TRIUMF

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

Peter Gysbers

UBC

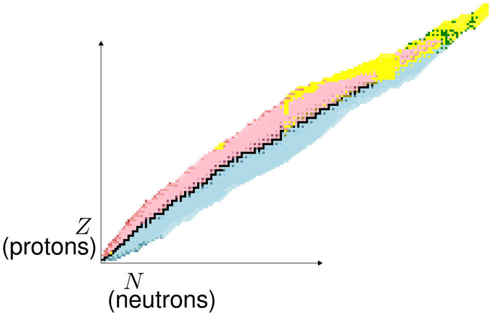
TRIUMF Ab Initio Workshop

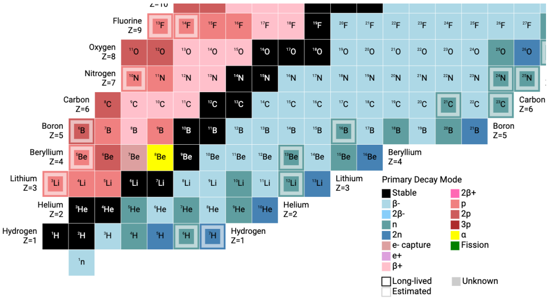
February 28, 2023

Discovery, accelerated

Goal

- A predictive theory for nuclei across the nuclear chart



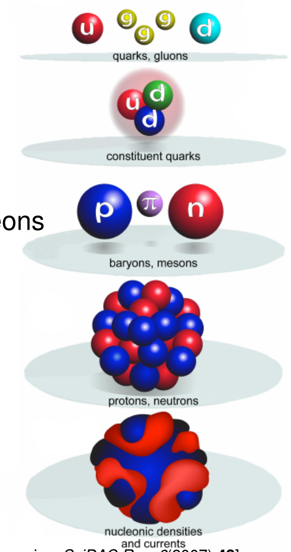


[https://people.physics.anu.edu.au/ ecs103/chart]

Ab Initio (First Principles) Nuclear Theory

- Nucleons as the degrees of freedom

nucleons



[Adapted from: G. F. Bertsch, D. J. Dean, W. Nazarewicz, *SciDAC Rev.* *6*(2007) **42**]

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- Nuclear forces from chiral effective field theory (χEFT)
  - In principle, calculable from QCD
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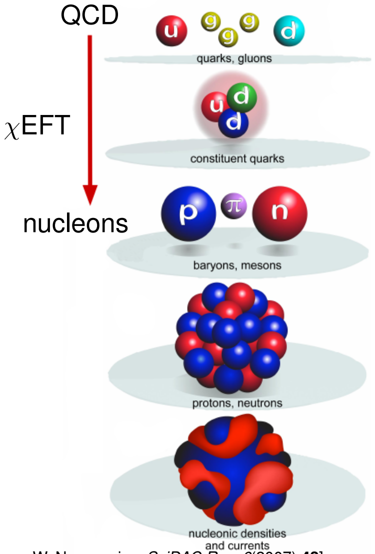

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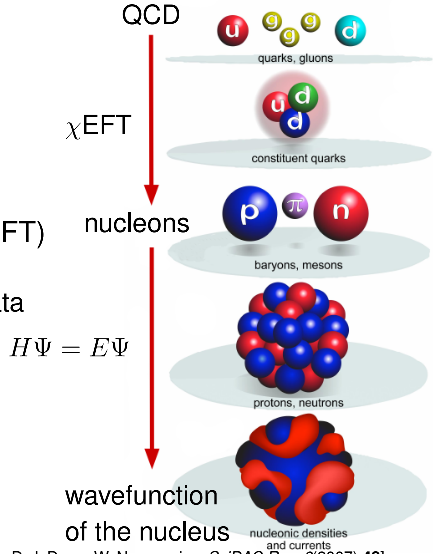
Ab Initio (First Principles) Nuclear Theory

- Nucleons as the degrees of freedom
- Nuclear forces from chiral effective field theory (χEFT)
  - In principle, calculable from QCD
  - In practice, parameters set by few (2,3) nucleon data
- Solve the many-nucleon Schrödinger equation
  - Systematically improvable calculations



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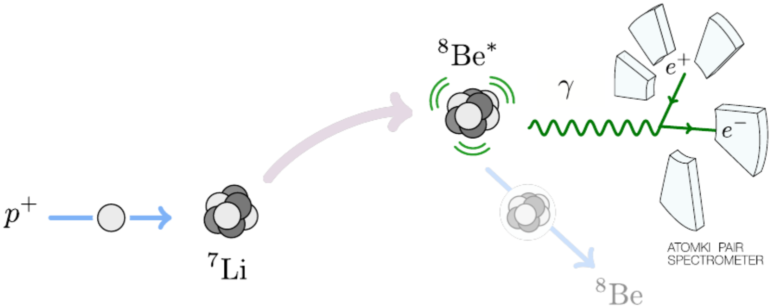
The X17 Anomaly in $p + {}^7\mathrm{Li} \to {}^8\mathrm{Be} + e^+e^-$

- ${}^7\mathrm{Li}(p, e^+e^-)^8\mathrm{Be}$ @ATOMKI (Hungary) [PRL **116** 042501 (2016)]
- Decay of composite ${}^8\mathrm{Be}$ produces electron-positron pairs



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

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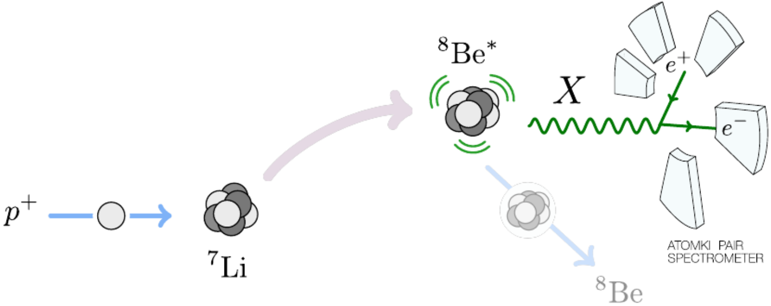
- Anomaly first seen at the energy of the second 1^{+} resonance



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Radiative Capture: $A + B \rightarrow C + \gamma$

- Notation: $B(A, \gamma)C$

More Notation:
$d = {}^2\mathrm{H}$
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  - Stellar burning: $d(p,\gamma)^3\mathrm{He}$, $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$, ...
  - Big Bang Nucleosynthesis: $d(p,\gamma)^3\mathrm{He}$, $^4\mathrm{He}(d,\gamma)^6\mathrm{Li}$, ...
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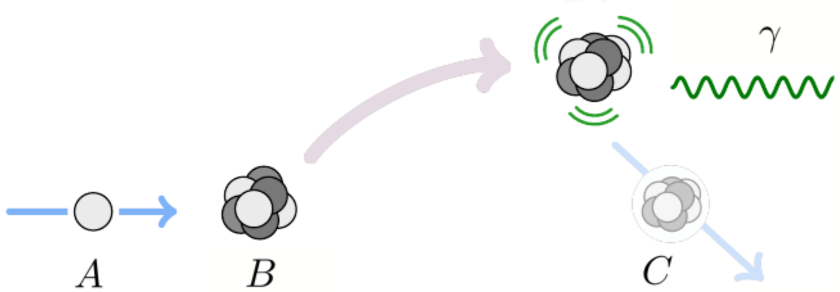

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Calculating Radiative Capture

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): $\hat{O}_\gamma$

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We need to calculate the transition matrix elements: $\langle\Psi_f|\,\hat{O}_\gamma\,|\Psi_i\rangle$

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

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

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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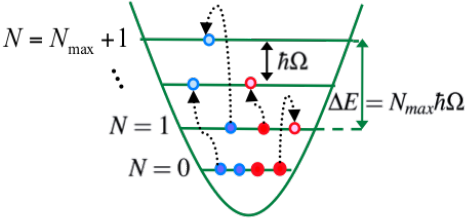
The No-Core Shell Model (NCSM)

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

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

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



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

- The incoming state is made of distinct clusters with center of mass separation
- 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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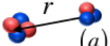
No-Core Shell Model with Continuum (NCSMC)

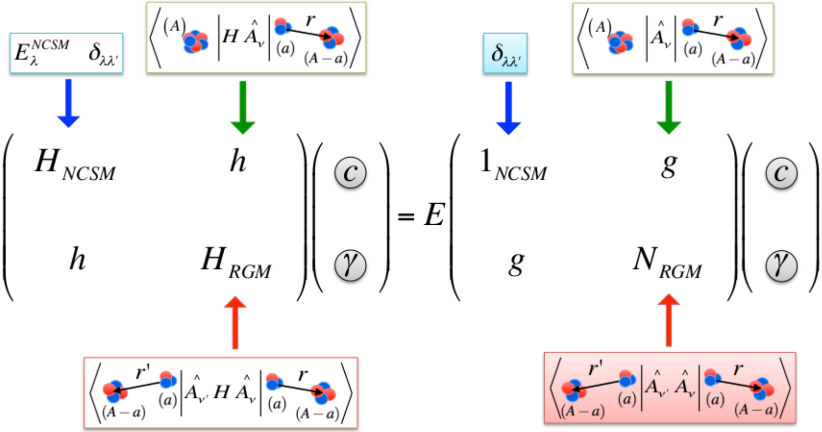
- Solution: extend the NCSM basis!

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



NCSMC Equations

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



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

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

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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. $\langle\Psi(E_f)|\,\hat{O}_\gamma\,|\Psi(E_i)\rangle$

Results

The NCSMC allows simultaneous calculation of many observables

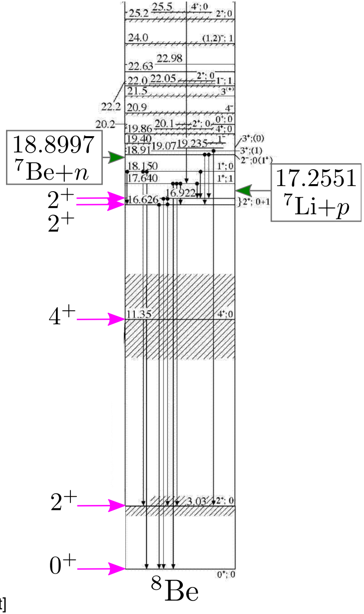
- ■ $^{8}\mathrm{Be}$ Structure
- □ Scattering: $^{7}\mathrm{Li}(p,p)^{7}\mathrm{Li}$, $^{7}\mathrm{Be}(n,n)^{7}\mathrm{Be}$
- □ Transfer Reactions: $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$, $^{7}\mathrm{Be}(n,p)^{7}\mathrm{Li}$
- ■ Radiative Capture: $^{7}\mathrm{Li}(p,\gamma)^{8}\mathrm{Be}$
- ■ Search 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]

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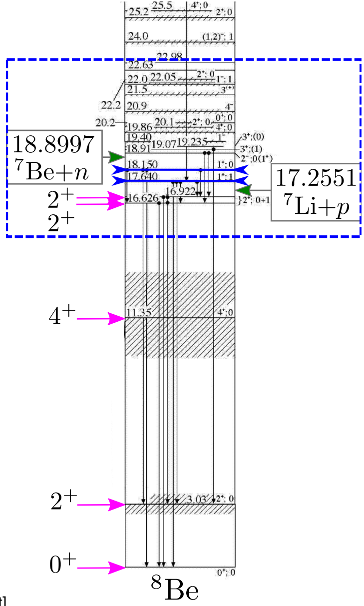

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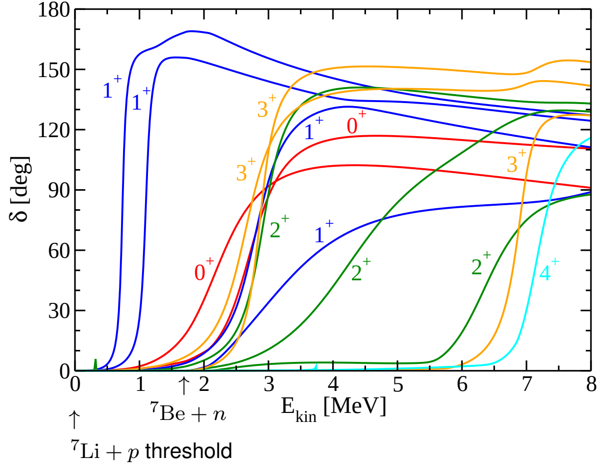
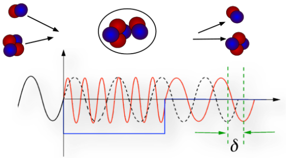
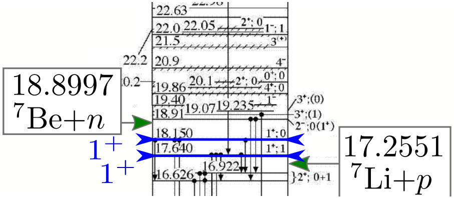
Eigenphase-shift Results (positive parity)

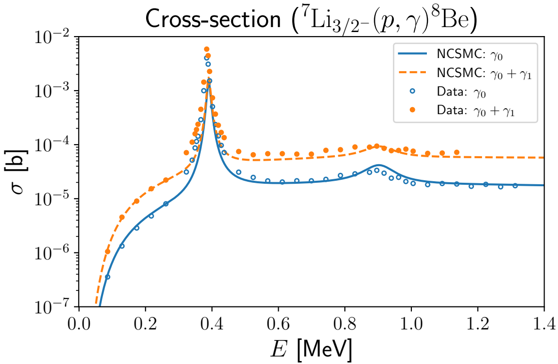






Additional resonances are seen compared to TUNL data evaluation

Radiative Capture: $^7\mathrm{Li}(p,\gamma)^8\mathrm{Be}$



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

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

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

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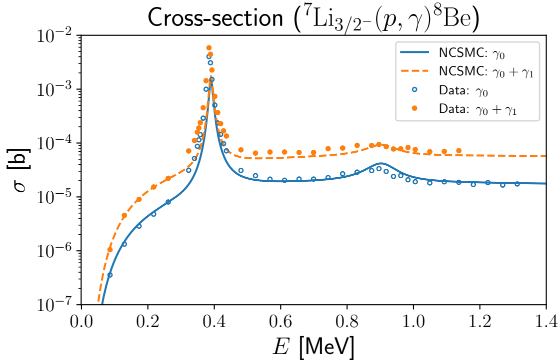
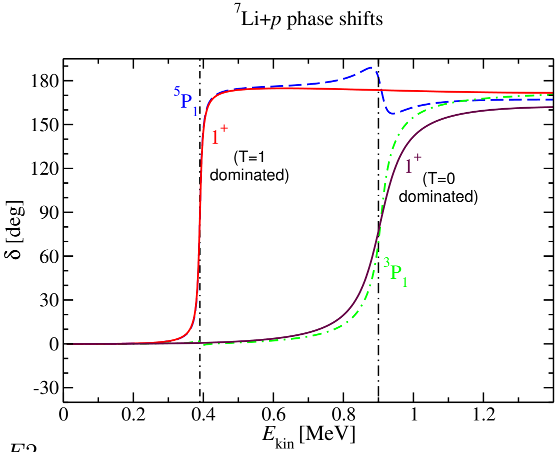
$${}^{2S+1}P_J : \left[\left(\left|{}^{7}\mathrm{Li}\right\rangle |p\rangle\right)^{(S)} Y_L(\hat{r})\right]^J$$

$$P : L = 1$$





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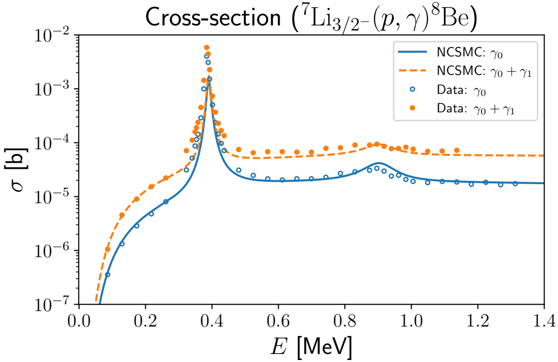
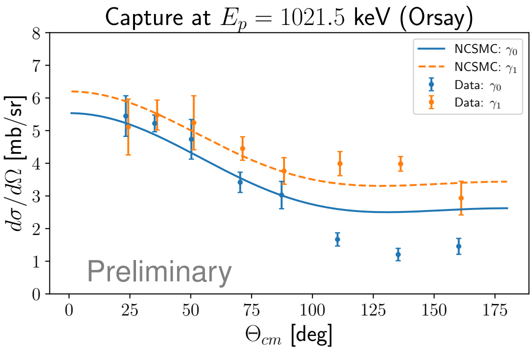
Phenomenological adjustment: fit threshold and resonance positions to match experiment

Radiative Capture (cont.)





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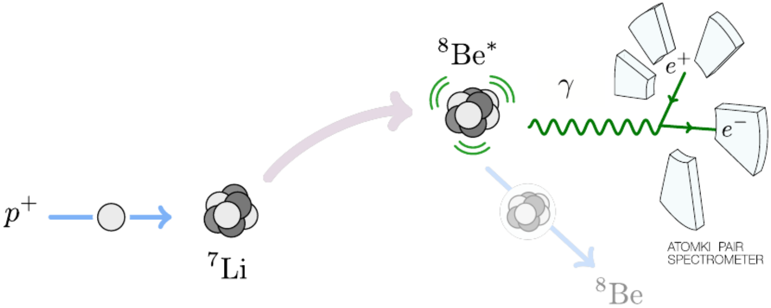
Radiative Capture with Pair Production: $^{7}\mathrm{Li}(p, e^{+}e^{-})^{8}\mathrm{Be}$



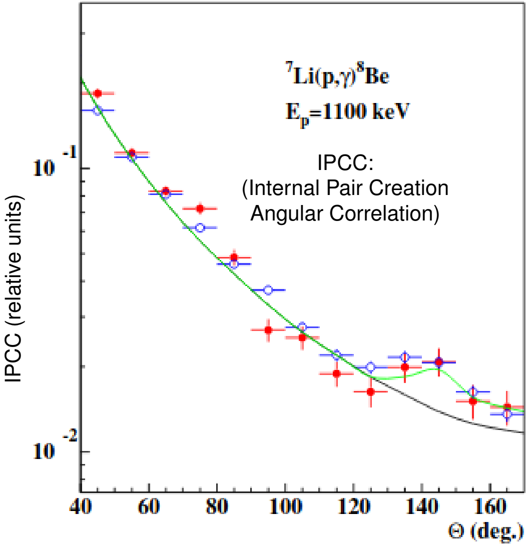
[Feng PRD **95**, 035017 (2017)]

The X17 Anomaly

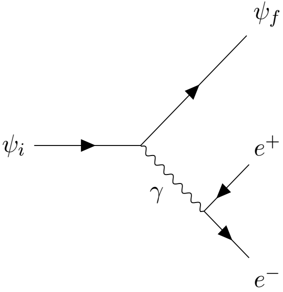
[Firak, Krasznahorkay, et al
EPJ Web of Conferences **232** 04005 (2020)]

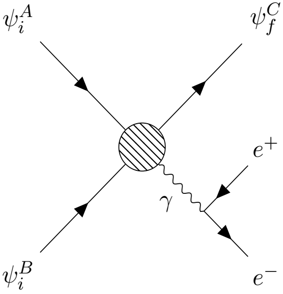
- The angle Θ between the electron and positron was measured
- Minimum angle from a massive intermediate particle: $\Theta \simeq 2\sin^{-1}(\frac{m_X}{E_X})$
- Bump could be explained by 17 MeV bosons decaying to e^+e^-

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



Pair Production: Bound vs Continuum

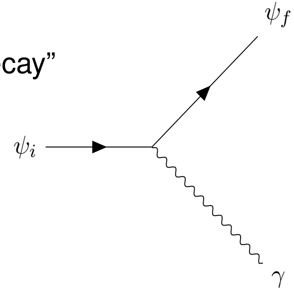




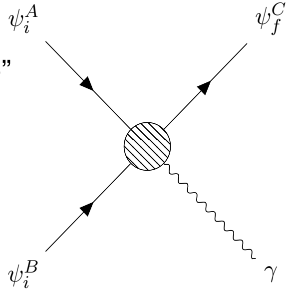
$\longrightarrow$
Time

Gamma Emission: Bound vs Continuum

"γ -decay"



"radiative capture"



- Rate:

$$\mathrm{d}\Gamma \sim \overline{\sum_{M_i}} \sum_{M_f} \sum_{\lambda} |\mathcal{M}_{fi}^{\lambda}|^2 \mathrm{d}^3 q$$

- Cross section:

$$\mathrm{d}\sigma \sim \frac{1}{v} \overline{\sum_{M_i^A M_i^B}} \sum_{M_f^C} \sum_{\lambda} |\mathcal{M}_{fi}^{\lambda}|^2 \mathrm{d}^3 q$$

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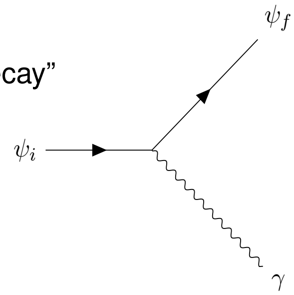

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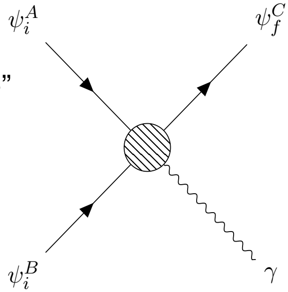


- Transition Matrix Elements:

$$\mathcal{M}^{\lambda}_{fi} \sim \langle J_f || \vec{e}_\lambda \cdot \vec{\mathcal{J}} || J_i \rangle$$

- Strict selection rules

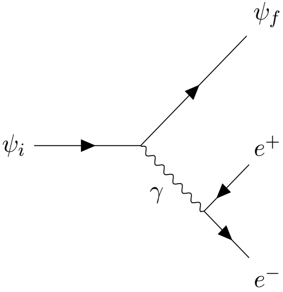
- Transition Matrix Elements:

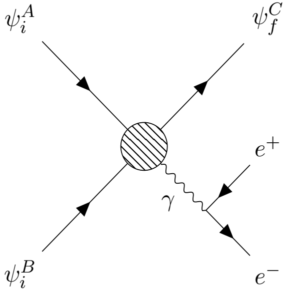
$$\mathcal{M}^{\lambda}_{fi} \sim \sum_{\nu_i} \langle J_f || \vec{e}_\lambda \cdot \vec{\mathcal{J}} || \nu_i \rangle$$

$$\nu_i = \{L_i, S_i, J_i\}$$

- Initial channels mix

Pair Production: Bound vs Continuum





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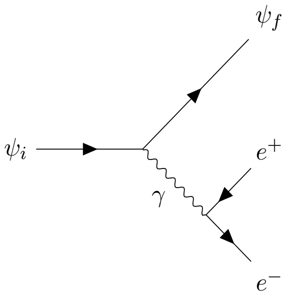
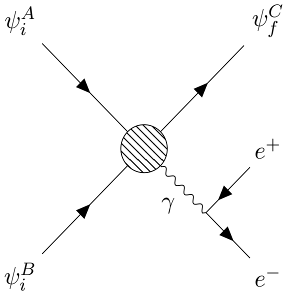
Pair Production: Bound vs Continuum





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$$\mathcal{M}_{fi}^{s_+ s_-} \sim \left(\frac{e^2}{Q^2}\right) \ell_\mu^{s_+ s_-} \langle J_f || \mathcal{J}^\mu || J_i \rangle$$

- 2 terms: longitudinal and transverse

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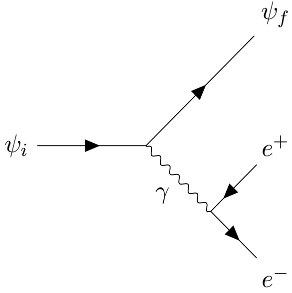
$$\nu_i = \{L_i, S_i, J_i\}$$

- 6 terms

Pair Production Distribution $\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\Theta}$

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



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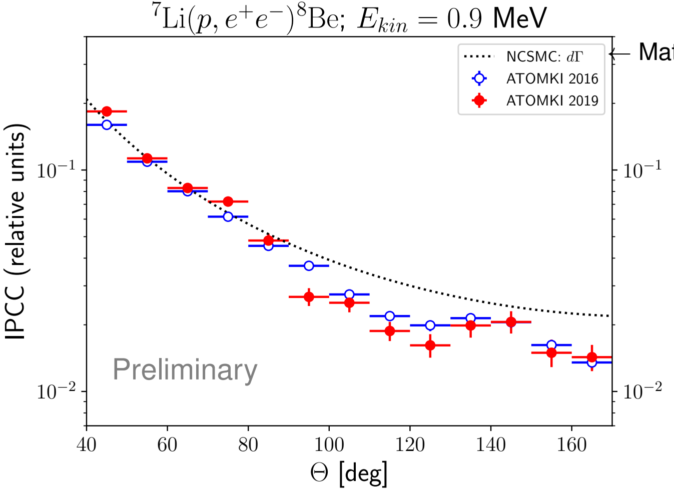
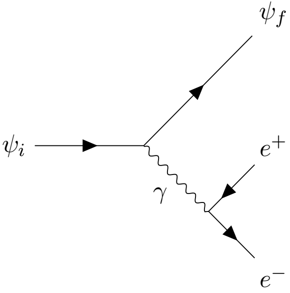
Theory does not support the background data



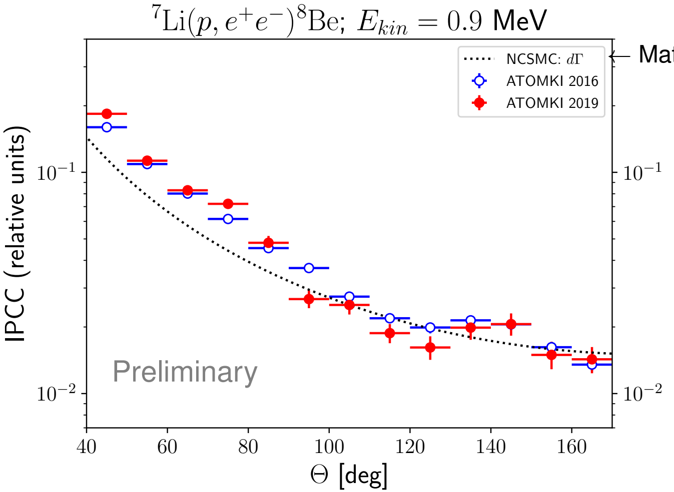
← Matched to data at $65°$



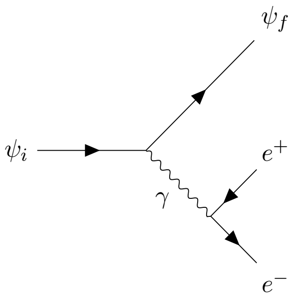
Pair Production Distribution $\frac{d\Gamma}{d\cos\Theta}$

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

Theory does not support the background data



← Matched to data at $105°$



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- Approximate calculation
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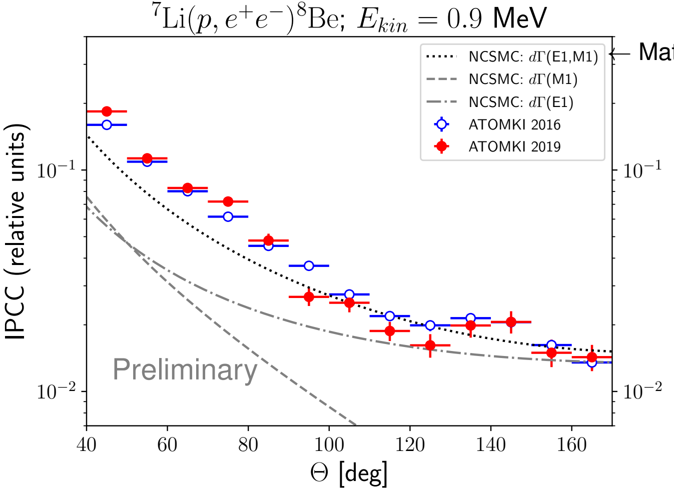
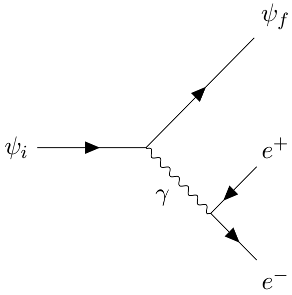
Theory does not support the background data



← Matched to data at $105°$

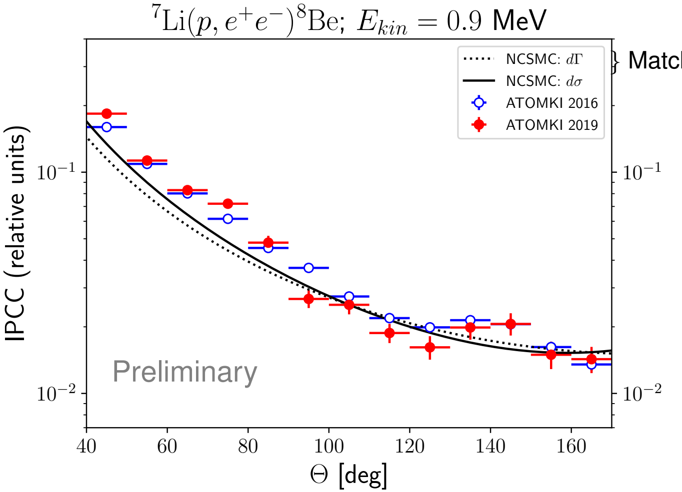


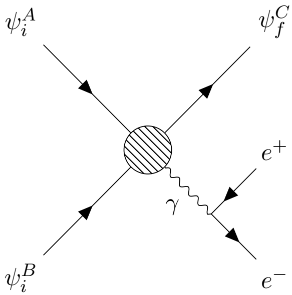
(Improved) Pair Production Distribution

- Full continuum → bound calculation
  - expect E1-M1 interference

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\Theta}$$

Improved agreement with data





(Improved) Pair Production Distribution

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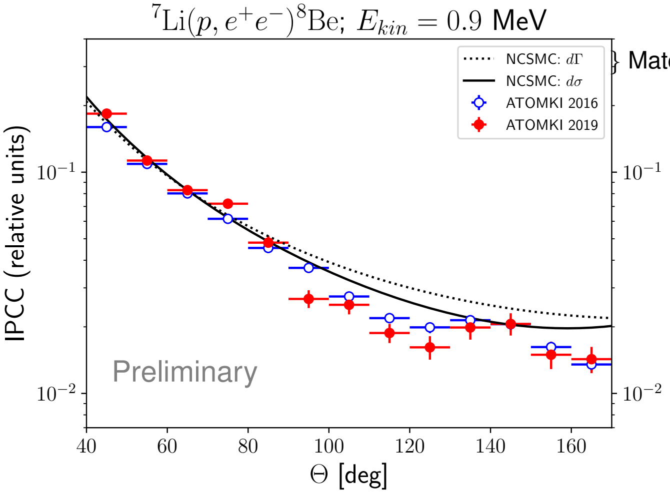
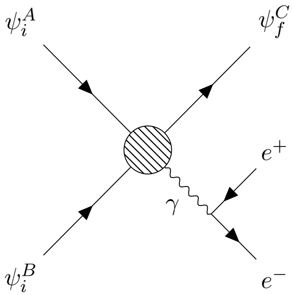
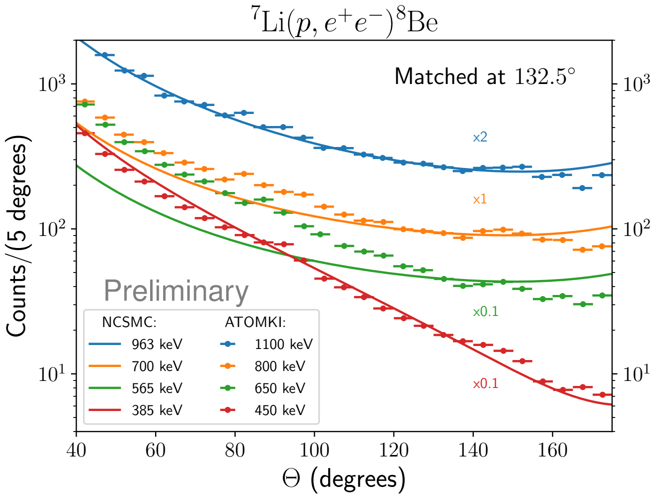


} Matched to data at 65°



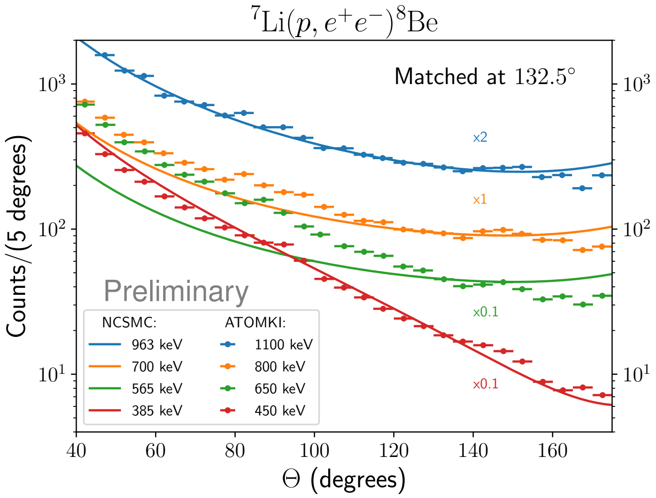
More Recent Data (2022)



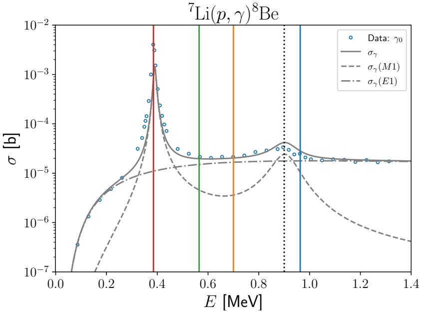
[Data: arXiv:2205.07744]

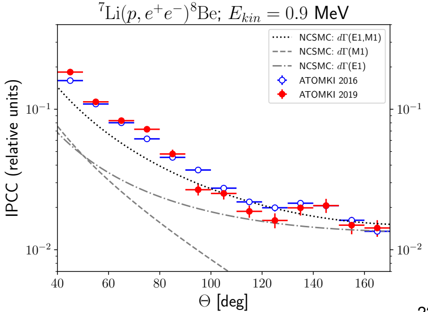
- On-resonance theory and experiment agree well
- Off-resonance experiment has additional M1 contamination

More Recent Data (2022)

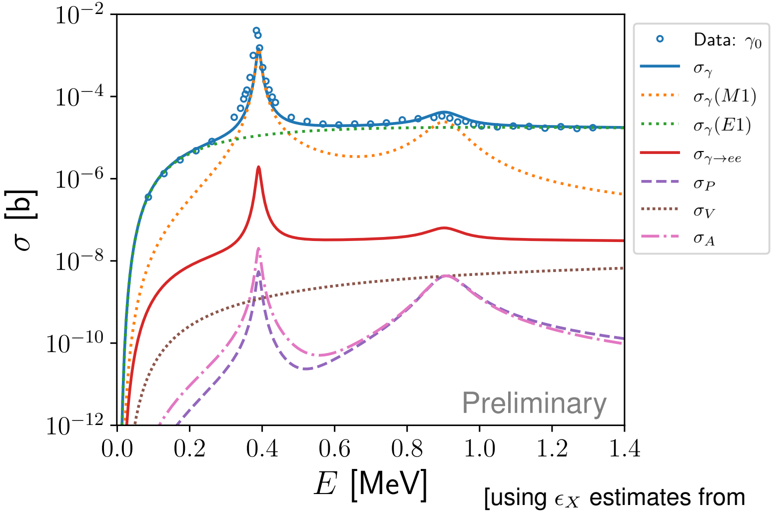


[Data: arXiv:2205.07744]



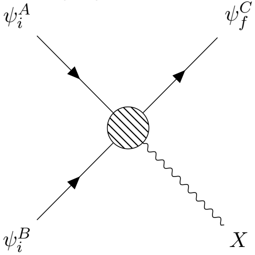


Estimated $^7\mathrm{Li}(p, X)^8\mathrm{Be}$ Cross-sections



- 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

- 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
- Full calculations of $^{7}\mathrm{Li}(p,e^{+}e^{-})^{8}\mathrm{Be}$ improve agreement to data

Outlook

- Compare $^{7}\mathrm{Li}(p,e^{+}e^{-})^{8}\mathrm{Be}$ to more data with $\gamma \to e^{+}e^{-}$ operator and various $X \to e^{+}e^{-}$ operators (e.g. axions, vector bosons, axial vector bosons)
- Calculations of $^{3}\mathrm{H}(p,e^{+}e^{-})^{4}\mathrm{He}$, $^{11}\mathrm{B}(p,e^{+}e^{-})^{12}\mathrm{C}$ 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

Nuclear Currents: $\langle f|\,|\vec{e_\lambda}\cdot\vec{\mathcal{J}}|\,|i\rangle \sim \sum_{J\geq 1}\lambda\mathcal{T}_J^M + \mathcal{T}_J^E$

Approximations:

$$\mathcal{T}_J^E \sim \omega^J E_J \qquad\qquad E_J \sim e\,\langle f|\,|r^J Y_J|\,|i\rangle$$

$$\mathcal{T}_1^M \sim \omega M_1 \qquad\qquad M_1 \sim \mu_N\,\langle f|\,|g_s S + g_l L|\,|i\rangle$$

- γ-decay rate

$$\frac{\mathrm{d}\Gamma_{fi}}{\mathrm{d}\Omega} = \sum_{n=\text{even}} b_n^{fi} P_n(\cos\theta)$$

$$\Gamma_{fi} \sim \sum_{J\geq 1}\sum_{\sigma=E,M} |\mathcal{T}_J^\sigma(f,i)|^2$$

- radiative capture cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \sum_n a_n P_n(\cos\theta), \quad \sigma = 4\pi a_0$$

$$a_0 \sim \sum_{J\geq 1}\sum_{\sigma=E,M}\sum_{\nu_i} |\mathcal{T}_J^\sigma(f,i)|^2$$

$$a_1 \sim \sum_{(-)=(-)^{\sigma+\sigma'+J+J'}}\sum_{\nu_i\nu_i'} \mathcal{T}_J^\sigma(f,i)\mathcal{T}_{J'}^{\sigma'*}(f,i')$$

Leptons:

$$\ell_\mu^{s_+ s_-} \sim \bar{u}^{s_-}(P_-)\gamma_\mu v^{s_+}(P_+)$$

$$\sum_{s_+ s_-} \ell_\mu \ell_\nu \sim P_{+\mu}P_{-\nu} + P_{+\nu}P_{-\mu} - \eta_{\mu\nu}(P_{+\alpha}P_-^\alpha + m_e^2)$$

Nuclear Currents: $\mathcal{J}_\mu = (\rho, \vec{\mathcal{J}})$

$$\langle f | \, |\rho| \, | i \rangle \sim \sum_{J \geq 0} \mathcal{C}_J$$

$$\langle f | \, |\vec{e_\lambda} \cdot \vec{\mathcal{J}}| \, | i \rangle \sim \sum_{J \geq 1} \lambda \mathcal{T}_J^M + \mathcal{T}_J^E$$

$$\langle f | \, \mathcal{J}_z \, | i \rangle \sim \sum_{J \geq 0} \mathcal{L}_J$$

Multipole Operators:

$$\mathcal{C}_{JM}(q) = \int \mathrm{d}^3 r M_{JM}(q,\vec{r})\rho(r)$$

$$\mathcal{L}_{JM}(q) = \int \mathrm{d}^3 r \left(\frac{i\vec{\nabla}}{q} M_{JM}(q,\vec{r})\right) \cdot \vec{\mathcal{J}}(\vec{r})$$

$$\mathcal{T}^{E}_{JM}(q) = \int \mathrm{d}^3 r \left(\frac{\vec{\nabla}}{q} \times \vec{M}_{JJM}(q,\vec{r})\right) \cdot \vec{\mathcal{J}}(\vec{r})$$

$$\mathcal{T}^{M}_{JM}(q) = \int \mathrm{d}^3 r \vec{M}_{JJM}(q,\vec{r}) \cdot \vec{\mathcal{J}}(\vec{r})$$

$$M_{JM}(q,\vec{r}) = j_J(qr) Y_{JM}(\hat{r})$$

$$\vec{M}_{JLM}(q,\vec{r}) = j_J(qr) \vec{Y}_{JLM}(\hat{r})$$

Approximations:

$$\vec{\nabla} \cdot \vec{\mathcal{J}} = \frac{\mathrm{d}\rho}{\mathrm{d}t} \simeq -i\omega\rho \implies \begin{cases} \mathcal{L}_J & \simeq \frac{\omega}{q}\mathcal{C}_J \\ \mathcal{T}^E_J & \simeq -\frac{\omega}{q}\sqrt{\frac{J+1}{J}}\mathcal{C}_J \end{cases}$$

$$\mathcal{C}_J \sim q^J E_J = q^J e < r^J Y_J >$$

$$\mathcal{T}^M_1 \sim q M_1 = q\mu_N < g_s S + g_l L >$$

- Rate:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\Theta} = a_C|\rho|^2 + a_T\left[|\mathcal{J}_+|^2 + |\mathcal{J}_-|^2\right]$$

$$= a_C\sum_{J\geq 0}|\mathcal{C}_J(f,i)|^2 + a_T\sum_{J\geq 1}\sum_{\sigma=E,M}|\mathcal{T}_J^\sigma(f,i)|^2$$

$$\left[\mathcal{J}_\lambda = \vec{e}_\lambda\cdot\vec{\mathcal{J}}\right]$$

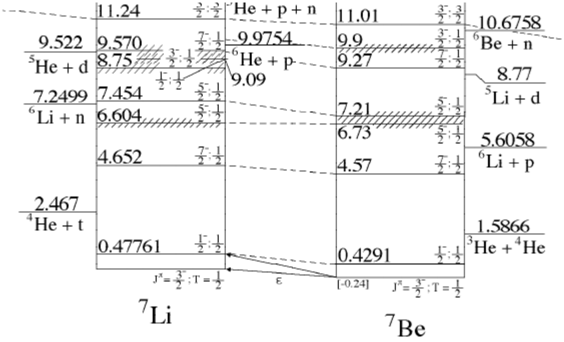
- Cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\Theta} = \sum_{\nu_i\nu_i'}\Big\{v_1|\rho|^2 + v_2\left[\rho\left(\mathcal{J}_+ + \mathcal{J}_-\right)^* + h.c.\right] + v_3\left[\rho\left(\mathcal{J}_+ - \mathcal{J}_-\right)^* + h.c.\right] + v_4\left[|\mathcal{J}_+|^2 + |\mathcal{J}_-|^2\right] + v_5\left[\mathcal{J}_+\mathcal{J}_-^* + \mathcal{J}_-\mathcal{J}_+^*\right] + v_6\left[\mathcal{J}_+\mathcal{J}_-^* - \mathcal{J}_-\mathcal{J}_+^*\right]\Big\}$$

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



[TUNL Nuclear Data Evaluation Project]

Input States from NCSM

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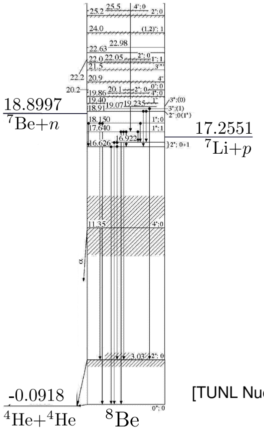
- 3 NCSM calculations: ${}^{7}\text{Li}$, ${}^{7}\text{Be}$ and ${}^{8}\text{Be}$
- $\{\frac{3}{2}^{-}, \frac{1}{2}^{-}, \frac{7}{2}^{-}, \frac{5}{2}^{-}, \frac{5}{2}^{-}\}$ ${}^{7}\text{Li}$ and ${}^{7}\text{Be}$ states in cluster basis
- 15 positive and 15 negative parity states in ${}^{8}\text{Be}$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



[TUNL Nuclear Data Evaluation Project]

PHYSICAL REVIEW C 101, 014318 (2020)

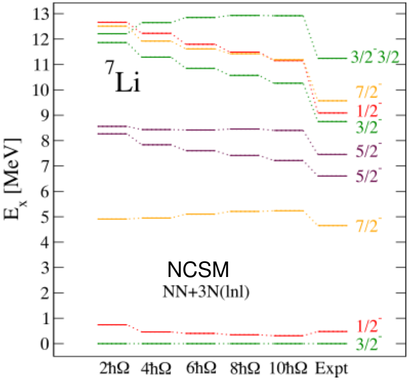
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

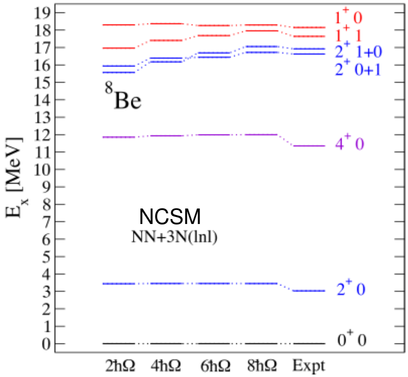
V. Somà,[1,*] P. Navrátil,[2,†] F. Raimondi,[3,4,‡] C. Barbieri,[4,§] and T. Duguet[1,5,||]

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

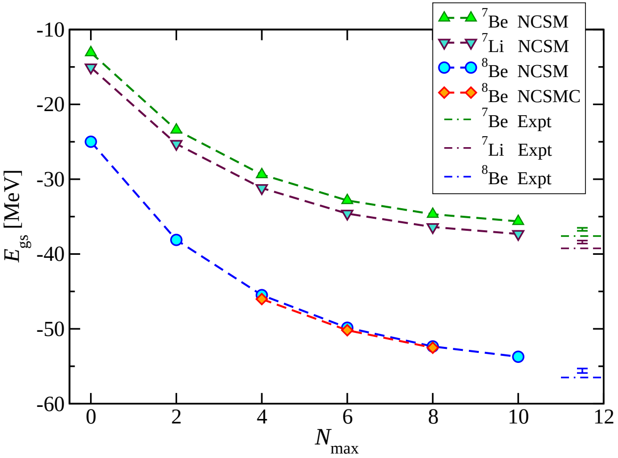
- Good description of excitation energies in light nuclei
- Hamiltonian determined in $A = 2, 3, 4$ systems
  - Nucleon-nucleon scattering, deuteron, ^{3}H, ^{4}He

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

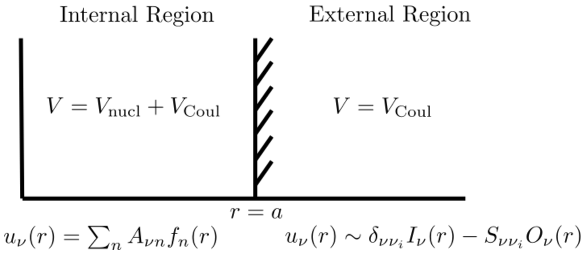




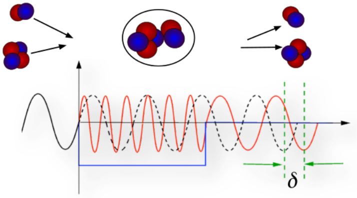
Convergence of ground state energies:



NCSMC 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



More X17 Experiments

- Many ongoing experiments aim to reproduce the results: Orsay, Montreal, DarkLight (TRIUMF),...
- Additional ATOMKI experiments
  - Anomaly seen in $^3\mathrm{H}(p, e^+e^-)^4\mathrm{He}$, between 0^+ and 0^- resonances [PRC **104** 044003 (2021)]
  - Updated $^7\mathrm{Li}(p, e^+e^-)^8\mathrm{Be}$ results for off-resonance energies (anomaly remains after better experimental background determination) [arXiv:2205.07744]
  - New claim: anomaly in the 1^- resonance of $^{11}\mathrm{B}(p, e^+e^-)^{12}\mathrm{C}$ [PRC **106** L061601 (2022)]
- The quantum numbers of a new particle will determine how it interacts with the nucleus

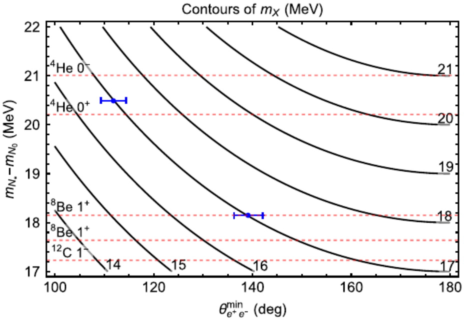
Constraints on m_X

[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:

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

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

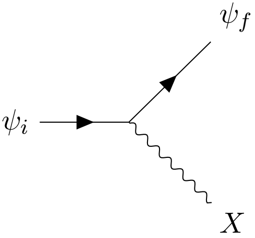


X17 Candidate Bosons

($m_X \simeq 17$ 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)]

Exclusion Plot

Current (gray) and projected sensitivities of future experiments

Feng **PRD 95** 035017 (2017)