Sensitivity of one-neutron knockout of halo nuclei to their nuclear structure

[arXiv :1906.07660]

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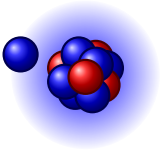
Introduction

- **Halo nuclei** exhibit a very large matter radius
  Compact core + one or two loosely-bound neutrons
  Ex : $^{11}\mathrm{Be} \equiv {}^{10}\mathrm{Be} + n,\ {}^{15}\mathrm{C} \equiv {}^{14}\mathrm{C} + n$

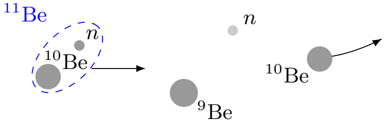
  Short-lived : studied through **reactions processes**
  (elastic scattering, **breakup**,...)



- **Knockout**

  Measurement of only the core
  ⇒ more statistics

  2 contributions : $\sigma = \sigma_{\mathrm{diff}} + \sigma_{\mathrm{strip}}$



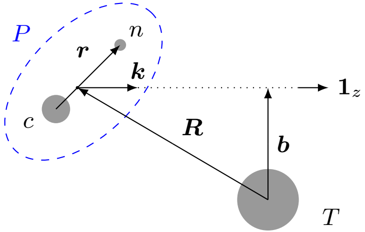
[J. A. Tostevin *et al.*, PRC **66**, 024607 (2002)]

What can we probe with knockout ?

1. Ground-state wavefunction and which part ?
2. Presence of excited state ?
3. Description of the continuum ?

Reaction model :

- Two-body projectile (P) :
  $P \equiv$ core (c) + neutron (n)
  Internal Hamiltonian : $h_{cn} = T_r + V_{cn}(r)$
  V_{cn} effective potential



- Structureless target (T)
- $P - T$ interactions : optical potentials V_{cT} and V_{nT}

Three-body Schrödinger equation :

$$[T_R + h_{cn} + V_{cT} + V_{nT}]\,\Psi(\boldsymbol{R}, \boldsymbol{r}) = E\,\Psi(\boldsymbol{R}, \boldsymbol{r})$$

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

where Φ_0 is the ground state of P : $h_{cn}\Phi_0 = \epsilon_0\Phi_0$

Three-body Schrödinger equation :

$$[T_R + h_{cn} + V_{cT} + V_{nT}]\,\Psi(\boldsymbol{R},\boldsymbol{r}) = E\,\Psi(\boldsymbol{R},\boldsymbol{r})$$

① Eikonal approximation : at high energy, $\Psi \approx$ plane wave (e^{iKZ})

Factorization : $\Psi(\boldsymbol{R},\boldsymbol{r}) = e^{iKZ}\,\widehat{\Psi}(\boldsymbol{R},\boldsymbol{r})$ with $|\Delta_{\mathbf{R}}\widehat{\Psi}| \ll K\left|\frac{\partial}{\partial Z}\widehat{\Psi}\right|$

② Adiabatic approximation : $h_{cn} \approx \epsilon_0$

$$\boxed{\Psi^{\rm eik}(\boldsymbol{b},Z,\boldsymbol{r}) \underset{Z\to+\infty}{\longrightarrow} e^{iKZ} e^{i\chi(\boldsymbol{b},\boldsymbol{r})}\Phi_0(\boldsymbol{r}),}$$

with $\chi(\boldsymbol{b},\boldsymbol{r}) = -\frac{1}{\hbar v}\int_{-\infty}^{+\infty}[V_{cT}(\boldsymbol{b}_{\boldsymbol{cT}},Z) + V_{nT}(\boldsymbol{b}_{\boldsymbol{nT}},Z)]\,dZ$

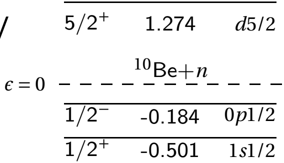
[R. J. Glauber, *High energy collision theory*, (1959).]

Advantages :

⊕ **Fast** computations

⊕ **Easy** interpretation : P follows a **straight-line**

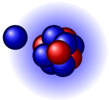
Test case $^{11}\mathrm{Be} + {}^{12}\mathrm{C} \to {}^{10}\mathrm{Be} + X$ @ $68A$ MeV



^{11}Be spectrum

$\underline{^{11}\mathrm{Be}\ :}$ g.s. $\epsilon_{1/2^+} = -0.501$ MeV
e.s. $\epsilon_{1/2^-} = -0.184$ MeV

Halo-EFT : uses the **separation of scale** to expand low-energy behaviour with $R_{\mathrm{core}}/R_{\mathrm{halo}} \sim 0.4$



[H.-W. Hammer *et al.* , JPG **44**, 103002 (2017)]

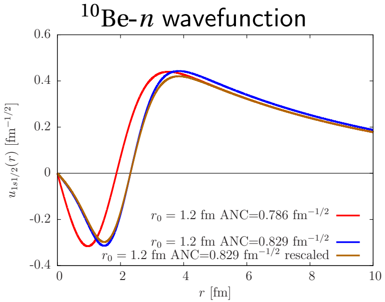
→ effective potential in **each** partial wave lJ

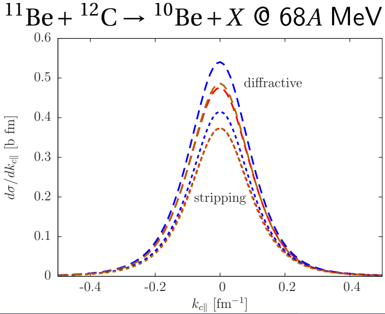
$$\text{At NLO : } V_{lJ}(r) = V^{(0)}_{lJ}\, e^{-\frac{r^2}{2r_0^2}} + V^{(2)}_{lJ}\, r^2 e^{-\frac{r^2}{2r_0^2}} \text{ with } r_0 \text{ cutoff}$$

We constrain $V^{(0)}$ and $V^{(2)}$ in $s1/2$ and $p1/2$

1. Experimental binding energies
2. Asympt. Norm. Constant (ANC) from *ab initio* computations

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





Use of different effective potentials

- Reference : r_0=1.2 fm
  ANC=0.786 fm$^{-1/2}$
- same r_0=1.2 fm
  larger ANC$=\frac{0.786}{\sqrt{0.9}}$ fm$^{-1/2}$:
  increases the cross sections

→ **Rescale** with ANC :
same cross sections

Inclusive observables sensitive only to the asymptotics !

[P. G. Hansen, PRL **77**, 1016 (1996)]

[C. A. Bertulani and P. G. Hansen, PRC **70**, 034609 (2004)]

→ **Possibility to extract ANC**

Influence of excited states

<u>^{11}Be :</u> g.s. $\epsilon_{1/2^+} = -0.501$ MeV
e.s. $\epsilon_{1/2^-} = -0.184$ MeV

$5/2^+$	1.274	$d5/2$
	^{10}Be+n ($\epsilon = 0$)	
$1/2^-$	-0.184	$0p1/2$
$1/2^+$	-0.501	$1s1/2$

^{11}Be spectrum

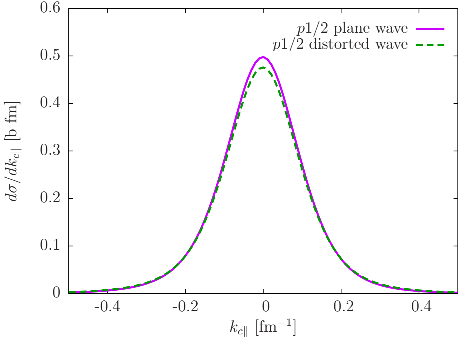
Halo-EFT : potentials in $s1/2$ & $p1/2$ → distorts the continuum

How does it influence the inclusive observables ?

Stripping insensitive to excited states ⇒ only **diffractive breakup**

Influence of excited states

$^{11}\text{Be} + {}^{12}\text{C} \rightarrow {}^{10}\text{Be} + X$ @ $68A$ MeV



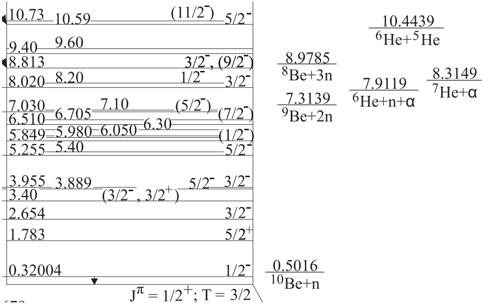
σ_{diff} **decreases** by 2.6 % : $0p1/2$ affects the overlap of Φ_0 and $\phi_{\boldsymbol{k}}$

→ **transferred to the inelastic channel**

→ **Approximated closure relation within a partial wave lj :**

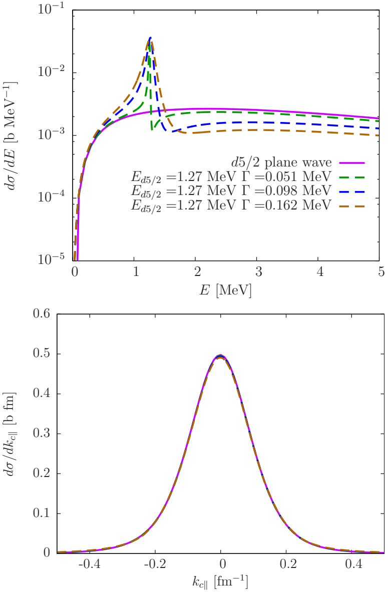
$$\sigma^{lj}_{\text{reac}} = \sigma^{lj}_{\text{diff}} + \sigma^{lj}_{\text{inel}} + \sigma^{lj}_{\text{abs}}$$

How are breakup observables sensitive to the continuum ?



- Beyond NLO : effective potential in $d5/2$ to model $5/2^+$ state
- Stripping independent from the continuum → **only diffractive**

$^{11}Be + ^{12}C \rightarrow ^{10}Be + n + ^{12}C$ at $68A$ MeV



Study of the $d5/2$ continuum

$d5/2$ plane wave

$d5/2$ **resonances** with different Γ

- Energy distribution sensitive : peak + destructive interferences
- Inclusive observables **insensitive**

→ **Similar for larger E**

→ **Similar for p and f resonances**

Inclusive observables insensitive to the continuum !

Summary

Halo nuclei : short-lived → use reaction processes like **breakup**

Inclusive measurements have **more statistics**

What are knockout observables sensitive to ?

1. The **asymptotics** of the ground state wavefunction
   ⇒ information about the size of the nucleus
   ⇒ possible **extraction of the ANC**
2. The **excited states** : distortion in the continuum
   ⇒ existence of a closure relation within a partial wave
   ⇒ they have to be included in the analysis !
3. **Insensitive** to the description of the **continuum**

Prospects : Systematic analyses of experiments at MSU and GSI