Nuclear Haloes
and how to study them through reactions

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Halo nuclei

Exotic nuclear structures are found far from stability

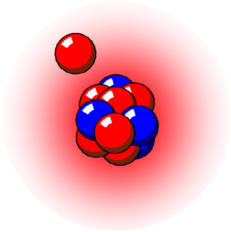
In particular halo nuclei with peculiar quantal structure :

- Light, n-rich nuclei
- Low S_{n} or $S_{2\mathrm{n}}$

Exhibit large matter radius

due to strongly clusterised structure :

neutrons tunnel far from the core and form a halo



One-neutron halo

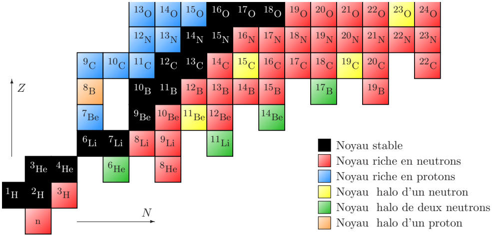
^{11}Be ≡ ^{10}Be + n

^{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]
⇒ require indirect techniques, like reactions

Elastic scattering

Breakup ≡ 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

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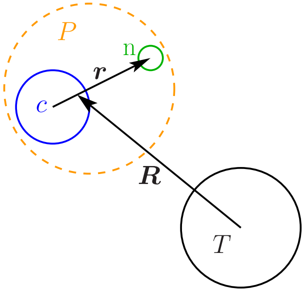
. . . or a reaction-independent observable

Framework

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

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



$V_{c\mathrm{n}}$ adjusted to reproduce
bound state Φ_0
and resonances

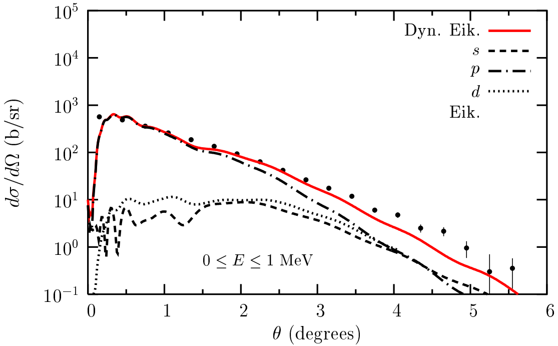
Target T seen as
structureless particle
P-T interaction simulated by optical potentials
$\Rightarrow$ collision reduces to three-body scattering problem :

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

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

Various techniques to solve this equation : CDCC, eikonal,...

^{11}Be+Pb @ $69A$MeV : Angular distribution

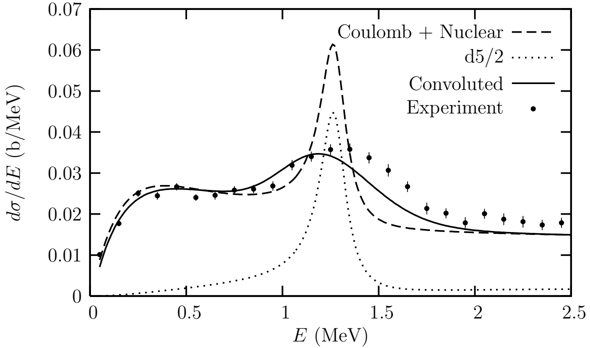


Theory : [Goldstein, Baye, P.C., PRC 73, 024602 (2006)]

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

Dynamical model in excellent agreement with experiment

^{11}Be+C @ $67A$MeV : Energy distribution



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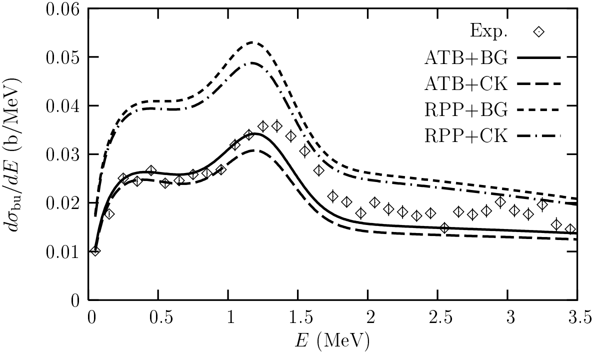
Excellent agreement with experiment

Peak due to a $5/2^+$ resonance described in the $d_{5/2}$ partial wave

However. . .

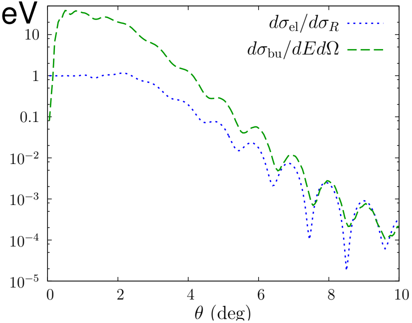
. . . results depends on V_{cT} (and slightly on V_{nT})



Since the core c is itself exotic, V_{cT} is usually poorly known
$\Rightarrow$ need an observable independent from the reaction mechanism

Analysis of angular distributions

^{11}Be+Pb @ $69A$MeV



[P.C., Hussein, Baye, PLB 693, 448 (2010)]

Very similar features for scattering and breakup :

- oscillations at forward angles
- Coulomb rainbow ($\sim 2°$)
- oscillations at large angles

⇒ projectile scattered similarly bound or broken up

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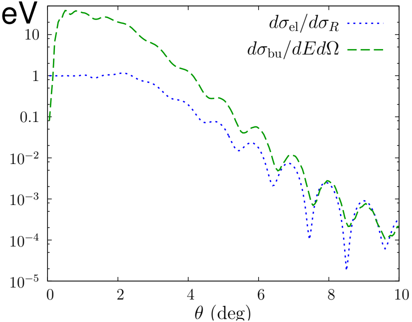

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Explained by Recoil Excitation and Breakup model. . .

Recoil Excitation and Breakup

REB assumes [Johnson, Al-Khalili, Tostevin PRL 79, 2771 (1997)]

- adiabatic approximation
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Elastic scattering : $$\frac{d\sigma_{\mathrm{el}}}{d\Omega} = |F_{00}|^2 \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{pt}}$$

with $F_{00} = \int |\Phi_0|^2 e^{i\boldsymbol{Q}\cdot\boldsymbol{r}} d\boldsymbol{r}$ $\quad \boldsymbol{Q} \propto (\boldsymbol{K} - \boldsymbol{K}')$

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Similarly for breakup : $$\frac{d\sigma_{bu}}{dEd\Omega} = |F_{E0}|^2 \left(\frac{d\sigma}{d\Omega}\right)_{pt}$$

with $|F_{E0}|^2 = \sum_{ljm} \left| \int \Phi_{ljm}(E)\, \Phi_0\, e^{i\boldsymbol{Q}\cdot\boldsymbol{r}} d\boldsymbol{r} \right|^2$

$\Rightarrow$ explains similarities in angular distributions

provides the idea for the ratio method...

Ratio method

$$d\sigma_{\rm bu}/d\sigma_{\rm el} = |F_{E0}(\boldsymbol{Q})|^2/|F_{00}(\boldsymbol{Q})|^2$$

- independent of reaction mechanism
  not affected by V_{PT} ; i.e. the same for all targets
- probes only projectile structure

Test this using a dynamical reaction model,

- without adiabatic approximation
- including $V_{\rm n\mathit{T}}$

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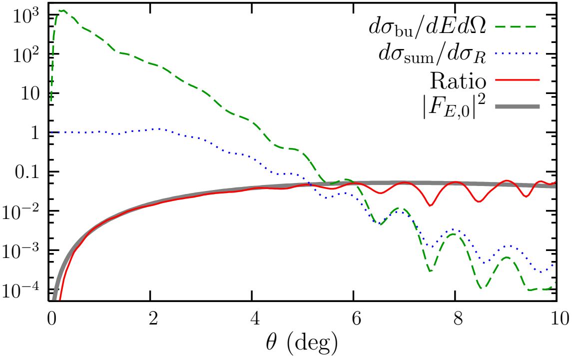
Alternative :

$$\begin{aligned} d\sigma_{\rm bu}/d\sigma_{\rm sum} &= |F_{E0}|^2 \\ &= \sum_{ljm} \left| \int \Phi_{ljm}(E)\, \Phi_0\, e^{i\boldsymbol{Q}\cdot\boldsymbol{r}} d\boldsymbol{r} \right|^2 \end{aligned}$$

$$\text{with } \frac{d\sigma_{\rm sum}}{d\Omega} = \frac{d\sigma_{\rm el}}{d\Omega} + \frac{d\sigma_{\rm inel}}{d\Omega} + \int \frac{d\sigma_{\rm bu}}{dE\,d\Omega} dE$$

Testing with dynamical model of reaction

^{11}Be+Pb @ $69A$MeV



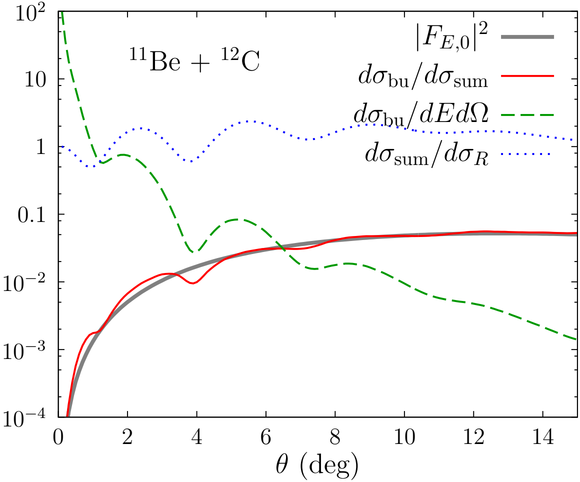
[P.C., Johnson, Nunes, PLB 705, 112 (2011) and PRC 88, 044602 (2013)]

- removes most of the angular dependence
- REB predicts ratio = $|F_{E0}|^2$
  confirmed by our calculations

$\Rightarrow$ probe structure with little dependence on reaction

^{11}Be+C @ 67AMeV

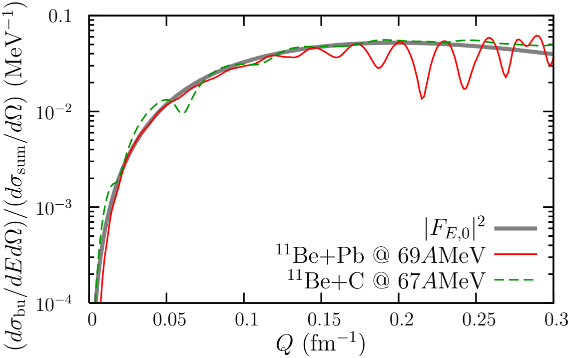
Same result on C target (i.e. nuclear dominated)



Very different $d\sigma_{\rm el}/d\Omega$ and $d\sigma_{\rm bu}/d\Omega$ but same ratio

⇒ independent of reaction mechanism

(In)sensitivity to V_{PT}

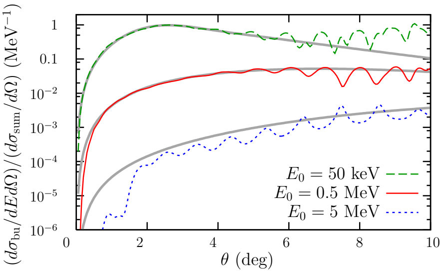


Similar for Coulomb and nuclear dominated collisions
⇒ independent of the reaction mechanism
⇒ probes only projectile structure

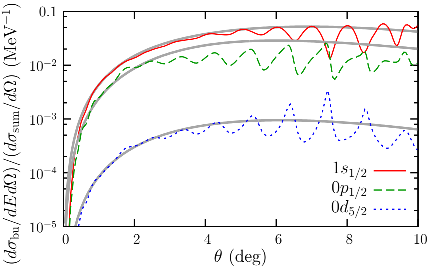
Sensitivity to projectile description

Sensitivity to

binding energy



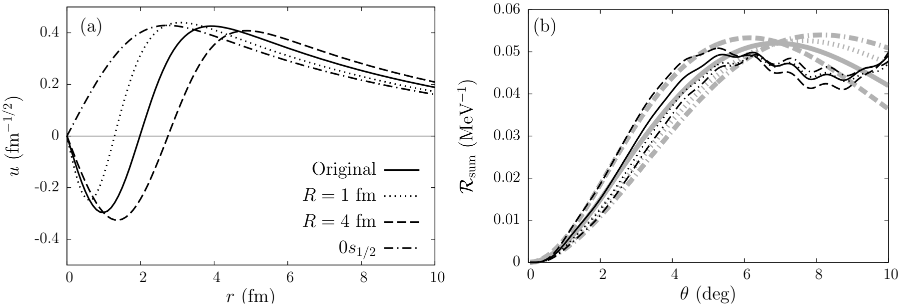
bound-state orbital



- Sensitive to both binding energy and orbital in both shape and magnitude
- Works better for loosely-bound projectiles (adiabatic approximation)

Sensitivity to radial wave function

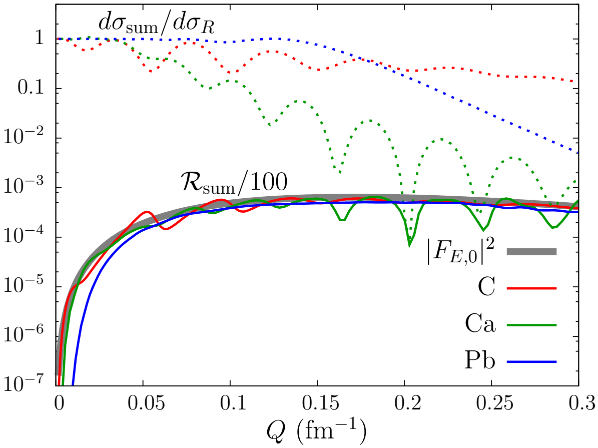
Calculations performed with different initial radial wave functions



- Smaller sensitivity than binding energy and partial wave
- At forward angles, scales with ANC
- At larger angles, probes the internal part of the wave function

Valid also at low energy

^{11}Be+ C, Ca, Pb @ $20A$MeV



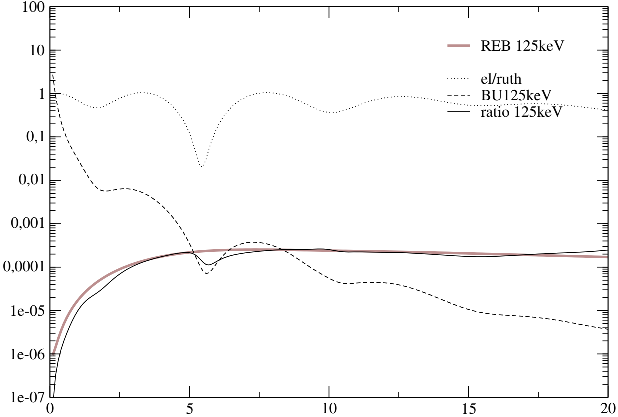
[Colomer, P.C., Nunes, Johnson, PRC 93, 054621 (2016)]

⇒ works also at low energy (HIE-Isolde, Re12@FRIB,. . .)

Extension to charged cases

What happens when p instead of n ?

Tests performed for $^{8}\mathrm{B} \equiv {}^{7}\mathrm{Be} + \mathrm{p}(p3/2)$ @ $44A$MeV on C



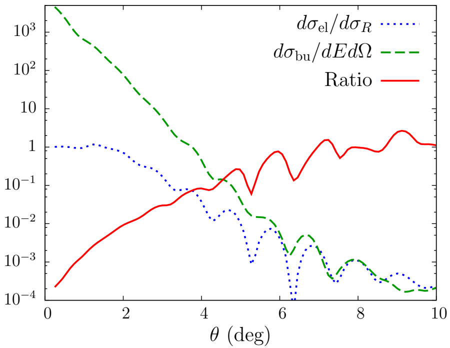
calculations by F. Colomer

Similar result as for c-n structure even if $V_{\mathrm{p}T}$ includes Coulomb

Extension to two-neutron haloes

Test on ^{11}Li + Pb @ $70A$MeV

[Pinilla, Descouvemont, Baye, PRC 85, 054610 (2012)]

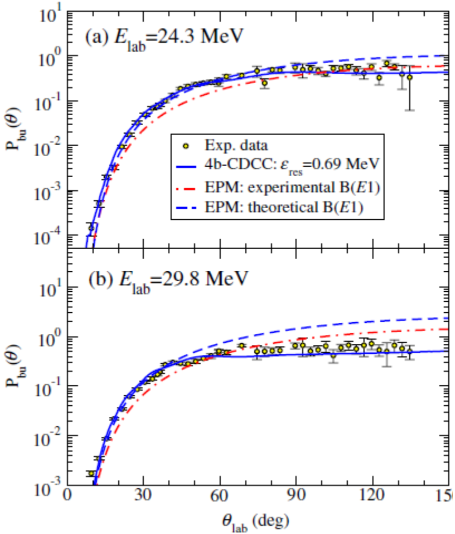


calculations by E. C. Pinilla

- Similar angular distributions for elastic scattering and breakup
- Ratio is smooth
- Need to extend REB to three-body projectiles

Experimental hopes

Scattering and breakup of ^{11}Li on Pb measured at TRIUMF



The breakup probability

$$P_{\rm bu}(\theta) = \frac{d\sigma_{\rm bu}/d\Omega}{d\sigma_{\rm el}/d\Omega + d\sigma_{\rm bu}/d\Omega}$$

follows a smooth curve,
as expected by ratio method

Excellent agreement with precise calculations

⇒ ratio could be extended to Borromean nuclei

[Fernàndez-Garcìa *et al.* PRL 110, 142701 (2013)]

Summary and prospect

- Halo nuclei exhibit a strongly clusterised structure : core + halo
- Studied mostly through reactions
  - elastic scattering
  - breakup
- Mechanism of reactions with halo nuclei understood
  but there remain uncertainties : optical potential choice
- Angular distributions similar for elastic scattering and breakup
  ⇒ ratio removes dependence on reaction mechanism
  ⇒ probes structure in more detail than other observables : see
  [P.C., Johnson, Nunes, PLB 705, 112 (2011)
  and PRC 88, 044602 (2013)]
- Can be used at low energy ($20A$MeV) and for proton haloes
- Can it be extended to Borromean nuclei ?
- Can it be used experimentally ?

Thanks to my collaborators

Filomena Nunes — NSCL

Daniel Baye
Edna Pinilla
Frederic Colomer — ULB

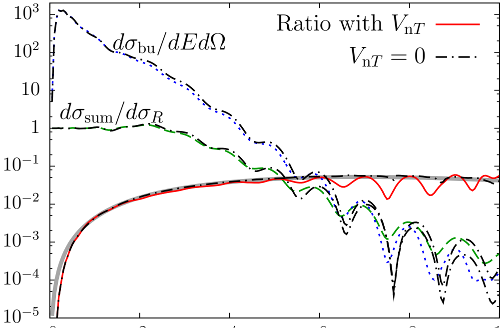
Mahir Hussein — Universidade de São Paulo

Ron Johnson — University of Surrey

Role of V_{nT}

REB neglects V_{nT}, it shifts slightly the angular distributions

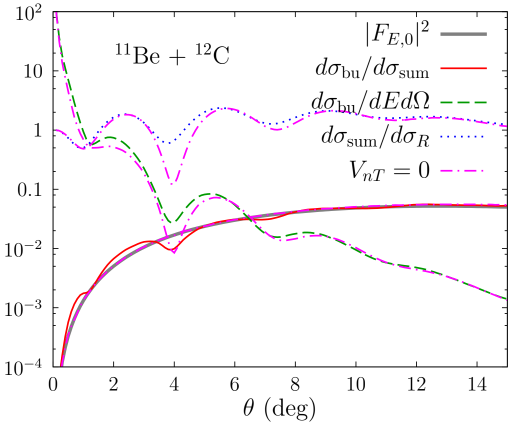
[R. Johnson *et al.* PRL 79, 2771 (97)]



⇒ responsible for the residual oscillations in the ratio

Role of $V_{\mathrm{n}T}$

Same conclusion on C



Oscillations at 2–4° due to $V_{\mathrm{n}T}$

$V_{\mathrm{n}T}$ known $\Rightarrow$ well under control