

Canada's national laboratory for particle and nuclear physics Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Ab Initio **Unified Approach to Nuclear Structure and Reactions**

INT Program INT 16-1 Nuclear Physics from Lattice QCD April 5, 2016

Petr Navratil | TRIUMF

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d operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada

- No-Core Shell Model with Continuum (NCSMC) approach
- Connection to nuclear lattice EFT
- N-⁴He scattering

TRIUMF

- ⁶Li structure & d-⁴He scattering
- ¹¹Be as a laboratory for testing of nuclear forces
- ¹¹N and ¹⁰C-p scattering
- ³He-⁴He and ³H-⁴He radiative capture

From QCD to nuclei

Nuclear structure and reactions

TRIUMF

To develop such a about the Chiral Effective Field Theory 1) Start with accurate nuclear forces (and currents)

- effective field theory and the summary contains the set Inter-nucleon forces from chiral
	- Based on the symmetries of QCD
		- Chiral symmetry of QCD $(m_u \approx m_d \approx 0)$, spontaneously broken with pion as the Goldstone boson
		- Degrees of freedom: nucleons + pions
	- Systematic low-momentum expansion to a given order $(Q/\Lambda_{\rm v})$
	- Hierarchy
	- Consistency
	- Low energy constants (LEC)
		- Fitted to data
		- Can be calculated by lattice QCD

Chiral symmetry breaking scale

From QCD to nuclei

RETRIUMF Unified approach to bound & continuum states; to nuclear structure & reactions

- *Ab initio* no-core shell model
	- Short- and medium range correlations
	- Bound-states, narrow resonances

Harmonic oscillator basis

From QCD to nuclei

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- ... with resonating group method
	- Bound & scattering states, reactions
	- Cluster dynamics, long-range correlations

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S. Baroni, P. Navratil, and S. Quaglioni, PRL **110**, 022505 (2013); PRC **87**, 034326 (2013).

Coupled NCSMC equations where \sim to be simultaneously determined by \sim to be simultaneously determined by \sim **by solving the coupled NCSMC equations**

asymptotic with microscopic *R*-matrix on Lagrange mesh 11 Scattoring matrix (and observables) from matching solutio Scattering matrix (and observables) from matching solutions to known

nuclei.
However, and the second se

owing to the exponential growth of the number of computational operations with the number of particles. Here we describe an

In recent years there has been much progress in *ab initio* scattering

technique called the 'adiabatic projection method' to reduce the eight-body system to a two-cluster system. We take advantage of

LETTER

Connection to nuclear lattice EFT jection we mean multiplication by exp(−*Hτ*), where *H* is the underlying microscopic Hamiltonian and *Connection to nuclea* units, where the reduced Planck constant ћ and the speed of light *c* notational simplicity. **COURECLION TO HUGIE** of three-dimensional vectors *R*, we project onto spherical harmonics with angular momentum $\mathbf x$ attice **EET** $\overline{\mathbf{u}}$ auclear lattice EFT radial excitations (2*s* and 3*s*) at NNLO using chiral EFT. The error bars systematic errors, we are currently working on including lattice nuclear **Forces and the chiral expansion in the chiral expansion of the chiral expansi** Ref. 22 Harmonic oscillator basis

doi:10.1038/nature16067 are set to one. Even though the actual lattice calculations use α time steps, we refer to the continuous Euclidean time parameter $\frac{1}{2}$ for \frac states |*R*〉, labelled by their separation vector *R*, as illustrated in Fig. 1. we take the initial alpha wavefunctions to be Gaussian wavefunctions to be Gaussian wavefunctions to be Gaussi
The initial alpha wavefunctions to be Gaussian wavefunctions to be Gaussian wavefunctions to be Gaussian wavefu **Figure 1** | **Initial state clusters.** Initial state |*R*〉 composed of two alpha- $\overline{\mathsf{d}}$ do scattering states, reactions states, reactions states, reactions states, $\overline{\mathsf{d}}$ do scattering states, $\overline{\mathsf{d}}$

to the energies of near-threshold states of 16O.

of systematic errors in the adiabatic projection method. If α

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adiabatic projection method and halo EFT. Therefore it might be

Scattering states Scattering states by fitting to the asymptotic behaviour of the radial wavefunction as in Scattering states range operators in the adiabatic Hamiltonian to make fine adjustments of the adiabatic Hamiltonian to make fine There is an obvious overlap between lattice calculations using the

 $W_{\rm eff}$ the radial adiabatic Hamiltonian defined in the large (120fm)33

show 1-standard deviation (s.d.) Monte Carlo errors calculated using

ref. 17; however, it is more accurate to extract the phase shifts from the

Figure 3 shows the phase shifts for *s*-wave scattering versus labo-

modes. In Fig. 2 we show *s*-wave radial functions for two different radii exclusive (2*s* and 3*s*) at N_n riard sprierical wall

ref. 17; however, it is more accurate to look for synergies between the two methods. In cases where \sim

hard spherical wall

Ab initio alpha-alpha scattering \overline{AB} **the low-energy interactions of protons and neutrons, and apply a** Ab initio alpha-alpha scattering. $\overline{1}$ $\overline{1}$ $\overline{1}$ $\overline{2}$ $\overline{3}$ $\overline{4}$ $\overline{5}$ $\overline{6}$ $\overline{2}$ $\overline{6}$ $\overline{2}$ $\overline{6}$ $\overline{2}$ $\overline{$ individual alpha clusters: $\overline{1}$ $\overline{1}$ nucleons. Therefore it remains a challenge to study many important *R*= |*R*| < *L*/2. **Figure 1** | **Initial state clusters.** Initial state |*R*〉 composed of two alpha-Each alpha-particle wave packet consists of four nucleons. Protons are red; nutro arpha-arpha scattering **Figure 3** *s* $\mathbf{A} \cdot \mathbf{A} = \mathbf{A} \cdot \mathbf{A} \cdot \mathbf{A}$ at LO (green) shifts. $\mathbf{A} \cdot \mathbf{A} = \mathbf{A} \cdot \mathbf{A} \cdot \mathbf{A}$ h-alpha scattering, and no energy *E*Lab, compared with experimental data19–22 (black asterisks). The **… to be simultaneously determined**

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Serdar Elhatisari¹, Dean Lee², Gautam Rupak³, Evgeny Epelbaum⁴, Hermann Krebs⁴, Timo A. Lähde⁵, Thomas Luu^{1,5} & Ulf-G. Meißner^{1,5,6} Ulf-G. Meißner 1,5,6 **Serdar Elhatis
LULC Meißne** Serdar Elhatisa
Luf C Moißne to a cubic subgroup. Nevertheless, at low scattering energies, this approx $r_{\text{max Luu}^{1.5}$ and $r_{\text{max Luu}^{1.5}}$ and spherical wall h_{hong} internal excitations, benchmark tests can be made benchmark tests can be made between h_{a} and h_{a} benchmark tests can be made between h_{a} and h_{a} benchmark tests of h_{a} and $h_{\text{a$ and the extrapolation of that data to infinite projection time. The green time \mathcal{L}

| 〉 = (∑ ′)*δ* | ′〉

0 2 4 6 8 10 12

particle wave packets on the lattice separated by the displacement vector *R*.

R R

| |′ ℓ ℓ *R Y*ℓ ℓ *R R*

, , *^z*

 $\mathcal{P}(\mathcal{P})=\mathcal{P}(\mathcal{P})$. We are some method with resonation $\mathcal{P}(\mathcal{P})$

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R

*p***-4He scattering within NCSMC**

Differential *p*-4He cross section with NN+3N potentials

R-matrix analysis of Ref. [16] leads to an overestimation of the cross section and triggered the search for new fitting parameters [15]. Except for the 2*.*4 MeV *E^p* 3*.*5

*n***-4He scattering within NCSMC**

n-4He scattering phase-shifts for chiral NN and NN+3N potential

Total *n*-4He cross section with NN and NN+3N potentials

RIUMF

Unified description of 6Li structure and d+4He dynamics

• Continuum and three-nucleon force effects on d+⁴He and ⁶Li

29 MAY 2015

Unified Description of ⁶Li Structure and Deuterium-⁴He Dynamics with Chiral Two- and Three-Nucleon Forces Guillaume Hupin,^{1,*} Sofia Quaglioni,^{1,†} and Petr Navrátil^{2,‡} Lawrence Livermore National Laboratory, P.O. Box 808, L-414, Livermore, California 94551, USA ²

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NCSMC N_{max}=11 (164)

 \overline{y} is the target. A typical example is the target. A typical example is the target. A typical example is the target.

 $\text{et al.} (168)$ (165) **particles** 1, 2 and 3. To calculate 1, 2 and 3. To calculate 1, 3. To calculate $\begin{bmatrix} 103 \end{bmatrix}$ $\left(1 - N \right)$ $\begin{bmatrix} \alpha, a \\ \alpha, a \end{bmatrix}$ in a factorization $\begin{bmatrix} 1 & 2 \\ 2 & 3 \end{bmatrix}$ fields is represented by the exorbitant number of \mathbb{R} $3N-1$ of \mathbb{Z} elements (see Fig. 1 of Ref. \mathbb{Z} we have to limit by specifying a maximum three-nucleon HO model space size E3max [25]. To minimize the ef- \sim such truncation we include 3 $\begin{array}{c} \begin{array}{c} \hline \end{array} \end{array}$ $\mathbb{E}_{\mathbf{a}}$ and continuous states are comparatively less demanding. The states are comparatively less demanding. The states \mathcal{L}_1 $R_{\rm max}$ and $\frac{1}{2}$ and $\frac{1}{2}$ $\frac{1}{10}$ force of Ref. [30], constrained to provide an accurate de-

 \mathbf{a} lts are found with as little as the as three deuteron \mathbf{a} pseudostates per channel. This is a strong reduction of the strong reduction o t_i (data) $\begin{bmatrix} 1 \\ \text{max} \end{bmatrix}$ eigenstates. Nonetheless, above the 2H breakup thresh- $(d)^4$ He 1 30° and 1 ing three-cluster basis states [24] in the ansazt of Eq. (1).

 Ω treatment of Ω \mathcal{L} and \mathcal{L} major technical and computational challenges. The first challenges. The first challenges. The first challenges. The first challenges of \mathcal{L}_1 is the derivation of the matrix elements of the matrix eleme between the continuous basis states of \mathbb{R} $\frac{10}{\pi}$

angles of angles of angles of angles of angles of the 30 and *d* energies compared with $\frac{1}{2}$ and $\frac{1}{2}$

Galonsky et al. (168) Mani et al. (165) Mani et al. (163)

Besenbacher et al. Browning et al. Kellock et al. Nagata et al. Quillet et al. (data) Quillet et al. (fit) NCSMC $N_{max} = 11$

> 1 $^{+}$

 $\overline{2}$ $^{+}$

 $\overline{}$

 \overline{a} ,

 $\frac{1}{2}$ 5 10

 $\frac{1}{2}$ 5 10 E_{α} [MeV]

7

 $\frac{1}{1+\frac{1}{2}}$

 $\overline{}$

3 $\overline{}$ 1 \blacksquare

 E_d [MeV]

 2.0×10^2

5.0×10²

 2.0×10^2

 5.0×10

 $\frac{\partial \sigma}{\partial \Omega_d}$ [mb/sr]

 1.0×10^{3}

 $\frac{1}{3}$ \mathbf{I} $\mathbf{1}$

FIG. 1. (Color online) Computed d-

 $q = \frac{4}{\pi} + \frac{4}{\pi} + \frac{4}{\pi}$

45

 $[\mbox{mb/sr}]$

 $\frac{1.0\times10^3}{E}$

 $\frac{1}{\infty}$

 1.0×10^{2} \bullet

an extension of the microscopic R-matrix theory [22, 23]. $\frac{1}{1}$ $\frac{2}{2}$ $\frac{1}{5}$

 ω -

state and the scattering matrix \mathbf{s} $\frac{1}{\sqrt{2}}$ and $\frac{1}{\sqrt{2}}$ with the solutions of Eq. (1) with the so

3 $+$

shifts at \mathbb{Z}^2 and \mathbb{Z}^2 and integrable 6Li eigenstates, as a function of the number of \sim $\begin{bmatrix} 2.0 \times 10^2 \end{bmatrix}$ N3LO NN potential (NN-only) with Λ = 2.0 fm−1 was used. NN-only with Λ = 2.0 fm = 2.0 fm = 2.0 fm = 2.0 fm = 2.0

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Ekim

d-4He data pseudostates de

 β β ⁺ (b) $\sqrt{\frac{N_{\text{CSMCN}_m}}{N_{\text{CSMCN}_m}}}$

ciated with the continuous basis states of 3 , and α (b) and α the operator (with Pi,j exchanging particles in \mathbb{R}

> *1 j=5

ensures its function. Finally, the unknown \mathcal{L} $\overline{}$ discrete coefficients, characteristic relations, characteristic relations, $\overline{}$ \mathbb{R} motion, and \mathbb{R} Schr¨odinger equation in the Hilbert space spanned by the

 $\sum_{i=1}^{n}$ binding $\sum_{i=1}^{n}$ ground state. This can be understand state. This can be understand state. This can be understanded by $\sum_{i=1}^{n}$ and $\sum_{i=1}^{n}$ and $\sum_{i=1}^{n}$ and $\sum_{i=1}^{n}$ and $\sum_{i=1}^{n}$ and $\frac{1}{2}$ stoch and a more existence of $\frac{1}{2}$ the clusterization of \mathcal{A} cle at long distances, which is harder to describe within $\frac{a^{\circ}}{b}$ and $\frac{a^{\circ}}{b}$, $\frac{a^{\circ}}{b}$, $\frac{a^{\circ}}{b}$, $\frac{a^{\circ}}{b}$ 1.0×10^2 $\frac{4}{1}$ for the absolute value of the $\frac{4}{10}$ extrapolating to E_d [MeV] **1** brings the E_d [MeV]

 $\begin{array}{c} \begin{array}{c} \bullet \\ \bullet \\ \bullet \end{array} \end{array}$

 $\overline{1}$ $\overline{1}$ $\overline{1}$ $\overline{2}$ $\overline{1}$ $\overline{2}$ $\overline{$

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force of Ref. [30], constrained to provide an accurate de-

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RIUMF

Unified description of ⁶Li structure and d+⁴He dynamics accrim † quaglioni1@llnl.gov [25] G. Hupin, J. Langhammer, P. Navr´atil, S. Quaglioni, Ire and d+*He dvnan [26] R. Roth, A. Calci, J. Langhammer, and S. Binder, Phys. Iacorini UGSCHDHOH OF EL SH U H. M. Hofmann, J. H. Kelley, C. G. Sheu, and H. R. [26] R. Roth, A. Calci, J. Langhammer, and S. Binder, Phys. Rev. and drand and a. The aynan and D. Boerma, Nucl. Phys. A 242, 265 (1975).

■ S- and D-wave asymptotic normalization constants Weller, Nucl. Phys. A 708, 3 (2002). D-wave asymptotic normali: -wavu asyii \mathbf{a} becomes a subset of \mathbf{a} becomes a subset of \mathbf{a} . an constants. A 397, 61 (1983). \mathbf{r} \sum wous courantation proposition -wave asymptotic normalization c [4] F. Hammache, M. Heil, S. Typel, D. Galaviz, [29] D. R. Entem and R. Machleidt, Phys. Rev. C 68, 041001 tion constants

29 MAY 2015

[1] D. R. Tilley, C. M. Cheves, J. L. Godwin, G. M. Hale,

mano, D. Cortina, H. Geissel, M. Hellstr¨om, N. Iwasa,

d+4He Scattering Phase Shifts [4] F. Hammache, M. Heil, S. Typel, D. Galaviz, ring, Phaea Shifte. I J. Kiener, P. Koczon, B. Kohlmeyer, P. Mohr, E. Schwab,

spanned only by the continuous basis states of Eq. (2) PRL 114, 212502 (2015) PHYSICAL REVIEW LETTERS week ending
29 MAY 2015

 $\mathcal{L}(\mathcal{G})$ NCSM (\mathcal{G}) NCSM (\mathcal{G}) $\mathcal{L}(\mathcal{G})$ is a set of \mathcal{G}) experiment in \mathcal{G} E_{X} = E_{X} ₂ C_0 [fm^{-1/2}] $-$ 2.695 2.91(9) [39] $-$ 2.93(15) [38] $\frac{135}{2}$ $\frac{135}{2}$ $\frac{1}{2}$ $\frac{1}{2$ 90 $\left[\begin{array}{ccc} & & \end{array}\right]$ $\left[\begin{array}{ccc} & & x & x \\ \hline C_2/C_0 & & -0.027 & -0.025(6)(10) & 39 \end{array}\right]$ 0.0003(9) [41] Eα+E^d [MeV] −30.52 −30.58 −30.61(4) −30.52 −30.520 C⁰ [fm[−]1/²] −− − 2.695 2.91(9) [39] 2.93(15) [38] [5] A. M. Mukhamedzhanov, L. D. Blokhintsev, and B. F. [6] M. Anders, D. Trezzi, R. Menegazzo, M. Aliotta, Ground-State Properties NCSM (10) NCSM (12) NCSM (∞) [37] NCSMC (10) Experiment C⁰ [fm[−]1/²] −− − 2.695 2.91(9) [39] 2.93(15) [38] C⁰ [fm[−]1/²] −− − 2.695 2.91(9) [39] 2.93(15) [38] REV. NO. 2007). erg. H. H. Roth, Phys. Rev. R. Roth, Phys. Ref. [14], lacking of square-integrable 6Linux of square-integrable 2.695 $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ -0.074 $-0.077(18)$ [39] $t_0 = -0.027$ $-0.025(6)(10)$ [39] 0.000 $[0.0003(9)$ |41|| of the phase shifts is maximal and Γ=2/δ′ (ER). [37] Extrapolated values E[∞] are obtained from fitting the [34] E. D. Jurgenson, P. Navr´atil, and R. J. Furnstahl, Phys. [35] R. Roth, J. Langhammer, A. Calci, S. Binder, and P. Navr´atil, Phys. Rev. Lett. 107, 072501 (2011). $\begin{bmatrix} 2 \ 2 \end{bmatrix}$ 2.695 2.91(9) [39] 2.93 -0.074 $-0.077(18)$ [3] $\sqrt{39}$ $-0.027 -0.025(6)(10)$ [39] 0.000 E(Nmax)=E∞+a exp(−b Nmax). -0.027 U_0 0.021 0.029 $(0)(10)$ |0 integrable ⁶Li eigenstates, as a function of the number of ²H \mathbf{t} influence with respect to the more limited study \mathbf{t} eigenstates. Nonetheless, above the ²H breakup thresh- $2.93(15)$ [38] $\left[\begin{array}{cc} 2.66(10) & [90] \end{array} \right]$ ing the ansa α in the ansazt of Eq. (1). malism to compute deuteron-nucleus collisions involves major technical and computational challenges. The first

[32] S. K. Bogner, R. J. Furnstahl, and R. J. Perry, Phys.

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- $\frac{2390}{1000}$ $\frac{(1993)}{H}$. $\frac{1}{200}$ $\frac{1}{200}$ [38] L. D. Blokhintsev, V. I. Kukulin, A. A. Sakharuk, $2390 (1993).$ [38] L. D. Blokhintsev, V. I. Kukulin, A. A. Sakharuk, α Tα; 2H λd $\ddot{\mathbf{r}}$ associated to $\ddot{\mathbf{r}}$ jectile with those of the target. A typical example is
- parenthesis is the Nmax value of the Nmax value of (1999) . $(1999).$ E. A. George and L. D. Knutson, Phys. Rev. C 59 , 598 [39] E. A. George and L. D. Knutson, Phys. R $(1999).$ σ by, by σ corresponds to *γγ*ργασία του γράψου του γρ
Στα συνεργασία του γράψου του γράψ
- 1. L. Drummer, K. W. Nemper, A. M. Elfo, F. D. Santos,
B. Kozlowska, H. J. Maier, and I. J. Thompson, Phys. Rev. Lett. **81**, 1187 (1998). is smaller. Compared to the best (Nmax = 12) NCSM $\frac{1}{2}$ smaller. Compared to the best $\frac{1}{2}$ $\left[41\right]$ K. D. Veal, C. R. Brune, W. H. Geist, H. J. Karwowski, H₁ H. D. Veal, Θ. H. Drame, W. H. Gels6, H. 9. Hal wowski,
E. J. Ludwig, A. J. Mendez, E. E. Bartosz, P. D. Cathers,
T. L. Drummer, K. W. Kemper, A. M. Eiró, F. D. Santos. 11. J. Drummer, K. W. Kemper, A. M. Eiró, F. D. Santos, T. L. Drummer, K. D. Drummer, K. W. Eiró, F. D. B. Eiró, F. D. B. Eiró, F. D. Santos, F. D. Santos, F. D. Santos,

[42] F. Besenbacher, I. Stensgaard, and P. Vase, Nucl. Instr.

tion. This and the ensuing underestimation of the splitting between the 2⁺ and 3⁺ states point to remaining

is not sufficient to correct for the slight overestimation in the slight overestimation in \mathbb{R}^n excitation energy already already observed in the NCSM calculation. This and the ensuing underestimation of the split-

is not sufficient to correct for the slight overestimation in excitation energy already observed in the NCSM calcula-

and 3D3−3G3 channels. Similar to our earlier study perfor \mathcal{A} soften a soften a soften but in a model space \mathcal{A}

Nmax=10(11) for positive (negative) parity channels. We adopt the HO frequency of 20 MeV around which the ⁶Li

Results. We adopt an Hamiltonian based on the chiral N3LO NN interaction of Ref. [29] and N²LO 3N force of Ref. [30], constrained to provide an accurate de-

g.s. energy calculated with the square-integrable basis \mathcal{L}_{max} Nmax=10(11) for positive (negative) parity channels. We N_{min} for positive energy contained by particle (negative) particle (negative) particle (negative) particle (negative) particle (negative) N_{min} (negative) N_{min} (negative) N_{min} (negative) N_{min} (nega Lawrence Livermore National Laboratory, P.O. Box 808, L-414, Livermore, California 94551, USA ²

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90, 061601 (2014).

PRL 114, 212502 (2015) PHYSICAL REVIEW LETTERS week ending 29 MAY 2015

Neutron-rich halo nucleus 11Be

• $Z=4$, N=7

- $-$ In the shell model picture g.s. expected to be $J^{\pi}=1/2^{-}$
	- Z=6, N=7 13 C and Z=8, N=7 15 O have J^{π}=1/2 g.s.
- In reality, 11Be g.s. is **J^π=1/2+** parity inversion
- Very weakly bound: E_{th} =-0.5 MeV
	- Halo state dominated by 10Be-n in the *S*-wave
- The 1/2 state also bound only by 180 keV
- Can we describe ¹¹Be in *ab initio* calculations?
	- Continuum must be included
	- Does the 3N interaction play a role in the parity inversion?

 $0s_{1/2}$ $Op_{3/2}$ $Op_{1/2}$ $1s_{1/2}$

TRIUMF

10C(p,p) @ IRIS with solid H₂ target

- New experiment at ISAC TRIUMF with reaccelerated ¹⁰C
	- The first ever ¹⁰C beam at TRIUMF
	- Angular distributions measured at $E_{CM} \sim 4.16$ MeV and 4.4 MeV

TRIUMF

p+10C scattering: structure of 11N resonances

- NCSMC calculations with **chiral NN+3N** (N3LO NN+N2LO 3NF400, NNLOsat)
	- $-$ p-¹⁰C + ¹¹N

 \Rightarrow *r* +

- $10C$: 0^+ , 2^+ , 2^+ NCSM eigenstates
- \cdot ¹¹N: ≥4 π = -1 and ≥3 π = +1 NCSM eigenstates

p+10C scattering: structure of 11N resonances

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p+10C scattering: structure of 11N resonances

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PETRIUMF

Structure of 11Be from chiral NN+3N forces

- NCSMC calculations including chiral 3N (N³LO NN+N²LO 3NF400)
	- $-$ n-¹⁰Be + ¹¹Be

 \Rightarrow *r* +

- $•¹⁰Be: 0⁺, 2⁺, 2⁺ NCSM eigenstates$ $\ddot{}$ 2
-
- 11 Be: ≥6 π = -1 and ≥3 π = +1 NCSM eigenstates \bullet ¹¹Be: ≥ 6 π = -1 4

*E*thr. [MeV] **TRIUMF** ¹¹Be within NCSMC: 9889
19Be: Niscrimination ar **Discrimination among chiral nuclear forces)** <u>Umman mortier</u>

 $\frac{1}{2}$ $\frac{1}{2}$ A. Calci, P. Navratil, G. Hupin, S. Quaglioni, R. Roth *et al.*, in preparation

*E*thr. [MeV] **TRIUMF** ¹¹Be within NCSMC: 9889
19Be: Niscrimination ar **Discrimination among chiral nuclear forces)** <u>Umman mortier</u>

 $\frac{1}{2}$ $\frac{1}{2}$

*E*thr. [MeV] **TRIUMF** ¹¹Be within NCSMC: 9889
19Be: Niscrimination ar **Discrimination among chiral nuclear forces)** <u>UTILI CITTLE DE L'ON CHAN</u>

 $\frac{1}{2}$ $\frac{1}{2}$

*E*thr. [MeV] **TRIUMF** ¹¹Be within NCSMC: 9889
19Be: Niscrimination ar **Discrimination among chiral nuclear forces)**

p+10C scattering: structure of 11N resonances

TRIUMF

A. Calci, P. Navratil, G. Hupin, S. Quaglioni, R. Roth *et al* with IRIS collaboration, in preparation

 \otimes TRIU *E*thr. [MeV]

Mirror nuclei¹¹Be and ¹¹N *Langhammer, Navrátil, Quaglioni, Hupin, Calci, Roth; Phys. Rev. C 91, 021301(R) (2015)*

NCSMC wave function UNIFIED *AB INITIO* APPROACH TO BOUND AND *...* PHYSICAL REVIEW C **87**, 034326 (2013)

$$
\Psi^{(A)} = \sum_{\lambda} c_{\lambda} |^{(A)}(A) \sum_{\nu} \mathbf{1}_{\nu} \mathbf{1}_{\nu} + \sum_{\nu} \int d\vec{r} \gamma_{\nu}(\vec{r}) \hat{A}_{\nu} | \mathbf{1}_{(A-a)} \overrightarrow{r} \mathbf{1}_{(a)} \gamma_{\nu} \rangle
$$

$$
\left|\Psi_{A}^{J^{\pi}T}\right\rangle = \sum_{\lambda} |A\lambda J^{\pi}T\rangle \bigg[\sum_{\lambda'} (N^{-\frac{1}{2}})^{\lambda\lambda'} \bar{c}_{\lambda'} + \sum_{\nu'} \int dr' \, r'^2 (N^{-\frac{1}{2}})^{\lambda}_{\nu' r'} \frac{\bar{\chi}_{\nu'}(r')}{r'} \bigg] + \sum_{\nu\nu'} \int dr \, r^2 \int dr' \, r'^2 \hat{\mathcal{A}}_{\nu} |\Phi_{\nu r}^{J^{\pi}T}\rangle \mathcal{N}_{\nu\nu'}^{-\frac{1}{2}}(r, r') \bigg[\sum_{\lambda'} (N^{-\frac{1}{2}})^{\lambda'}_{\nu' r'} \bar{c}_{\lambda'} + \sum_{\nu''} \int dr'' \, r''^2 (N^{-\frac{1}{2}})_{\nu' r'\nu'' r''} \frac{\bar{\chi}_{\nu''}(r'')}{r''}\bigg].
$$

νν′ i c be * *rr*′ − δνν′*Rn*ℓ(*r*)δ*nn*′*Rn*′ ^ℓ′(*r*′) expression borramore Asymptotic behavior $r \to \infty$:

$$
\overline{\chi}_{v}(r) \sim C_{v}W(k_{v}r) \qquad \overline{\chi}_{v}(r) \sim \overline{V}_{v}^{\frac{1}{2}}\Big[\delta_{vi}I_{v}(k_{v}r) - U_{vi}O_{v}(k_{v}r)\Big]
$$

* P *dr⁄′′ r²^{<i>n*} *r*² *l*²*<i>d***₁** *d***₂***<i>n***⁴** *d***₂***n***⁴** *d***₂***n***⁴** *d***₂***n***⁴** *d***₂***n***⁴** *d***₂***n***⁴** *b* and *blate*

Scattering state *SCATTER SCATTERING* state NCSMC equations are solved dividing the space into an **internal region,** *regional region* Scattering state Scattering matrix Scattering matrix

E1 transitions in NCSMC

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

$$
\vec{E1} = e \sum_{i=1}^{A-a} \frac{1 + \tau_i^{(3)}}{2} \left(\vec{r}_i - \vec{R}_{c.m.}^{(A-a)} \right) \qquad \mathcal{B}_{fi}^{E1} = \sum_{\lambda \lambda'} \frac{1 + \tau_j^{(3)}}{2} \left(\vec{r}_i - \vec{R}_{c.m.}^{(a)} \right) \qquad + e \frac{Z_{(A-a)}a - Z_{(a)}(A-a)}{A} \vec{r}_{A-a,a} \qquad + \sum_{\lambda'} \frac{Z_{(A-a)}a - Z_{(A)}(A-a)}{A} \vec{r}_{A-a,a} \qquad + \sum_{\lambda
$$

Unified ab initio *approaches to nuclear structure and reactions* 36

$$
\mathcal{B}_{fi}^{E1} = \sum_{\lambda\lambda'} c_{\lambda'}^{*f} \langle A\lambda' J_f^{\pi_f} T_f ||\mathcal{M}_1^{E} || A\lambda J_i^{\pi_i} T_i \rangle c_{\lambda}^i
$$

+
$$
\sum_{\lambda'\nu} \int dr r^2 c_{\lambda'}^{*f} \langle A\lambda' J_f^{\pi_f} T_f ||\mathcal{M}_1^{E} \hat{\mathcal{A}}_{\nu} || \Phi_{\nu r}^i \rangle \frac{\gamma_{\nu}^i(r)}{r} + \sum_{\lambda\nu'} \int dr' r'^2 \frac{\gamma_{\nu'}^{*f}(r')}{r'} \langle \Phi_{\nu' r'}^f || \hat{\mathcal{A}}_{\nu'} \mathcal{M}_1^{E} || A\lambda J_i^{\pi_i} T_i \rangle c_{\lambda}^i
$$

+
$$
\sum_{\nu\nu'} \int dr' r'^2 \int dr r^2 \frac{\gamma_{\nu'}^{*f}(r')}{r'} \langle \Phi_{\nu' r'}^f || \hat{\mathcal{A}}_{\nu'} \mathcal{M}_1^{E} \hat{\mathcal{A}}_{\nu} || \Phi_{\nu r}^i \rangle \frac{\gamma_{\nu}^i(r)}{r}.
$$

$$
\mathcal{M}_{1\mu}^{E} = e \sum_{j=1}^{A} \frac{1 + \tau_j^{(3)}}{2} \Big| \vec{r}_j - \vec{R}_{\text{c.m.}}^{(A)} \Big| Y_{1\mu} (r_j - \widehat{R}_{\text{c.m.}}^{(A)}) +
$$

Photo-disassociation of 11Be

NCSMC phenomenology where the simultaneously determined and a simulated by the simulated of the simulated **by solving the coupled NCSMC priems**

Photo-disassociation of 11Be

TRIUMF

Capture reactions important for astrophysics

Z

Z

^N ¹

3He-4He and 3H-4He scattering

!

J. Dohet-Eraly, P.N., S. Quaglioni, W. Horiuchi, G. Hupin, F. Raimondi, arXiv:1510.07717 [nucl-th]

NCSMC calculations with chiral SRG-N3LO *NN* potential (λ=2.15 fm-1)

³He, ³H, ⁴He ground state, $8(\pi -) + 6(\pi +)$ eigenstates of ⁷Be and ⁷Li

Preliminary: N_{max} =12, hΩ=20 MeV

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*M*1 contribution is essentially negligible and the *E*2 transitions

Figure ³He-⁴He and ³H-⁴He capture

E1 and **E2** transitions as well as L Dohet-Eraly, P.N., S. Qu Figure 3: The Government online in the Struck online the Section of the 3He
In the Saint-Struck for the 3He (1916) and the 3He (1916) and the Section of the 3He (1916) and the 3He (1916)
In the 3He (1916) and the 3He (1916 J. Dohet-Eraly, P.N., S. Quaglioni, W. Horiuchi, G. Hupin, F. Raimondi, arXiv:1510.07717 [nucl-th]

have been considered. For the energy ranges which are considered, The **E1 transitions is dominant with chiral SRG-N**³LO *NN* potential (λ=2.15 fm⁻¹) and from its phenomenological version and compared with other theoretical color (online) and old data are in light grey.

³He, ³H, ⁴He ground state, $8(\pi)$ + $6(\pi)$ eigenstates of ⁷Be and ⁷Li

Preliminary: *N*_{max}=12, hΩ=20 MeV

Theoretical calculations suggest that the most recent and precise *TBe and TLI data are inconsistent*

Z

³He-⁴He S-wave phase shifts

!

J. Dohet-Eraly, P.N., S. Quaglioni, W. Horiuchi, G. Hupin, F. Raimondi, arXiv:1510.07717 [nucl-th] σ : Donot Erary, 1711, O. Quagnoni, V. Hondoni, O. Haphi, 17 Kalinot $\sum_{i=1}^N \sum_{i=1}^N \sum_{i$ we can compare directly theoretical and experimental cross sec-

NCSMC calculations with chiral SRG-N³LO NN potential (λ=2.15 fm⁻¹) are considered; the *N*max value used for computing the colliding-nuclei wave \times fm -1 are displayed for displayed for displayed for \mathbb{R}

³He, ³H, ⁴He ground state, $8(\pi -) + 6(\pi +)$ eigenstates of ⁷Be and ⁷Li ergies and compared with experimental data from Ref. [55], for which no phase-shift analysis exists. Our approach reproduces \mathbb{R}

Preliminary: *N*_{max}=12, hΩ=20 MeV

the general trends of the experimental data.

To evaluate the impact of the discrepancies in the elastic scat-

 \mathbf{r}

] *N*max *a*1/2⁺ [fm]

- *Ab initio* calculations of nuclear structure and reactions is a dynamic field with significant advances
- We developed a new unified approach to nuclear bound and unbound states
	- Merging of the NCSM and the NCSM/RGM = **NCSMC**
	- Inclusion of three-nucleon interactions in reaction calculations for *A*>5 systems
	- Extension to three-body clusters (6He ~ 4He+*n*+*n*): NCSMC in progress

• Ongoing projects:

- Transfer reactions
- Sensitivity analysis of nuclear interactions for halo ¹¹Be and exotic ¹¹N
- Applications to capture reactions important for astrophysics
- Bremsstrahlung

• Outlook

RIUMF

- Alpha-clustering (4He projectile)
	- \cdot ¹²C and Hoyle state: 8 Be+⁴He
	- $16O: 12C+4He$