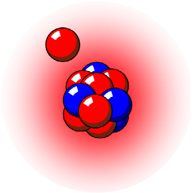
From *ab initio* structure predictions to reaction calculations via effective field theory

P. Capel, D. Phillips, H.-W. Hammer and L. Moschini

5 June 2018

Introduction

Halo nuclei are exotic nuclei
with large matter radius :
seen as a compact core
+ one or two loosely bound neutrons



Ex. : ^{11}Be ≡ ^{10}Be + n, ^{6}He ≡ ^{4}He + n + n
⇒ challenging for nuclear-structure models
Recently ^{11}Be has been computed *ab initio* by Calci *et al.*
[PRL 117, 242501 (2016)]

How can we test their prediction ?

$\tau_{1/2}(^{11}\text{Be}) = 13$ s ⇒ studied by reactions like breakup
Breakup ^{11}Be→^{10}Be + n has been measured on Pb and C

- $70A$MeV @ RIKEN [Fukuda *et al.* PRC 70, 054606 (2004)]
- $520A$MeV @ GSI [Palit *et al.* PRC 68, 054606 (2003)]

Using *ab initio* wave function in reaction calculation is too heavy
⇒ we use a Halo-EFT description of ^{11}Be fitting the *ab initio* outputs

1. Reaction model

2. Halo-EFT description of ^{11}Be

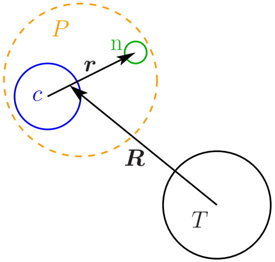
3. Breakup calculations of ^{11}Be into ^{10}Be+n
   - RIKEN experiment $70A$MeV
   - GSI experiment $520A$MeV

4. Summary

Framework

Projectile (P) modelled as a two-body nucleus :
core (c)+loosely bound neutron (n) described by

$$H_0 = T_r + V_{c\mathrm{n}}(\boldsymbol{r})$$



$V_{c\mathrm{n}}$ effective interaction
describes the c-n system
with ground state Φ_0

Target T seen as structureless

Interaction with target simulated by optical potentials
⇒ breakup reduces to three-body scattering problem :

$$[T_R + H_0 + V_{cT} + V_{\mathrm{n}T}]\,\Psi(\boldsymbol{r},\boldsymbol{R}) = E_T\Psi(\boldsymbol{r},\boldsymbol{R})$$

with initial condition $\Psi(\boldsymbol{r},\boldsymbol{R}) \underset{Z\to-\infty}{\longrightarrow} e^{iKZ}\Phi_0(\boldsymbol{r})$

We use the Dynamical Eikonal Approximation (DEA)

[Baye, P. C., Goldstein, PRL 95, 082502 (2005)]

Ab initio description of ^{11}Be

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

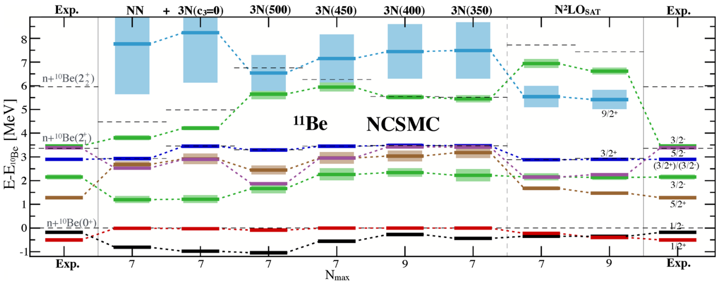


FIG. 2. NCSMC spectrum of ^{11}Be with respect to the $n + {}^{10}$Be threshold. Dashed black lines indicate the energies of the ^{10}Be states. Light boxes indicate resonance widths. Experimental energies are taken from Refs. [1,51].

- $\frac{1}{2}^+$ ground state :
  $\epsilon_{\frac{1}{2}^+} = -0.500$ MeV
  $C_{\frac{1}{2}^+} = 0.786\ \mathrm{fm}^{-1/2}$
  $\mathcal{S}_{1s\frac{1}{2}} = 0.90$

- $\frac{1}{2}^-$ bound excited state :
  $\epsilon_{\frac{1}{2}^-} = -0.184$ MeV
  $C_{\frac{1}{2}^-} = 0.129\ \mathrm{fm}^{-1/2}$
  $\mathcal{S}_{0p\frac{1}{2}} = 0.85$

Halo-EFT description of ^{11}Be

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

Original idea : Bertulani, Hammer, Van Kolck, NPA 712, 37 (2002)
Review : Hammer, Ji, Phillips JPG 44, 103002 (2017)

Use narrow Gaussian potentials

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

Fit V_0^{lj} and V_2^{lj} to reproduce ϵ_{nlj}, and C_{nlj} (@ NLO)

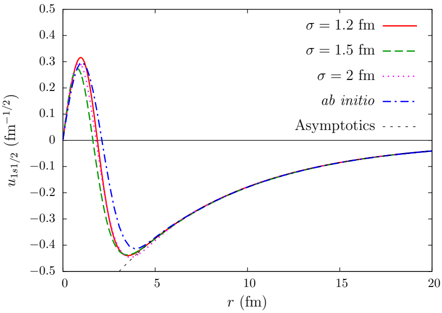
$\sigma =$ 1.2, 1.5 or 2 fm is a parameter used to evaluate the sensitivity of the calculations to this effective model

ϵ_{nlj} is known experimentally, but what about C_{nlj} ?
Fortunately, for ^{11}Be, we've got the *ab initio* calculation of Calci *et al.*
[A. Calci *et al.* PRL 117, 242501 (2016)]

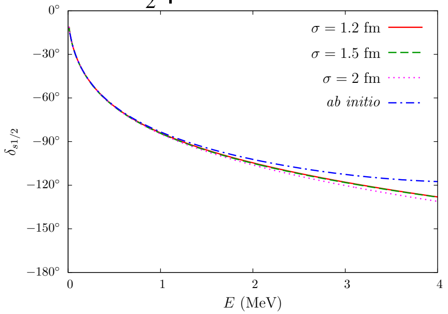
$s\frac{1}{2}$: @ NLO potentials fitted to $\epsilon_{\frac{1}{2}^+}$ and $C_{\frac{1}{2}^+}$

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

Ground-state wave function



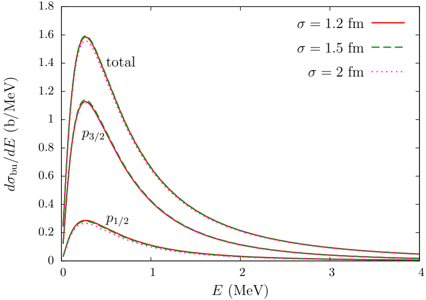
$s\frac{1}{2}$ phaseshifts



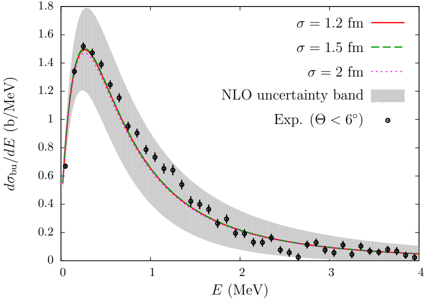
- Wave functions : same asymptotics but different interior
- $\delta_{s\frac{1}{2}}$: all effective potentials are in good agreement with *ab initio* up to 1.5 MeV (same effective-range expansion)
- Similar results obtained for $p\frac{1}{2}$ (excited bound state)

NLO analysis of ^{11}Be+Pb→^{10}Be+n+Pb @ 69AMeV

Total breakup cross section and p contributions

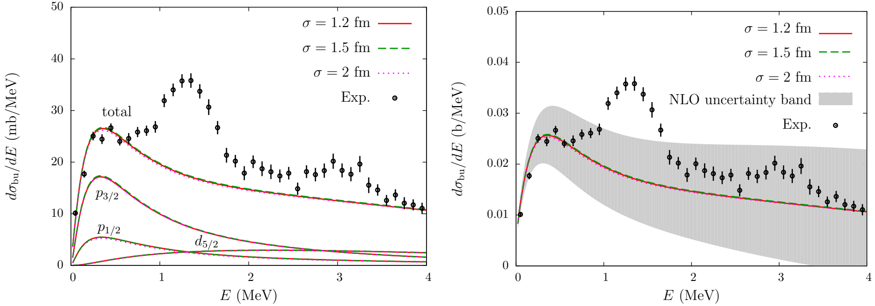


Folded with experimental resolution



- All calculations provide very similar results, for all σ, despite difference in internal part of wave function $\Rightarrow$ reaction is peripheral
- Excellent agreement with data [Fukuda *et al.* PRC 70, 054606 (2004)]

NLO analysis of ^{11}Be+C→^{10}Be+n+C @ 67AMeV



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

- All potentials produce very similar breakup cross sections
  ⇒ still peripheral (even if nuclear dominated)

  [Nunes, P. C. PRC 75, 054609 (2007)]
- Order of magnitude of experiment well reproduced
- Breakup strength missing at the $5/2^+$ and $3/2^+$ resonances

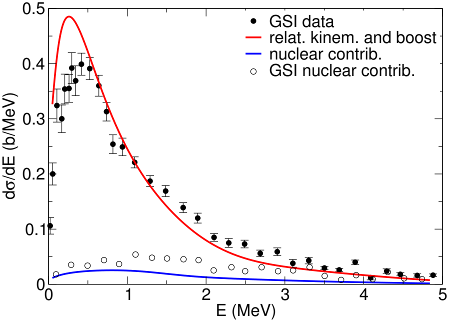
⇒ for this observable, the continuum must be better described

NLO analysis of GSI data @ 520AMeV

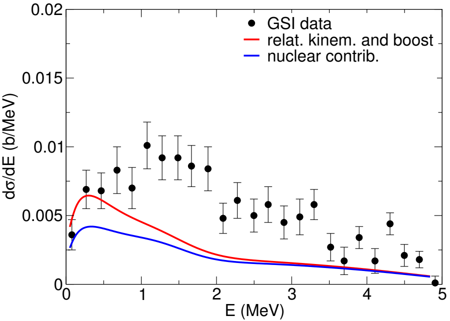
Using the same NLO description of ^{11}Be ($\sigma = 1.2$ fm)
and an eikonal description of reaction, with relativistic corrections
we compare our calculations to Palit *et al.* PRC 68, 054606 (2003)

Calculations by L. Moschini

^{11}Be+Pb→^{10}Be+n+Pb



^{11}Be+C→^{10}Be+n+C



- On Pb : Fair agreement with data, problem at low E (?)
- On C : good order of magnitude (missing resonances)

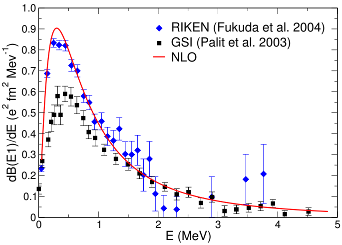
Summary

We have coupled a Halo-EFT description of ^{11}Be
with an accurate model of breakup

- ⇒ constrain the projectile description to *ab initio* outputs
  - identify the most significant degrees of freedom (ANC, δ_l)
  - and the missing ones (resonances in nuclear breakup)
- Good agreement with data (RIKEN and GSI)
  - validates the prediction of Calci *et al.*
  - one description of ^{11}Be can reproduce both data sets

  What about $dB(\mathrm{E1})/dE$ then ?

Halo-EFT



Calci *et al.* PRL 117, 242501 (2016)