Dissecting reaction calculations using halo EFT and *ab initio* input

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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}

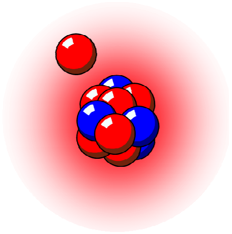
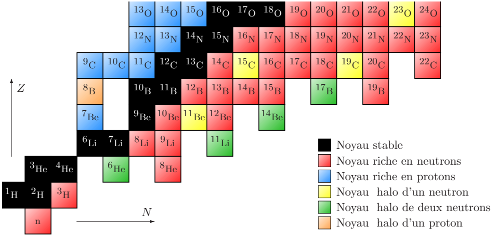


Exhibit large matter radius
due to strongly clusterised structure :
neutrons tunnel far from the core and form a halo

One-neutron halo
^{11}Be $\equiv$ ^{10}Be + n
^{15}C $\equiv$ ^{14}C + n
Two-neutron halo
^{6}He $\equiv$ ^{4}He + n + n
^{11}Li $\equiv$ ^{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 [$\tau_{1/2}(^{11}\text{Be}) = 13$ s]
$\Rightarrow$ require indirect techniques, new probes, like reactions :

Knock-out (see N. Orr's talk)
Breakup $\equiv$ dissociation of halo from core
by interaction with target

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

We address this by coupling precise reaction models with halo EFT

1. Reaction model

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

3. Breakup calculations of ^{11}Be into ^{10}Be+n
   - NLO analysis ($s_{\frac{1}{2}}$ and $p_{\frac{1}{2}}$ constrained)
   - Constraining the ^{10}Be-n continuum

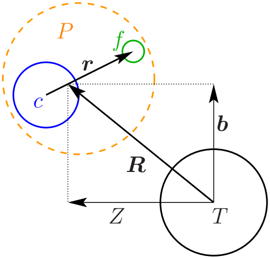
4. Summary

Framework

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

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

V_{cf} effective interaction
describes the quantum system
with ground state Φ_0



Target T seen as structureless

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

We use the Dynamical Eikonal Approximation (DEA)
[Baye, P. C., Goldstein, PRL 95, 082502 (2005)]

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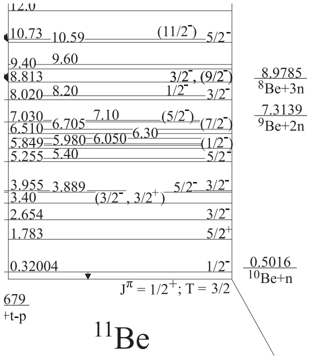
Usual phenomenological description

In reaction models, projectile ≡ two-body system :

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

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

^{11}Be $\equiv$ ^{10}Be $\otimes$ n



- $\frac{1}{2}^+$ ground state :
  $\epsilon_{\frac{1}{2}^+} = -0.503$ 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^+)
- What should we do for the continuum ?
  (e.g. what about the $p_{\frac{3}{2}}$ partial wave ?)
  Does it matter ?
  Can halo EFT provide an answer ?

^{10}Be-n potential

Replace the ^{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
[H.-W. Hammer, C. Ji, D. R. Phillips JPG 44, 103002 (2017)]

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} (@ LO), and C_{lj} (@ NLO for bound states)

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

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

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)]

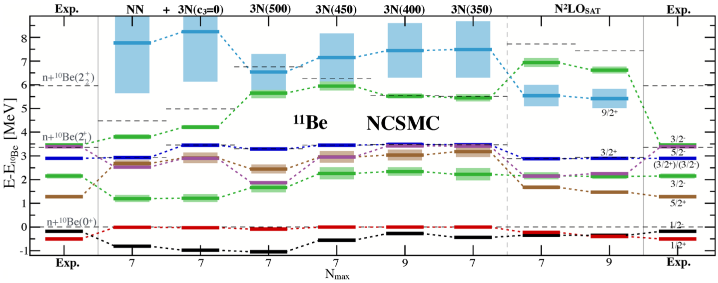


FIG. 2. NCSMC spectrum of ^{11}Be with respect to the $n + {}^{10}$Be threshold. Dashed black lines indicate the energies of the ^{10}Be states. Light boxes indicate resonance widths. Experimental energies are taken from Refs. [1,51].

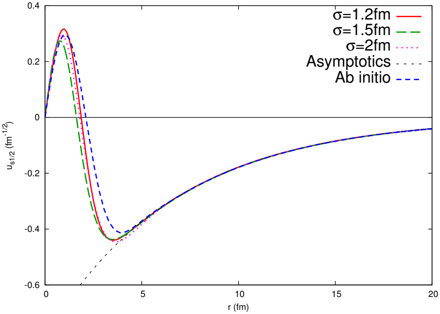
- $\frac{1}{2}^+$ ground state :
  $\epsilon_{\frac{1}{2}^+} = -0.500$ MeV
  $C_{\frac{1}{2}^+} = 0.786$ fm$^{-1/2}$
  $\mathcal{S}_{1s\frac{1}{2}} = 0.90$

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

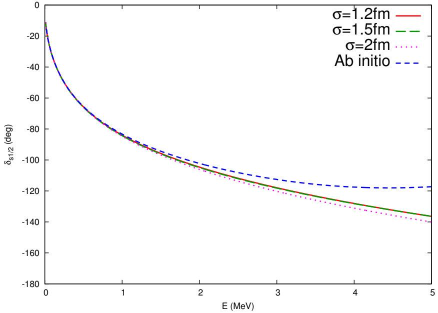
$s\frac{1}{2}$: @ NLO potentials fitted to $\epsilon_{\frac{1}{2}^+}$ and $C_{\frac{1}{2}^+}$

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

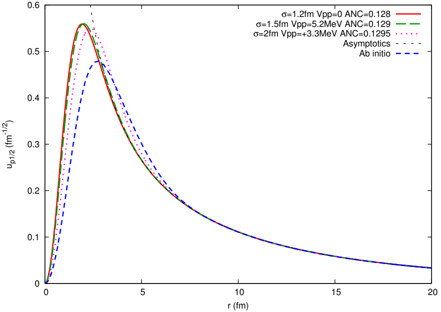


- Wave functions : same asymptotics but different interior
- $\delta_{s\frac{1}{2}}$: all effective potentials are in good agreement with ab initio up to 1.5 MeV (same effective-range expansion)

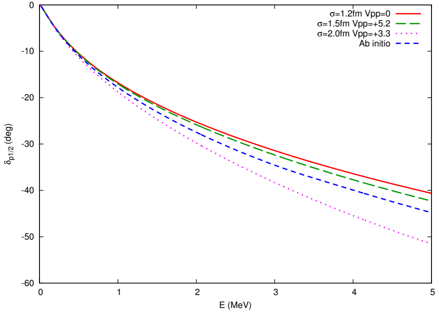
$p\frac{1}{2}$: @ NLO potentials fitted to $\epsilon_{\frac{1}{2}^-}$ and $C_{\frac{1}{2}^-}$

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 0.5 MeV
- In higher partial waves ($lj \geq p3/2$) $V_{lj} = 0$

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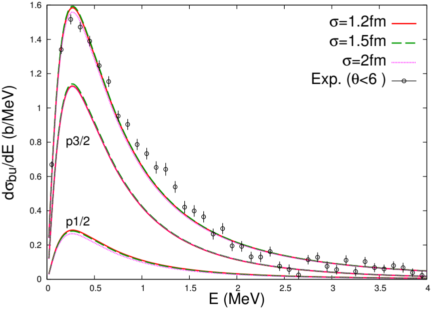
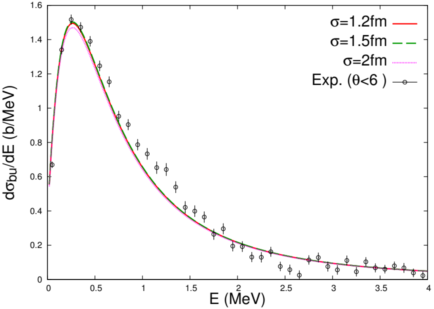
NLO analysis of ^{11}Be+Pb→^{10}Be+n+Pb @ 69AMeV

Total breakup cross section and p contributions

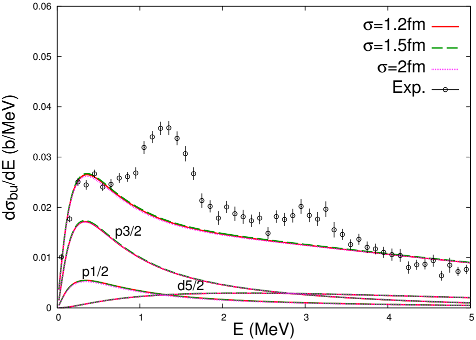


Folded with experimental resolution



- All calculations provide very similar results,
  for all σ, despite the difference in the internal part of the wave function
  ⇒ reaction is peripheral
- Slight differences in the $p_{1/2}$ contribution, due to differences in $\delta_{p1/2}$
- 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)
- 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

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

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

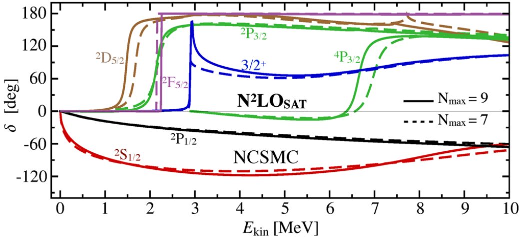
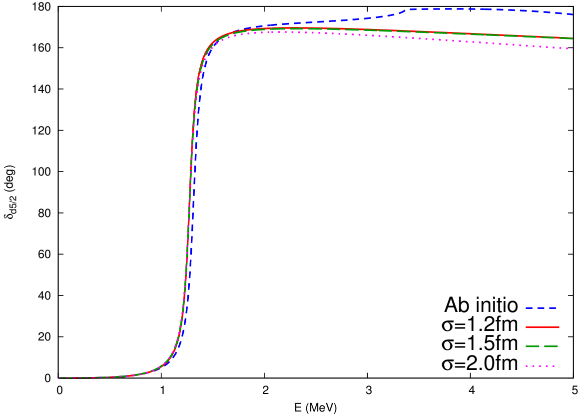


FIG. 3. The $n + {}^{10}$Be phase shifts as a function of the kinetic energy in the center-of-mass frame. NCSMC phase shifts for the N^{2}LO$_{\rm SAT}$ interaction are compared for two model spaces indicated by $N_{\rm max}$.

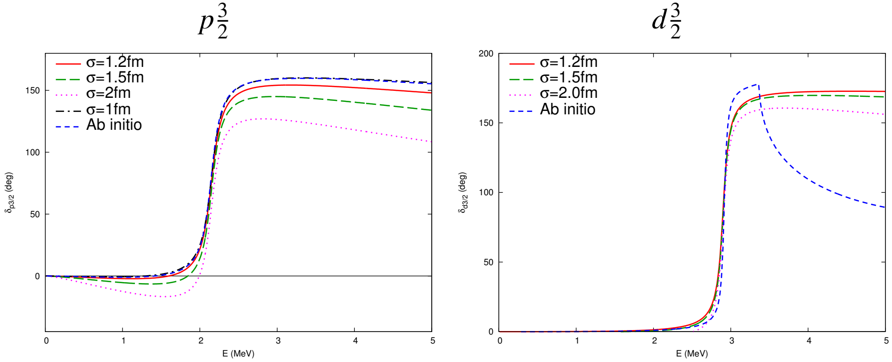
Idea : constrain the ^{10}Be-n potential in the reaction code
to reproduce ab initio δ_{lj},
i.e. fit V_0 and V_2 to reproduce ϵ_{lj} & Γ_{lj} (in $d_{\frac{5}{2}}$, $p_{\frac{3}{2}}$, and $d_{\frac{3}{2}}$)

$d\frac{5}{2}$: 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

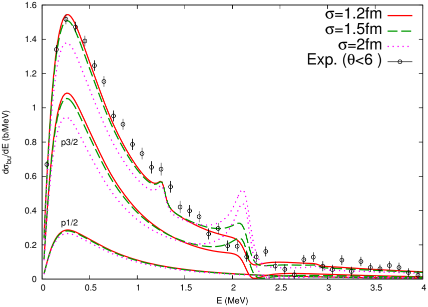
$p\frac{3}{2}$ and $d\frac{3}{2}$: potentials fitted to ϵ^{res} and Γ



- 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 @ 69AMeV (beyond NLO)

Total breakup cross section and p contributions



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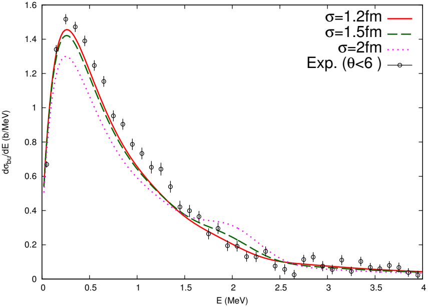
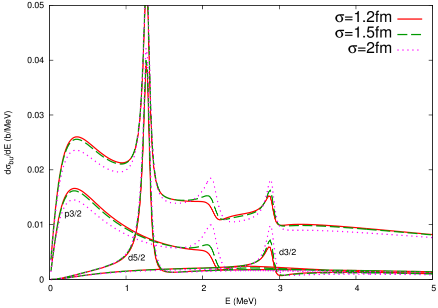


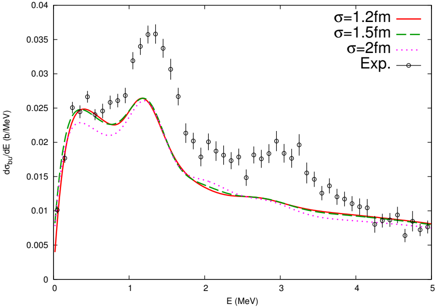
- Major differences in $p_{3/2}$ partial wave ; due to differences in $\delta_{p_{3/2}}$
- Broad potential ($\sigma = 2$ fm) produces unrealistic $p_{3/2}$ contribution
- Tiny peak at 1.27 MeV due to $d_{\frac{5}{2}}$ resonance
- Excellent agreement with data [Fukuda *et al.* PRC 70, 054606 (2004)]
  Best agreement with $\sigma = 1.2$ and 1.5 fm, whose $\delta_{p3/2} \sim \delta^{\text{ab initio}}_{3/2^-}$

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

Total breakup cross section and dominant contributions



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



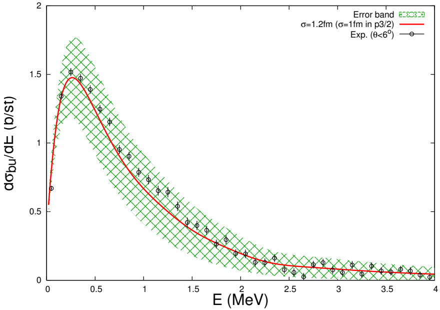
- All potentials produce similar breakup cross sections (but $\sigma = 2$ fm)
- In nuclear breakup, resonances play significant role
- Order of magnitude of experiment well reproduced
- But resonant breakup not correctly described due to degrees of freedom [$^{10}\mathrm{Be}(2^+)$] missing in the effective model

Estimation of the uncertainty within halo-EFT

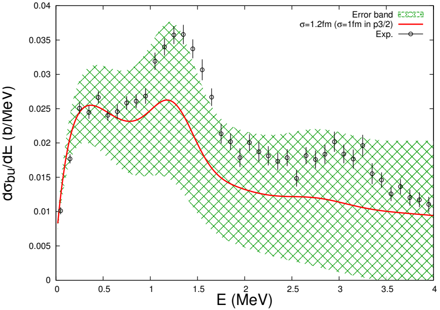
We estimate the uncertainty @ NLO through

$$\frac{E + S_n}{E(^{10}\mathrm{Be}(2^+)) + S_n}$$

^{11}Be+Pb→^{10}Be+n+Pb @ $69A$MeV



^{11}Be+C→^{10}Be+n+C @ $67A$MeV



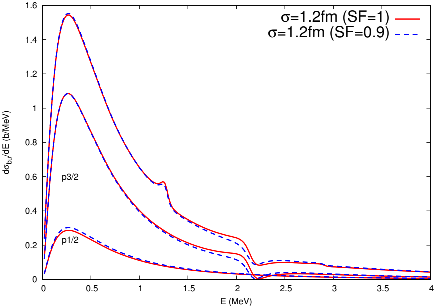
- Data are within uncertainty bands
- Effect of $^{10}\mathrm{Be}(2^+)$ more significant in reaction on C

SF vs ANC

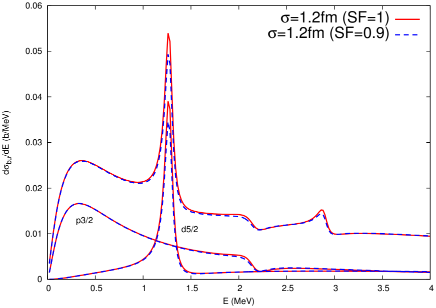
Calci *et al.* predict $\mathcal{S}_{1s\frac{1}{2}} = 0.90$, but we use $\mathcal{S}_{1s\frac{1}{2}} = 1\ldots$

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

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



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



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
  Can we understand what reactions probe using halo EFT ? Yes
- 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
- Halo EFT
  - efficient way to include the significant degrees of freedom
    e.g., by fitting ab initio predictions
    (for ^{11}Be, we confirm the ANC predicted by Calci *et al.*)
  - estimates the influence of omitted mechanisms
    e.g., short-range details missing in resonances description

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Daniel Phillips

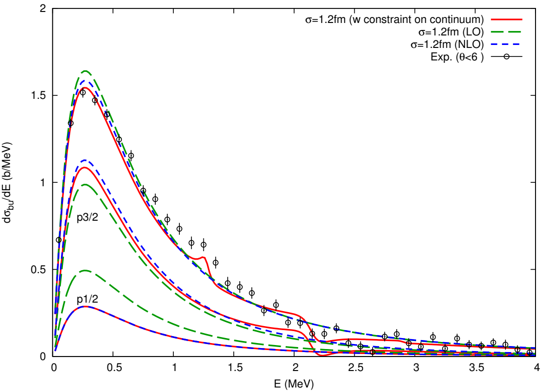
OHIO UNIVERSITY

Filomena Nunes

NSCL

LO, NLO and beyond

Calculations repeated with $\sigma = 1.2$ fm @ LO, NLO and beyond



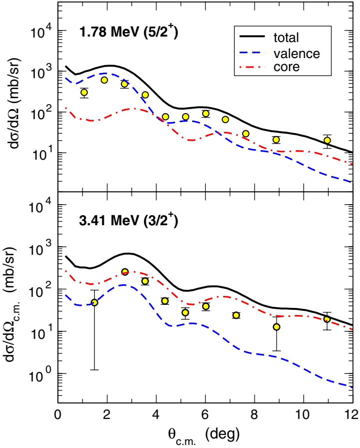
- Similar $p_{3/2}$ contributions, consistent with $\delta_{p3/2} = 0$
- Significant change in $p_{1/2}$ contribution due to excited bound state

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