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^{7}Li in the no-core shell model with continuum framework with coupling of mass partitions

Jakub Herko

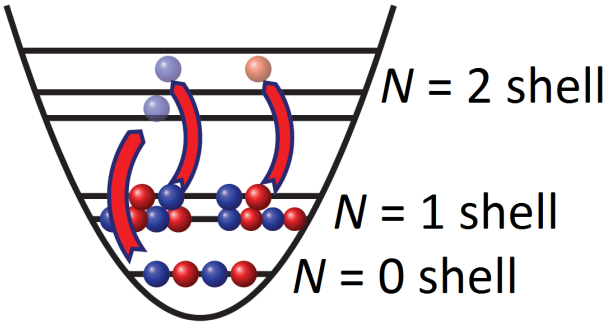
Collaborators: Konstantinos Kravvaris, Petr Navratil, Sofia Quaglioni, Guillaume Hupin, Mark A. Caprio

Outline

- No-core shell model (NCSM)
- No-core shell model with continuum (NCSMC)
- Calculations for ^{7}Li within NCSMC
  with coupling of mass partitions ^{6}Li + n and ^{6}He + p
  - Bound-state energies
  - Resonances - experimentally observed and predicted
  - Charge-exchange reaction ^{6}Li$(n, p)^{6}$He

No-core shell model (NCSM)

- System of nucleons described by intrinsic Hamiltonian $H = T_{\text{int}} + \sum_{i<j} V_{ij}$
- Schrödinger equation $H|\Psi\rangle = E|\Psi\rangle$ solved as eigenvalue problem for Hamiltonian matrix
- Basis of Slater determinants constructed from harmonic oscillator single-particle states with frequency Ω
- Each basis state carries $N = N_0 + N_{\text{ex}}$ oscillator quanta
  N_0 ... number of oscillator quanta in the lowest Pauli-allowed configuration



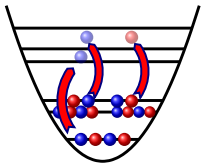
- Basis truncated by keeping only states with $N_{\text{ex}} \leq N_{\text{max}}$

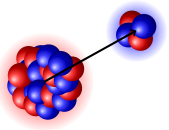
Figure courtesy of K. Kravvaris

No-core shell model with continuum (NCSMC)

- Describes both bound and scattering states
- Combines NCSM and NCSM/RGM methods
- NCSM/RGM organizes nucleons into clusters, each described within NCSM
- First, NCSM calculations for the whole system and the clusters are done
- Wave function expanded in terms of NCSM eigenstates and NCSM/RGM binary-cluster states:

$$\Psi = \sum_{\lambda} c_{\lambda} \left| \right\rangle + \sum_{\nu} \int dr u_{\nu}(r) \left| \right\rangle$$





r ... parameter coordinate playing role of distance between clusters
$u_{\nu}(r)$ ... continuous amplitudes representing intercluster relative motion

- Distribution of nucleons between clusters is called “mass partition”
- Expansion coefficients c_{λ} and amplitudes $u_{\nu}(r)$ calculated by solving NCSMC equations on Lagrange mesh

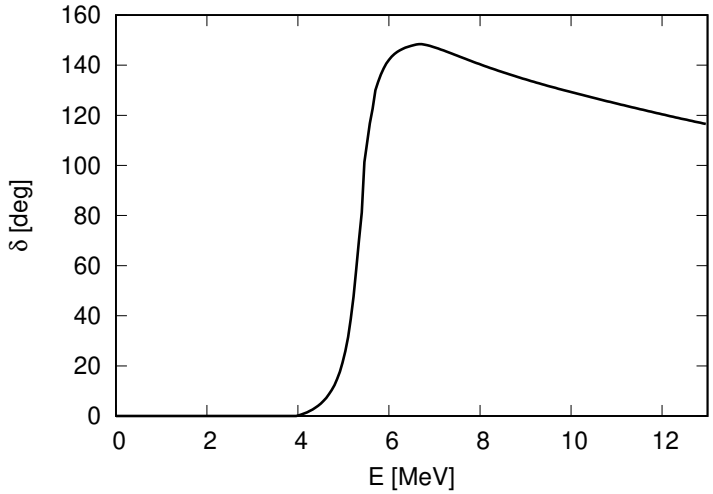
Figure courtesy of K. Kravvaris

No-core shell model with continuum (NCSMC)

- NCSMC equations can be solved for bound or scattering states by choosing asymptotic form of $u_\nu(r)$
- For scattering states:

$$u_\nu(r \to \infty) \propto \delta_{\nu i} I_\nu(r) - S_{\nu i} O_\nu(r)$$

  i ... initial channel
  $I_\nu(r)$, $O_\nu(r)$ ... ingoing and outgoing Coulomb wave functions
  $S_{\nu i}$ ... scattering matrix $\to$ cross sections
- Scattering matrix is unitary $\Rightarrow$ eigenvalues $e^{2i\delta}$
  δ ... eigenphase shifts $\to$ resonances:



Calculations for ^{7}Li within NCSMC with coupling of mass partitions ^{6}Li + n and ^{6}He + p

- Motivation: nuclear astrophysics, primordial nucleosynthesis, ^{3}H for fusion energy generation via ^{6}Li$(n,^3$H$)^4$He
- Previous work [1] taking into account relevant mass partitions in separate calculations predicts S-wave 1/2$^+$ resonance in ^{6}He + p just above proton eparation energy
- No such resonance was experimentally observed [2]
- We include mass partitions ^{6}Li + n and ^{6}He + p in single calculation
- We also predict S-wave 1/2$^+$ resonance just above proton separation energy, but only in ^{6}Li + n channel
- Coupling of mass partitions allows for calculation of charge-exchange reaction ^{6}Li$(n,p)^6$He

[1] Vorabbi *et al.* Phys. Rev. C **100**, 024304 (2019)
[2] Dronchi *et al.* Phys. Rev. C **107**, L061303 (2023)

Calculations for ^{7}Li within NCSMC with coupling of mass partitions ^{6}Li + n and ^{6}He + p

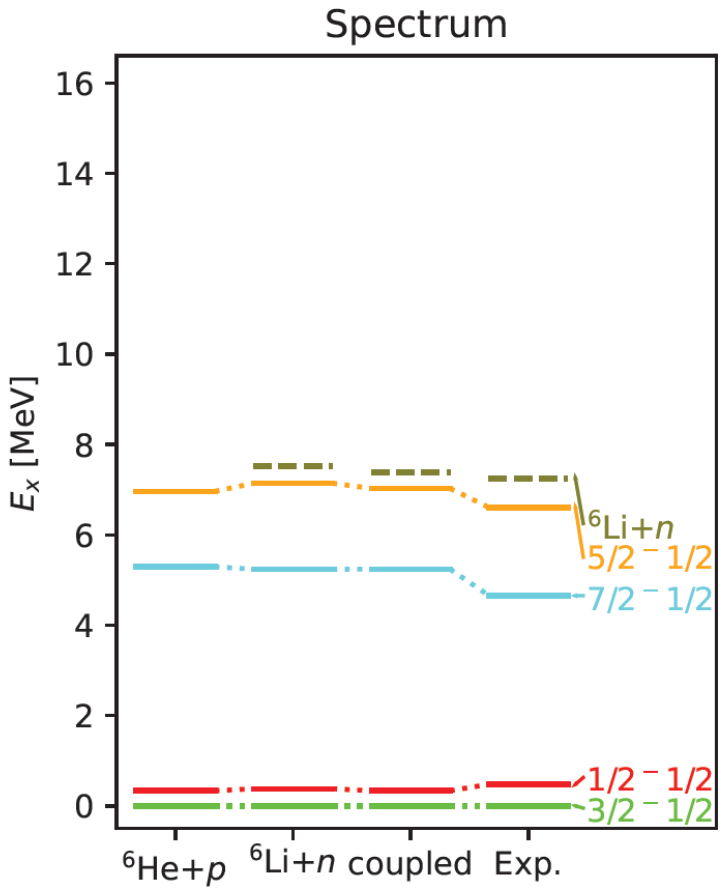
- Chiral N^{3}LO nucleon-nucleon interaction used

- NCSM eigenstates taken into account:
  - 4 states of ^{6}Li: 1^+0, 3^+0, 0^+1, 2^+1
  - 2 states of ^{6}He: 0^+1, 2^+1
  - Lowest 12 negative-parity and lowest 6 positive-parity states of ^{7}Li

- $\hbar\Omega = 20$ MeV, $N_{\max} = 11$

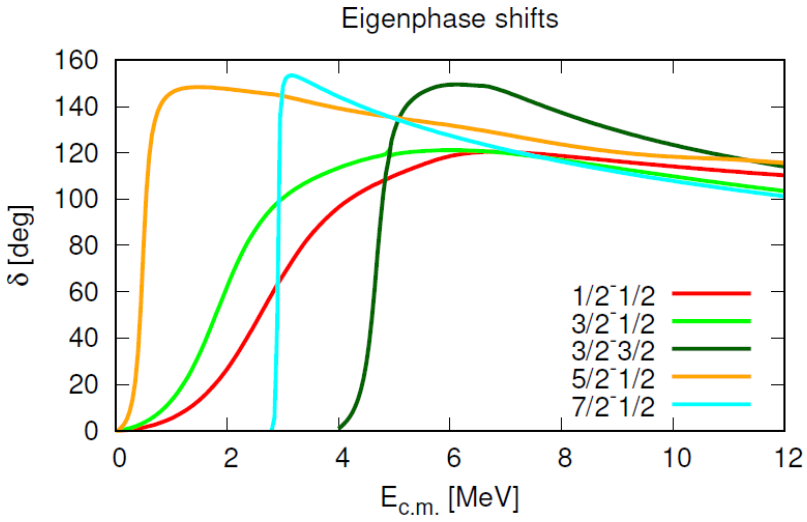
- Calculated observables: bound-state energies, energies and widths of resonances, cross section of ^{6}Li$(n,p)^6$He

Bound-state energies for ^{7}Li

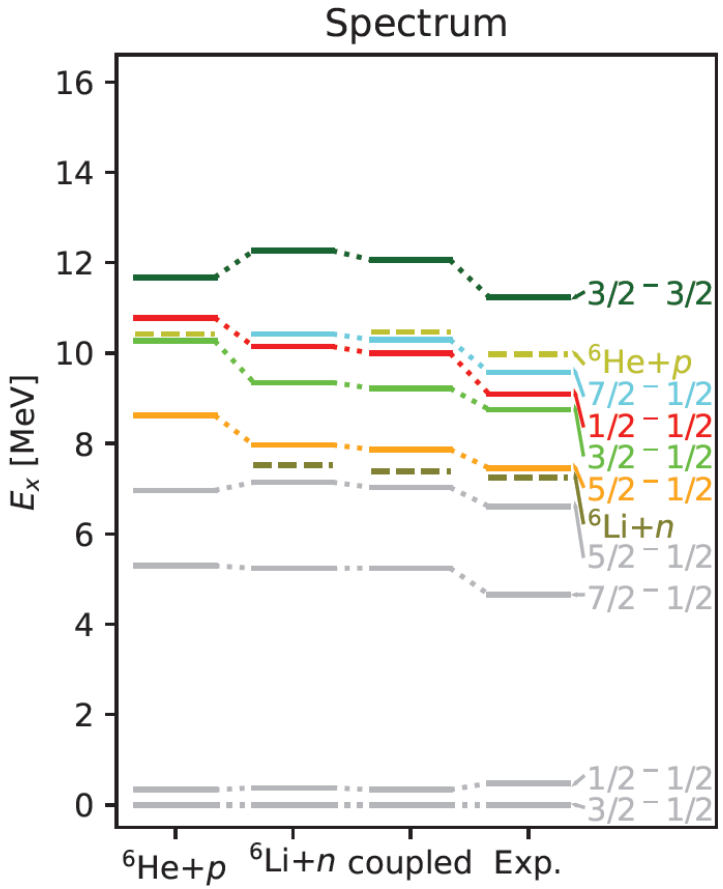


- Bound states reproduced in correct order
- Results almost independent of mass partition - bound states well described by NCSM
- Reasonable agreement between calculated and experimental excitation energies

Resonances in ^{7}Li - experimentally observed

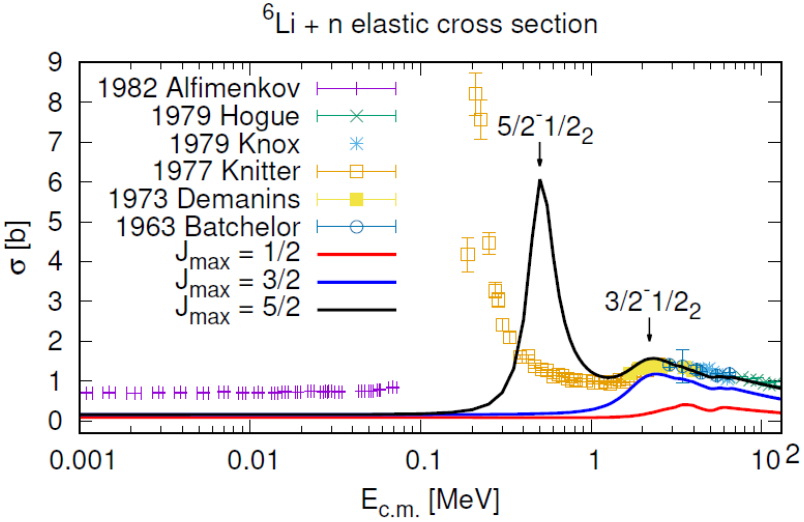


	Γ [MeV]			
$J^\pi T$	^{6}He + p	^{6}Li + n	coupled	Exp.
3/2$^-$3/2	0.41	0.36	0.40	0.26
7/2$^-$1/2		0.04	0.04	0.427
1/2$^-$1/2		2.81	2.67	2.752
3/2$^-$1/2		1.90	1.88	4.712
5/2$^-$1/2		0.22	0.24	0.080



- Experimentally observed resonances reproduced
- Discrepancy between calculated and experimental widths
- Results depend on mass partition

Resonances in ^{7}Li - experimentally observed



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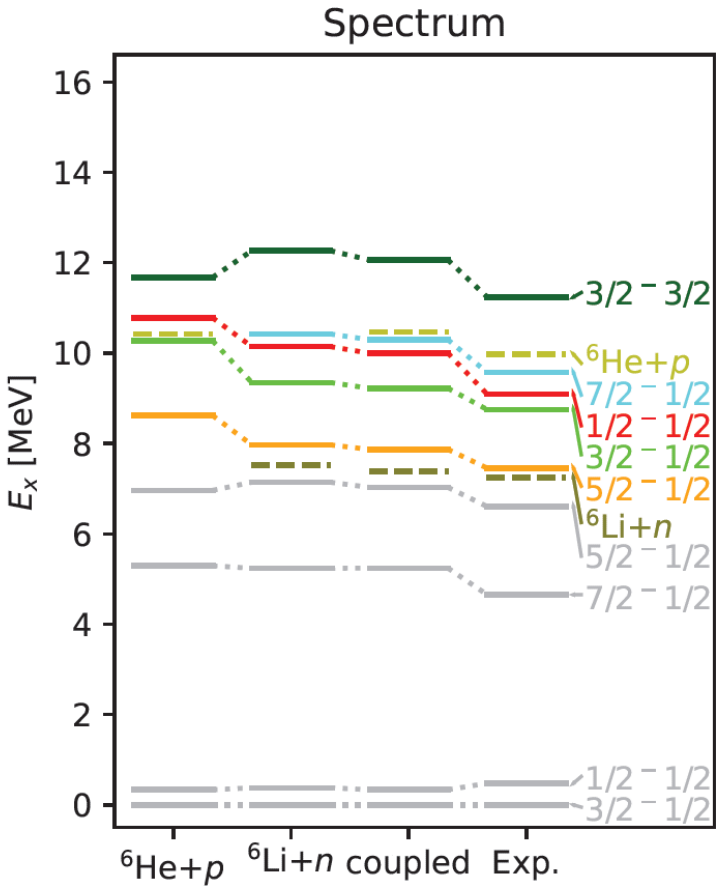
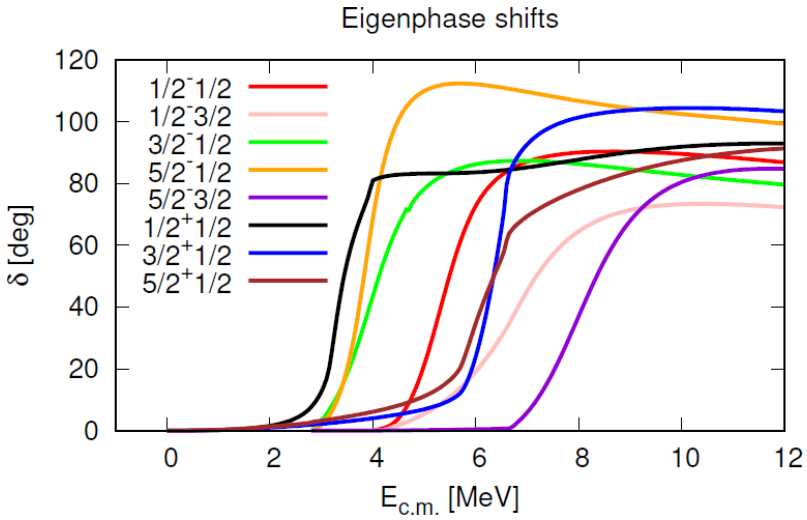
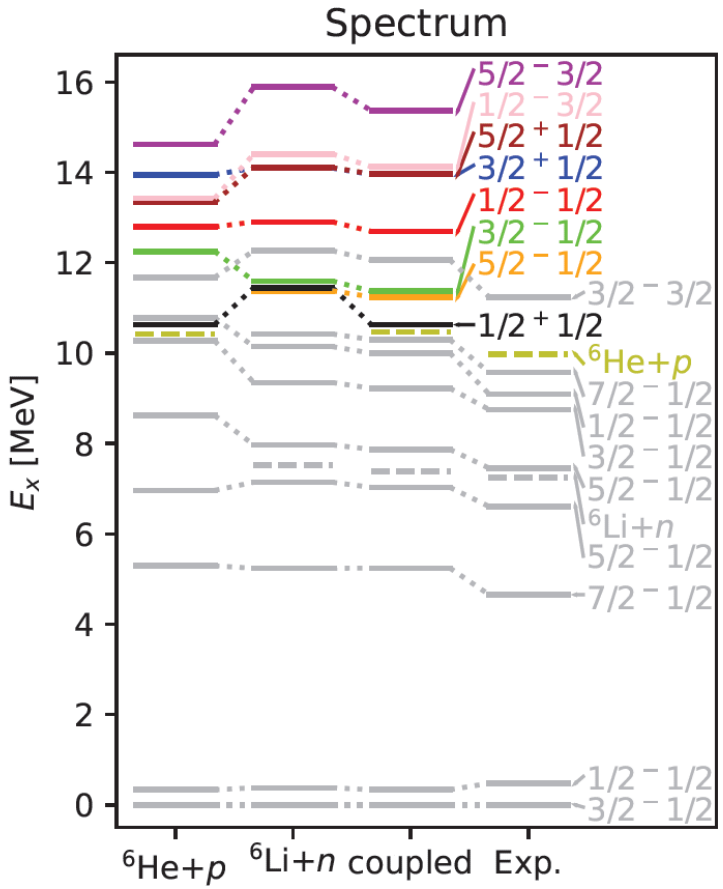


- Experimentally observed resonances reproduced
- Discrepancy between calculated and experimental widths
- Results depend on mass partition

Resonances in ^{7}Li - predicted



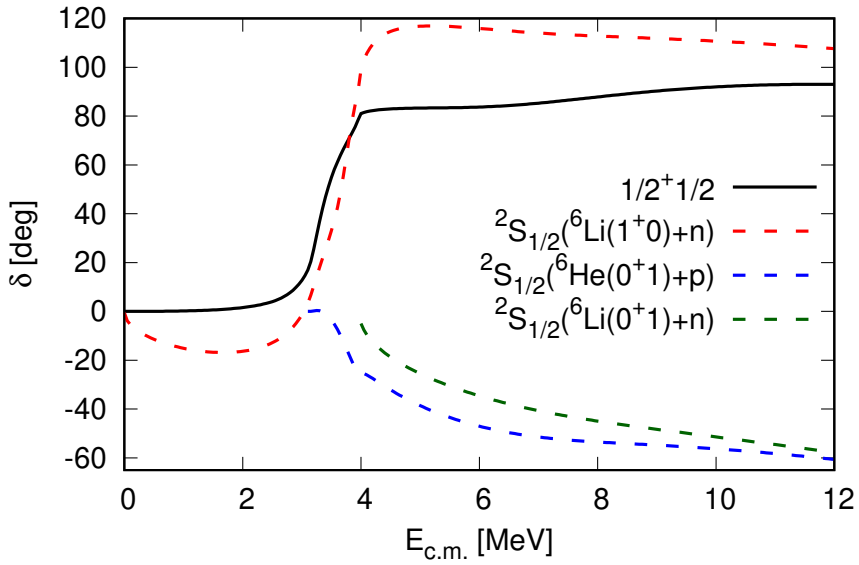
$J^\pi T$	Γ [MeV] ^{6}He + p	^{6}Li + n	coupled
$3/2^+1/2$	1.15	0.29	0.86
$1/2^-1/2$	0.15	1.79	1.87
$3/2^-1/2$	0.48	2.15	2.09
$5/2^-1/2$		1.06	1.04
$1/2^+1/2$	0.15	0.80	1.01



- Eight resonances predicted
- Results depend on mass partitions
- Effect of coupling

$1/2^+$ eigenphase shift and diagonal phase shifts

- Previous NCSMC calculations neglecting coupling of mass partitions [1] predict S-wave $1/2^+$ resonance in ^{6}He + p just above proton separation energy
- No such resonance was experimentally observed [2]



- In present calculation the $1/2^+$ resonance is dominated by $^2S_{1/2}(^6\text{Li}(1^+0) + n)$ channel
- In present calculation no $1/2^+$ resonance found in ^{6}He + p channels

[1] Vorabbi *et al.* Phys. Rev. C **100**, 024304 (2019)
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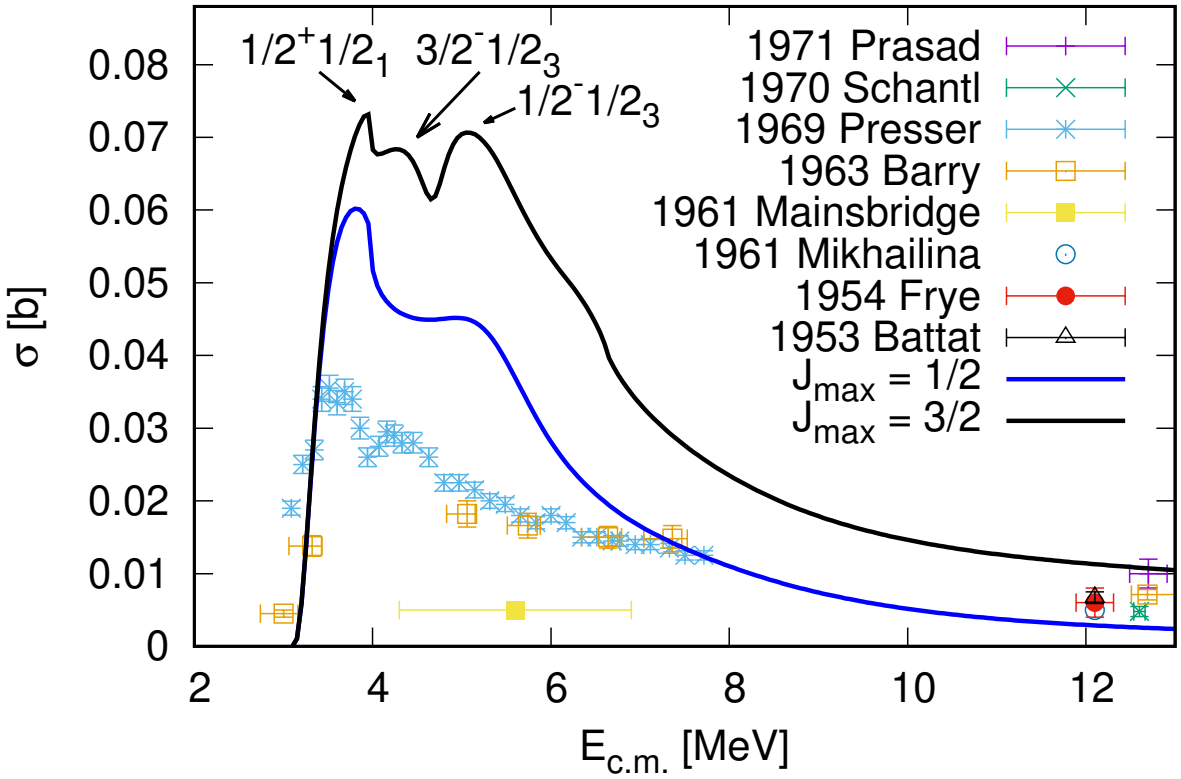
Cross section of ^{6}Li(*n*,*p*)^{6}He reaction



- Threshold and overall shape reproduced
- Values overestimated
- Missing (n, α) channel

Conclusion

- NCSMC calculations for ^{7}Li coupling mass partitions ^{6}Li + n and ^{6}He + p done
- Experimentally observed states reproduced
- Excitation energies in reasonable agreement with experiment
- Widths of resonances differ from experiment probably due to omitted mass partitions
- Energies and widths of resonances affected by coupling of mass partitions
- 1/2^{+} resonance predicted, but only in ^{6}Li + n - discrepancy between previous NCSMC prediction and experiment explained
- Cross section of ^{6}Li$(n, p)^{6}$He calculated: overall shape reproduced, values overestimated
- Future work: Include ^{4}He + ^{3}H and three-nucleon iteraction

Collaborators

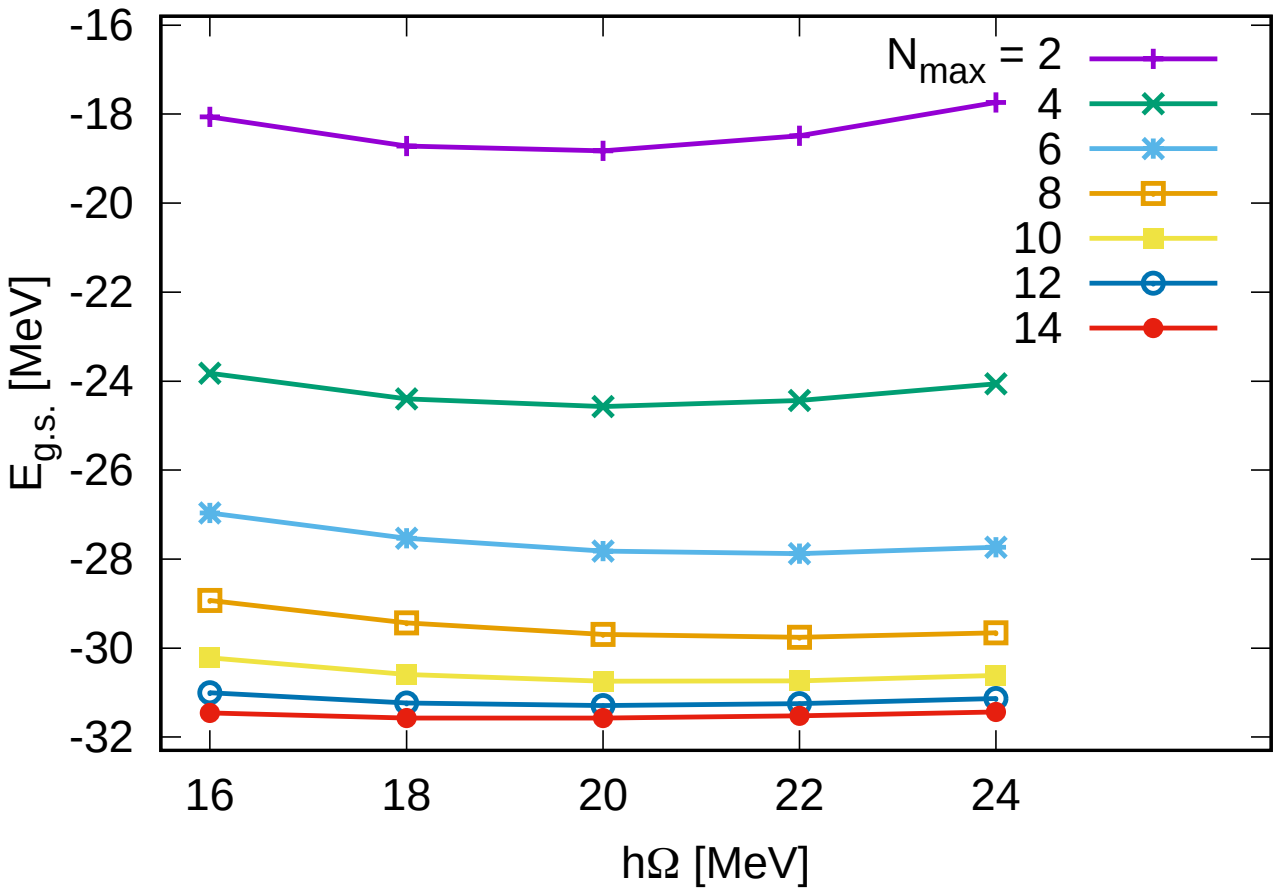
Konstantinos Kravvaris, Sofia Quaglioni
Lawrence Livermore National Laboratory

Petr Navrátil
TRIUMF

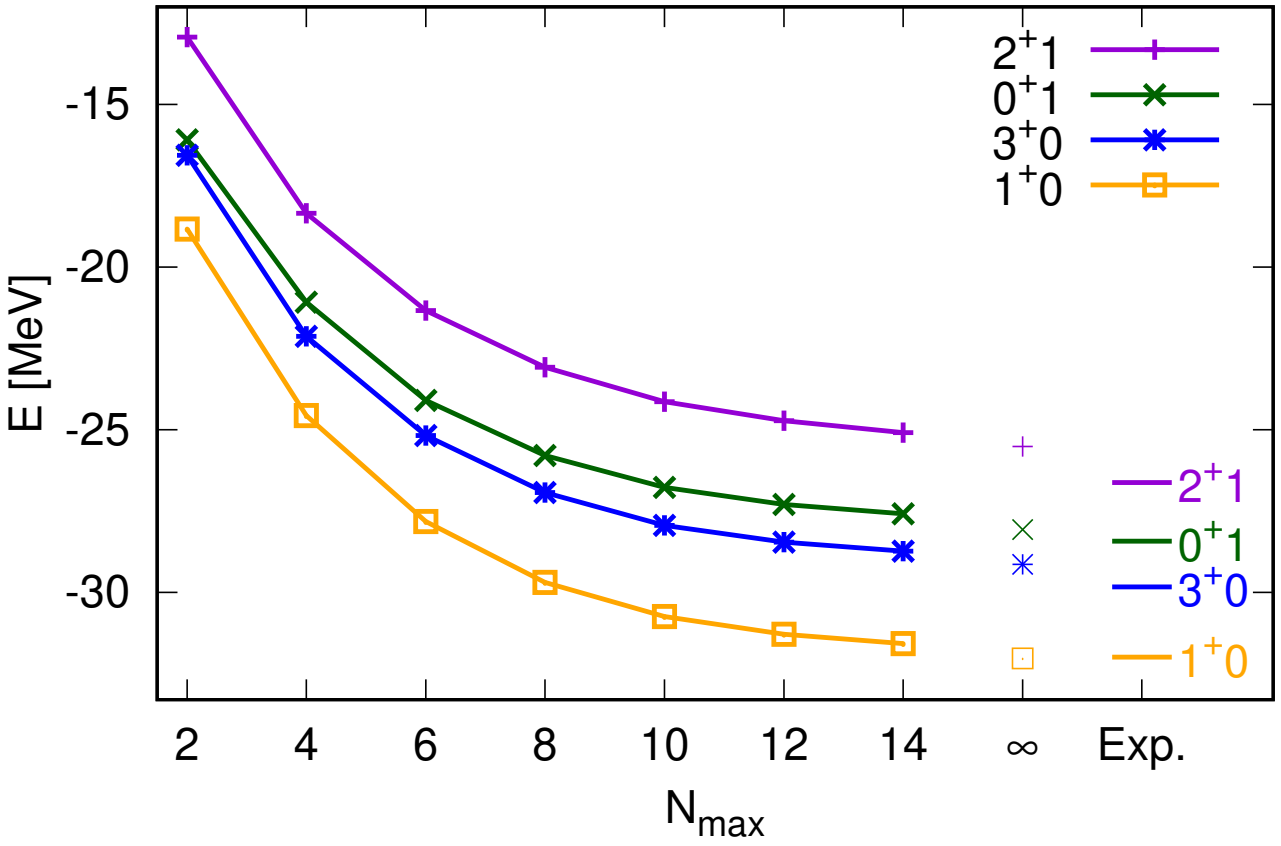
Guillaume Hupin
Université Paris-Saclay, CNRS/IN2P3, IJCLab

Mark A. Caprio
University of Notre Dame

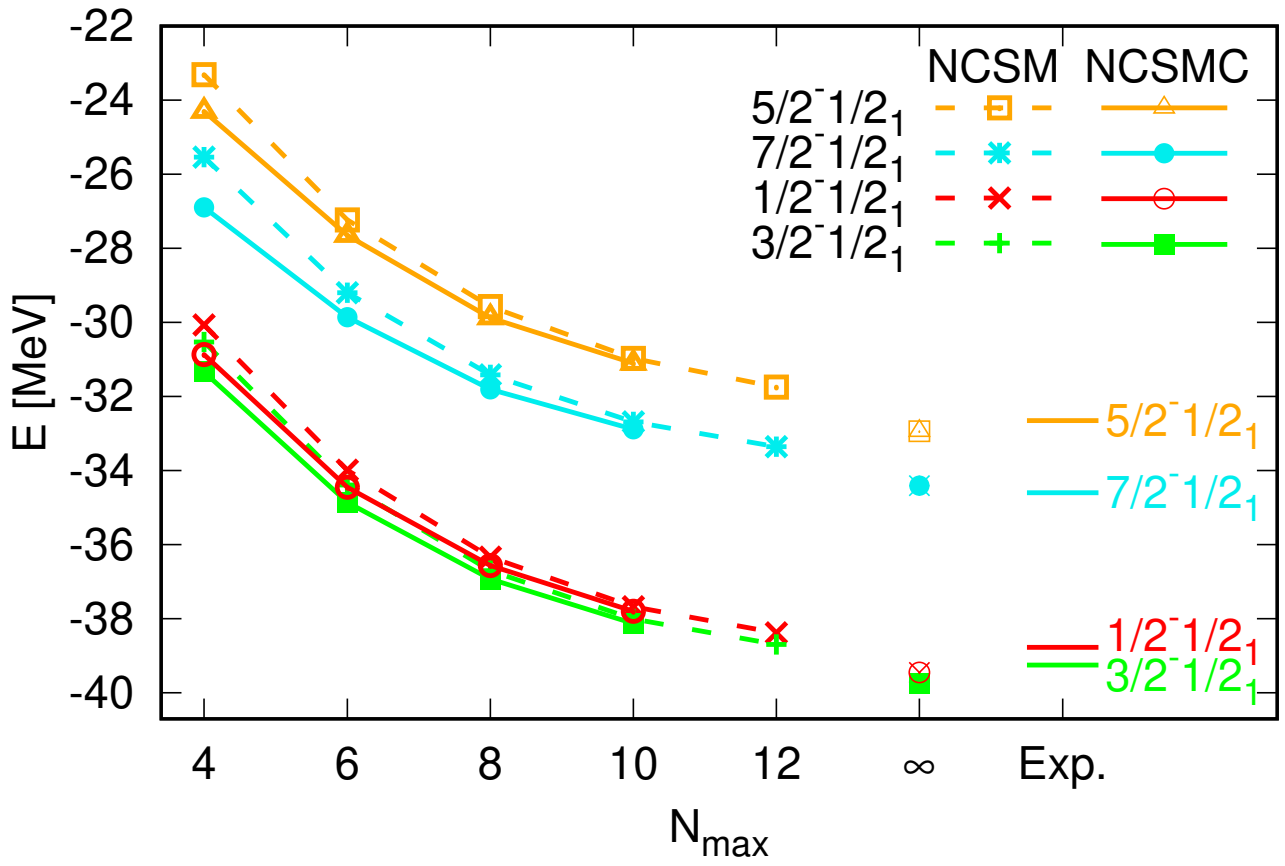
NCSM energy of ground state of ^{6}Li



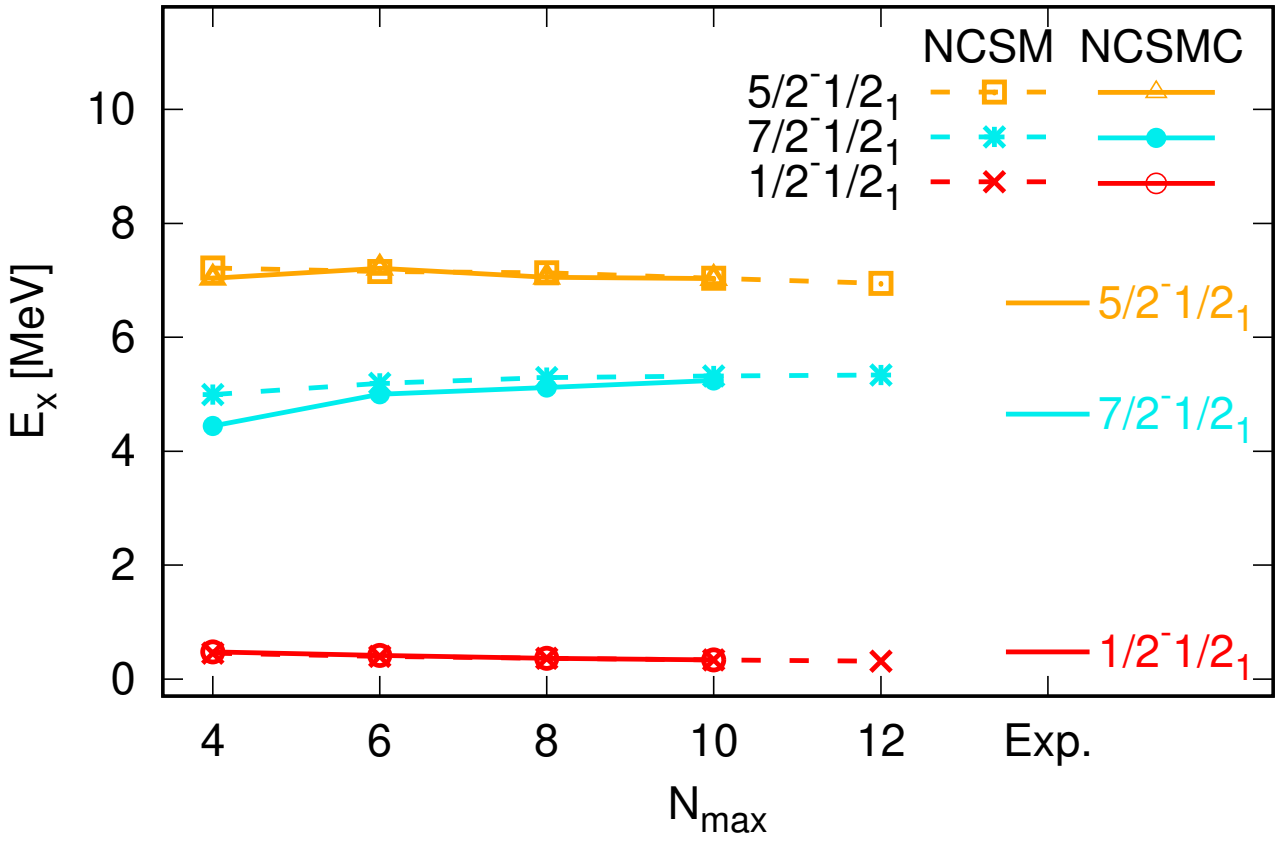
Energies of NCSM states of ^{6}Li



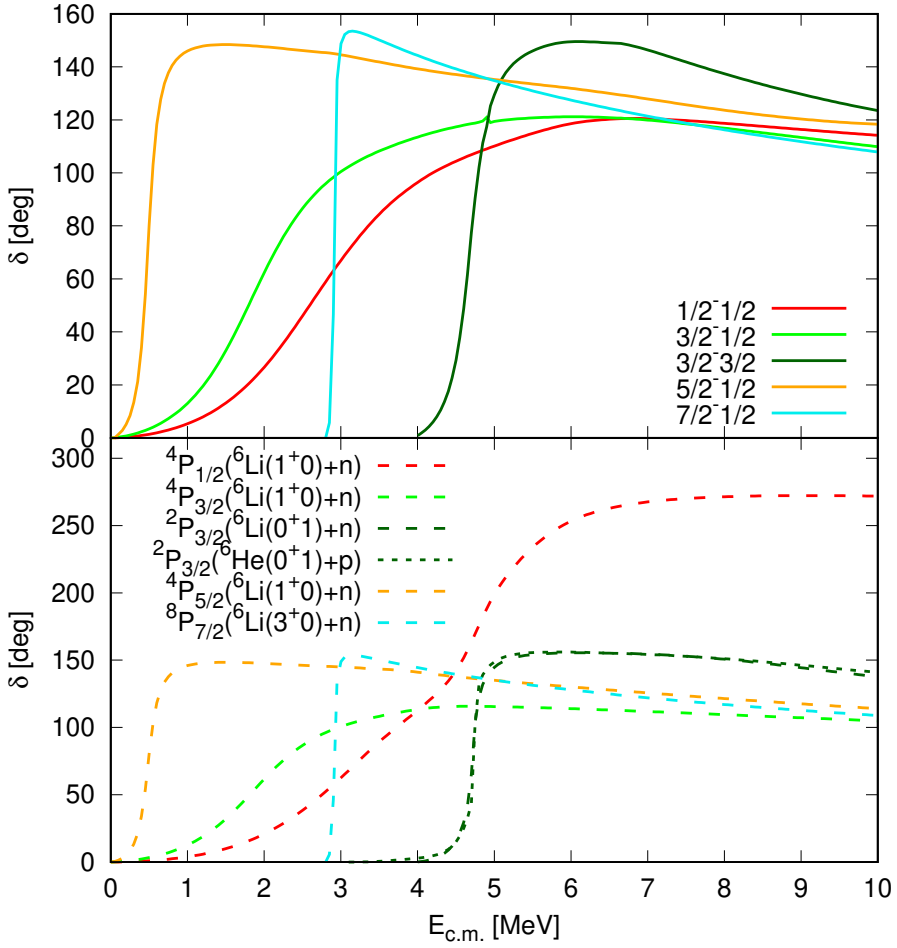
Energies of bound states of ^{7}Li



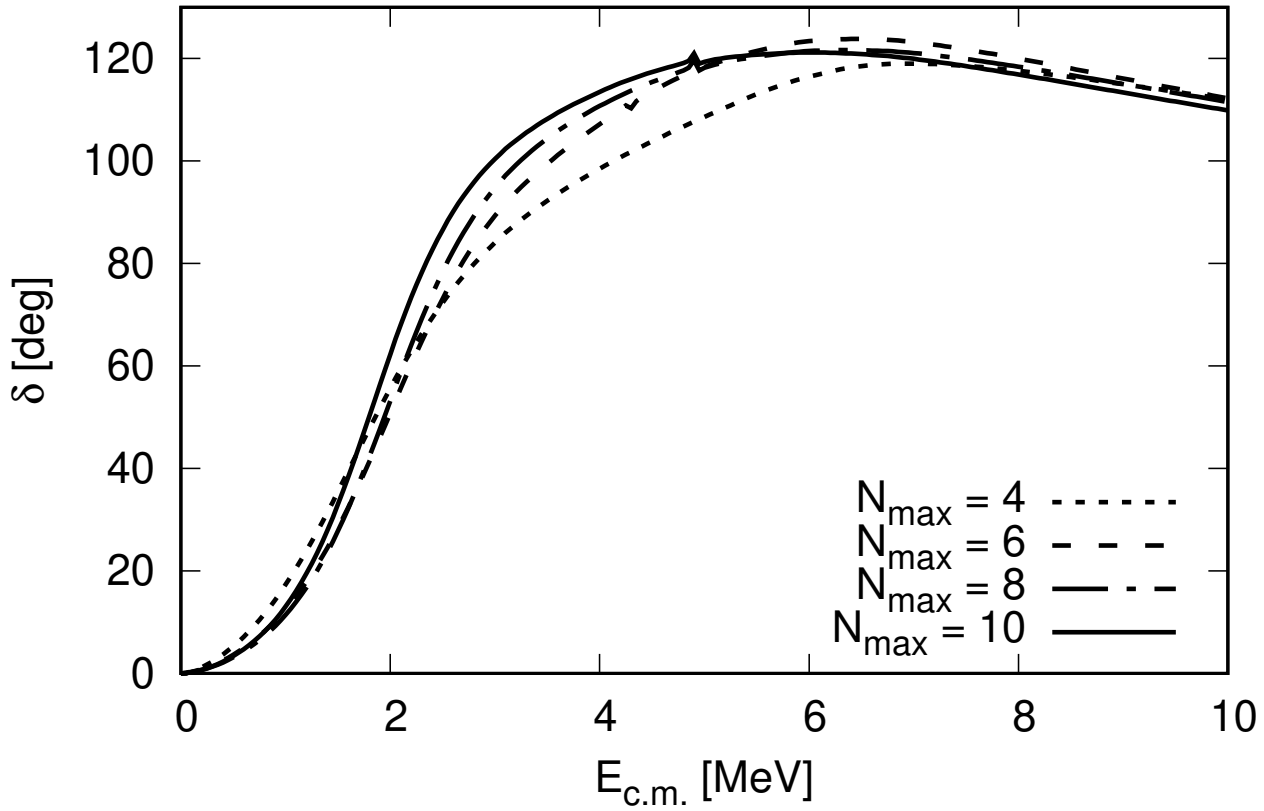
Excitation energies of bound states of ^{7}Li



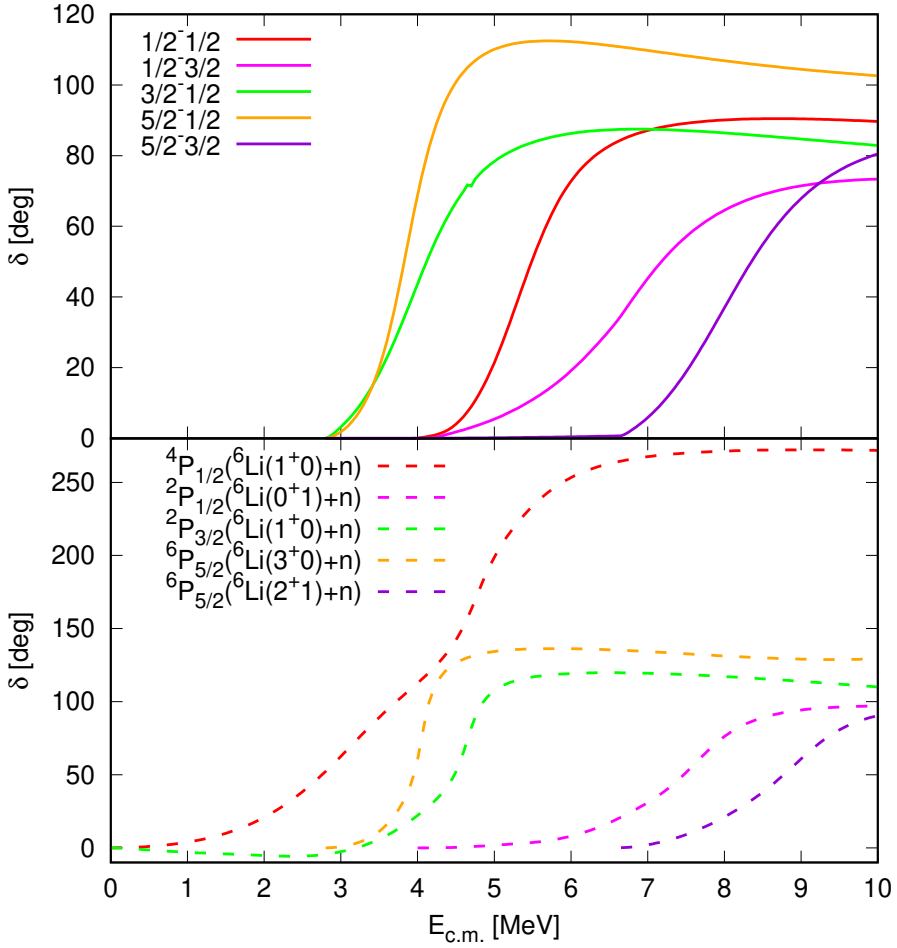
Reproduced resonances in ^{7}Li



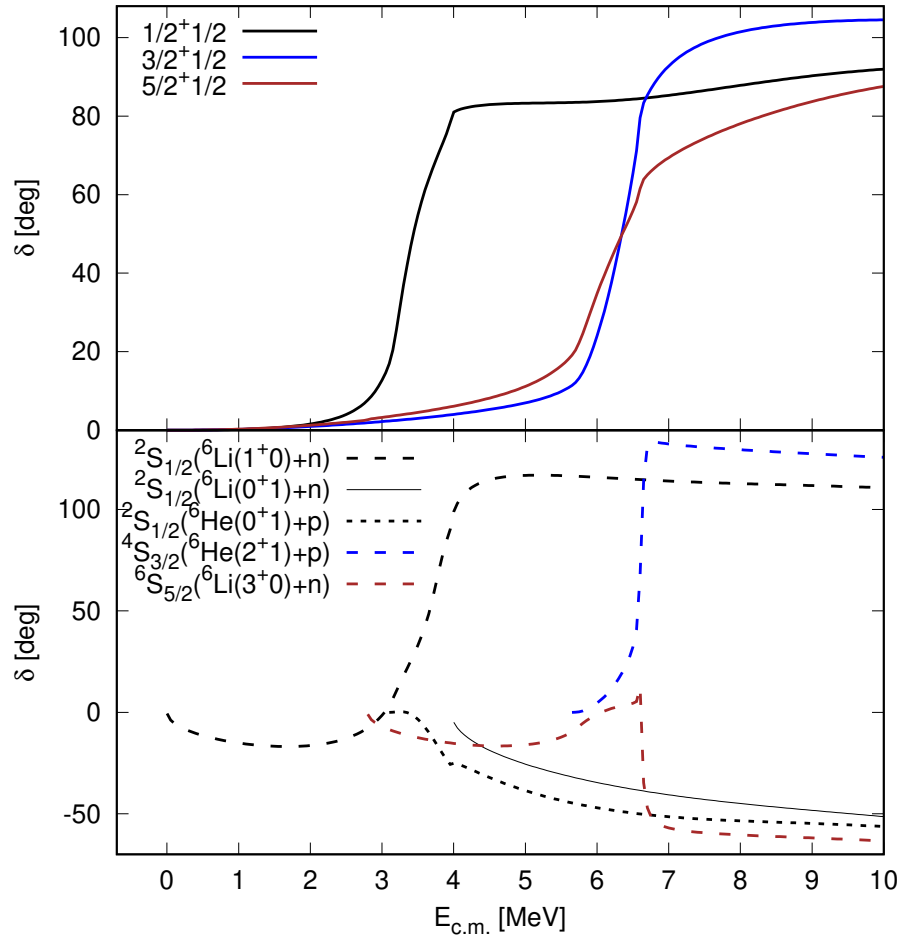
$3/2^-$ eigenphase shift



Predicted negative-parity resonances in ^{7}Li



Predicted positive-parity resoances in ^{7}Li



$1/2^+$ eigenphase shift