Extension of the ratio method to low energies and to charged halœs

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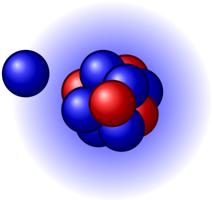
Halo Nuclei



- Very **neutron(/proton)-rich** nuclei
- **Large matter radius**

- **Compact core** surrounded by loosely-bound nucleon(s)
  → the neutron(s)(/the proton) form a **halo**.

  Examples: ^{11}Be, ^{15}C (one-neutron halo),
  ^{6}He, ^{11}Li (two-neutron halo).
  ^{8}B, ^{17}F (one-proton halo).

- **Small life times** → studied through **reactions**
  (e.g. elastic scattering, breakup, . . .)

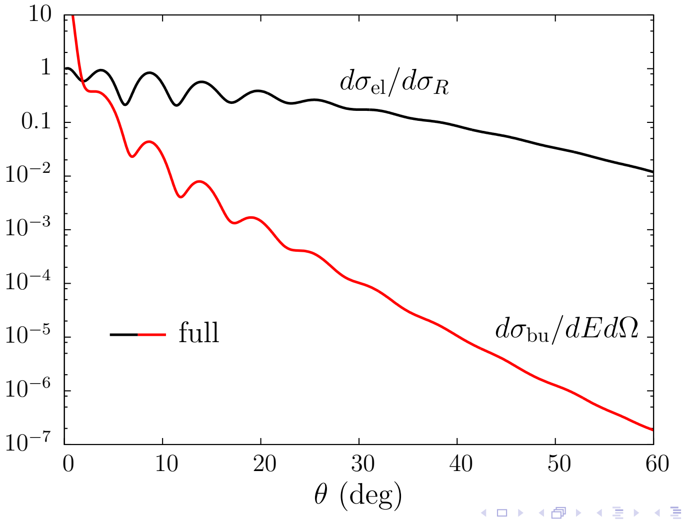
→ Need **accurate theoretical description of reactions**

Sensitivity of observables to reaction model

^{11}Be + ^{12}C → ^{11}Be + ^{12}C

^{11}Be + ^{12}C → ^{10}Be + n + ^{12}C

@20AMeV



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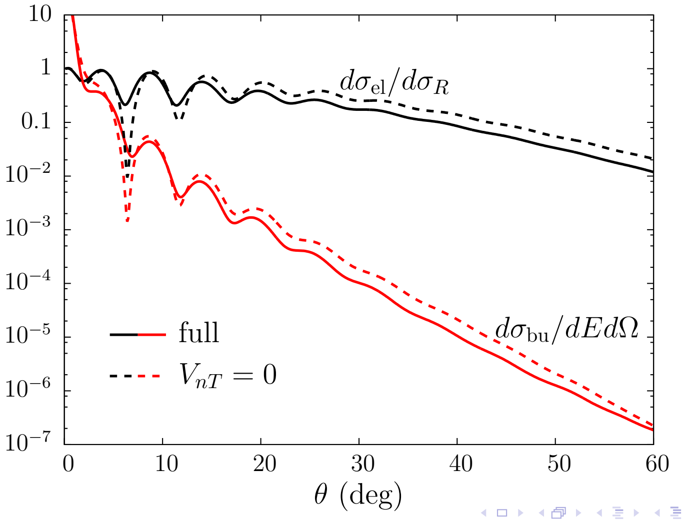

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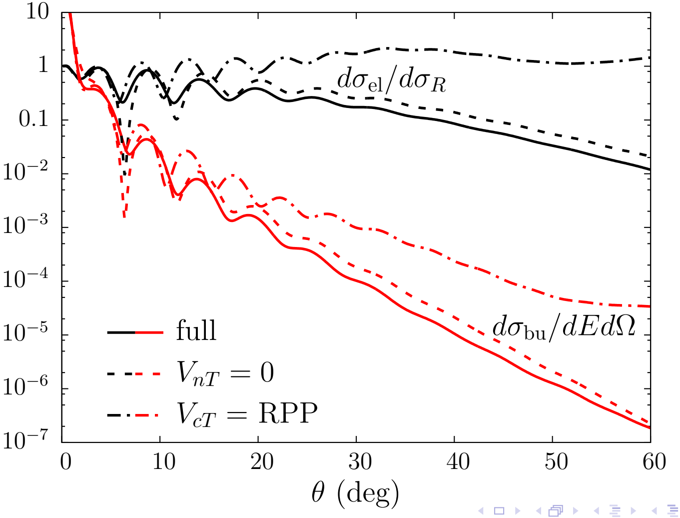

Sensitivity of observables to reaction process

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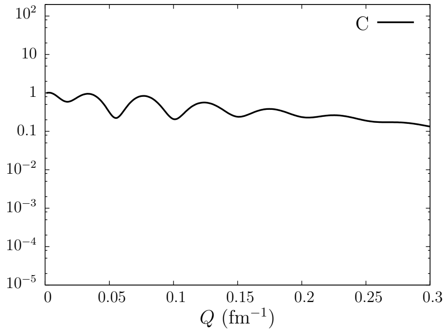
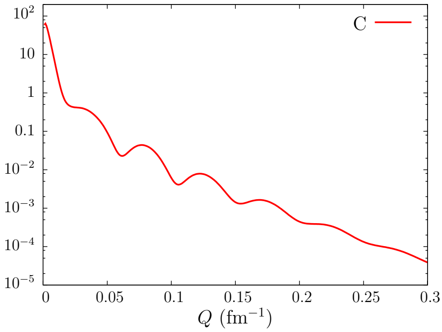
$d\sigma_{\text{el}}/d\sigma_{\text{R}}$



$d\sigma_{\text{bu}}/d\Omega dE$



Sensitivity of observables to reaction process

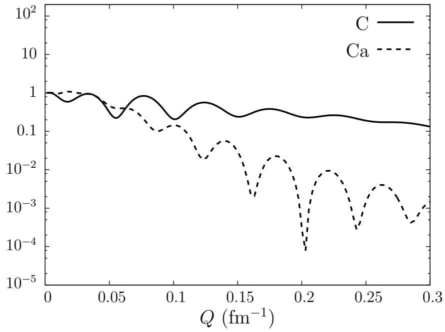
^{11}Be + ^{12}C/^{40}Ca → ^{11}Be + ^{12}C/^{40}Ca

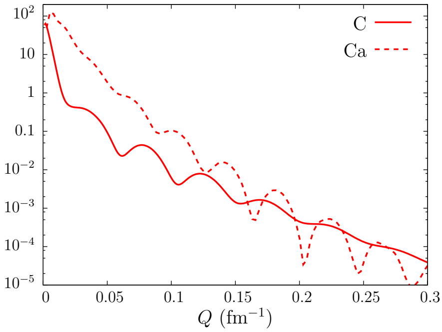
^{11}Be + ^{12}C/^{40}Ca → ^{10}Be + n + ^{12}C/^{40}Ca

@20AMeV

$d\sigma_{\text{el}}/d\sigma_{\text{R}}$

$d\sigma_{\text{bu}}/d\Omega dE$





Sensitivity of observables to reaction process

^{11}Be + ^{12}C/^{40}Ca/^{208}Pb $\rightarrow$ ^{11}Be + ^{12}C/^{40}Ca/^{208}Pb

^{11}Be + ^{12}C/^{40}Ca/^{208}Pb $\rightarrow$ ^{10}Be + n + ^{12}C/^{40}Ca/^{208}Pb

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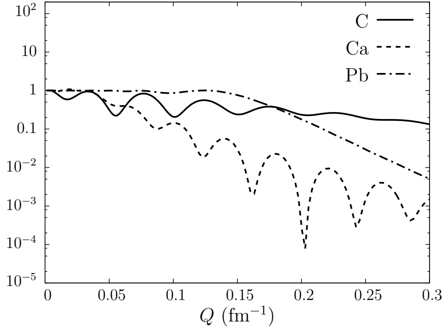
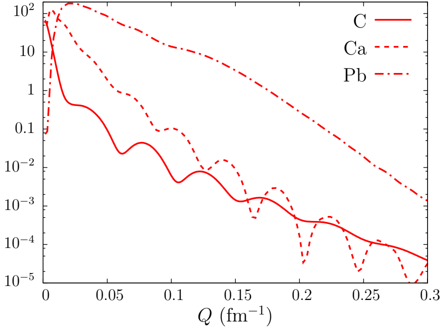
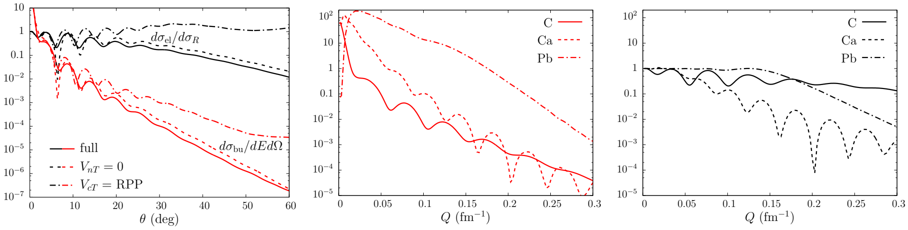
$d\sigma_{\text{el}}/d\sigma_{\text{R}}$



$d\sigma_{\text{bu}}/d\Omega dE$



The ratio



Sensitivity of elastic scattering and breakup in

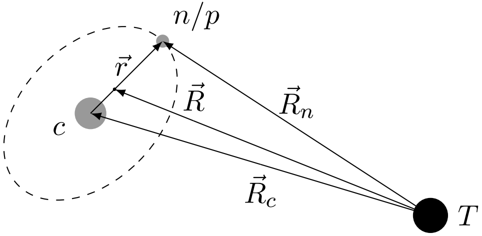
- the reaction model
- the reaction process

Information about the halo is **hidden**.

$\rightarrow$ Can we find an observable independent on reaction model/process ?

The **Ratio** ? ($\rightarrow$ Phys. Lett. B705, 112 (2011))

Projectile (P)
=
core (c)
+
neutron/proton (n/p)



Internal system hamiltonian

$$H_0 = -\frac{\hbar^2}{2\mu_{cN}}\Delta + V_{cN}(\vec{r})$$
$$(H_0 - E)\ \phi_{ljm}(E, \vec{r}) = 0$$

- $E_i < 0$ bound states
- $E \geq 0$ continuum breakup

Three-body problem hamiltonian

$$H_{3B}(\vec{R}, \vec{r}) = \hat{T}_{\vec{R}} - H_0(\vec{r}) + V_{cT}(\vec{R}_c) + V_{NT}(\vec{R}_n)$$

$$(H_{3B} - E_{tot})\ \Psi(\vec{R}, \vec{r}) = 0$$

The Recoil Excitation and Breakup model (REB)

Assumptions of the method:
(Phys. Rev. Lett. 79, 2771 (1997))

- Adiabatic approximation
- $V_{NT} = 0$

The elastic scattering amplitude of composite nucleus can be factorized

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{el}} = |F_{0,0}(\mathbf{Q})|^2 \left(\frac{d\sigma}{d\Omega}\right)_{\text{pt,el}}$$

- $\left(\frac{d\sigma}{d\Omega}\right)_{\text{pt,el}}$: el. scatt. of pointlike projectile by V_{cT}
- $|F_{0,0}(\mathbf{Q})|^2$ depends only on halo structure

$$|F_{0,0}(\mathbf{Q})|^2 = \frac{1}{2j_0+1} \sum_{m_0} \left| \int |\phi_{l_0 j_0 m_0}(\mathbf{r})|^2 e^{i\mathbf{Q}\cdot\mathbf{r}}\, d\mathbf{r} \right|^2$$

$\mathbf{Q} \propto$ transferred momentum

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For non-elastic processes : inelastic scattering, breakup

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{inel}} = |F_{i,0}(\mathbf{Q})|^2 \left(\frac{d\sigma}{d\Omega}\right)_{\text{pt,el}} \qquad \left(\frac{d\sigma}{dE d\Omega}\right)_{\text{bu}} = |F_{E,0}(\mathbf{Q})|^2 \left(\frac{d\sigma}{d\Omega}\right)_{\text{pt,el}}$$

Ratio of cross sections: cancel out V_{cT} dependence

The REB model and the ratio $\mathcal{R}_{\text{sum}}$

$$\mathcal{R}_{\text{sum}}(E, \mathbf{Q}) = \frac{(d\sigma/dEd\Omega)_{\text{bu}}}{(d\sigma/d\Omega)_{\text{sum}}}$$

with

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{sum}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{el}} + \sum_{i>0} \left(\frac{d\sigma_i}{d\Omega}\right)_{\text{inel}} + \int \left(\frac{d\sigma}{dEd\Omega}\right)_{\text{bu}} dE$$

and we have hence (in the REB model!)

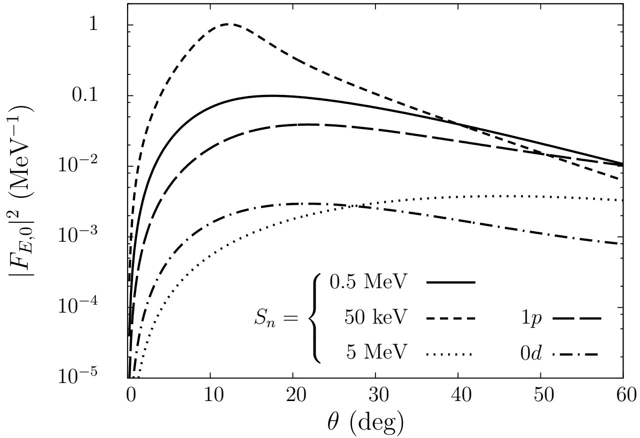
$$\mathcal{R}_{\text{sum}}(E, \mathbf{Q}) \overset{\text{(REB)}}{=} |F_{E,0}(\mathbf{Q})|^2$$

$$|F_{E,0}(\mathbf{Q})|^2 = \frac{1}{2j_0+1} \sum_{m_0} \sum_{ljm} \left| \int \phi_{ljm}(E, \mathbf{r}) \phi_{l_0 j_0 m_0}(\mathbf{r}) e^{i\mathbf{Q}\cdot\mathbf{r}} \, d\mathbf{r} \right|^2$$

Sensitivity of the $F_{E,0}$ to projectile structure

The form factor $|F_{E,0}|^2$ sensitive to

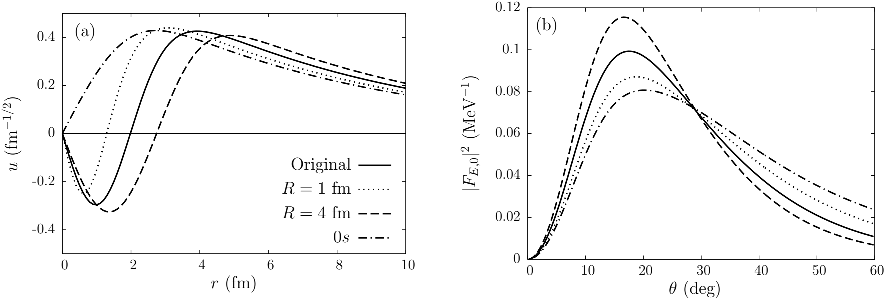
- Binding energy
- Bound state partial wave



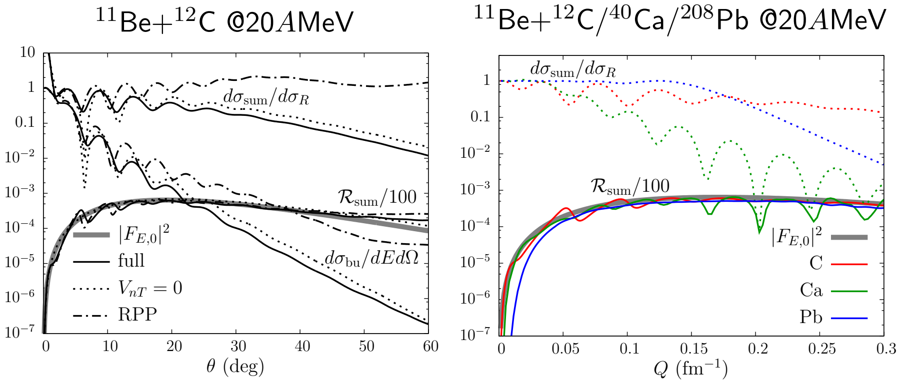
Sensitivity of the $F_{E,0}$ to projectile structure

The form factor $|F_{E,0}|^2$ sensitive to

- Bound state radial wave function



One-neutron halo at low energy

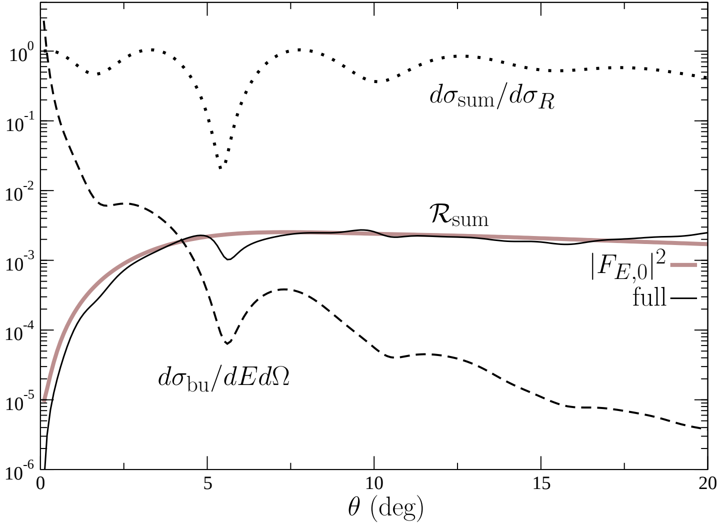


- Independence of the reaction model
- Independence of the reaction process

→ valid at low energy one-neutron halos (Phys. Rev. C 93, 054621 (2016))

One-proton halo at intermediate energy

^{8}B+^{12}C @44AMeV



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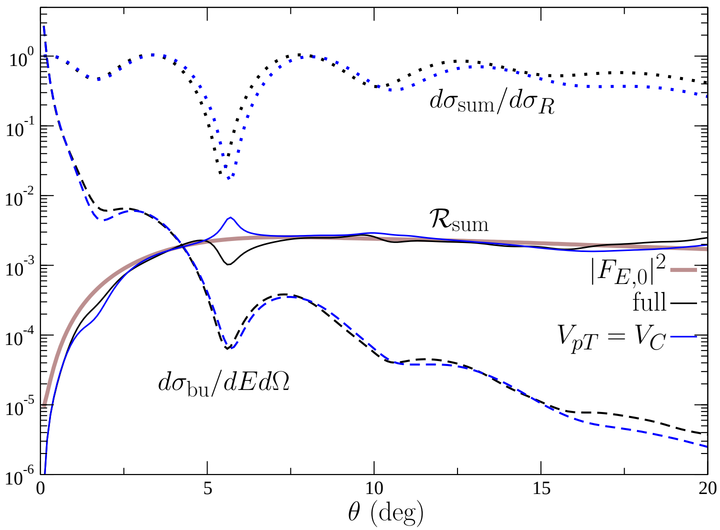

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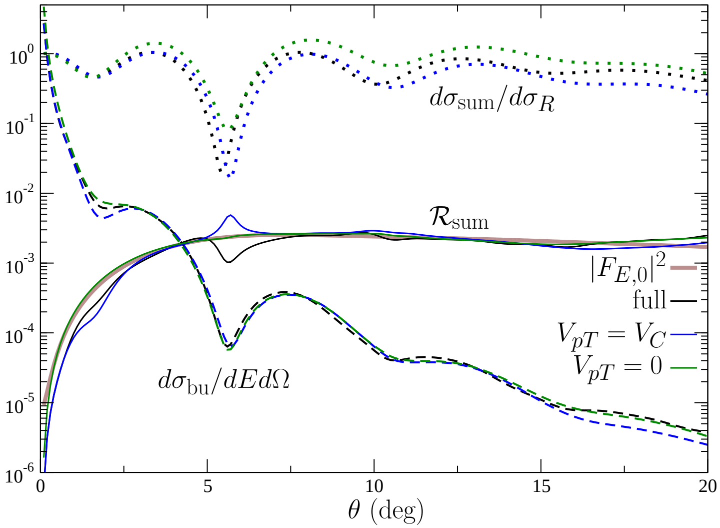

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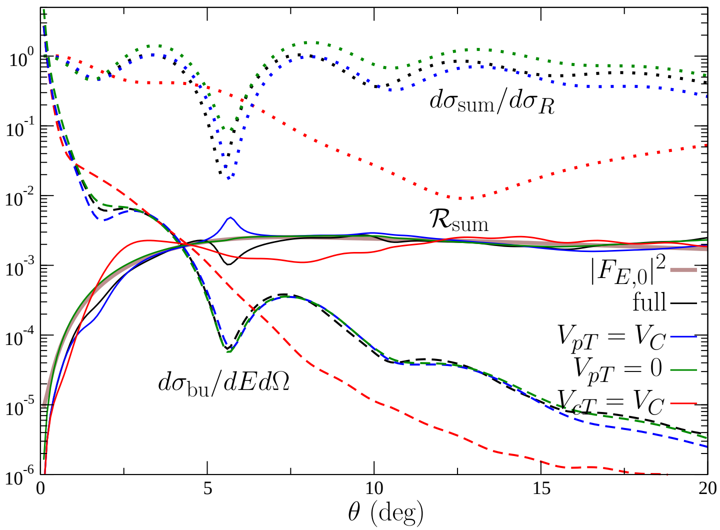
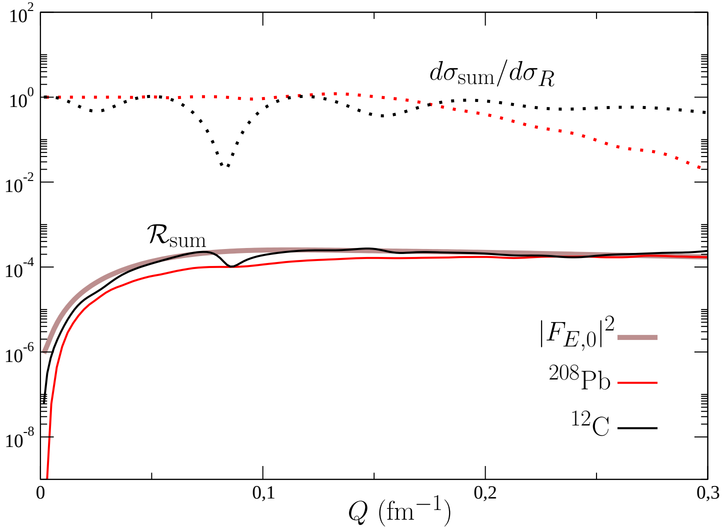


One-proton halo at intermediate energy

^{8}B+^{12}C/^{208}Pb @44AMeV



Conclusions and prospects

Conclusions

- The ratio removes the dependence in the reaction mechanism
- The ratio is still valid at low energies
- The ratio works for proton halœs at intermediate energies

Prospects

- Experimental confirmation
- Applicability to proton-halœs at low energy?
- Applicability to two-neutron halo systems?