^{10}C and ^{10}Be: Effects of including the continuum

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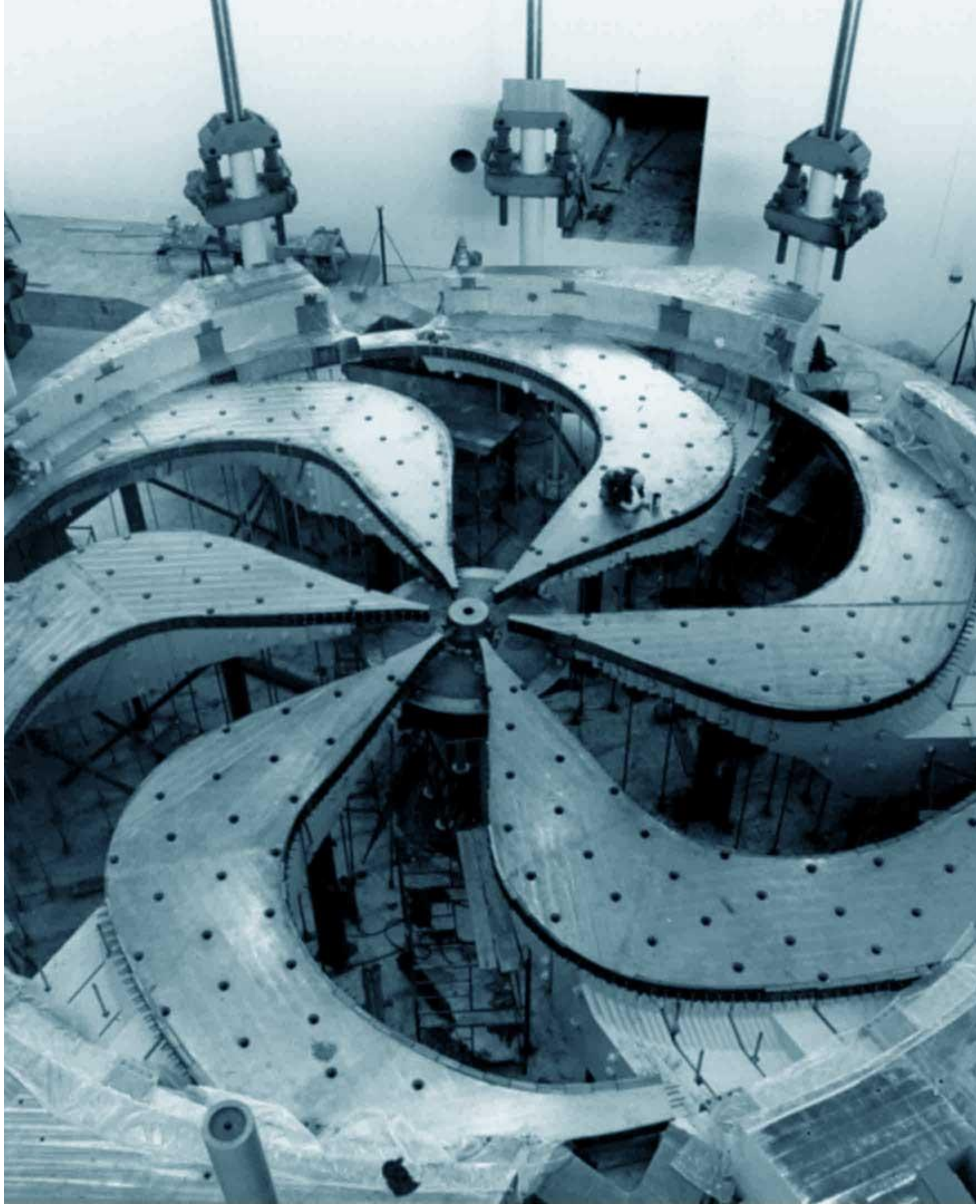
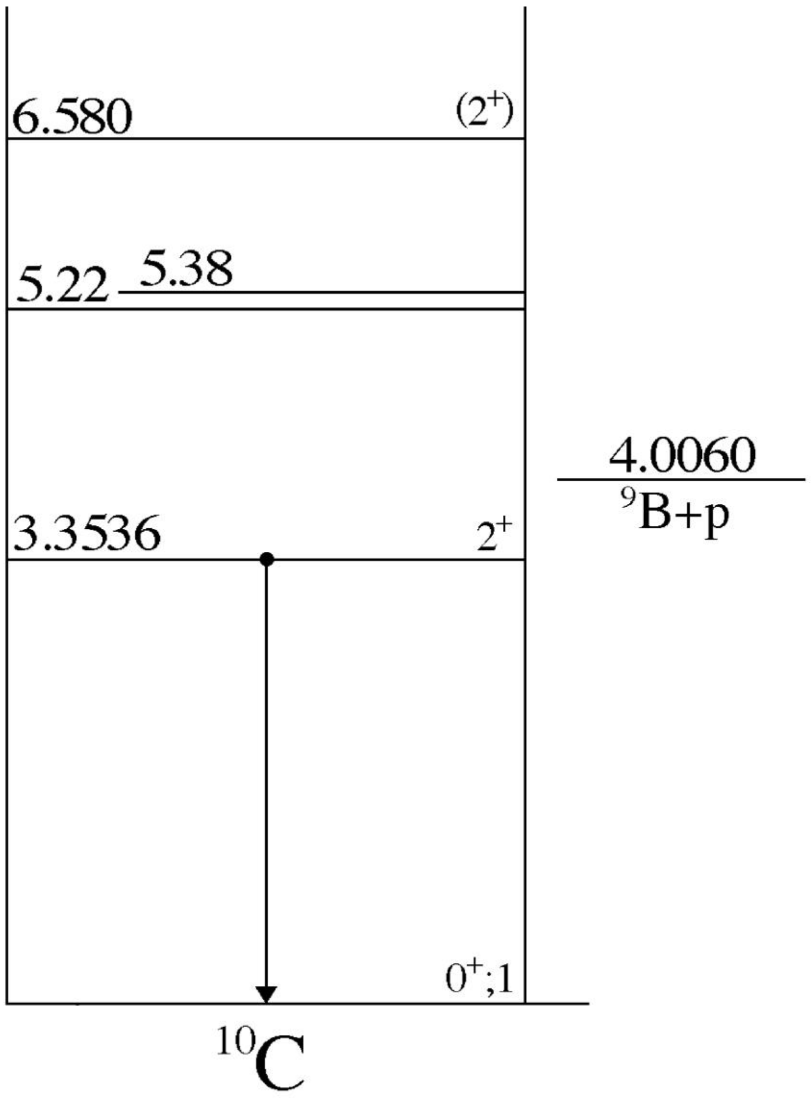
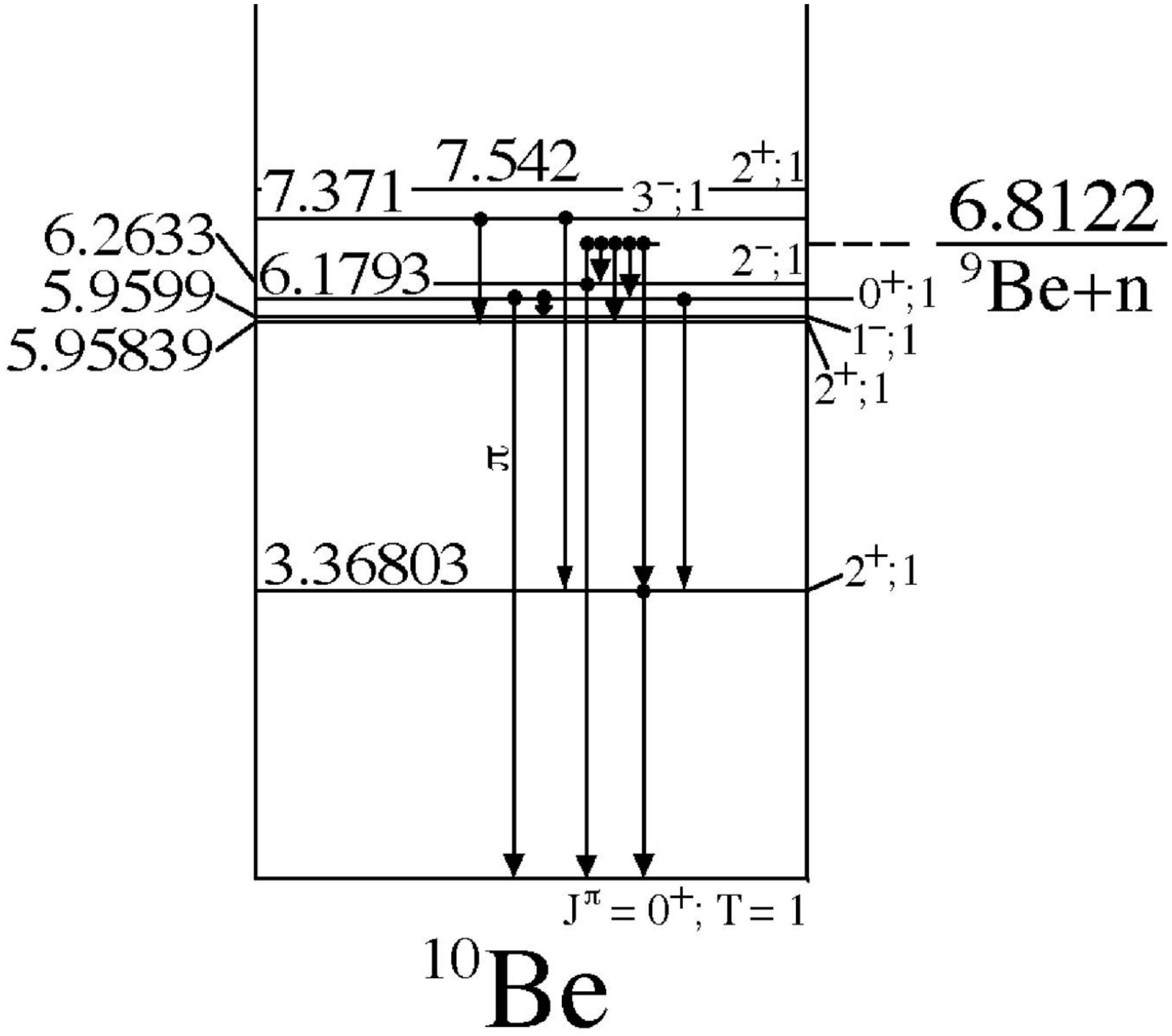
2022-07-06



Discovery, accelerated

What is the problem?





[1] Barrett et al. (2013)
[2] Entem et al. (2017)
[3] Somà et al. (2020)

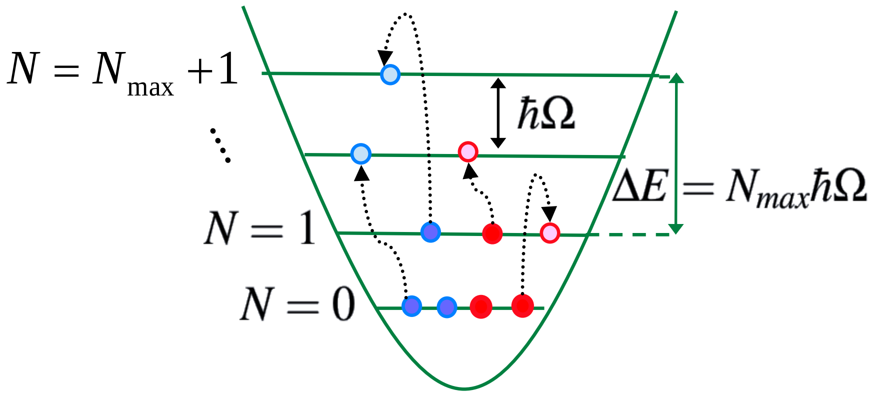
No-core shell model (NCSM)

- *Ab initio* approach to many-body Schrödinger equation for bound states and narrow resonances **[1]**
- Non-relativistic with point-like nucleons active degrees of freedom

$$H\left|\Psi_A^{J^\pi T}\right\rangle = E^{J^\pi T}\left|\Psi_A^{J^\pi T}\right\rangle$$

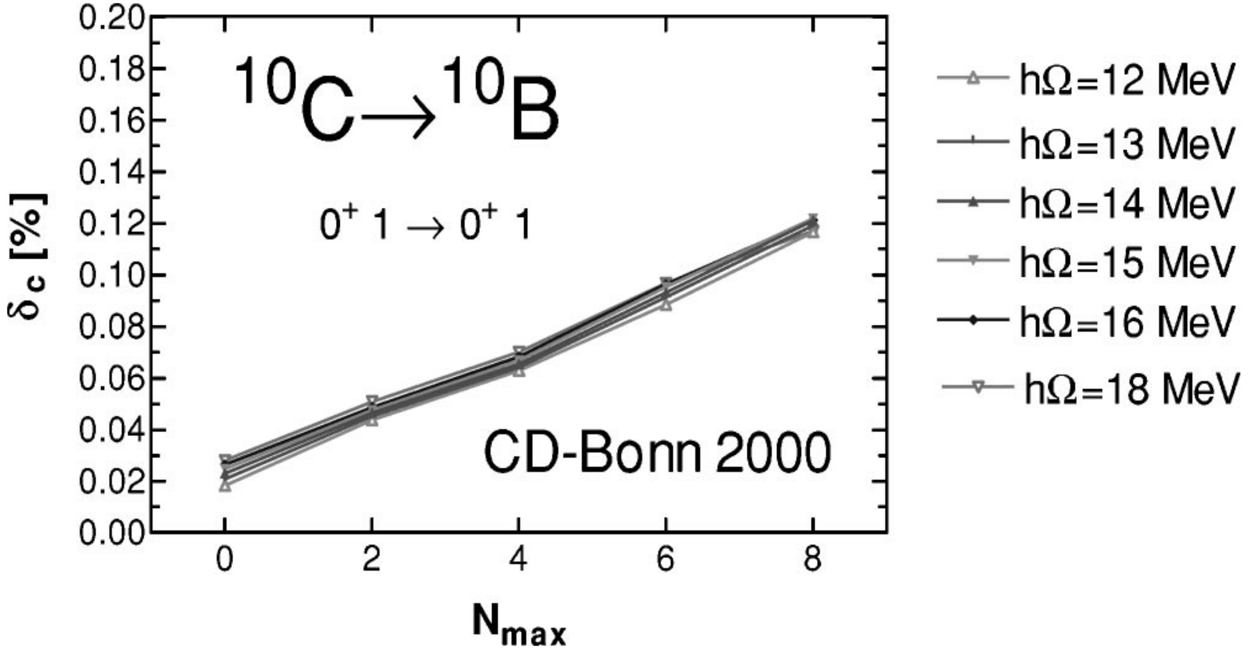
$$|\Psi_A^{J^\pi T}\rangle = \sum_{N=0}^{N_{max}} \sum_{\alpha} c_{N\alpha}^{J^\pi T} |\Phi_{N\alpha}^{J^\pi T}\rangle$$

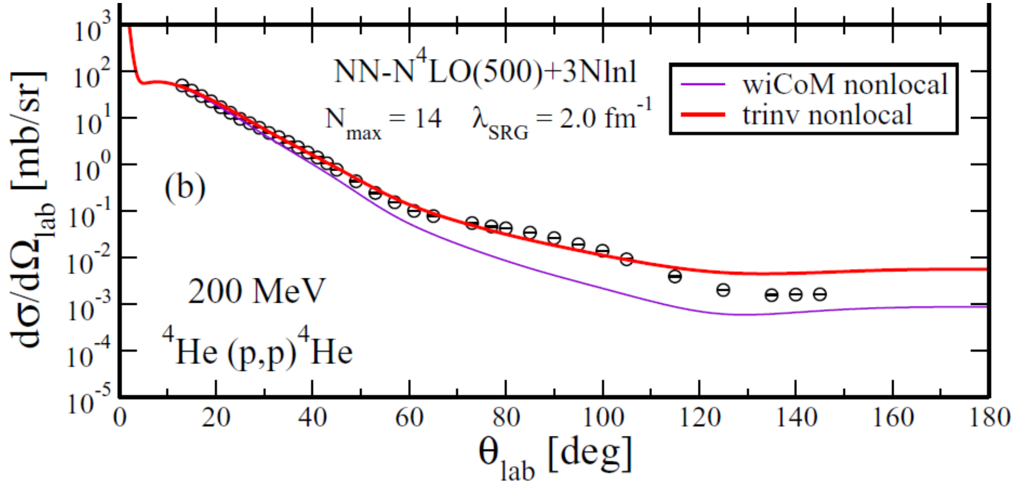
Anti-symmetrized products of many-body HO states

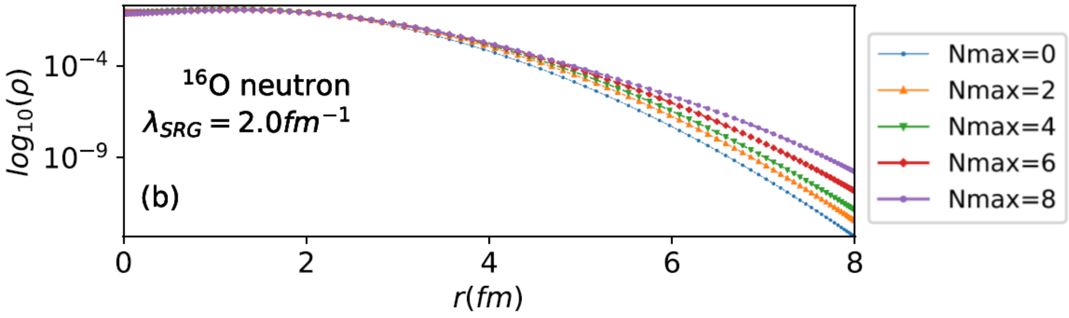


– NN+3N interactions are sole input
– NN-N^{4}LO(500) **[2]** + 3N$_{\text{lnl}}$ **[3]**

Limitations of NCSM







PHYSICAL REVIEW C **66**, 024314 (2002)

Ab initio **shell model for** $A=10$ **nuclei**

E. Caurier,[1] P. Navrátil,[2] W. E. Ormand,[2] and J. P. Vary[3]
[1]*Institut de Recherches Subatomiques (IN2P3-CNRS-Université Louis Pasteur), Batiment 27/1, 67037 Strasbourg Cedex 2, France*
[2]*Lawrence Livermore National Laboratory, L-414, P.O. Box 808, Livermore, California 94551*
[3]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011*
(Received 10 May 2002; published 13 August 2002)

PHYSICAL REVIEW C **97**, 034619 (2018)

Microscopic optical potentials derived from *ab initio* translationally invariant nonlocal one-body densities

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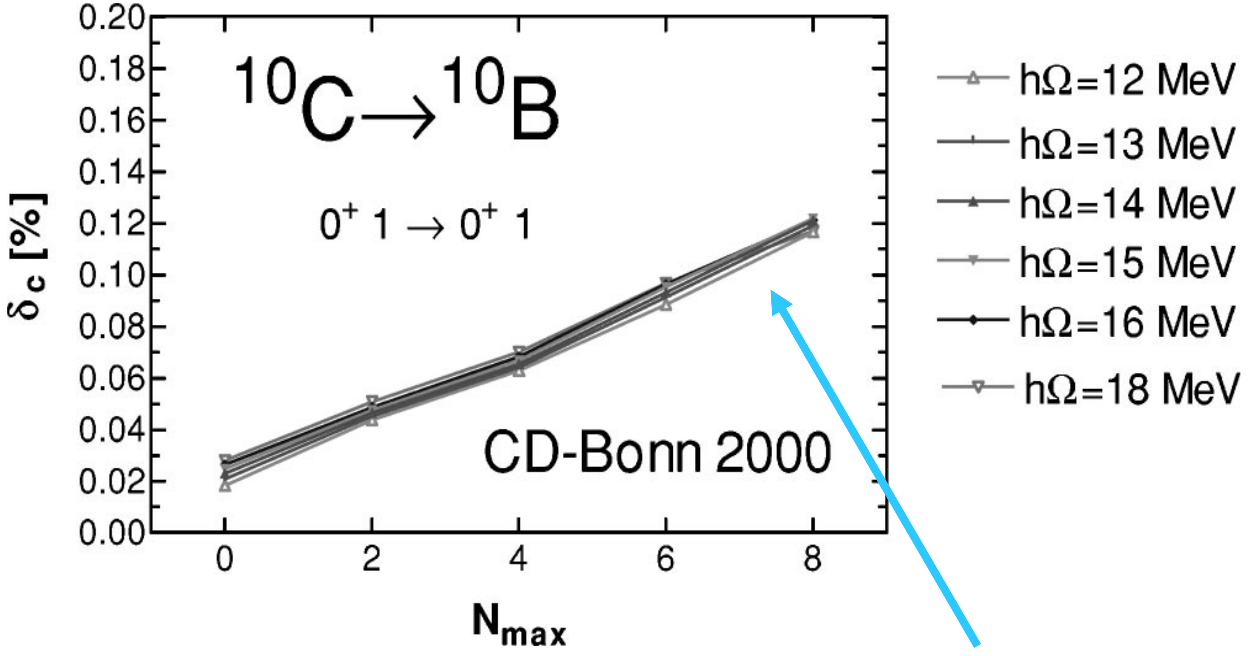
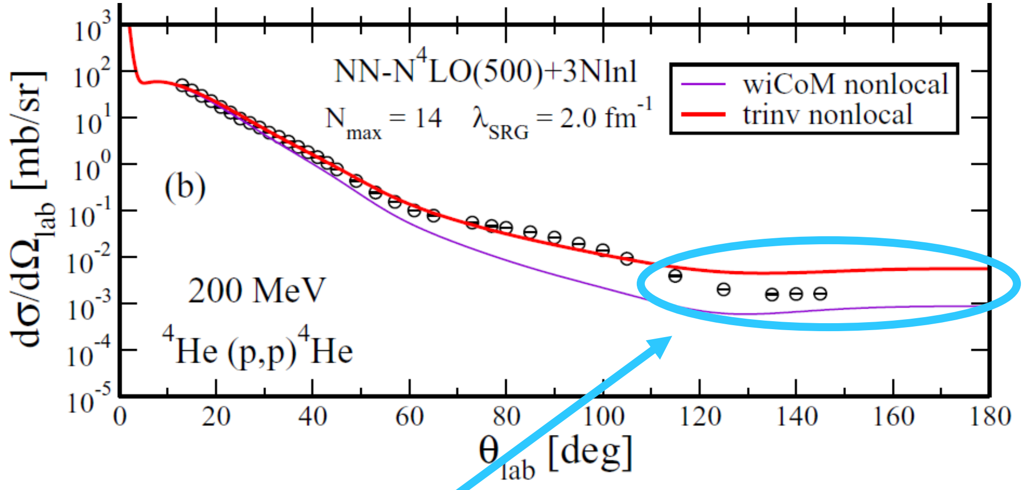
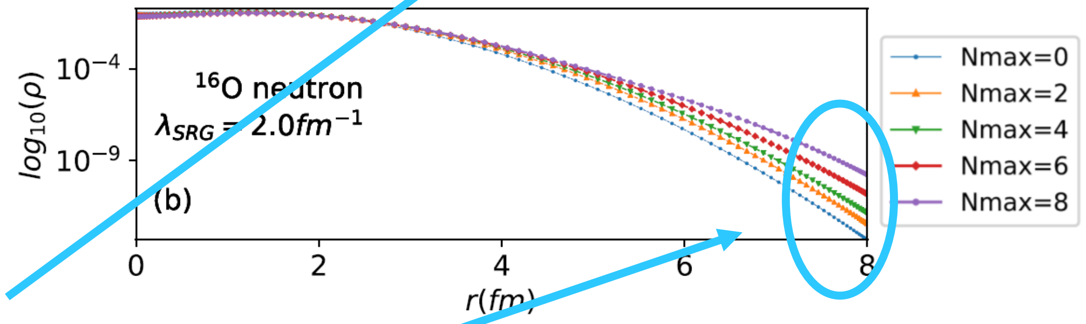
Limitations of NCSM







Non-convergent features in NCSM wave functions

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***Ab initio* shell model for *A* = 10 nuclei**

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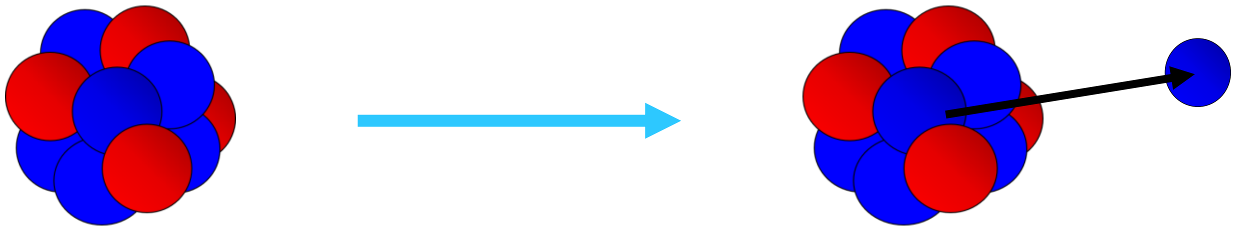
Limitations of NCSM

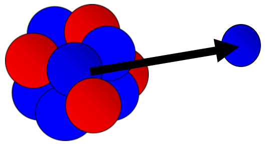
- HO expansion incompatible with reaction theory
  1. imprecise asymptotics
  2. missing correlations in excited states
  3. description of scattering states not feasible

- Combine NCSM with resonating group method (RGM) **[4]**
  - ability to deal with scattering states and reactions
  - combine microscopic A-nucleon Hamiltonians and clustering description



[4] Navrátril et al. (2009)

NCSM/RGM

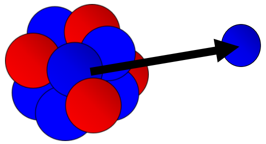


- Combine NCSM with RGM **[4]**
  - $(A-a)$-target and a-nucleon projectile in ${}^{2s+1}l_J$ relative motion waves
  - $\hat{r}_{A-a,a}$ connects c.m. of each cluster

$$\left|\Phi^{J^\pi T}_{\nu r}\right\rangle = \left[\left(\left|A-a\,\alpha_1 I_1^{\pi_1} T_1\right\rangle \otimes \left|a\,\alpha_2 I_2^{\pi_2} T_2\right\rangle\right)^{(sT)} Y_l(\hat{r}_{A-a,a})\right]^{(J^\pi T)} \frac{\delta(r - r_{A-a,a})}{r\, r_{A-a,a}}$$

$$H^{(A-a)}\left|\Psi^{I_1^{\pi_1} T_1}_{A-a}\right\rangle = E^{I_1^{\pi_1} T_1}\left|\Psi^{I_1^{\pi_1} T_1}_{A-a}\right\rangle \qquad H^{(a)}\left|\Psi^{I_2^{\pi_2} T_2}_{a}\right\rangle = E^{I_2^{\pi_2} T_2}\left|\Psi^{I_2^{\pi_2} T_2}_{a}\right\rangle$$

NCSM/RGM



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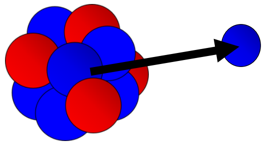
- Require anti-symmetrization to preserve Pauli principle

$$\hat{\mathcal{A}}_\nu = \sqrt{\frac{(A-a)!\,a!}{A!}}\left(1+\sum_{P\neq\mathbb{1}}(-1)^p P_\nu\right)$$

→ Anti-symmetrize between clusters

NCSM/RGM



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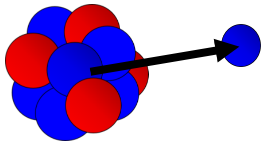
- Require anti-symmetrization to preserve Pauli principle
- Use anti-symmetrized channel states as continuous basis ansatz

$$\left|\Psi^{J^\pi T}\right\rangle = \sum_\nu \int dr\; r^2 \mathcal{A}_\nu \left|\Phi^{J^\pi T}_{\nu r}\right\rangle \frac{\left[\mathcal{N}^{-\frac{1}{2}} \cdot \chi\right]^{J^\pi T}_\nu (r)}{r}$$

Linear variational amplitudes

Solving RGM equations



- Solve orthogonalized RGM equations

Linear variational amplitudes

$$\sum_{\nu'} \int dr'\, r'^2 \left[\mathcal{N}^{-\frac{1}{2}} \mathcal{H} \mathcal{N}^{-\frac{1}{2}}\right]^{J^\pi T}_{\nu\nu'}(r,r')\, \frac{\chi^{J^\pi T}_{\nu'}(r')}{r'} = E \frac{\chi^{J^\pi T}_{\nu}(r)}{r}$$

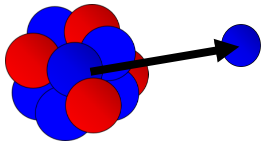
$$\mathcal{H}^{J^\pi T}_{\nu'\nu}(r',r) = \left\langle \Phi^{J^\pi T}_{\nu' r'} \middle| \hat{\mathcal{A}}_{\nu'} \mathcal{H} \hat{\mathcal{A}}_{\nu} \middle| \Phi^{J^\pi T}_{\nu r} \right\rangle$$

Hamiltonian kernels

$$\mathcal{N}^{J^\pi T}_{\nu'\nu}(r',r) = \left\langle \Phi^{J^\pi T}_{\nu' r'} \middle| \hat{\mathcal{A}}_{\nu'} \hat{\mathcal{A}}_{\nu} \middle| \Phi^{J^\pi T}_{\nu r} \right\rangle$$

Norm kernels

Solving RGM equations



- Solve orthogonalized RGM equations

$$\sum_{\nu'} \int dr' \, r'^2 \left[\mathcal{N}^{-\frac{1}{2}} \mathcal{H} \mathcal{N}^{-\frac{1}{2}}\right]^{J^\pi T}_{\nu\nu'}(r,r') \frac{\chi^{J^\pi T}_{\nu'}(r')}{r'} = E \frac{\chi^{J^\pi T}_{\nu}(r)}{r}$$

- Norm and Hamiltonian kernels primary computational challenge

$$\mathcal{H}^{J^\pi T}_{\nu'\nu}(r',r) = \left\langle \Phi^{J^\pi T}_{\nu' r'} \middle| \hat{\mathcal{A}}_{\nu'} \mathcal{H} \hat{\mathcal{A}}_{\nu} \middle| \Phi^{J^\pi T}_{\nu r} \right\rangle$$

Hamiltonian kernels

$$\mathcal{N}^{J^\pi T}_{\nu'\nu}(r',r) = \left\langle \Phi^{J^\pi T}_{\nu' r'} \middle| \hat{\mathcal{A}}_{\nu'} \hat{\mathcal{A}}_{\nu} \middle| \Phi^{J^\pi T}_{\nu r} \right\rangle$$

Norm kernels

Well established solutions of multi-channel Schrödinger equations

[5] Lane et al. (1958)
[6] Hesse et al. (1998)
[7] Descouvemont et al. (2010)

Solving RGM equations

$$\sum_{\nu'} \int dr' \, r'^2 \, \left[\mathcal{N}^{-\frac{1}{2}} \mathcal{H} \mathcal{N}^{-\frac{1}{2}}\right]^{J^\pi T}_{\nu\nu'}(r,r') \, \frac{\chi^{J^\pi T}_{\nu'}(r')}{r'} = E \frac{\chi^{J^\pi T}_{\nu}(r)}{r}$$

- Solve coupled channel nonlocal integro-differential equations **[5-7]**
  - split configuration space by large matching radius r_0
  - require continuity of wave function and derivative

Internal region

$$\chi^{J^\pi T}_{\nu}(r) = \frac{i}{2v_\nu}\left[\delta_{\nu i} H^{-}_{l}(\kappa_\nu r) - S^{J^\pi T}_{\nu i} H^{+}_{l}(\kappa_\nu r)\right]$$

- Coulomb functions
- Expand over square integrable Lagrange functions

External region

$$\chi^{J^\pi T}_{\nu}(r) = C^{J^\pi T}_{\nu} W_l(\kappa_\nu r)$$

- Whittaker function asymptotics
- Normalization constant $C^{J^\pi T}_{\nu}$

[5] Lane et al. (1958)
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Solving RGM equations

$$\sum_{\nu'} \int dr' \, r'^2 \, \left[\mathcal{N}^{-\frac{1}{2}} \mathcal{H} \mathcal{N}^{-\frac{1}{2}}\right]^{J^\pi T}_{\nu\nu'}(r, r') \, \frac{\chi^{J^\pi T}_{\nu'}(r')}{r'} = E \frac{\chi^{J^\pi T}_{\nu}(r)}{r}$$

- Solve coupled channel nonlocal integro-differential equations **[5-7]**
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  - require continuity of wave function and derivative

- Eigenstates and eigenenergies for bound states
- Scattering matrix and eigenstates for unbound states
- *Ab initio* description of scattering off light-nuclei

Can we go further?

No-core shell model with continuum (NCSMC)

- Generalize NCSM/RGM expansion with discrete NCSM eigenstates **[8]**

$$\left|\Psi^{J^\pi T}\right\rangle = \sum_\alpha c_\alpha^{J^\pi T}\left|A\alpha J^\pi T\right\rangle + \sum_\nu \int dr\; r^2 \mathcal{A}_\nu \left|\Phi_{\nu r}^{J^\pi T}\right\rangle \frac{\left[\mathcal{N}^{-\frac{1}{2}}\cdot\chi\right]_\nu^{J^\pi T}(r)}{r}$$

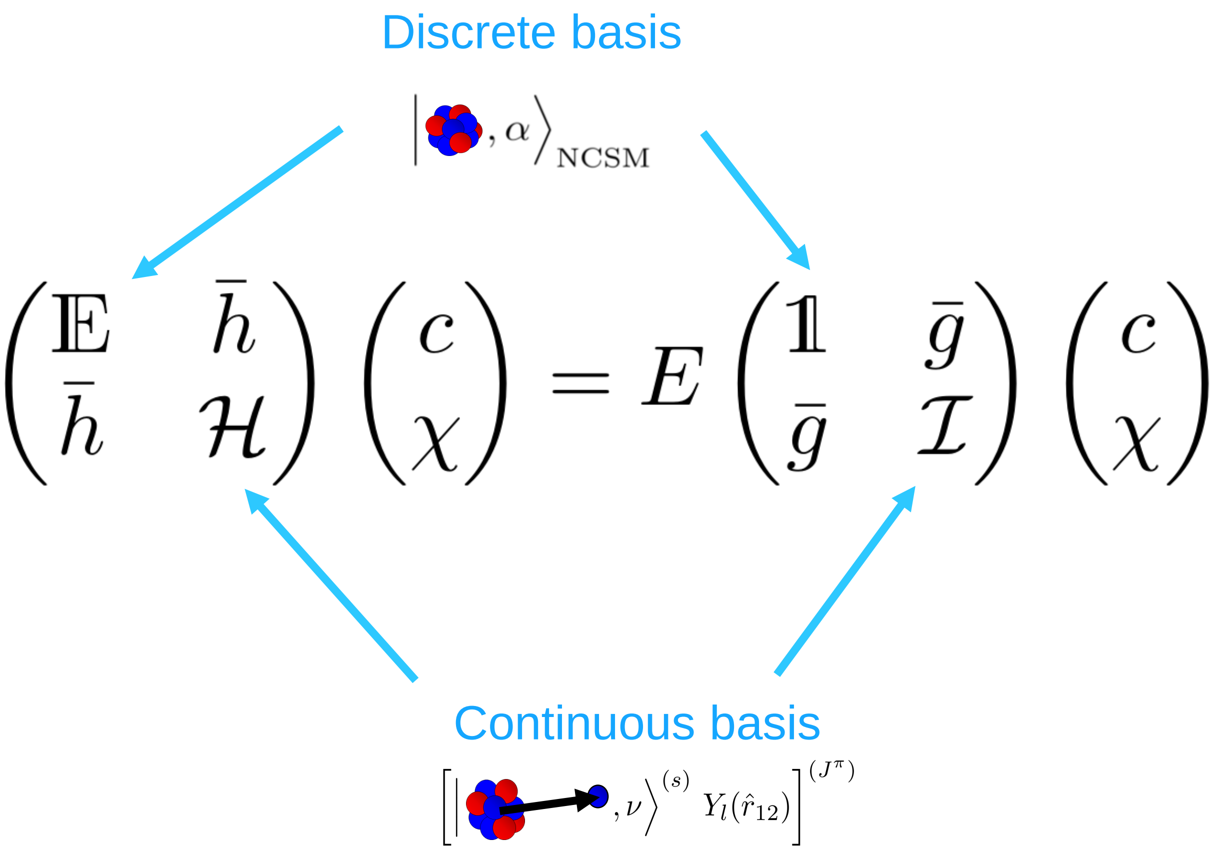
- Solve coupled equations

$$\begin{pmatrix} \mathbb{E} & \bar{h} \\ \bar{h} & \mathcal{H} \end{pmatrix}\begin{pmatrix} c \\ \chi \end{pmatrix} = E\begin{pmatrix} \mathbb{1} & \bar{g} \\ \bar{g} & \mathcal{I} \end{pmatrix}\begin{pmatrix} c \\ \chi \end{pmatrix}$$

No-core shell model with continuum (NCSMC)

$$\left|\Psi^{J^\pi T}\right\rangle = \sum_\alpha c_\alpha^{J^\pi T}\left|A\alpha J^\pi T\right\rangle + \sum_\nu \int dr\, r^2 \mathcal{A}_\nu \left|\Phi_{\nu r}^{J^\pi T}\right\rangle \frac{\left[\mathcal{N}^{-\frac{1}{2}}\cdot\chi\right]_\nu^{J^\pi T}(r)}{r}$$

- Generalize NCSM/RGM expansion with discrete NCSM eigenstates **[8]**
- Determine $c_\alpha^{J\pi T}$ and $\chi_\nu^{J\pi T}(r)$ simultaneously by solving coupled equations



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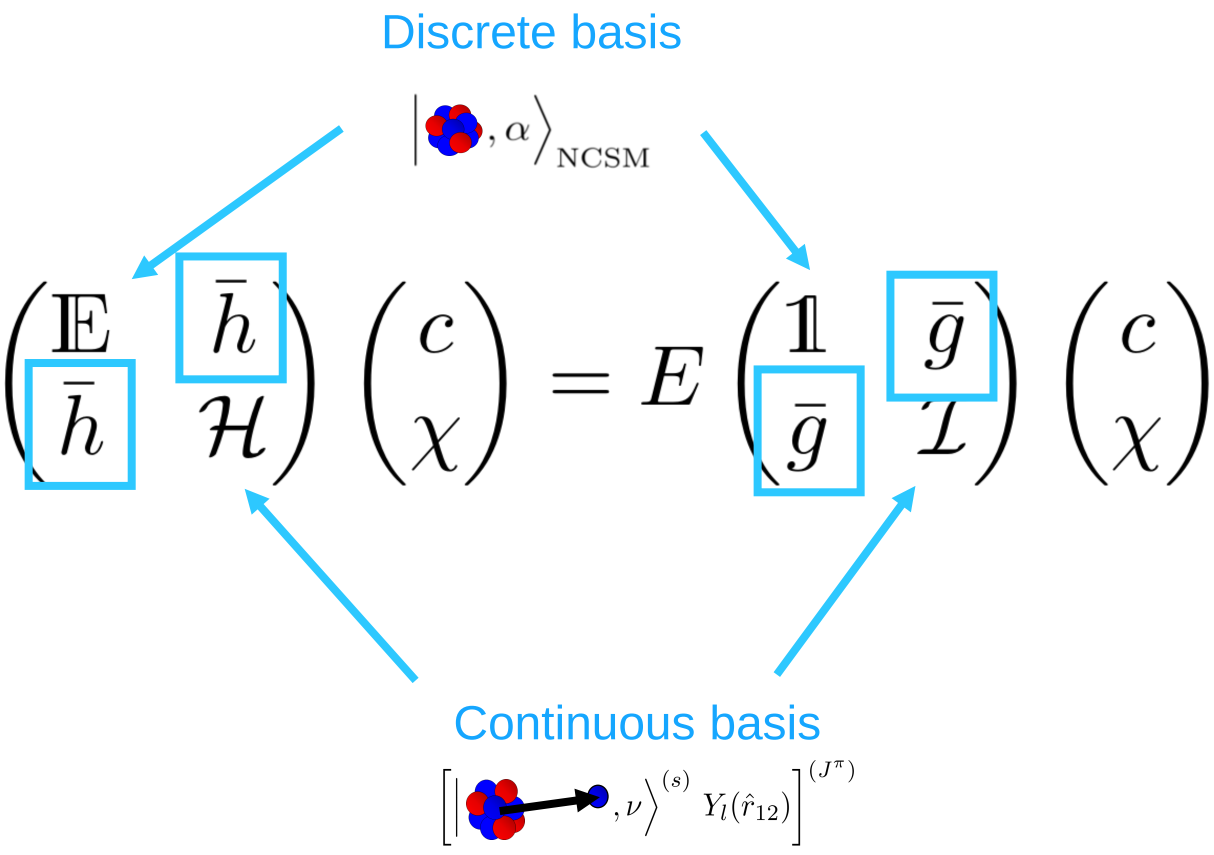

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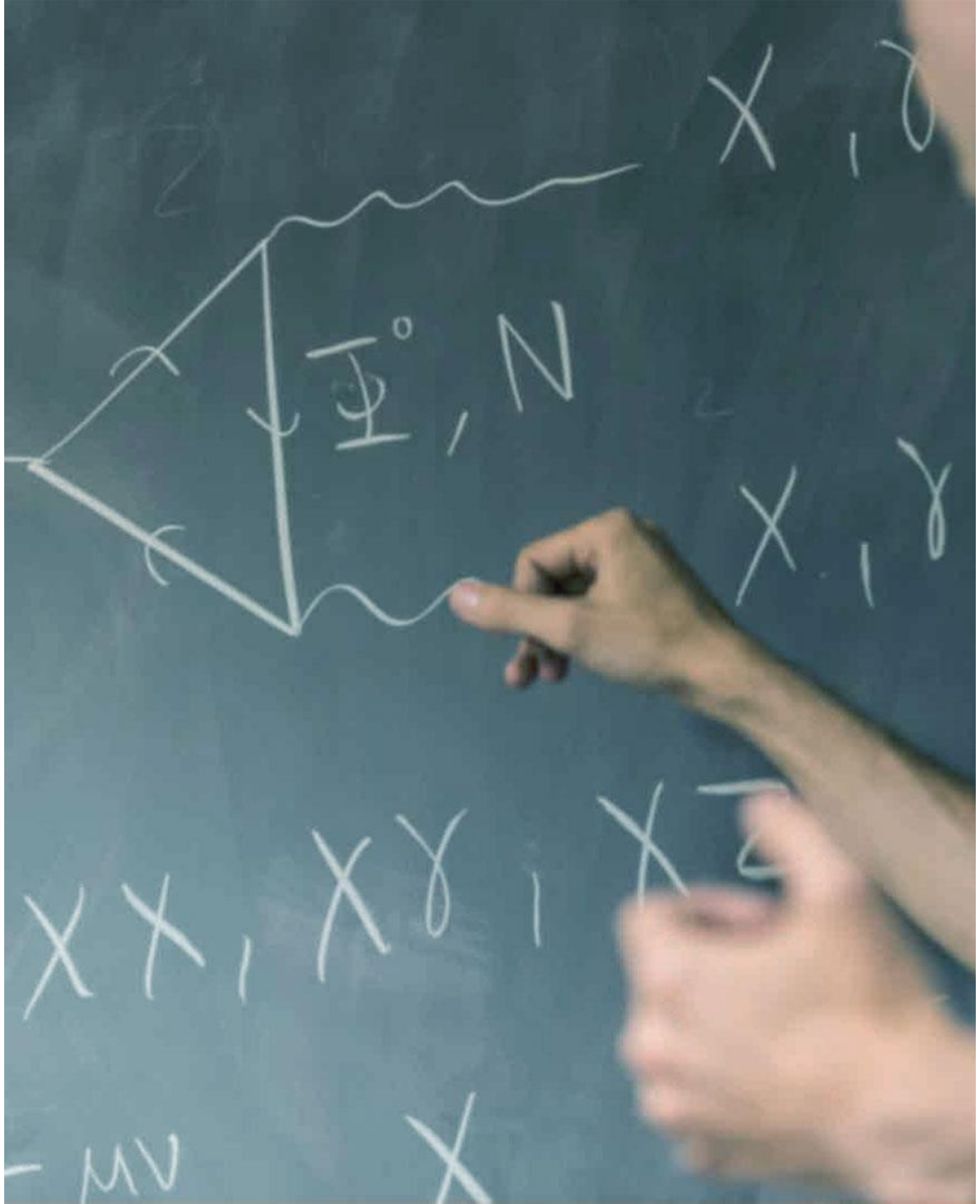
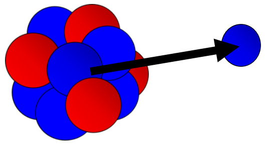
^{10}C and ^{10}Be in the NCSMC



Discovery, accelerated

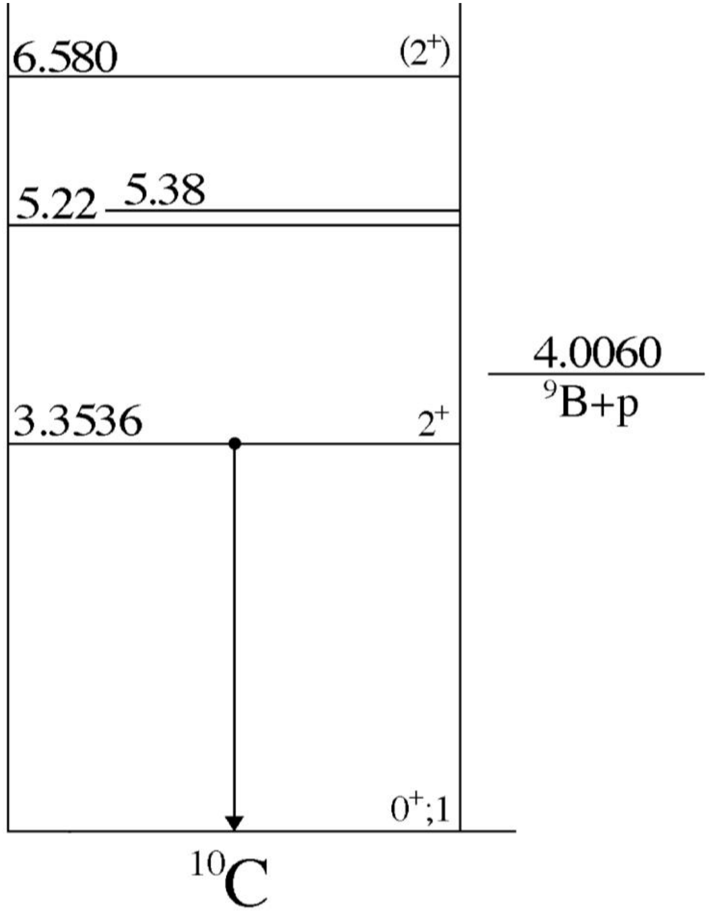
^{10}C structure



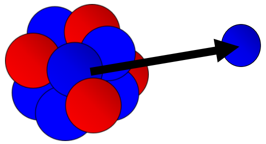
$$|^{10}\mathrm{C}\rangle = \sum_{\alpha} c_{\alpha} |^{10}\mathrm{C}, \alpha\rangle_{\mathrm{NCSM}} + \sum_{\nu} \int dr\, \gamma_{\nu}^{J^{\pi}T}(r) \mathcal{A}_{\nu} |^{9}\mathrm{B} + \mathrm{p}, \nu\rangle$$

- Treat as mass partition of proton plus ^{9}B
- Use $3/2^-$ and $5/2^-$ states of ^{9}B
- Known bound states captured by NCSMC

State	E_{NCSM} (MeV)	E (MeV)	E_{exp} (MeV)
0^+	-3.09	-3.46	-4.006
2^+	$+0.40$	-0.03	-0.652



^{10}C structure



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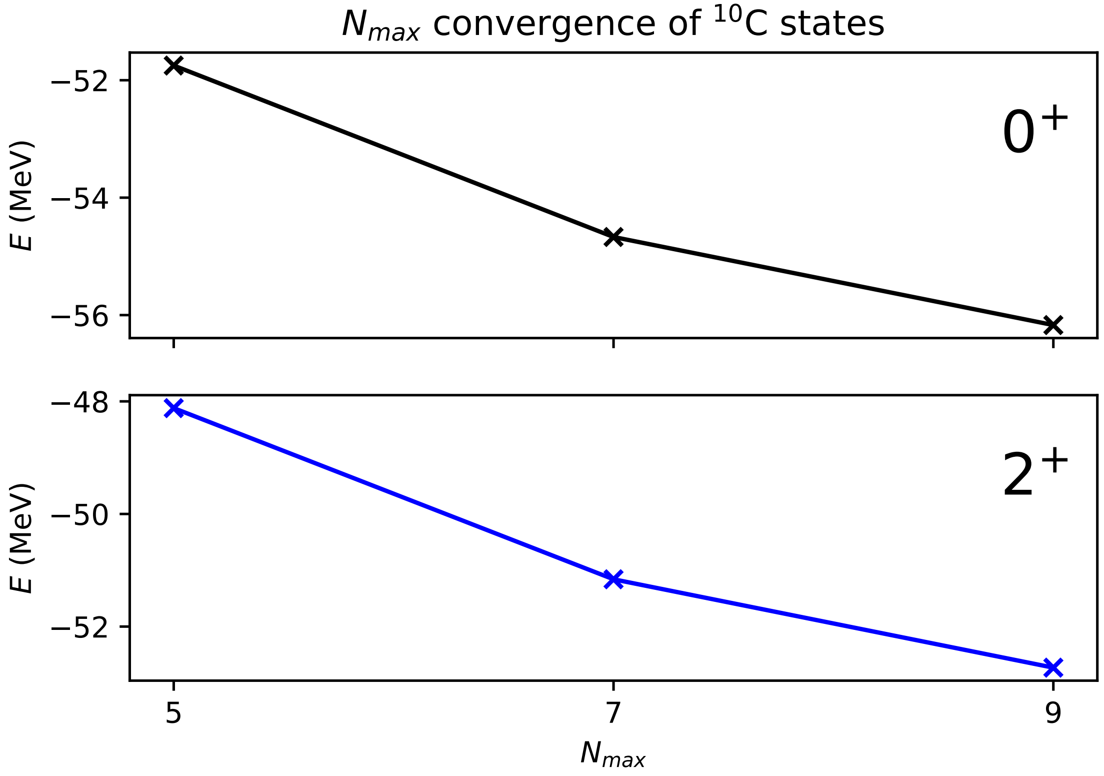
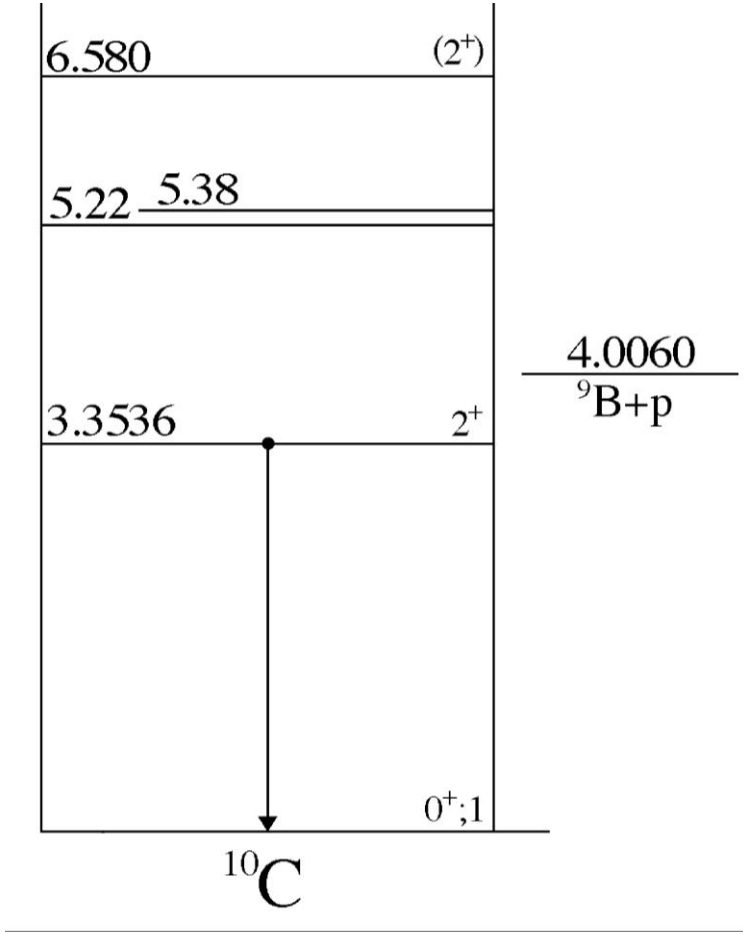
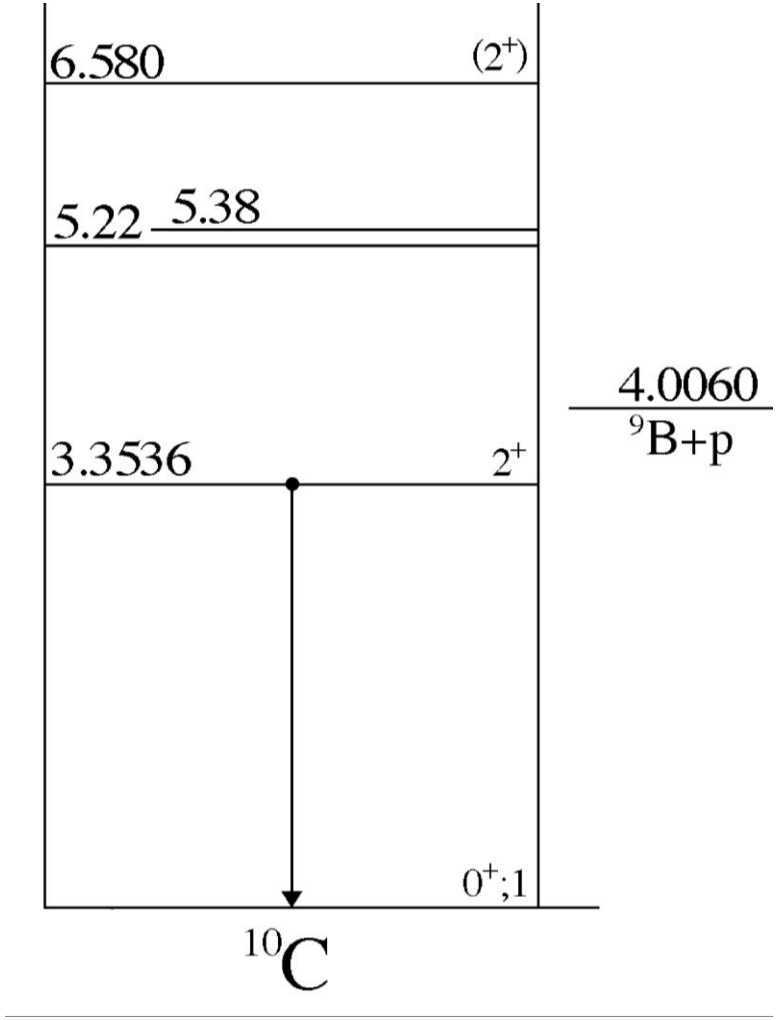
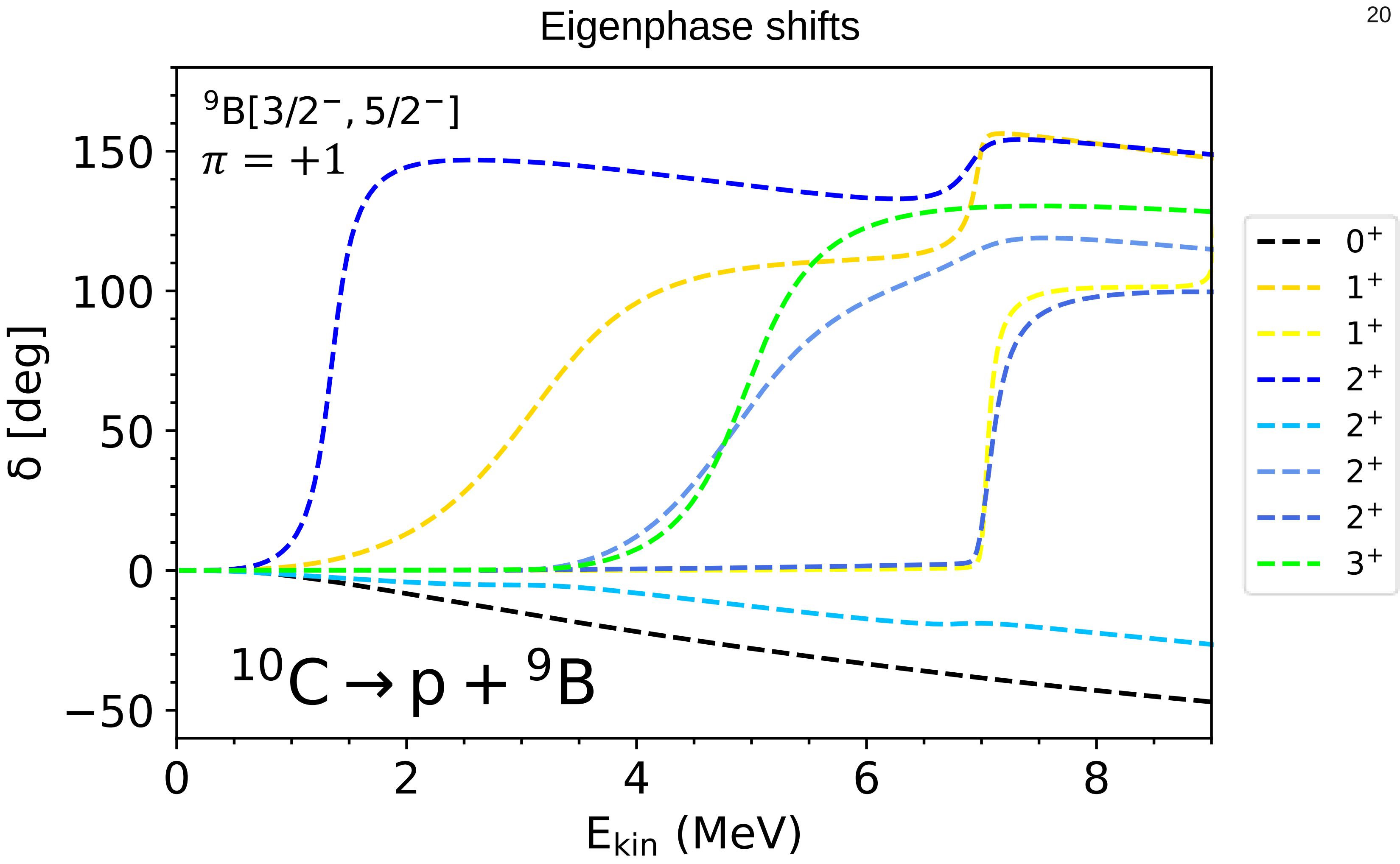




^{10}C structure at $N_{max} = 9$





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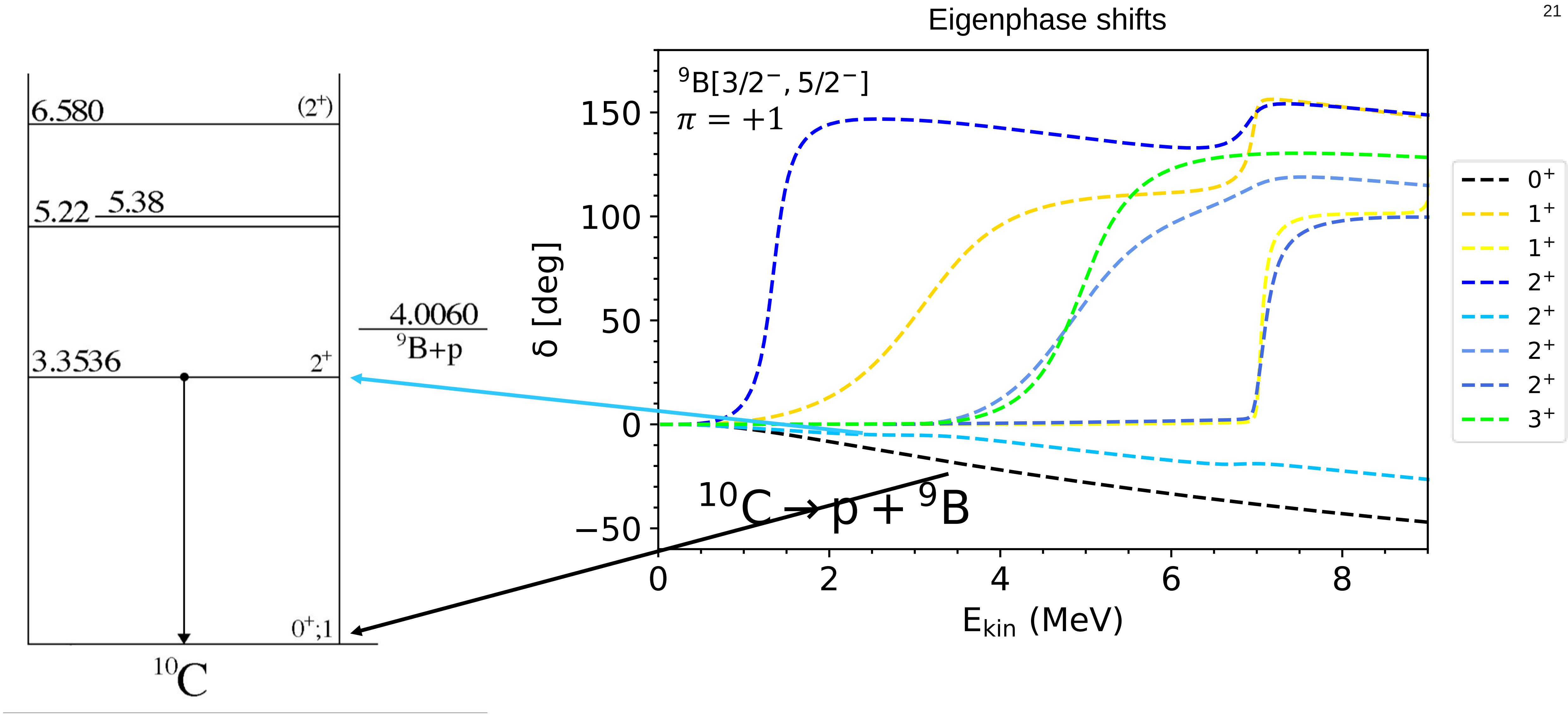

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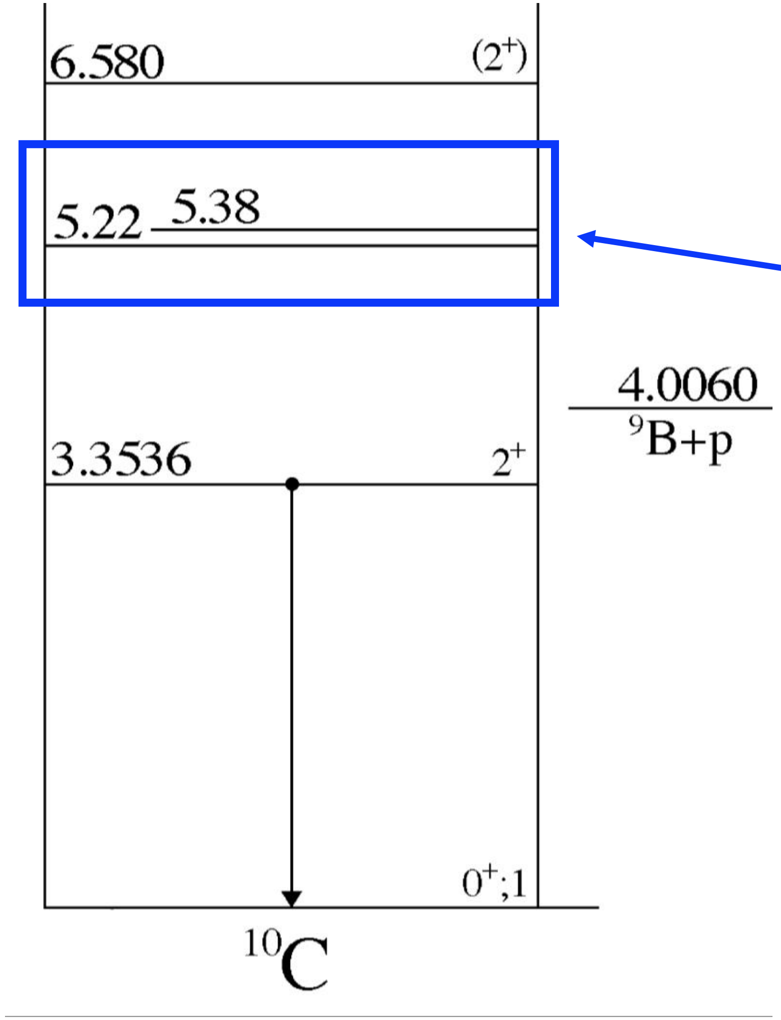

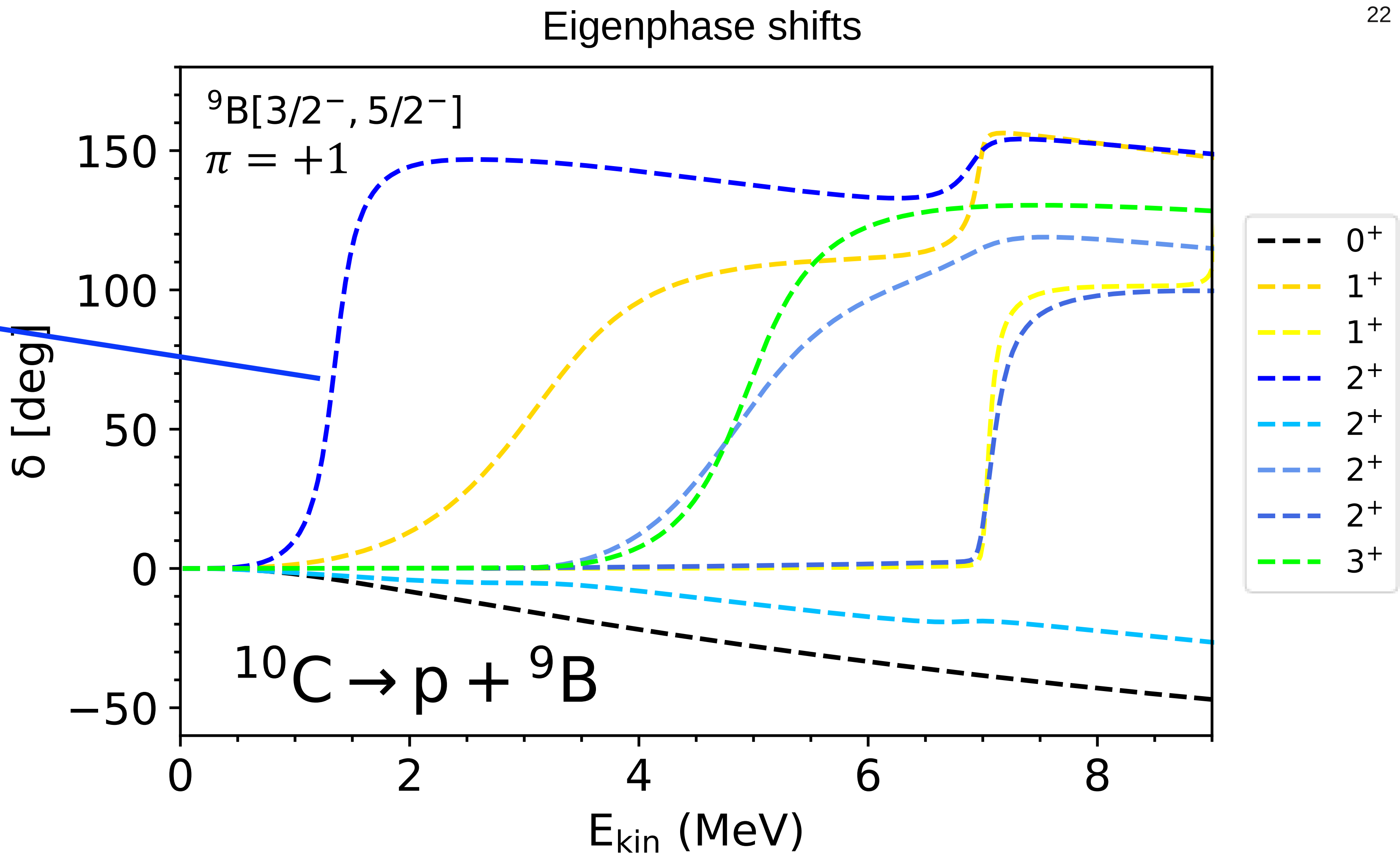

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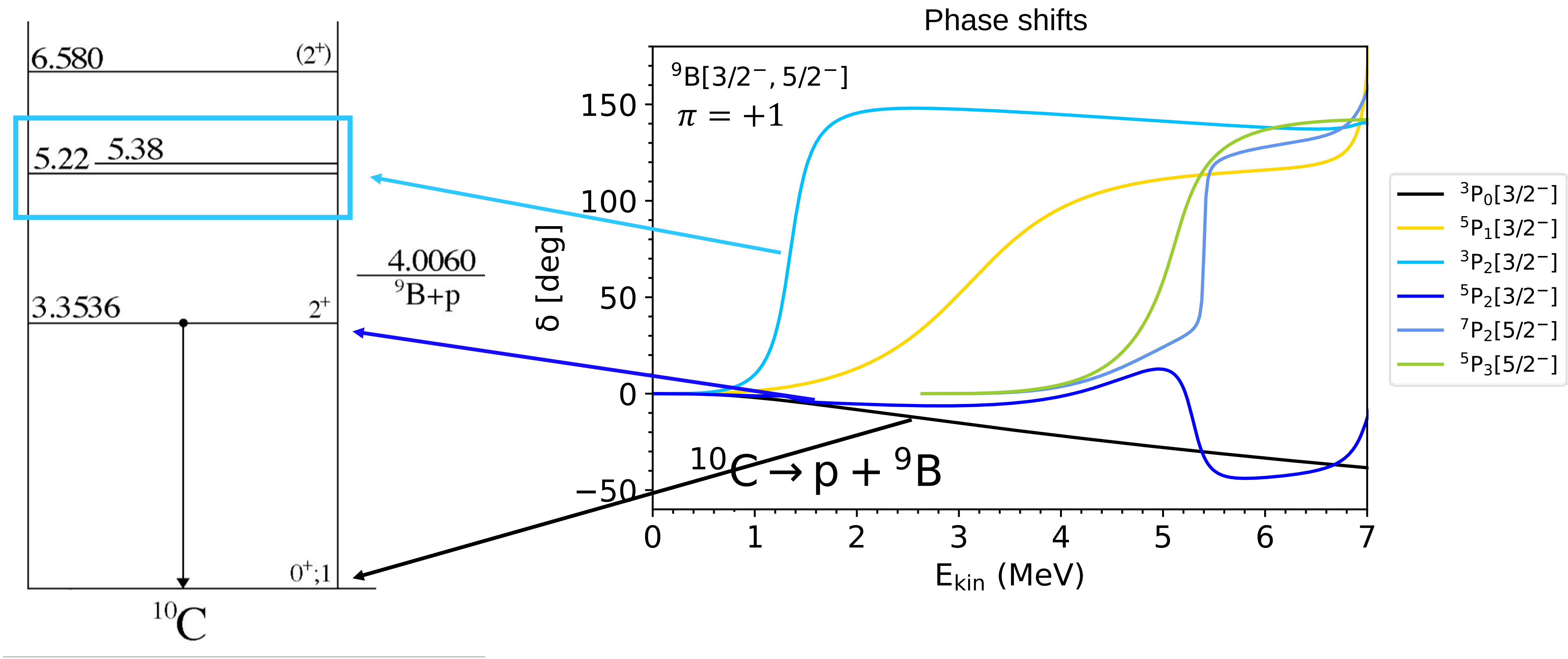
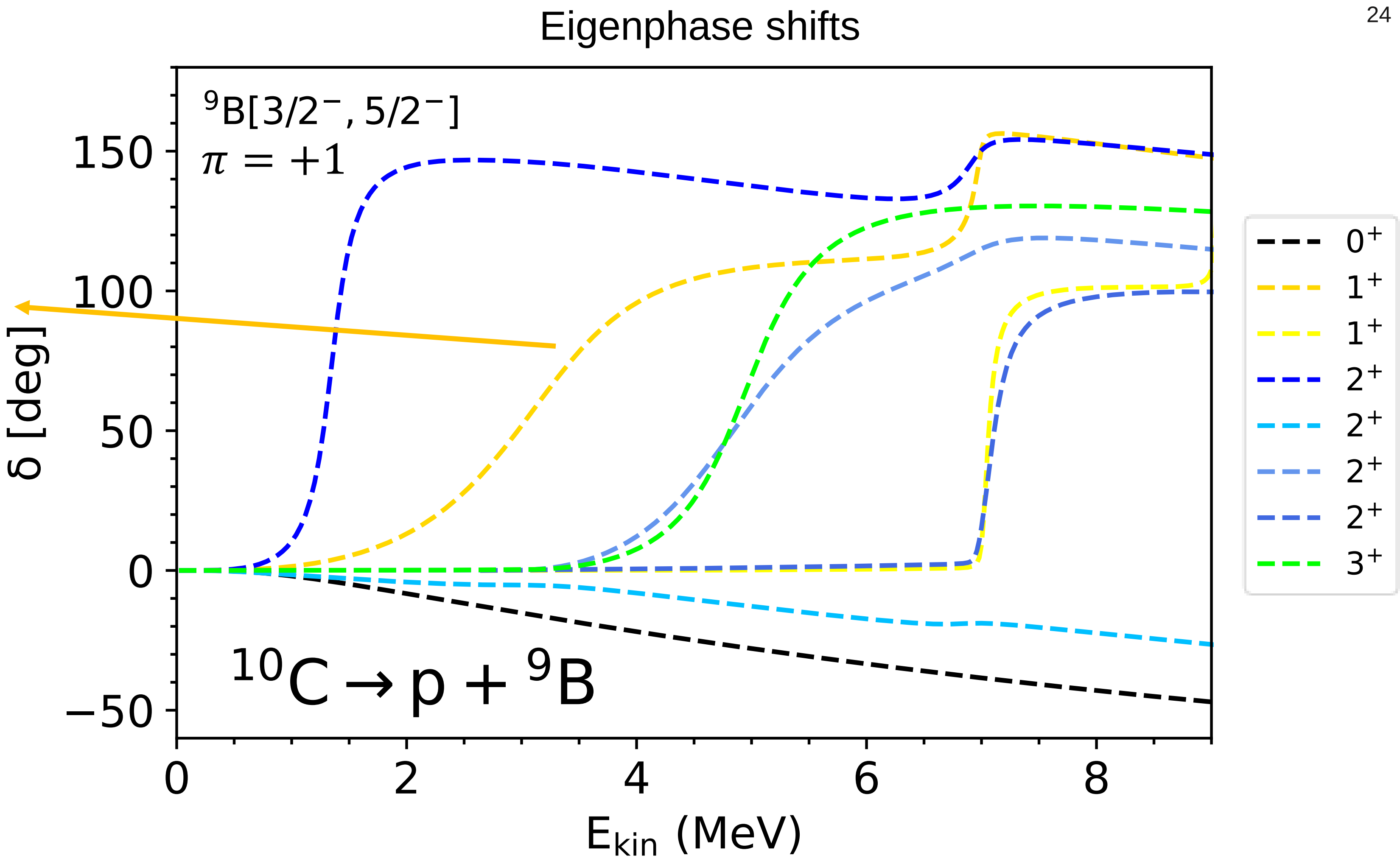


^{10}C structure at $N_{max} = 9$

- 1^+ resonance previously predicted **[9]**
- Sharp 1^+ and 2^+ resonances
- Additional 3^+ resonance



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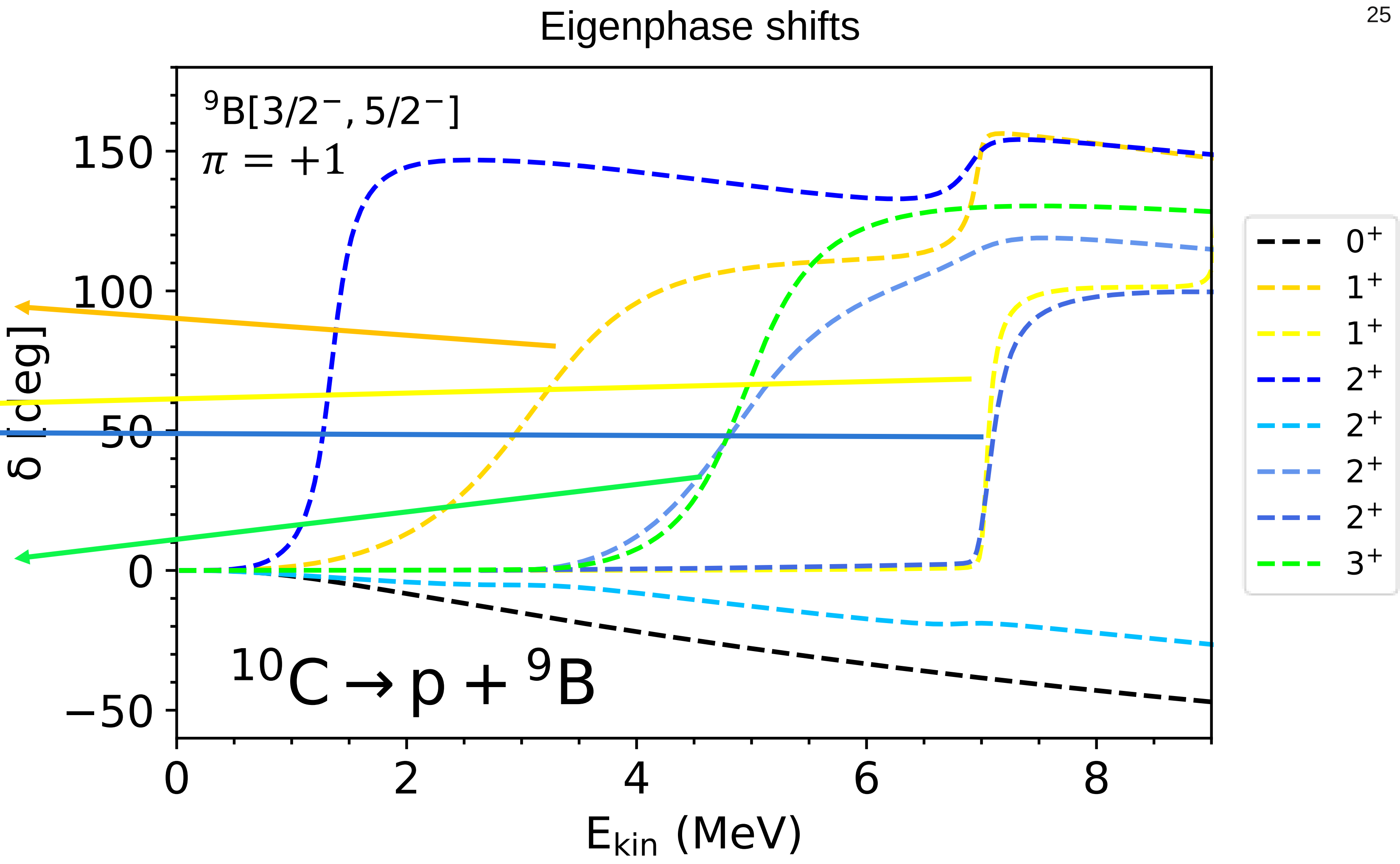
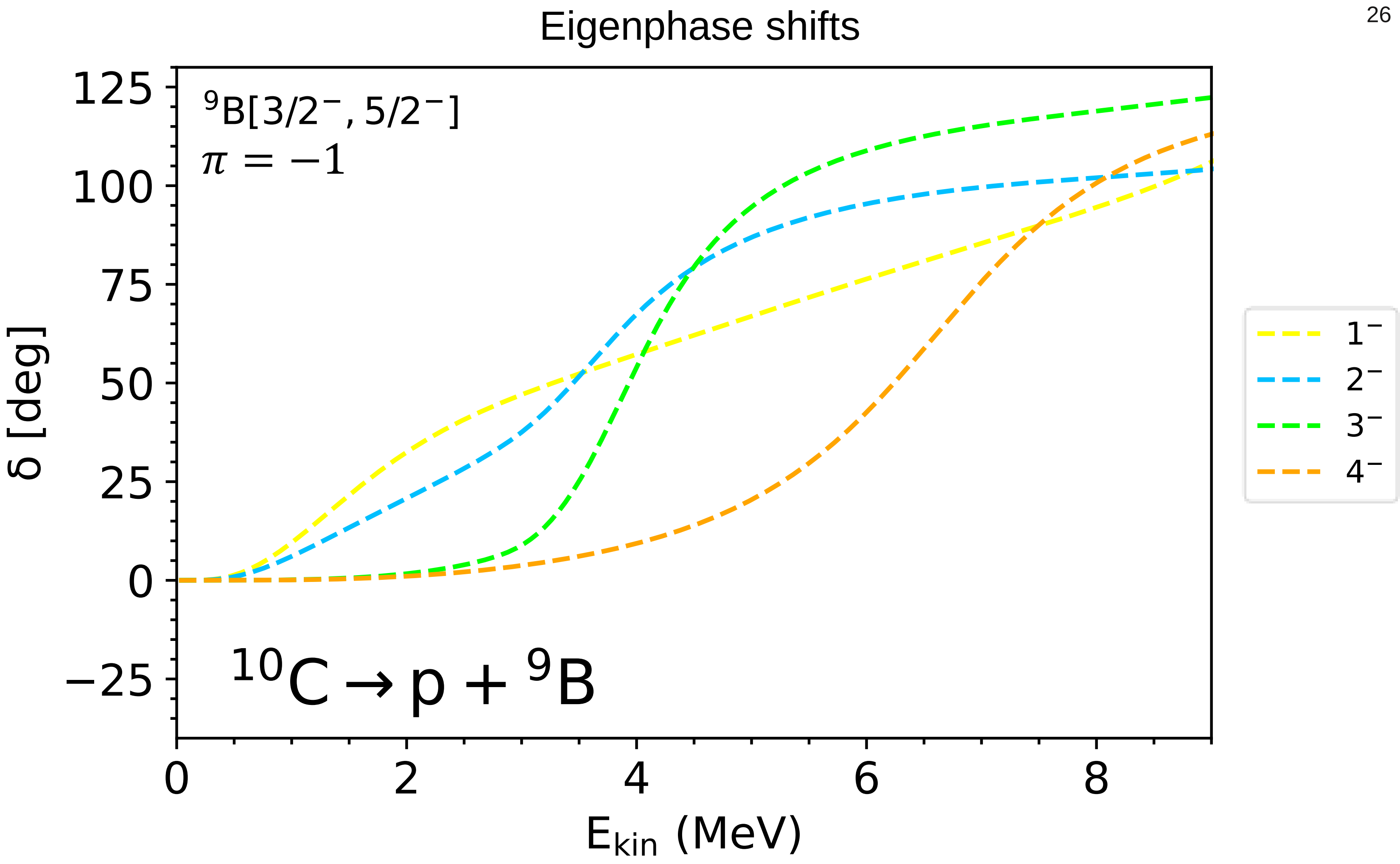


^{10}C structure at $N_{max} = 9$

- 1^- and 2^- resonances in ^{10}C analogs of ^{10}Be halo states
- 3^- resonance expected in ^{10}Be present
- Indication of consistency



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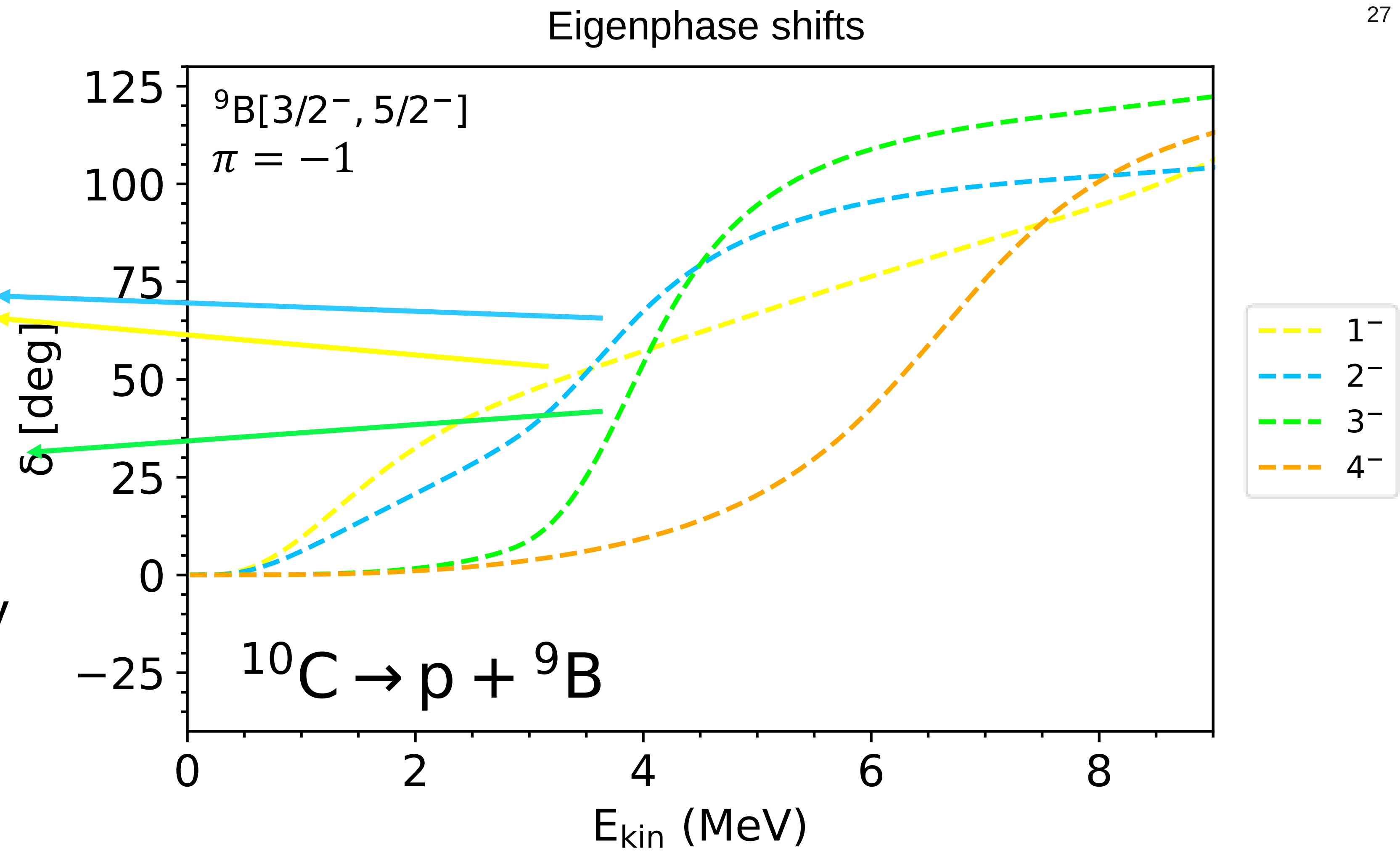
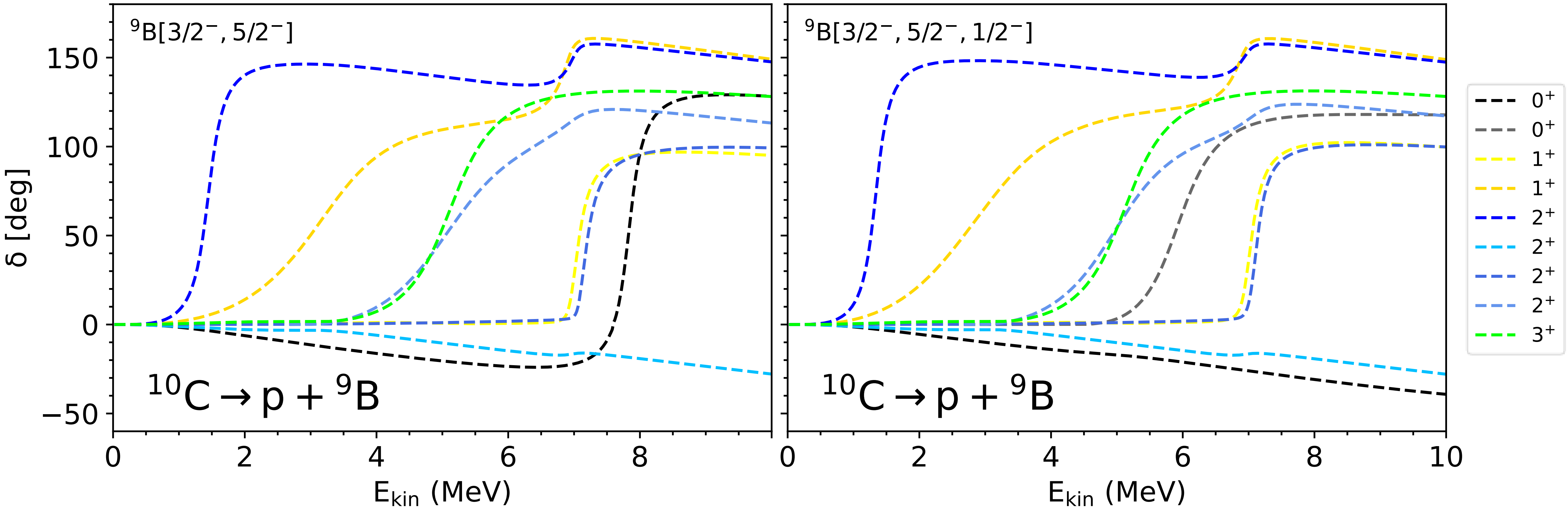


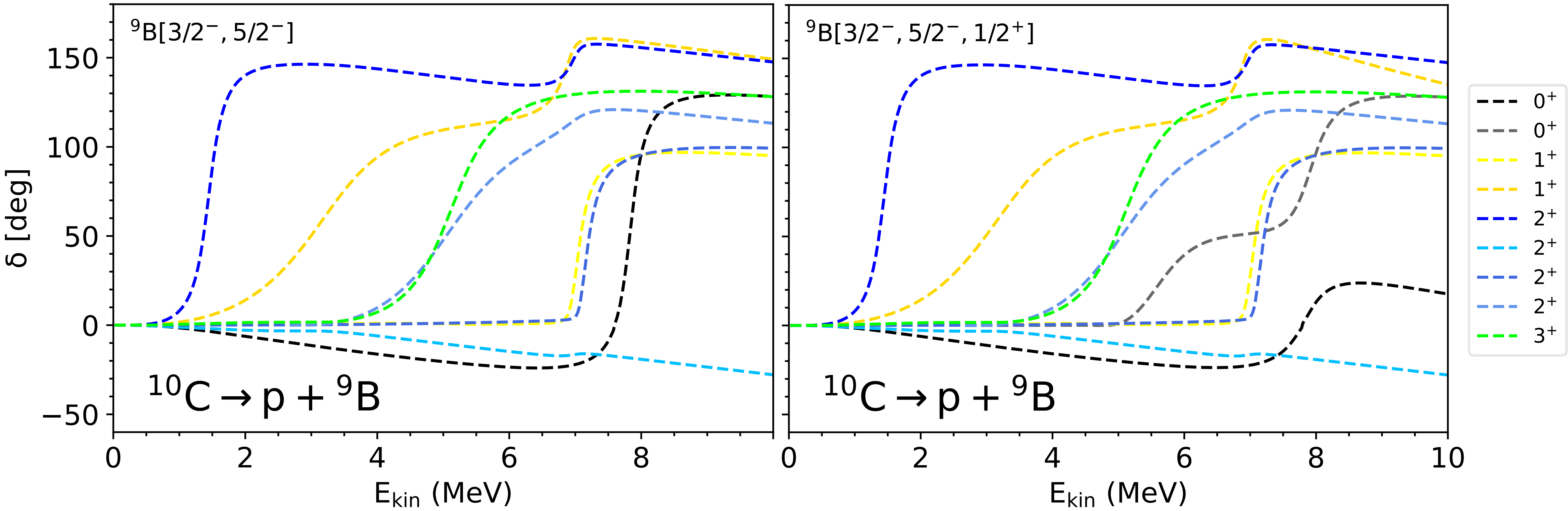
^{10}C eigenphase shifts at $N_{max} = 7$

$\pi = +1$



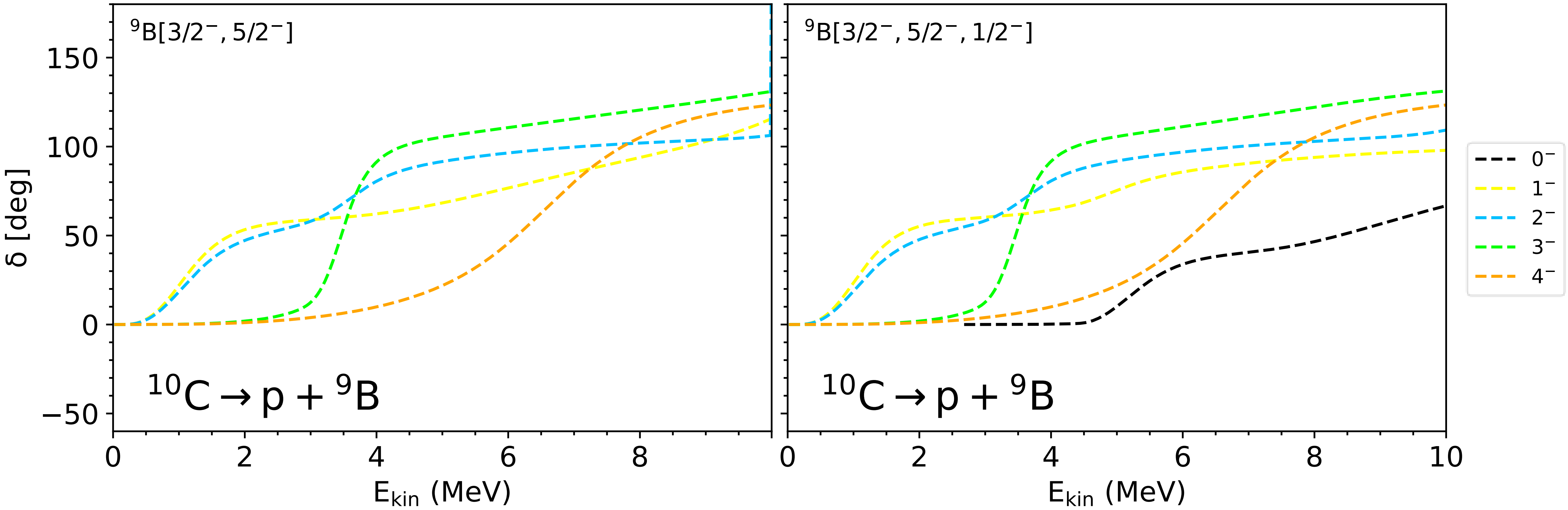
^{10}C eigenphase shifts at $N_{max} = 7$

$\pi = +1$



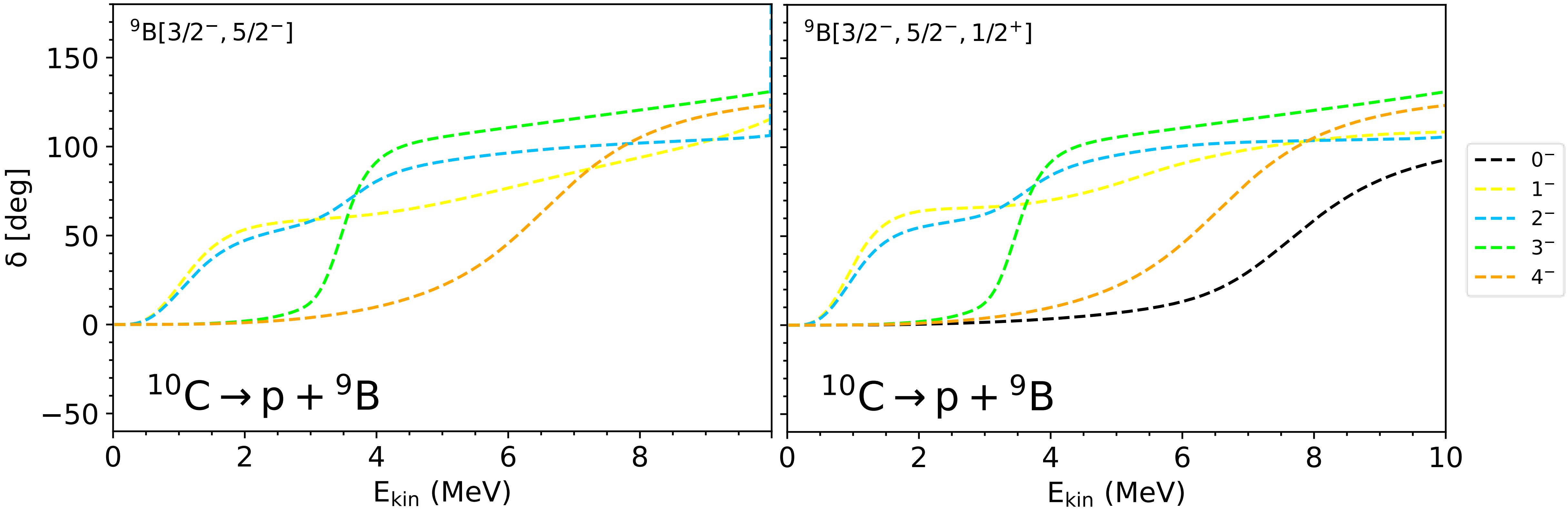
^{10}C eigenphase shifts at $N_{max} = 7$

$$\pi = -1$$

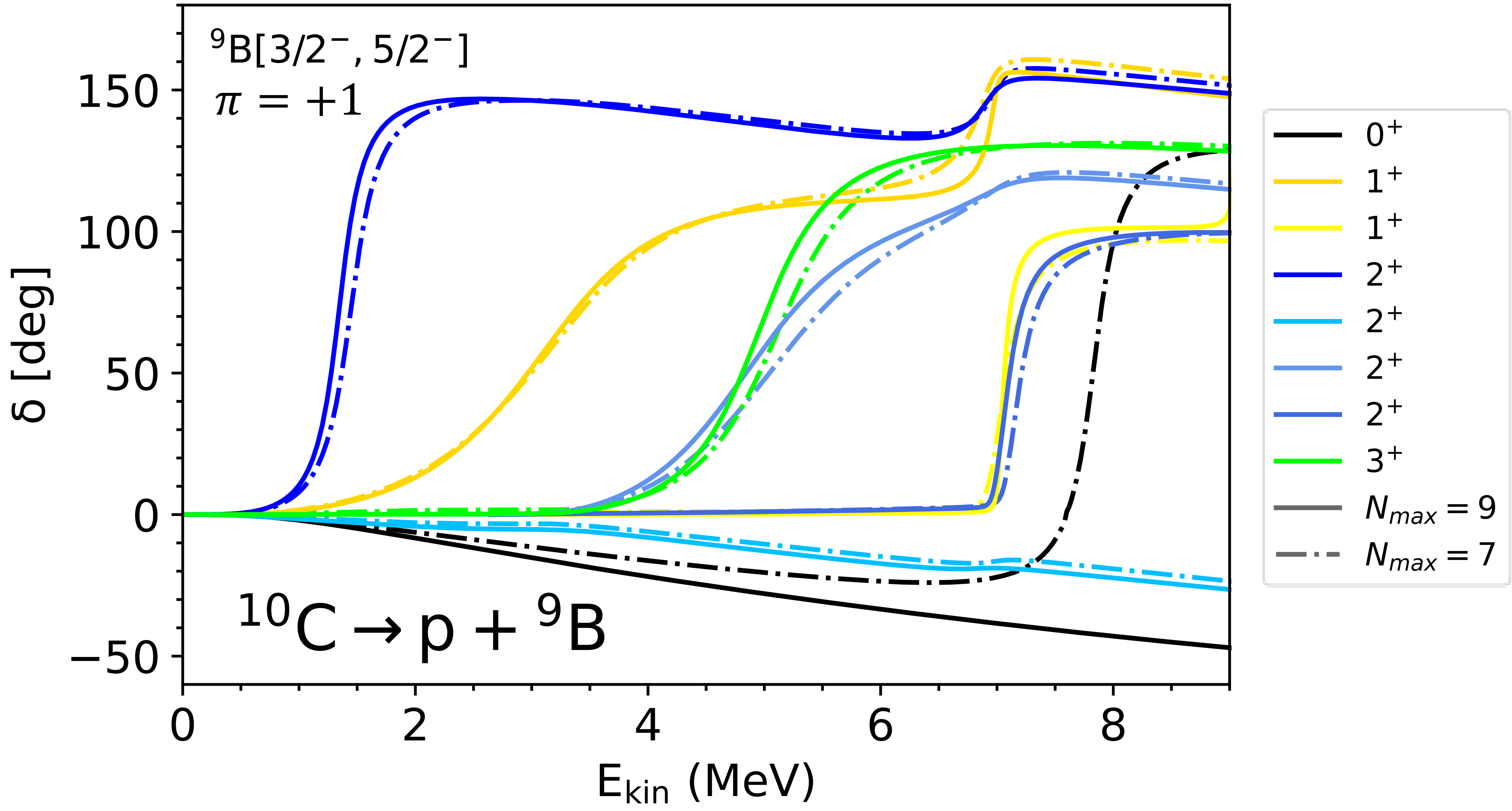


^{10}C eigenphase shifts at $N_{max} = 7$

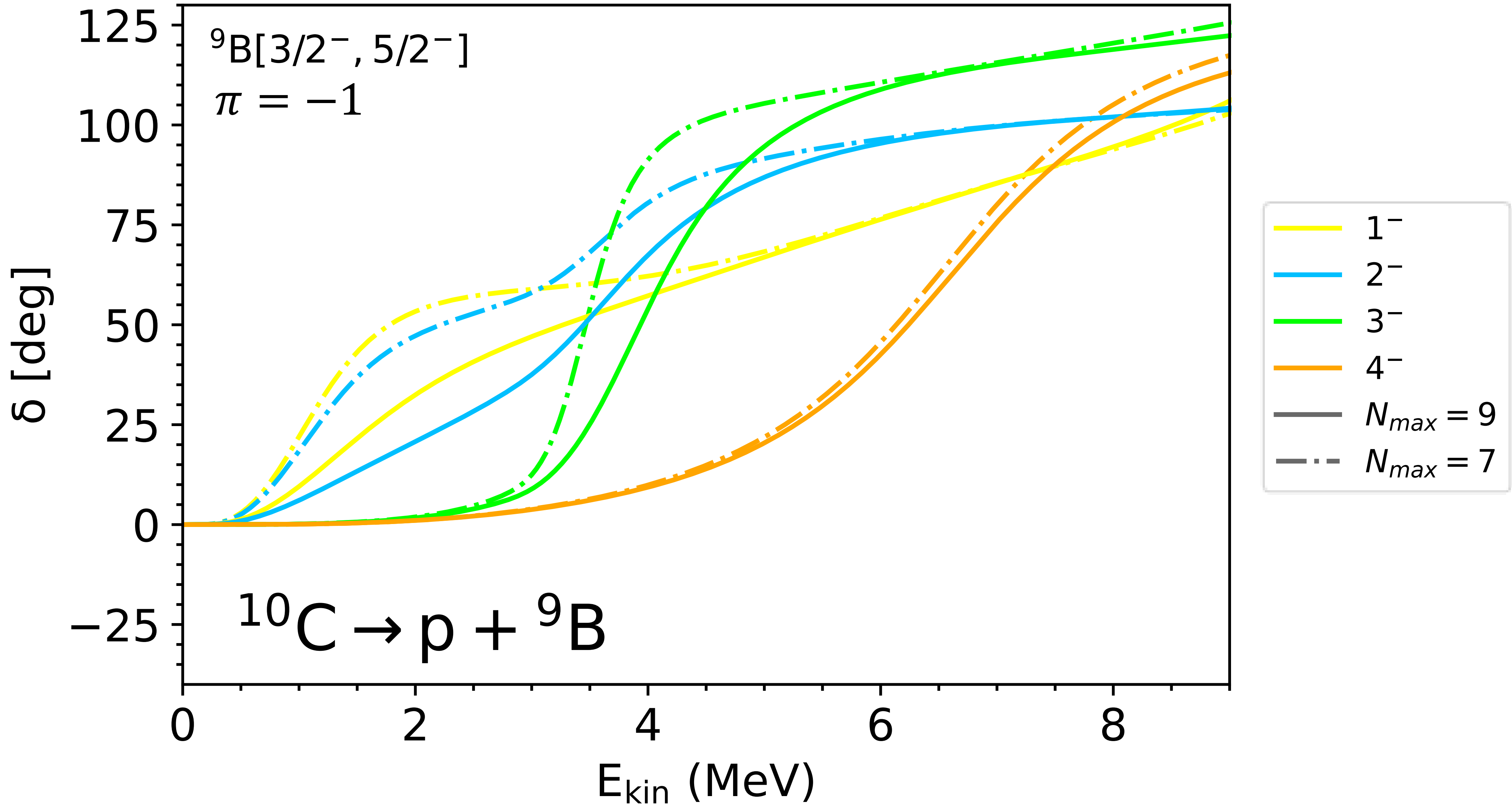
$$\pi = -1$$



^{10}C **eigenphase shifts** $N_{max} = 7 - 9$ comparison

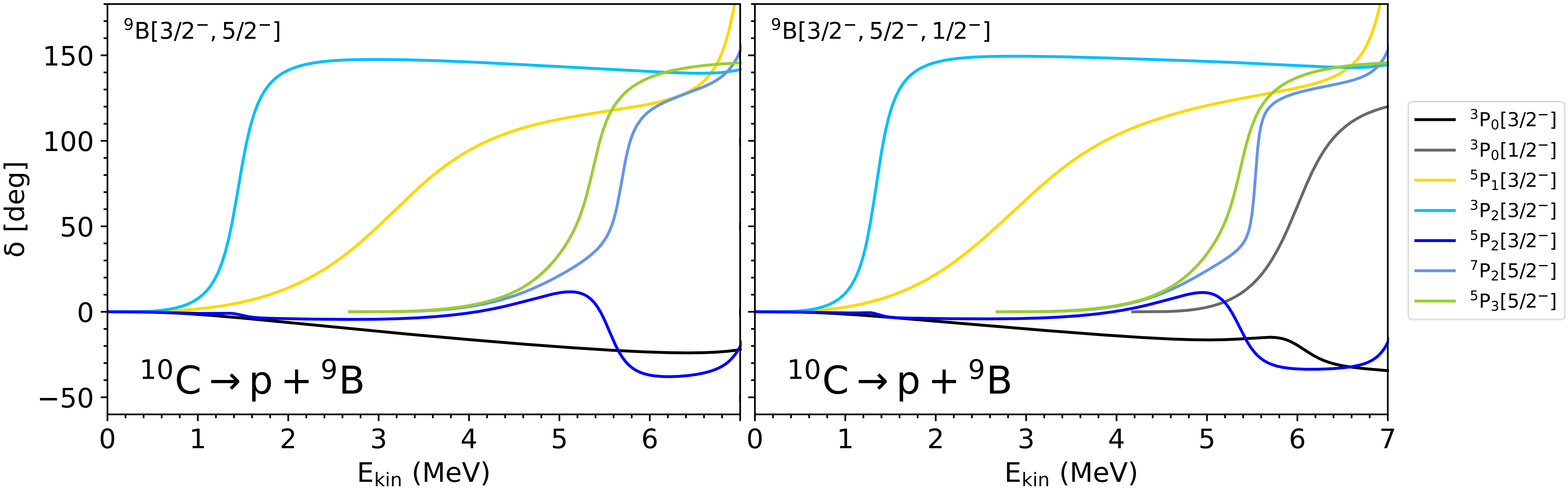


^{10}C eigenphase shifts $N_{max} = 7 - 9$ comparison



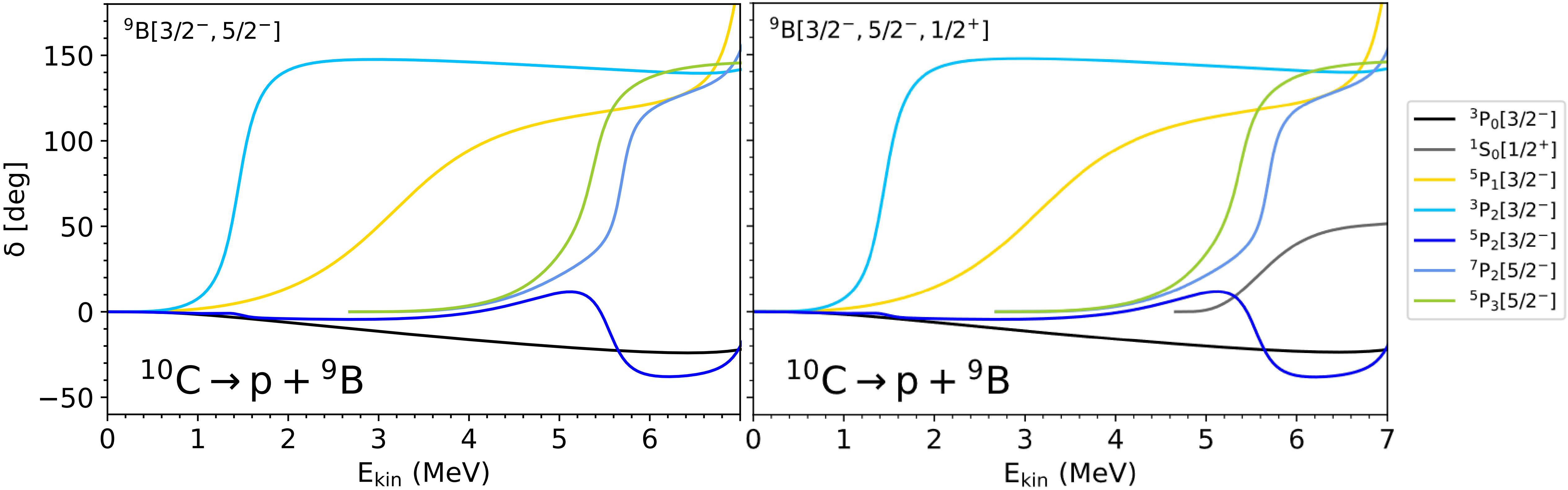
^{10}C phase shifts at $N_{max} = 7$

$\pi = +1$



^{10}C phase shifts at $N_{max} = 7$

$\pi = +1$



^{10}C phase shifts at $N_{max} = 7$

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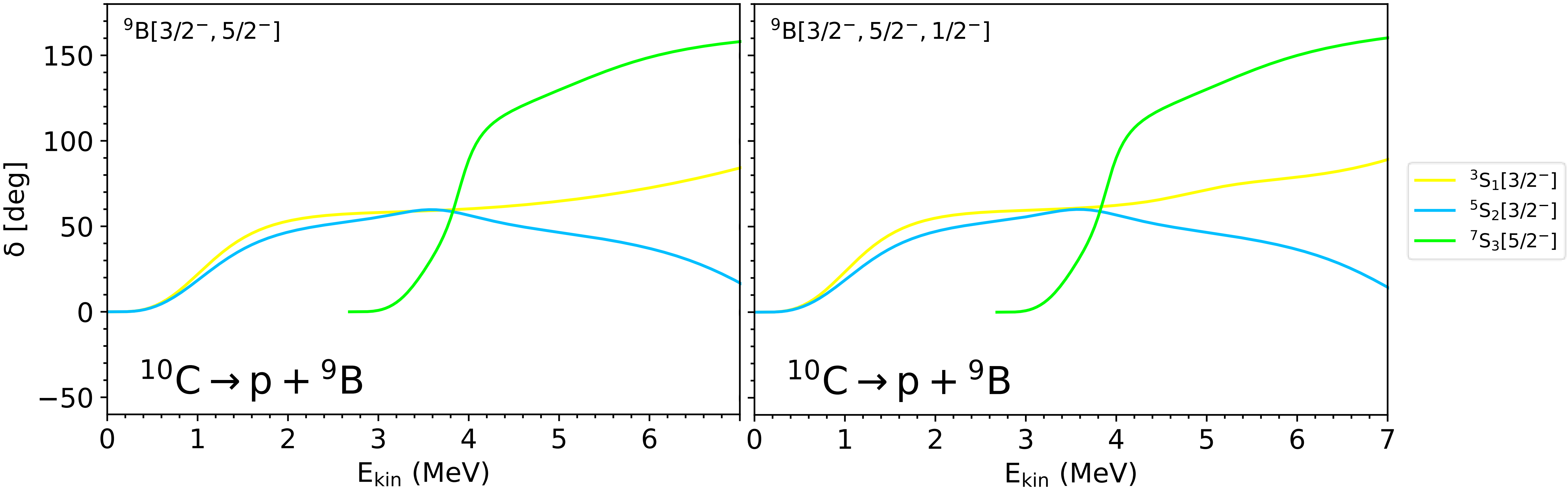
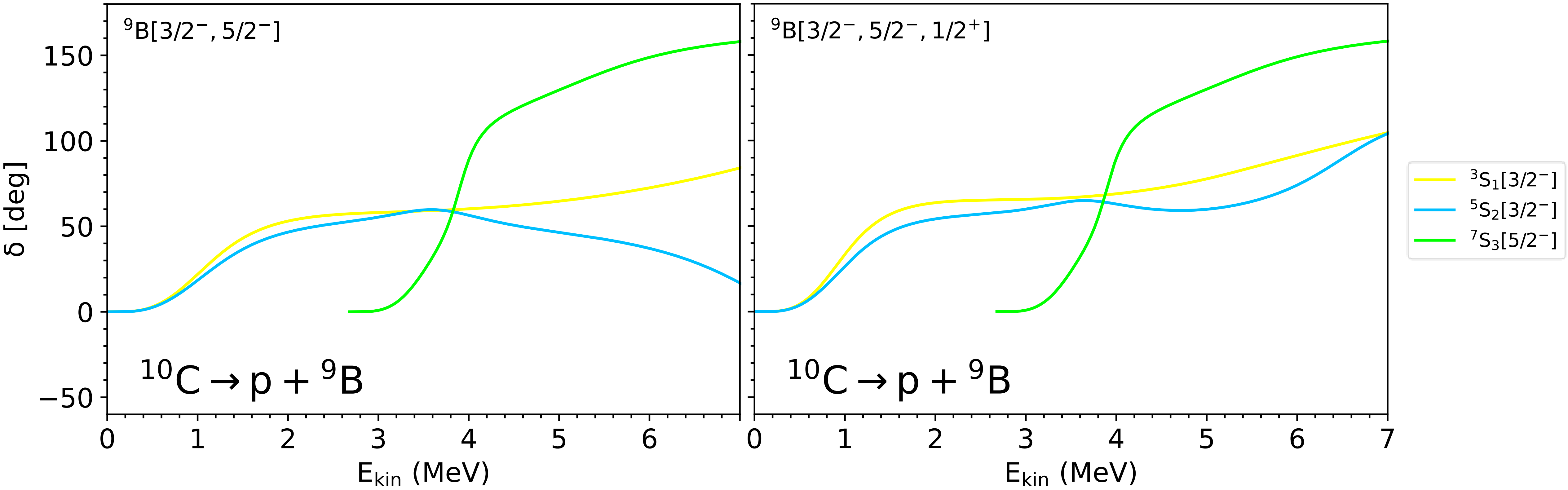
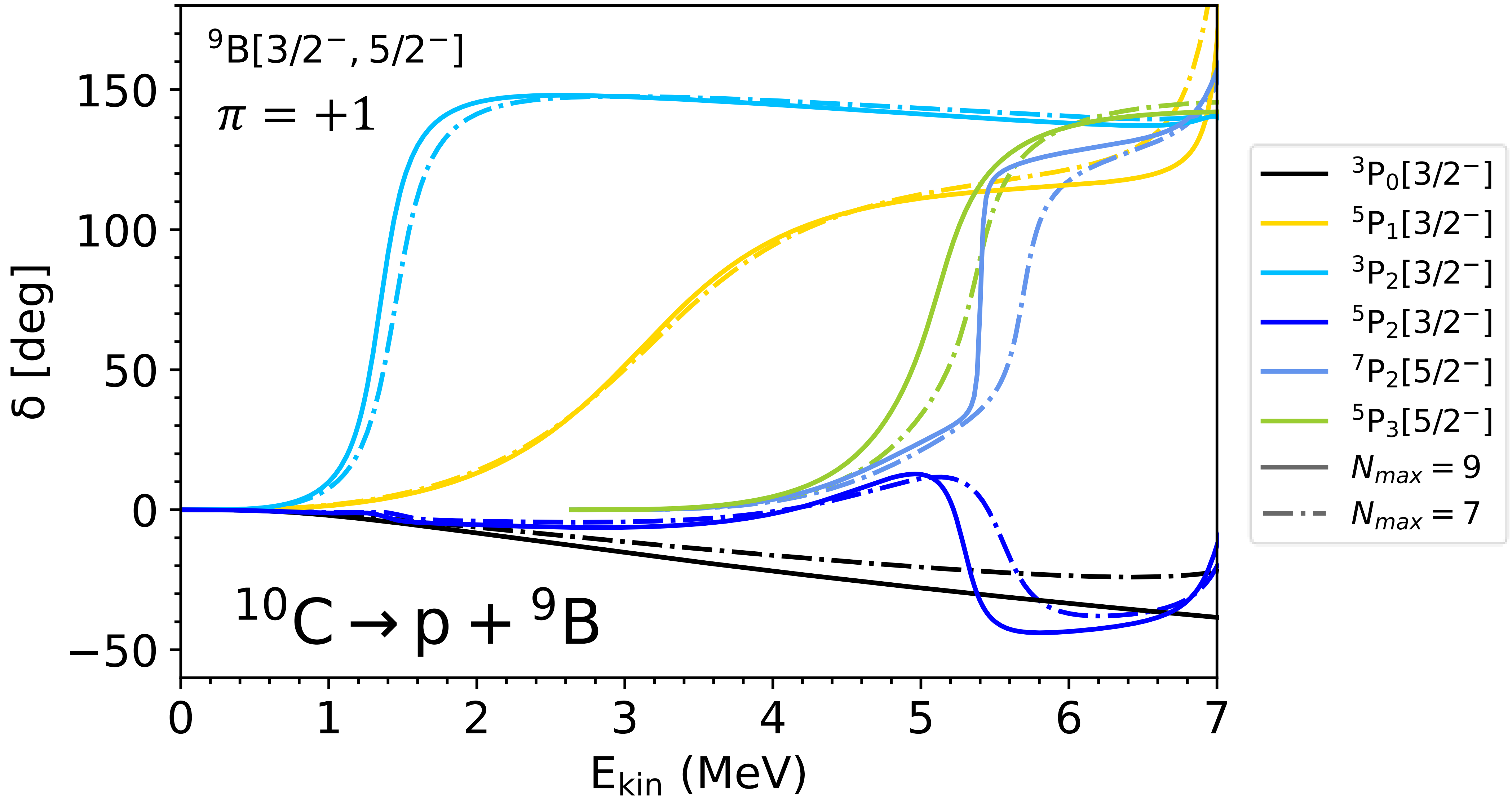


^{10}C phase shifts at $N_{max} = 7$

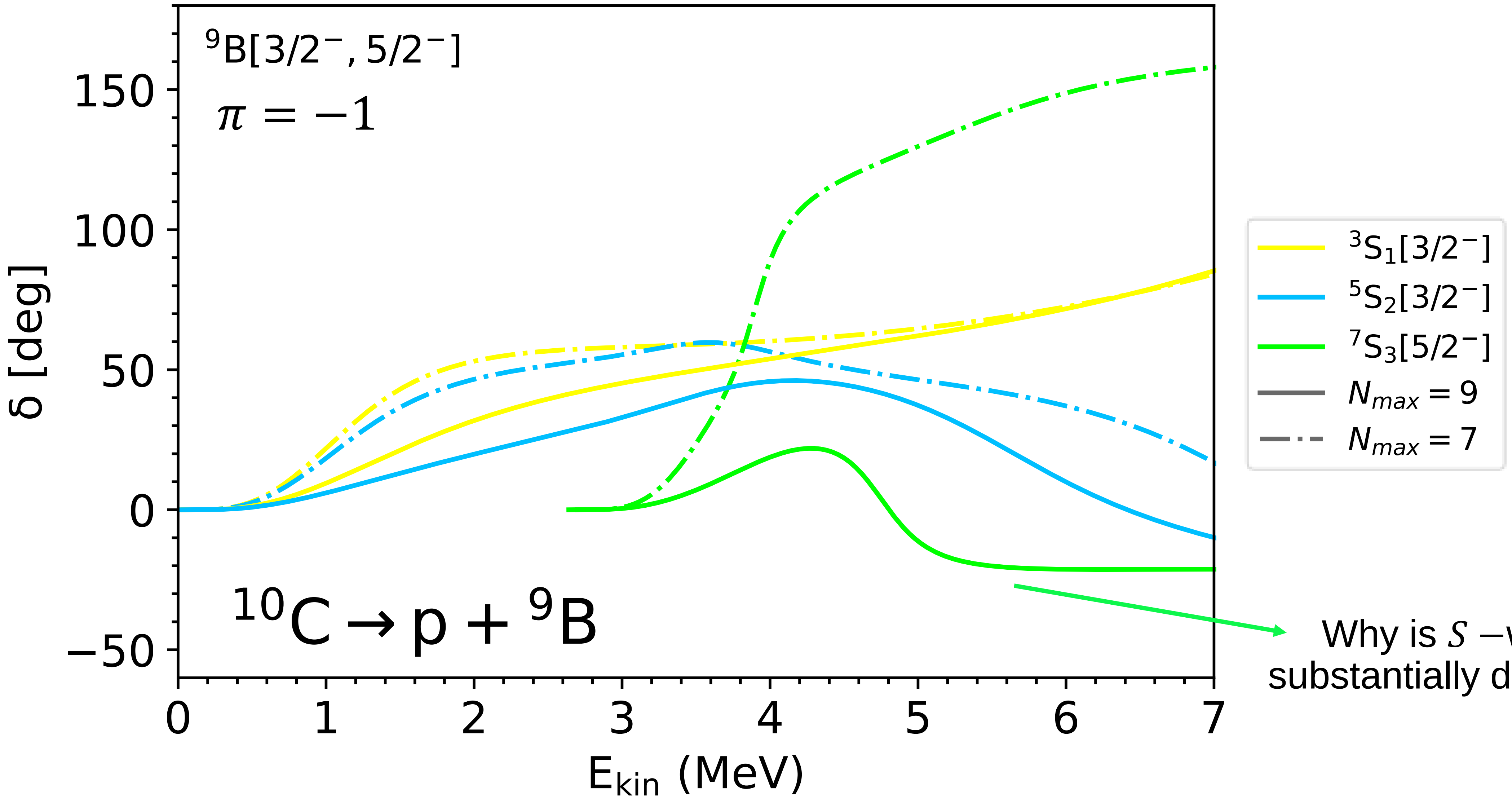
$\pi = -1$



^{10}C **phase shifts** $N_{max} = 7 - 9$ comparison

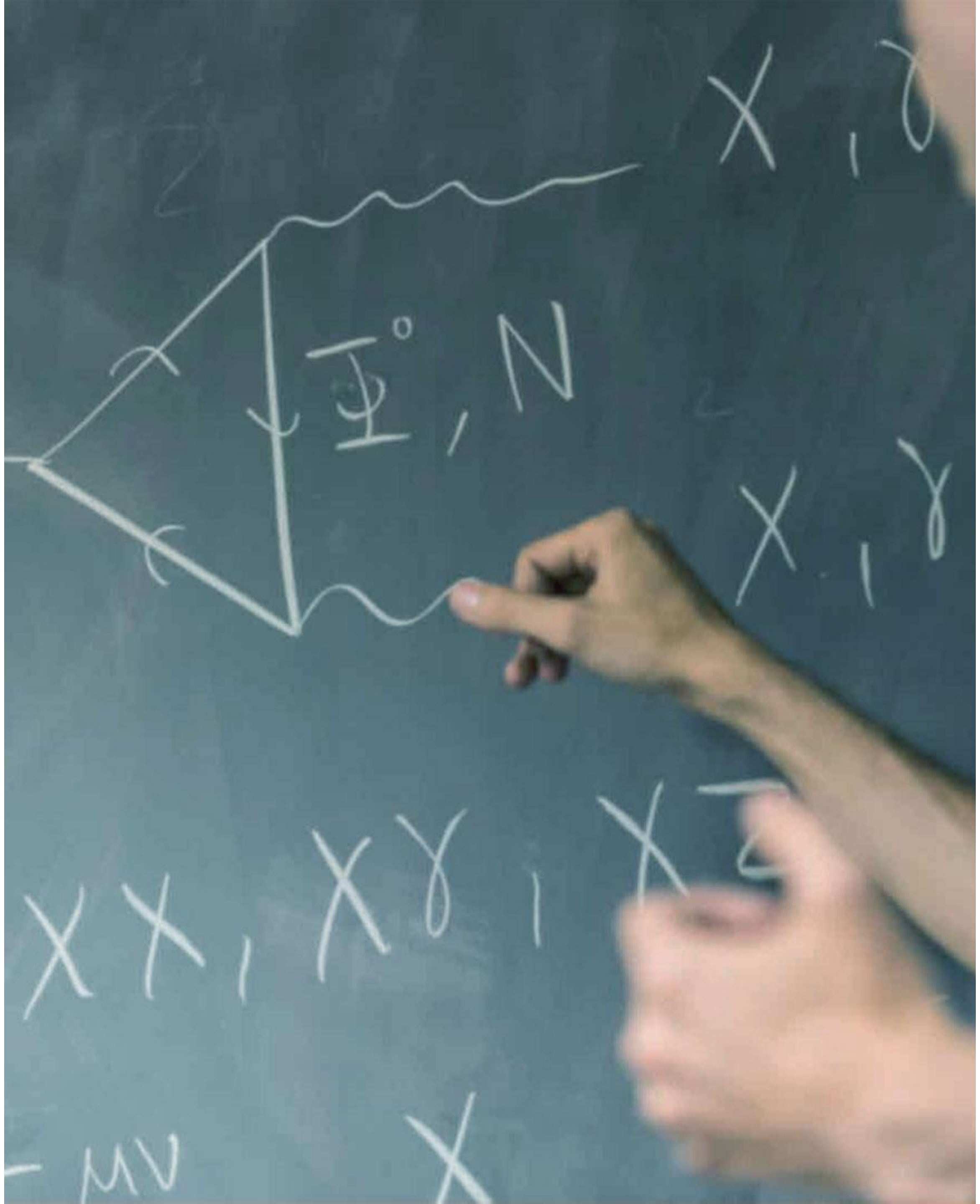


^{10}C **phase shifts** $N_{max} = 7 - 9$ comparison

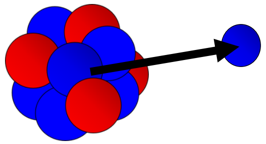


Why is S −wave substantially different?

^{10}Be structure



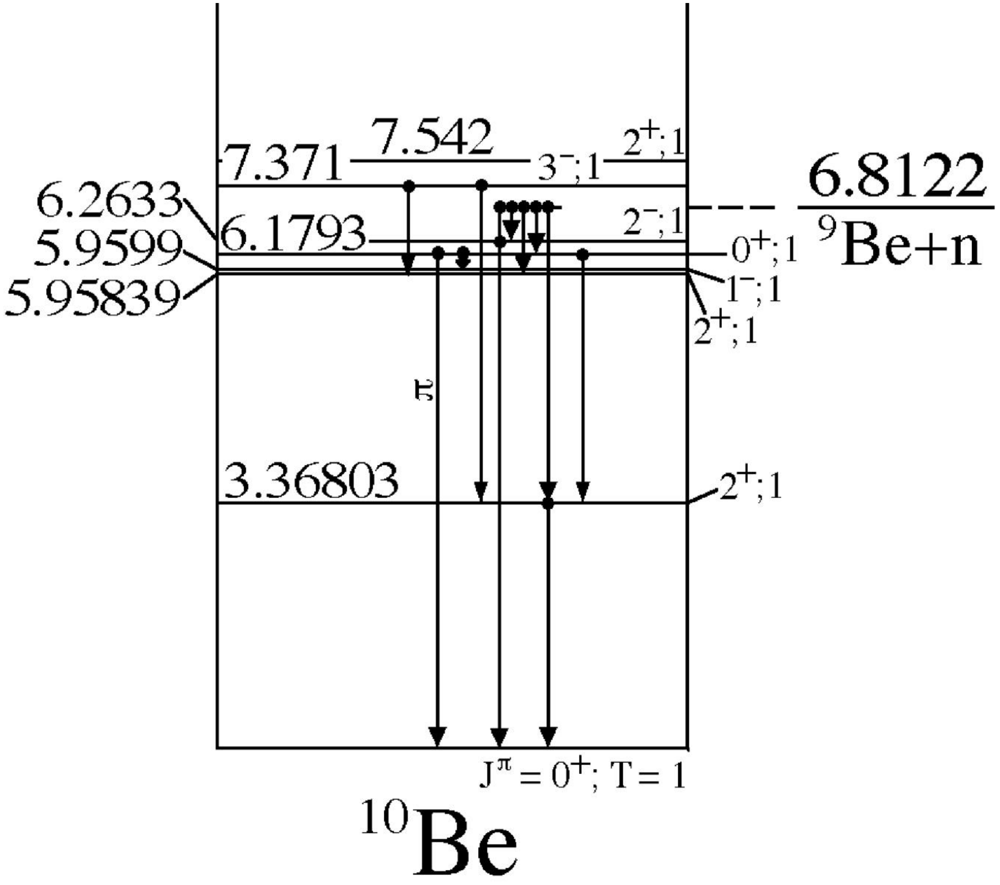
^{10}Be structure



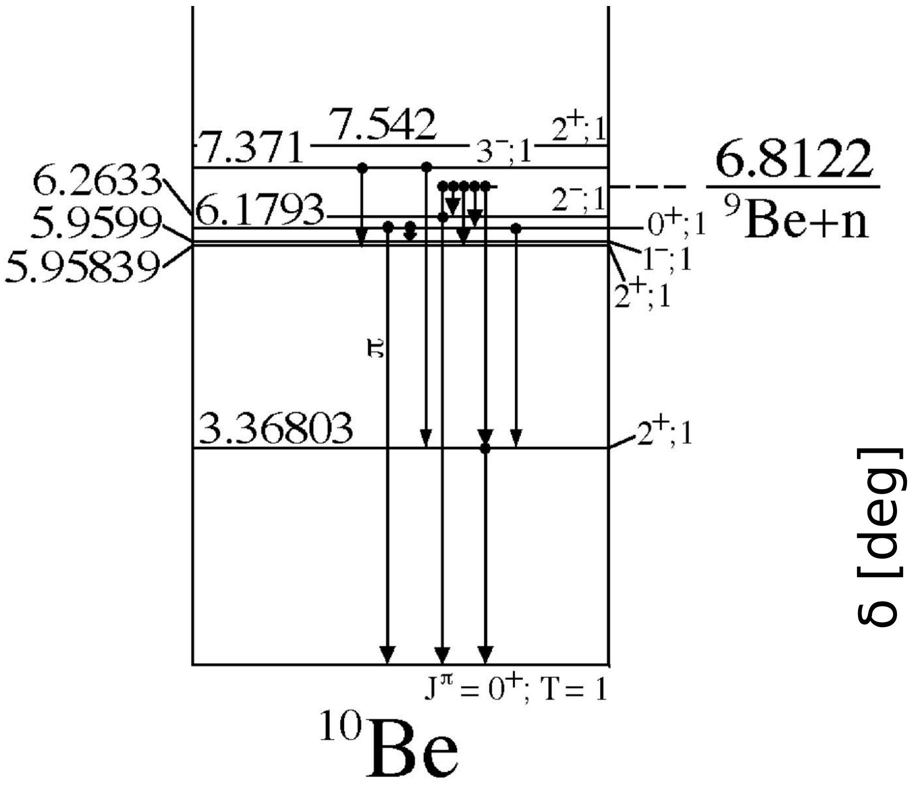
$$|{}^{10}\mathrm{Be}\rangle = \sum_{\alpha} c_{\alpha} |{}^{10}\mathrm{Be}, \alpha\rangle_{\mathrm{NCSM}} + \sum_{\nu} \int dr\ \gamma_{\nu}^{J^{\pi}T}(r) \mathcal{A}_{\nu} |{}^{9}\mathrm{Be} + \mathrm{n}, \nu\rangle$$

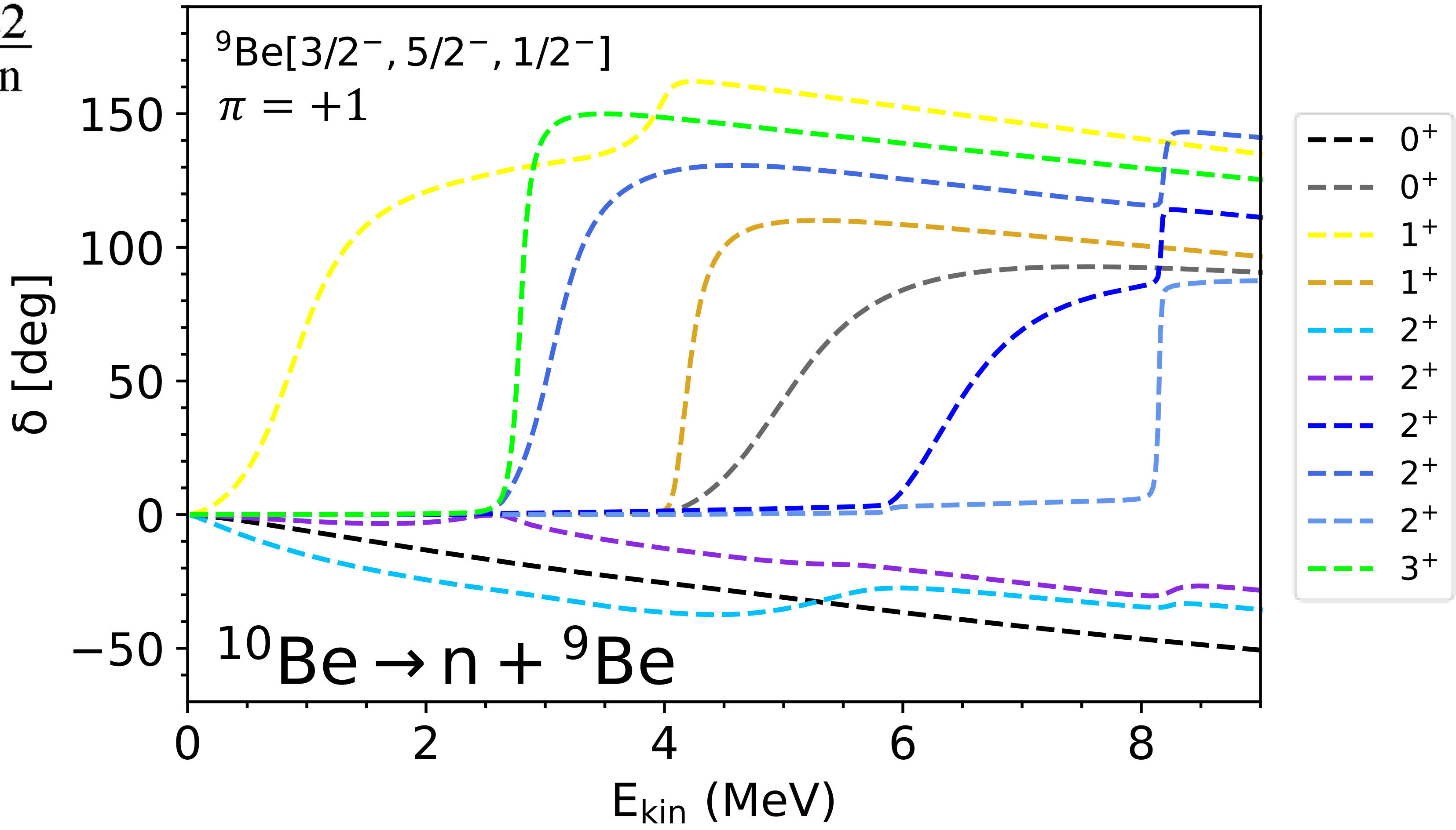
- Treat as mass partition of neutron plus ^{9}Be
- Use $3/2^{-}$, $5/2^{-}$, and $1/2^{-}$ states of ^{9}Be
- Four bound states produced in NCSMC

State	E_{NCSM} (MeV)	E (MeV)	E_{exp} (MeV)
0^{+}	-5.70	-5.97	-6.8122
2^{+}	-2.25	-2.51	-3.4442
2^{+}	-0.02	-0.67	-0.8538
1^{-}	$+2.23$	-0.03	-0.8523
0^{+}	$--$	$+0.56$	-0.6329
2^{-}	$+2.52$	$+0.02$	-0.5489

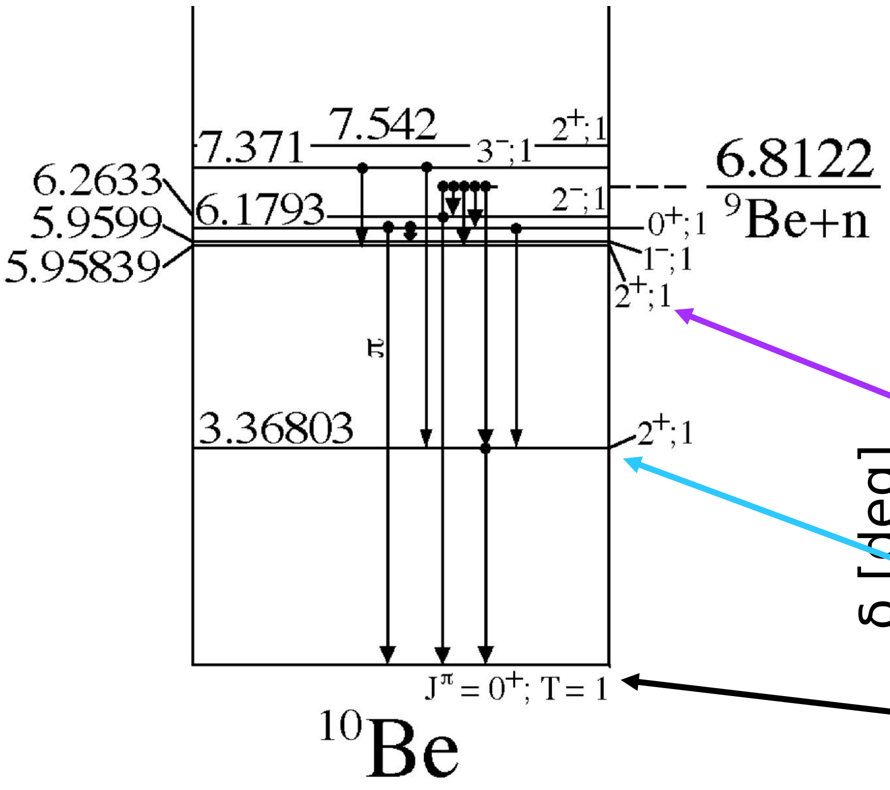


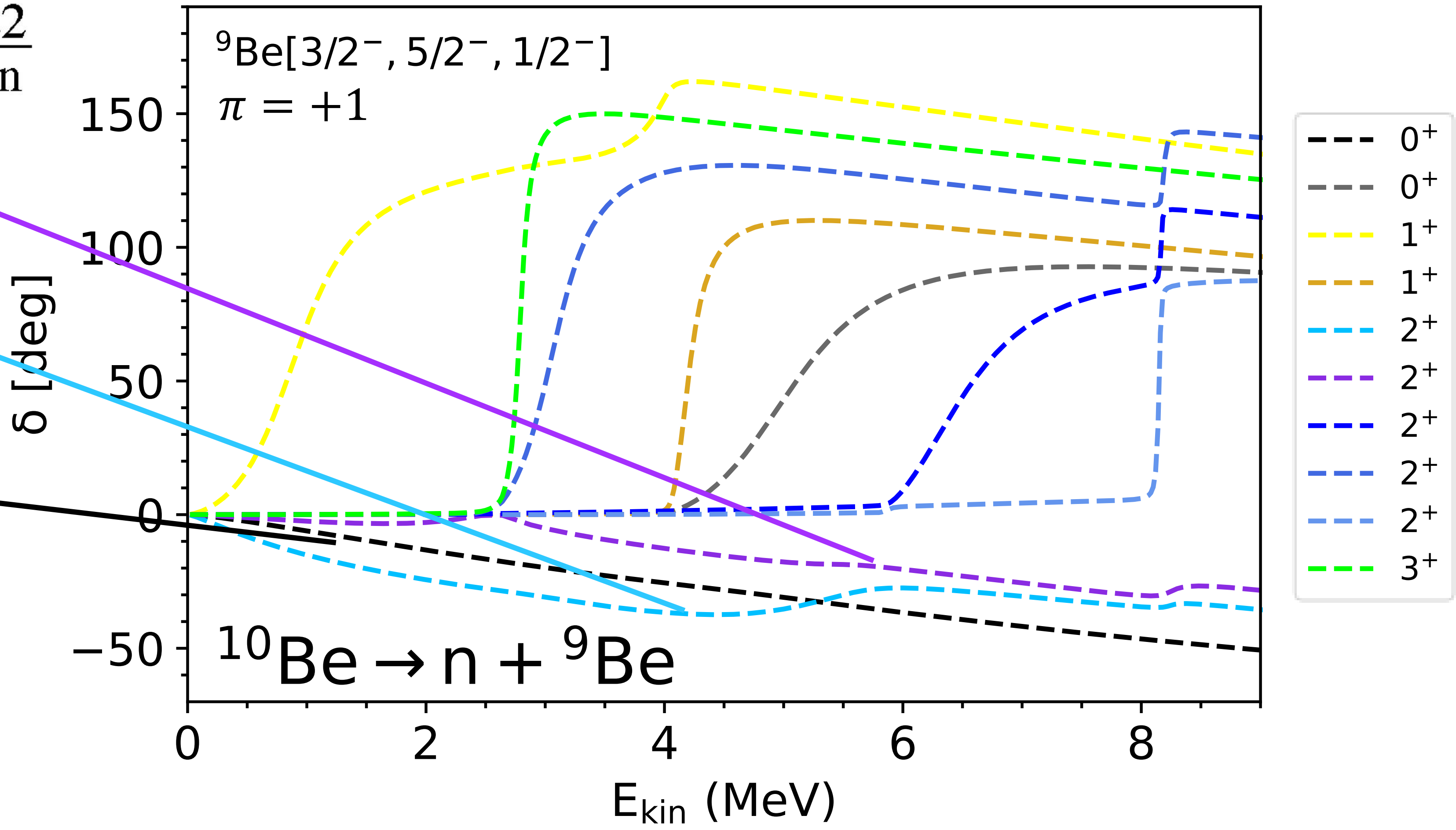
^{10}Be structure at $N_{max} = 9$





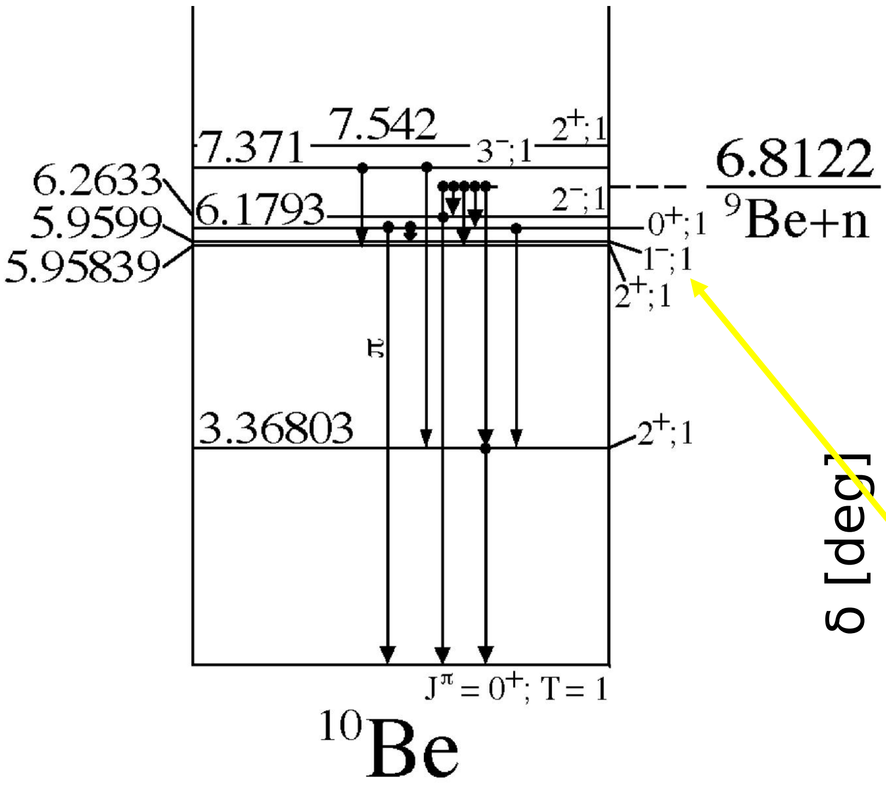
^{10}Be structure at $N_{max} = 9$

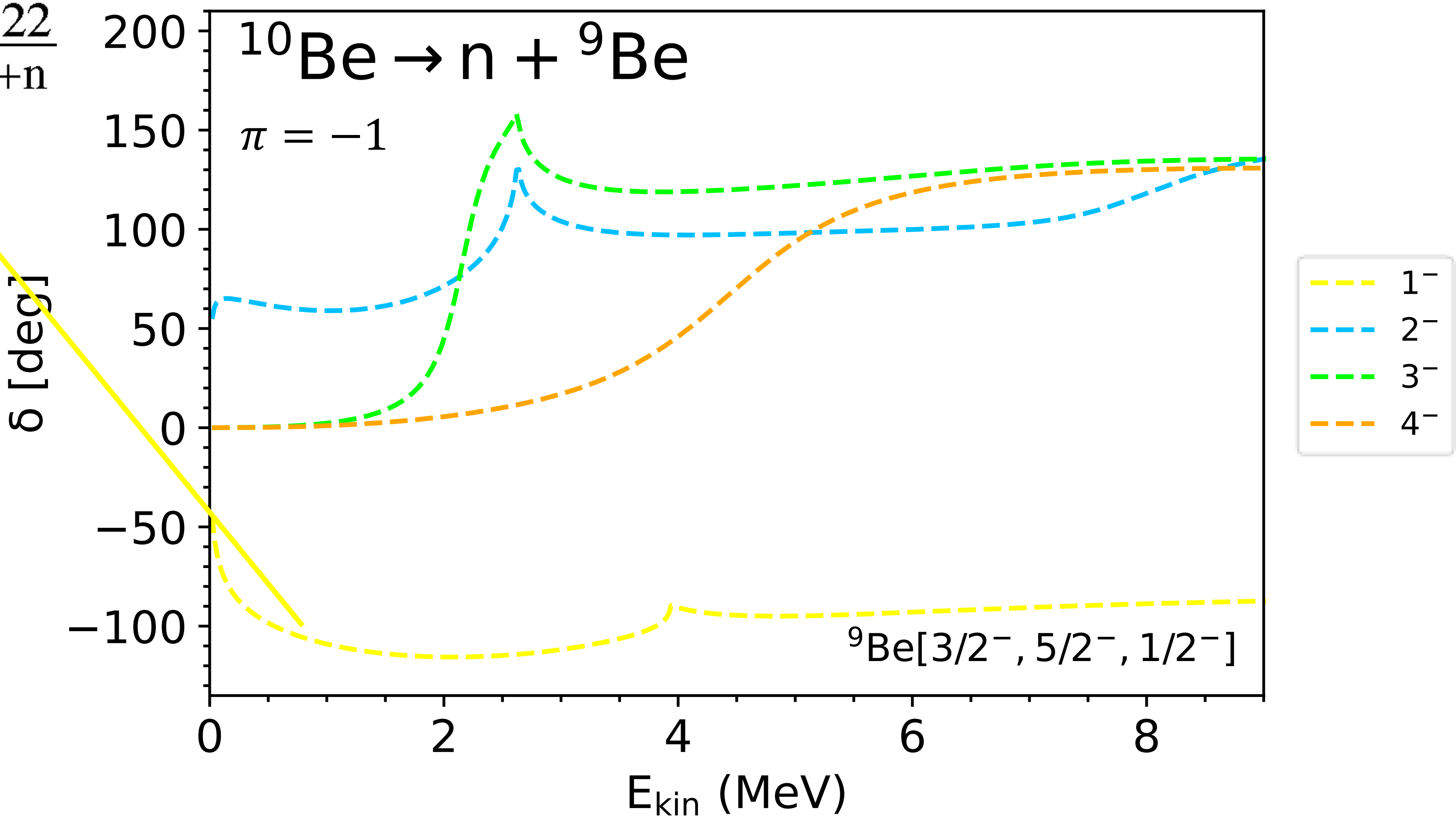




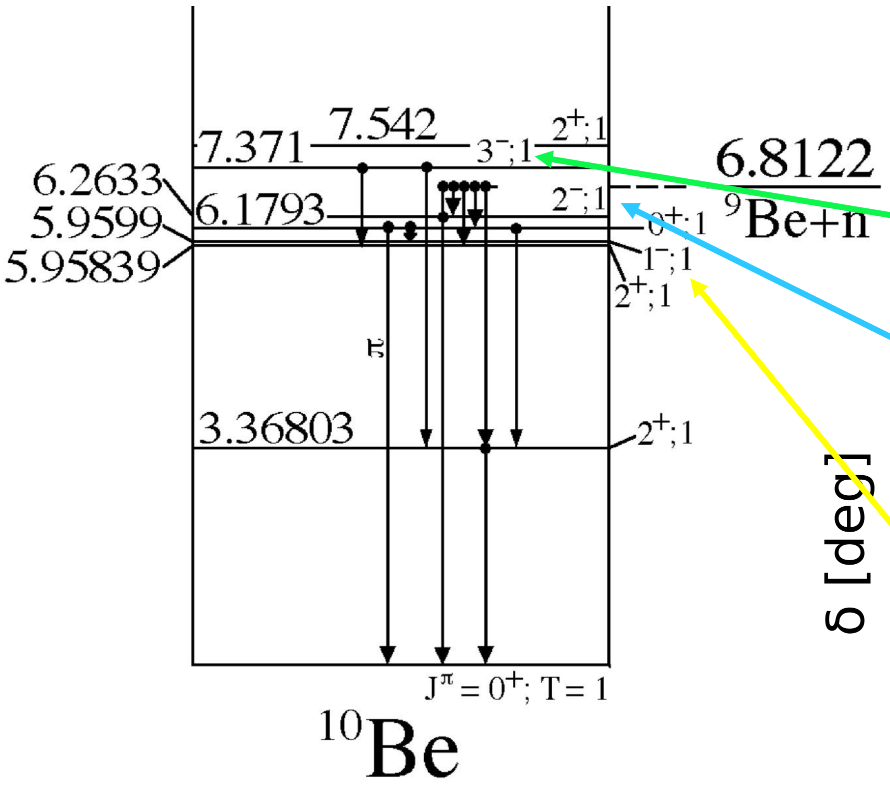
- Missing 0^+ due to missing ^{6}He+α mass partition

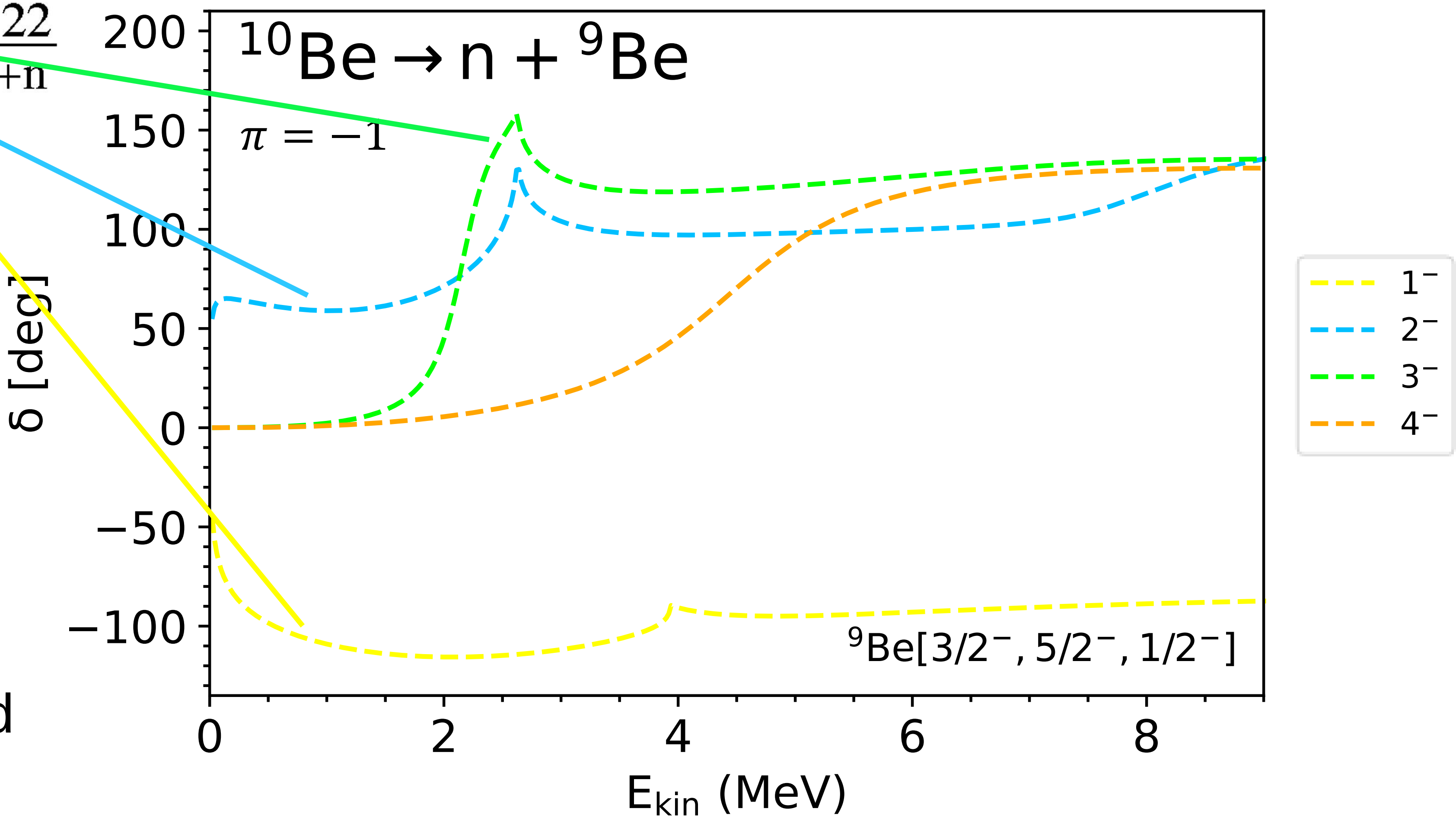
^{10}Be structure at $N_{max} = 9$





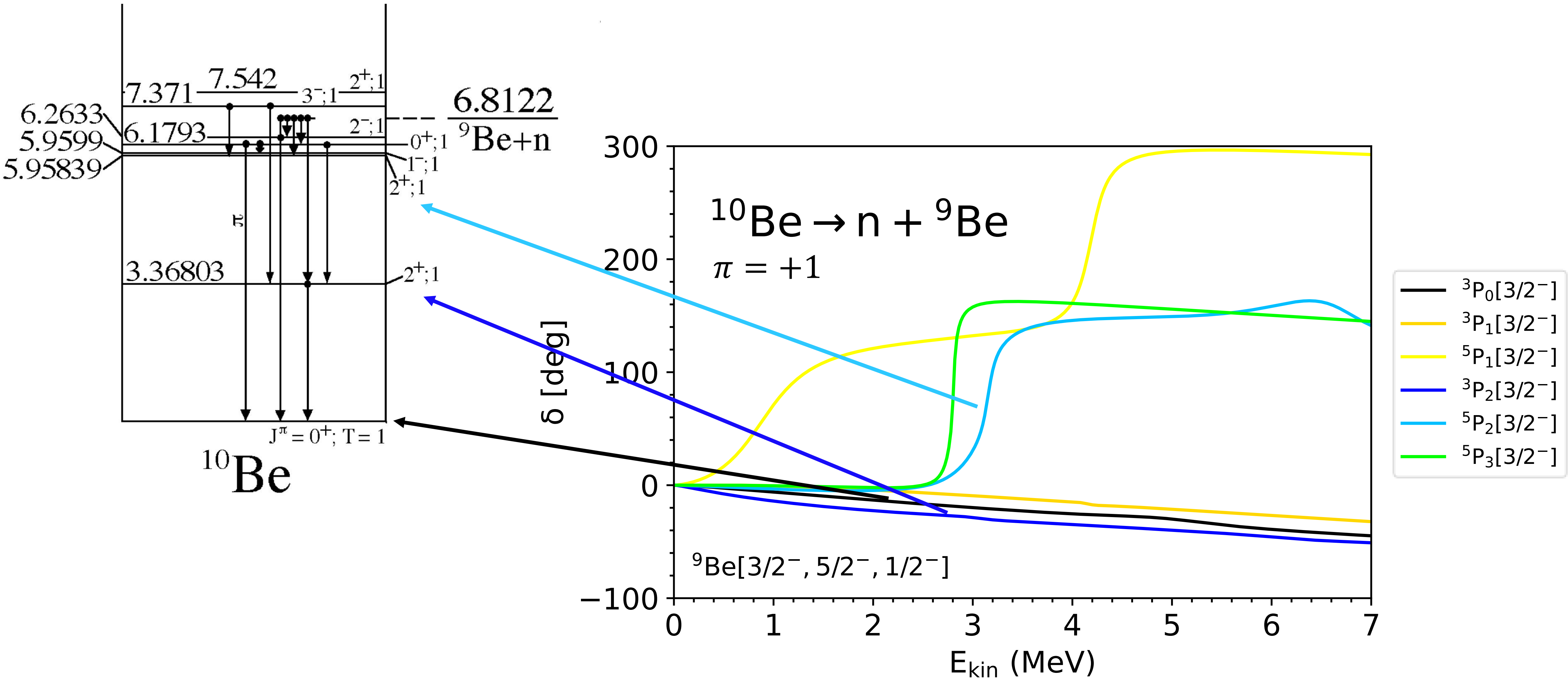
^{10}Be structure at $N_{max} = 9$



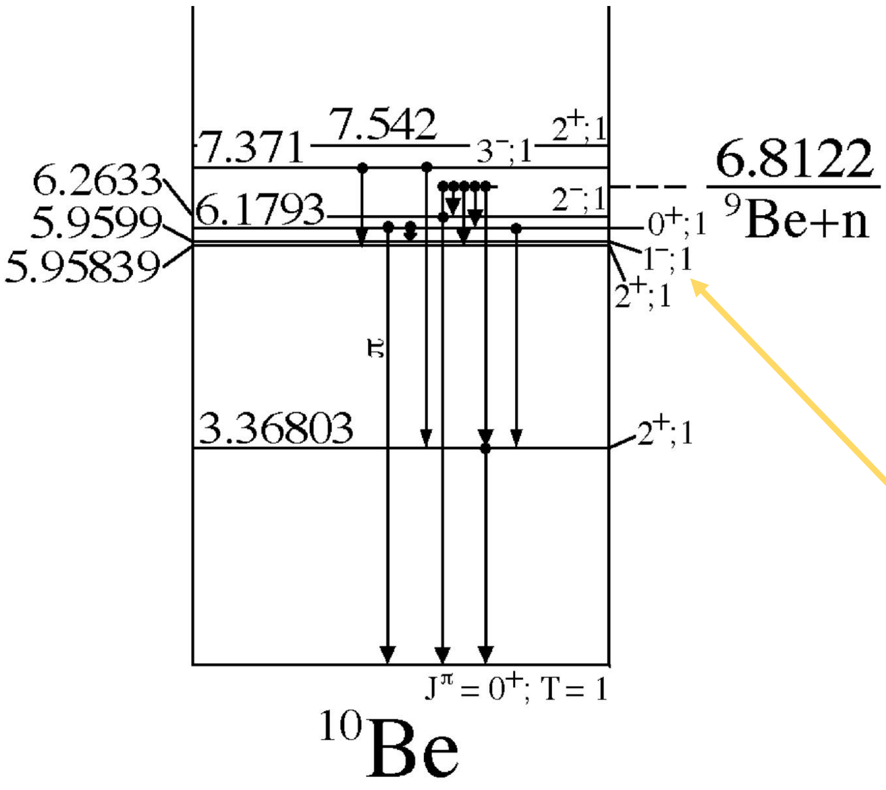


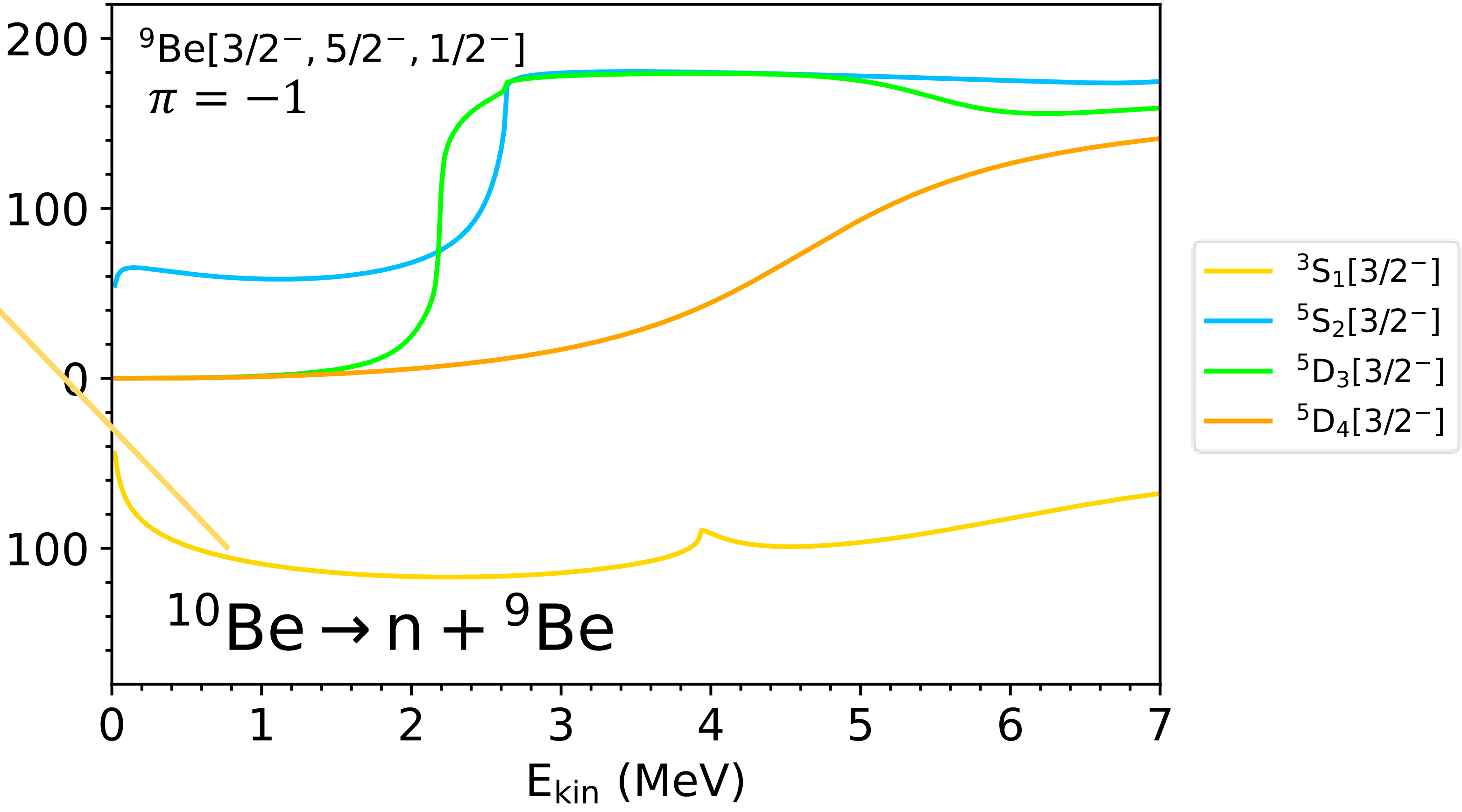
- 2^- halo state only 20 KeV from being bound

^{10}Be structure at $N_{max} = 9$

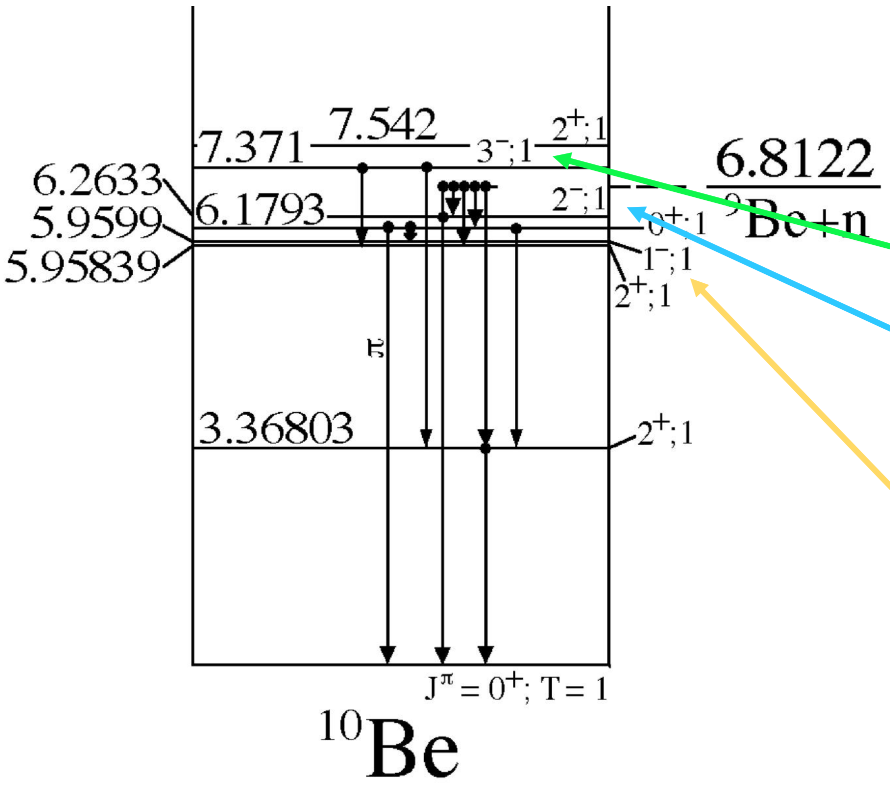


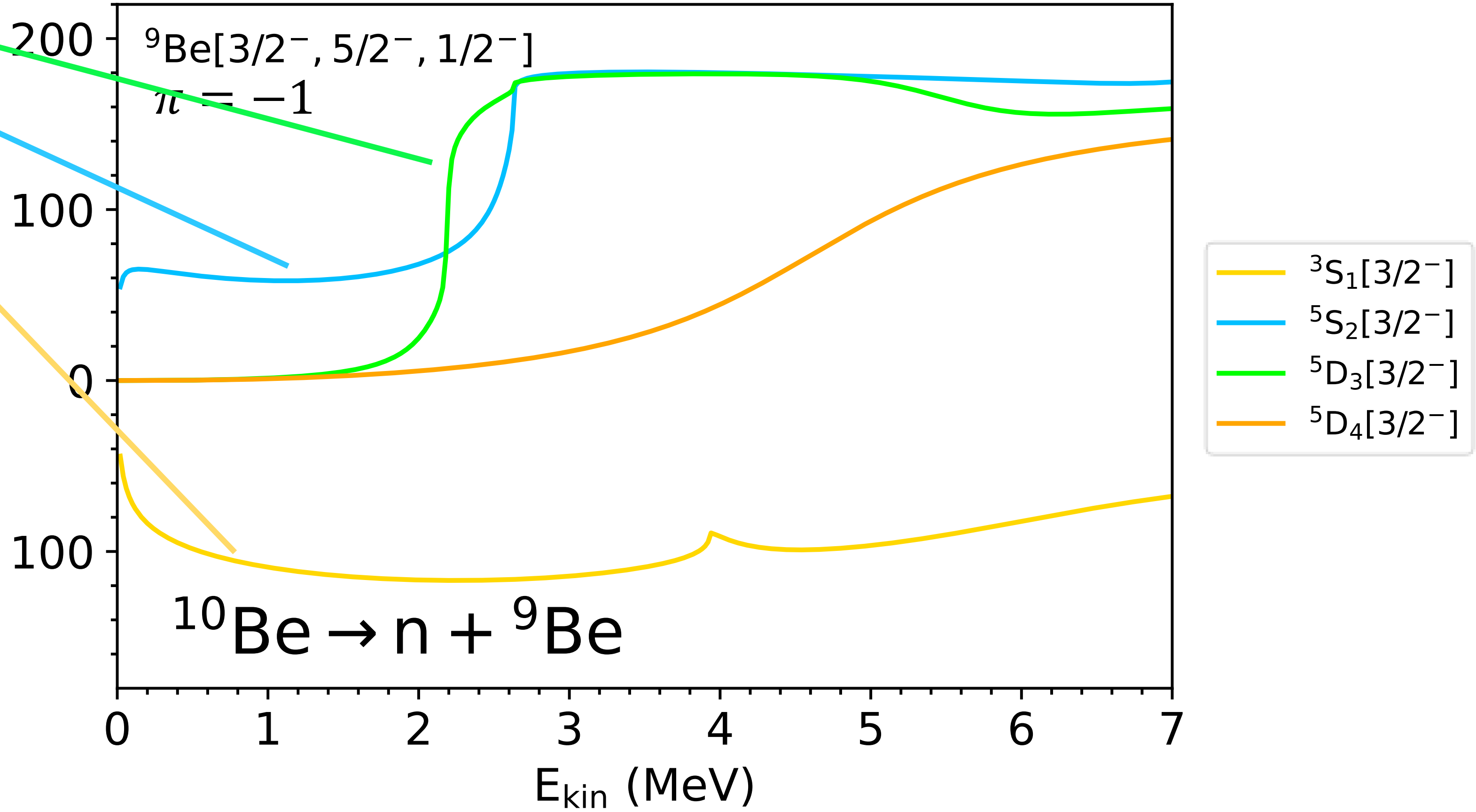
^{10}Be structure at $N_{max} = 9$





^{10}Be structure at $N_{max} = 9$





^{10}Be ANC's at $N_{max} = 9$

1^- ANCs

State	l	S	ANC $(\mathrm{fm}^{-1/2})$	ANC pheno $(\mathrm{fm}^{-1/2})$
$3/2^-$	0	1	0.363	0.951
$3/2^-$	2	1	0.7×10^{-3}	0.392×10^{-1}
$3/2^-$	2	2	-0.244×10^{-3}	-0.137×10^{-1}
$5/2^-$	2	2	-0.102	-0.230
$5/2^-$	2	3	0.104×10^{-1}	0.399×10^{-1}
$5/2^-$	4	3	-0.603×10^{-4}	-3.60×10^{-3}
$1/2^-$	0	1	0.257	0.425
$1/2^-$	2	1	0.184×10^{-1}	0.506×10^{-1}

2^- ANCs

State	l	S	ANC pheno $(\mathrm{fm}^{-1/2})$
$3/2^-$	2	1	-0.288×10^{-1}
$3/2^-$	0	2	-0.756
$3/2^-$	2	2	-0.103×10^{-1}
$3/2^-$	4	2	-0.274×10^{-4}
$5/2^-$	0	2	-0.451
$5/2^-$	2	2	0.164
$5/2^-$	4	2	0.849×10^{-4}
$5/2^-$	2	3	0.126
$5/2^-$	4	3	-0.128×10^{-3}
$1/2^-$	2	0	-0.184×10^{-1}
$1/2^-$	2	1	-0.348×10^{-1}

^{10}Be ANC's at $N_{max} = 9$

2^- ANCs

State	l	S	ANC pheno $(\mathrm{fm}^{-1/2})$
$1/2^-$	2	0	-0.184×10^{-1}
$1/2^-$	2	1	-0.348×10^{-1}

State				
$3/2^-$				
$3/2^-$				
$3/2^-$				
$5/2^-$				
$5/2^-$				
$5/2^-$				
$1/2^-$	0	1	0.257	0.425
$1/2^-$	2	1	0.184×10^{-1}	0.506×10^{-1}

^{10}Be-nucleus optical potentials developed from chiral effective field theory NN interactions

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We present a determination of optical potentials for ^{10}Be-nucleus collisions using the double-folding method to compute the real part and Kramers-Kronig dispersion relations to derive the imaginary part. As microscopic inputs we use chiral effective field theory nucleon-nucleon interactions at next-to-next-to-leading order combined with state-of-the-art nucleonic densities. With these potentials, we compute elastic scattering cross sections for the exotic nucleus ^{10}Be off various targets, and compare them to experiment. Without any fitting parameter, we obtain good agreement with data. For collisions on light targets, we observe significant uncertainty related to the short-range physics, whereas for heavy targets that uncertainty remains small.

Conclusions

- Exploration of continuum effects on $A = 10$ systems
- Consistency between ^{10}C and ^{10}Be calculations
  - 1^-, 2^- and 3^- resonances appear in ^{10}C
- Predictions of ^{10}Be halo states challenging
  - NCSMC close to getting bound 2^-
  - additional mass partitions could help, i.e. ^{8}Be+2n or ^{6}He+α

Outlook

- Include additional mass partitions in ^{10}Be

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Thank you
Merci

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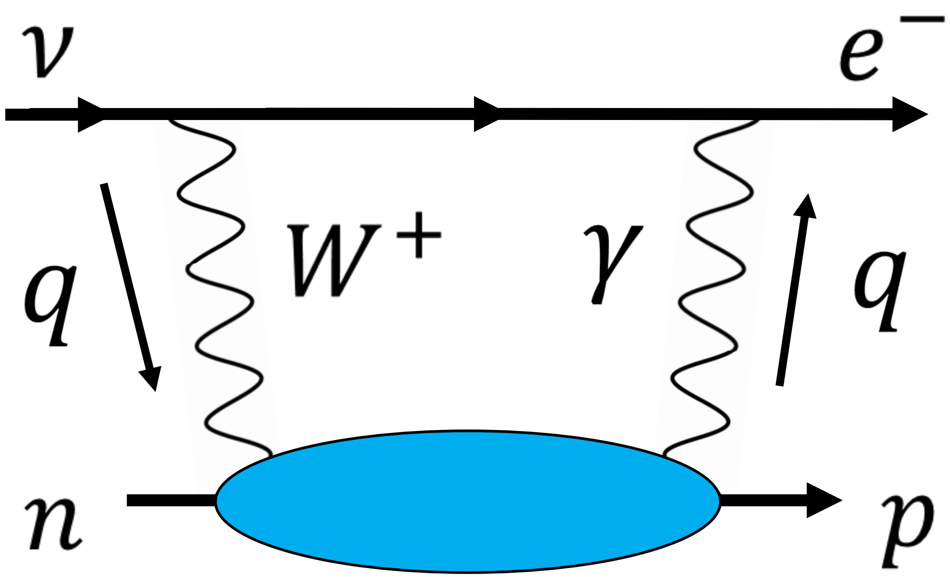
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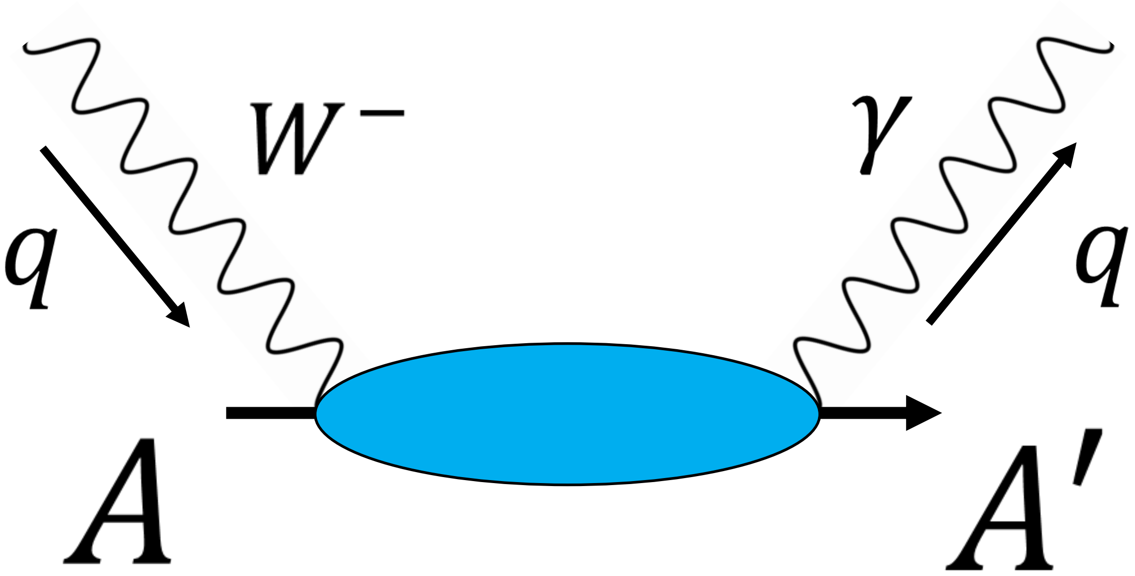
W⁻
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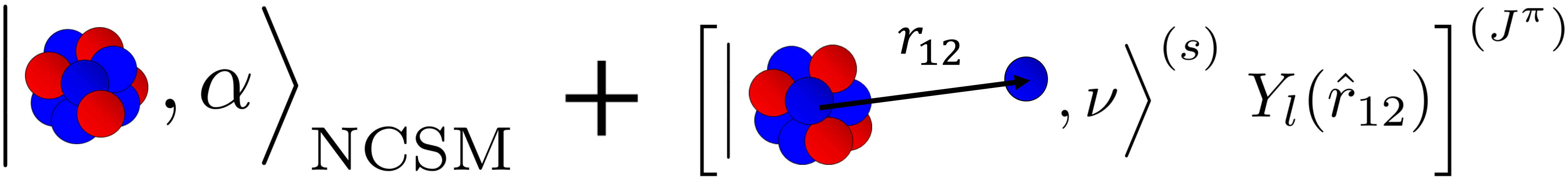
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