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

Peter Gysbers
Facility for Rare Isotope Beams

NN2024 - August 21, 2024

Acknowledgements

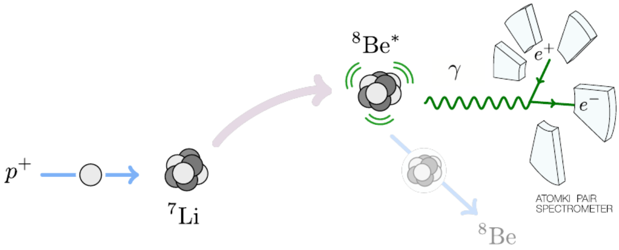
Ab Initio investigation of the $^{7}\mathrm{Li}(p, e^{+}e^{-})^{8}\mathrm{Be}$ process and the X17 boson.
PRC **110**, 015503 (2024) arXiv:2308.13751

Coauthors

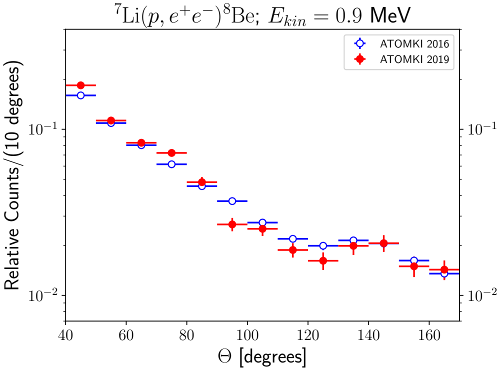
- TRIUMF: Petr Navratil
- LLNL: Sofia Quaglioni, Kostas Kravvaris
- IJCLab: Guillaume Hupin

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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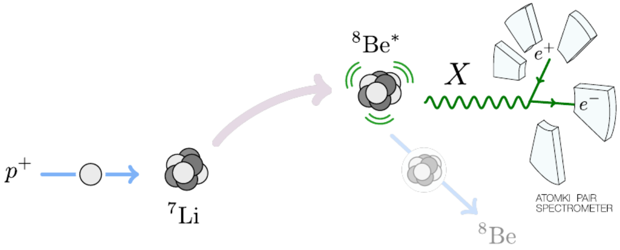

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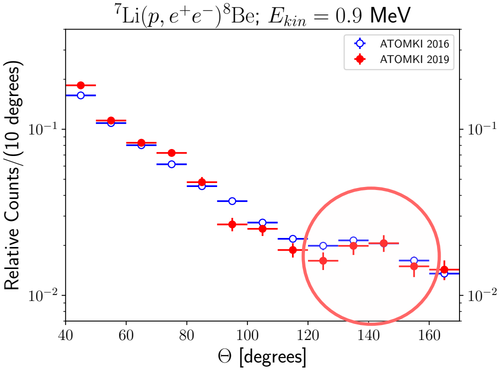

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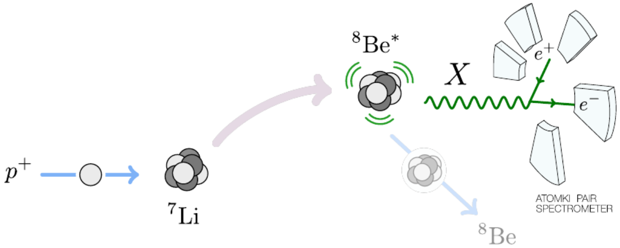
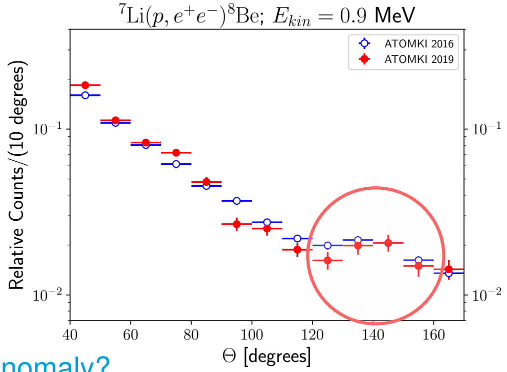
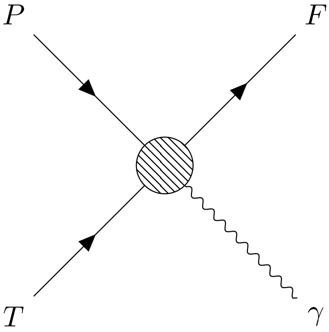
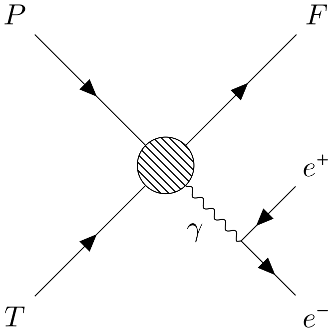




Can *ab initio* nuclear physics help interpret the anomaly?

Radiative Capture: $P + T \to F + \gamma/e^+e^-$





$$\mathrm{d}\sigma \sim \mathrm{d}q_\gamma |\langle\psi(P+T)|\hat{O}_\gamma|\psi(F)\rangle|^2$$

$$\mathrm{d}\sigma \sim \mathrm{d}p_+\mathrm{d}p_- \int \frac{\mathrm{d}q}{q^4} |\langle\psi(P+T)|\hat{O}_{e^+e^-}|\psi(F)\rangle|^2$$

Ab Initio Calculations of Many-Nucleon Systems

Want to find the eigenstates of a realistic Hamiltonian

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

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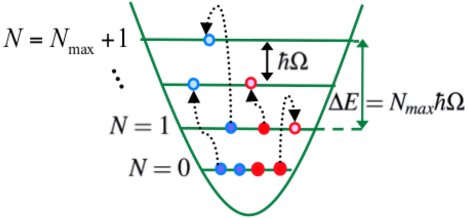
No-Core Shell Model (NCSM)

$$\left|^{(A)} \square, \lambda\right\rangle\rangle = \sum_{N=0}^{N_{\text{max}}} \sum_j c_{Nj}^\lambda \left|\Phi_{Nj}\right\rangle$$



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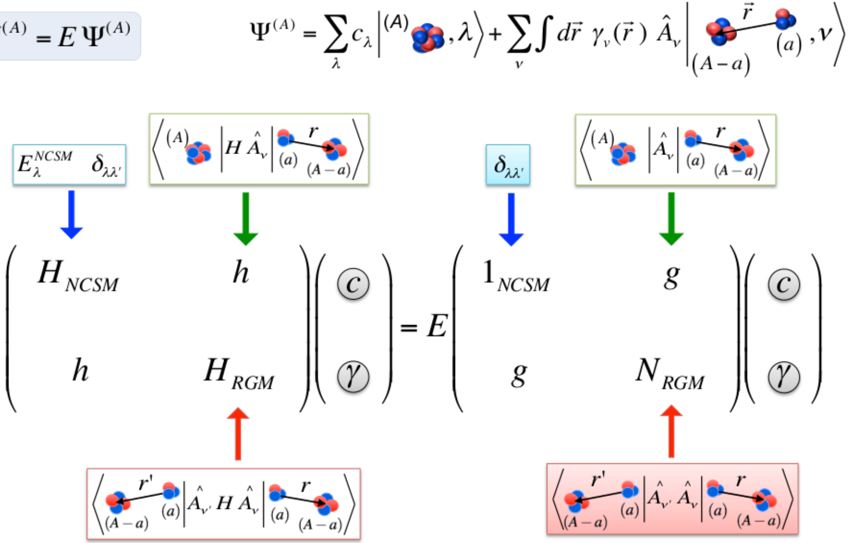
No-Core Shell Model with Continuum (NCSMC)

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

NCSMC Equations

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



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

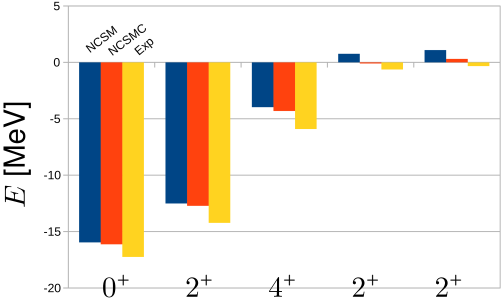
Results

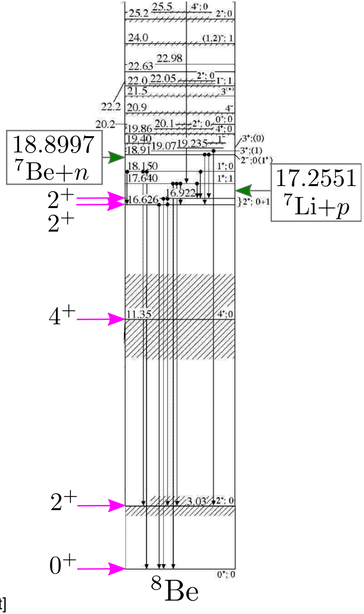
The NCSMC allows simultaneous calculation of many observables

- ● $^{8}\mathrm{Be}$ 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}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)





- 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

[TUNL Nuclear Data Evaluation Project]

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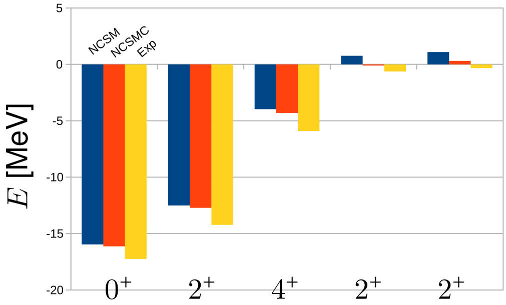

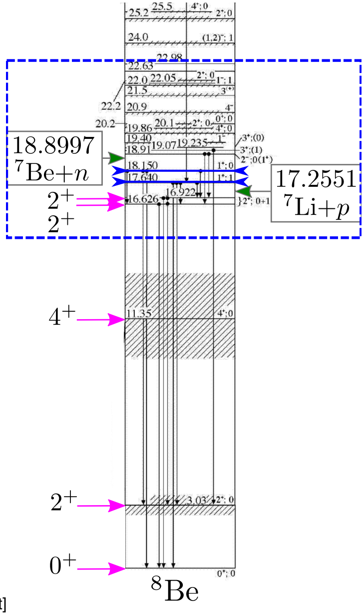

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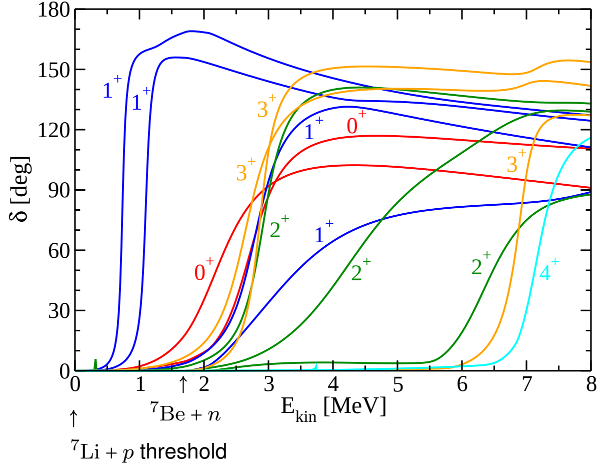
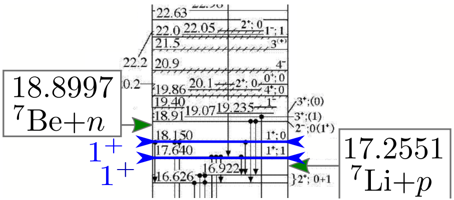
[TUNL Nuclear Data Evaluation Project]

Eigenphase-shift Results (positive parity)



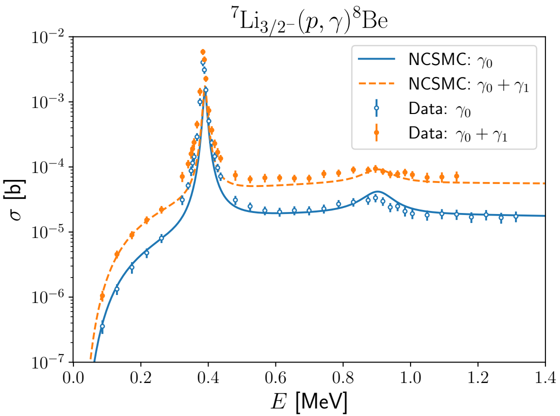


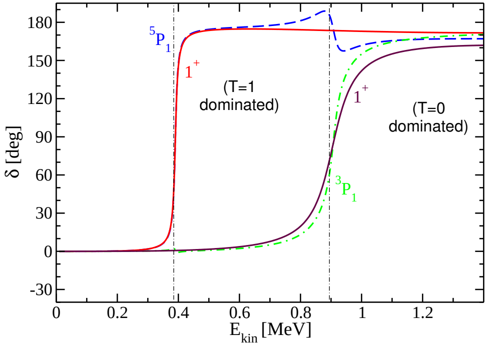
Additional resonances are seen compared to TUNL data evaluation

Radiative Capture (γ)

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

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





γ_0: decay to ground state (0^+)

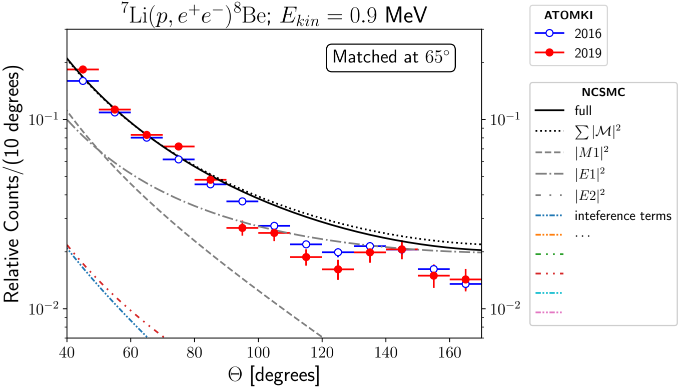
γ_1: decay to first excited (2^+)

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

Phenomenological adjustment: fit threshold and resonance positions to match experiment

Radiative Capture (e^+e^-)

- Counts $\propto$ partially integrated differential cross section



(electron-positron separation angle)

Radiative Capture (e^+e^-)

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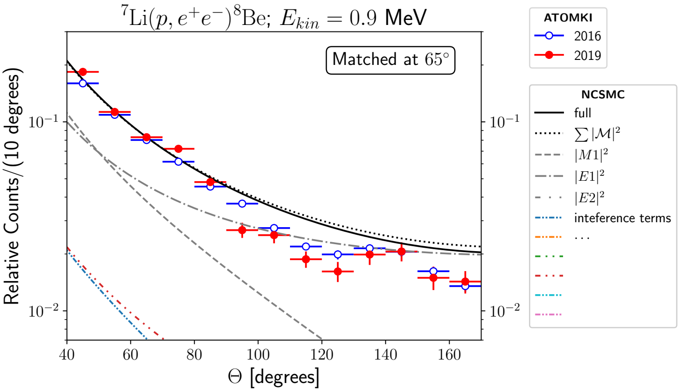
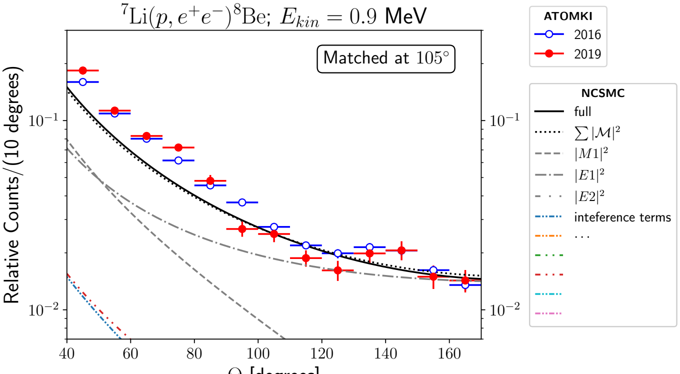
- $E1$ and $M1$ are dominant
- Inclusion of interference between initial channels improves agreement



(electron-positron separation angle)

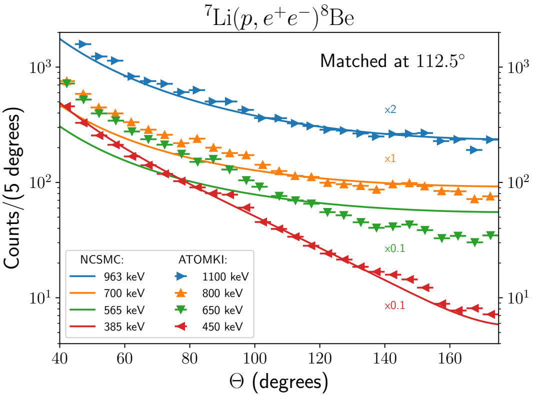
Radiative Capture (e^+e^-)

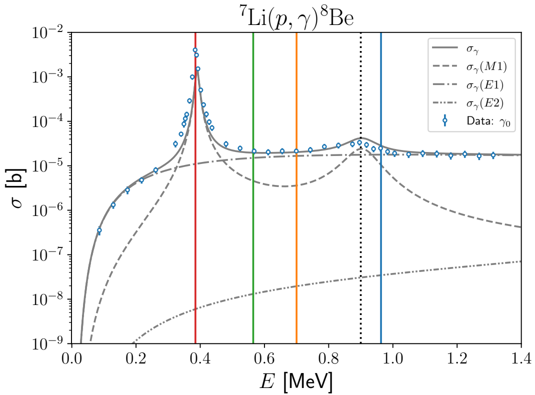
- Counts $\propto$ partially integrated differential cross section
- $E1$ and $M1$ are dominant
- Inclusion of interference between initial channels improves agreement
- But theory and data still inconsistent - possible $M1$ contamination from lower resonance



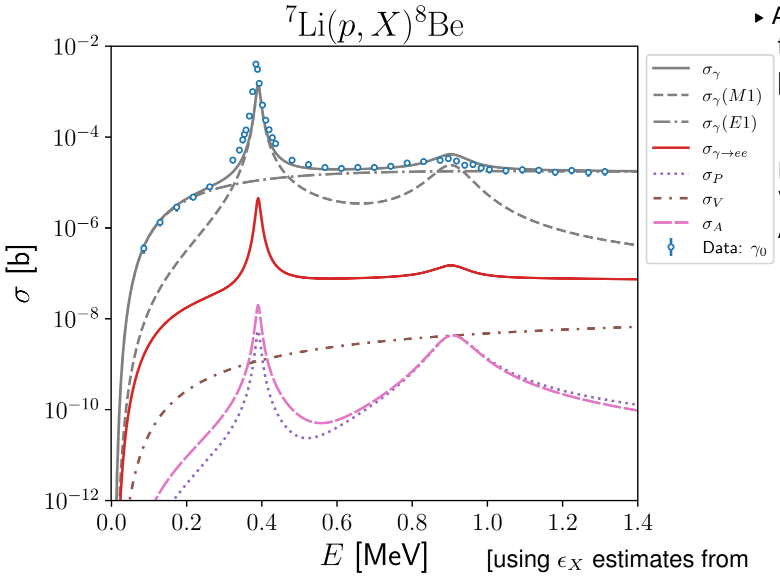
(electron-positron separation angle)

More Results



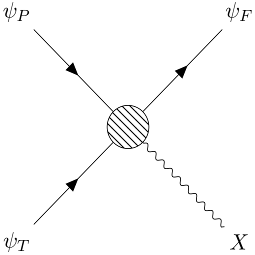


- Updated ATOMKI data (2022) arXiv:2205.07744
- Data in-between resonances seems to be contaminated by $M1$ from first resonance



- 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
  - pair production for capture to the 2^{+}
- Investigation and adjustment of higher-lying resonances necessary for scattering and charge exchange reactions

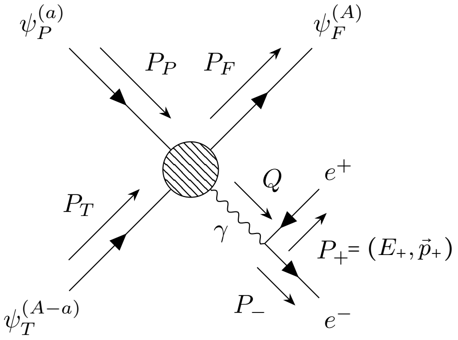
Backup Slides

Electron-Positron Pair Production

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

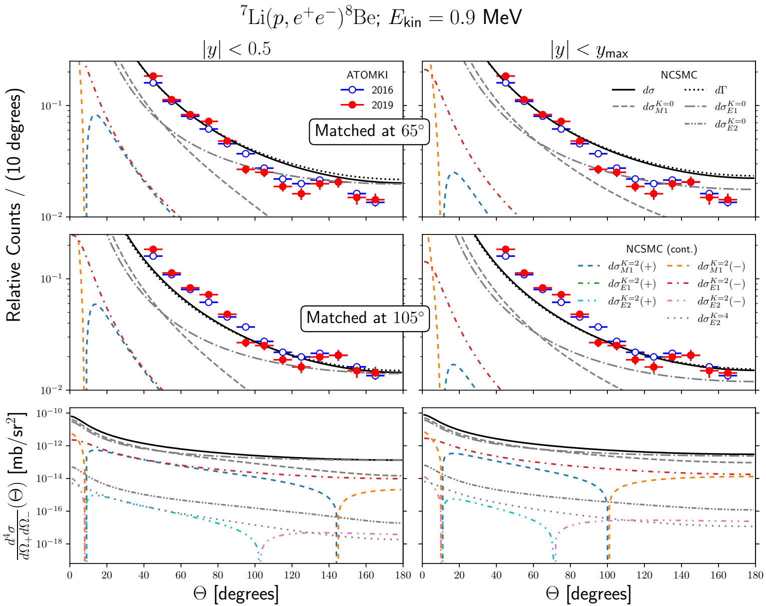
- $\hat{O}_{ee} \sim \ell_\mu \mathcal{J}^\mu$
- v_n are kinematic factors
- R_n are products of operator matrix elements
  - $R_1 \sim |\mathcal{C}|^2$: Coulomb
  - $R_4 \sim |\mathcal{T}|^2$: Transverse
  - others mix e.g. $\mathcal{C}^*\mathcal{T} + \mathcal{T}^*\mathcal{C}$
- y is the “pair asymmetry”:

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

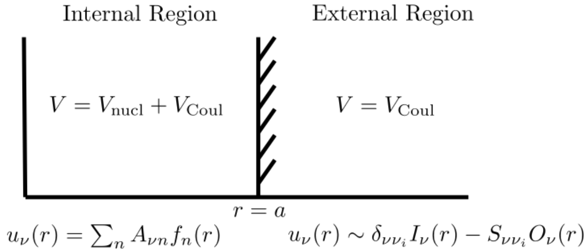


Results

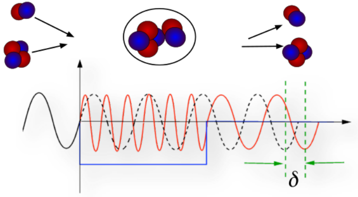
- Measurement against the electron-positron separation angle Θ
  - v_n and Q are functions of $\cos\Theta$
  - $R_n \sim \sum_K a_K^{(n)} P_K(\cos\frac{\pi}{2})$
- $E1$ and $M1$ are dominant
- Inclusion of interference between initial channels improves agreement with data



Solving the NCSMC



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

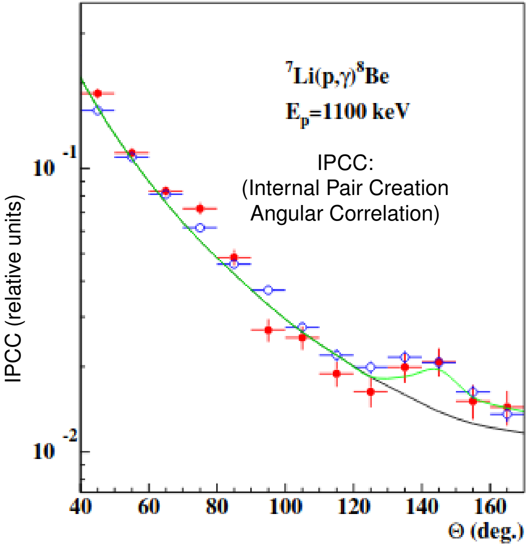


The X17 Anomaly in $p + {}^{7}\mathrm{Li} \to {}^{8}\mathrm{Be} + e^{+}e^{-}$

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

- The angle Θ between the electron and positron was measured
- Anomaly in pair distribution observed at the energy of the second 1^{+} resonance
- Bump could be explained by 17 MeV bosons decaying to $e^{+}e^{-}$

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



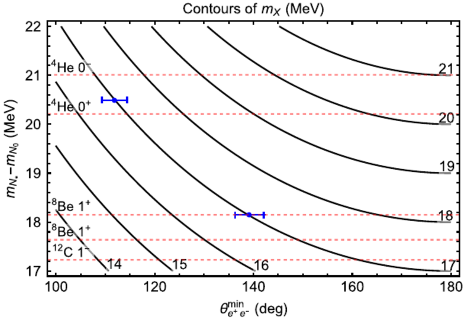
Constraints on m_X

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

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

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

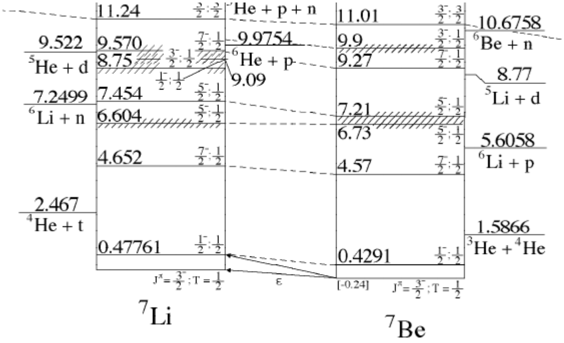
- Anomaly in pair distribution observed at the energy of the second 1^+ resonance
- Observed in-between resonances in ^4He ($^3\text{H}(p, e^+e^-)^4\text{He}$)
- Both experiments consistent with 17 MeV bosons decaying to e^+e^-



Input States from NCSM

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

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



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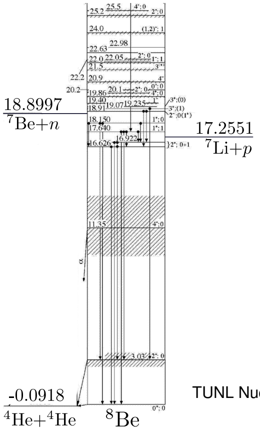


TUNL Nuclear Data Evaluation Project

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

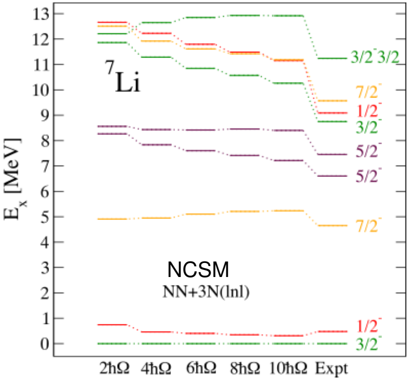
Interaction: Chiral NN N^{3}LO + 3N(lnl)

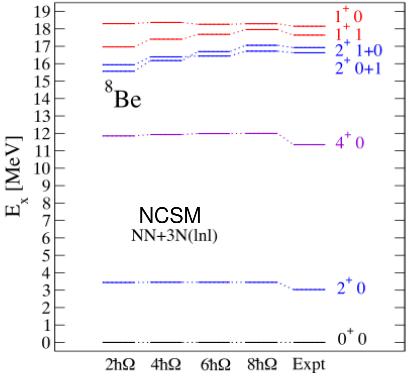
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

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: