Challenges in Nuclear-Reaction Theory

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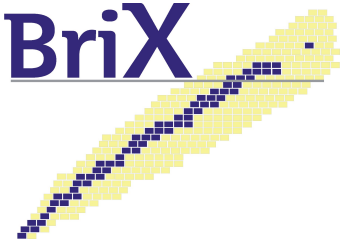

TECHNISCHE
UNIVERSITÄT
DARMSTADT

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1. Halo nuclei
2. Reaction model
   - CDCC
   - Eikonal approximation
   - Time-dependent approach
3. Optical potential choice
4. Projectile description
   - Ab initio calculation
   - Effective model
5. Summary

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}

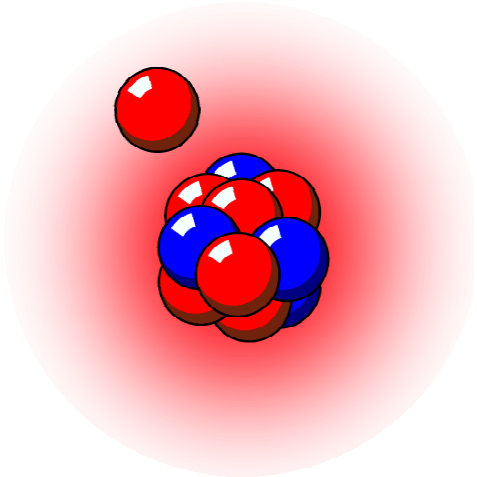


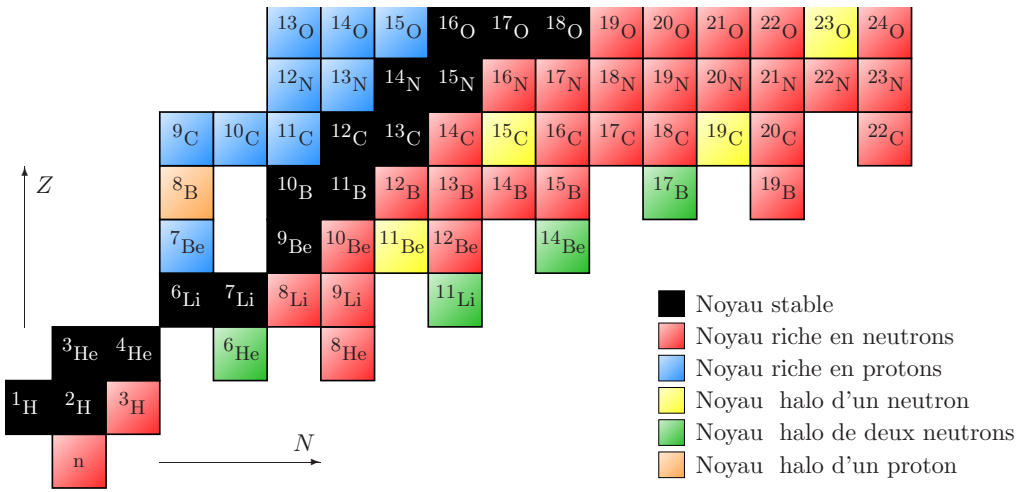
Exhibit large matter radius
due to strongly clusterised structure :
neutrons tunnel far from the core and form a halo

One-neutron halo

$^{11}\mathrm{Be} \equiv {}^{10}\mathrm{Be} + \mathrm{n}$
$^{15}\mathrm{C} \equiv {}^{14}\mathrm{C} + \mathrm{n}$

Two-neutron halo

$^{6}\mathrm{He} \equiv {}^{4}\mathrm{He} + \mathrm{n} + \mathrm{n}$
$^{11}\mathrm{Li} \equiv {}^{9}\mathrm{Li} + \mathrm{n} + \mathrm{n}$



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

Reactions with halo nuclei

Halo nuclei are fascinating objects
but difficult to study [$\tau_{1/2}(^{11}\text{Be}) = 13$ s]

$\Rightarrow$ require indirect techniques, like reactions

Elastic scattering

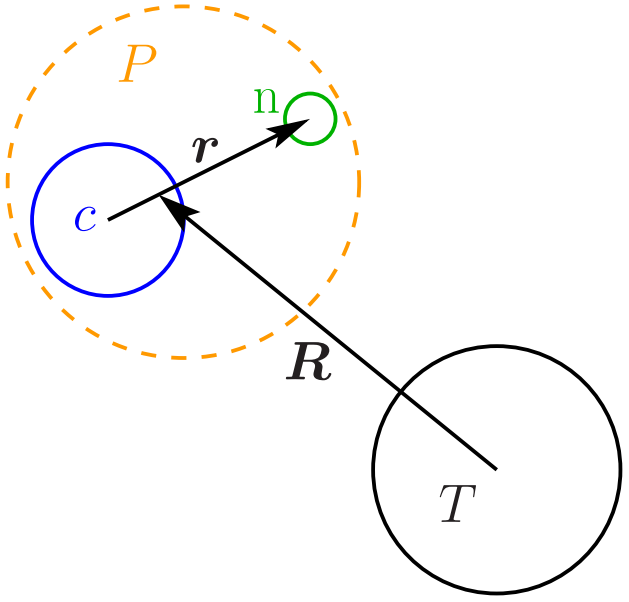
Breakup $\equiv$ dissociation of halo from core
by interaction with target

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 neutron (n) described by

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



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

Target T seen as
structureless particle
P-T interaction simulated by optical potentials
$\Rightarrow$ collision reduces to three-body scattering problem :

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

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

Various techniques to solve this equation :
CDCC, eikonal, time-dependent approach...

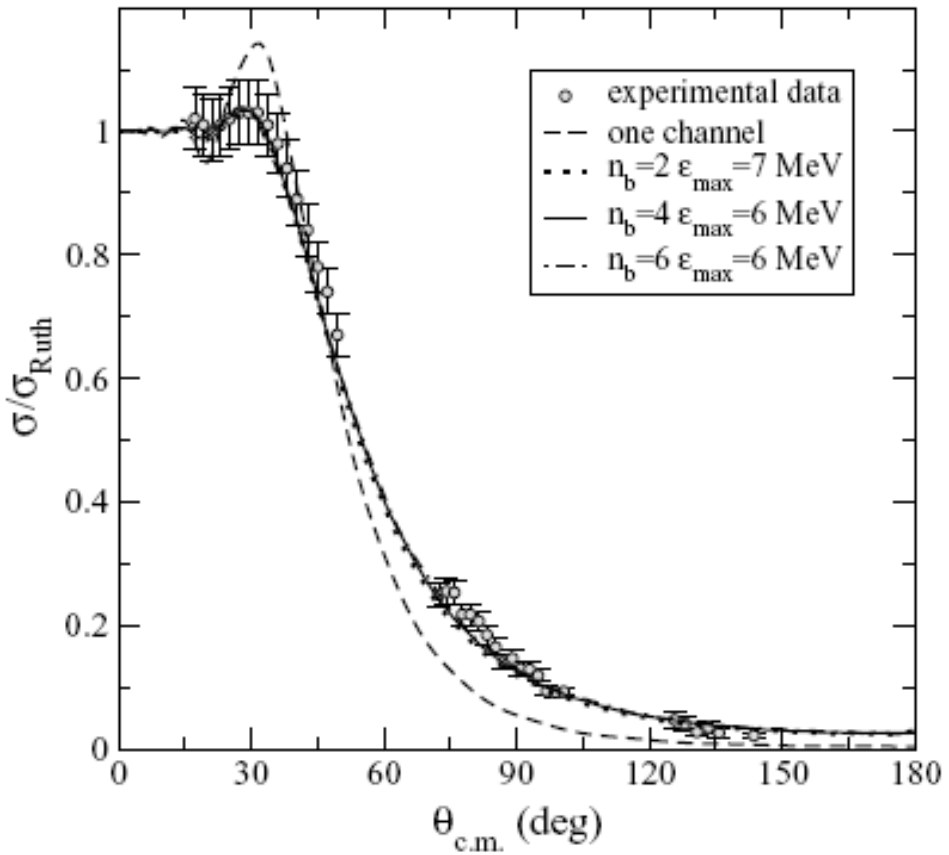
CDCC

The wave function is expanded on the projectile eigenstates :

$\Psi(\boldsymbol{r}, \boldsymbol{R}) = \sum_i \chi_i(\boldsymbol{R})\Phi_i(\boldsymbol{r})$ with $H_0\Phi_i = \epsilon_i\Phi_i$

The c-n continuum is discretised $\Rightarrow$ set of coupled equations

^{6}He+Zn elastic scattering @ 13.6 MeV

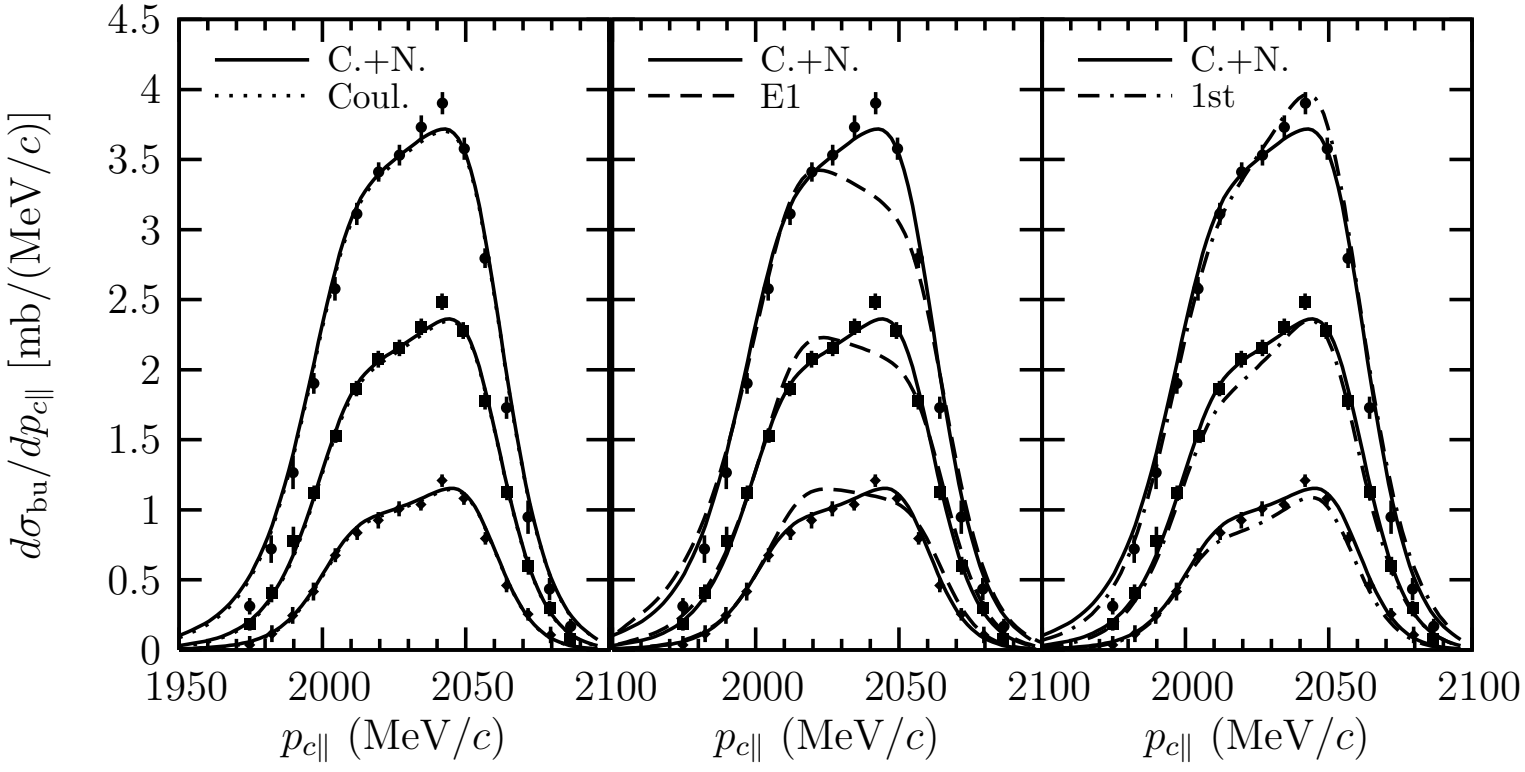


[M. Rodríguez-Gallardo *et al.* PRC 77, 064609 (2008)]

Eikonal approximation

Factorise $\Psi(\boldsymbol{r}, \boldsymbol{R}) = e^{iKZ}\widehat{\Psi}(\boldsymbol{r}, \boldsymbol{b}, Z)$
and assume $\Delta\widehat{\Psi} \ll K\frac{\partial}{\partial Z}\widehat{\Psi}$
$\Rightarrow$ simplifies the equation to be solved

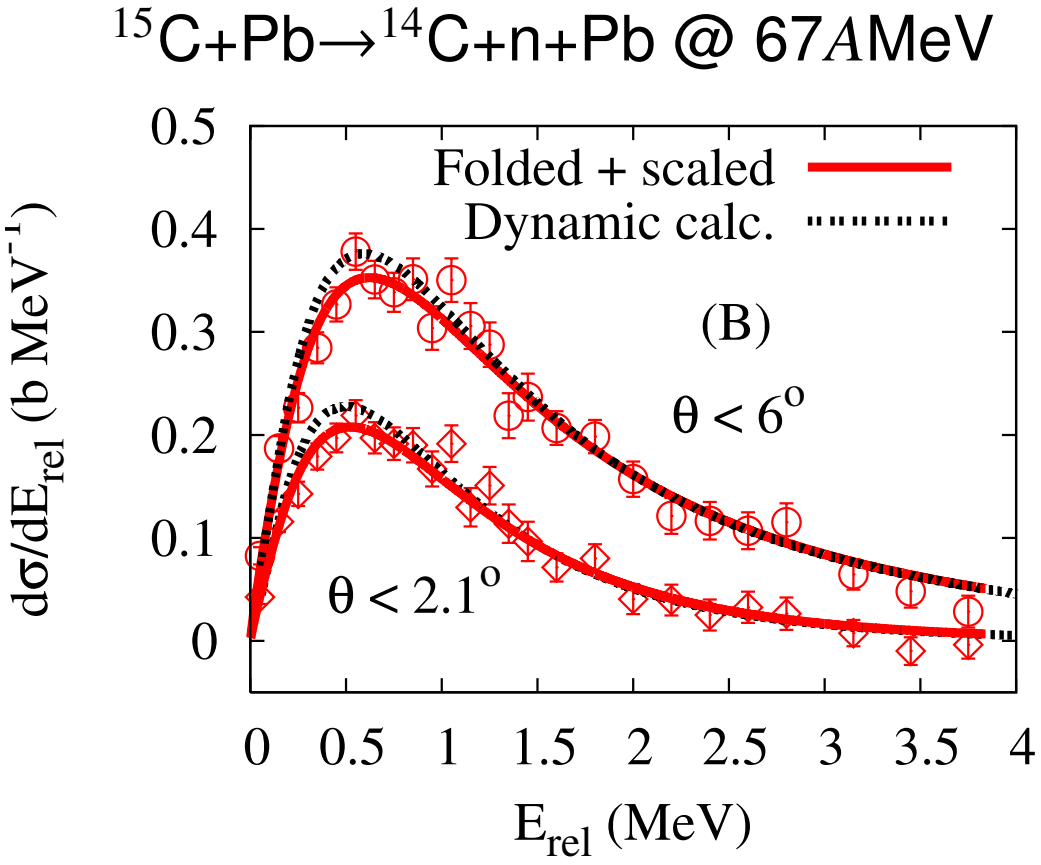
^{8}B+Pb$\rightarrow$ ^{7}Be+X @ 44AMeV



[G. Goldstein *et al.* PRC 76, 024608 (2007)]

Time-dependent approach

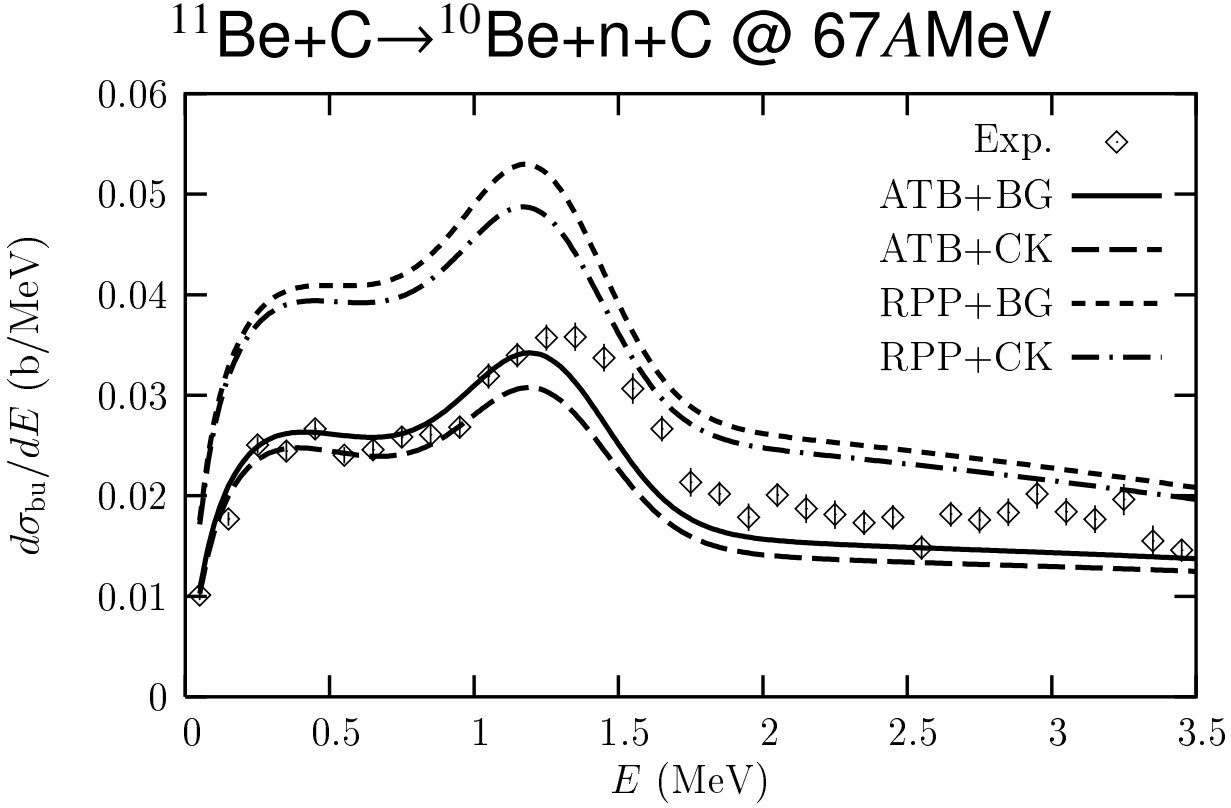
Assume a semic-classical approximation : $R \rightarrow R(t)$
$\Rightarrow$ time-dependent Schrödinger equation



[H. Esbensen PRC 77, 024608 (2007)]

However...

...results depends on the optical potentials V_{cT} and V_{nT}



[P. C. *et al.* PRC 70, 064605 (2004)]

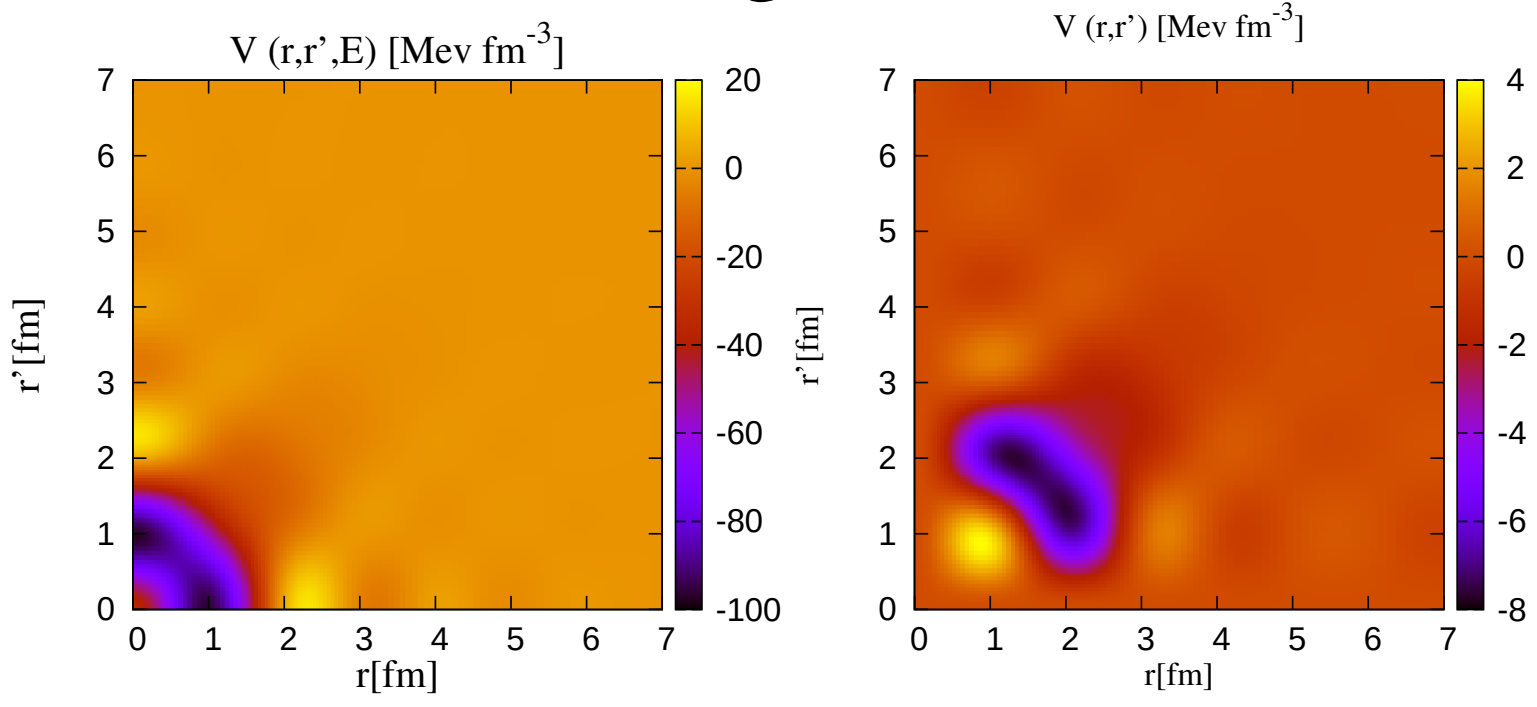
Since the core c is itself exotic, V_{cT} is usually poorly known
$\Rightarrow$ need more reliable optical potentials

Optical potentials from first principles

Rotureau *et al.* have built a nucleon-nucleus optical potential as the self-energy of a Coupled-Cluster calculation

[J. Rotureau *et al.* arXiv :1611.04554]

n+^{16}O @ 10 MeV



$s_{1/2}$ $d_{3/2}$

- Highly non-local and energy dependent $\Rightarrow$ difficult to handle

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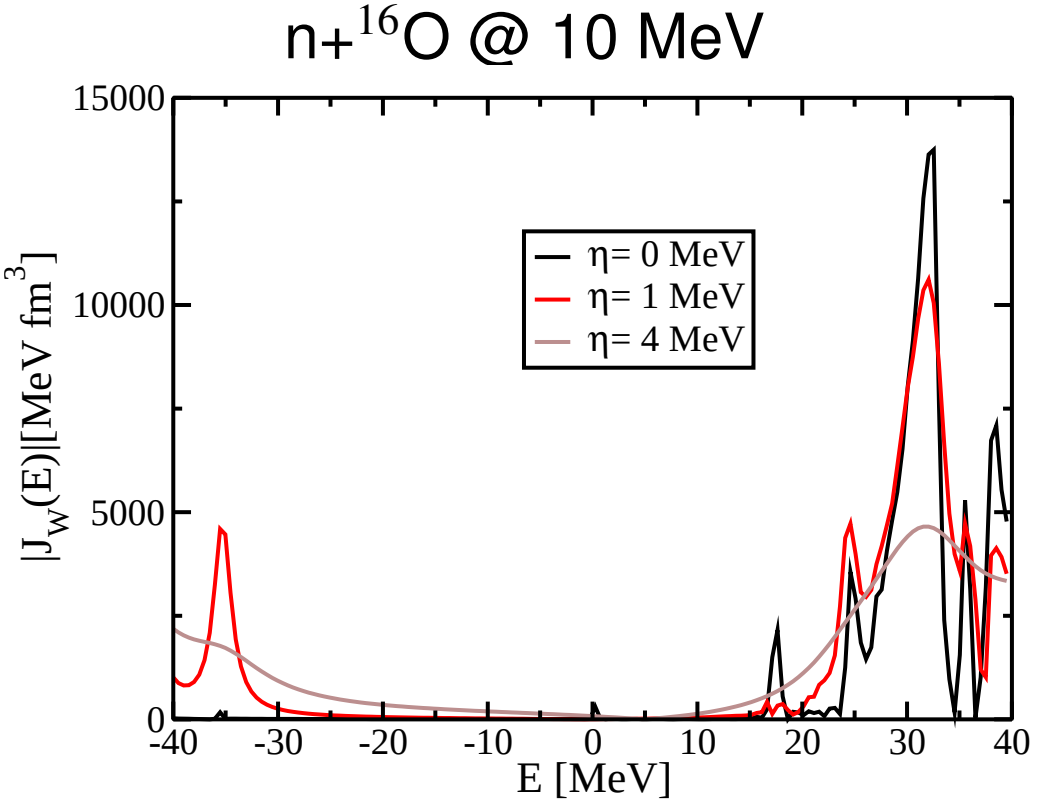
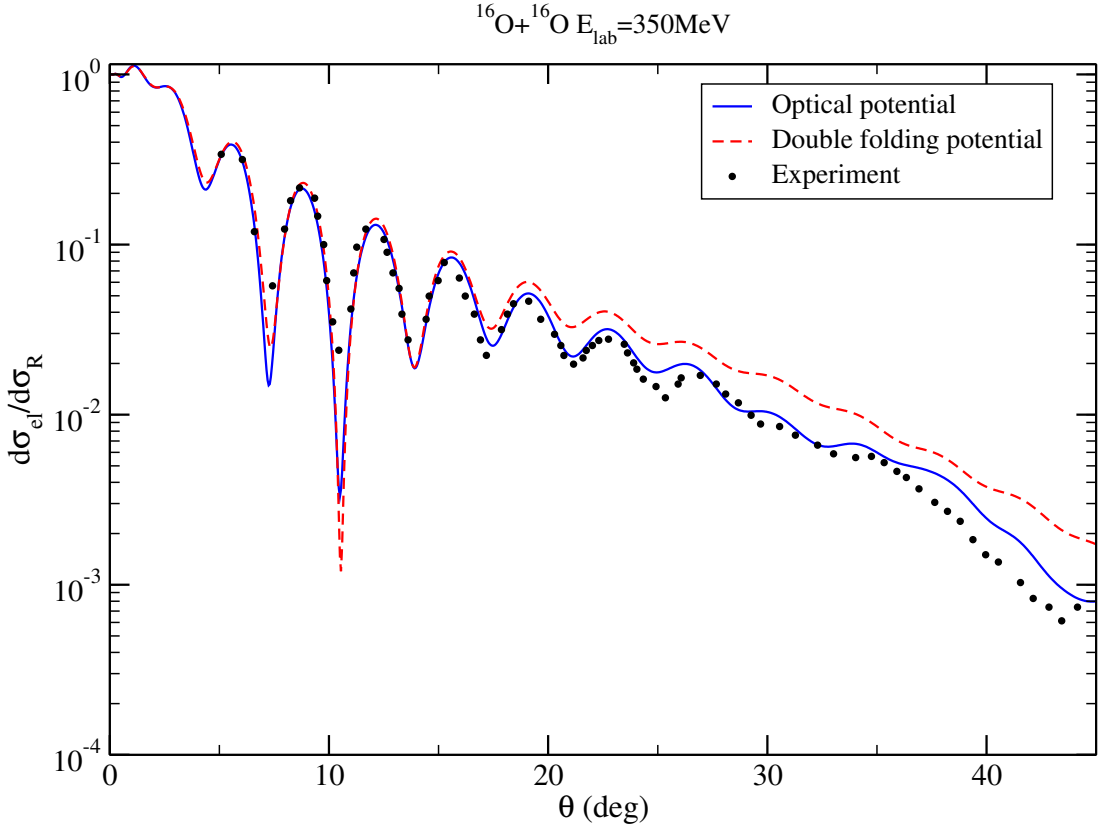


- Highly non-local and energy dependent ⇒ difficult to handle
- Lacks absorption at low energy

Double-folding potential

Using a χEFT (N^{2}LO) local in coordinate space
double folded with ^{16}O densities $\rightarrow$ optical potential



calculations by V. Durant

- Good agreement with data at forward angle
- Lack of absorption at larger angle

Usual phenomenological description

In reaction models, projectile ≡ two-body system :

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

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 ⇒ probe :

- ANC of the ground state
- phaseshifts in the continuum

⇒ constrain two-body description by *ab initio* prediction

Stare of the art : *ab initio*

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

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

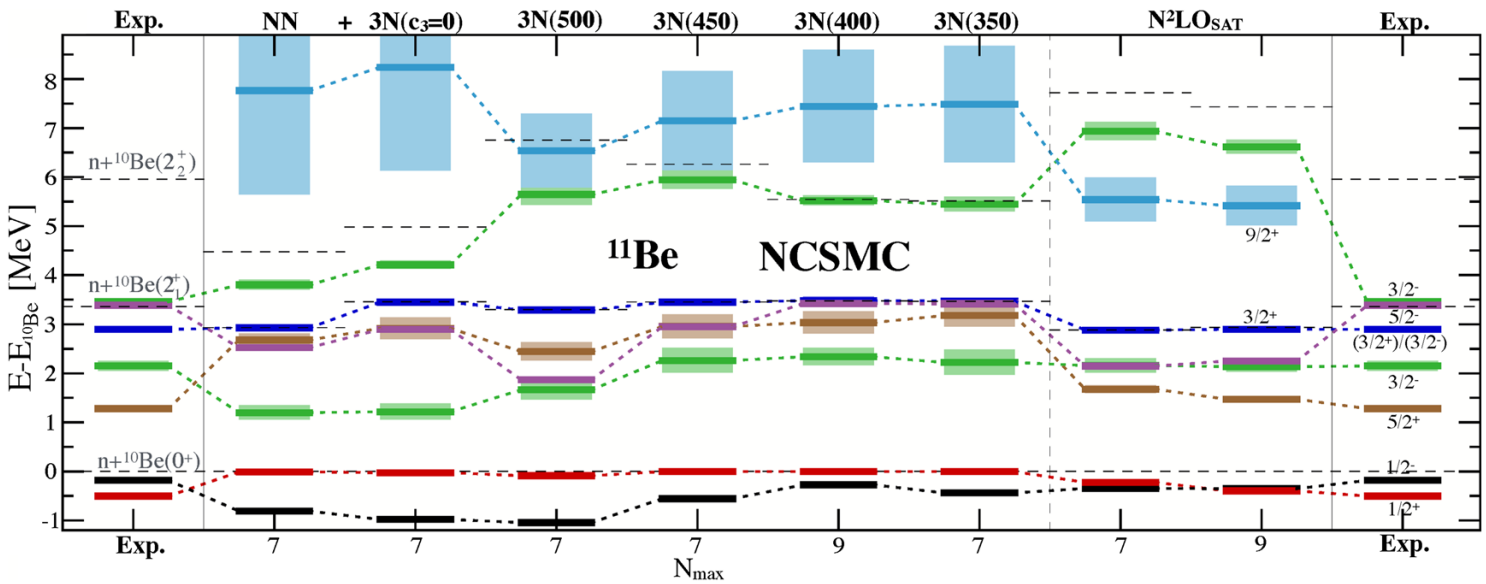


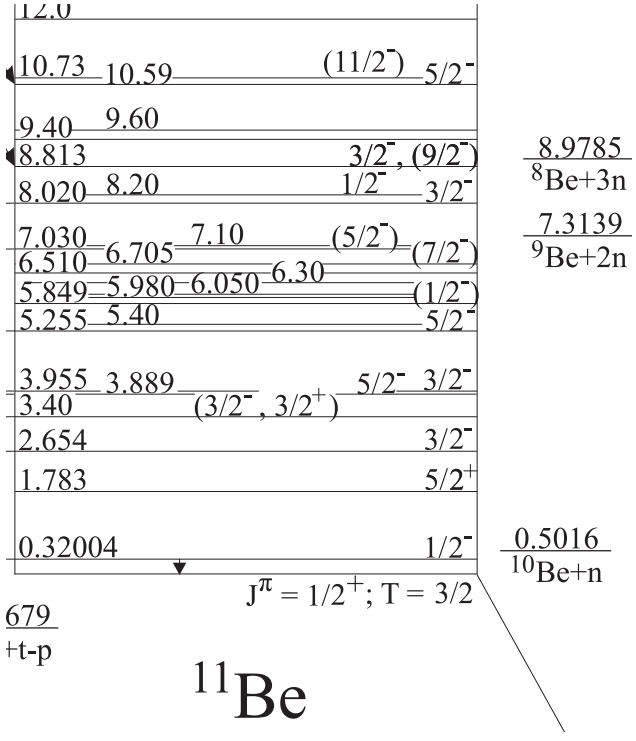
FIG. 2. NCSMC spectrum of ^{11}Be with respect to the $n + {}^{10}$Be threshold. Dashed black lines indicate the energies of the ^{10}Be states. Light boxes indicate resonance widths. Experimental energies are taken from Refs. [1,51].

Slow convergence

$\Rightarrow$ difficulties to reproduce the shell inversion

$\Rightarrow$ 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

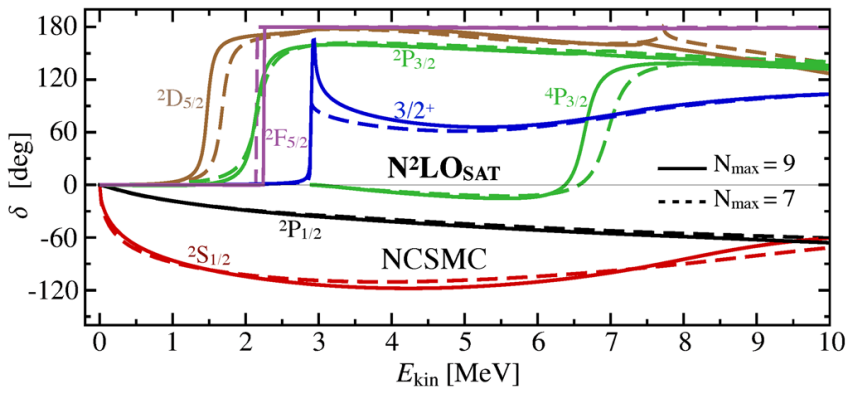


FIG. 3. The $n + {}^{10}$Be phase shifts as a function of the kinetic energy in the center-of-mass frame. NCSMC phase shifts for the N^2LO_{SAT} interaction are compared for two model spaces indicated by N_{max}.

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 an effective potential
in each partial wave

Use the spirit of halo EFT : separation of scales
in energy or in distance
Work in collaboration with Hammer (TUD) and Philips (U. Ohio)

Use a narrow Gaussian potential

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

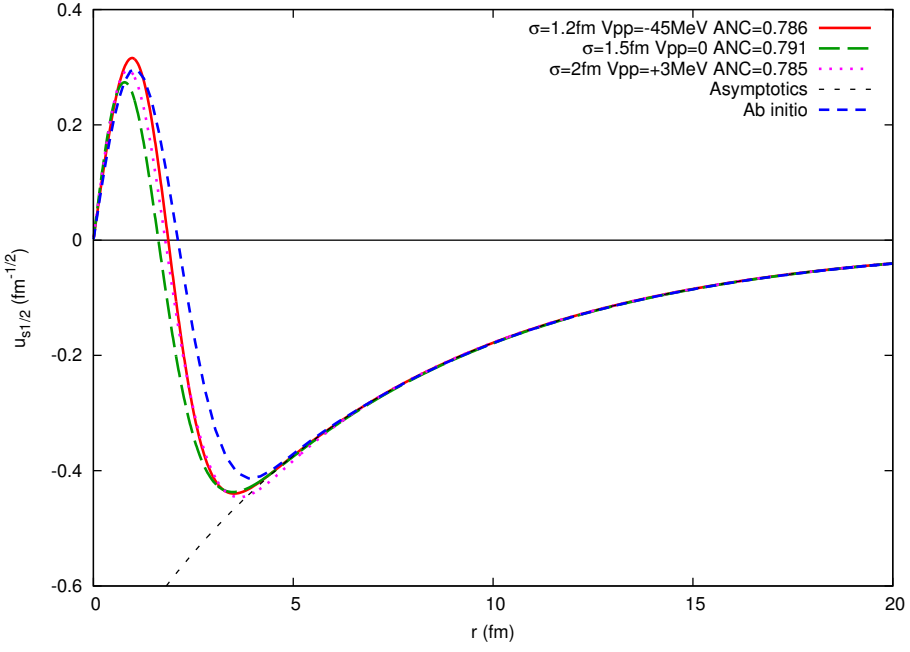
Fit V_0 and V_2 to reproduce ϵ_{lj}, and C_{lj} (bound states)
or Γ_{lj} for resonances

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

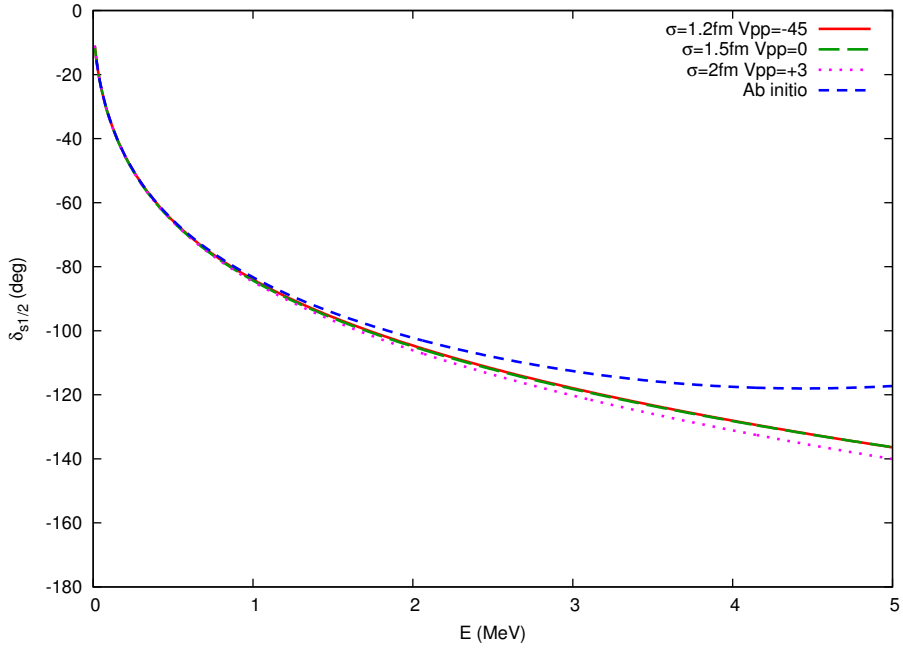
$s\frac{1}{2}$: potentials fitted to $\epsilon_{\frac{1}{2}^+}$ and $C_{\frac{1}{2}^+}$

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



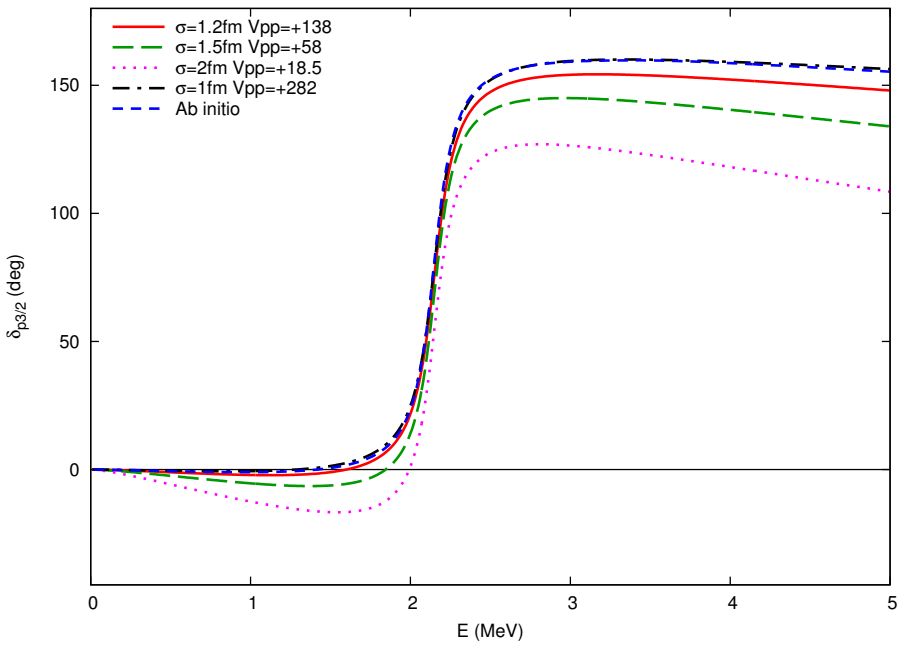
$s\frac{1}{2}$ phaseshifts



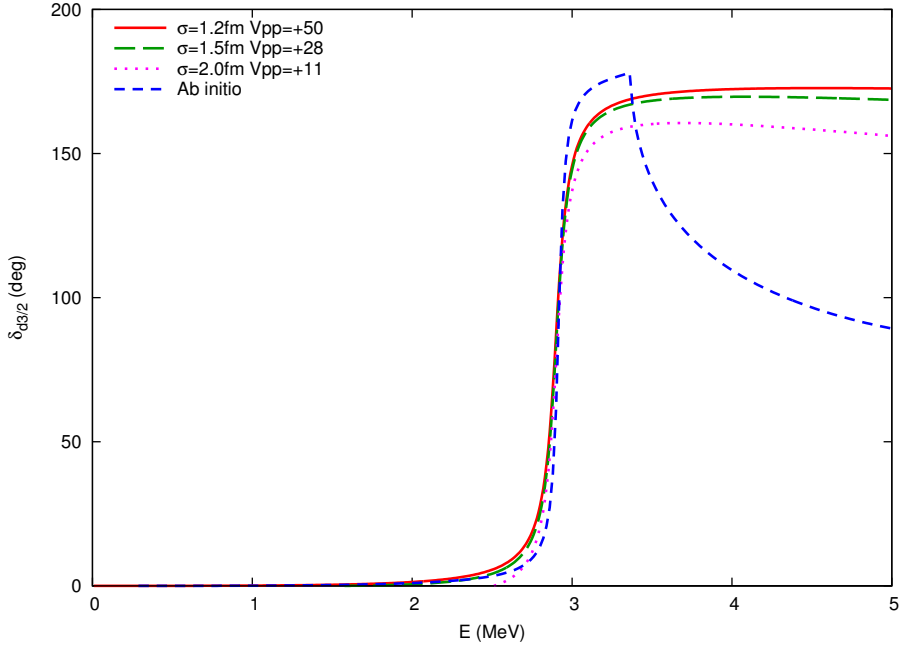
- Wave functions : same asymptotics but different interior
- $\delta_{s\frac{1}{2}}$: all effective potentials are in good agreement with ab initio up to 1.5 MeV (same effective-range expansion)
- Similar results obtained for $p\frac{1}{2}$ and $d\frac{5}{2}$ partial waves

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

$p\frac{3}{2}$



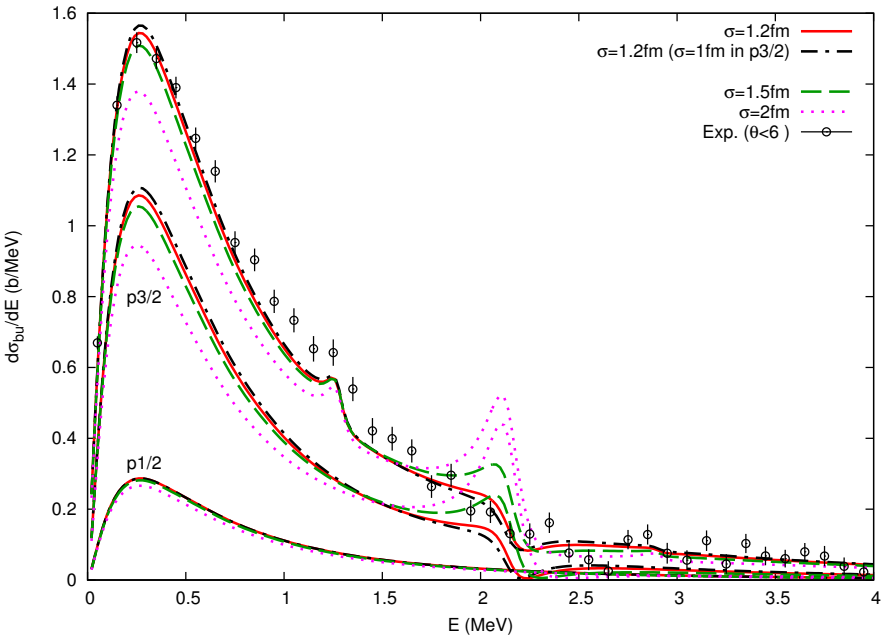
$d\frac{3}{2}$



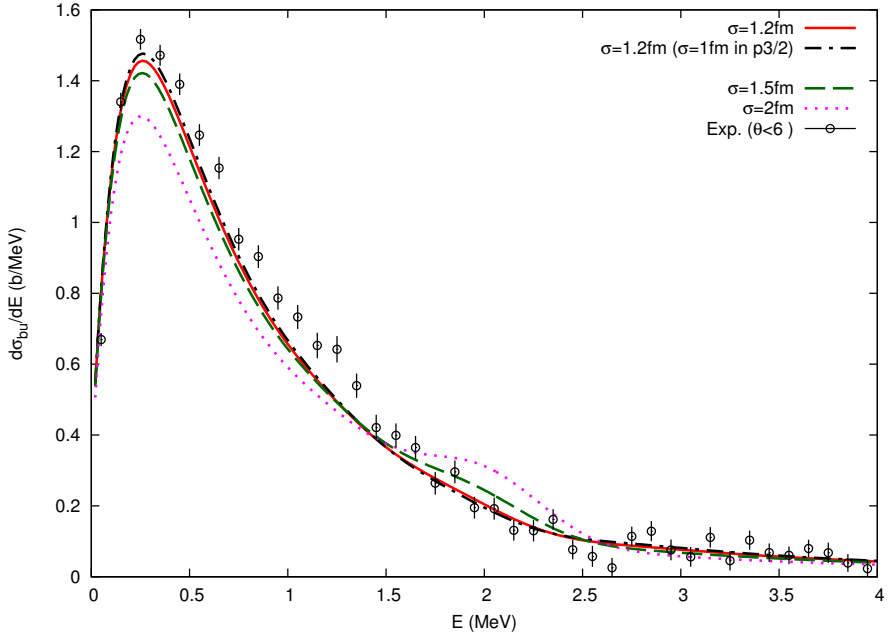
- Large variation in δ obtained by effective potentials
  Broad potential ($\sigma = 2$ fm) cannot reproduce correct behaviour
- Fair agreement with ab initio results up to 2.5 MeV
- ^{10}Be core excitation @ 3.4 MeV not described in effective model

^{11}Be+Pb→^{10}Be+n+Pb @ 69AMeV

Total breakup cross section and p contributions



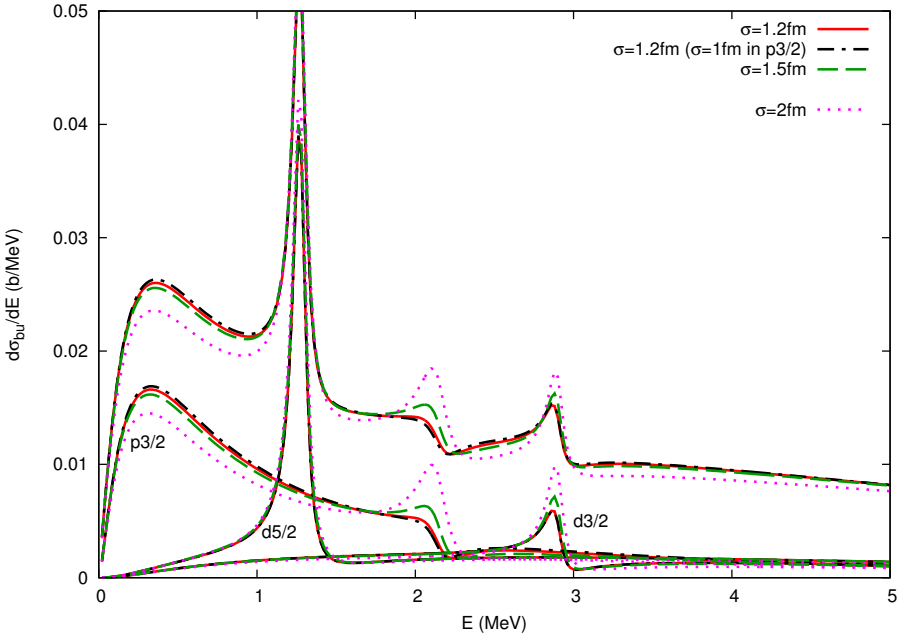
Folded with experimental resolution



- 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 experiment

^{11}Be+C→^{10}Be+n+C @ 67AMeV

Total breakup cross section and dominant contributions



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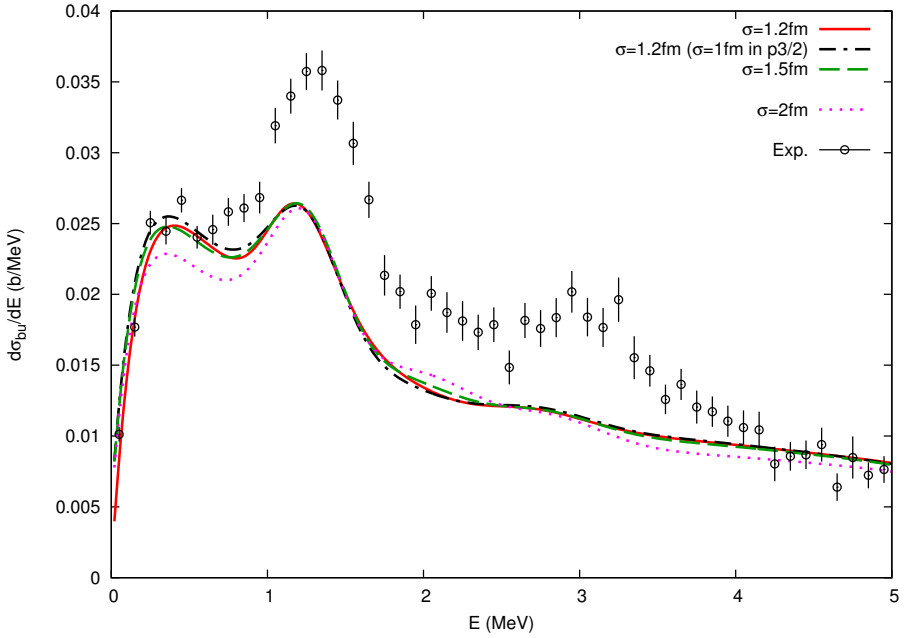
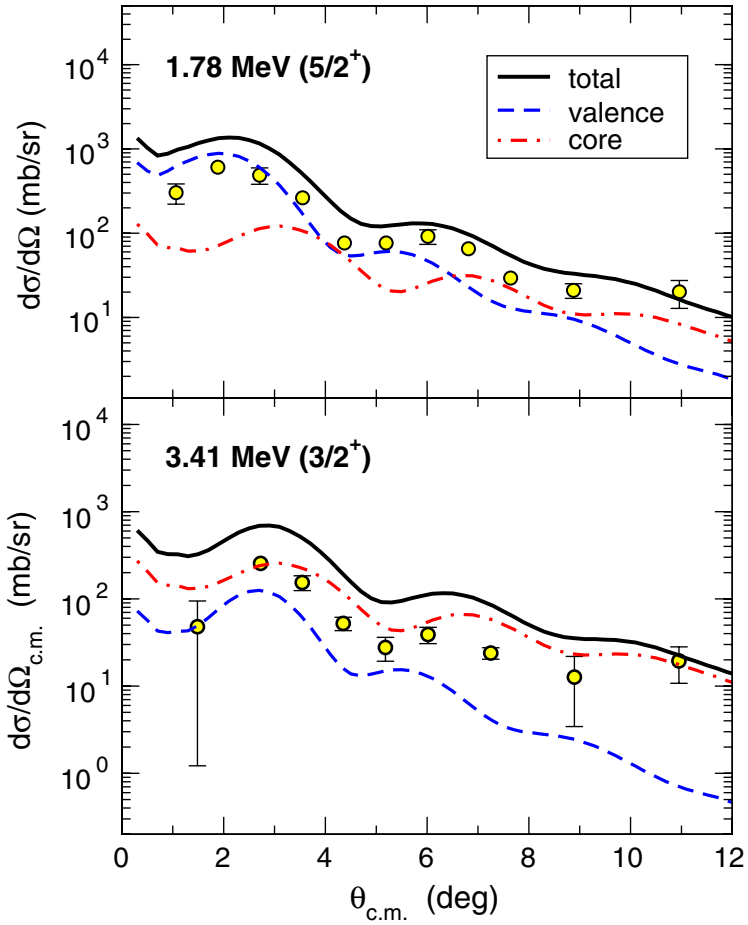


- All potentials produce similar breakup cross sections
- In nuclear breakup, resonances play significant role
- Order of magnitude of experiment well reproduced
- But resonant breakup not correctly described due to short-range details missing in the effective model

Effect of core-excitation in resonant breakup

^{11}Be+C$\rightarrow^{10}$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

Summary and prospect

- Exotic nuclei studied mostly through reactions
  - elastic scattering
  - breakup
- Mechanism of reactions with halo nuclei understood but there remain uncertainties :
  - optical potential choice
  - description of the projectile
- Optical potential can be built
  - from first principles
    $\Rightarrow$ strongly non-local and energy dependent
  - by folding χEFT interactions
    $\Rightarrow$ simpler to use (predictive power ?)
- *Ab initio* models too expensive to be used in reaction codes
  $\Rightarrow$ include the predictions that matter in effective model
  - efficient way to include the significant degrees of freedom
  - enables us to estimate the influence of omitted mechnisms

Thanks to my collaborators

Daniel Baye
Gerald Goldstein
Frederic Colomer
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Hans-Werner Hammer
Victoria Durant

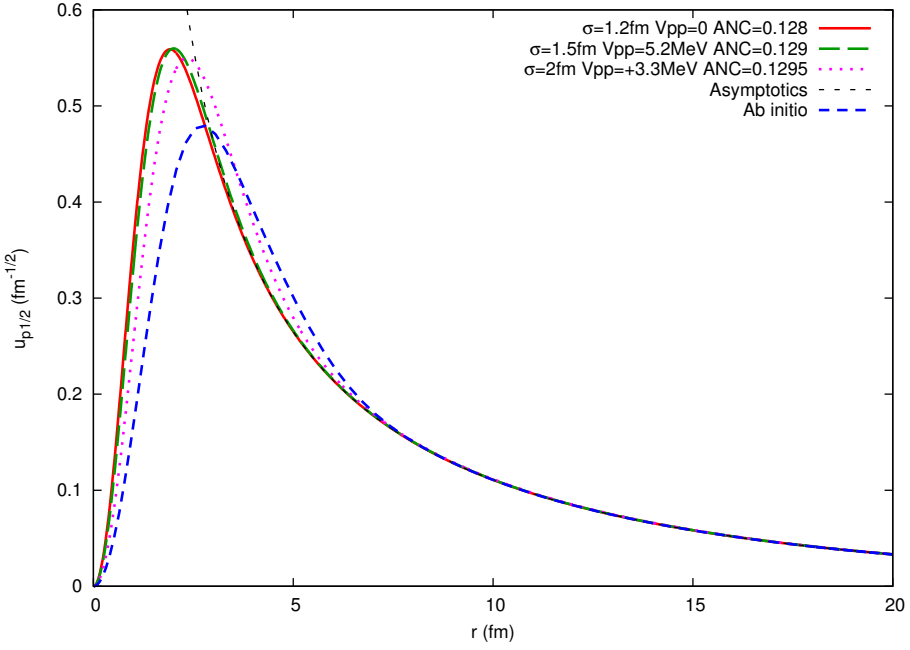
Daniel Phillips

Filomena Nunes

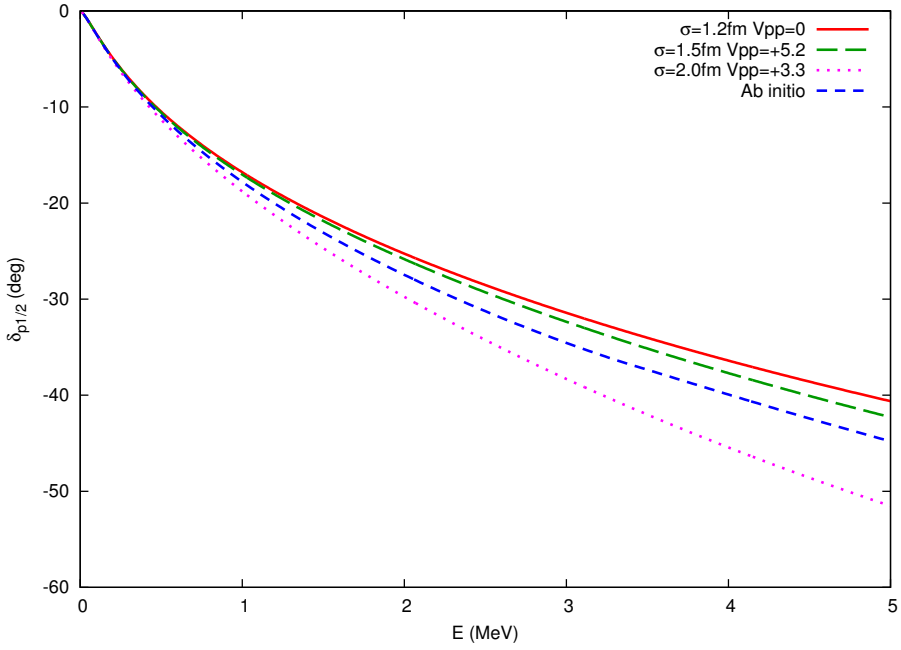
$p\frac{1}{2}$: potentials fitted to $\epsilon_{\frac{1}{2}^-}$ and $C_{\frac{1}{2}^-}$

Potentials fitted to $\epsilon_{0p\frac{1}{2}} = -0.184$ MeV and $C_{0p\frac{1}{2}} = 0.129$ fm$^{-1/2}$

Excited-state wave function

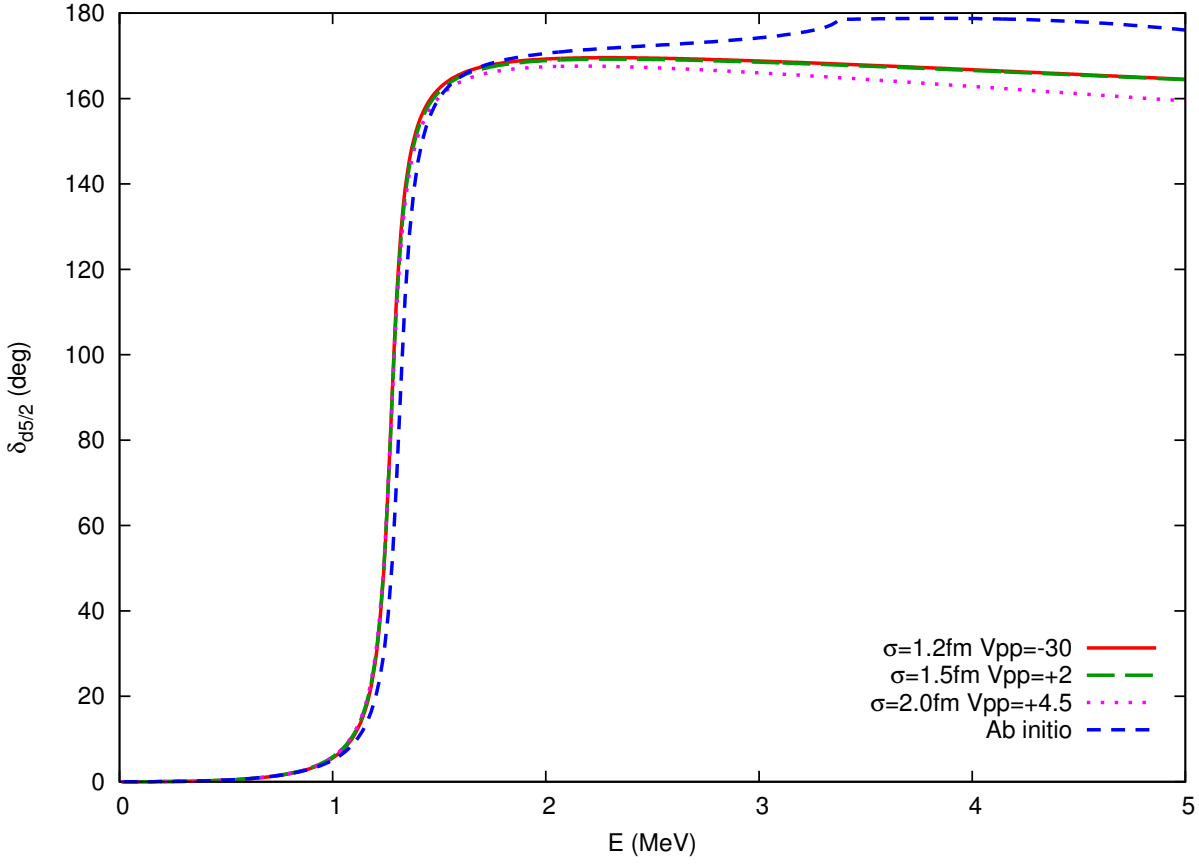


$p_{1/2}$ phaseshifts



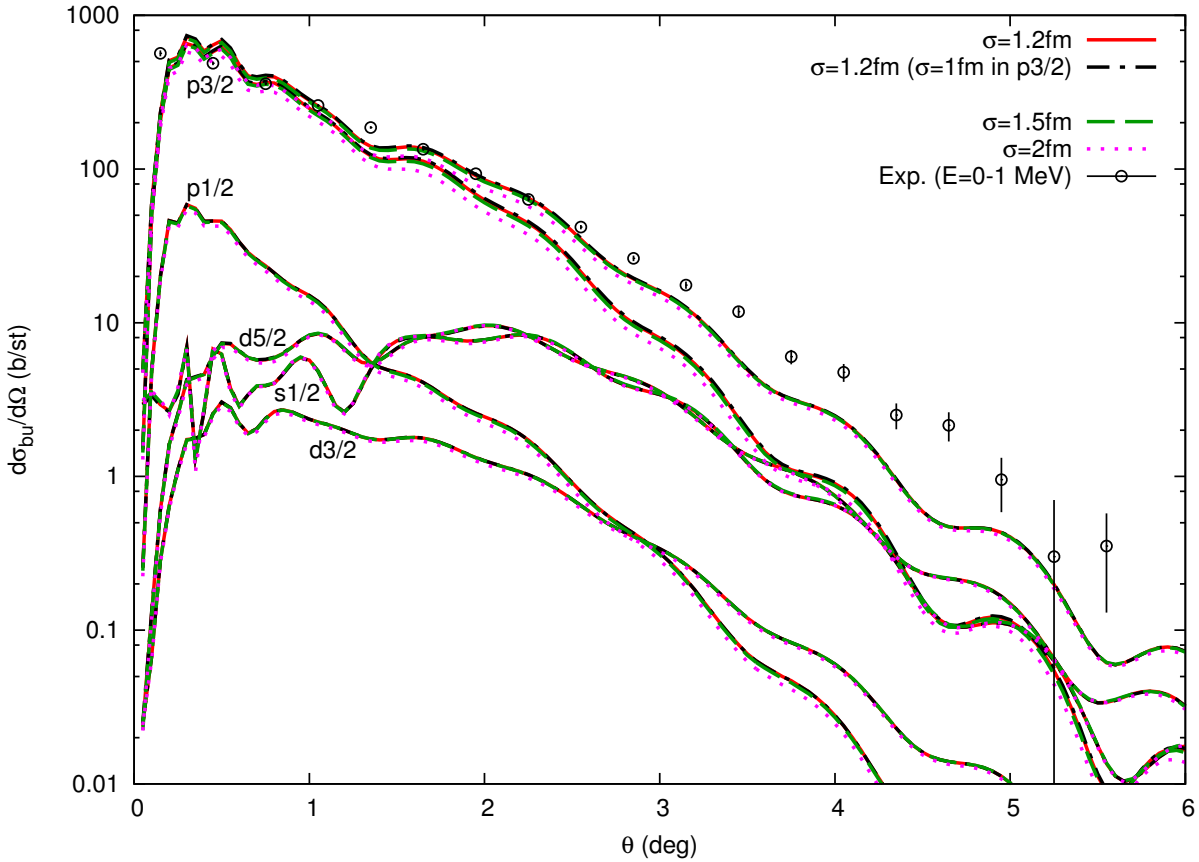
- Wave functions : same asymptotics but different interior
- Larger variation in $\delta_{p\frac{1}{2}}$ obtained by effective potentials
  Fair agreement with ab initio results up to 1 MeV

$d\frac{5}{2}$: 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 for all potentials
  up to 5 MeV for the narrow potentials ($\sigma = 1.2$ and 1.5 fm)
- Good agreement with ab initio results up to 2 MeV

^{11}Be+Pb$\rightarrow^{10}$Be+n+Pb @ 69AMeV



- Good agreement with experiment
- All potential provide similar cross sections ($\sigma = 2$ fm slightly lower)