TRIUMF

Radiative Capture and Pair Production in $p + {}^{7}\mathrm{Li}$

Peter Gysbers
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UBC

APCTP: Aug. 11, 2022

Discovery, accelerated

Radiative Capture $A + B \to C + \gamma$

- Notation: $B(A, \gamma)C$
- A nuclear reaction that often occurs in astrophysics:
  - Stellar burning: $d(p,\gamma)^3\mathrm{He}$, $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$, ...
  - Big Bang Nucleosynthesis: $d(p,\gamma)^3\mathrm{He}$, $^4\mathrm{He}(d,\gamma)^6\mathrm{Li}$, ...
  - Search for new physics: $^7\mathrm{Li}(p,\gamma)^8\mathrm{Be}$, $^3\mathrm{H}(p,\gamma)^4\mathrm{He}$

More Notation:
$d = {}^2\mathrm{H}$
$\alpha = {}^4\mathrm{He}$

adapted from:
Feng PRD **95**, 035017 (2017)

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Calculating Radiative Capture

To calculate the rate of reaction (cross section) we need:

- initial wavefunction: $|\Psi_i\rangle$ $(A + B)$
- final wavefunction: $|\Psi_f\rangle$ (C)
- photon interaction (electromagnetic operator): $\hat{O}_\gamma$

We need to calculate the square of the transition matrix elements:

$$\sigma \sim \sum_{if} |\langle\Psi_f|\,\hat{O}_\gamma\,|\Psi_i\rangle|^2$$

Bound States: $\left|\Psi_f\right\rangle = \left|J_f^{\pi_f} T_f\right\rangle$

Eigenstate of the nuclear Hamiltonian:

$$H^A \left|\Psi_k\right\rangle = E_k \left|\Psi_k\right\rangle \text{, where } H^A = \sum_i^A T_i + \sum_{i<j} V_{ij}^{NN} + \sum_{i<j<f} V_{ijf}^{3N}$$

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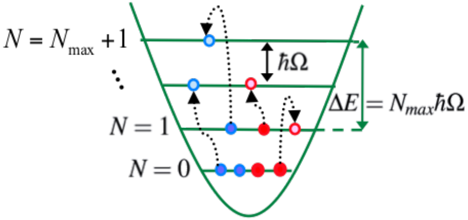
The No-Core Shell Model (NCSM)

Expand in anti-symmetrized products of harmonic oscillator single-particle states:

$$|\Psi_k\rangle = \sum_{N=0}^{N_{max}} \sum_j c_{Nj}^k |\Phi_{Nj}\rangle$$



Convergence to exact as $N_{max} \to \infty$

Unbound (Continuum) States: $|\Psi_i\rangle = \left| \left[|\Psi_A\rangle \, |\Psi_B\rangle \, \psi(\vec{r}_A - \vec{r}_B) \right]^{(J_i^{\pi_i} T_i)} \right\rangle$

- The incoming state is made of distinct clusters with relative motion
- Harmonic oscillator states cannot describe the tail of the wavefunction (long-range physics)
- A method beyond the NCSM is needed for scattering and reactions

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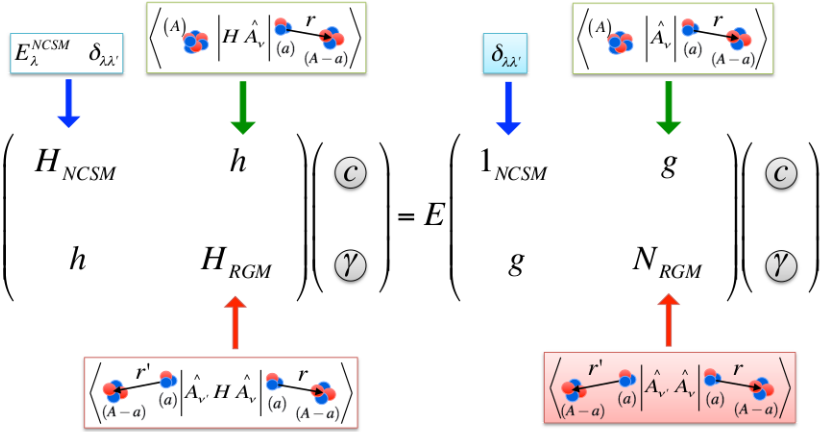
No-Core Shell Model with Continuum (NCSMC)

- Solution: extend the NCSM basis!

NCSMC Equations

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



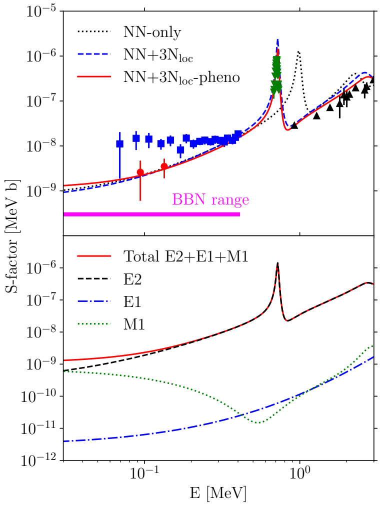
Results Part I

Radiative capture: $^{4}\mathrm{He} + d \to {}^{6}\mathrm{Li} + \gamma$

Recent results for $^4\mathrm{He}(d,\gamma)^6\mathrm{Li}$

[Hebborn et al.
PRL **129**, 042503 (2022)]

$$\Psi^{(6)}_{\text{NCSMC}} = \sum_{\lambda} c_\lambda \left|^6\mathrm{Li},\lambda\right\rangle + \sum_{\nu} \int \mathrm{d}r \gamma_\nu(r) \hat{\mathcal{A}}_\nu \left|^4\mathrm{He}+d,\nu\right\rangle$$



Process:

- Solve NCSM for each constituent nucleus i.e. $^6\mathrm{Li}, ^4\mathrm{He}$ and d ($^2\mathrm{H}$)
- Solve NCSMC for $c_\lambda(E)$, $\gamma_\nu(r,E)$
- Cross-section (S-factor) depends on transition matrix elements e.g. $\langle\Psi(E_0)|\,M1\,|\Psi(E)\rangle$

$$S = \sigma \cdot E e^{\sqrt{\frac{E_G}{E}}}$$

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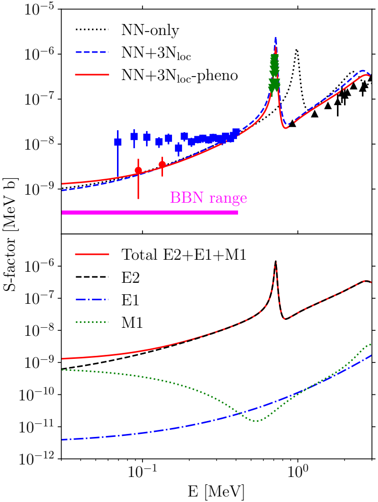


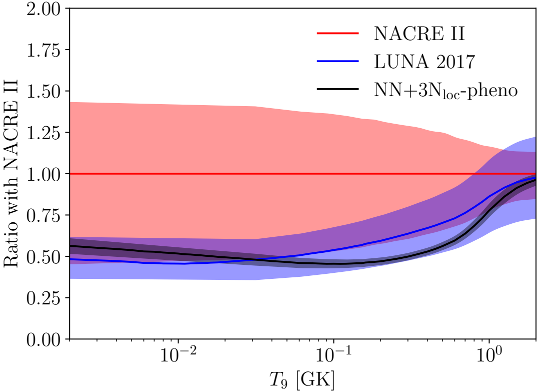
Results:

- Agreement with red points (direct measurement)
- Disagreement with blue points
  (indirect: $^6\mathrm{Li}$ disintegration on a lead target)
- "pheno" fits input NCSM energies to $^6\mathrm{Li}$ g.s.
- Can predict the S-factor at BBN energies
- Previous studies neglect M1 and don't include internal structure of clusters

$$S = \sigma \cdot E e^{\sqrt{\frac{E_G}{E}}}$$

Impact on Reaction Rates

- Reaction rate $\propto \int E\sigma(E)\exp(-E/k_BT)\mathrm{d}E$
- Rate smaller than NACRE II evaluation (2013) with less uncertainty
- Agreement with LUNA result (2017)



[Hebborn et al.
PRL **129**, 042503 (2022)]

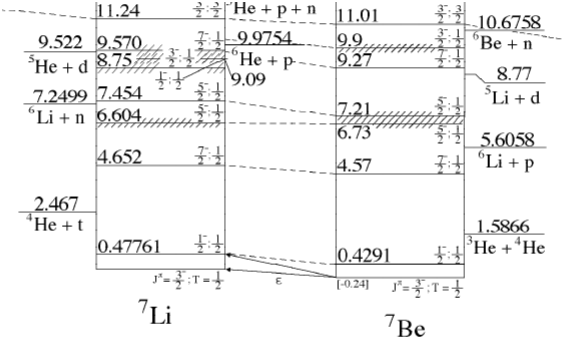
Results Part II

Radiative capture: $^{7}\mathrm{Li} + p \to {}^{8}\mathrm{Be} + \gamma$
Pair production: $^{7}\mathrm{Li} + p \to {}^{8}\mathrm{Be} + e^{+}e^{-}$

Input States from NCSM

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

- 3 NCSM calculations: ${}^{7}\text{Li}$, ${}^{7}\text{Be}$ and ${}^{8}\text{Be}$
- $\{\frac{3}{2}^{-}, \frac{1}{2}^{-}, \frac{7}{2}^{-}, \frac{5}{2}^{-}, \frac{5}{2}^{-}\}$ ${}^{7}\text{Li}$ and ${}^{7}\text{Be}$ states in cluster basis
- 15 positive and 15 negative parity states in ${}^{8}\text{Be}$ composite state basis



TUNL Nuclear Data Evaluation Project

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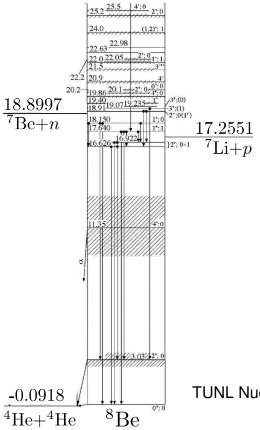


TUNL Nuclear Data Evaluation Project

NCSMC for $^7\mathrm{Li}(p,\gamma)^8\mathrm{Be}$

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

Process:

- Solve NCSM for each constituent nucleus: $^8\mathrm{Be}$, $^7\mathrm{Li}$ and $^7\mathrm{Be}$
  - 30 eigenstates from $^8\mathrm{Be}$
  - 5 eigenstates each from $^7\mathrm{Li}$ and $^7\mathrm{Be}$
- Solve NCSMC for $c_\lambda(E)$, $\gamma_\nu(r,E) \to \Psi(E)$
- Cross-section depends on transition matrix elements e.g. $\langle\Psi(E_0)|\, M1 \,|\Psi(E)\rangle$

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

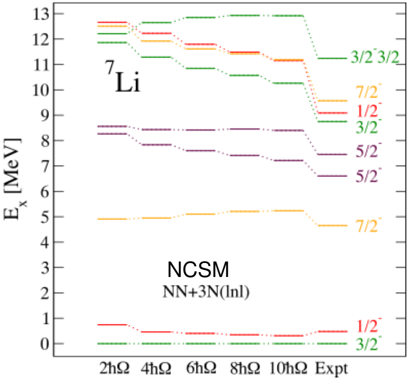
Interaction: Chiral NN N^{3}LO + 3N(lnl)

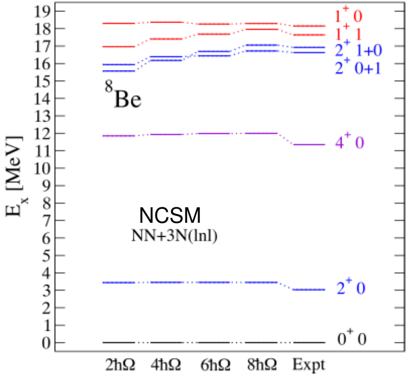
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

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

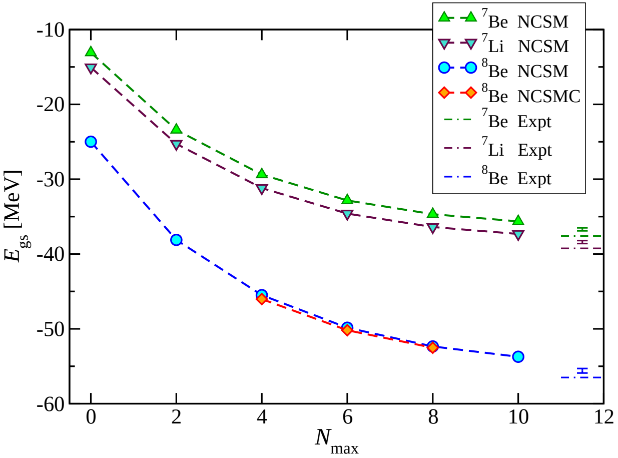
- Good description of excitation energies in light nuclei
- Hamiltonian determined in $A = 2, 3, 4$ systems
  - Nucleon-nucleon scattering, deuteron, ^{3}H, ^{4}He

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





Convergence of ground state energies:



NCSMC Results

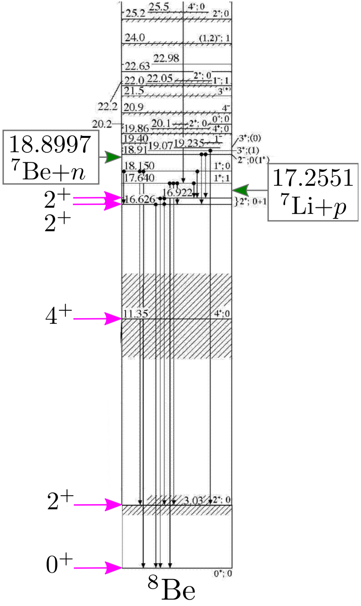
- ■ $^{8}\mathrm{Be}$ Structure
- ☐ Scattering: $^{7}\mathrm{Li}(p,p)^{7}\mathrm{Li}$
- ☐ Transfer Reactions: $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$, $^{7}\mathrm{Be}(n,p)^{7}\mathrm{Li}$
- ■ Radiative Capture: $^{7}\mathrm{Li}(p,\gamma)^{8}\mathrm{Be}$
- ■ Search for new physics: $^{7}\mathrm{Li}(p,X)^{8}\mathrm{Be}$

^{8}Be Structure

Calculations of ^{8}Be “bound” states (w.r.t. ^{7}Li $+ p$ threshold) are improved by inclusion of the continuum ($N_{max} = 9$)

State	Energy [MeV]		
	NCSM	NCSMC	Experiment
0^+	-15.96	-16.13	-17.25
2^+	-12.51	-12.72	-14.23
4^+	-3.97	-4.31	-5.91
2^+	$+0.76$	-0.10	-0.63
2^+	$+1.09$	$+0.31$	-0.33

- Energies likely too high due to neglected $\alpha + \alpha$ breakup
- Matches experiment well, except the 3rd 2^+ is still slightly above the ^{7}Li $+ p$ threshold



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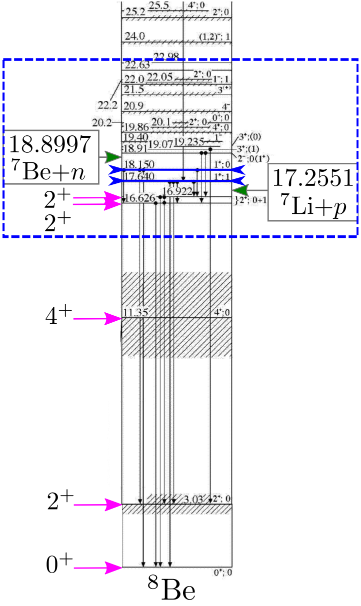
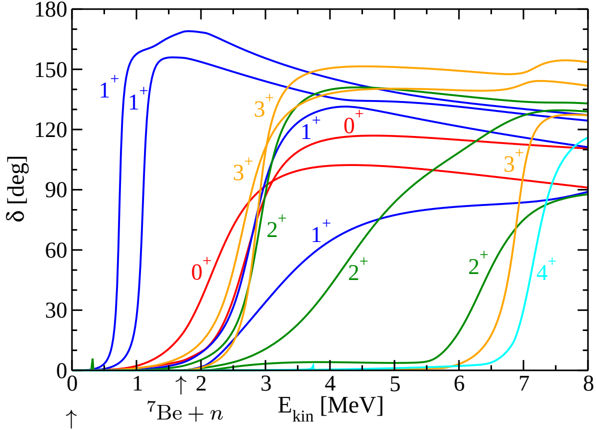
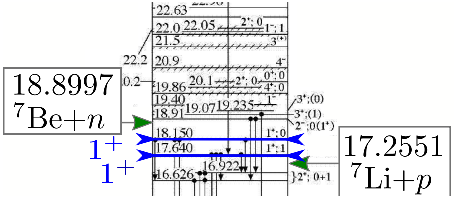


TUNL Nuclear Data Evaluation Project

Eigenphase-shift Results (positive parity)



↑
^{7}Li + p threshold



Additional resonances are seen compared to TUNL data

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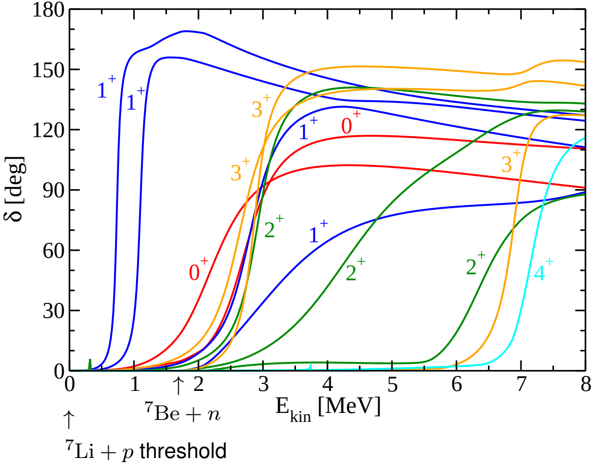

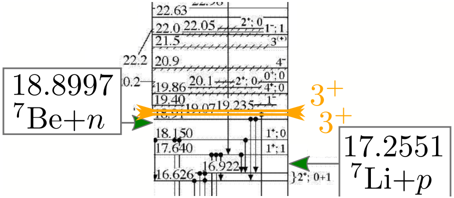

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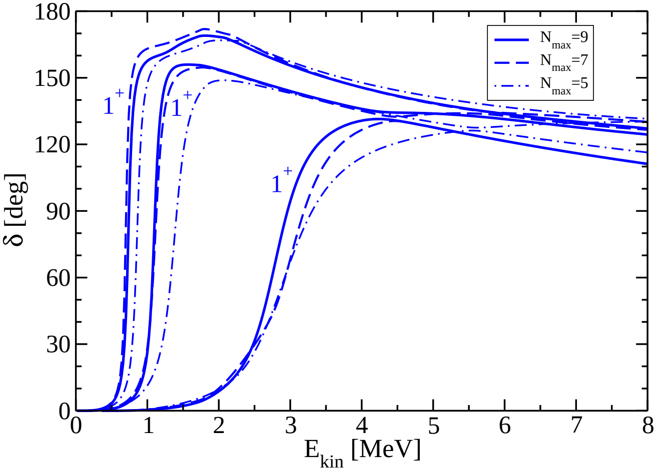
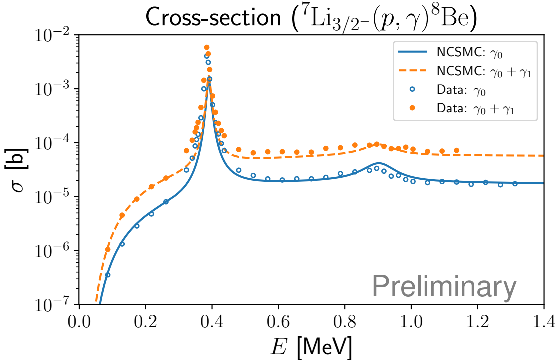
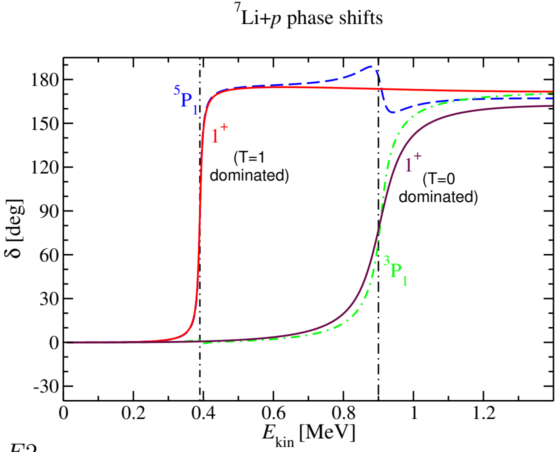
Convergence with N_{max}



Radiative Capture

$$^{2S+1}P_J : \left[\left(\left| ^7\mathrm{Li} \right\rangle |p\rangle \right)^{(S)} Y_L(\hat{r}) \right]^J$$
$$P : L = 1$$





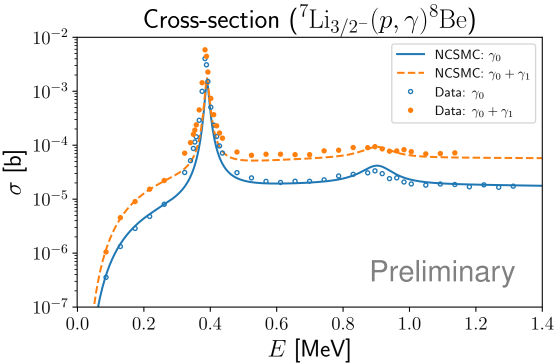
γ_0: decay to ground state (0^+)
γ_1: decay to first excited (2^+)

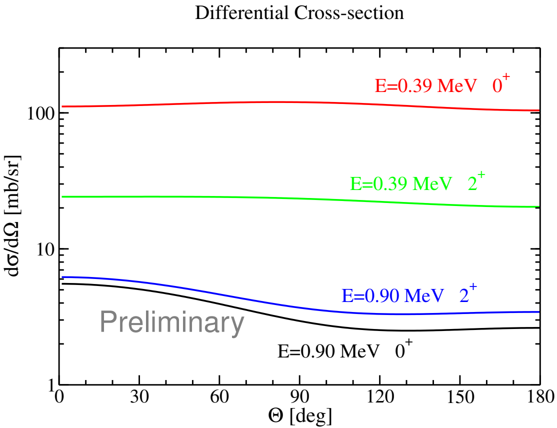
$$\hat{O}_\gamma = E1 + M1 + E2$$

Phenomenological adjustment: fit threshold and resonance positions to match experiment

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

Radiative Capture (cont.)





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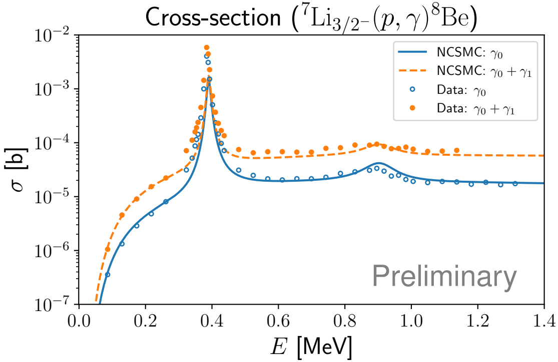

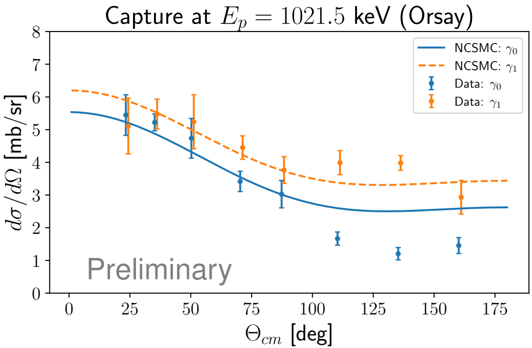

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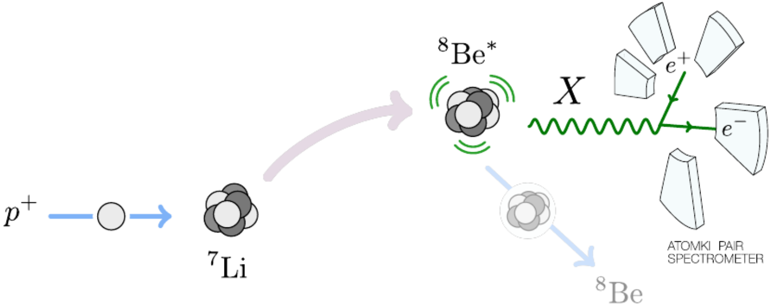
The X17 Anomaly in $p + {}^7\mathrm{Li} \to {}^8\mathrm{Be} + e^+e^-$

- ${}^7\mathrm{Li}(p, e^+e^-){}^8\mathrm{Be}$ @ATOMKI (Hungary)
- The decay of ${}^8\mathrm{Be}\ 1^+$ excited states produces electron-positron pairs



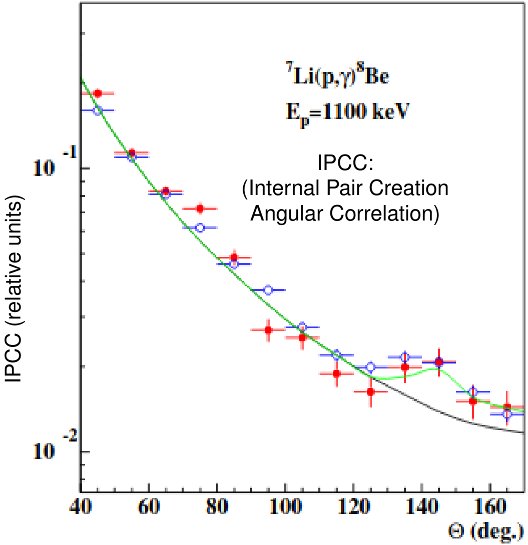
Feng PRD **95**, 035017 (2017)

The X17 Anomaly in $p + {}^7\mathrm{Li} \to {}^8\mathrm{Be} + e^+e^-$

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

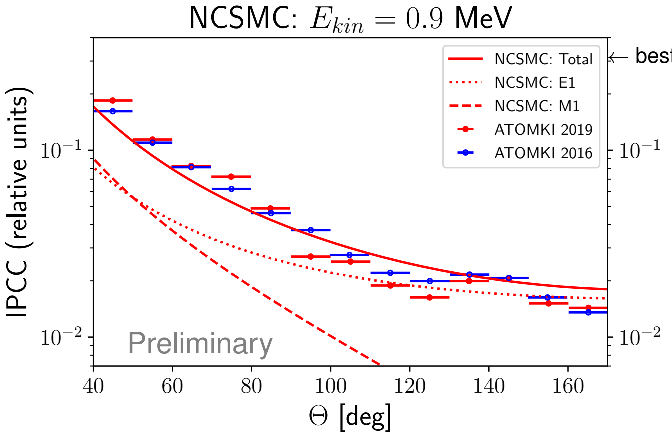
- The angle θ between the electron and positron was measured
- Minimum angle from a massive intermediate particle: $\theta \simeq \sin^{-1}(\frac{m_X}{E_X})$
- Bump could be explained by 17 MeV bosons decaying to e^+e^-

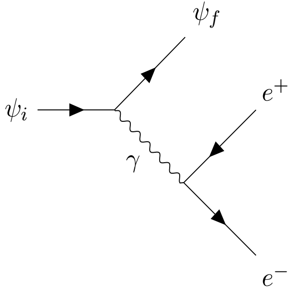
Can *ab initio* nuclear physics help interpret the anomaly?



Pair Production Distribution

- Approximate calculation
  - based on Hayes [PRC **105**, 055502 (2022)]



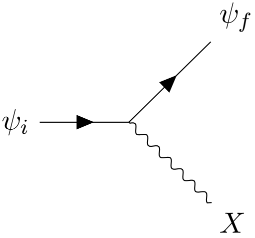


X17 Candidate Bosons

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

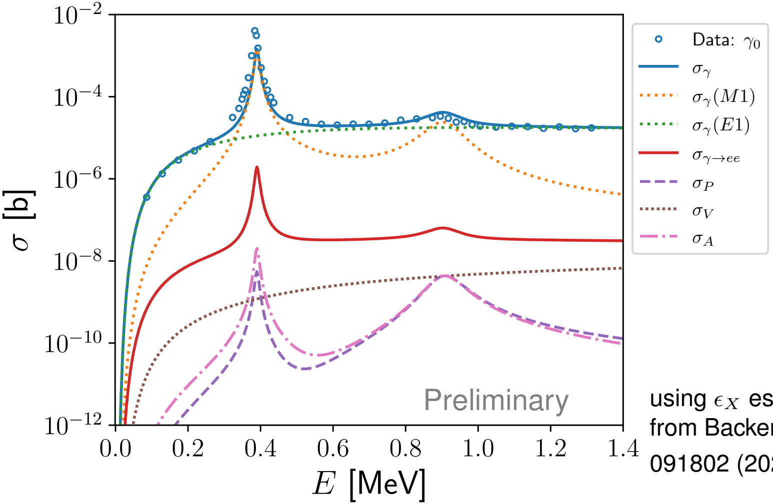
Operators for $1^\pm \to 0^+$ decay (in the long-wavelength approximation)

- 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)
  $\langle E1 \rangle \sim \langle r Y_1 \rangle k_\gamma$
  $\langle M1 \rangle \sim \left(g_l \left\langle \hat{L} \right\rangle + g_s \left\langle \hat{S} \right\rangle \right) k_\gamma$



[Backens, PRL **128**, 091802 (2022)]

Preliminary $^7\mathrm{Li}(p,X)^8\mathrm{Be}$ Cross-sections



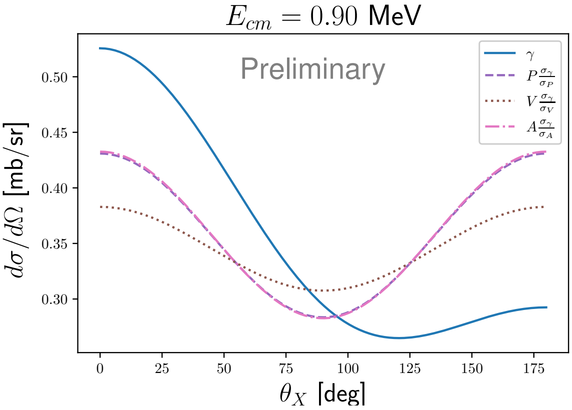
Pseudo-scalar (0^-)
Vector (1^-)
Axial-vector (1^+)

using ϵ_X estimates from Backens, PRL **128** 091802 (2022)

Angular Distributions

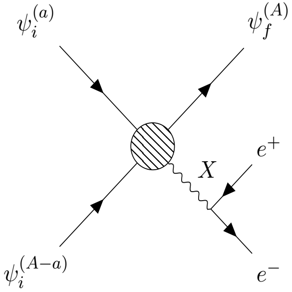
- Ongoing and planned experiments at Orsay and Montreal will provide an independent verification of the anomaly
- They can change the angle (relative to the beam) at which the pairs are measured

(ATOMKI: $\theta_X = 90°$)



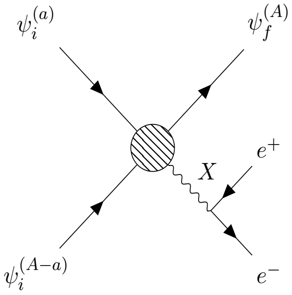
In progress

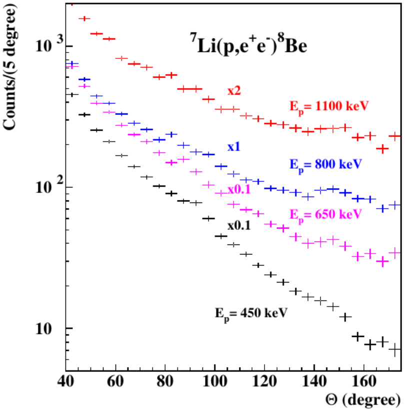
- Full continuum→bound calculation
  - expect E1-M1 interference between different LSJ channels in angular distributions



In progress

- Full continuum→bound calculation
  - expect E1-M1 interference between different LSJ channels in angular distributions
- Comparison to new ATOMKI data (2205.07744)
  - bump observed off-resonance suggests vector character





Summary

- NCSMC successfully describes the spectrum of $^{8}\mathrm{Be}$ including the 1^{+} resonances
- Calculations of $^{7}\mathrm{Li}(p,\gamma)^{8}\mathrm{Be}$ radiative capture match data

Outlook

- Compare $^{7}\mathrm{Li}(p,e^{+}e^{-})^{8}\mathrm{Be}$ to data with $\gamma \to e^{+}e^{-}$ operator
  and various $X \to e^{+}e^{-}$ operators (e.g. axions, vector bosons, axial vector bosons)
- Calculations of $^{3}\mathrm{H}(p,e^{+}e^{-})^{4}\mathrm{He}$ are also relevant to the X17 anomaly
- Explore charge-exchange reactions relevant for nucleosynthesis:
  $^{7}\mathrm{Be}(n,p)^{7}\mathrm{Li}$, $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$

Backup Slides

Constraints on m_X

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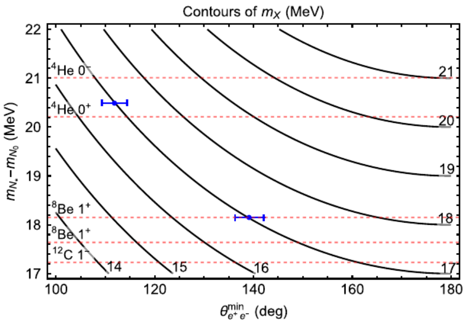
In the frame of the X boson the electron and positron momenta are anti-parallel.
Boosted to a minimum separation angle:

$$\theta = 2\sin^{-1}\left(\frac{m_X}{E_X}\right)$$

- $^8\mathrm{Be}$ anomaly occurs in the isoscalar transition (decay of 1^+0 resonance)
- In-between resonances in $^4\mathrm{He}$
- Bumps could be explained by 17 MeV bosons decaying to e^+e^-



Exclusion Plot

Current (gray) and projected sensitivities of future experiments

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