Using halo-EFT descriptions of nuclei within precise models of reactions

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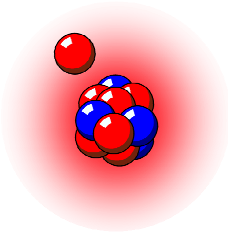
Halo nuclei

Halo nuclei are found far from stability

Exhibit peculiar quantal structure :

- Light, n-rich nuclei
- Low S_{n} or $S_{2\mathrm{n}}$



With large matter radius

due to strongly clusterised structure :

neutrons tunnel far from the core and form a diffuse halo

One-neutron halo

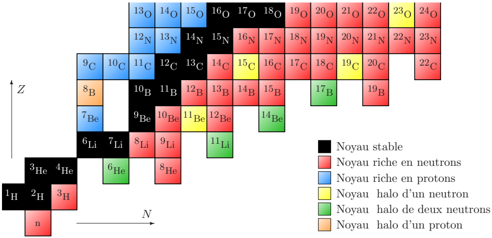
^{11}Be ≡ ^{10}Be + n

^{15}C ≡ ^{14}C + n

Two-neutron halo

^{6}He ≡ ^{4}He + n + n

^{11}Li ≡ ^{9}Li + n + n



This exotic structure challenges nuclear-structure models

Reactions with halo nuclei

Halo nuclei are fascinating objects

Some have been calculated *ab initio* [Calci *et al.* PRL 117, 242501 (2016)]

However difficult to study experimentally [$\tau_{1/2}(^{11}\text{Be}) = 13$ s]

How can one probe their structure ?
test the *ab initio* predictions ?

⇒ require indirect techniques, like reactions :

- breakup : ^{11}Be + Pb/C → ^{10}Be + n + Pb/C
- transfer : ^{10}Be(d,p)^{11}Be
- knockout : ^{11}Be + Be → ^{10}Be + X

Need good understanding of the reaction mechanism
(i.e. a good reaction model)
to know what nuclear-structure information is probed

Here, we couple precise reaction models with Halo EFT
(For a short review, see [P.C. Few Body Syst 63, 14 (2022)])

We consider ^{11}Be, the archetypical one-neutron halo nucleus

1. Introduction : halo nuclei

2. Description of ^{11}Be
   - Ab initio calculation of ^{11}Be
   - EFT description

3. Reactions with ^{11}Be
   - Coulomb breakup
   - Nuclear breakup
   - Transfer
   - KO

4. Summary

Ab initio description of ^{11}Be

NCSMC calculation of ^{11}Be [Calci *et al.* PRL 117, 242501 (2016)]

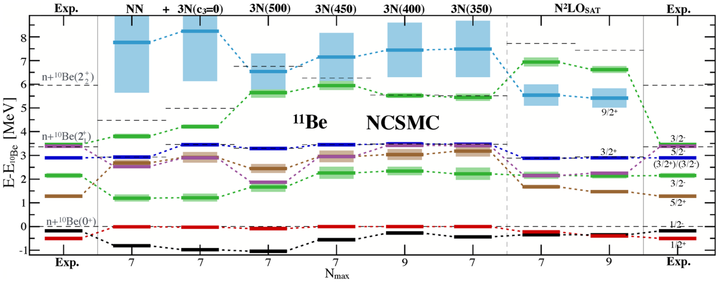


FIG. 2. NCSMC spectrum of ^{11}Be with respect to the $n + {}^{10}$Be threshold. Dashed black lines indicate the energies of the ^{10}Be states. Light boxes indicate resonance widths. Experimental energies are taken from Refs. [1,51].

- $\frac{1}{2}^+$ ground state :
  $\epsilon_{\frac{1}{2}^+} = -0.500$ MeV
  $C_{\frac{1}{2}^+} = 0.786$ fm$^{-1/2}$
  $\mathcal{S}_{1s\frac{1}{2}} = 0.90$
- $\frac{1}{2}^-$ bound excited state :
  $\epsilon_{\frac{1}{2}^-} = -0.184$ MeV
  $C_{\frac{1}{2}^-} = 0.129$ fm$^{-1/2}$
  $\mathcal{S}_{0p\frac{1}{2}} = 0.85$

Calci *et al.* also predict the ^{10}Be-n phaseshift

^{10}Be-n Halo-EFT potential

Replace ^{10}Be-n interaction by effective potentials in each partial wave

Use Halo EFT : clear separation of scales (in energy or in distance)
⇒ provides an expansion parameter (small scale / large scale)
along which the low-energy behaviour is expanded

[C. Bertulani, H.-W. Hammer, U. Van Kolck, NPA 712, 37 (2002)]
[H.-W. Hammer, C. Ji, D. R. Phillips JPG 44, 103002 (2017)]

Use narrow Gaussian potentials @ NLO

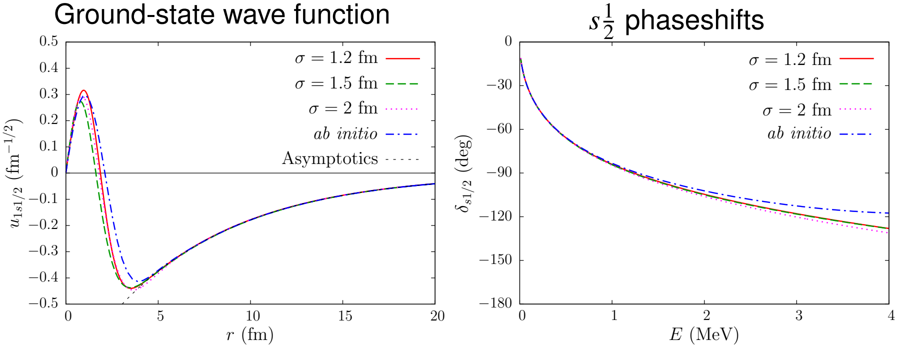
$$V_{lj}(r) = V_0^{lj}\, e^{-\frac{r^2}{2\sigma^2}} + V_2^{lj}\, r^2 e^{-\frac{r^2}{2\sigma^2}}$$

- In $s\frac{1}{2}$ and $p\frac{1}{2}$: fit V_0^{lj} and V_2^{lj} to reproduce
  - ϵ_{nlj} (known experimentally)
  - C_{nlj} (predicted *ab initio*) [Calci *et al.* PRL 117, 242501 (2016)]
- $V_{p3/2} = 0$ to reproduce *ab initio* $\delta_{3/2^-} \sim 0$
- For $l > 1$: $V_{lj} = 0$ @ NLO

$\sigma = 1.2$, 1.5 or 2 fm used to evaluate the sensitivity of calculations to short-range physics

$s\frac{1}{2}$: @ NLO potentials fitted to $\epsilon_{\frac{1}{2}^+}$ and $C_{\frac{1}{2}^+}$

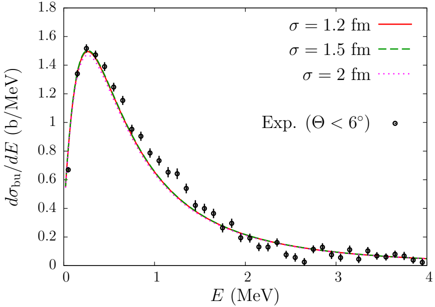
Potentials fitted to $\epsilon_{1s\frac{1}{2}} = -0.503$ MeV and $C_{1s\frac{1}{2}} = 0.786$ fm$^{-1/2}$



- Wave functions : same asymptotics but different interior
- $\delta_{s\frac{1}{2}}$: all effective potentials are in good agreement with *ab initio* up to 1.5 MeV (same effective-range expansion)
- Similar results obtained for $p\frac{1}{2}$ (excited bound state)

Coulomb breakup : ^{11}Be+Pb→^{10}Be+n+Pb

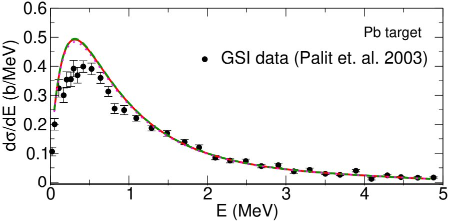
RIKEN : $69A$ MeV



Exp : [Fukuda *et al.* PRC 70, 054606 (2004)]

Th. : [P.C., Phillips & Hammer, PRC 98, 034610]

GSI : $520A$ MeV



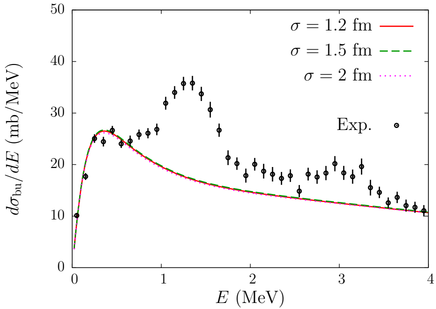
Exp : [Palit *et al.* PRC 68, 034318 (2003)]

Th. : [Moschini & P.C. PLB 790 367 (2019)]

- All calculations provide very similar results for all σ
  despite the difference in the internal part of the wave function
  ⇒ reaction is peripheral [P.C. & Nunes PRC75, 054609 (2007)]
- Excellent agreement with data (no fitting parameter)
  ⇒ confirms *ab initio* ANC and phaseshift

Nuclear breakup : ^{11}Be+C→^{10}Be+n+C

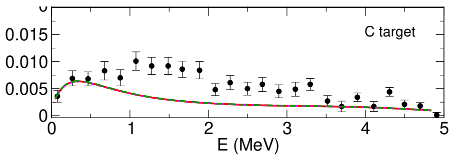
RIKEN : $67A$ MeV



Exp : [Nakamura *et al.* PRC 70, 054606 (2004)]

Th. : [P.C., Phillips & Hammer, PRC 98, 034610]

GSI : $520A$ MeV



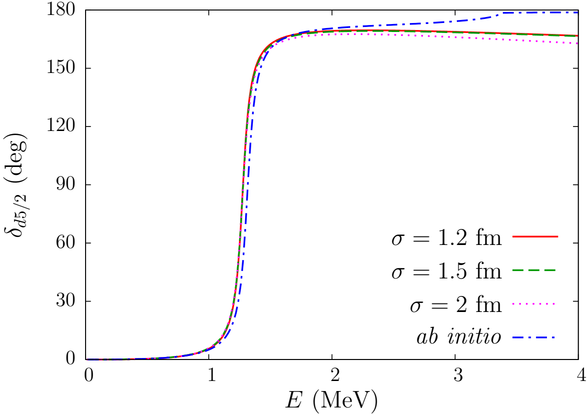
Exp : [Palit *et al.* PRC 68, 034318 (2003)]

Th. : [Moschini & P.C. PLB 790 367 (2019)]

- All potentials produce very similar breakup cross sections
  ⇒ still peripheral (even if nuclear dominated)
  [P.C. & Nunes PRC 75, 054609 (2007)]
- Order of magnitude of experiment well reproduced
- Breakup strength missing at the $5/2^+$ and $3/2^+$ resonances

⇒ for this observable, the continuum must be better described

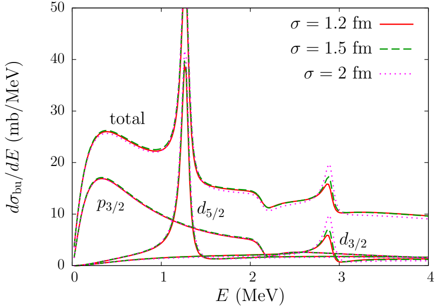
$d\frac{5}{2}$: potentials fitted to $\epsilon^{\rm res}_{\frac{5}{2}^+}$ and $\Gamma_{\frac{5}{2}^+}$



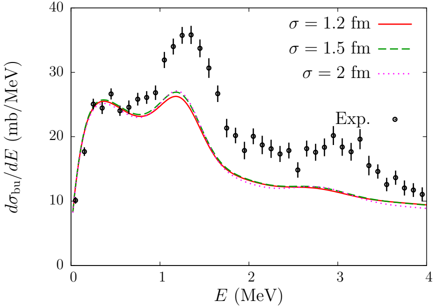
- Identical $\delta_{d\frac{5}{2}}$ up to 1.5 MeV
  up to 5 MeV for the narrow potentials (σ = 1.2 or 1.5 fm)
- Excellent agreement with ab initio results up to 2 MeV

^{11}Be+C→^{10}Be+n+C @ 67AMeV (beyond NLO)

Total breakup cross section and dominant contributions



Folded with energy resolution [Fukuda *et al.* PRC 70, 054606 (2004)]



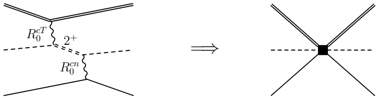
- All potentials produce similar breakup cross sections
- In nuclear breakup, resonances play significant role

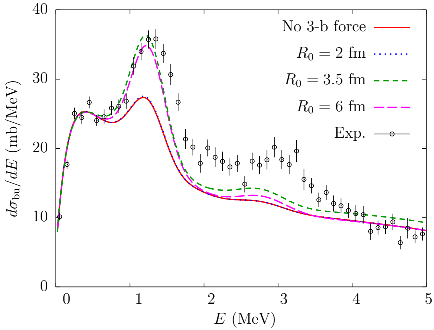
  [P.C., Goldstein & Baye PRC 70, 064605 (2004)]
- Still, resonant breakup not correctly described
  degrees of freedom [$^{10}\mathrm{Be}(2^+)$] missing in the effective model

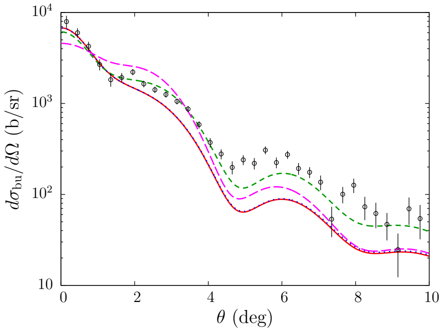
  [Moro & Lay PRL 109, 232502 (2012)]

Simulating core excitation with 3-b force

Virtual excitation of ^{10}Be(2^+)
can be simulated by 3 body force :





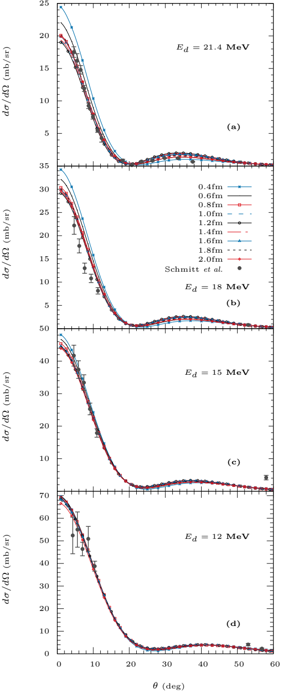


- 3-b force can efficiently simulate ^{10}Be excitation

  [P.C., Phillips & Hammer PLB 825, 136847 (2022)]
- The range in the c-T distance should equal that of V_{cT} ($R_0 = 3.5$ fm)
  - too small ($R_0 = 2$ fm) : no effect
  - too large ($R_0 = 6$ fm) : erroneous angular distribution

^{10}Be(d,p)^{11}Be

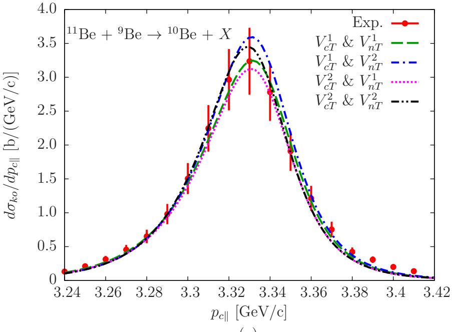
- This idea can be extended to transfer
  [Yang & P.C. PRC 98, 054602 (2018)]
- Various descriptions of ^{11}Be (@ LO)
  with $\sigma = 0.4 - 2.0$ fm
  show that ^{10}Be(d,p)^{11}Be is peripheral
  at fwd angle and low E_d
- This enables to reliably infer ^{11}Be ANC
  Provides a value identical to *ab initio*
- Excellent agreement with data
  Schmidt *et al.* PRL 108, 192701 (2012)]



^{11}Be+^{9}Be→^{10}Be+X @ 60AMeV

Using Halo-EFT within eikonal model of KO gives also good results

[Hebborn & P.C. PRC 100, 054607 (2019), *ibid* 104, 024616 (2021)]



(a)

- Excellent agreement with experiment [Aumann PRL 84, 35 (2000)]
- Different wave functions with same ANC give same cross section ⇒ reaction purely peripheral
- Insensitive to description of continuum ⇒ good probe of ANC

Summary and prospect

- Halo nuclei studied mostly through reactions
- Mechanism of reactions with halo nuclei understood

  How can we relate *ab initio* calculations to reaction observables ?

  Halo EFT : [P.C., Phillips, Hammer, PRC 98, 034610 (2018)]

  Efficient way to include the significant degrees of freedom
- Using one Halo-EFT description of ^{11}Be, we reproduce
  - Coulomb and nuclear breakup :
    - $70A$ MeV : [P.C., Phillips, Hammer, PRC 98, 034610 (2018)]
    - $520A$ MeV : [Moschini & P.C. PLB 790 367 (2019)]
  - ^{10}Be(d,p) : [Yang & P.C., PRC 98, 054602 (2018)]
  - KO : [Hebborn, P.C., PRC 104, 024616 (2021)]
- These reactions are peripheral ⇒ sensitive to ANC and phaseshifts
- Validate the *ab initio* predictions
- Same results on ^{15}C : [Moschini, Yang & P.C., PRC 100, 044615 (2019)]
- Future :
  - Extend to other nuclei (e.g., ^{31}Ne)
  - Include core excitation in Halo EFT

Thanks to my collaborators

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