The exotic He-9 nucleus studied with NCSM/RGM and the NCSMC

Progress in ab-initio Techniques in Nuclear Physics

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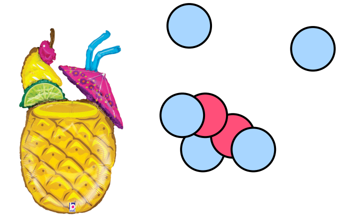
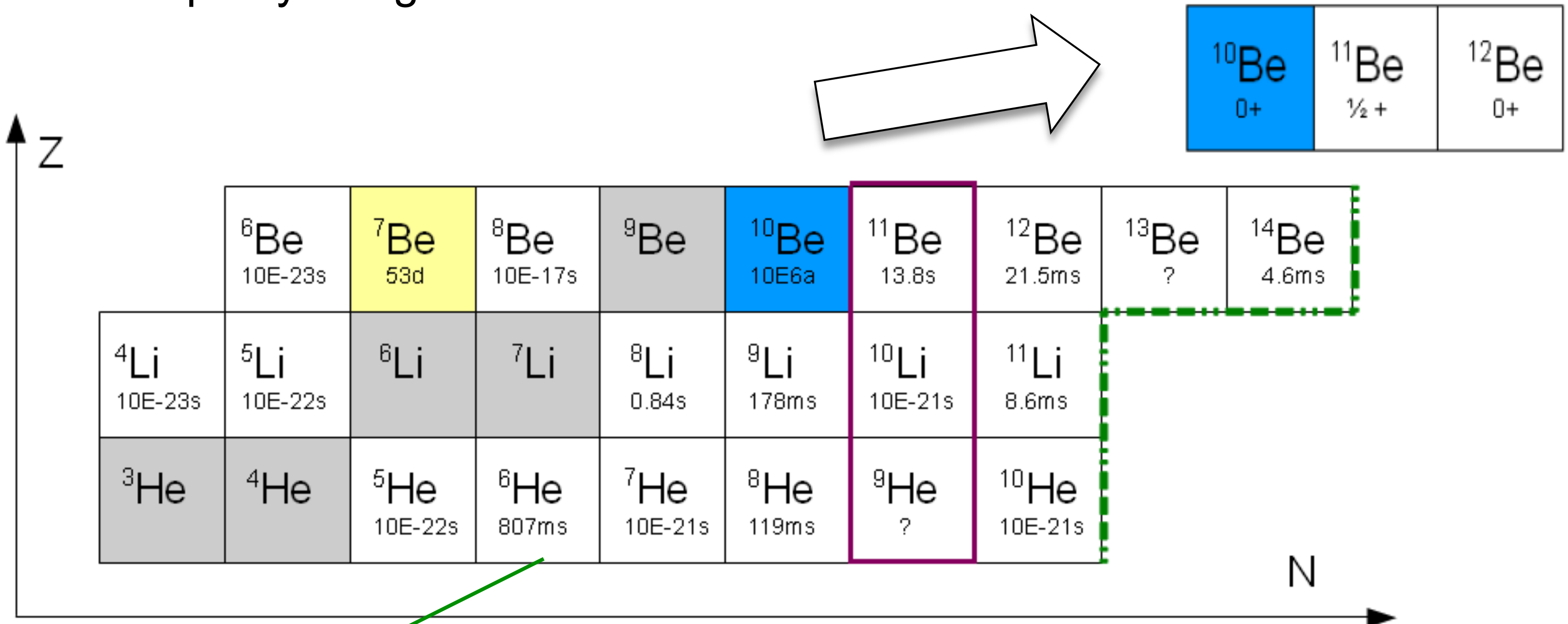
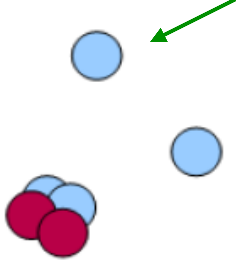
Exotic nuclei



- Nuclei away from the valley of stability exhibit a rich set of phenomena, such as relatively long half-lives or unnatural ground state parity assignments.

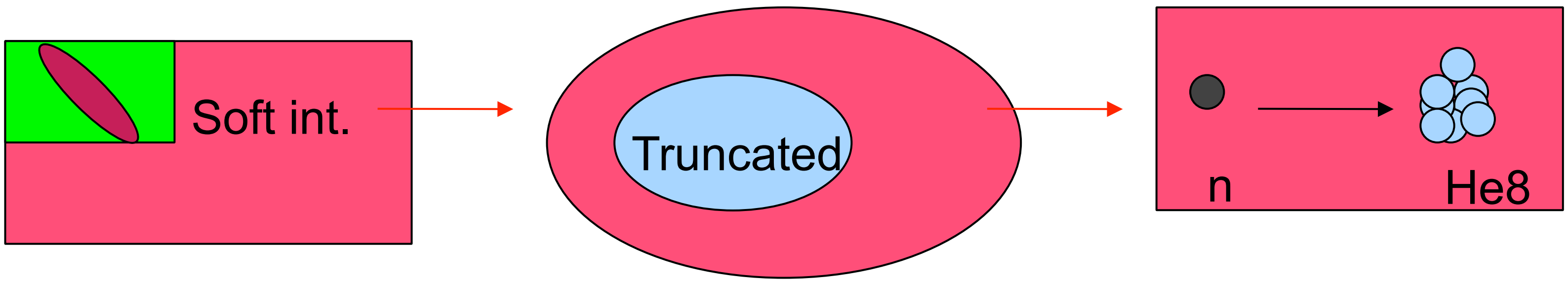




- **NCSM is good at calculating bound-states,**
- **But has problems with weakly bound states**
- **Weakly bound states → scattering observables.**

Is ^{9}He bound?

- Interesting physics question: One of the few nuclei that can be studied theoretically and experimentally that lies near the neutron drip-line.
- Be-11 and Li-10, both N=7 isotones, have un-natural parity assignments. What about He-9?
- Theory possibilities: Intruder states from the sd shell. Sensitive test of theory that bridges p-sd shell.



Use „soft“ interactions as input. Note:NN only <u>SRG potentials.</u>

Truncate the full model space to a smaller feasible space. <u>Importance Truncation.</u>

Do a scattering calculation of a neutron on He8 – look for bound states in He9. <u>NCSM/RGM calculation</u>

Importance truncation schematically

$\langle \Phi_\nu |$?

Nmax=6
Next-larger space

Nmax=4
Reference space

$$\kappa_\nu = \frac{|\langle \Phi_\nu | H | \Psi_{ref} \rangle|}{\epsilon_\nu - \epsilon_{ref}}$$

Typically choose κ ~ 10^{-5}

$$\Delta_{\text{excl}}(\kappa_{\min}) = -\sum_{\nu \notin \mathcal{M}(\kappa_{\min})} \frac{|\langle \Phi_\nu | H | \Psi_{\text{ref}} \rangle|^2}{\epsilon_\nu - \epsilon_{\text{ref}}}$$

$\langle \Phi_\nu |$

Nmax=6
Kept states

Nmax=4

New results in IT-NCSM.

Extrapolation uncertainties in the importance-truncated No-Core Shell Model

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Careful investigation of IT-NCSM results as a function of Nmax, HO energy, SRG momentum decoupling (lambda) and multiple reference states.

Full NCSM Li-6 calculations up to Nmax = 14 are used to benchmark IT-NCSM calculations of Li-6 varying the quantities above.

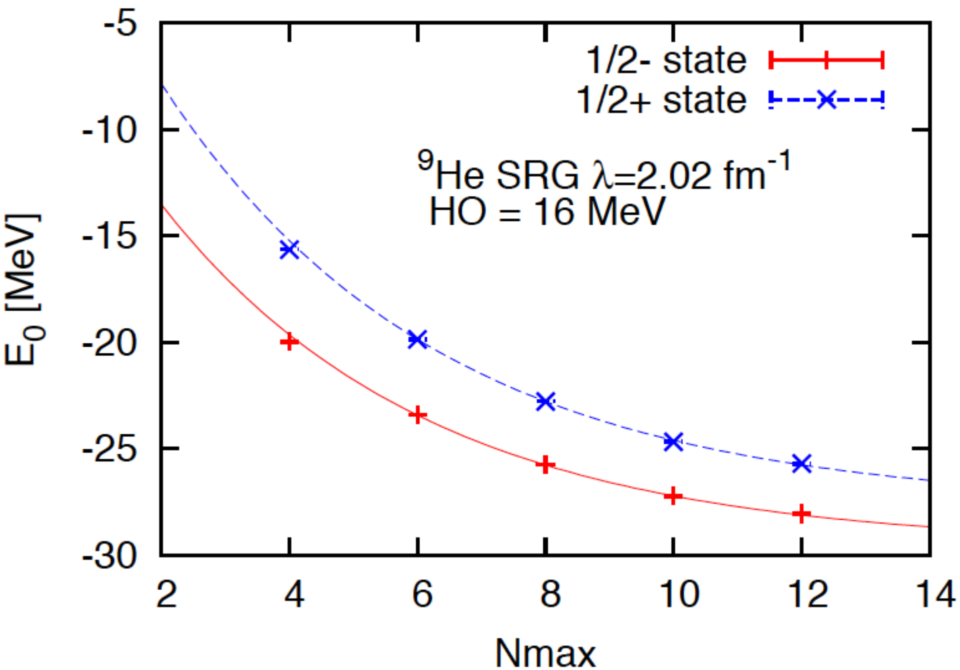
Extrapolations to Nmax infinity are handled very carefully taking into account uncertainties of extrapolating to kappa = 0 in a given Nmax space.

arXiv:1302.1226 [nucl-th]

NCSM calculation of He-9

To demonstrate the advantages of the NCSM/RGM and NCSMC techniques
I will briefly show a NCSM calculation of He-9.
This is to be compared to later results.

All calculations use **HO = 16 MeV** and SRG NN chiral interaction at **λ = 2.02 fm^{-1}.**



IT-NCSM calculations with k~1.0x10^{-5}.
Extrapolated to k = 0.

Predict ½- state to be ground-state.

Extrapolated to Nmax = infinity.

	IT-NCSM	
J^π	$\frac{1}{2}^-$	$\frac{1}{2}^+$
E [MeV]	-28.040	-25.694

NCSM/RGM key ideas

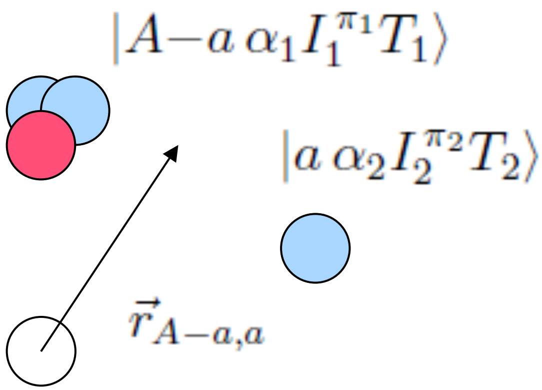
Sofia Quaglioni and Petr Navrátil
PRL **101**, 092501 (2008)
PHYSICAL REVIEW C **79**, 044606 (2009)

- Expand wavefunction on a basis of binary clusters.
- Clusters themselves are anti-symmetric, but not anti-symmetric with each respect to each other.

$$|\Phi^{J^\pi T}_{\nu r}\rangle = \Big[\big(|A{-}a\,\alpha_1 I_1^{\pi_1} T_1\rangle\,|a\,\alpha_2 I_2^{\pi_2} T_2\rangle\big)^{(sT)} \times Y_\ell(\hat{r}_{A-a,a})\Big]^{(J^\pi T)} \frac{\delta(r - r_{A-a,a})}{r\,r_{A-a,a}}\,.$$

$$|\Psi^{J^\pi T}\rangle = \sum_\nu \int dr\, r^2 \frac{g_\nu^{J^\pi T}(r)}{r}\,\hat{\mathcal{A}}_\nu\,|\Phi^{J^\pi T}_{\nu r}\rangle$$

$$\sum_\nu \int dr\, r^2 \left[\mathcal{H}^{J^\pi T}_{\nu'\nu}(r',r) - E\,\mathcal{N}^{J^\pi T}_{\nu'\nu}(r',r)\right] \frac{g_\nu^{J^\pi T}(r)}{r} = 0$$



- **Clusters determined from NCSM calculation**
- **Calculate matrix elements for kernels.**

Norm and Hamiltonian kernel

- The Hamiltonian

$$H = T_{\rm rel}(r) + \mathcal{V}_{\rm rel} + \bar{V}_C(r) + H_{(A-a)} + H_{(a)}$$

Relative kinetic between clusters

Relative NN int between clusters

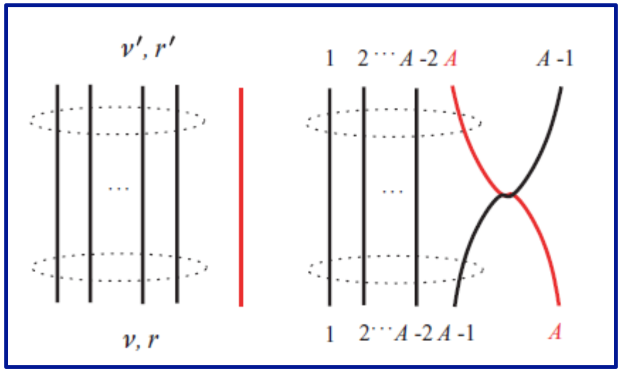
Avg. Coulomb

Determined in same (Nmax,hΩ) space

$$\sum_\nu \int dr\, r^2 \left[\mathcal{H}^{J^\pi T}_{\nu'\nu}(r',r) - E\mathcal{N}^{J^\pi T}_{\nu'\nu}(r',r)\right] \frac{g^{J^\pi T}_\nu(r)}{r} = 0$$

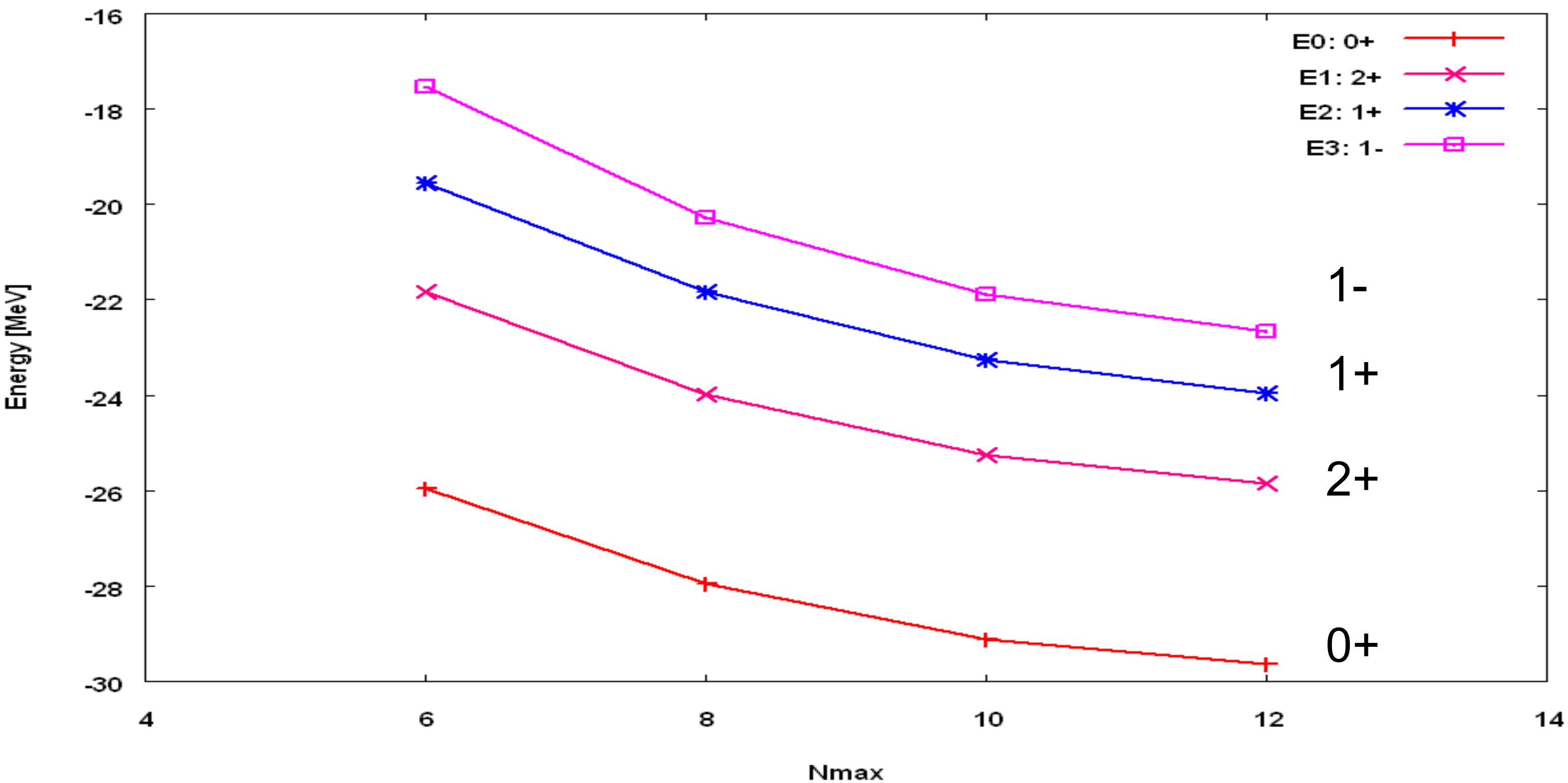
$$\mathcal{H}^{J^\pi T}_{\nu'\nu}(r',r) = \left\langle \Phi^{J^\pi T}_{\nu' r'} \right| \hat{A}_{\nu'} H \hat{A}_\nu \left| \Phi^{J^\pi T}_{\nu r} \right\rangle$$

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



Direct **Exchange**

He 8: Nmax=12 (Importance Truncated)

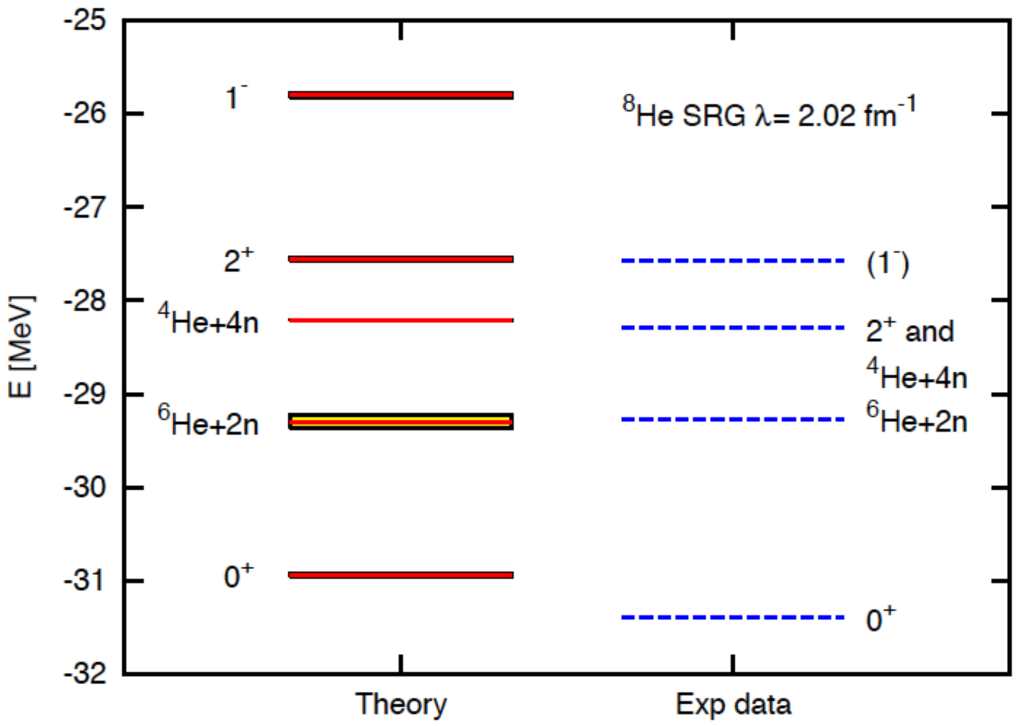


Nmax	E0 (MeV)	E1 (MeV)	E2 (MeV)	E3 (MeV)
12	-29.604	-25.854	-23.951	-22.664

Nmax	Full space (+) Parity	IT space (k=1E-5)
12	~ 428 million	~ 13.65 million

SRG-tuning of NN interaction

- We use the chiral N3LO NN interaction (500 MeV/c)
- SRG transformed to $\lambda = 2.02\ \text{fm}^{-1}$.
- How well do you describe other He isotopes then?



Performed NCSM calculations for He-6 and He-4 using same interaction and HO = 16 MeV.

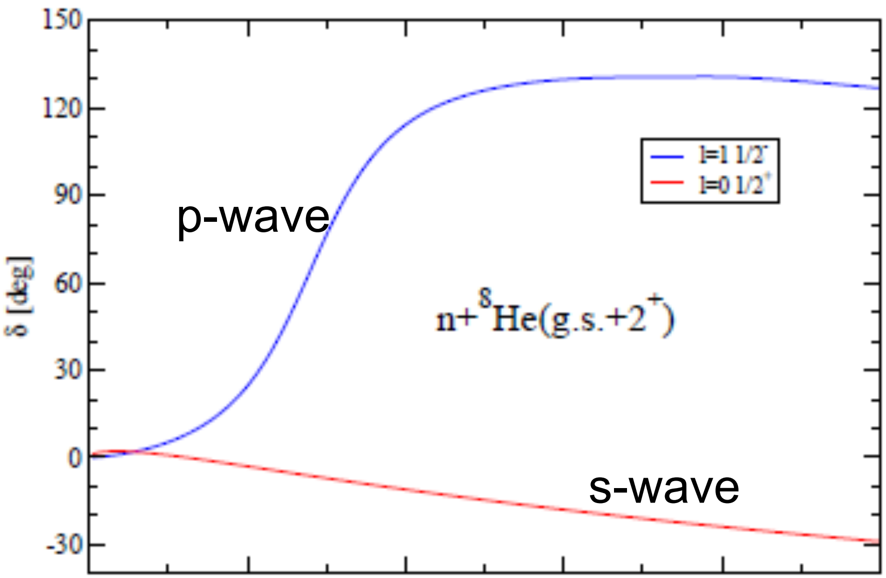
Note: These results are extrapolations to Nmax infinity.

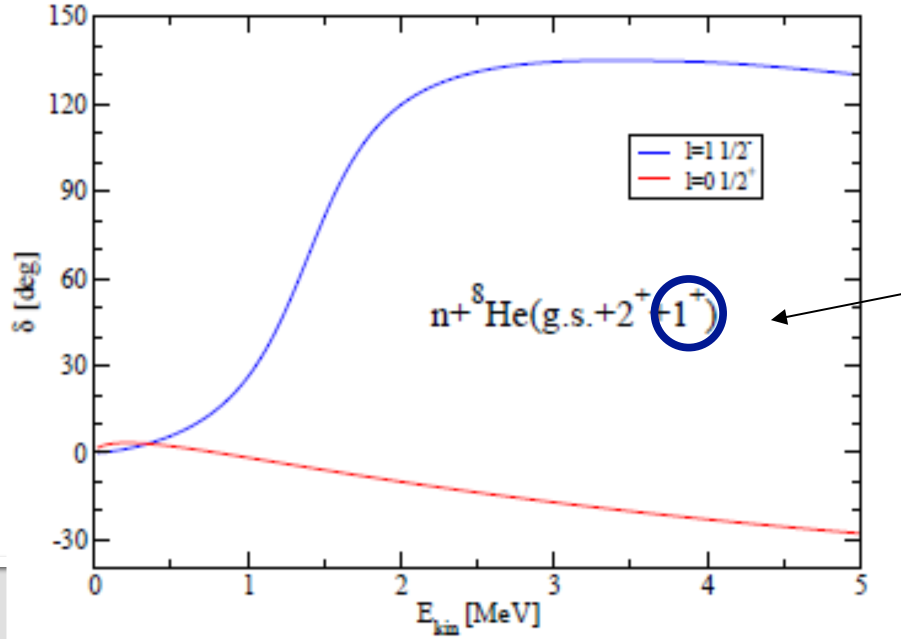
We find that $\lambda = 2.02\ \text{fm}^{-1}$ tunes the NN interaction in such a way as to accurately reproduce exp.

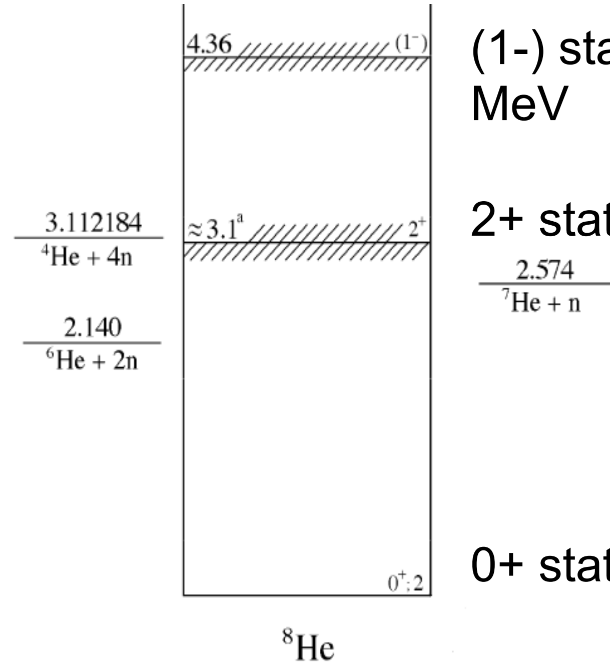
Compares well to S. Bacca Phys. Rev. C 86, 034321 (2012)

NCSM/RGM: Inclusion of various states

Nuclear Physics A 745 (2004) 155–362







(1-) state: 4.36 MeV

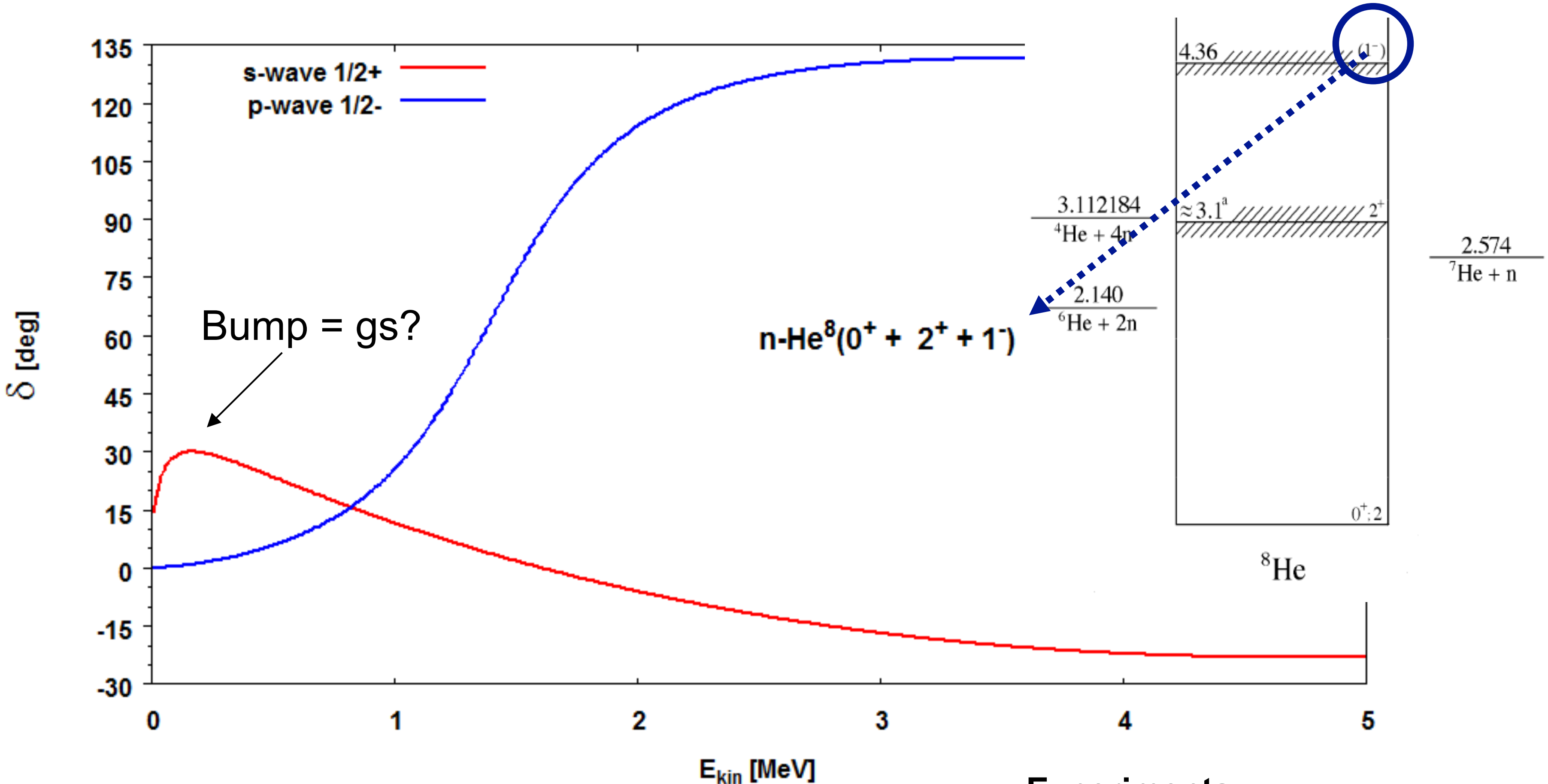
2+ state: 3.1 MeV

0+ state

There is almost no difference in the calculated phase shifts for including the 1+ state as well. Scattering length a_0 = -1 fm.

No bound state.

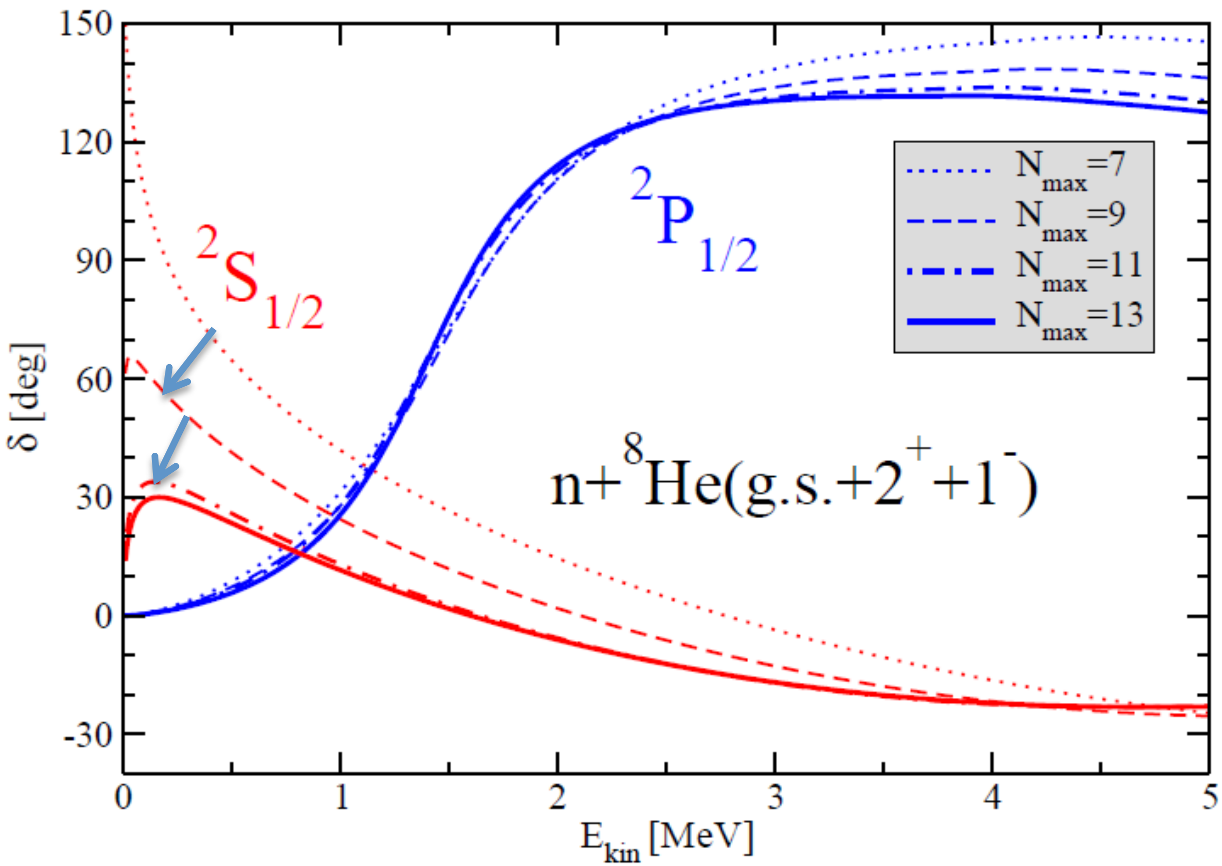
NCSM/RGM: Inclusion of negative parity state



The inclusion of the negative parity state has a large effect! Now the predicted scattering length is a_0 = -12.59 fm.

Experiments:
a_0 **< -10 fm** (Chen et al.) [PLB 505, 2001]
a_0**~ -3 fm** (Al Falou, et al.) [arxiv:nucl-ex: 1008:0543]

Convergence check: Nmax



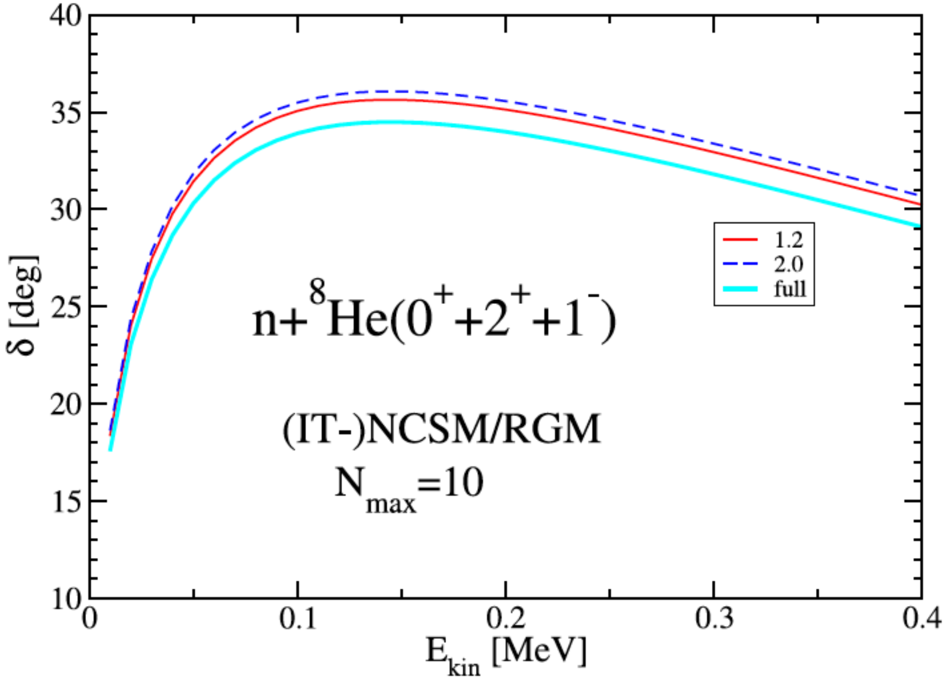
Use the full NCSM basis for Nmax = 7 – 11.

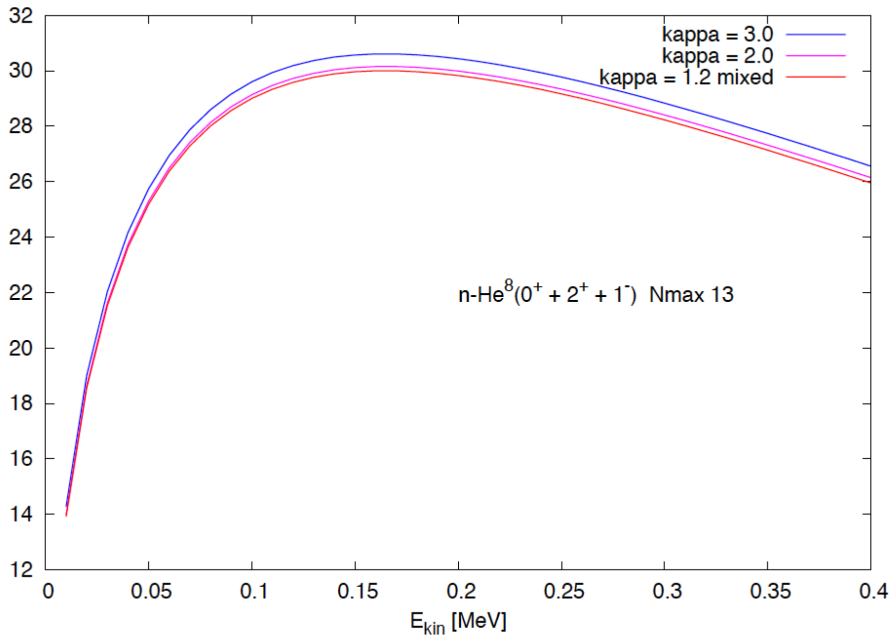
Nmax = 13 has IT-NCSM wavefunctions.

Convergence of s-wave seems ok.

Convergence of p-wave is very good up to 2.5 MeV.

Convergence check: IT-NCSM “kappa” s-wave phase-shifts at Nmax = 11 - 13.





At Nmax = 10 we can still compare IT-NCSM wavefunctions to full NCSM. Note that we underestimate the peak about 3 degrees. Overall trend is reproduced.

Nmax = 12 uses only IT-NCSM wavefunctions. Convergence in kappa seems reasonable. True peak is probably a little lower than shown.

Status of He-9 calculation (NCSM/RGM)

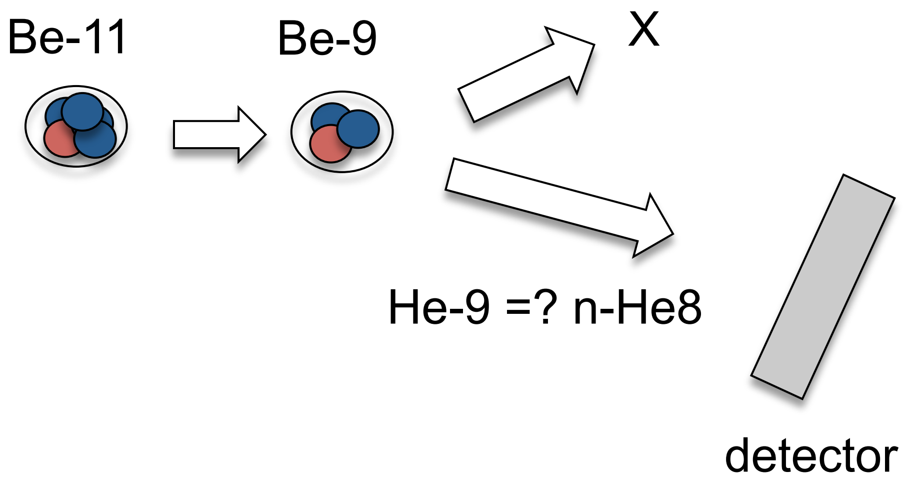
- Predict a resonance in the ½+ channel, but no bound state.
- ½- resonance agrees with experiments.
- Agrees with other theory calculations, but only agrees with the 2001 MSU experiment.
- Experiments are tough. Can't just get some He-8 and fire neutrons at it! (Well, not easily).
- Need to do a NCSM He-9 calculation and use the NCSM/ (NCSM/RGM) technique to study the missing many-body correlations in the n-He8 calculation.
- Bench-mark calculation of He-8 with Roth in Nmax=14. Agreement seems pretty good, even though he uses a different IT-NCSM scheme.

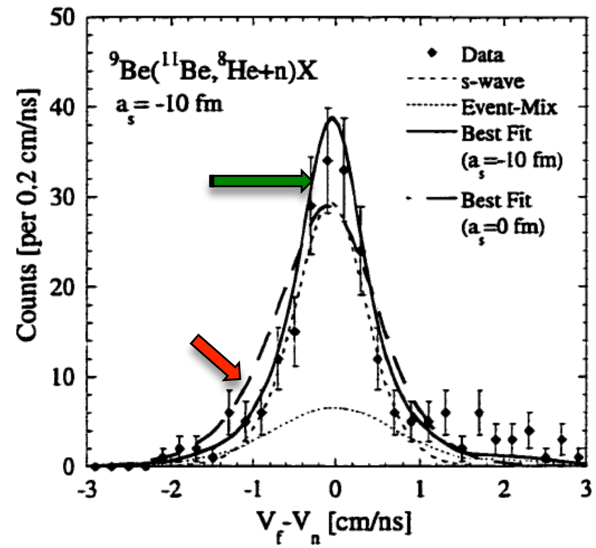
MSU experiment: Chen et al (2001)

The half-life of He-8 is 120 ms, which is typically too small to perform experiments on. Thus, one can't study the reaction n-He8 directly.

But you can try produce He-9 perhaps in some loosely bound n-He8 configuration by other means.

$$^{9}\mathrm{Be}(^{11}\mathrm{Be},{}^{8}\mathrm{He}+\mathrm{n})\mathrm{X}$$





Potential-model fit to differences in velocities between neutron and He-8 fragment favor a Scattering length of < -10 fm.
The s-wave is determined by selection rule arguments from Be-11 and from the Shape of the velocity distribution above.

NCSM/RGM coupled with NCSM = NCSMC

Why do we need yet another technique when we already have NCSM and NCSM/RGM?

NCSM: excellent technique for light nuclei that are tightly bound (e.g. He-4, Li-6). Poor asymptotic behavior of wavefunctions = poor description of halo-nuclei.

NCSM/RGM: keep the power of many-body correlations from the NCSM and improve the tail of intrinsic wavefunctions from the RGM part (e.g. A=5). But, there are limitations. If you want to include dynamic effects in the target projectile you need to include many excited states (e.g. d-alpha). The more excited states needed the tougher the calculation.

NCSMC: Couple the NCSM basis with the NCSM/RGM. Introduces dynamic properties of the target/projectile nucleus (i.e. less excited states needed in calculations). Particularly useful for d-t reactions.

***Ab Initio* Description of the Exotic Unbound ^{7}He Nucleus**

Simone Baroni,[1,2,*] Petr Navrátil,[2,3,†] and Sofia Quaglioni[3,‡]

PRL **110**, 022505 (2013)

Unified *ab initio* approach to bound and unbound states: no-core shell model with continuum and its application to ^{7}He

Simone Baroni,[1,2,*] Petr Navrátil,[2,3,†] and Sofia Quaglioni[3,‡]

Arxiv:1301.3450

NCSMC formalism

$$|\Psi_A^{J^\pi T}\rangle = \sum_\lambda c_\lambda |A\lambda J^\pi T\rangle + \sum_\nu \int dr\, r^2 \frac{\gamma_\nu(r)}{r} \hat{A}_\nu |\Phi_{\nu r}^{J^\pi T}\rangle .$$

NCSM eigenstates.

Expansion coefficient is unknown.

NCSM/RGM part

Relative motion wavefunction unknown.

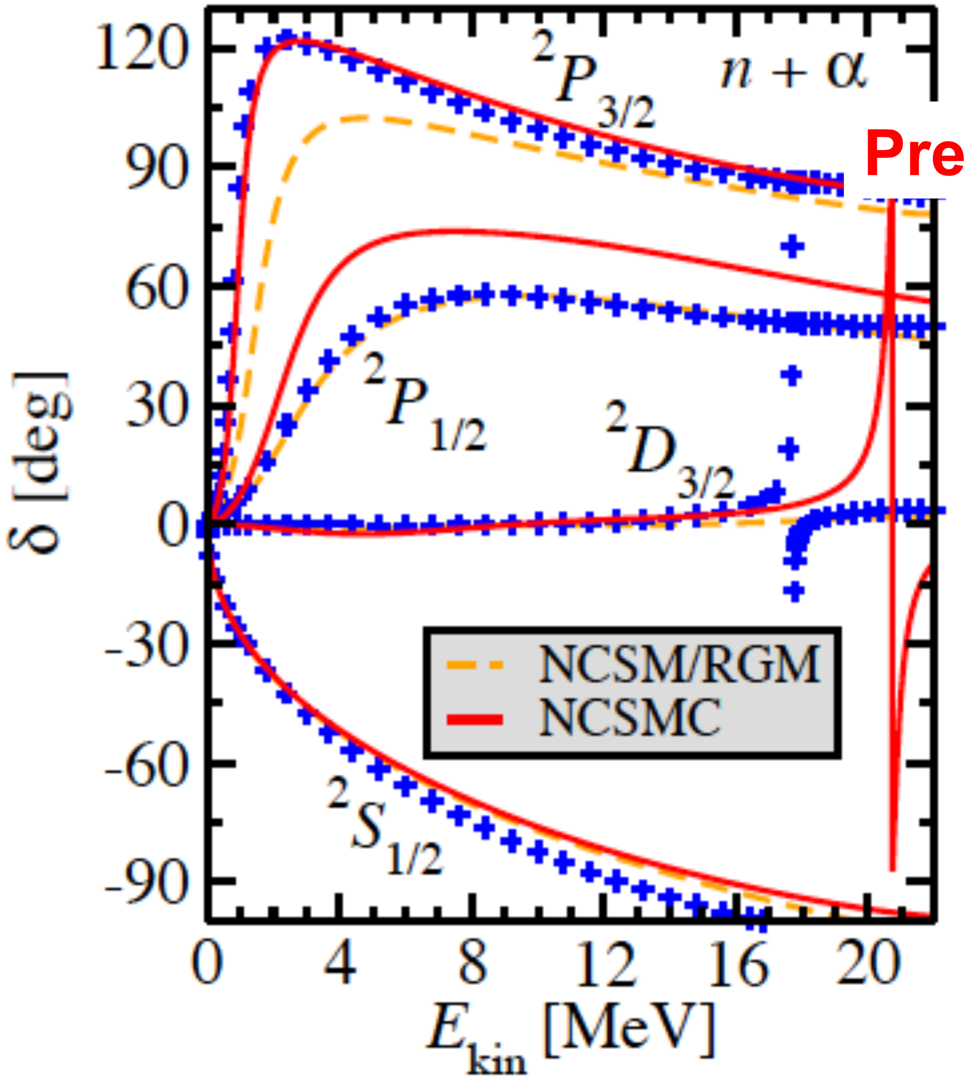
We then have to solve the following matrix equation

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

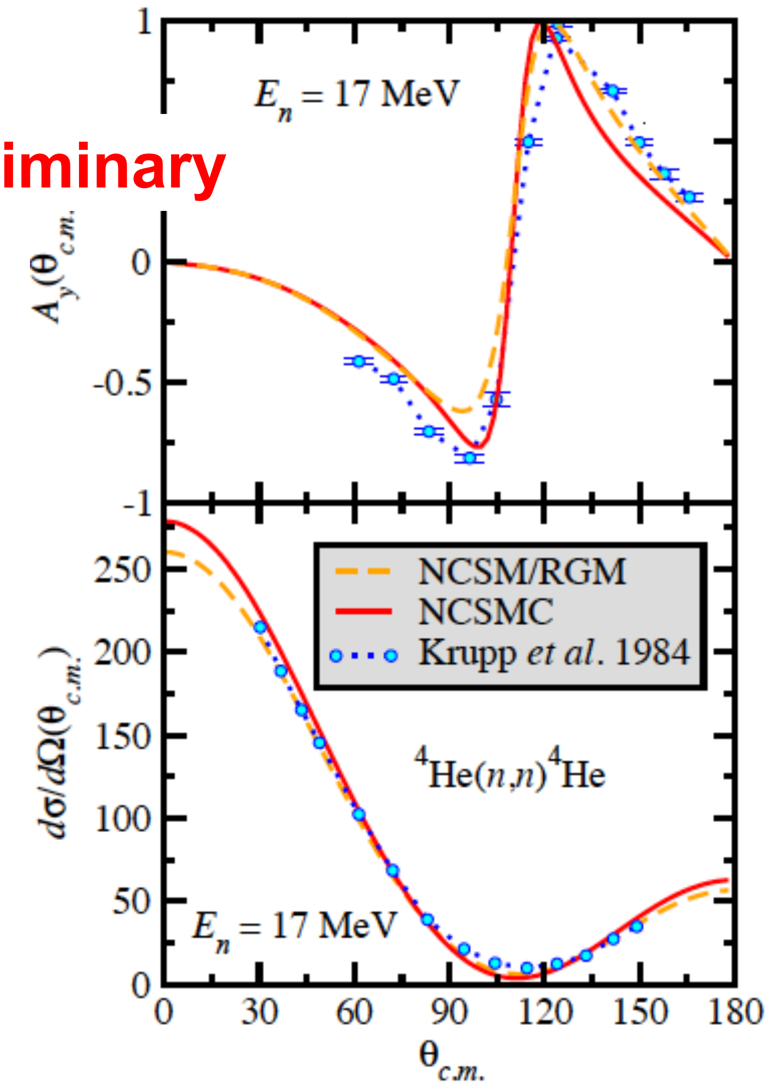
The norm kernel is of course diagonal
For the NCSM and NCSM/RGM parts.
The off-diagonal elements are the
cluster form factors.

$$N^{\lambda\lambda'}_{\nu r \nu' r'} = \begin{pmatrix} \delta_{\lambda\lambda'} & \bar{g}_{\lambda\nu'}(r') \\ \bar{g}_{\lambda'\nu}(r) & \delta_{\nu\nu'} \frac{\delta(r-r')}{rr'} \end{pmatrix}$$

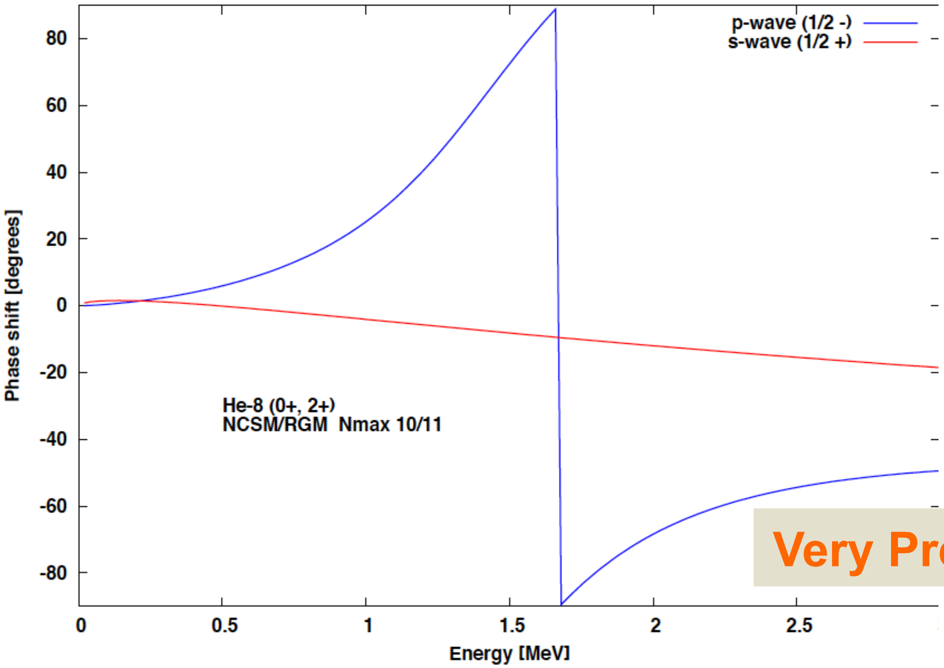
Interlude: n-He4 NCSMC

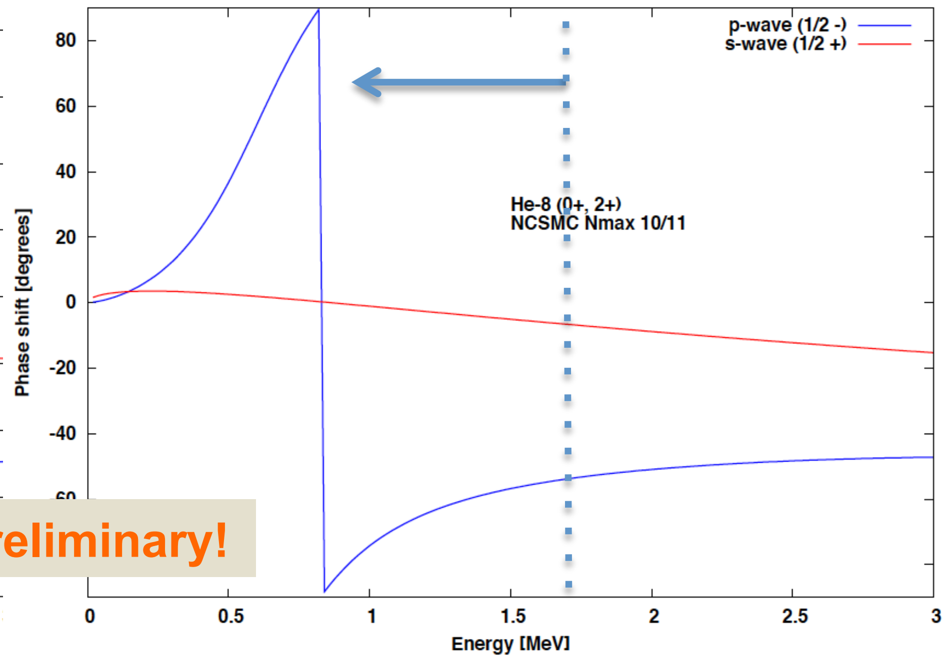


Preliminary



NCSM/RGM vs. NCSMC calculations





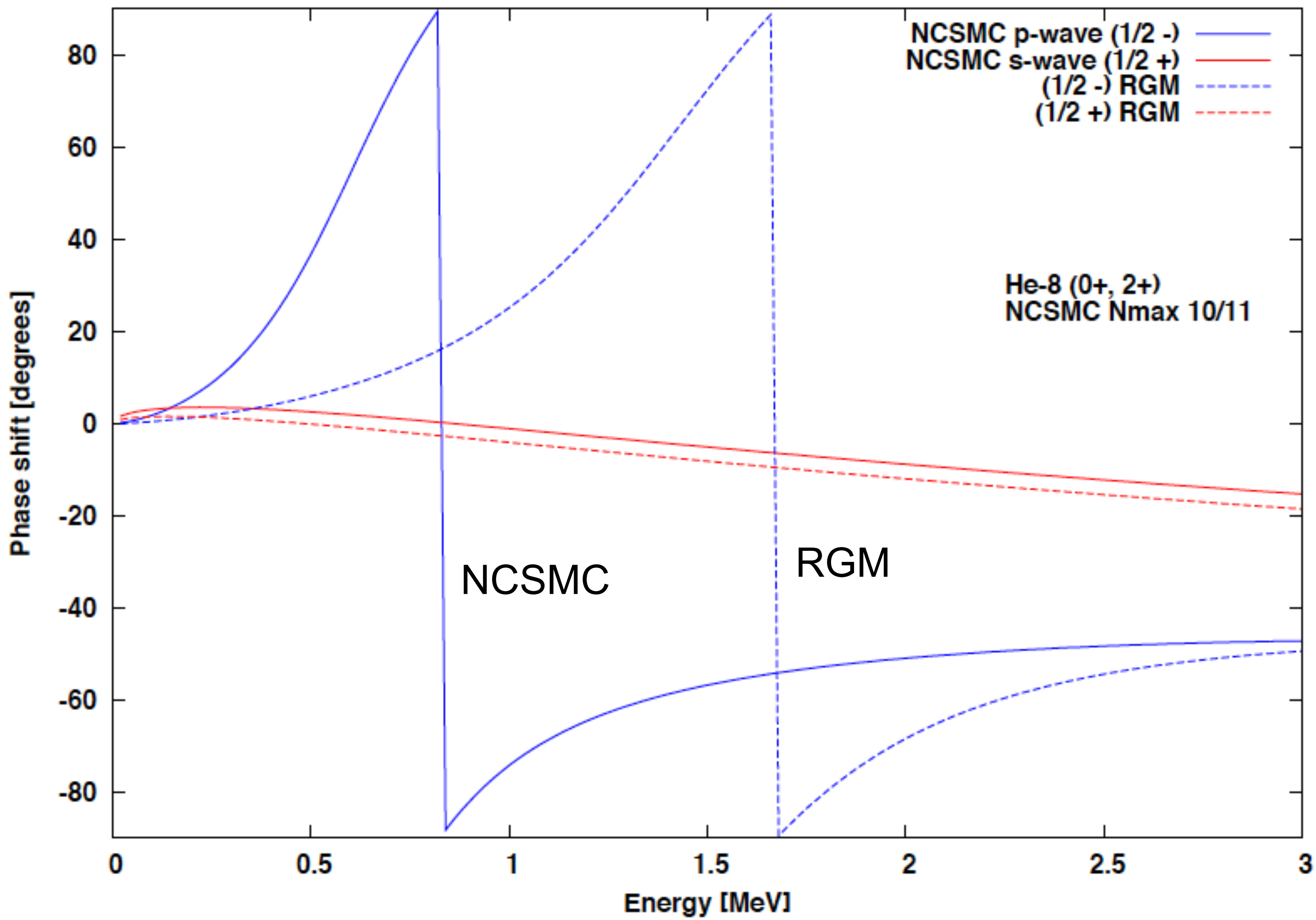
Very Preliminary!

NCSM/RGM:
Full NCSM wavefunctions used!
He-8: 0+ and 2+
S-wave: no bump (missing 1-).
P-wave resonance is located at 1.7 MeV

NCSMC:
He-9: 1/2-, 3/2-, 1/2+, 5/2+
The p-wave resonance is now at 0.8 MeV.

Will need more excited states in He-8 and larger Nmax values.

NCSMC vs. NCSM/RGM



Conclusions

- We have begun to investigate the results that the NCSMC gives.
- May need to include the 1- state in He-8 NCSM.
- Also need to check higher Nmax which will require IT-NCSM.
- Ongoing work…

Collaborations

- Petr Navrátil (TRIUMF)
- Sofia Quaglioni (LLNL)

n-He8 project

- Erich Ormand (LLNL)
- Bruce Barrett (Arizona)
- Sid Coon (Arizona)

Other projects