# Calculations of $p + {}^7\mathrm{Li}$ Capture Reactions

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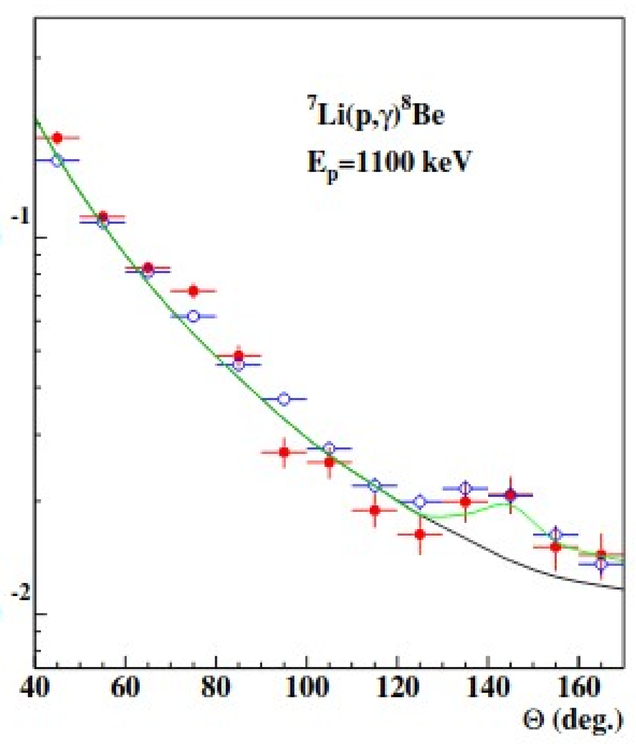
## The X17 Anomaly in $p + {}^7\mathrm{Li} \longrightarrow {}^8\mathrm{Be}$

- The decay of ${}^8\mathrm{Be}$ $1^+$ excited states produces electron-positron pairs.
- The bump in the angular correlation between pairs in transitions from one of these resonances could indicate the existence of a new particle!

**Experiment at ATOMKI (Hungary)**

IPCC
(Internal Pair Creation
Angular Correlation)




"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" [1]

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

## Background: *Ab Initio* Nuclear Theory

Atomic nuclei are complex strongly-interacting systems. An accurate theoretical description of nuclei is needed to interpret experiments.

*Ab initio* nuclear theory uses realistic two- and three-nucleon interactions to construct a Hamiltonian with the nucleons as the degrees of freedom. We can find the bound states of the nucleus by solving the eigenvalue problem:

$$\hat{H}\,|\psi_k\rangle = E_k\,|\psi_k\rangle$$

The no-core shell model (NCSM) [2] uses an ansatz wavefunction which is a linear combination of products of harmonic oscillator states.

$$|\psi_k\rangle = \sum_{N=0}^{N_{max}} \sum_j c^k_{Nj}\,|\phi_{Nj}\rangle$$

In this framework the wavefunction and energies will converge to the exact value as $N_{max} \to \infty$ but the extension "**no-core shell model with continuum**" (NCSMC) is needed to capture properties of weakly bound and scattering states.

## References


[1] Firak, Krasznahorkay, et al EPJ Web of Conferences **232** 04005 (2020)
[2] Barrett et al. Prog. Part. Nucl. **69** 131 (2013)
[3] Navratil et al. Physica Scripta **91** (5):053002 (2016)
[4] TUNL Nuclear Data Evaluation Project https://nucldata.tunl.duke.edu/nucldata/
[5] Zahnow et al, Z.Phys.A, **351** 229-236 (1995)


## Acknowledgements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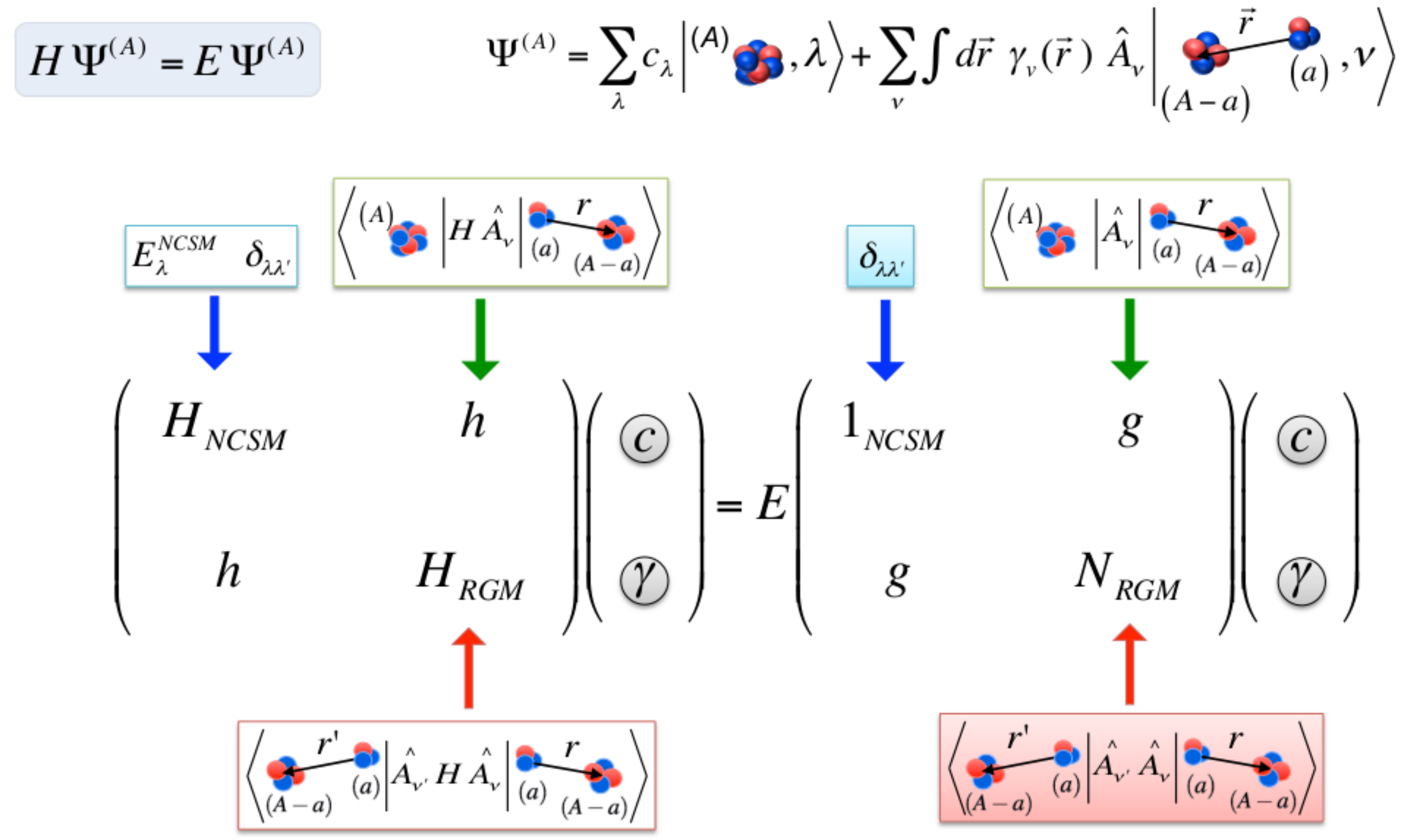
## Method: No-core Shell Model with Continuum

- Nuclear reactions require access to continuum degrees of freedom.
- We extend our ansatz to include cluster states with relative motion [3].
- We then solve coupled equations at each value of total energy $E$.



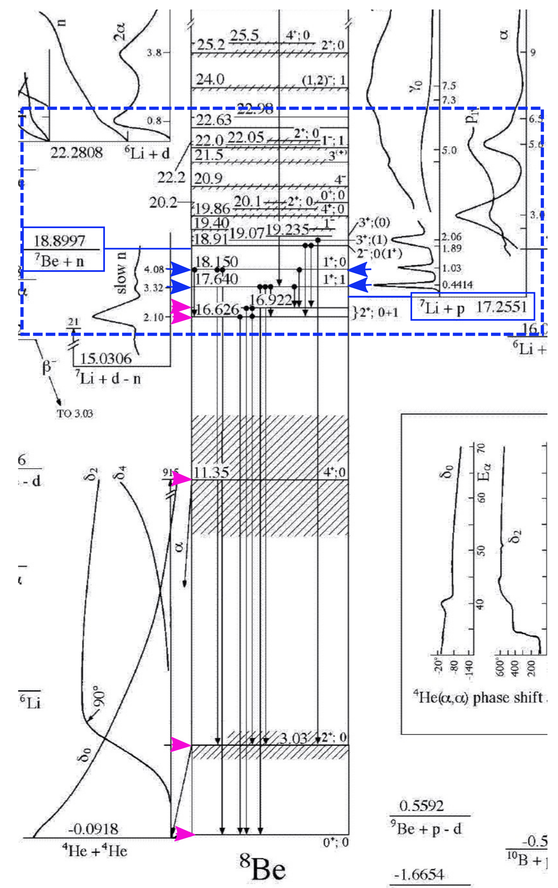

Our ansatz includes both $p + {}^7\mathrm{Li}$ and $n + {}^7\mathrm{Be}$ cluster states:

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

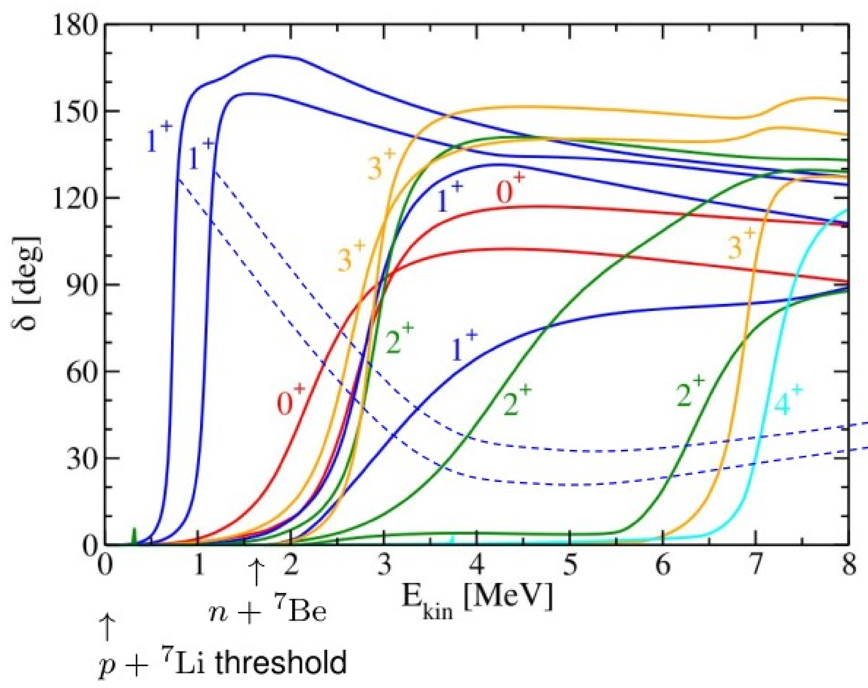
## Results: Bound states and resonances

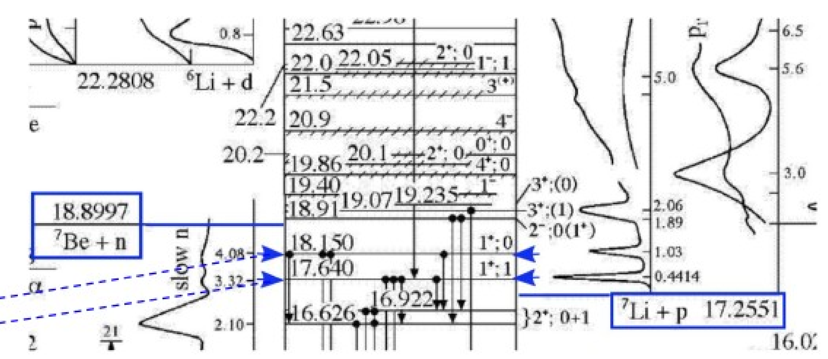
Calculations of bound states are improved by inclusion of the continuum. ($N_{max}$=9)

| State | Energy [MeV] | | | Excitation Energy [MeV] | | |
|---|---|---|---|---|---|---|
| | NCSM | NCSMC | Expt. | NCSM | NCSMC | Expt. |
| $0^+$ | −15.96 | −16.13 | −17.25 | 0.00 | 0.00 | 0.00 |
| $2^+$ | −12.51 | −12.72 | −14.23 | 3.45 | 3.41 | 3.03 |
| $4^+$ | −3.97 | −4.31 | −5.91 | 11.99 | 11.82 | 11.35 |
| $2^+$ | +0.76 | −0.10 | −0.63 | 16.72 | 16.03 | 16.63 |
| $2^+$ | +1.09 | +0.31 | −0.33 | 17.05 | 16.44 | 16.92 |



Eigenphase shifts indicate the position and width of resonances in the composite system, the $1^+$ resonances are most relevant to the anomaly.

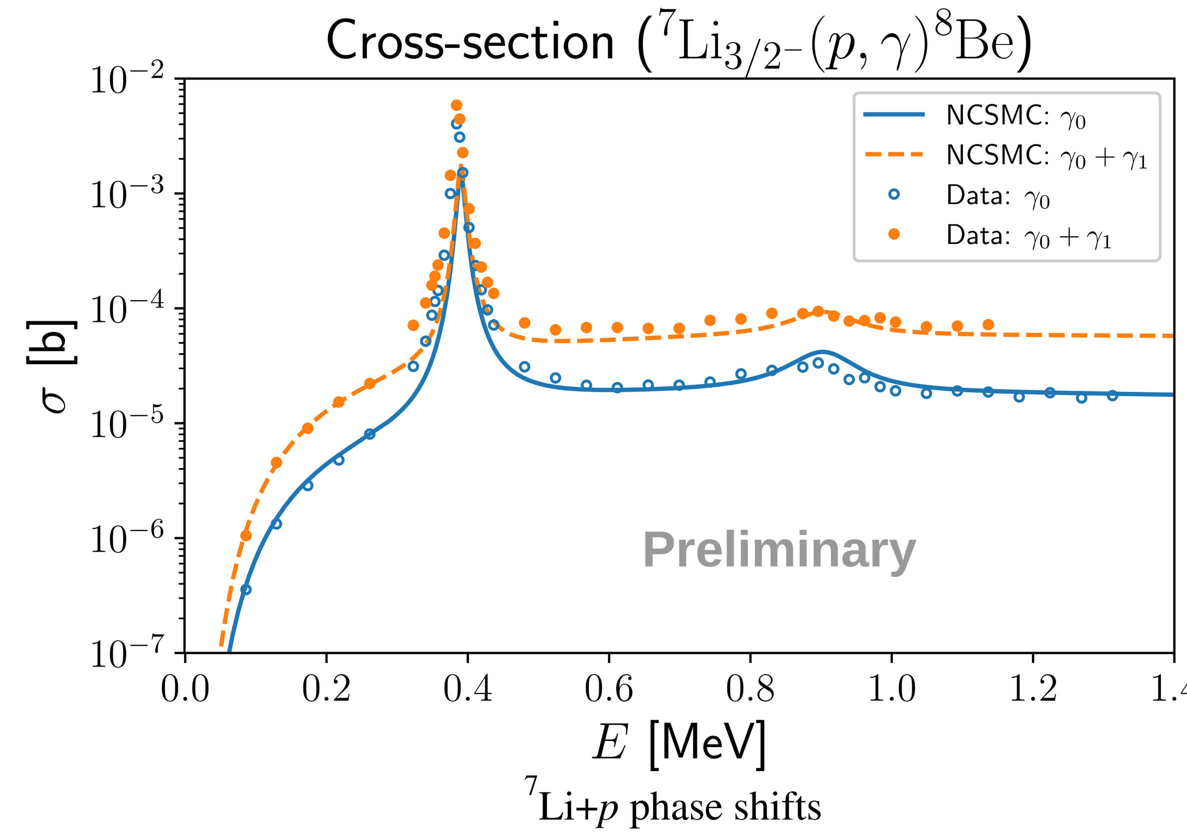


Additional resonances are seen compared to TUNL data [4]

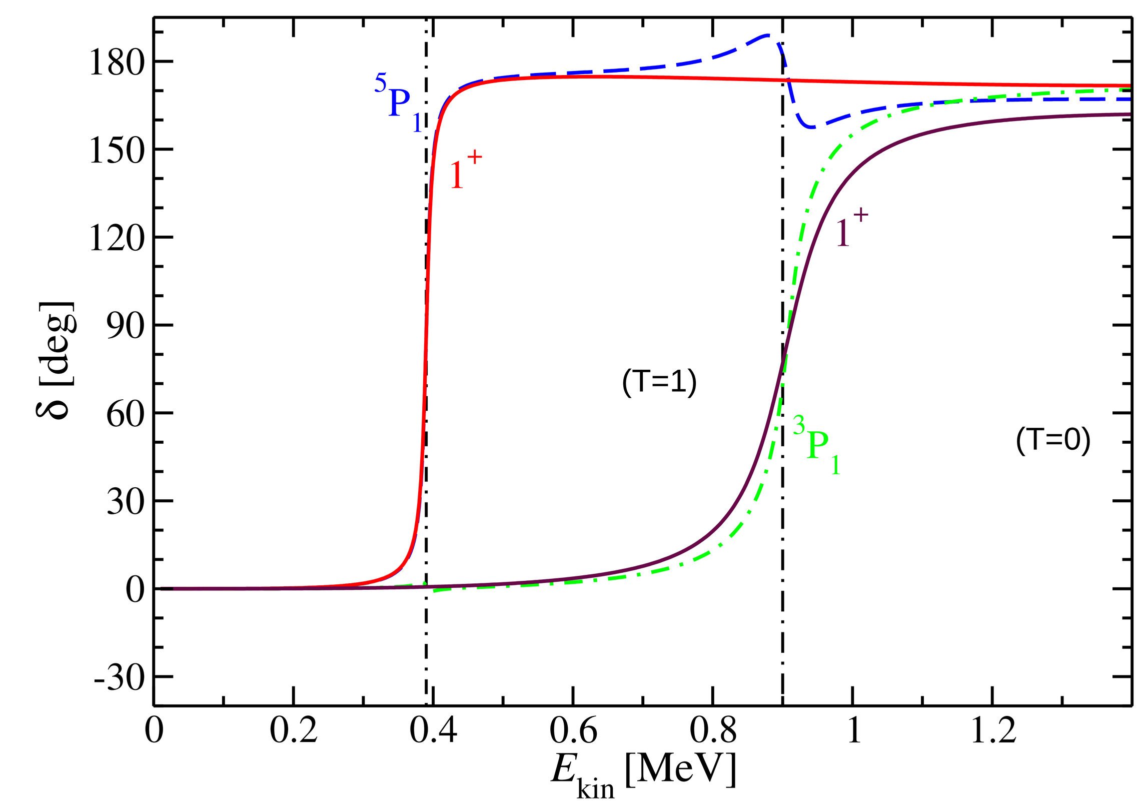
## Results: ${}^7\mathrm{Li}(p,\gamma){}^8\mathrm{Be}$

The $1^+$ resonances enhance the cross section of ${}^7\mathrm{Li}(p,\gamma){}^8\mathrm{Be}$ capture.



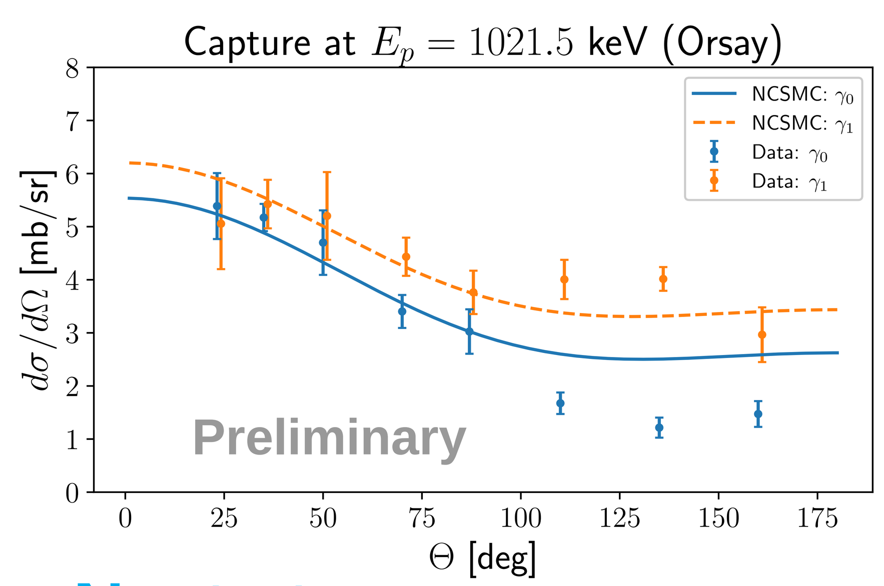

$\gamma_0$ : decay to ground state ($0^+$)
$\gamma_1$ : decay to first excited ($2^+$)

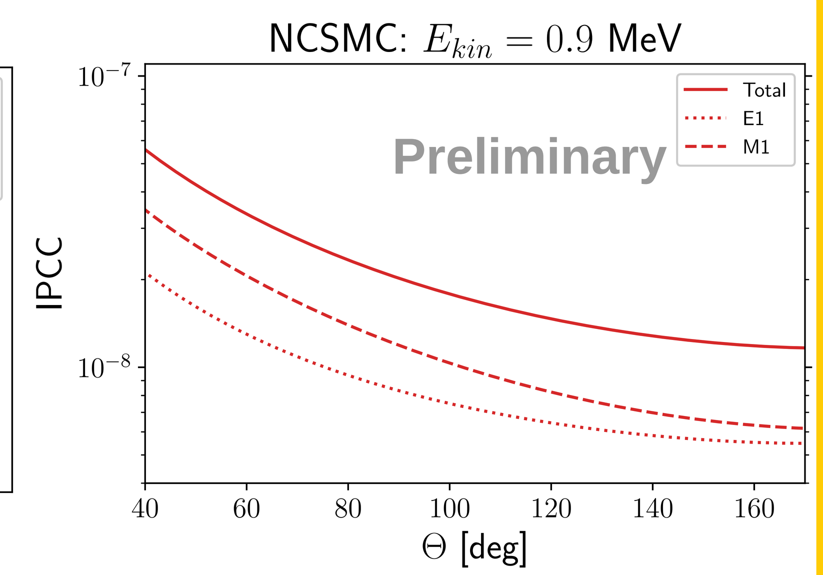
Data from [5]




Phenomenological adjustment is needed to get the $1^+$ resonances at the correct energies (i.e. shifting input NCSM energies).

Ongoing and planned measurements at Orsay and Montreal may confirm the X17. Calculated differential cross-sections for the isoscalar transition (decay of the second $1^+$) have reasonable agreement with experiment.




## Next steps

- Calculate ${}^7\mathrm{Li}(p,e^+e^-){}^8\mathrm{Be}$ with $\gamma \to e^+e^-$ operator and various $\mathrm{X} \to e^+e^-$ operators (e.g. axions, axial vector bosons)
- Explore charge-exchange reactions relevant for nucleosynthesis (${}^7\mathrm{Be}(n,p){}^7\mathrm{Li}$, ${}^7\mathrm{Li}(p,n){}^7\mathrm{Be}$)
- Include $\alpha$ degrees of freedom (${}^8\mathrm{Be}$ is unstable to $\alpha+\alpha$ break-up)