Ab Initio Investigation of $^{7}\mathrm{Li}(p,\gamma)^{8}\mathrm{Be}$ and $^{7}\mathrm{Li}(p,e^{+}e^{-})^{8}\mathrm{Be}$

Peter Gysbers
Facility for Rare Isotope Beams

TRIUMF - February 27, 2024

Acknowledgements

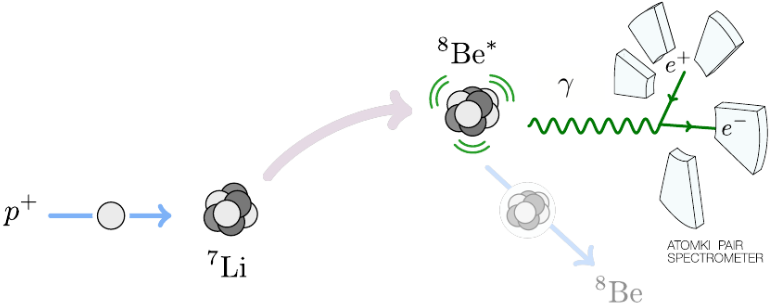
Based on my PhD thesis at the University of British Columbia
Submitted PRC **arXiv:2308.13751**

Coauthors

- TRIUMF: Petr Navratil
- LLNL: Sofia Quaglioni, Kostas Kravvaris
- IJCLab: Guillaume Hupin

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) [PRL **116** 042501 (2016)]
- Decay of composite ${}^8\mathrm{Be}$ produces electron-positron pairs



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

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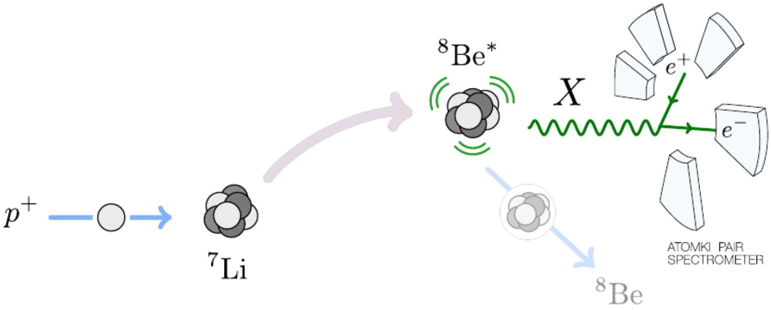
- Decay of composite ${}^8\mathrm{Be}$ produces electron-positron pairs
- Anomaly in pair distribution at the energy of the second 1^+ resonance



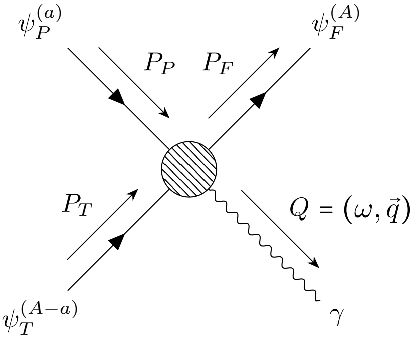
[Feng PRD **95**, 035017 (2017)]

Radiative Capture: $P + T \to F + \gamma$

- Notation: $T(P, \gamma)F$
- Often astrophysically relevant:
  - 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: $^7\mathrm{Li}(p,\gamma)^8\mathrm{Be}$, $^3\mathrm{H}(p,\gamma)^4\mathrm{He}$, $^{11}\mathrm{B}(p,\gamma)^{12}\mathrm{C}$

[Adapted from:
Feng PRD **95**, 035017 (2017)]

Calculating Radiative Capture



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

- initial wavefunction: $|\Psi_i\rangle$ $(P+T)$
- final wavefunction: $|\Psi_f\rangle$ (F)
- photon interaction (electromagnetic operator): $\hat{O}_\gamma(\lambda, q) = \vec{e}^{\,*}_\lambda \cdot \vec{\mathcal{J}}(q) \sim \sum_{J\geq 1} \lambda \mathcal{T}^{MJ}_\lambda(q) + \mathcal{T}^{EJ}_\lambda(q)$
- transition matrix elements: $\langle \Psi_f | \hat{O}_\gamma | \Psi_i \rangle$

$$\sigma \sim \sum\!\!\!\!\!\!\int \mathrm{d}q \left| \langle \Psi_f | \hat{O}_\gamma | \Psi_i \rangle \right|^2$$

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

$NN + 3N_{lnl}$

Somá et al, PRC **101** 014318 (2020)

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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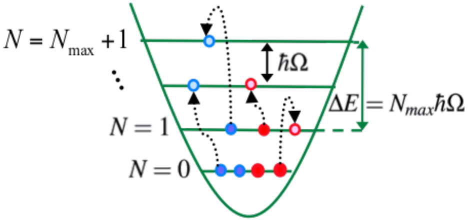
The No-Core Shell Model (NCSM)

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 an exact solution as $N_{max} \to \infty$

Unbound (Continuum) States: $|\Psi_i\rangle = \left[\left(|\psi_P\rangle \, |\psi_T\rangle \right)^{(S_i)} \psi_{L_i}(\vec{r}_P - \vec{r}_T) \right]^{(J_i^{\pi_i})}$

- The incoming state is made of distinct clusters with relative motion
- Harmonic oscillator states cannot describe long-range physics (the tails of the wavefunction are too small)
- A method beyond the NCSM is needed for scattering, reactions and proper bound state asymptotics

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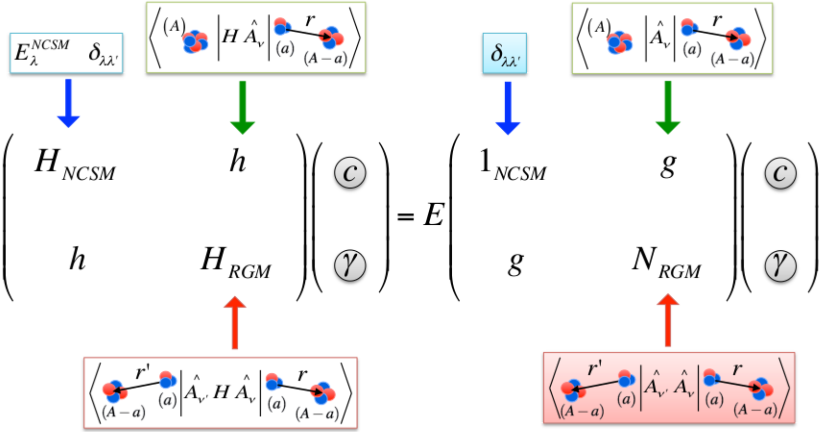
No-Core Shell Model with Continuum (NCSMC)

- Solution: extend the NCSM basis!

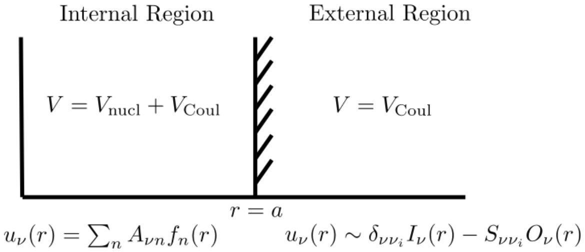
$$\Psi^{(A)} = \sum_{\lambda} c_\lambda \left|^{(A)} \, , \lambda \right\rangle + \sum_{\nu} \int d\vec{r} \; \gamma_\nu(\vec{r}\,) \; \hat{A}_\nu \left|_{(A-a)} \overset{\vec{r}}{\longrightarrow} {}_{(a)} \, , \nu \right\rangle$$

NCSMC Equations

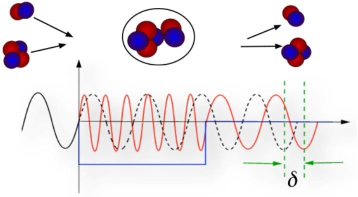
$$H\,\Psi^{(A)} = E\,\Psi^{(A)}$$



More Details



- R-matrix on a Lagrange mesh
- Solve for generalized S-matrix: $S^{J\pi}_{\nu\nu_i}$
- Diagonal phase shifts: $S^{J\pi}_{\nu\nu} = e^{2i\delta^{J\pi}_\nu}$
- Eigen-phase shifts: $e^{2i\delta^{J\pi}_\mu}$, eigenvalues of S



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

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

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 $c_{\lambda}(E)$, $\gamma_{\nu}(r,E)$, $\gamma_{\mu}(r,E) \to |\Psi(E)\rangle$
- Cross-section depends on transition matrix elements e.g. $\left\langle \Psi(E_f)\right| M1 \left|\Psi(E_i)\right\rangle$

Results

The NCSMC allows simultaneous calculation of many observables

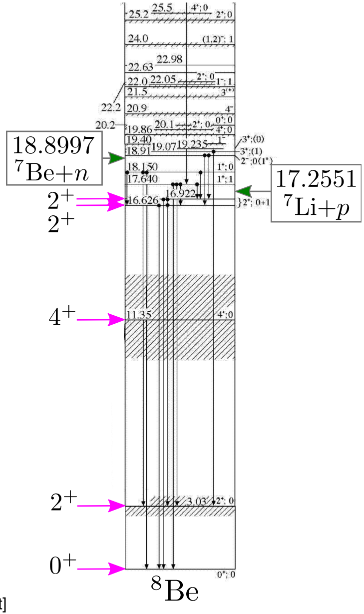
- ● $^{8}\mathrm{Be}$ Structure
- ◐ Scattering: $^{7}\mathrm{Li}(p,p)^{7}\mathrm{Li}$, $^{7}\mathrm{Be}(n,n)^{7}\mathrm{Be}$
- ○ Transfer Reactions: $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$, $^{7}\mathrm{Be}(n,p)^{7}\mathrm{Li}$
- ● Radiative Capture: $^{7}\mathrm{Li}(p,\gamma)^{8}\mathrm{Be}$
- ● Search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

$^{8}\mathrm{Be}$ Structure

Calculations of $^{8}\mathrm{Be}$ “bound” states (w.r.t. $^{7}\mathrm{Li} + p$ 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 $^{7}\mathrm{Li} + p$ threshold



[TUNL Nuclear Data Evaluation Project]

^{8}Be Structure

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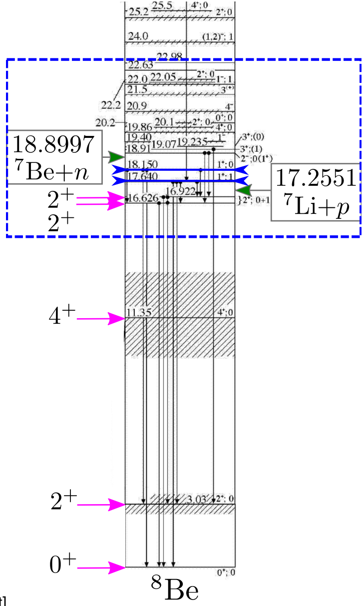
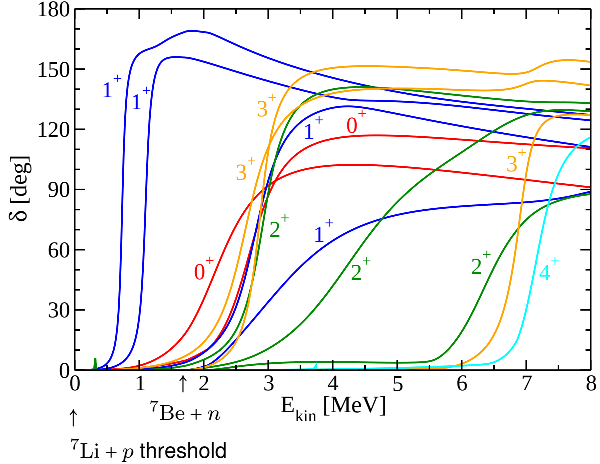
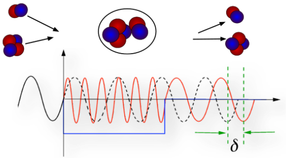
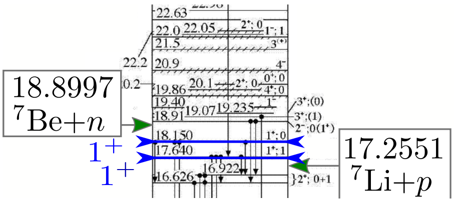


[TUNL Nuclear Data Evaluation Project]

Eigenphase-shift Results (positive parity)

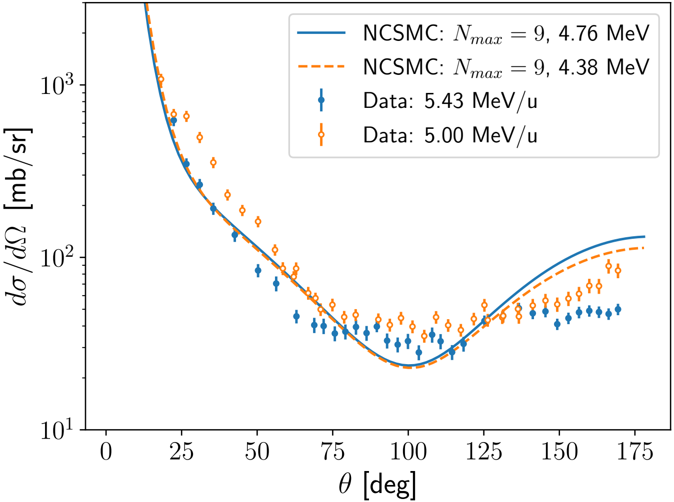






Additional resonances are seen compared to TUNL data evaluation

$^7\mathrm{Li}(p,p)^7\mathrm{Li}$ Elastic Scattering

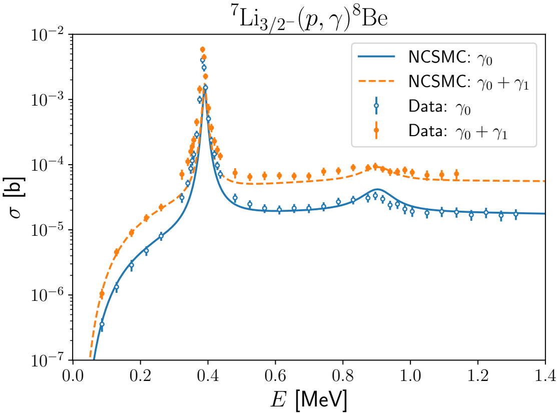


$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \sim \sum_\nu (1 - \Re(S_{\nu\nu}))$$

Radiative Capture

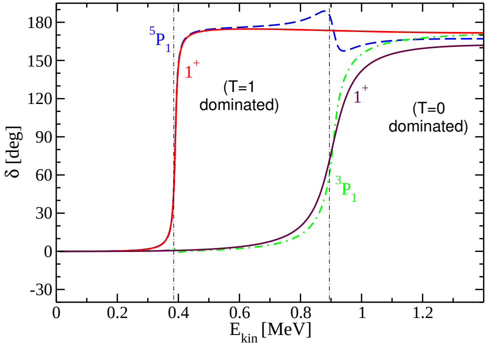
$$\hat{O}_\gamma = E1 + M1 + E2$$

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



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

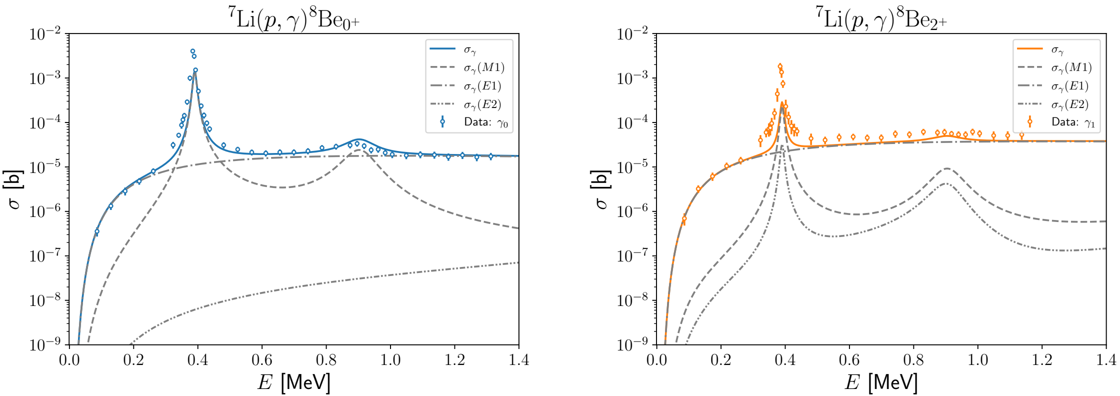
[Data: Zahnow et al
Z.Phys.A **351** 229-236 (1995)]



Phenomenological adjustment: fit threshold and resonance positions to match experiment

Integrated Cross Sections

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



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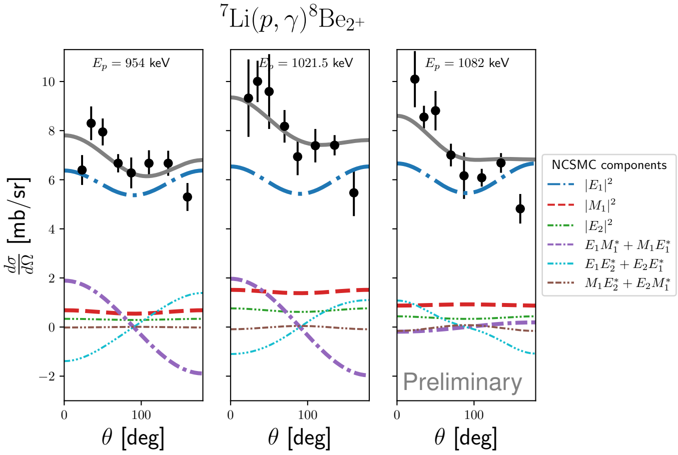
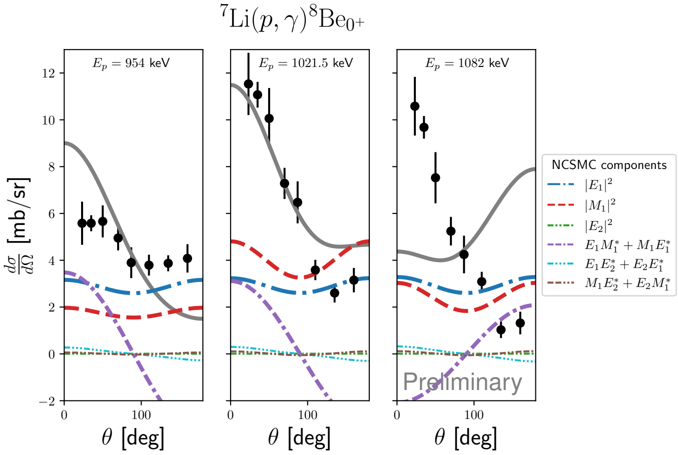
Differential Cross Sections



- Preliminary data from IJCLab (Orsay, FR)
- $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \sim \sum_K a_K P_K(\theta)$
- Interference between initial channels

Differential Cross Sections



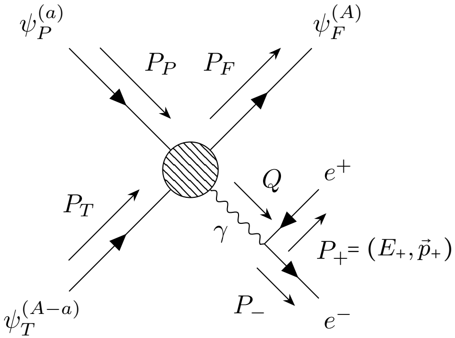
- Preliminary data from IJCLab (Orsay, FR)
- $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \sim \sum_K a_K P_K(\theta)$
- Interference between initial channels
- Data could be contaminated by protons with energy lost in target

Electron-Positron Pair Production

$$\frac{d^4\sigma}{d\Omega_+ d\Omega_-}(\Theta) = \int dy \frac{2\alpha^2}{(2\pi)^3}\frac{\omega p_+ p_-}{Q^4}\sum_{n=1}^{6} v_n R_n$$

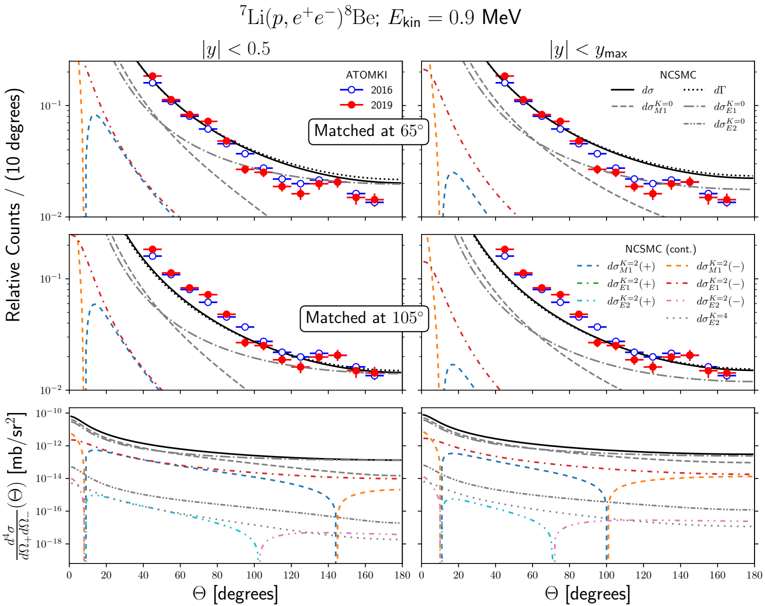
- $\hat{O}_{ee} \sim \ell_\mu \mathcal{J}^\mu$
- v_n are kinematic factors
- R_n are products of operator matrix elements
  - $R_1 \sim |\mathcal{C}|^2$: Coulomb
  - $R_4 \sim |\mathcal{T}|^2$: Transverse
  - others mix e.g. $\mathcal{C}^*\mathcal{T} + \mathcal{T}^*\mathcal{C}$
- y is the "pair asymmetry":

$$y = \frac{E_+ - E_-}{E_+ + E_-}$$



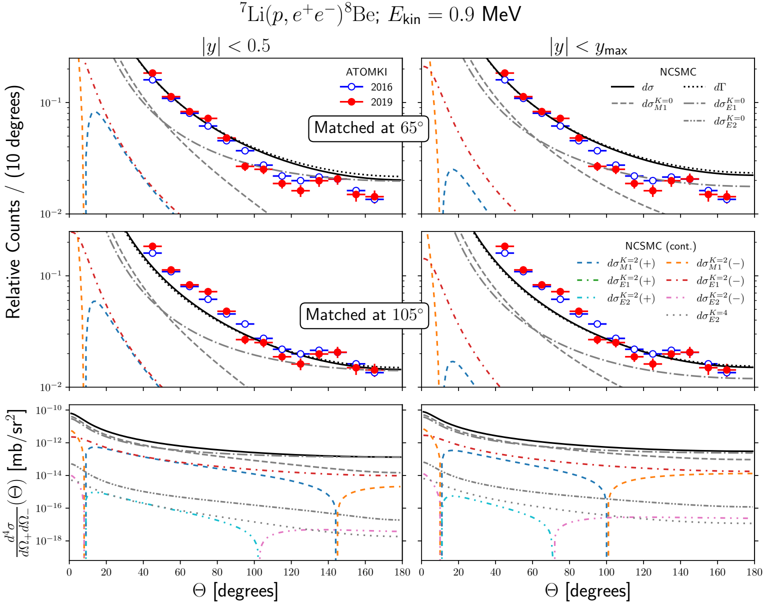
Results

- Measurement against the electron-positron separation angle Θ



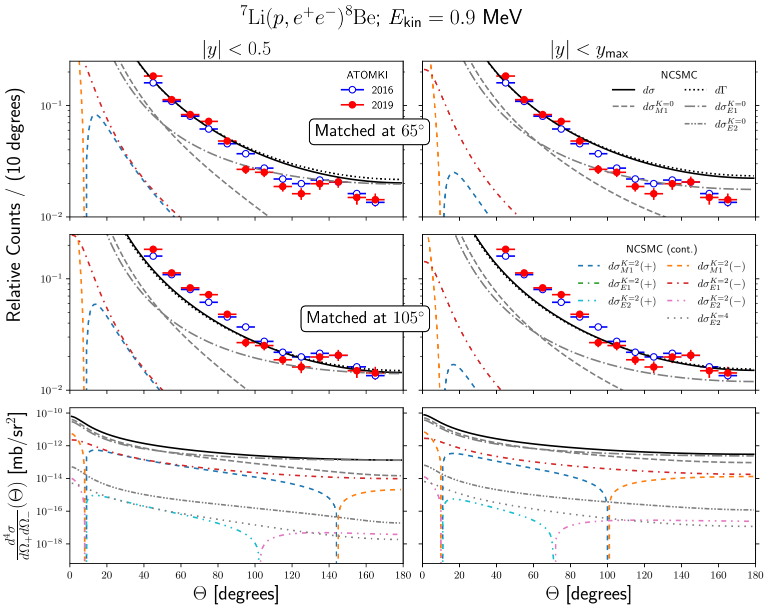
Results

- Measurement against the electron-positron separation angle Θ
  - v_n and Q are functions of $\cos\Theta$
  - $R_n \sim \sum_K a_K^{(n)} P_K(\frac{\pi}{2})$

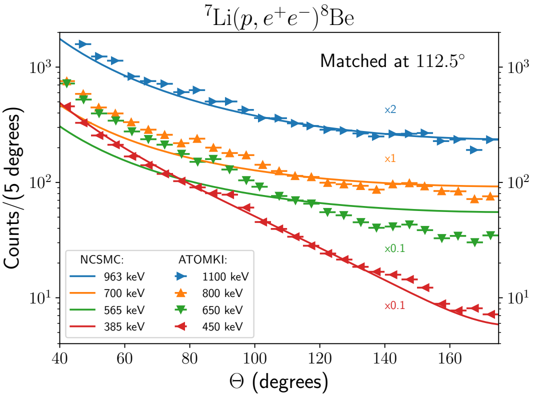


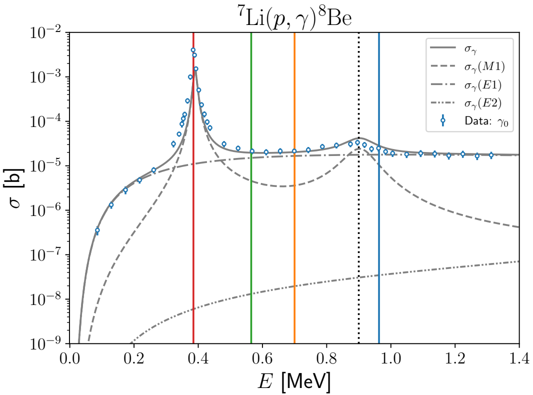
Results

- Measurement against the electron-positron separation angle Θ
  - v_n and Q are functions of $\cos\Theta$
  - $R_n \sim \sum_K a_K^{(n)} P_K(\frac{\pi}{2})$
- $E1$ and $M1$ are dominant
- Inclusion of interference between initial channels improves agreement with data

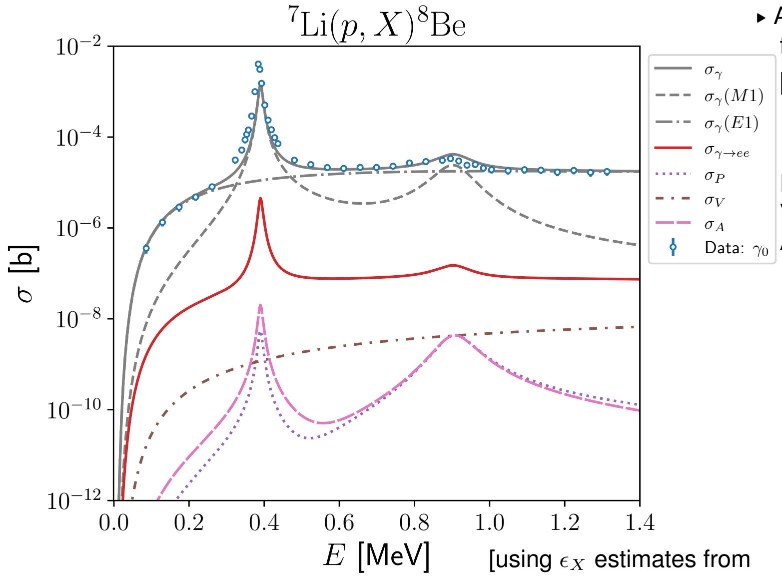


More Results



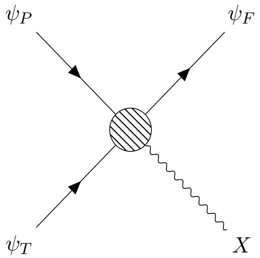


- Updated ATOMKI data (2022) arXiv:2205.07744
- Data in-between resonances seems to be contaminated by $M1$ from first resonance



- A vector X17 is the best candidate for anomalies off-resonance [arXiv:2205.07744]

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



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

Summary and Outlook

- The NCSMC successfully describes the spectrum of ${}^{8}\mathrm{Be}$, radiative capture and electron-positron production
- The X17 remains unconfirmed
  - apparent contamination of data between resonances due to proton energy loss in the thick target
  - independent experimental tests are in analysis phase (e.g. the NewJEDI collaboration)
- To do:
  - ATOMKI experiments in other systems: ${}^{3}\mathrm{H}(p,e^{+}e^{-}){}^{4}\mathrm{He}$, ${}^{11}\mathrm{B}(p,e^{+}e^{-}){}^{12}\mathrm{C}$
  - investigate γ angular distributions at more energies
  - pair production for capture to the 2^{+}
- Investigation and adjustment of higher-lying resonances necessary for scattering and charge exchange reactions