Halo Nuclei from Low-momentum Interactions

in collaboration with:
Nir Barnea, Gaute Hagen, Thomas Papenbrock and Achim Schwenk

Sonia Bacca | Theory Group | TRIUMF
Outline

• Why are halo nuclei interesting?

• Brief summary on experimental advances

• Overview of different theoretical approaches

• Our approach:
  - Use hyper-spherical harmonics for $^6$He
  - Use coupled cluster theory for $^8$He

• Results for binding energy and radii

• Using the EIHH to improve radii

• Summary and Outlook
Halo Nuclei

- One proton halo
- Two proton halo
- One neutron halo
- Two neutron halo
- Four neutron halo

$^{208}\text{Pb}$

$^{11}\text{Li}$

$^{48}\text{Ca}$
The helium isotope chain

\[ ^3\text{He} \quad ^4\text{He} \quad ^5\text{He} \quad ^6\text{He} \quad ^7\text{He} \quad ^8\text{He} \quad \ldots \]

- \( ^3\text{He} \) bound
- \( ^4\text{He} \) bound
- \( ^5\text{He} \) unbound
- \( ^6\text{He} \) bound halo
- \( ^7\text{He} \) unbound
- \( ^8\text{He} \) bound halo
The helium isotope chain

$^3\text{He}$  $^4\text{He}$  $^5\text{He}$  $^6\text{He}$  $^7\text{He}$  $^8\text{He}$

bound  bound  unbound  bound (halo)  unbound  bound (halo)

Borromean system

Most exotic nucleus "on earth"

$N \over Z = 3$

lives 806 ms  lives 108 ms
The helium isotope chain

Even if they are exotic short lived nuclei, they can be investigated experimentally. From a comparison of theoretical predictions with experiment we can test our knowledge on nuclear forces in the neutron rich region.

$N/Z = 3$
Halo Nuclei - Experiment
New Era of Precision Measurements for masses and radii

Mass measurement of $^8\text{He}$ with the Penning trap

Measurement of charge radii via isotope shift

$\delta \nu_{AA'} = \delta \nu_{A,A'}^{\text{mass}} + K \delta \langle r_{ch}^2 \rangle_{AA'}$

$\langle r_p^2 \rangle = \langle r_{ch}^2 \rangle - \langle R_p^2 \rangle - \frac{3}{4M_p^2} = \frac{N}{Z} \langle R_n^2 \rangle$

TRIUMF, Ryjkov et al. PRL 101, 012501 (2008)

ARGONNE, Wang et al. PRL 93, 142501 (2004)
Masses and radii of helium isotopes are important challenges for theory!

\[ \delta \nu_{AA'} = \delta \nu_{A,A'}^{mass} + K \delta \langle r_{ch}^2 \rangle_{AA'} \]

\[ \langle r_p^2 \rangle = \langle r_{ch}^2 \rangle - \langle R_p^2 \rangle - \frac{3}{4M_p^2} - \frac{N}{Z} \langle R_n^2 \rangle \]

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Halo Nuclei - Theory

Why are halo nuclei a challenge to theory?

• It is difficult to describe the long extended wave function

• They test nuclear forces at the extremes, where less is known
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Cluster models:

3-body models with phenomenological interactions

$^6\text{He}, ^{11}\text{Li} - \text{borromean systems}$

can do reactions, Faddeev calculations

but difficult to add core polarizations

Efros, Fedorov, Garrido, Hagino, Bertulani, ...
Why are halo nuclei a challenge to theory?

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Cluster models:

- 3-body models with phenomenological interactions
- $^6\text{He}, ^{11}\text{Li}$ - borromean systems
- can do reactions, Faddeev calculations
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New: Revived by halo EFT

Efros, Fedorov, Garrido, Hagino, Bertulani, ...
Halo Nuclei - Theory

Why are halo nuclei a challenge to theory?

• It is difficult to describe the long extended wave function
• They test nuclear forces at the extremes, where less is known

Ab-initio calculations: treat the nucleus as an A-body problem

full antisymmetrization of the w.f.

use modern Hamiltonians to predict halo properties

\[ H = T + V_{NN} + V_{3N} + \ldots \]

Methods: GFMC, NCSM, CC, HH
Ab-initio Calculations

GFMC
Quantum Monte Carlo Method, Uses local two- and three-nucleon forces
short range phenomenology

Argonne $\nu_{18}$
With Illinois-2

GFMC Calculations
6 November 2002

Pieper et al. (2002)
Ab-initio Calculations

GFMC
Quantum Monte Carlo Method, Uses local two- and three-nucleon forces

Argonne v\textsubscript{18}
With Illinois-2
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6 November 2002

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Pieper et al. (2002)

AV18 does not bind the helium halo with respect to 2n emission
Ab-initio Calculations

GFMC - Quantum Monte Carlo Method, Uses local two- and three-nucleon forces

Short range phenomenology

Avr. v_{18} with Illinois-2

GFMC Calculations

6 November 2002

\[ V_{ijk} = V_{ij}^{2\pi} + V_{ij}^{3\pi} + V_{ij}^{R} \]

Avr. v_{18} does not bind the helium halo with respect to 2n emission

Pieper et al. (2002)
Ab-initio Calculations

GFMC
Quantum Monte Carlo Method,
Uses local two- and three-nucleon forces

Argonne v$_{18}$
With Illinois-2
GFMC Calculations
6 November 2002

$V_{ijk} = V^{2\pi}_{ijk} + V^{3\pi,R}_{ijk} + V^{R}_{ijk}$

AV18
does not bind the helium halo with respect to 2n emission

IL2

N.B.: parameters of the IL2 force are obtained from a fit of 17 states of A<9 including the binding energy of $^6$He and $^8$He

Pieper et al. (2002)
- GFMC estimation of the proton radius -

Ab-initio Calculations

NCSM
Diagonalization Method using Harmonic Oscillator Basis
Can use non-local two- and three-nucleon forces

\[ \psi_{nl}(r) \sim e^{-\nu r^2} L_n^{1/2}(2\nu r^2) \quad \nu = m\omega/2\hbar \]

so far not for halo nuclei in large spaces
Navratil and Ormand, PRC 68, 034305 (2003),
\(^6\text{He AV8'+TM} \quad 6\hbar\omega\)

Helium Isotopes
Caurier and Navratil, PRC 73, 021302(R) (2006)

CD-Bonn \[ \rightarrow \] meson exchange theory

<table>
<thead>
<tr>
<th>( E_B ) [MeV]</th>
<th>Expt.</th>
<th>CD-Bonn 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^4\text{He})</td>
<td>28.296</td>
<td>26.16 (6)</td>
</tr>
<tr>
<td>(^6\text{He})</td>
<td>29.269</td>
<td>26.9 (3)</td>
</tr>
<tr>
<td>(^8\text{He})</td>
<td>31.408(7)</td>
<td>26.0 (4)</td>
</tr>
</tbody>
</table>

NN only with effective interaction (Lee-Suzuki)
Slow convergence and HO parameter dependence in radius
What we aim at

An ab-initio calculation of helium halo nuclei from chiral effective field theory potentials
Ideally we want:

- To use methods that enable to incorporate the correct asymptotic of the w.f. for loosely bound systems
- To obtain convergent calculations, with no dependence on the model space parameters
- To systematically study the cutoff (in)dependence of predicted observables
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- To use methods that enable to incorporate the correct asymptotic of the w.f. for loosely bound systems
- To obtain convergent calculations, with no dependence on the model space parameters
- To systematically study the cutoff (in)dependence of predicted observables

To facilitate convergence we use low-momentum interactions
Effective field theory potentials and low-momentum evolution $V_{\text{low } k}$ evolve to lower resolution (cutoffs) by integrating out high-momenta. Bogner, Kuo, Schwenk (2003) smooth cutoff. Bogner, Furnstahl, Ramanan, Schwenk (2007)

\[ H(\Lambda) = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + \ldots \]
Low momentum interactions

Effective field theory potentials and low-momentum evolution $V_{\text{low } k}$ evolve to lower resolution (cutoffs) by integrating out high-momenta Bogner, Kuo, Schwenk (2003)
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Low momentum interactions

Effective field theory potentials and low-momentum evolution $V_{\text{low } k}$ evolve to lower resolution (cutoffs) by integrating out high-momenta

$$H(\Lambda) = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + \ldots$$

Variation of the cutoff provides a tool to estimate the effect of short range 3N forces
Our Approach

• Hyper-spherical Harmonics Expansion for $^6$He

• Cluster Cluster Theory for $^8$He
Few-body method - uses relative coordinates

\[ \psi(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) = \phi(\vec{R}_CM) \Psi(\vec{\eta}_1, \vec{\eta}_2, \ldots, \vec{\eta}_{A-1}) \]

Recursive definition of hyper-spherical coordinates

\[ \rho, \Omega \]
\[ \rho^2 = \sum_{i=1}^{A} r_i^2 = \sum_{i=1}^{A-1} \eta_i^2 \]
\[ \vec{\eta}_0 = \sqrt{A} \vec{R}_{CM} \quad \vec{\eta}_1, \ldots, \vec{\eta}_{A-1} \]
Hyper-spherical Harmonics

- Few-body method - uses relative coordinates

\[ |\psi(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A)\rangle = |\varphi(\vec{R}_{CM})\Psi(\vec{\eta}_1, \vec{\eta}_2, \ldots, \vec{\eta}_{A-1})\rangle \]

Recursive definition of hyper-spherical coordinates

\[ \rho, \Omega \]
\[ \rho^2 = \sum_{i=1}^{A} r_i^2 = \sum_{i=1}^{A-1} \eta_i^2 \]

A=3

\[ \vec{\eta}_0 = \sqrt{A} \vec{R}_{CM} \quad \vec{\eta}_1, \ldots, \vec{\eta}_{A-1} \]

\[ \begin{cases} \vec{\eta}_1 = \{\eta_1, \theta_1, \phi_1\} \\ \vec{\eta}_2 = \{\eta_2, \theta_2, \phi_2\} \end{cases} \]

\[ \rho = \sqrt{\eta_1^2 + \eta_2^2} \]
\[ \sin \alpha_2 = \frac{\eta_2}{\rho} \]
Hyper-spherical Harmonics

- Few-body method - uses relative coordinates

\[
|\psi(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A)\rangle = |\varphi(\vec{R}_{CM})\Psi(\vec{\eta}_1, \vec{\eta}_2, \ldots, \vec{\eta}_{A-1})\rangle
\]

Recursive definition of hyper-spherical coordinates

\[
\rho, \Omega
\]

\[
\rho^2 = \sum_{i=1}^{A} r_i^2 = \sum_{i=1}^{A-1} \eta_i^2
\]

A=3

\[
\begin{align*}
\vec{\eta}_0 &= \sqrt{A} \vec{R}_{CM} \\
\vec{\eta}_1 &= \{\eta_1, \theta_1, \phi_1\} \\
\vec{\eta}_2 &= \{\eta_2, \theta_2, \phi_2\}
\end{align*}
\]

\[
\begin{align*}
\rho &= \sqrt{\eta_1^2 + \eta_2^2} \\
\sin \alpha_2 &= \frac{\eta_2}{\rho}
\end{align*}
\]

A=4

\[
\begin{align*}
\vec{\eta}_1 &= \{\eta_1, \theta_1, \phi_1\} \\
\vec{\eta}_2 &= \{\eta_2, \theta_2, \phi_2\} \\
\vec{\eta}_3 &= \{\eta_3, \theta_3, \phi_3\}
\end{align*}
\]

\[
\begin{align*}
\rho &= \sqrt{\eta_1^2 + \eta_2^2 + \eta_3^2} \\
\sin \alpha_2 &= \frac{\eta_2}{\rho} \\
\sin \alpha_3 &= \frac{\eta_3}{\rho}
\end{align*}
\]
Hyper-spherical Harmonics

- Few-body method - uses relative coordinates

\[ |\psi(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A)\rangle = |\varphi(\vec{R}_{CM})\Psi(\vec{\eta}_1, \vec{\eta}_2, \ldots, \vec{\eta}_{A-1})\rangle \]

Recursive definition of hyper-spherical coordinates

\[ \rho, \Omega \]

\[ \rho^2 = \sum_{i=1}^{A} r_i^2 = \sum_{i=1}^{A-1} \eta_i^2 \]

\[ H(\rho, \Omega) = T_\rho + \frac{K^2(\Omega)}{\rho^2} \]

\[ \Psi = \sum_{[K],\nu} c_{\nu}^{[K]} e^{-\rho/2} b_{\nu}^{n/2} L_\nu^{(\rho/4)} [Y_{[K]}(\Omega) \chi_{ST}] J_{\nu} \]

Asymptotic \( e^{-a\rho} \) \( \rho \to \infty \)

Model space truncation \( K \leq K_{max} \), Matrix Diagonalization

\[ \langle \psi|H_{(2)}|\psi\rangle = \frac{A(A-1)}{2} \langle \psi|H_{(A,A-1)}|\psi\rangle \]

Can use non-local interactions

Most applications in few-body; challenge in \( A>4 \)  

|ψ(\vec{r}_1, \vec{r}_2, ..., \vec{r}_A)\rangle = e^T \phi(\vec{r}_1, \vec{r}_2, ..., \vec{r}_A)\rangle \quad \text{reference SD} \quad T = \sum T_{(A)}

CCSD Equations

\begin{align*}
E &= \langle \phi | e^{-T} H e^T | \phi \rangle \\
0 &= \langle \phi^a_i | e^{-T} H e^T | \phi \rangle \\
0 &= \langle \phi^a_{ij} | e^{-T} H e^T | \phi \rangle
\end{align*}

Use it for $^8\text{He}$, closed shell nucleus

Asymptotic \quad \phi_i \sim e^{-k_i r_i} \quad r \to \infty

Model space truncation \quad N \leq N_{max}

Can use non-local interactions

Applicable to medium-mass nuclei
Results for binding energies
Benchmark on $^4$He

HH-CC-FY

$\Lambda = 2.0$ fm$^{-1}$

$E_{\text{exp}} = -28.296$ MeV

<table>
<thead>
<tr>
<th>Method</th>
<th>$\Lambda = 2.0$ fm$^{-1}$</th>
<th>$E_0(^4\text{He})$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faddeev-Yakubovsky (FY)</td>
<td></td>
<td>-28.65(5)</td>
</tr>
<tr>
<td>Hyperspherical harmonics (HH)</td>
<td></td>
<td>-28.65(2)</td>
</tr>
<tr>
<td>CCSD level coupled-cluster theory (CC)</td>
<td></td>
<td>-28.44</td>
</tr>
<tr>
<td>Lambda-CCSD(T) (CC with triples corrections)</td>
<td></td>
<td>-28.63</td>
</tr>
</tbody>
</table>
Helium Halo Nuclei

$V_{\text{low } k} \text{ NN from } N^3 \text{LO}$

$\Lambda = 2.0 \text{ fm}^{-1}$

$E_0 [\text{MeV}]$

$K_{\text{max}}$

$N_{\text{max}} = \text{Max}(2n + l)$

$\hbar \omega = 12 \text{ MeV}$

$\hbar \omega = 14 \text{ MeV}$

$\hbar \omega = 14 \text{ MeV}$

Helium Halo Nuclei

- Extrapolation -

\[ E(K_{max}) = E^\infty + Ae^{-BK_{max}} \]

<table>
<thead>
<tr>
<th>( \Lambda )</th>
<th>( E(K_{max} = 14) )</th>
<th>( E^\infty )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>(-30.13)</td>
<td>(-30.28(3))</td>
</tr>
<tr>
<td>2.0</td>
<td>(-29.13)</td>
<td>(-29.35(13))</td>
</tr>
<tr>
<td>2.4</td>
<td>(-26.91)</td>
<td>(-27.62(19))</td>
</tr>
</tbody>
</table>
Hilbert space: 15 major shell
Values in MeV

<table>
<thead>
<tr>
<th>$\Lambda$</th>
<th>$E[\text{CCSD}]$</th>
<th>$E[\text{Lambda-CCSD}(T)]$</th>
<th>$\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>-30.33</td>
<td>-31.21</td>
<td>0.88</td>
</tr>
<tr>
<td>2.0</td>
<td>-28.72</td>
<td>-29.84</td>
<td>1.12</td>
</tr>
<tr>
<td>2.4</td>
<td>-25.88</td>
<td>-27.54</td>
<td>1.66</td>
</tr>
</tbody>
</table>

- Triples corrections are larger for larger cutoff
- Their relative effect goes from 3 to 6%
Binding Energy Summary

$E_0$ [MeV]

-32
-31
-30
-29
-28
-27
-26
-25

$^6\text{He}$

HH

previous

$^8\text{He}$

$\Lambda$-CCSD(T)

previous

NCSM

GFMC

Experimental data

\begin{figure}
\centering
\includegraphics[width=\textwidth]{binding_energy_summary.png}
\caption{Binding Energy Summary}
\end{figure}
Binding Energy Summary

Experimental data

Our estimated error in neglected
For cutoff 2.0 fm\(^{-1}\) \(^4\)He and \(^6\)He are close to experiment, but \(^8\)He is under-bound.

Low momentum 3NF are overall repulsive in s-shell nuclei and nuclear matter, but two-pion exchange \(c_i\) are attractive in \(^4\)He and could provide further attractive spin-orbit (LS) contributions for the halo neutrons.

Experimental data

Our estimated error in neglected

- \(\Lambda = 1.8\) fm\(^{-1}\)
- \(\Lambda = 2.0\) fm\(^{-1}\)
- \(\Lambda = 2.4\) fm\(^{-1}\)
Results for radii
Radii for $^6$He
- Matter radius -

\[ r^2 = \frac{1}{A^2} \sum_{i<j} (r_i - r_j)^2 = \frac{1}{A} \rho^2 \quad \rightarrow \quad \text{rms radius} = \sqrt{\langle r^2 \rangle} \]

- Convergence in HH expansion is slow!

\[
V_{\text{low } k} \text{ NN from } N^3\text{LO}
\]

\[
\Lambda = 1.8 \text{ fm}^{-1} \\
\Lambda = 2.0 \text{ fm}^{-1} \\
\Lambda = 2.4 \text{ fm}^{-1}
\]
Radii for $^6$He
- Matter and proton radius -

$r^2 = \frac{1}{A^2} \sum_{i \neq j} (r_i - r_j)^2 = \frac{1}{A} \rho^2 \rightarrow \text{rms radius} = \sqrt{\langle r^2 \rangle}$

$r_p^2 = \frac{1}{ZA} \sum_{i \neq j} (r_i - r_j)^2 (q_i + q_j) - \frac{1}{A^2} \sum_{i < j} (r_i - r_j)^2 \rightarrow \ r_p = \sqrt{r_p^2}$

Vlowk NN from $N^3$LO $\Lambda=2.0 \text{ fm}^{-1}$
Radii for $^6\text{He}$

- Matter and proton radius -

\[ r^2 = \frac{1}{A^2} \sum_{i<j} (r_i - r_j)^2 = \frac{1}{A} \rho^2 \quad \rightarrow \quad \text{rms radius} = \sqrt{\langle r^2 \rangle} \]

\[ r_p^2 = \frac{1}{ZA} \sum_{i<j} (r_i - r_j)^2 (q_i + q_j) - \frac{1}{A^2} \sum_{i<j} (r_i - r_j)^2 \quad \rightarrow \quad r_p = \sqrt{r_p^2} \]

\[ \Lambda = 2.0 \text{ fm}^{-1} \]

- Proton radii converge better and are smaller than matter radii
- Halo structure
- Convergence is pretty slow. Can we improve it?
Introducing EIHH

Introduce $X$

$H \rightarrow H_{\text{eff}} = PXHX^{-1}P$

$H_{\text{eff}}$ is an A-body operator

For local potentials with a hard core

Barnea et al. PRC 61 (2000) 054001

Can be extended to nonlocal forces

Barnea et al., in preparation

Solve an a-body problem

Find $H_{\text{eff}}^a \rightarrow v_{ij}^{[a] \text{eff}}$

Use it into the A-body problem

$V = \sum_{ij} v_{ij}^{[2] \text{eff}}$

Increase the model space in the A-body problem
EIHH on $^4$He

- Convergence is sensibly accelerated both for energy and radius

$\Lambda = 2.0 \text{ fm}^{-1}$
EIHH on $^6$He

- Great improvement in convergence for both for energy and radius

$^6$He $V_{\text{lowk}}$ NN from $N^3$LO

- $\Lambda = 2.0$ fm$^{-1}$

- Bare
- EIHH
- Extrapolated from bare with error as in EPJ

$E_0$ [MeV]

$K_{\text{max}}$

$r_p$ [fm]

$K_{\text{max}}$

April 29 2010

Sonia Bacca
$^8$He with HH

$^8$He $V_{\text{lowk}}$ NN from N$^3$LO

- Difference between Bare and EIHH is about 2.4 MeV
- EIHH seems less effective than for $^6$He
\( ^8 \text{He} \ V_{\text{lowk}} \ \text{NN from } N^3 \text{LO} \)

- Difference between Bare and EIHH is about 2.4 MeV
- EIHH seems less effective than for \( ^6 \text{He} \)
\[ \Lambda - \text{CCSD(T) as in EPJ} \]

- Difference between Bare and EIHH is about 2.4 MeV
- EIHH seems less effective than for \(^6\text{He}\)

Extrapolating Bare results get:

\[ E_\infty = -31.49 \text{MeV} \]
\[ E_{\Lambda-\text{CCSD(T)}} = -31.21 \text{MeV} \]
Radii for $^8$He

$$r^2 = \frac{1}{A} \sum_i^A r_i^2$$

$\sqrt{\langle r^2 \rangle}$ matter radius

$$r_p^2 = \frac{1}{Z} \sum_i^A r_i^2 \left( \frac{1 + \tau_i^3}{2} \right)$$

$\sqrt{\langle r_p^2 \rangle}$ point-proton radius

$V_{\text{low } k} \text{ NN from N}^3\text{LO}$ $\Lambda=1.8 \text{ fm}^{-1}$

$\langle r^2 \rangle = \hbar \omega = 14\text{MeV}$

$V_{\text{low } k} \text{ NN from N}^3\text{LO}$ $\Lambda=2.0 \text{ fm}^{-1}$

$\langle r_p^2 \rangle = \hbar \omega = 14\text{MeV}$

- Large Hilbert space $\rightarrow$ small model space dependence
- Point-proton radius is smaller than matter radius $\rightarrow$ halo structure
- Operators are not translational invariant
Matter radii Summary

- Benchmark on $^4$He, CC using translational invariant operators

  $\Lambda = 2.0 \text{fm}^{-1}$  \quad \text{HH} \quad 1.434 \text{ fm}  \quad \Lambda - \text{CCSD(T)} \quad 1.429 \text{ fm}
Matter radii Summary

- Benchmark on $^4$He, CC using translational invariant operators

\[ \Lambda = 2.0 \text{ fm}^{-1} \]

- HH \hspace{1em} 1.434 \text{ fm} \hspace{1em} \Lambda - \text{CCSD(T)} \hspace{1em} 1.429 \text{ fm}

![Graph showing matter radii for $^4$He, $^6$He, and $^8$He with different values of $\Lambda$.]
Matter radii Summary

- Benchmark on $^4$He, CC using translational invariant operators

\[ \Lambda = 2.0 \text{fm}^{-1} \]  
HH $1.434$ fm  
$\Lambda - \text{CCSD(T)}$ $1.429$ fm
Proton radii Summary

from laser spectroscopy
using binding energy as input
Proton radii Summary

from laser spectroscopy using
binding energy as input

Our estimated error in neglected is in percentage consistent with the results for binding energy
The fact that for some “choice” of the NN force one gets correct radii and wrong energies (or vice-versa) shows that halo nuclei provide important tests of the different aspects of nuclear forces, which includes 3NF.
• We provide improved description of helium halo nuclei from evolved EFT interactions with the correct asymptotic in the wave function

• We estimate the effect of short range three-nucleon forces on binding energies and radii by varying the cutoff of the evolved interaction

• Our matter radii agree with experiment whereas our point-proton radii under-predict experiment

Future:

• Include three-nucleon forces

• Extend coupled cluster theory calculations to heavier neutron rich nuclei, e.g. lithium $^{11}\text{Li}$ or oxygen isotope chain