



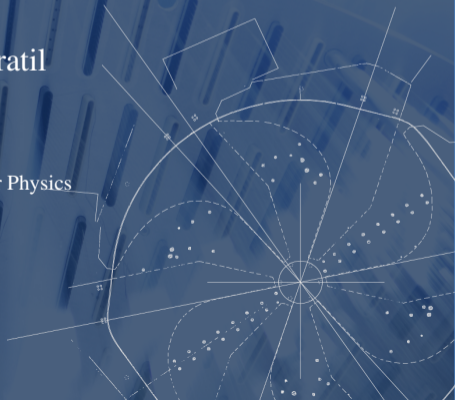
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Ab initio exploration of ^{12}C

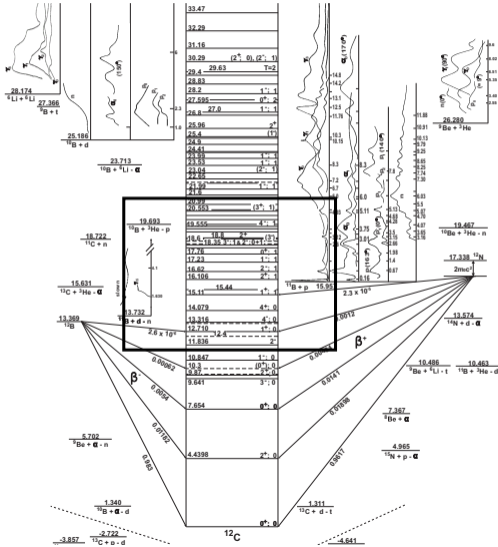
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TRIUMF, Canada

Progress in Ab Initio Techniques in Nuclear Physics
Feb. 27, 2019



$$p + {}^{11}\text{B} \rightarrow \alpha + \alpha + \alpha$$



${}^{10}\text{B} + {}^3\text{He} - p$ $\alpha + \alpha + \alpha$	19.693	20.555	(5 ⁺ , 1 ⁻)
	19.555	19.555	4 ⁻ ; 1 ⁻
	18.6	18.8	2 ⁺ (3 ⁻)
	17.76	18.35	3 ⁻ ; 1 & 2 ⁻ ; 0+1
	17.23		0 ⁺ ; 1 ⁻ ; 1 ⁻ ; 1 ⁻
	16.62		2 ⁻ ; 1 ⁻ ; 2 ⁺ ; 1 ⁻
	16.106		2 ⁺ ; 1 ⁻
	15.11	15.44	1 ⁺ ; 1 ⁻
	14.079		4 ⁺ ; 0 ⁻
	13.316		4 ⁻ ; 0 ⁻
	12.710		1 ⁺ ; 0 ⁻
	11.836	12.4	2 ⁻

${}^{11}\text{B} + p$ 15.957

Outline

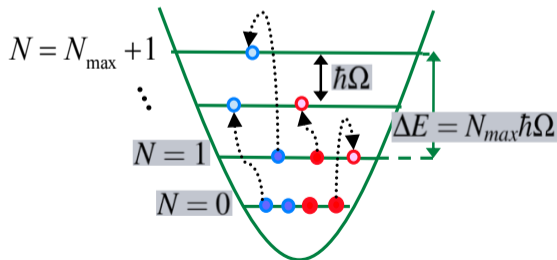
- No-core shell model (NCSM) ^{12}C
- NCSM with Resonating Group Method (NCSM/RGM) $^{11}\text{B} + p$
- NCSM with continuum (NCSMC) *preliminary results*

N4LO NN+3N, SRG 1.8

Ab initio calculation of ^{12}C

No-core shell model (NCSM):

- A -nucleon wavefunction expansion in the harmonic oscillator basis
- Short- and medium-range correlations
- Bound-states, narrow resonances



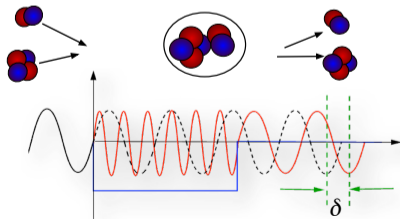
Ab initio calculation of ^{12}C

No-core shell model (NCSM):

- A -nucleon wavefunction expansion in the harmonic oscillator basis
- Short- and medium-range correlations
- Bound-states, narrow resonances

NCSM with Resonating Group Method (NCSM/RGM):

- Cluster expansion where clusters are described by NCSM
- Proper asymptotic behavior
- Long-range correlations



NCSM/RGM

$$\sum_{\nu} \int d\vec{r} \gamma_{\nu}(\vec{r}) \hat{A}_{\nu} \left| \begin{array}{c} \vec{r} \\ \text{(A-a)} \quad \text{(a)} \end{array} \right\rangle_{\nu} ;$$

$$= \sum_{\nu} \int \frac{\gamma_{\nu}^{J^{\pi T}}(r)}{r} \hat{A}_{\nu} \left[\left(\left| A-a \alpha_1 I_1^{\pi_1} T_1 \right\rangle \left| a \alpha_2 I_2^{\pi_2} T_2 \right\rangle \right)^{(sT)} Y_{\ell}(\hat{r}_{A-a,a}) \right]^{(J^{\pi T})} \frac{\delta(r - r_{A-a,a})}{r r_{A-a,a}} r^2 dr$$

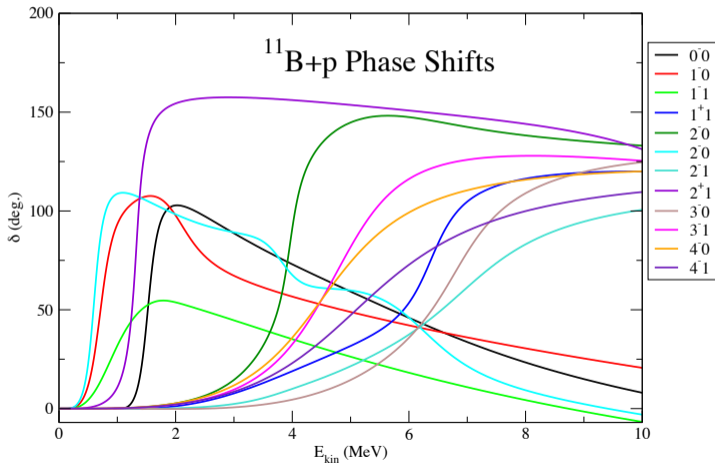
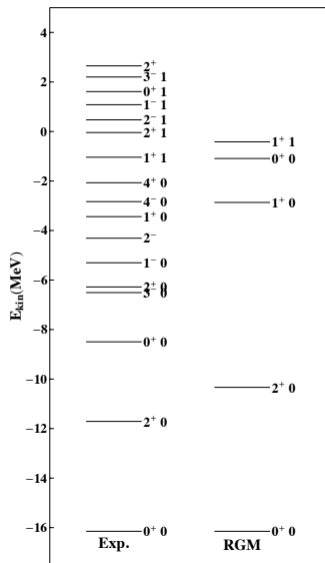
NCSM/RGM

$$\sum_{\nu} \int d\vec{r} \gamma_{\nu}(\vec{r}) \hat{A}_{\nu} \left| \begin{array}{c} \vec{r} \\ \text{---} \\ \text{---} \\ (A-a) \quad (a) \end{array} \right\rangle, \nu \rangle$$

$$= \sum_{\nu} \int \frac{\gamma_{\nu}^{J^{\pi T}}(r)}{r} \hat{A}_{\nu} \left[\left(\left| A-a \alpha_1 I_1^{\pi_1} T_1 \right\rangle \left| a \alpha_2 I_2^{\pi_2} T_2 \right\rangle \right)^{(J^{\pi T})} Y_{\ell}(\hat{r}_{A-a,a}) \right]^{(J^{\pi T})} \frac{\delta(r - r_{A-a,a})}{r r_{A-a,a}} r^2 dr$$

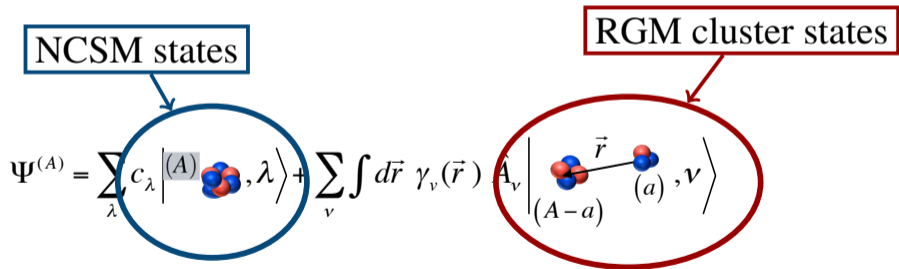
NCSM states

NCSM/RGM calculation of ^{12}C



No-Core shell model with continuum (NCSMC)

Put scattering (RGM) and bound state (NCSM) problems on equal footing



The diagram illustrates the decomposition of the total wave function $\Psi^{(A)}$ into two components:

- NCSM states:** Represented by a blue circle around the first term of the equation, $\sum_{\lambda} c_{\lambda} |(A), \lambda\rangle$. A blue box labeled "NCSM states" has an arrow pointing to this circle.
- RGM cluster states:** Represented by a red circle around the second term, $\sum_{\nu} \int d\vec{r} \gamma_{\nu}(\vec{r}) A_{\nu} |(A-a), (a), \nu\rangle$. A red box labeled "RGM cluster states" has an arrow pointing to this circle.

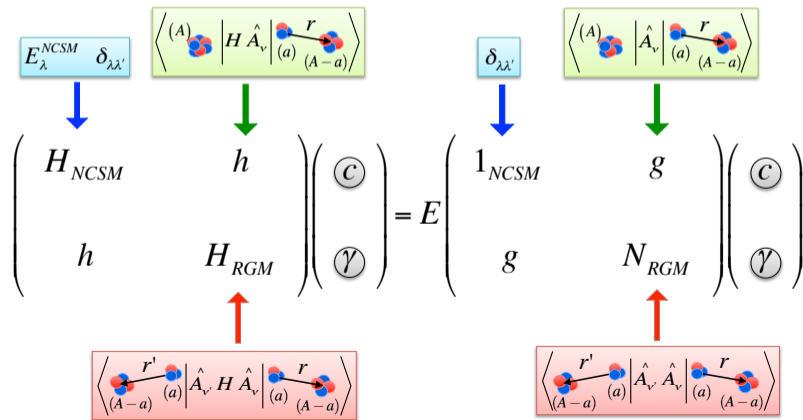
The equation is:

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

The diagram also includes a small 3D model of a nucleus with red and blue nucleons, and a cluster state diagram showing a nucleus of mass $(A-a)$ and a cluster of mass (a) separated by a distance \vec{r} .

No-Core shell model with continuum (NCSMC)

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

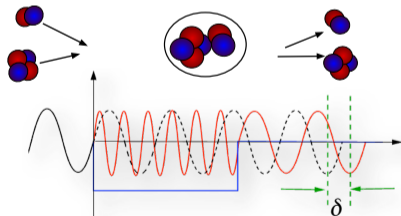


No-Core shell model with continuum (NCSMC)

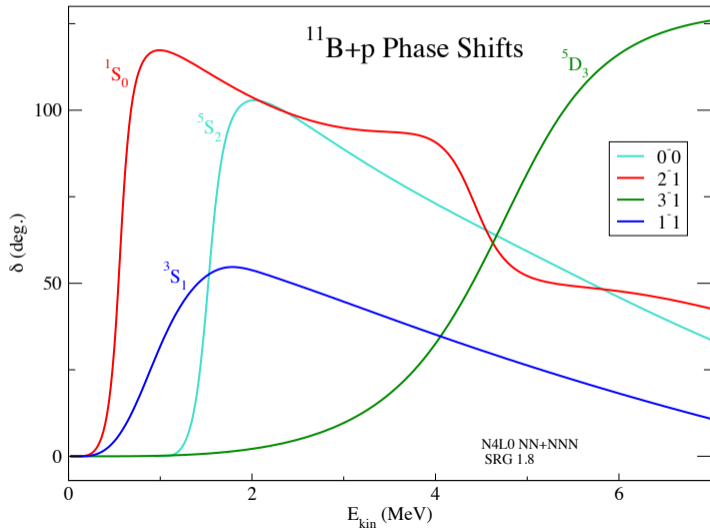
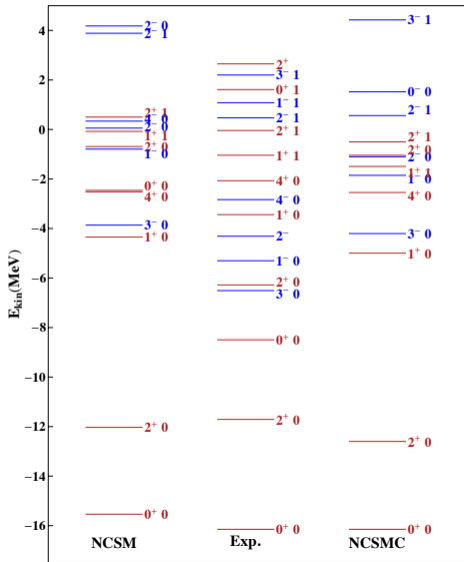
- Solve using R-matrix method on Lagrange mesh
- Get both bound state energies and phase shifts from scattering matrix

NCSMC calculation of ^{12}C

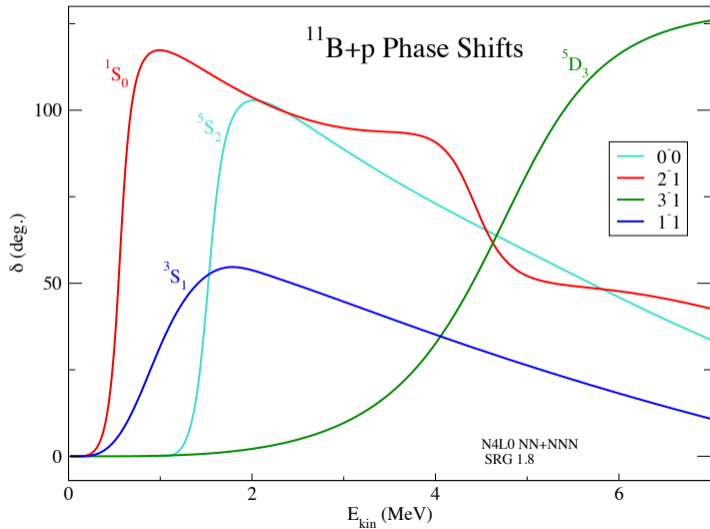
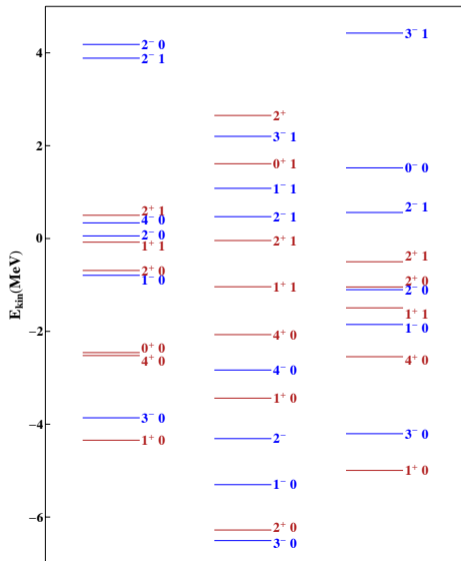
- NCSM: First 10 positive parity and first 6 negative parity states of ^{12}C
($N_{\text{max}} = 6/7$)
- RGM: First 2 negative parity states of ^{11}B plus proton ($N_{\text{max}} = 6$)



NCSMC calculation of ^{12}C



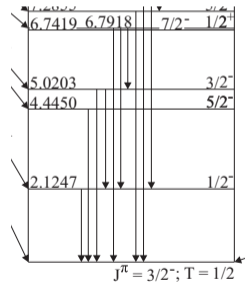
NCSMC calculation of ^{12}C



Summary

- Preliminary results for ^{12}C are promising
- Combining the $^{11}\text{B} + p$ cluster states with the ncsm basis improves the spectrum
- NCSMC calculation can be improved
 - Include the full 3N interaction
 - Include more of the NCSM states for both ^{11}B and ^{12}C

Thank you!



^{11}B



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Thank you!
Merci!

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