy in ^{6}He+p scattering with possible astrophysics implications.

S-wave resonance

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



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

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

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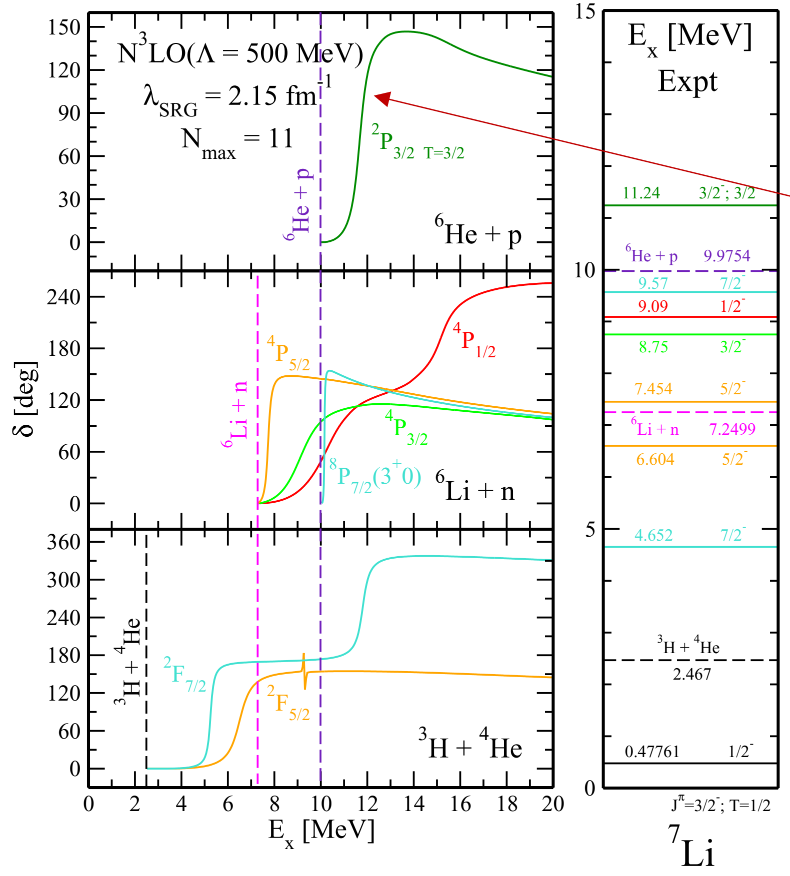
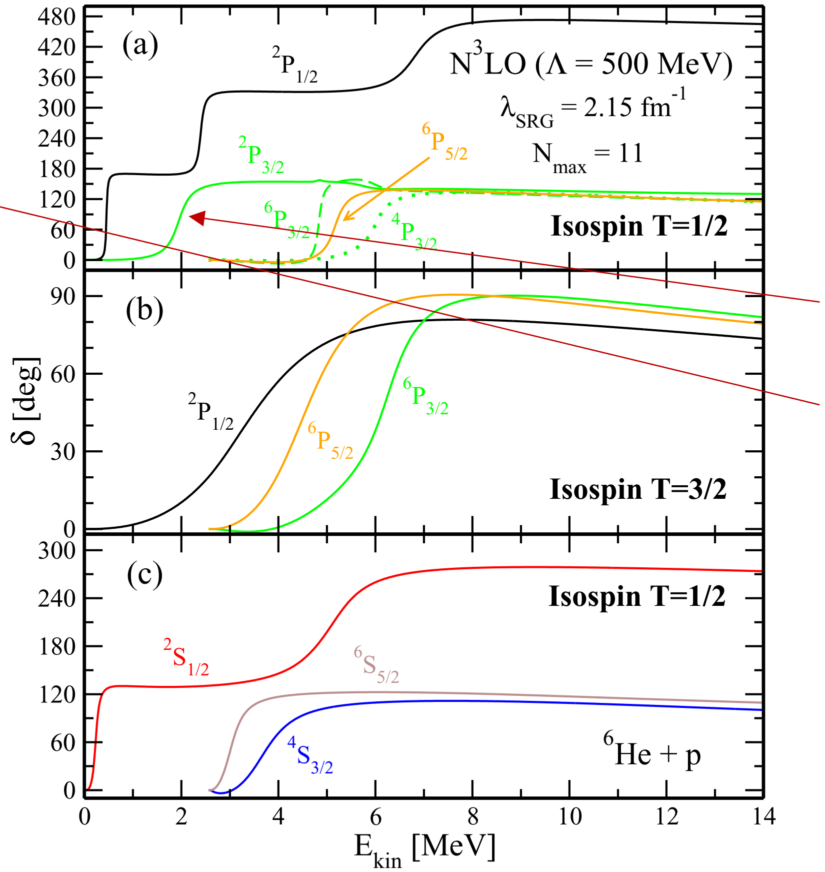




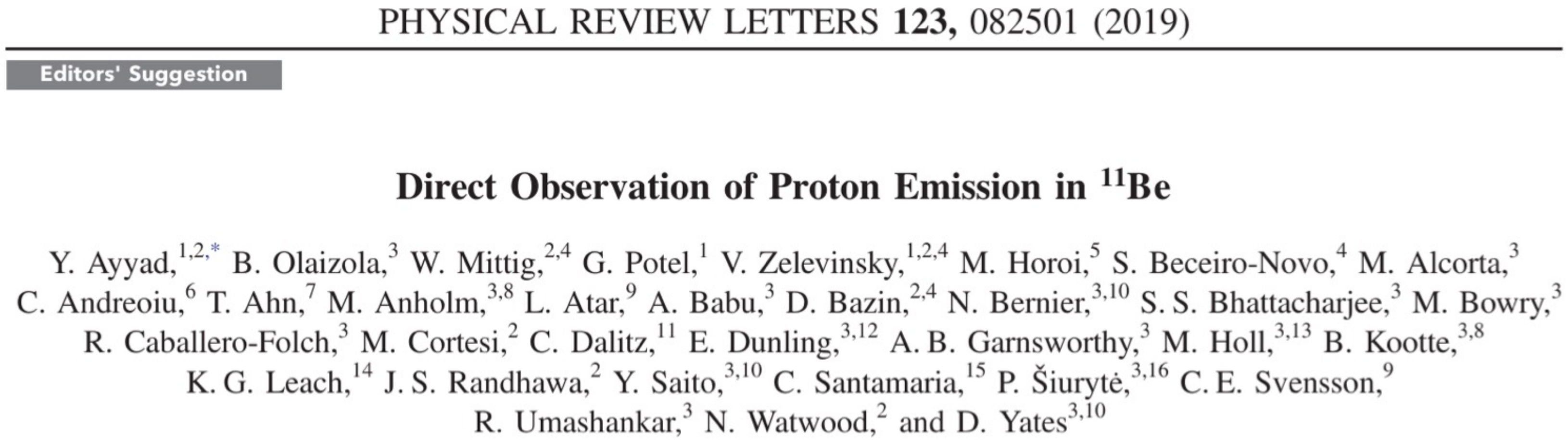
^{6}He(d,n)^{7}Li* → ^{6}He+p experiment at Texas A&M University Cyclotron Institute

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)

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]

Motivated by the hypothetical dark decay of the neutron

- Directly observed the protons from ^{11}Be(βp)^{10}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

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

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

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

Input chiral interaction

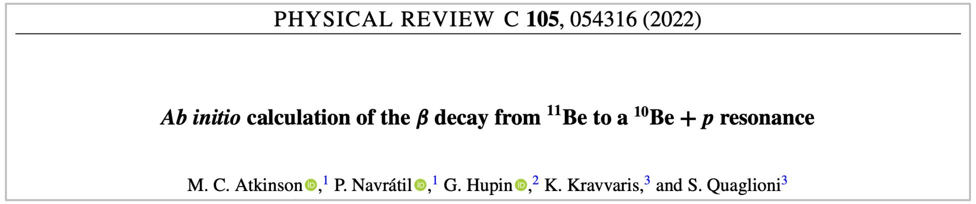
NN N^{4}LO(500) + 3N(lnl)

Entem-Machleidt-Nosyk 2017

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

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

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



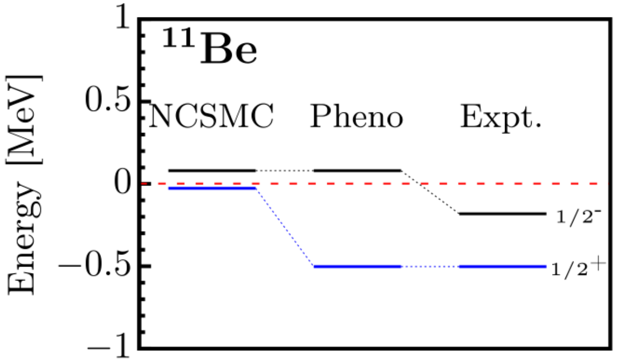
PHYSICAL REVIEW C **105**, 054316 (2022)

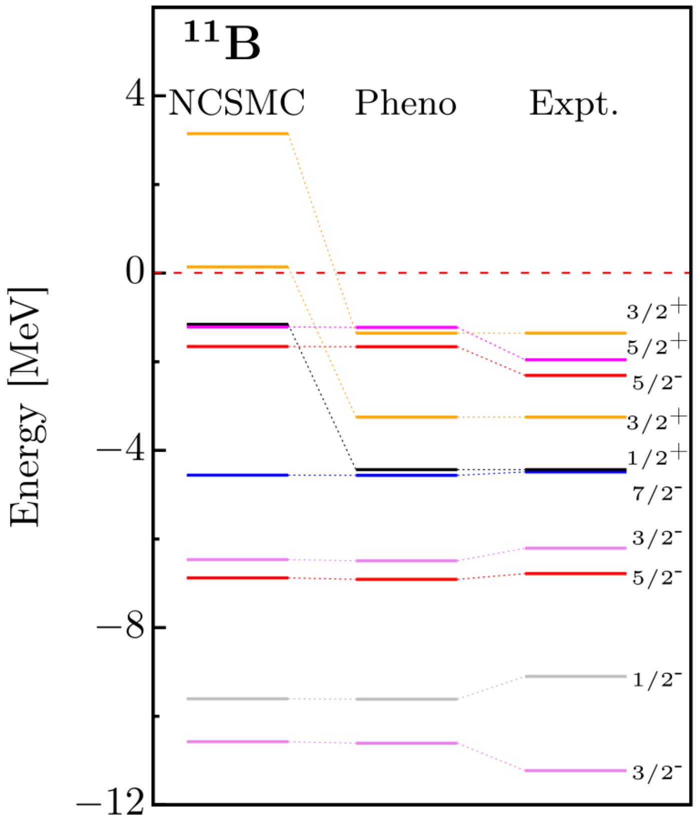
Ab initio calculation of the β decay from ^{11}Be to a ^{10}Be + p resonance

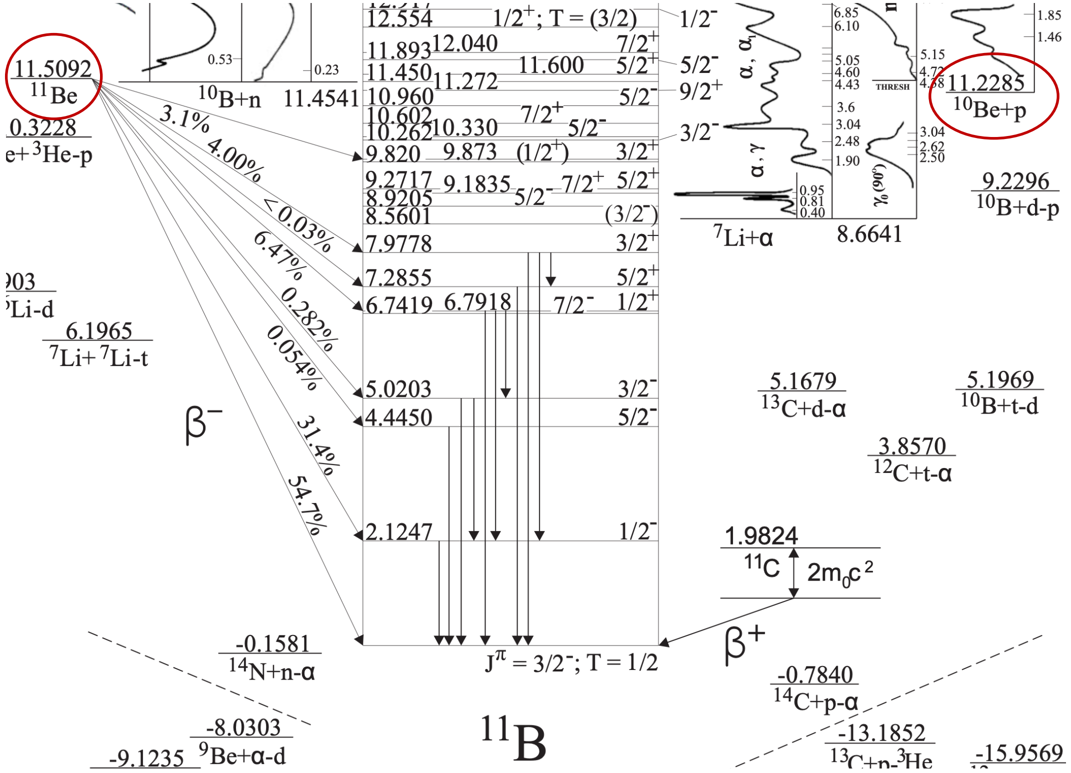
M. C. Atkinson,[1] P. Navrátil,[1] G. Hupin,[2] K. Kravvaris,[3] and S. Quaglioni[3]

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

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

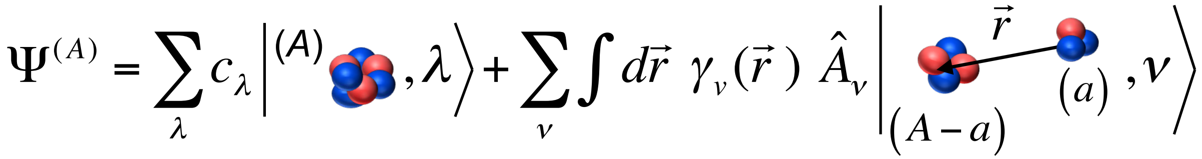




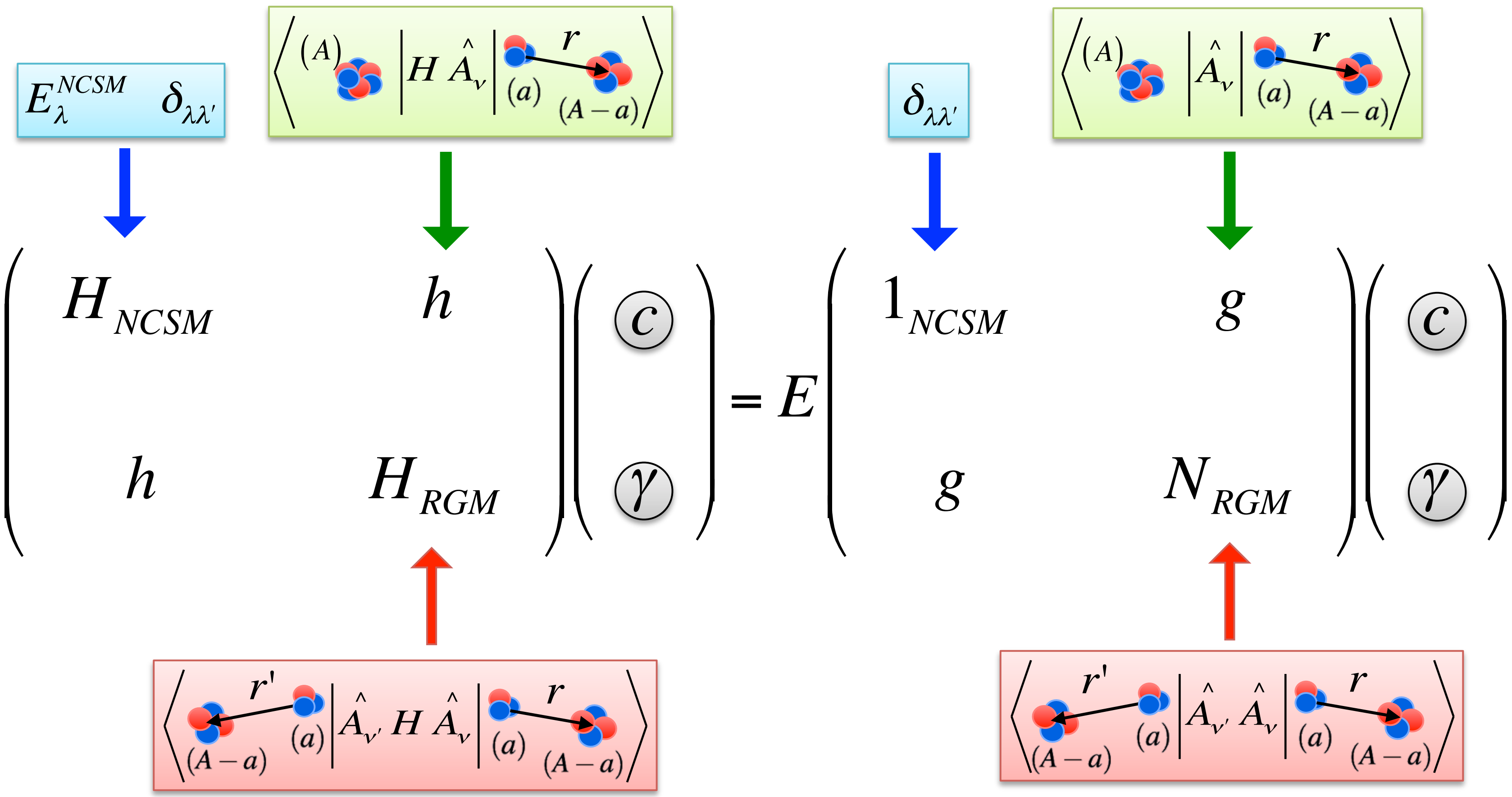


NCSMC phenomenology

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



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



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

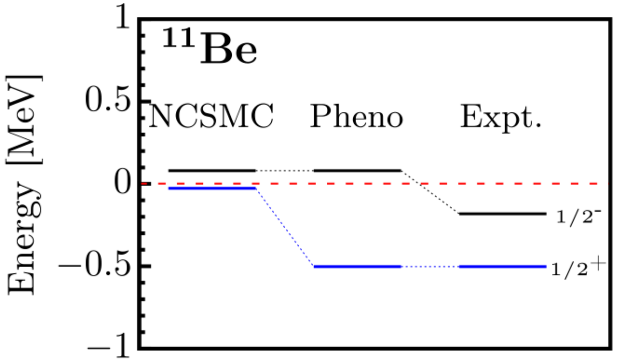
$$\begin{pmatrix} H_{NCSM} & h \\ h & H_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix} = E \begin{pmatrix} 1_{NCSM} & g \\ g & N_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix}$$

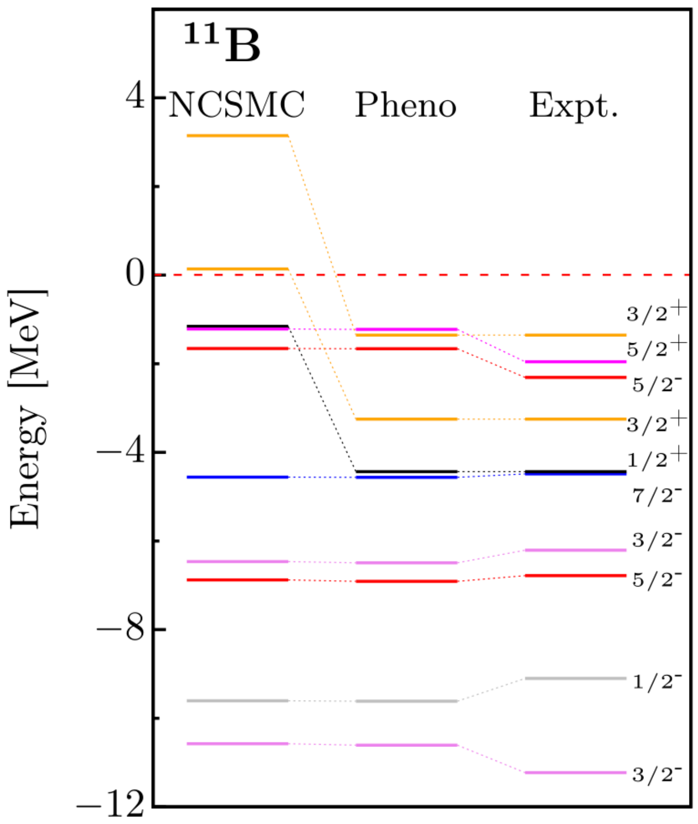
$$\left\langle {}_{(A-a)} \xleftarrow{r'} {}_{(a)} \middle| \hat{A}_{\nu'}\, H\, \hat{A}_{\nu} \middle| {}_{(a)} \xrightarrow{r} {}_{(A-a)} \right\rangle \qquad \left\langle {}_{(A-a)} \xleftarrow{r'} {}_{(a)} \middle| \hat{A}_{\nu'}\, \hat{A}_{\nu} \middle| {}_{(a)} \xrightarrow{r} {}_{(A-a)} \right\rangle$$

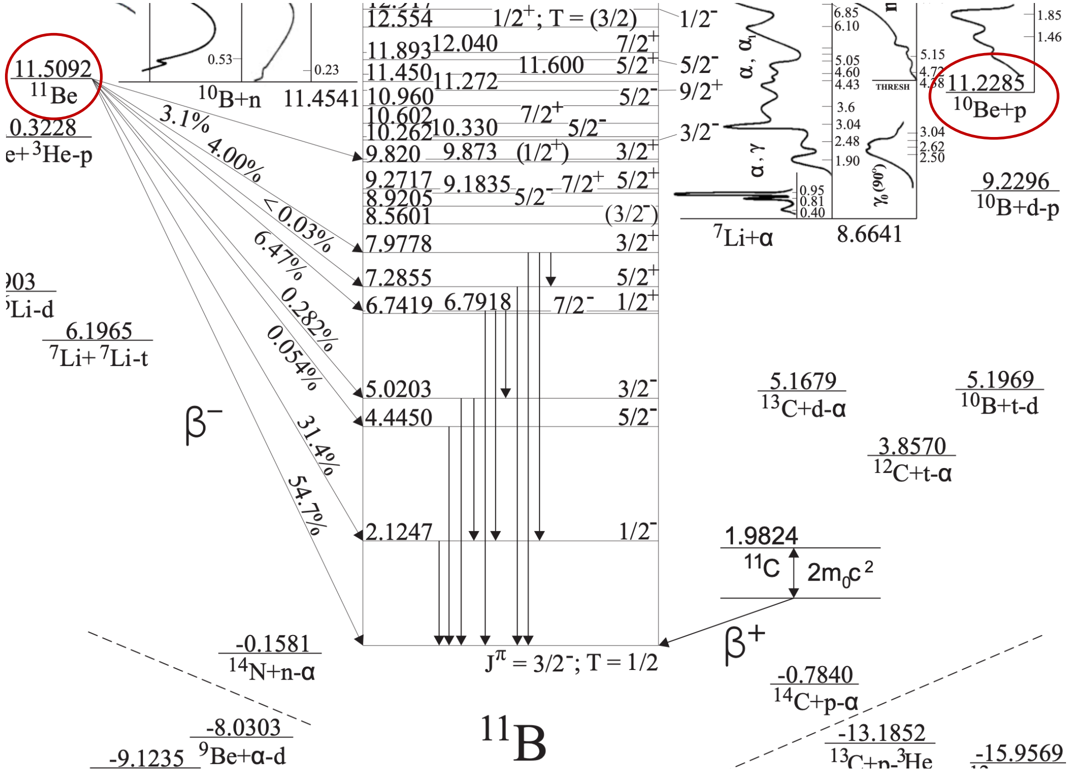
E_{λ}^{NCSM} energies treated as adjustable parameters

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

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



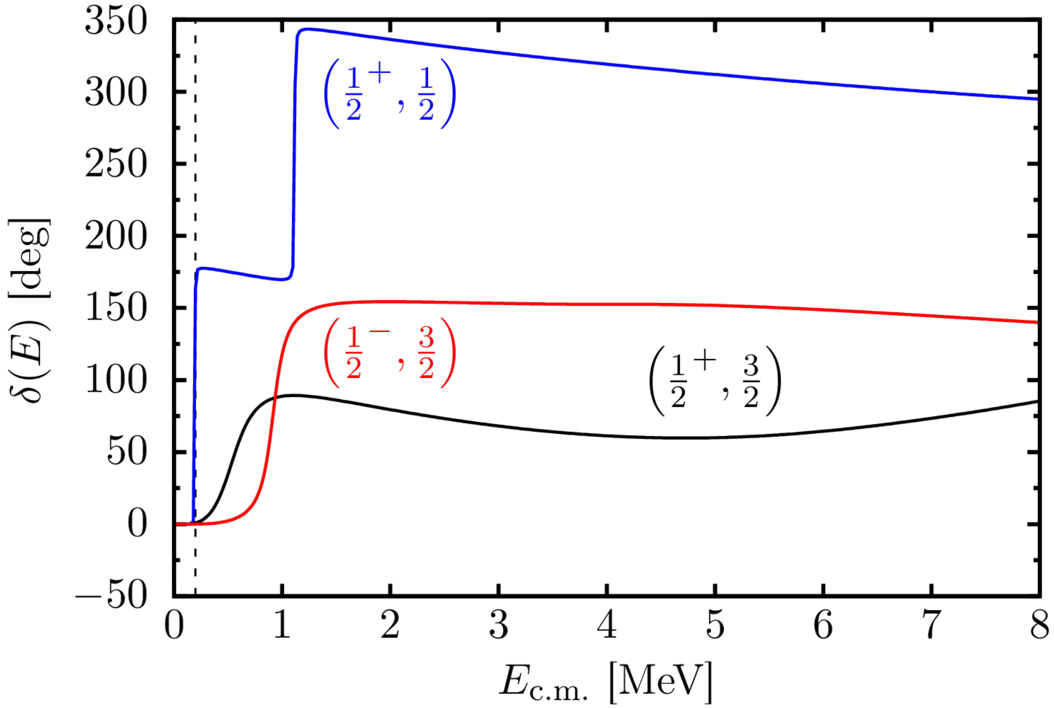


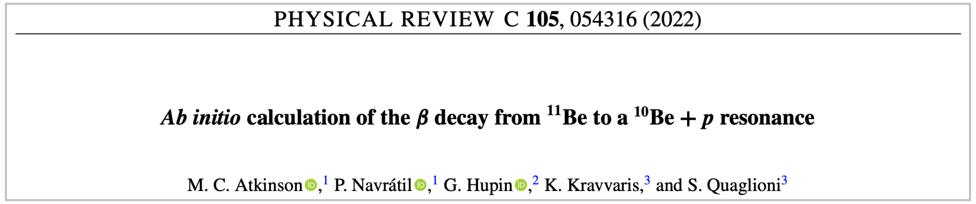


NCSMC extended to describe exotic ^{11}Be βp emission, supports large branching ratio due to narrow ½$^+$ resonance

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

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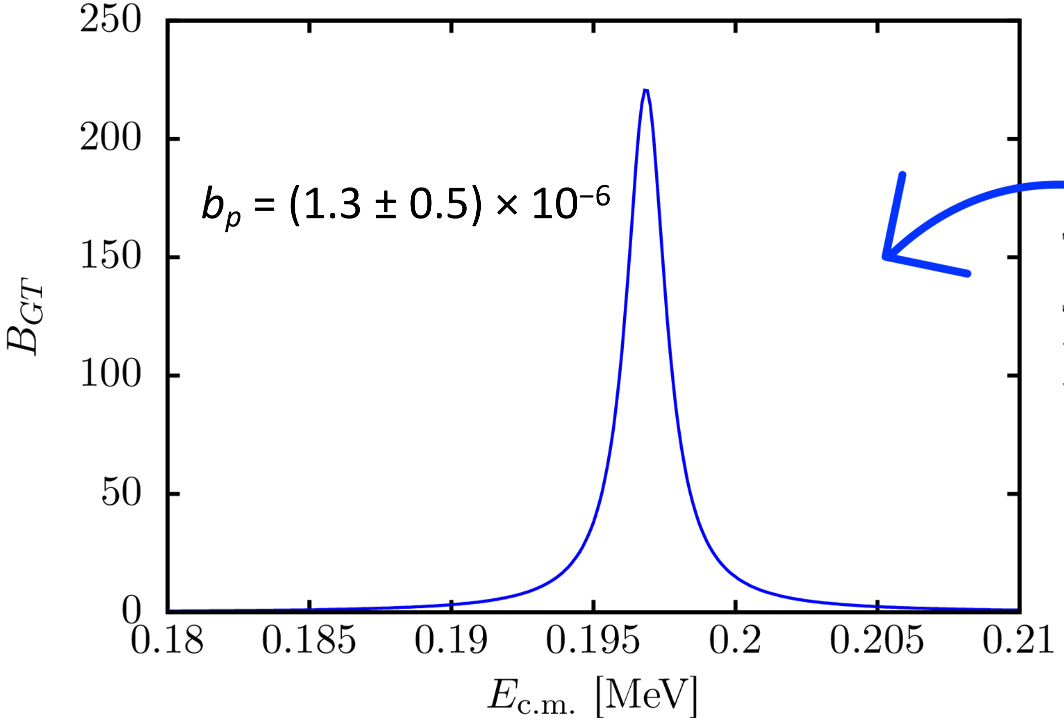
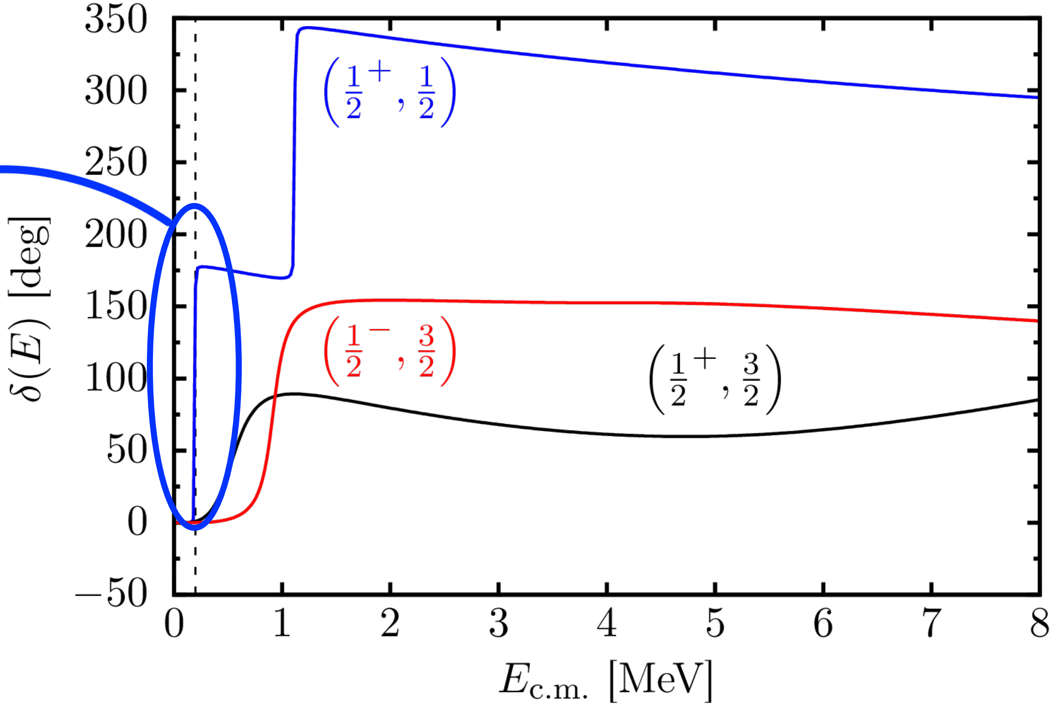
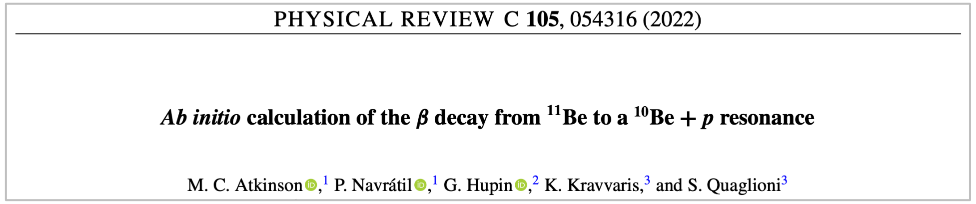


$b_p = (1.3 \pm 0.5) \times 10^{-6}$

p+^{10}Be Scattering Phase Shifts





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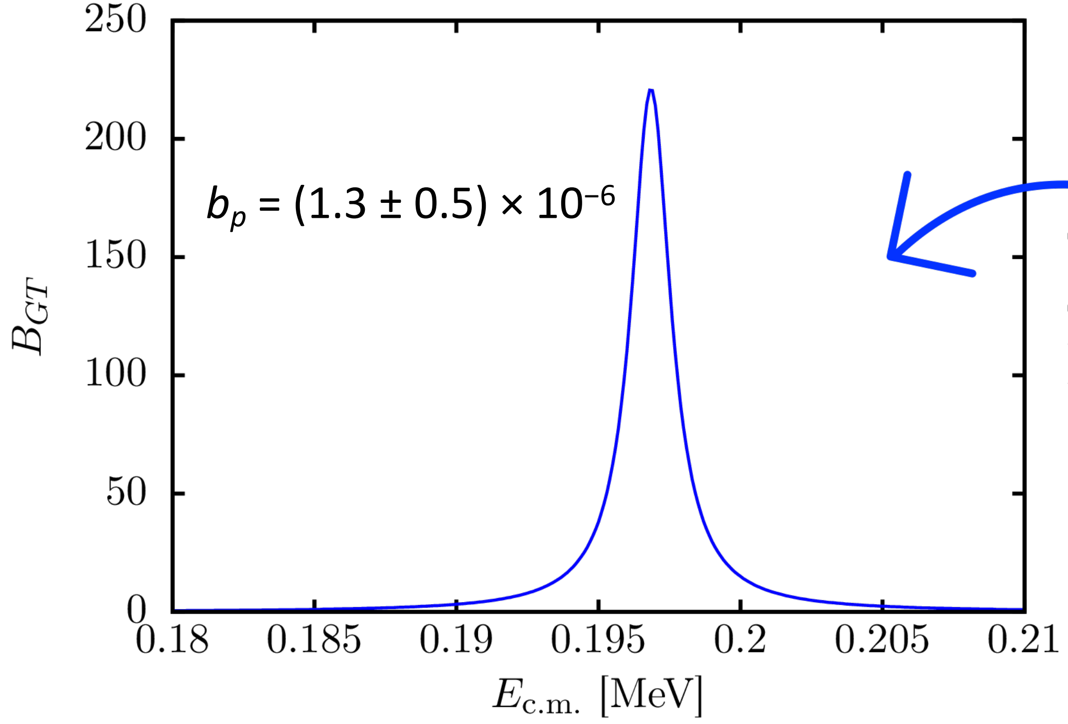

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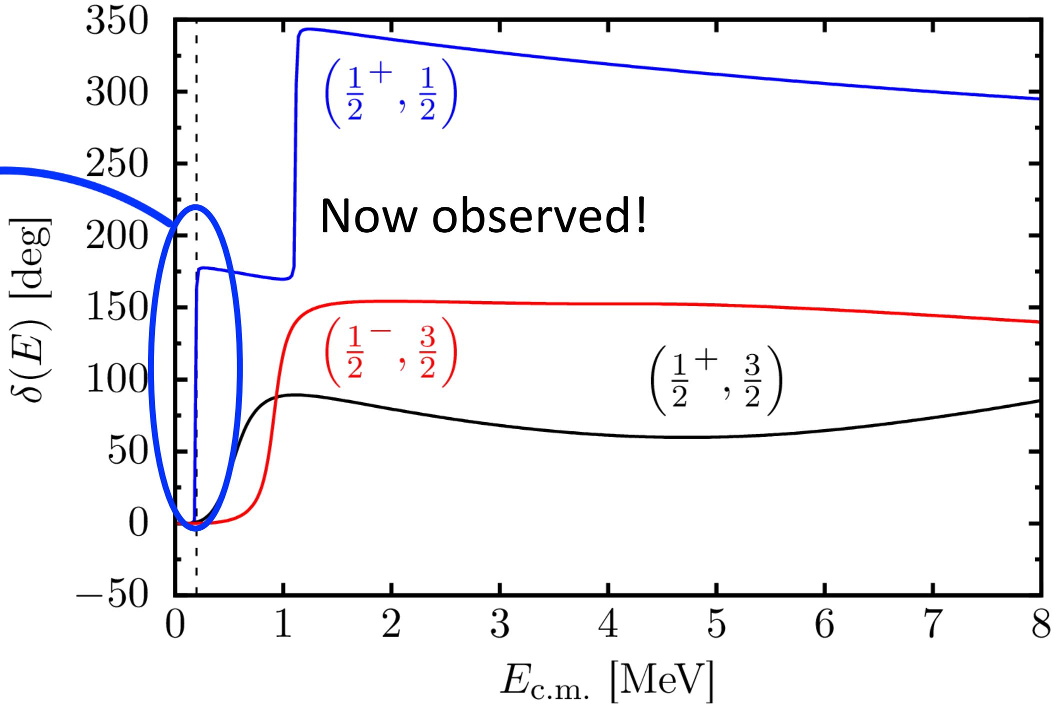
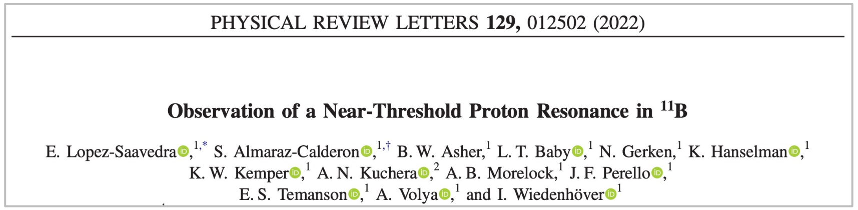
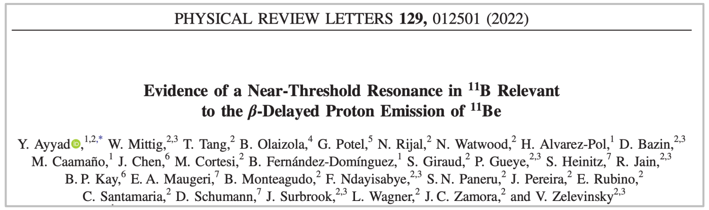




PHYSICAL REVIEW LETTERS **129,** 012502 (2022)

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

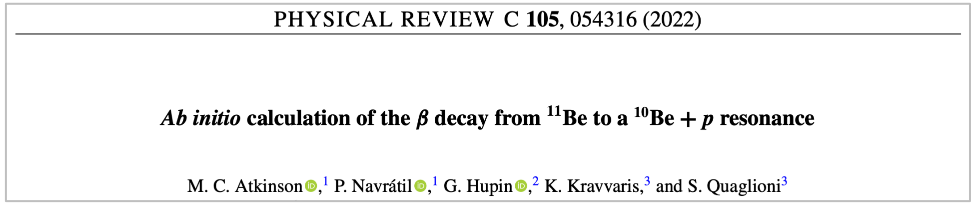
E. Lopez-Saavedra,[1,*] S. Almaraz-Calderon,[1,†] B. W. Asher,[1] L. T. Baby,[1] N. Gerken,[1] K. Hanselman,[1]
K. W. Kemper,[1] A. N. Kuchera,[2] A. B. Morelock,[1] J. F. Perello,[1]
E. S. Temanson,[1] A. Volya,[1] and I. Wiedenhöver[1]



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

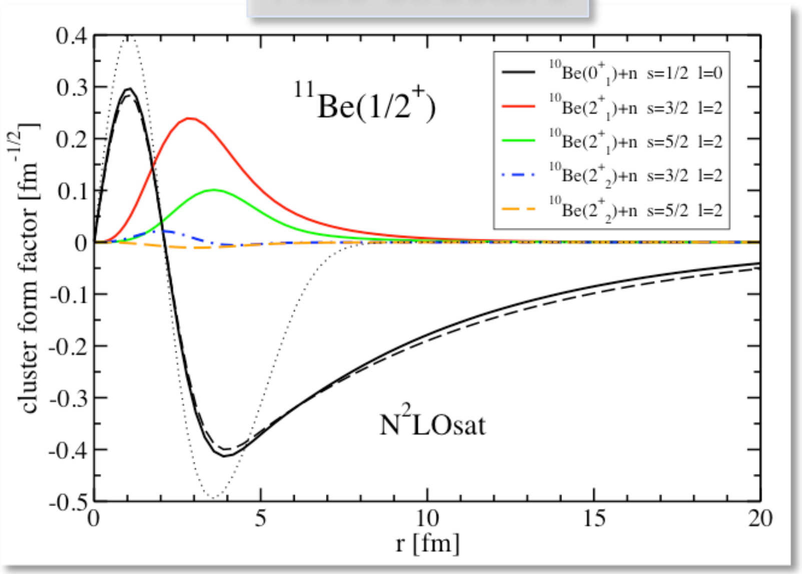
- More experiments planned!

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

Photo-disassociation of ^{11}Be

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

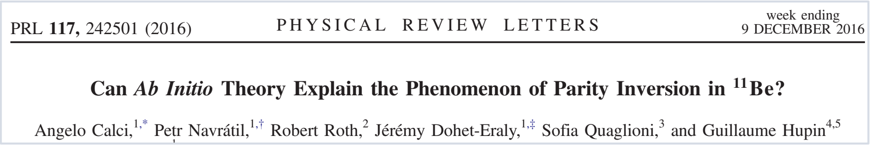
Halo structure



cluster form factor

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

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

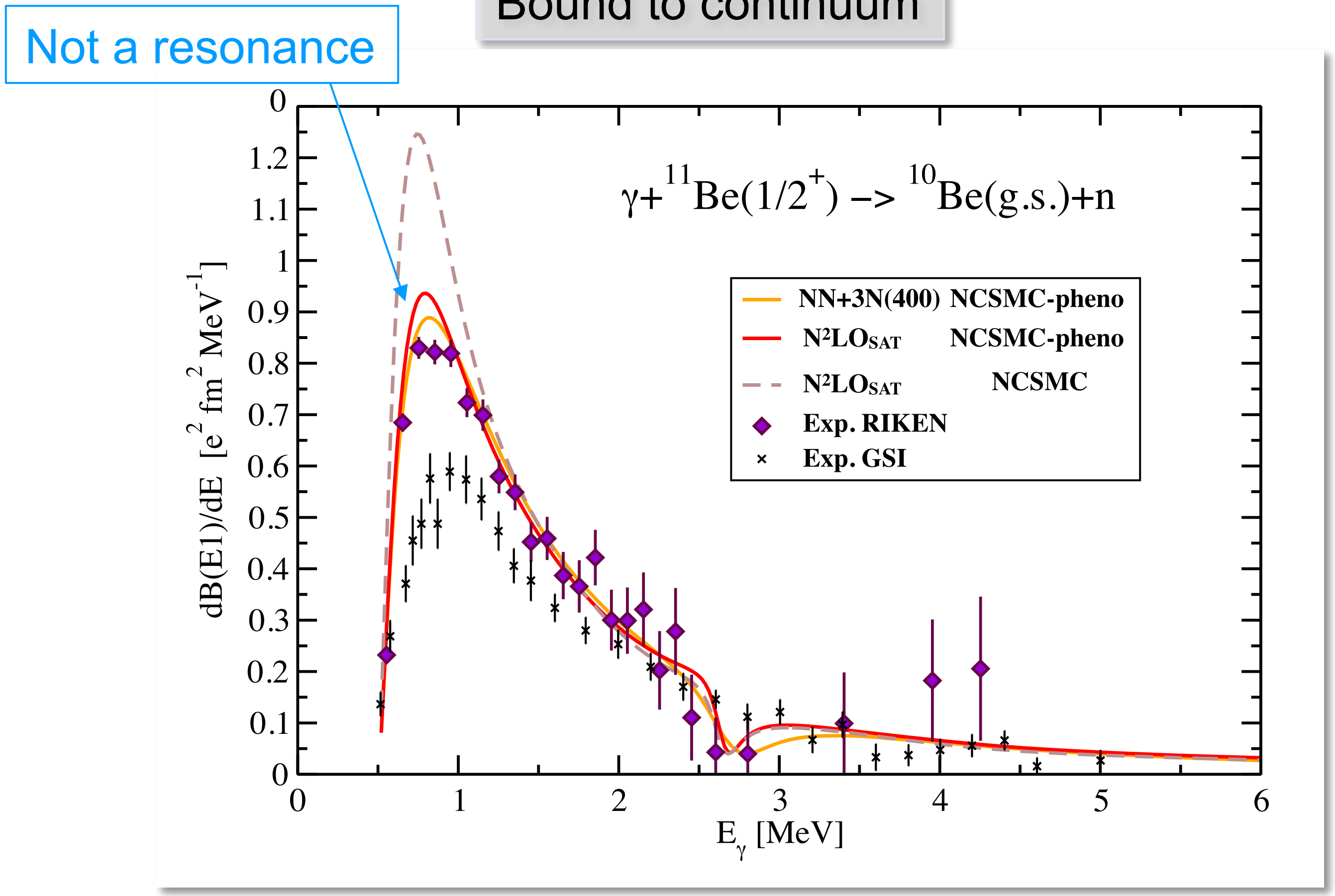


PRL **117,** 242501 (2016) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2016

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

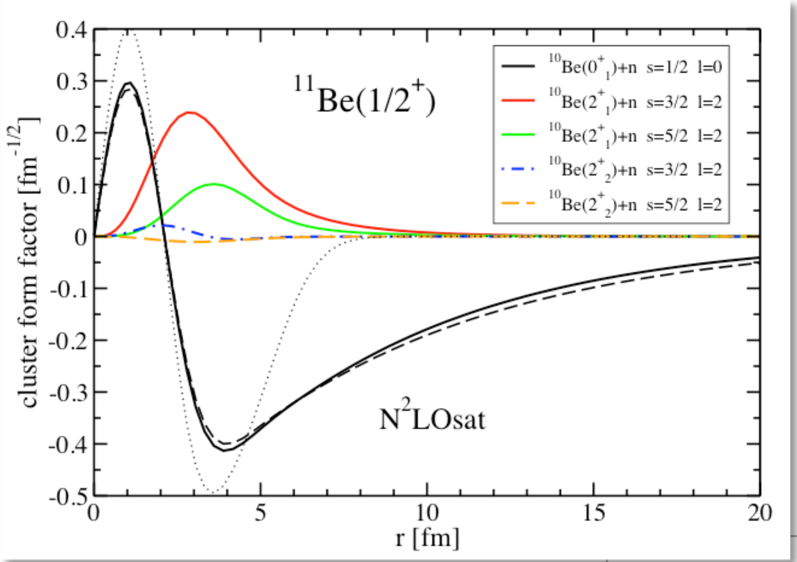
Angelo Calci,[1,*] Petr Navrátil,[1,†] Robert Roth,[2] Jérémy Dohet-Eraly,[1,‡] Sofia Quaglioni,[3] and Guillaume Hupin[4,5]

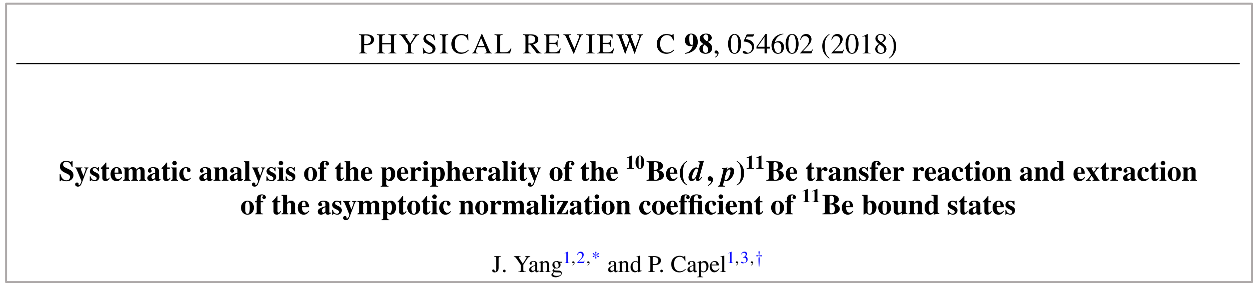
Bound to continuum



Not a resonance

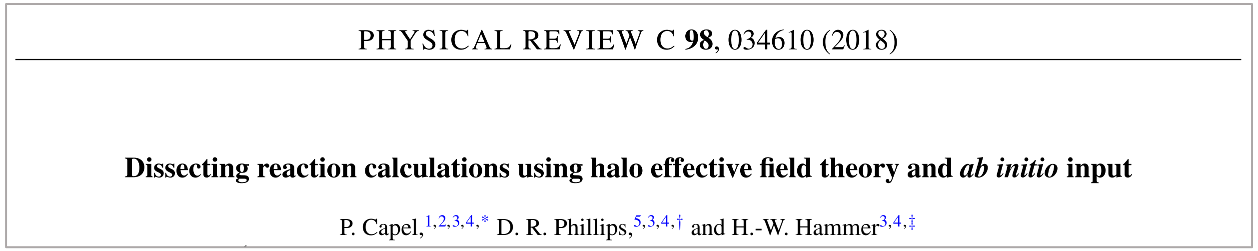
NCSMC wave functions of ^{11}Be used as input for other studies




PHYSICAL REVIEW C **98**, 054602 (2018)

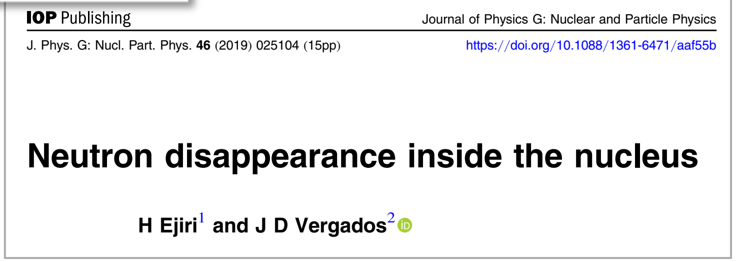
Systematic analysis of the peripherality of the ^{10}Be$(d,p)^{11}$Be transfer reaction and extraction of the asymptotic normalization coefficient of ^{11}Be bound states

J. Yang[1,2,*] and P. Capel[1,3,†]


PHYSICAL REVIEW C **98**, 034610 (2018)

Dissecting reaction calculations using halo effective field theory and *ab initio* input

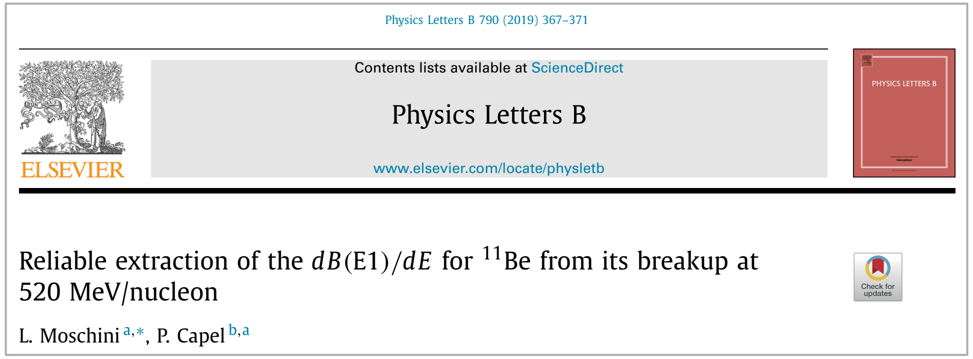
P. Capel,[1,2,3,4,*] D. R. Phillips,[5,3,4,†] and H.-W. Hammer[3,4,‡]


IOP Publishing Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **46** (2019) 025104 (15pp) https://doi.org/10.1088/1361-6471/aaf55b

Neutron disappearance inside the nucleus

H Ejiri[1] and J D Vergados[2]


Physics Letters B 790 (2019) 367–371

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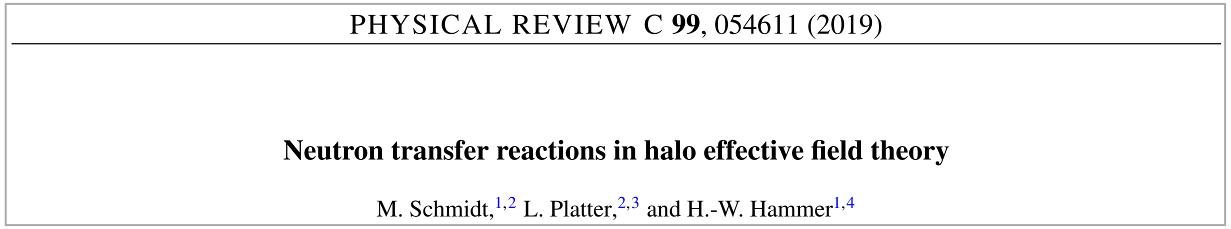
Reliable extraction of the $dB(\mathrm{E1})/dE$ for ^{11}Be from its breakup at 520 MeV/nucleon

L. Moschini[a,*], P. Capel[b,a]


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]

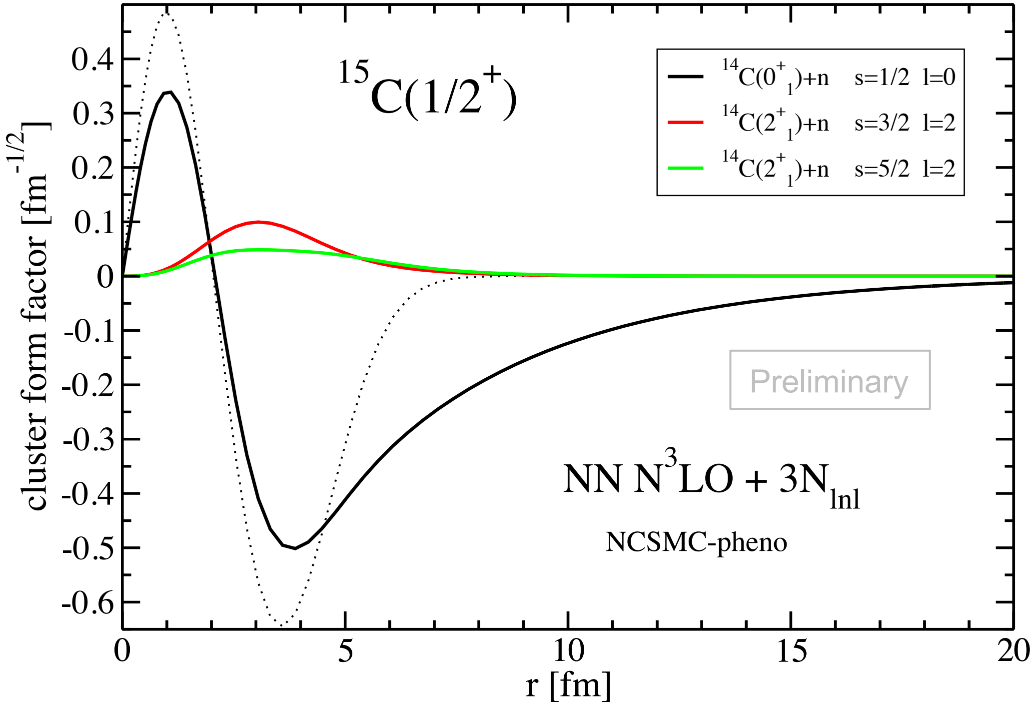

PHYSICAL REVIEW C **99**, 054611 (2019)

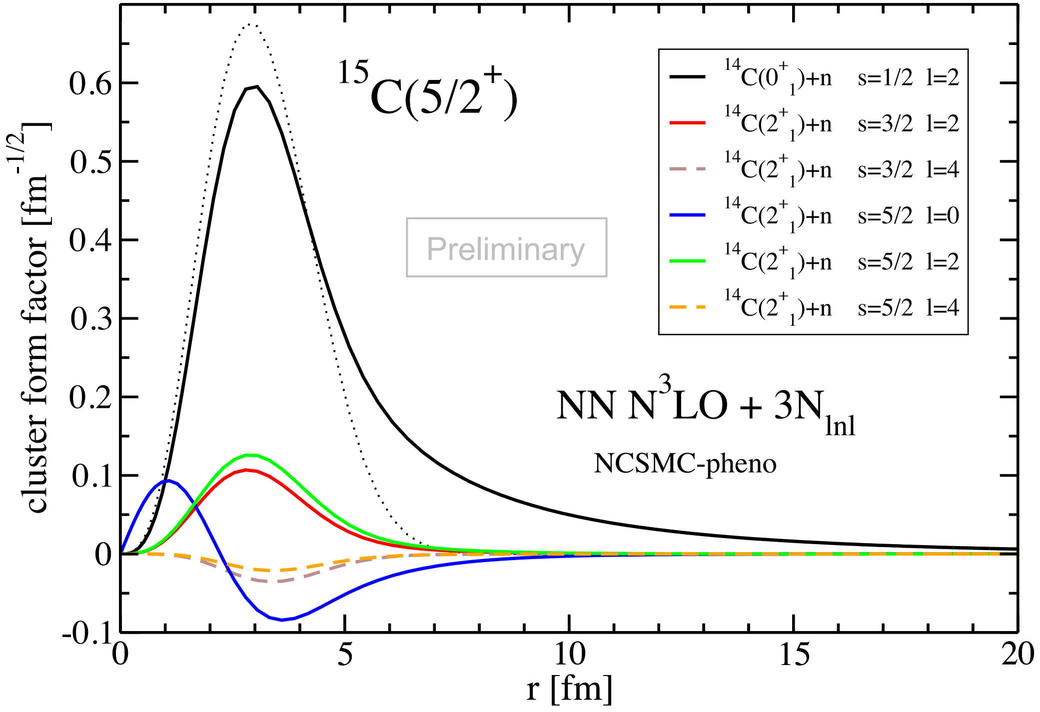
Neutron transfer reactions in halo effective field theory

M. Schmidt,[1,2] L. Platter,[2,3] and H.-W. Hammer[1,4]

^{15}C cluster form factors – NCSMC ^{14}C+n

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

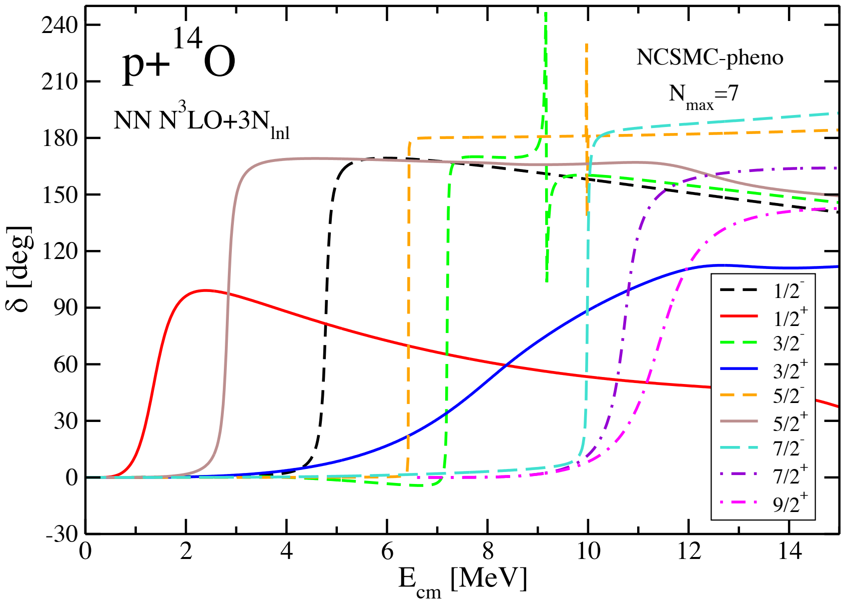




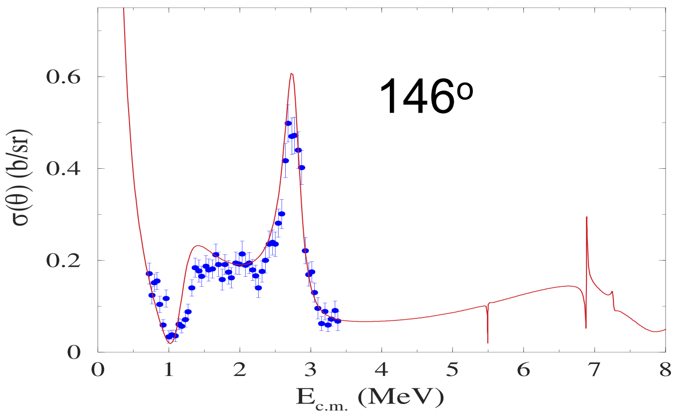
Unbound *sd*-shell nucleus ^{15}F – NCSMC calculations

- Very narrow *P*-wave resonances

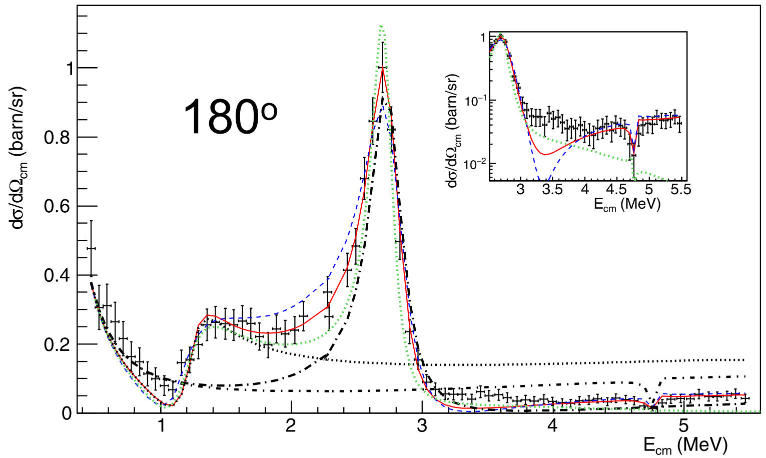
Preliminary

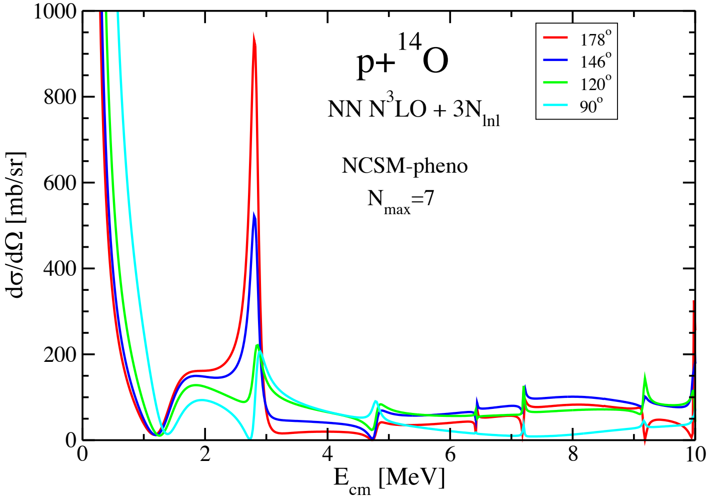


PRL **96,** 072502 (2006) PHYSICAL RE



F. de Grancey et al. / Physics Letters B 758 (2016) 26–31

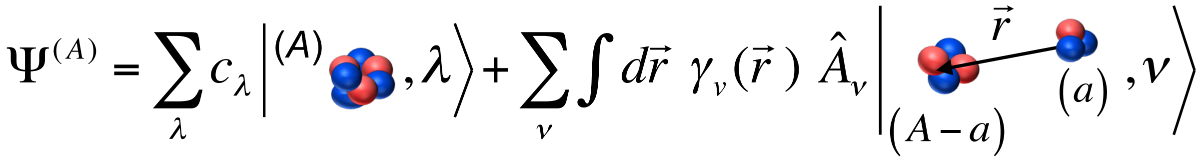




Energy Levels of ^{15}F from ENSDF (unpublished, September 2016)

$E_{\rm x}$ (MeV $\pm$ keV)	$J^\pi; T$	Γ (keV)	Decay
g.s.	$\frac{1}{2}^+; \frac{3}{2}$	660 ± 20	p
1.52 ± 50	$\frac{5}{2}^+; \frac{3}{2}$	300 ± 13	p
3.48 ± 40	$\frac{1}{2}^-$	36 ± 15	p
5.1 ± 200	$(\frac{3}{2}^-, \frac{5}{2}^-)$	0.2 ± 0.2 MeV	p
6.5 ± 200	$(\frac{3}{2}^+; \frac{5}{2}^+)$	0.4 ± 0.4 MeV	p

Data at 146° from PRC 69, 031302(R) (2004)



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

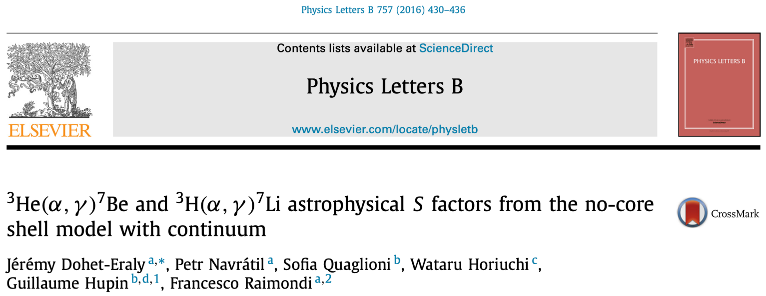
Nuclear radii from NCSMC

- Proper wave function tail – much superior to NCSM (HO)
- Computation more involved

$$\begin{aligned} M = {} & \sum_{\lambda\lambda'} c^{*f}_{\lambda'} \langle A\lambda' J_f^{\pi_f} T_f \| \mathcal{M}_1^E \| A\lambda J_i^{\pi_i} T_i \rangle \, c^i_{\lambda} \\ & + \sum_{\lambda'\nu} \int \mathrm{d}r r^2 \, c^{*f}_{\lambda'} \langle A\lambda' J_f^{\pi_f} T_f \| \mathcal{M}_1^E \hat{\mathcal{A}}_{\nu} \| \Phi^i_{\nu r} \rangle \, \frac{\gamma^i_{\nu}(r)}{r} \\ & + \sum_{\lambda\nu'} \int \mathrm{d}r' r'^{\,2} \frac{\gamma^{*f}_{\nu'}(r')}{r'} \langle \Phi^f_{\nu' r'} \| \hat{\mathcal{A}}_{\nu'} \mathcal{M}_1^E \| A\lambda J_i^{\pi_i} T_i \rangle \, c^i_{\lambda} \\ & + \sum_{\nu\nu'} \int \mathrm{d}r' r'^{\,2} \int \mathrm{d}r r^2 \frac{\gamma^{*f}_{\nu'}(r')}{r'} \\ & \times \langle \Phi^f_{\nu' r'} \| \hat{\mathcal{A}}_{\nu'} \mathcal{M}_1^E \hat{\mathcal{A}}_{\nu} \| \Phi^i_{\nu r} \rangle \, \frac{\gamma^i_{\nu}(r)}{r}. \end{aligned}$$

- Published results for ^{7}Li, ^{7}Be, ^{6}He (^{4}He+n+n cluster)

^{7}Be	NCSM	NCSMC	Exp.	Refs.
$E_{3/2^-}$ [MeV]	−0.82	−1.52	−1.587	[47]
$E_{1/2^-}$ [MeV]	−0.49	−1.26	−1.157	[47]
r_{ch} [fm]	2.375	2.62	2.647(17)	[48]
Q [e fm^2]	−4.57	−6.14	–	
μ [μ_N]	−1.14	−1.16	−1.3995(5)	[48]
^{7}Li	NCSM	NCSMC	Exp.	Refs.
$E_{3/2^-}$ [MeV]	−1.79	−2.43	−2.467	[47]
$E_{1/2^-}$ [MeV]	−1.46	−2.15	−1.989	[47]
r_{ch} [fm]	2.21	2.42	2.39(3)	[49]
Q [e fm^2]	−2.67	−3.72	−4.00(3)	[50]
μ [μ_N]	3.00	3.02	3.256	[51]



Physics Letters B 757 (2016) 430–436

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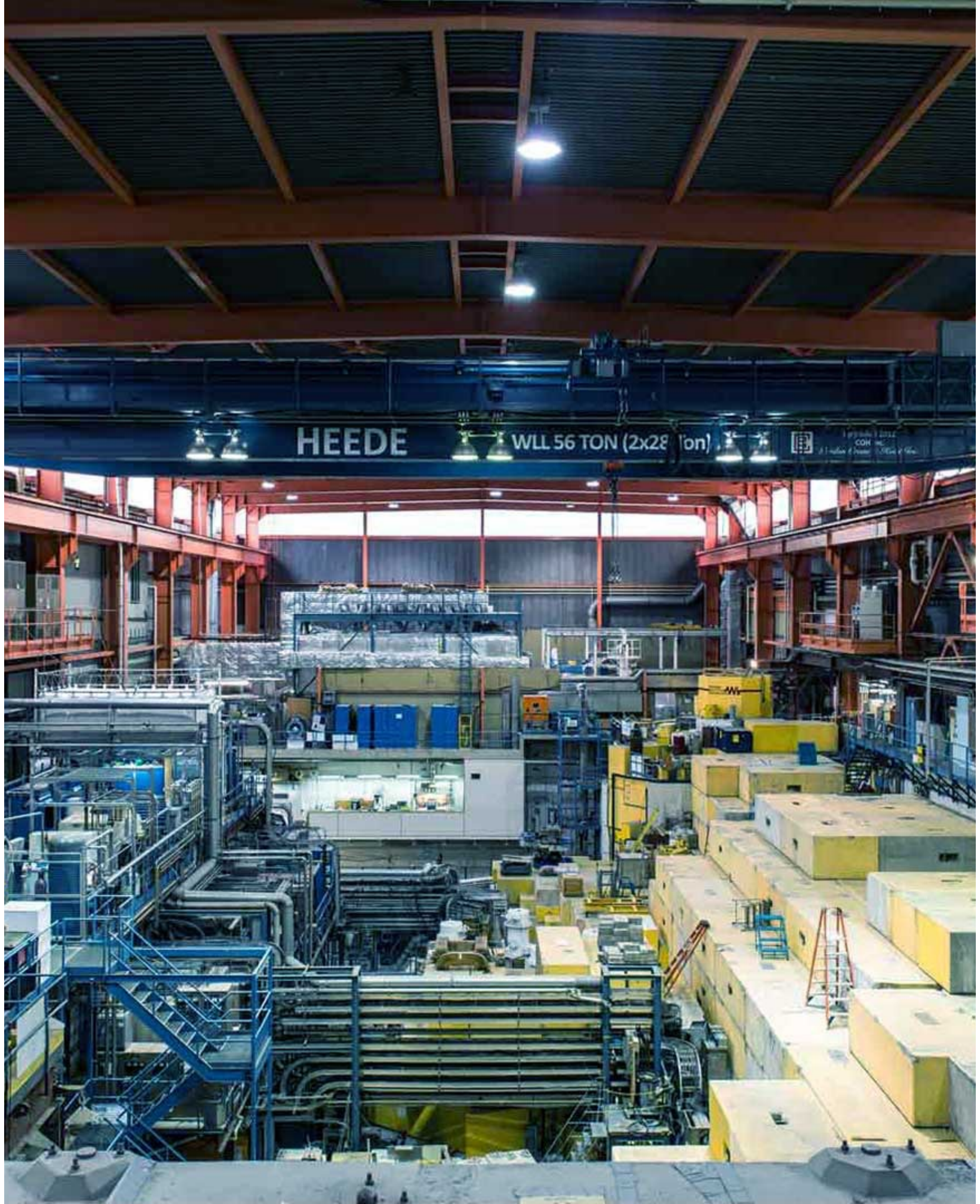
^{3}He$(\alpha,\gamma)^7$Be and ^{3}H$(\alpha,\gamma)^7$Li astrophysical S factors from the no-core shell model with continuum

CrossMark

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

TRIUMF

Nuclear astrophysics: Capture reactions



Discovery, accelerated

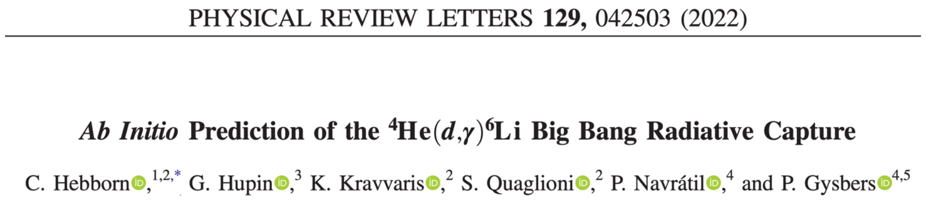
Reaction ^{4}He(d,γ)^{6}Li responsible for ^{6}Li production in BBN

- Three orders of magnitude discrepancy between BBN predictions and observations
    - Problem with astronomical observations?
    - Problem with our understanding of the reaction rate?
    - New physics?

- NCSMC calculations with chiral NN+3N interaction

    - Radiative capture S-factor
        - Dominated by E2
        - M1 significant at low energy
        - E1 negligible – isospin supressed (T=0 → T=0)

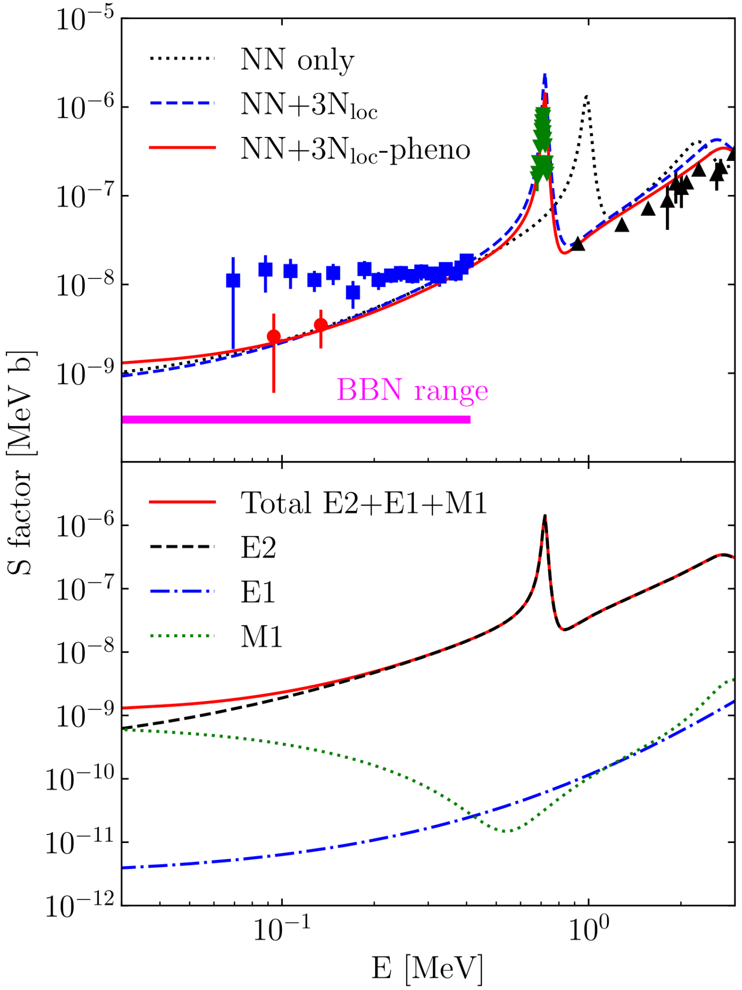
    - Thermonuclear reaction rate
        - Smaller than NACRE II evaluation
        - Agreement with LUNA result with reduced uncertainty

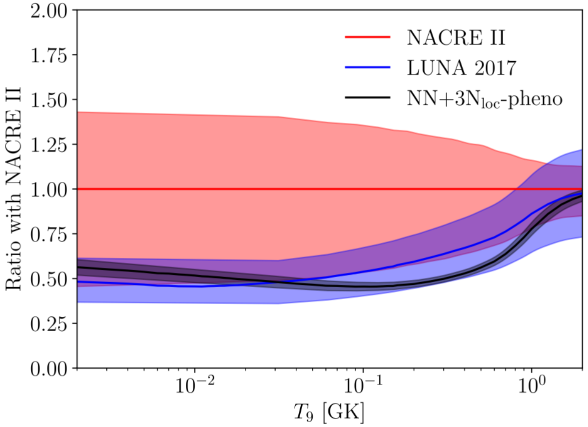


PHYSICAL REVIEW LETTERS **129,** 042503 (2022)

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]

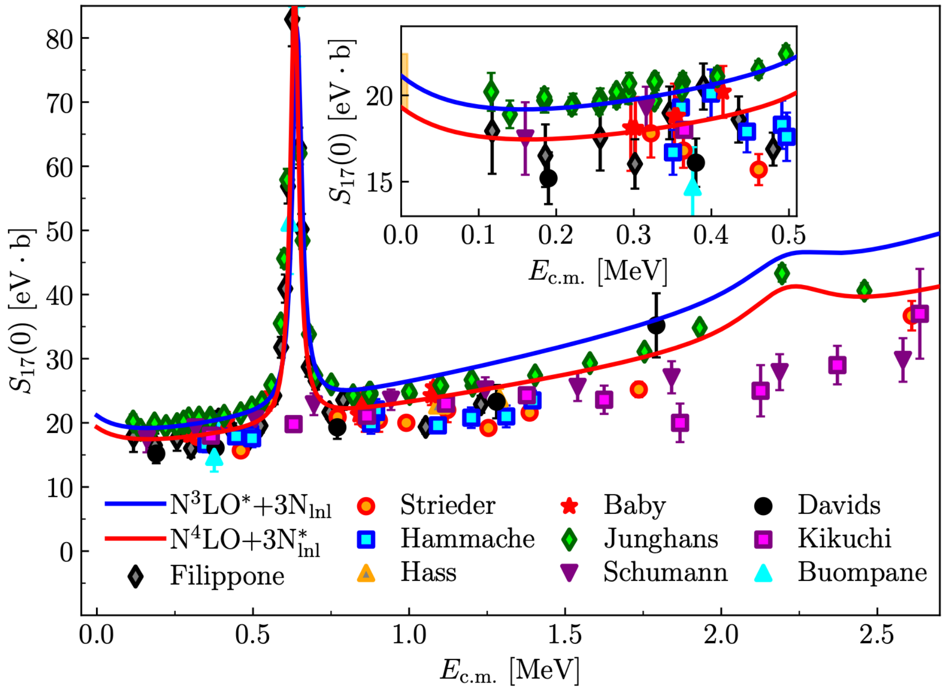




Radiative capture of protons on ^{7}Be

- Solar pp chain reaction, solar ^{8}B neutrinos
- NCSMC calculations with a set of chiral NN+3N interactions as input
  - Radiative capture S-factor
    - Dominated by E1 non-resonant
    - M1/E2 significant at 1^+ and 3^+ resonances
  - Correlations between results obtained by different chiral interactions and experimental data → evaluation of the S-factor at E=0 energy relevant for the solar physics

^{7}Be(p,γ)^{8}B



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

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

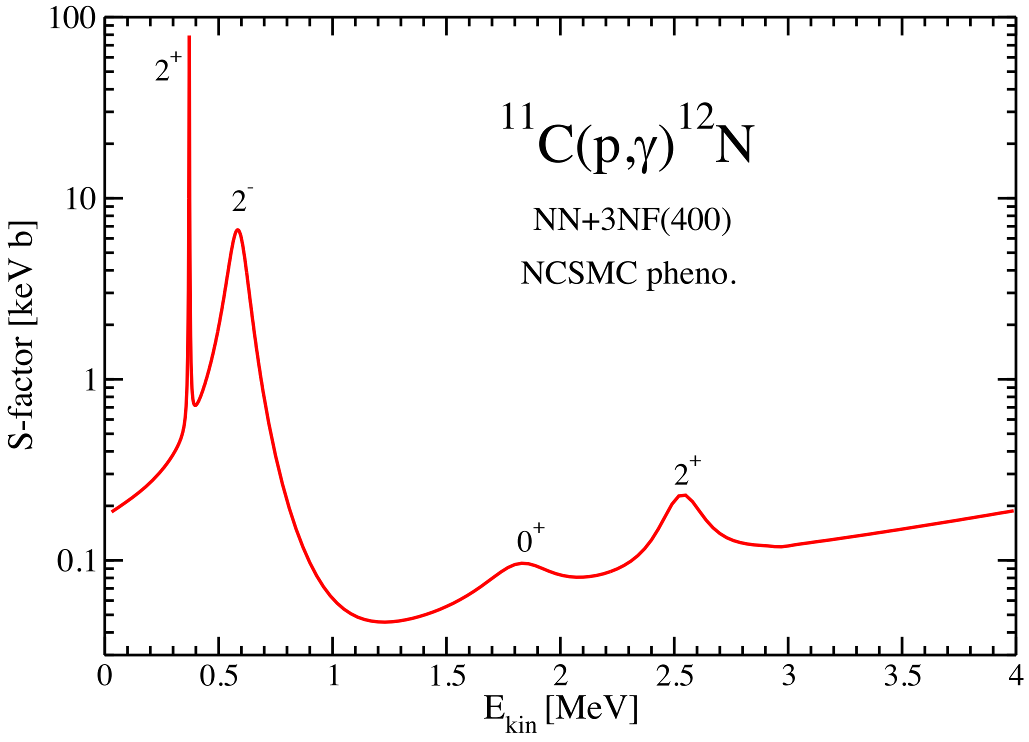
K. Kravvaris,[1] P. Navrátil,[2] S. Quaglioni,[1] C. Hebborn,[3,1] and G. Hupin[4]

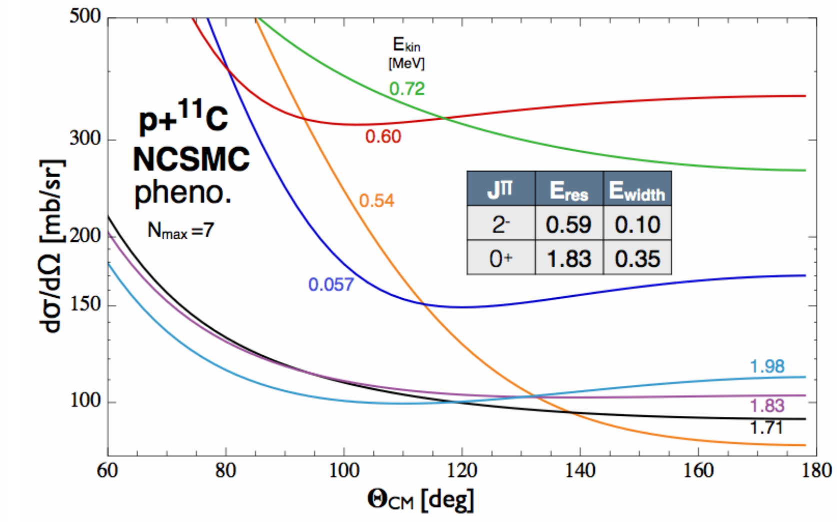
arXiv: 2202.11759

p+^{11}C scattering and ^{11}C(p,γ)^{12}N capture

Measurement of ^{11}C(p,p) resonance scattering planned at TRIUMF TUDA facility

- NCSMC calculations of ^{11}C(p,p) with chiral NN+3N
  - ^{11}C: 3/2$^-$, 1/2$^-$, 5/2$^-$, 3/2$^-$ NCSM eigenstates
  - ^{12}N: ≥6 π = +1 and ≥4 π = -1 NCSM eigenstates



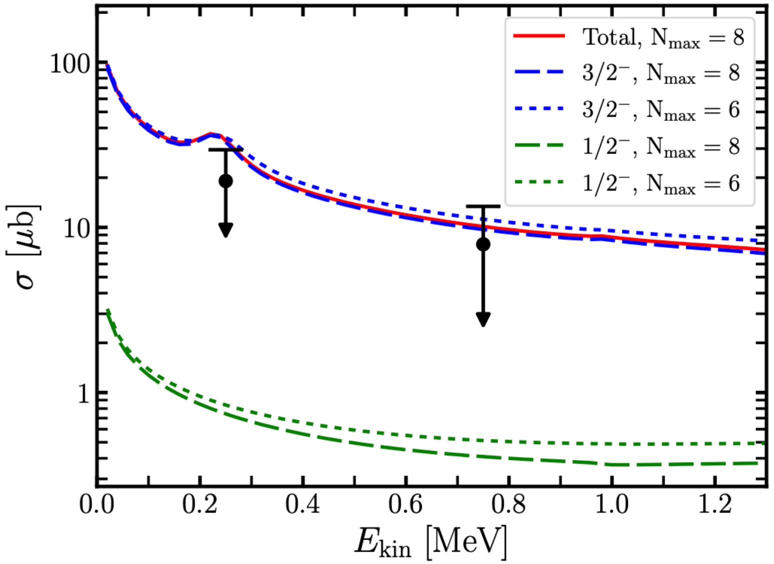


Jπ	E_{res}	E_{width}
2$^-$	0.59	0.10
0$^+$	1.83	0.35

NCSMC calculations to be validated by measured cross sections and applied to calculate the ^{11}C(p,γ)^{12}N capture

Radiative capture of neutrons on ^{8}Li

- Reactions involving the short-lived ^{8}Li nucleus may contribute to the synthesis of heavier nuclei by bridging the stability gap of mass A = 8 elements
- Cannot be measured directly as ^{8}Li half-life 840 ms
- NCSMC calculations - ^{8}Li(n,γ)^{9}Li – cross section higher compared to recent phenomenological calculations




PHYSICAL REVIEW C **103**, 035801 (2021)

Microscopic investigation of the ^{8}Li(n, γ) ^{9}Li reaction

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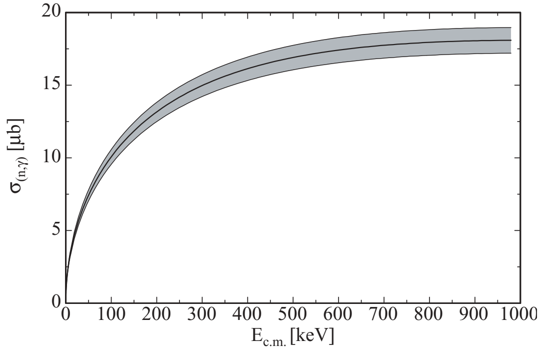
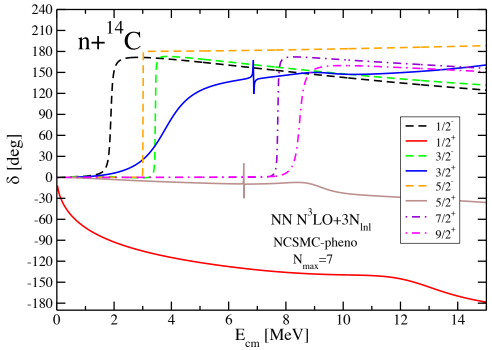
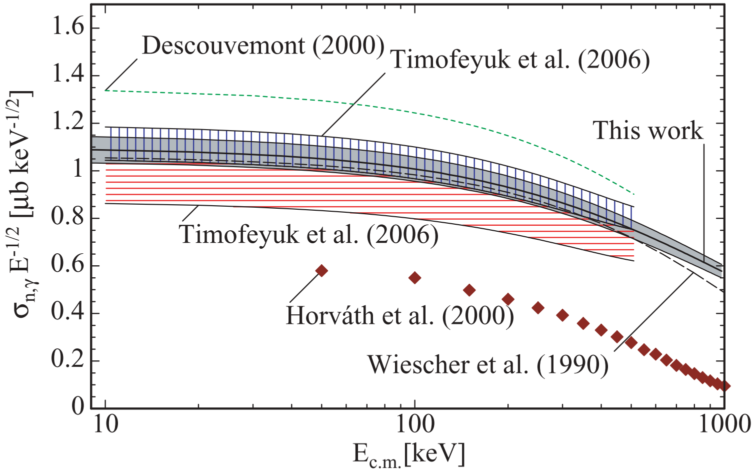
Guillaume Hupin‖
Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

$^{14}C(n,\gamma)^{15}C$ capture

- Comparison to Karlsruhe experiment – Phys. Rev. C 77, 015804 (2008)







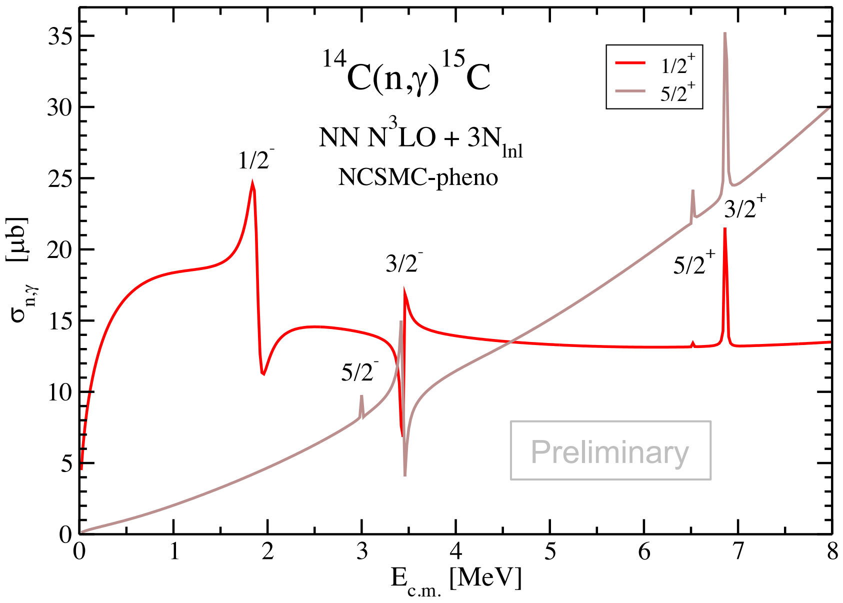
Relevant for

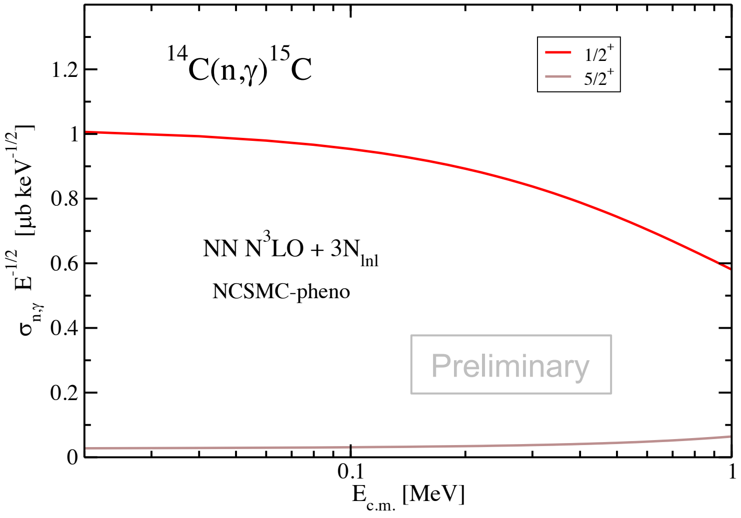
Inhomogeneous Big Bang models

Neutron induced CNO cycles

Neutrino driven wind models for the r-process

Validation of Coulomb dissociation method





Conclusions

- *Ab initio* NCSM and NCSMC with chiral EFT interactions as input applied to
- Tests of fundamental symmetries
    - Nuclear-structure corrections to β-decay observables
    - Structure corrections for the extraction of the V_{ud} matrix element from the Fermi transitions
    - Anapole and electric dipole moments of light nuclei
    - Proton capture on ^{7}Li and the hypothetical X17 boson
- Nuclear structure studies
    - Near-threshold resonances
    - Halo nuclei
- Nuclear astrophysics
    - Proton and neutron capture reactions