Integrating ab initio structure models into accurate reaction calculations using EFT

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Halo nuclei

Exotic nuclear structures are found far from stability
In particular halo nuclei with
peculiar quantal structure :

- Light, n-rich nuclei
- Low S_n or S_{2n}

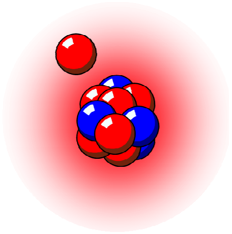


Exhibit large matter radius
due to strongly clusterised structure :
neutrons tunnel far from the core and form a halo

One-neutron halo

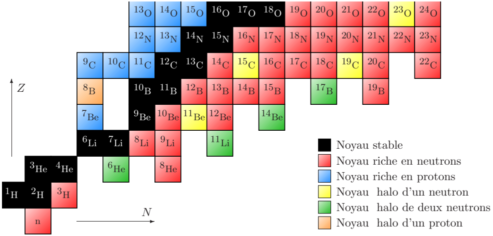
^{11}Be ≡ ^{10}Be + n

^{15}C ≡ ^{14}C + n

Two-neutron halo

^{6}He ≡ ^{4}He + n + n

^{11}Li ≡ ^{9}Li + n + n



Proton haloes are possible but less probable : ^{8}B, ^{17}F

Reactions with halo nuclei

Halo nuclei are fascinating objects
but difficult to study [$\tau_{1/2}$(^{11}Be)$= 13$ s]
$\Rightarrow$ require indirect techniques, like reactions

Elastic scattering

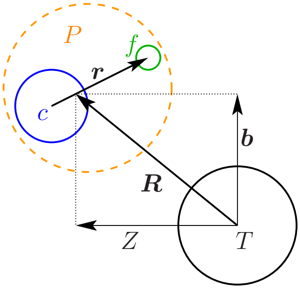
Breakup $\equiv$ dissociation of halo from core
by interaction with target

Need good understanding of the reaction mechanism
i.e. an accurate theoretical description of reaction
coupled to a realistic model of projectile

Framework

Projectile (P) modelled as a two-body system :
core (c)+loosely bound nucleon (f) described by

$$H_0 = T_r + V_{cf}(\boldsymbol{r})$$



V_{cf} adjusted to reproduce bound state Φ_0 and resonances

Target T seen as structureless particle

P-T interaction simulated by optical potentials
$\Rightarrow$ breakup reduces to three-body scattering problem :

$$\left[T_R + H_0 + V_{cT} + V_{fT}\right]\Psi(\boldsymbol{r},\boldsymbol{R}) = E_T\Psi(\boldsymbol{r},\boldsymbol{R})$$

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

Dynamical eikonal approximation (DEA)

Three-body scattering problem :

$$\left[T_R + H_0 + V_{cT} + V_{fT}\right]\Psi(\boldsymbol{r},\boldsymbol{R}) = E_T\Psi(\boldsymbol{r},\boldsymbol{R})$$

with condition $\Psi \underset{Z\to-\infty}{\longrightarrow} e^{iKZ}\Phi_0$

Eikonal approximation : factorise $\Psi = e^{iKZ}\widehat{\Psi}$

$$T_R\Psi = e^{iKZ}[T_R + vP_Z + \frac{\mu_{PT}}{2}v^2]\widehat{\Psi}$$

Neglecting T_R vs P_Z and using $E_T = \frac{1}{2}\mu_{PT}v^2 + \epsilon_0$

$$i\hbar v\frac{\partial}{\partial Z}\widehat{\Psi}(\boldsymbol{r},\boldsymbol{b},Z) = [H_0 - \epsilon_0 + V_{cT} + V_{fT}]\widehat{\Psi}(\boldsymbol{r},\boldsymbol{b},Z)$$

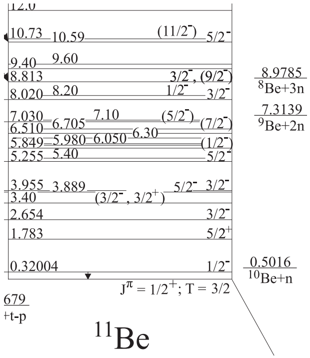
solved for each $\boldsymbol{b}$ with condition $\widehat{\Psi} \underset{Z\to-\infty}{\longrightarrow} \Phi_0(\boldsymbol{r})$

This is the dynamical eikonal approximation (DEA)

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

(Usual) eikonal includes the adiabatic approximation : $(H_0 - \epsilon_0) \approx 0$

^{11}Be ≡ ^{10}Be ⊗ n



- $\frac{1}{2}^+$ ground state :
  $\epsilon_{\frac{1}{2}^+} = -0.504$ MeV
  In our model, seen as $1s_{\frac{1}{2}}$ neutron bound to ^{10}Be(0^+)
- $\frac{1}{2}^-$ bound excited state :
  $\epsilon_{\frac{1}{2}^-} = -0.184$ MeV
  In our model, seen as $0p_{\frac{1}{2}}$ neutron bound to ^{10}Be(0^+)
- $\frac{5}{2}^+$ bound excited state :
  $\epsilon_{\frac{5}{2}^+} = 1.274$ MeV
  In our model, seen as a $d_{\frac{5}{2}}$ resonance

Usual phenomenological description

In reaction models, projectile ≡ two-body system :

$$H_0 = T_r + V_{cn}(\boldsymbol{r}),$$

where V_{cn} is a phenomenological Woods-Saxon that reproduces the basic nuclear properties of the projectile (binding energy, J^π,...)

Nowadays ab initio calculations of such exotic nuclei are available
Can we use them within a reaction code ?

But do we need to go that far ?
Breakup reactions are mostly peripheral, i.e., probe :

- ANC of the ground state [P.C. & Nunes, PRC 75, 054609 (2007)]
- phaseshifts in the continuum [P.C. & Nunes, PRC 73, 014615 (2006)]

⇒ constrain two-body description by ab initio prediction

Ab initio description of ^{11}Be

A recent ab initio calculation of ^{11}Be has been performed

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

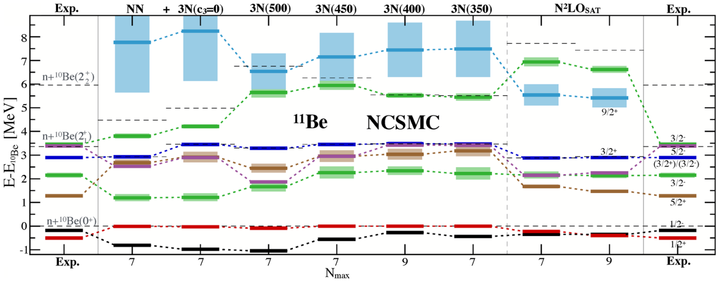
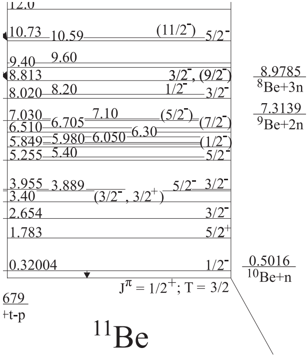


FIG. 2. NCSMC spectrum of ^{11}Be with respect to the $n + {}^{10}$Be threshold. Dashed black lines indicate the energies of the ^{10}Be states. Light boxes indicate resonance widths. Experimental energies are taken from Refs. [1,51].

Difficult to reproduce the shell inversion

⇒ include phenomenology to obtain the correct ordering

Ab initio description of ^{11}Be bound states



- $\frac{1}{2}^+$ 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$^{-1/2}$
  $\mathcal{S}_{0p\frac{1}{2}} = 0.85$

Ab initio description of ^{10}Be-n continuum

Provides the most accurate calculation for the ^{10}Be-n continuum

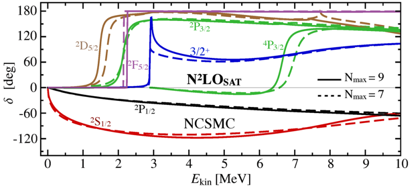


FIG. 3. The $n + {}^{10}$Be phase shifts as a function of the kinetic energy in the center-of-mass frame. NCSMC phase shifts for the N^{2}LO$_{SAT}$ interaction are compared for two model spaces indicated by N_{max}.

Idea : constrain the ^{10}Be-n potential in the reaction code to reproduce ab initio bound states ANC and δ_{lj}.

^{10}Be-n potential

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

Use the spirit of halo EFT : separation of scales (in energy or in distance)

Use narrow Gaussian potentials

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

Fit V_0 and V_2 to reproduce ϵ_{lj}, and C_{lj} (bound states)

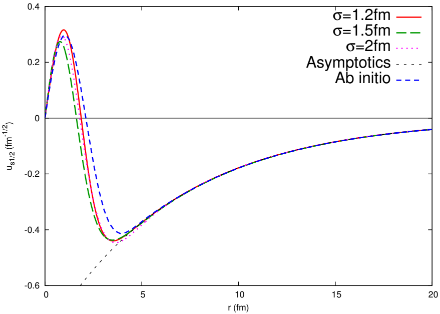
or Γ_{lj} for resonances

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

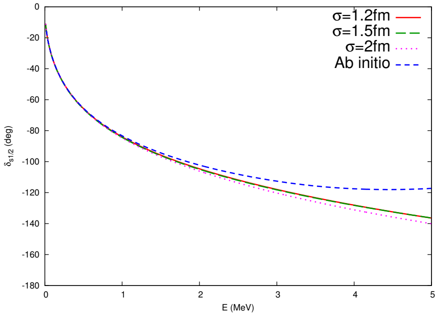
$s\frac{1}{2}$: potentials fitted to $\epsilon_{\frac{1}{2}^+}$ and $C_{\frac{1}{2}^+}$

Potentials fitted to $\epsilon_{1s\frac{1}{2}} = -0.504$ MeV and $C_{1s\frac{1}{2}} = 0.786$ fm$^{-1/2}$

Ground-state wave function

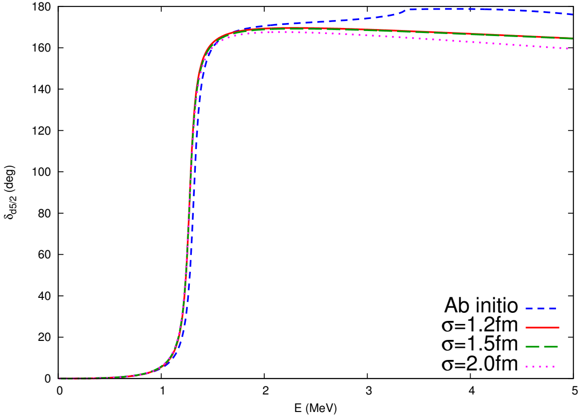


$s\frac{1}{2}$ phaseshifts



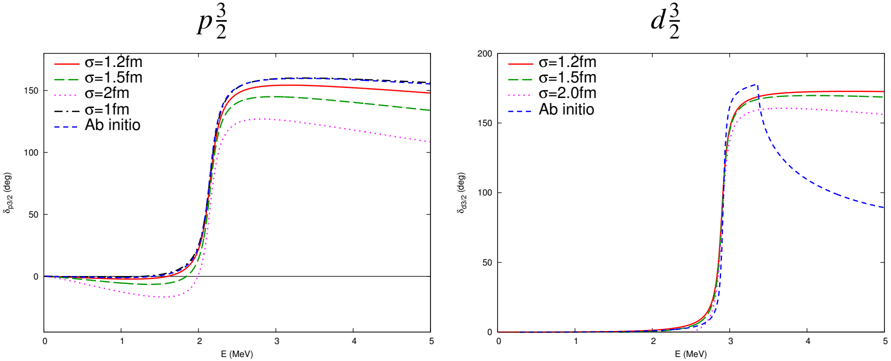
- Wave functions : same asymptotics but different interior
- $\delta_{s\frac{1}{2}}$: all effective potentials are in good agreement with ab initio up to 1.5 MeV (same effective-range expansion)
- Similar results obtained for $p\frac{1}{2}$ (excited bound state)

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

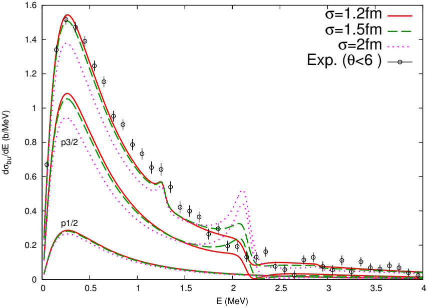
$p\frac{3}{2}$ and $d\frac{3}{2}$: potentials fitted to $\epsilon^{\rm res}$ and Γ



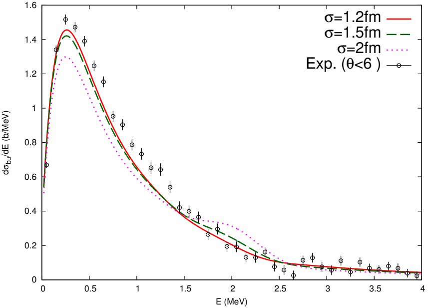
- Large variation in δ obtained by effective potentials
  Broad potential ($\sigma = 2$ fm) cannot reproduce correct behaviour
- Fair agreement with ab initio results up to 2.5 MeV
- ^{10}Be core excitation @ 3.4 MeV not described in effective model

^{11}Be+Pb→^{10}Be+n+Pb @ 69*A*MeV

Total breakup cross section and p contributions



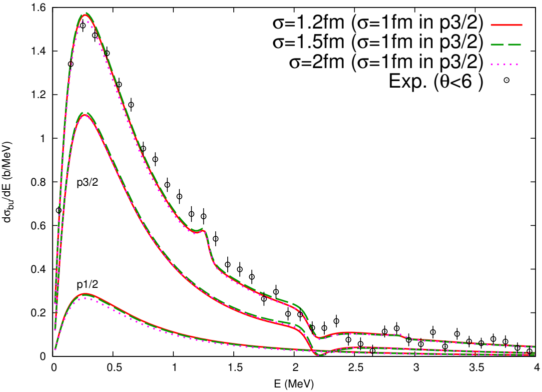
Folded with experimental resolution



- Major differences in $p_{3/2}$ partial wave ; due to differences in $\delta_{p_{3/2}}$
- Broad potential ($\sigma = 2$ fm) produces unrealistic $p_{3/2}$ contribution
- Excellent agreement with data [Fukuda *et al.* PRC 70, 054606 (2004)]

Role of $\delta_{p3/2}$

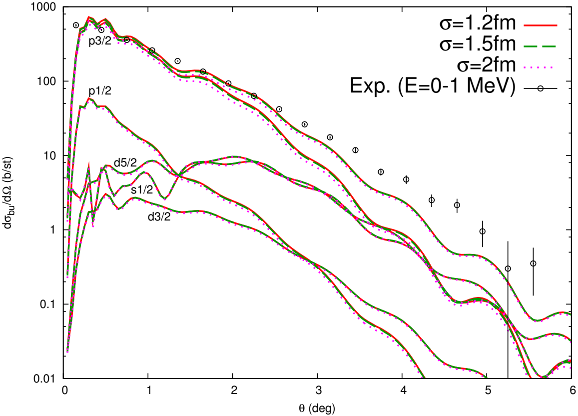
Calculations repeated with different potentials (σ = 1.2, 1.5 or 2 fm)
but in $p_{3/2}$, where $\sigma = 1$ fm (perfect agreement with ab initio)



All potentials provide the same $p_{3/2}$ contribution

- confirms the peripherality of reaction (no influence of the internal part)
- shows the significant role of phaseshifts

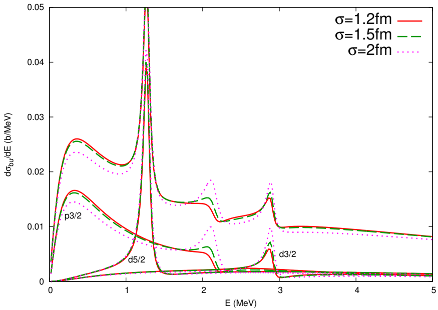
^{11}Be+Pb→^{10}Be+n+Pb @ 69AMeV



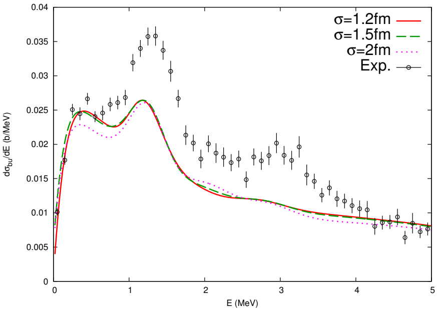
- Good agreement with experiment [Fukuda *et al.* PRC 70, 054606 (2004)]
- All potentials provide similar cross sections ($\sigma = 2$ fm slightly lower)

^{11}Be+C→^{10}Be+n+C @ 67*A*MeV

Total breakup cross section and dominant contributions



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



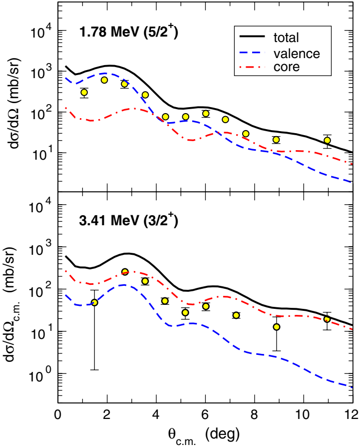
- All potentials produce similar breakup cross sections (but $\sigma = 2$ fm)
- In nuclear breakup, resonances play significant role
- Order of magnitude of experiment well reproduced
- But resonant breakup not correctly described due to short-range details missing in the effective model (?)

Effect of core-excitation in resonant breakup

^{11}Be+C→^{10}Be+n+C @ $67A$MeV

computed in an extended DWBA model including core excitation

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



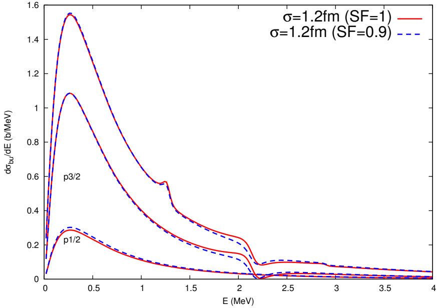
- Breakup due to the excitation of the valence neutron and of the core are considered
- Both are needed to reproduce the oscillatory pattern of experiment
- Core excitation dominates the $\frac{3}{2}^+$ resonant breakup
- Confirms the missing short-range details in our effective model

SF vs ANC

Calci *et al.* predict $\mathcal{S}_{1s\frac{1}{2}} = 0.90$, but we use $\mathcal{S}_{1s\frac{1}{2}} = 1$...

$\Rightarrow$ repeat calculations with $\mathcal{S}_{1s\frac{1}{2}} = 0.90$ (keeping $C_{\frac{1}{2}^+} = 0.786$ fm$^{-1/2}$)

^{11}Be+Pb→^{10}Be+n+Pb



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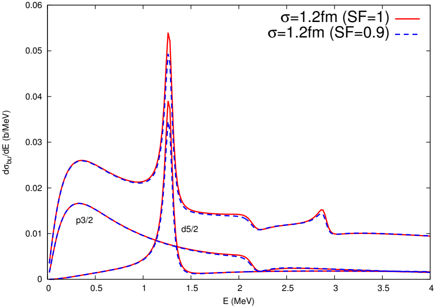

No difference $\Rightarrow$ SF cannot be extracted from these measurements

One exception : resonant breakup, where SF plays a role

$\Rightarrow$ influence of the short-range details (?)

Summary and prospect

- Exotic nuclei studied mostly through reactions
- Mechanism of reactions with halo nuclei understood
  How to improve the projectile description in reaction models ?
- Ab initio models too expensive to be used in reaction codes
  ⇒ include the predictions that matter in effective model
- Using Gaussian potentials, we reproduce the ANC
  and phase shifts predicted by ab initio calculations
- Our study confirms
  - peripherality of breakup reactions
  - influence of the continuum through phase shifts
- Using ab initio predictions gives excellent agreement with data
  - efficient way to include the significant degrees of freedom
  - provides an estimate the influence of omitted mechanisms
    e.g., resonances include short-range details

Thanks to my collaborators

Daniel Baye
Gerald Goldstein

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Achim Schwenk
Hans-Werner Hammer

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NSCL

Filomena Nunes

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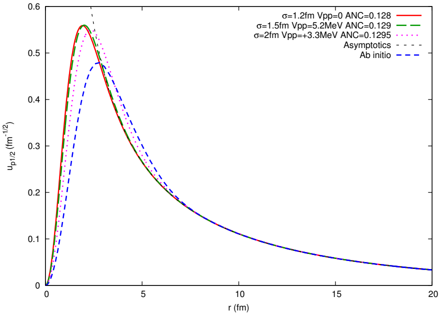

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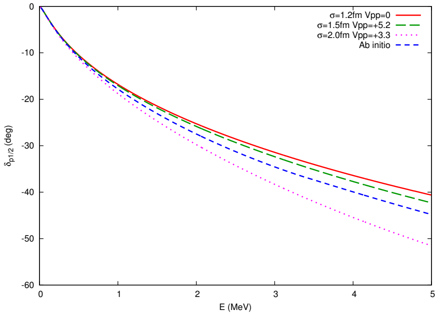

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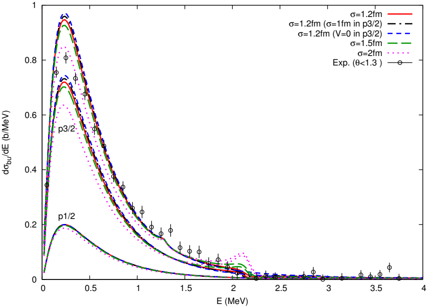

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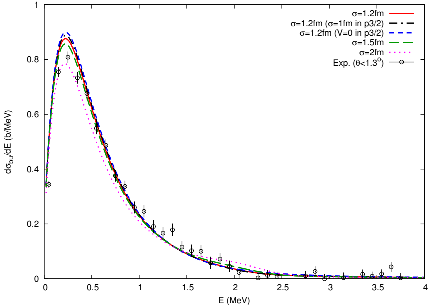

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