Influence of the halo upon angular distributions

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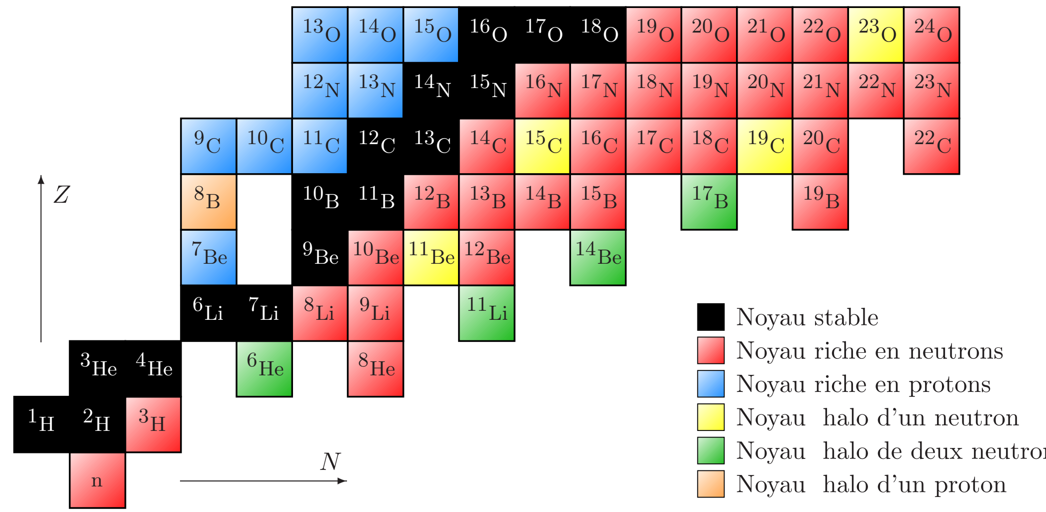
Outline

- Introduction on halo nuclei
- Description of reactions involving halo nuclei
  - DEA: Dynamical Eikonal Approximation
  - Angular distributions for elastic scattering and breakup
- Analysis of angular distributions
  - Near-Far decomposition
  - Sensitivity to V_{PT}
  - Sensitivity to extension of the halo
- Conclusions

Introduction: Halo Nuclei

Exotic nuclei with
peculiar quantal structure:

- Light, n-rich nuclei
- Large matter radius
- Low $S_{\rm n}$ or $S_{2\rm n}$



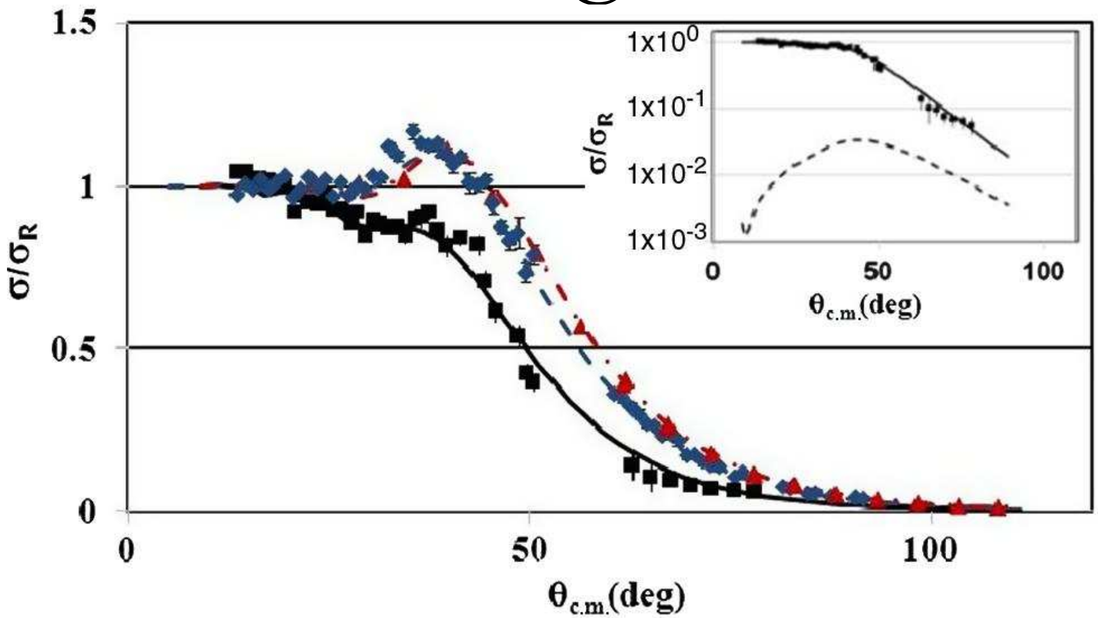
⇒ strongly clusterised system:
neutrons tunnel far from the core and form a halo

Halo nuclei are short-lived ⇒ studied in indirect ways:

- elastic scattering
- breakup
- …

Elastic scattering (experiment)

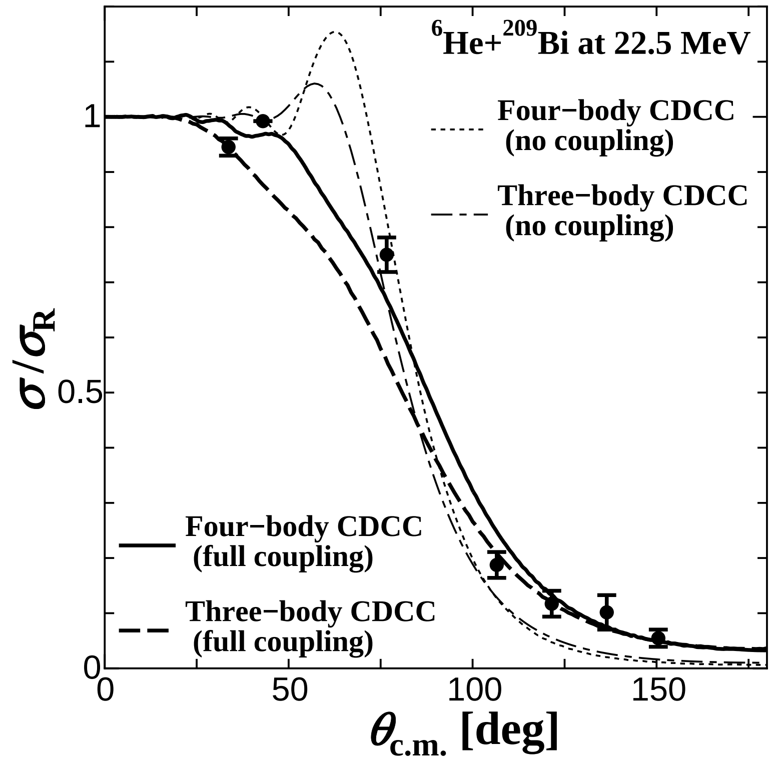
^{9,10,11}Be+Zn @ 24.5MeV



[Di Pietro *et al.*, PRL 105, 022701 (2010)]

- Scattering of ^{11}Be reduced compared to ^{9}Be and ^{10}Be
- Suggests transfer of flux from elastic channel to breakup channel

Elastic scattering (theory)



[Matsumoto *et al.*, PRC 73, 051602 (2006)]

- Scattering affected by breakup channel
  ⇒ Breakup must be included in description of reactions including loosely-bound projectile
- What happens in breakup angular distributions? Can we learn something about the halo?

Reaction model

To extract valuable information from experiment,
we need an accurate reaction model
coupled to realistic description of projectile

To analyse angular distributions, models should:

- describe coherently elastic scattering and breakup
- include quantal interferences

Dynamical Eikonal Approximation is such a model
valid at intermediate energies

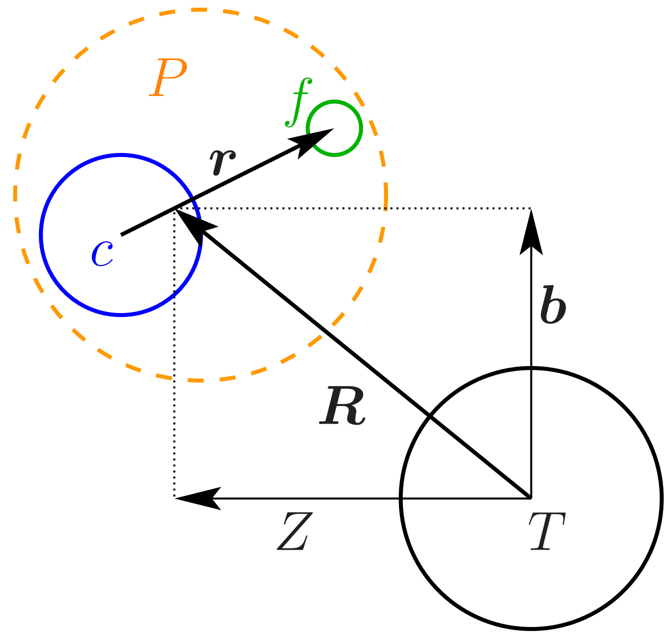
We will also compare our results with predictions of
adiabatic model of Johnson *et al.* [PRL 79, 2771 (1997)]

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 states and resonances



Target T seen as structureless particle

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

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

Eikonal model (1)

Three-body scattering problem

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

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

To remove the rapid variation in $\boldsymbol{R}$ we factorise $\Psi(\boldsymbol{r}, \boldsymbol{R}) = e^{iKZ}\widehat{\Psi}(\boldsymbol{r}, \boldsymbol{R})$:

$$\begin{aligned} H\Psi &= e^{iKZ}[T_R + vP_Z + \frac{1}{2}\mu_{PT}v^2 \\ &\quad + (H_0 + V_{cT} + V_{fT})]\widehat{\Psi} \end{aligned}$$

Neglecting T_R vs vP_Z and using $E_T = \frac{1}{2}\mu_{PT}v^2 + E_0$

$$i\hbar v \frac{\partial}{\partial Z}\widehat{\Psi}(\boldsymbol{r}, \boldsymbol{b}, Z) = [H_0 - E_0 + V_{cT} + V_{fT}]\widehat{\Psi}(\boldsymbol{r}, \boldsymbol{b}, Z)$$

Eikonal model (2)

$$i\hbar v \frac{\partial}{\partial Z}\widehat{\Psi}(\boldsymbol{r},\boldsymbol{b},Z) = [H_0 - E_0 + V_{cT} + V_{fT}]\widehat{\Psi}(\boldsymbol{r},\boldsymbol{b},Z)$$

is equivalent to a TDSE with straight line trajectories
but here $\boldsymbol{b}$ and Z are quantal
This is the Dynamical Eikonal Approximation
[Baye, Capel, Goldstein, PRL 95, 082502 (2005)]

Usual eikonal makes adiabatic approx. $H_0 - E_0 \sim 0$
$\Rightarrow$ neglects dynamical effects

$$\widehat{\Psi}^{\text{eik}}(\boldsymbol{r},\boldsymbol{b},Z\to\infty) = e^{i\chi(\boldsymbol{r},b)}\Phi_0(\boldsymbol{r}),$$

$$\chi(\boldsymbol{r},b) = -\frac{1}{\hbar v}\int_{-\infty}^{\infty} dZ\,[V_{cT}(\boldsymbol{r},\boldsymbol{b},Z) + V_{fT}(\boldsymbol{r},\boldsymbol{b},Z)]$$

DEA improves eikonal by including dynamical effects

Elastic-scattering

Elastic-scattering transition matrix element:

$$\begin{aligned}
T_{fi}^{\mathrm{el}} &= \langle e^{i\boldsymbol{K'}\cdot\boldsymbol{R}}\Phi_0|V_{cT}+V_{fT}|e^{iKZ}\widehat{\Psi}\rangle \\
&= \langle e^{i\boldsymbol{K'}\cdot\boldsymbol{R}}\Phi_0|H_0-E_0+V_{cT}+V_{fT}|e^{iKZ}\widehat{\Psi}\rangle \\
&= \langle\Phi_0|e^{i(KZ-\boldsymbol{K'}\cdot\boldsymbol{R})}(i\hbar v\frac{\partial}{\partial Z})|\widehat{\Psi}\rangle \\
&\approx i\hbar v\int d\boldsymbol{b}e^{i\boldsymbol{q}\cdot\boldsymbol{b}}\int_{-\infty}^{\infty}dZ\frac{\partial}{\partial Z}\langle\Phi_0|\widehat{\Psi}(\boldsymbol{R})\rangle,
\end{aligned}$$

assuming $\boldsymbol{q}=\boldsymbol{K'}-K\widehat{\boldsymbol{Z}}$ transverse

$$T_{fi}^{\mathrm{el}} = i\hbar v\int d\boldsymbol{b}e^{i\boldsymbol{q}\cdot\boldsymbol{b}}S_0(\boldsymbol{b}),$$

where $S_0(\boldsymbol{b})=\langle\Phi_0|\widehat{\Psi}(\boldsymbol{b},Z\to\infty)\rangle-1$

Elastic-scattering cross section

After integration over ϕ_b,

$$T_{fi}^{\rm el} \propto \int_0^\infty J_0(qb) S_0(b) b db$$

$\Rightarrow$ Cross section:

$$\frac{d\sigma_{\rm el}}{d\Omega} \propto \left| \int_0^\infty J_0(qb) S_0(b) b db \right|^2$$

DEA

- includes dynamical effects
  $\Rightarrow$ improves usual eikonal
- includes interferences between *trajectories*
  $\Rightarrow$ goes beyond semiclassical treatment

Near/Far decomposition

$\frac{d\sigma_{\text{el}}}{d\Omega}$ can be decomposed in Near and Far sides:

[Carlson, Filho, and M. H., PLB 154, 89 (1985)]

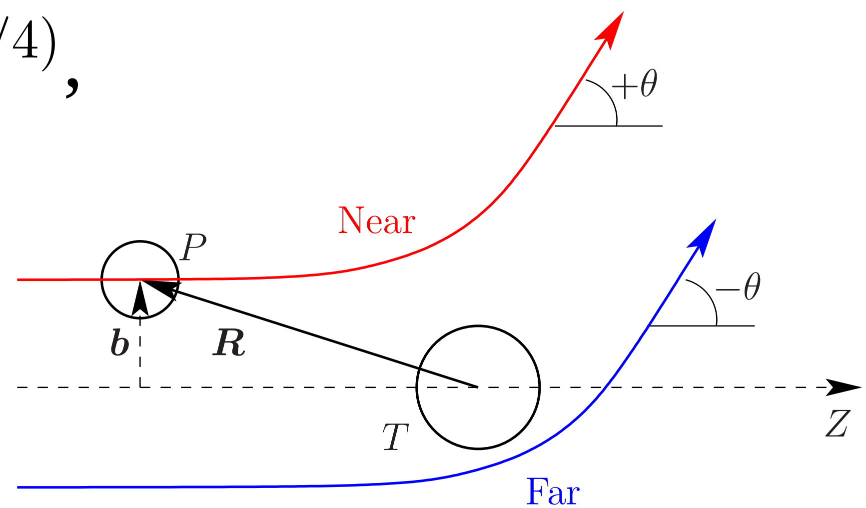
Using $J_0 = \frac{1}{2}(H_0^{(2)} + H_0^{(1)})$,

$$\frac{d\sigma_{\text{el}}^{\text{N,F}}}{d\Omega} \propto |\int_0^\infty H_0^{(2,1)}(qb)S_0(b)bdb|^2$$

$$H_0^{(1,2)}(z) \xrightarrow[z\to\infty]{} \sqrt{\frac{2}{\pi z}} e^{\pm i(z-\pi/4)},$$

Near $\equiv$ positive deflection

Far $\equiv$ negative deflection



$\Rightarrow$ tool to analyse angular distributions

Breakup cross section

Similarly,

$$T_{fi}^{\mathrm{bu}} \propto \sum_{lm} Y_l^m(\Omega_k) e^{im\varphi} \int_0^\infty J_{|m|}(qb) S_{klm}(b) b db,$$

where $S_{klm}(b) = \langle \Phi_{klm} | \widehat{\Psi}(Z \to \infty) \rangle$
contains all breakup information

Cross sections:

$$\frac{d\sigma_{\mathrm{bu}}}{d\boldsymbol{k} d\Omega} \propto |T_{fi}^{\mathrm{bu}}|^2 \xrightarrow{\int d\Omega_k} \frac{d\sigma_{\mathrm{bu}}}{dE d\Omega} \propto |\int_0^\infty J_{|m|}(qb) S_{klm}(b) b db|^2$$

⇒ DEA treats simultaneously and coherently
elastic scattering and breakup
N/F decomposition can also be done
for angular distributions for breakup

^{11}Be

We analyse $\frac{d\sigma_{\rm el}}{d\Omega}$ and $\frac{d\sigma_{\rm bu}}{dEd\Omega}$ for ^{11}Be on Pb @ $70A$MeV

^{11}Be is the best known one-neutron halo nucleus

Its breakup on C and Pb measured at RIKEN

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

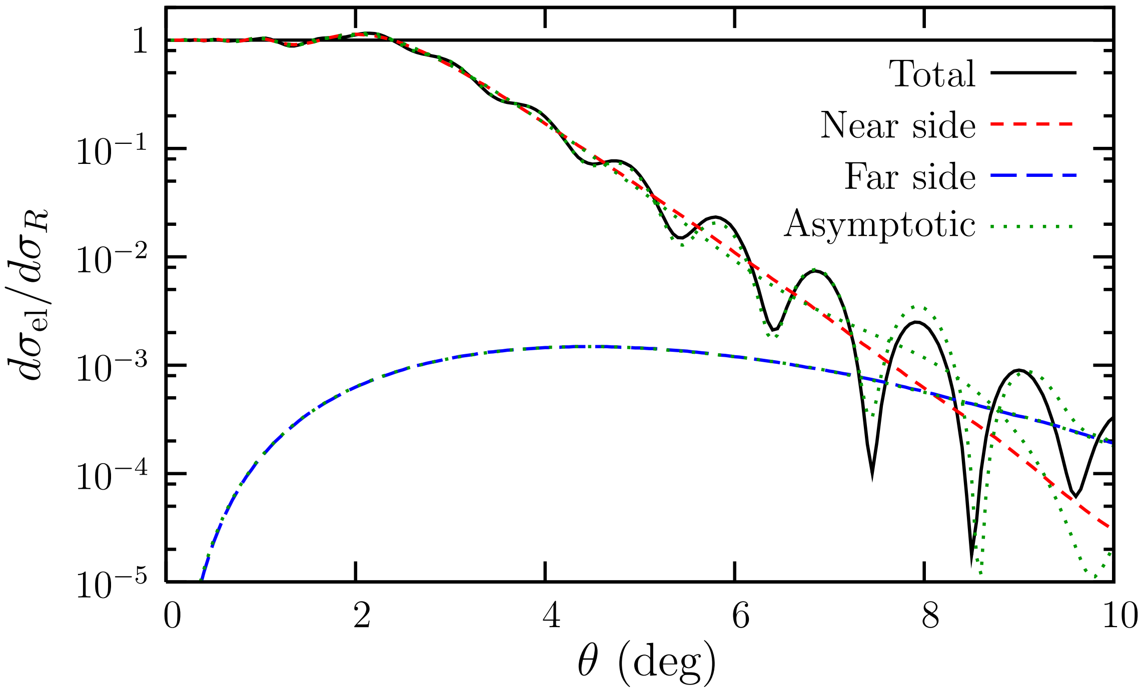
^{10}Be-n potential chosen to reproduce first three states

$5/2^+$	1.274 MeV	$d5/2$
$1/2^-$	-0.184 MeV	$0p1/2$
$1/2^+$	-0.504 MeV	$1s1/2$

We use a W-S with parity dependence depth plus S-O

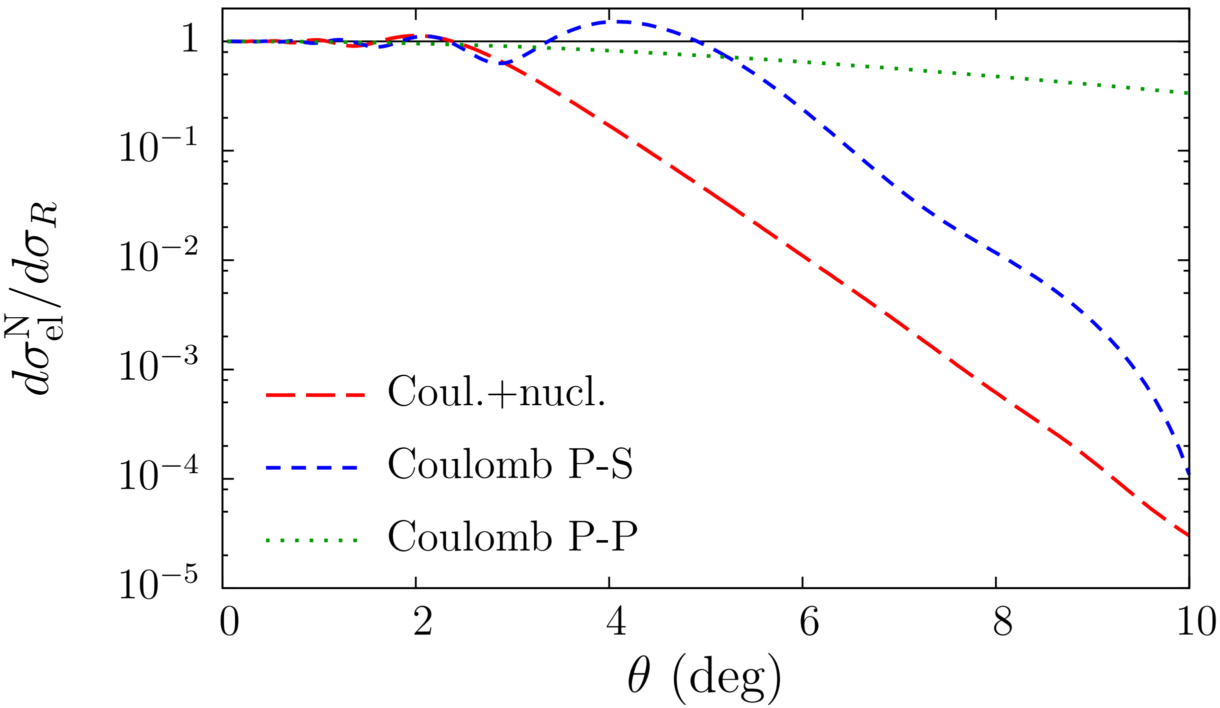
Optical potentials V_{cT} and V_{fT} chosen in the literature

Elastic scattering



- Near $\gg$ Far at forward angle (Coulomb)
- Large-angle oscillations $\equiv$ N/F interferences
  Forward angle pattern also present in Near side
- Asymptotics of J_0 and $H_0^{(1,2)}$ $\simeq$ exact expression
  $\Rightarrow$ validates N/F interpretation

Influence of P-T interaction

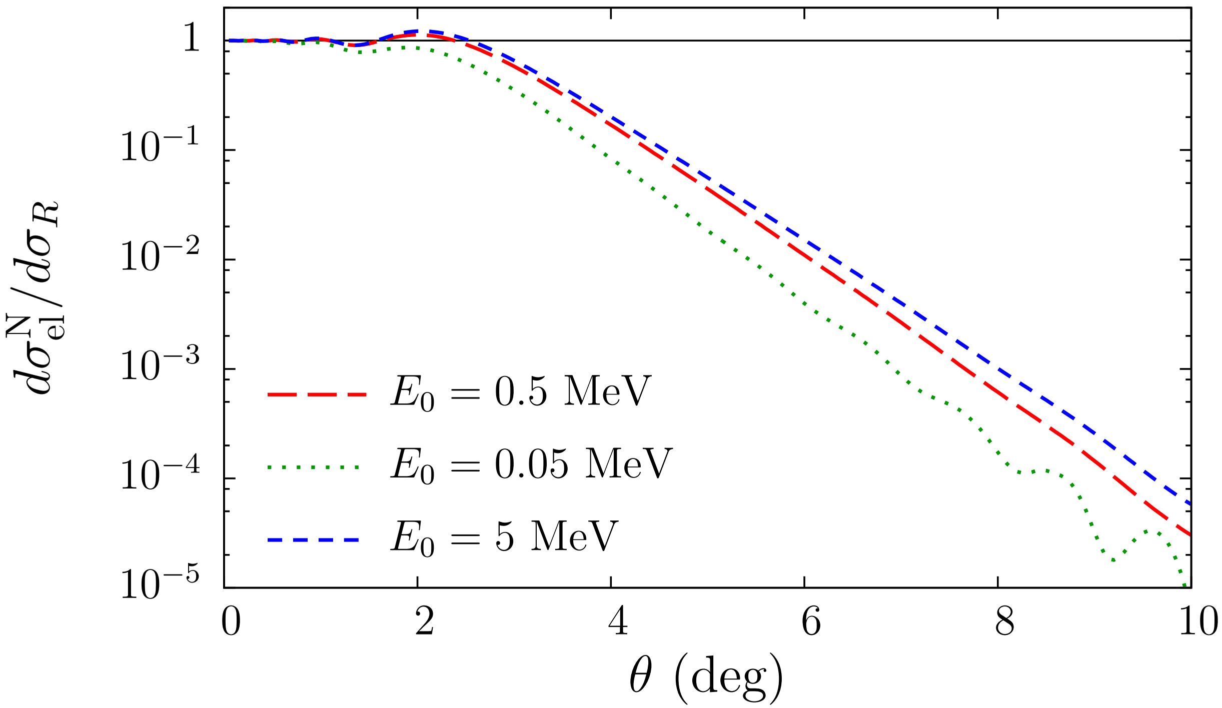


V_{PT}	σ_{bu}
C.+N.	1.70 b
PS	2.10 b
PP	2.58 b

- Features dependent strongly on V_{PT}:
  C.+N. and PS account for charge distributions and present a Coulomb rainbow. Not PP.
- drop not directly due to loss of flux to breakup:
  at large angle $\sigma_{el} \nearrow$ when $\sigma_{bu} \nearrow$ too

  $\Rightarrow$ influence of size of projectile?

Influence of size of the halo



E_0	σ_{bu}
0.5 MeV	1.70 b
0.05 MeV	23.6 b
5 MeV	0.07 b

- Small dependence of slope on E_0,
  but could provide information on extension of halo
- However σ_{bu} strongly affected by $E_0 \Rightarrow$ drop not directly due to loss of flux to breakup

Adiabatic model

These results agree with Johnson, Al-Khalili and Tostevin [PRL 79, 2771 (1997)]
Their adiabatic model uses

- Adiabatic approximation: $H_0 - E_0 \sim 0$
- $V_{fT} = 0$

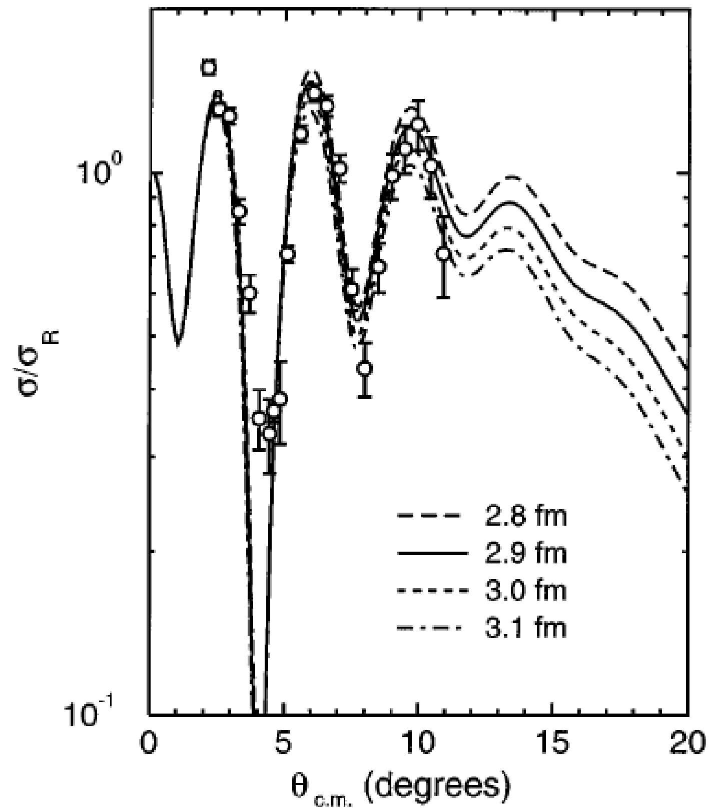
which gives $\frac{d\sigma_{\rm el}}{d\Omega} = |F(\boldsymbol{Q})|^2 \frac{d\sigma_{\rm el}^{cT}}{d\Omega}$, where

- $F(\boldsymbol{Q}) = \int |\Phi_0(\boldsymbol{r})|^2 e^{i\boldsymbol{Q}\cdot\boldsymbol{r}} d\boldsymbol{r} \quad (\boldsymbol{Q} \propto \boldsymbol{K} - \boldsymbol{K}')$
- $\frac{d\sigma_{\rm el}^{cT}}{d\Omega} \equiv$ scattering cross section induced by V_{cT}

$\Rightarrow$ suggests $\frac{d\sigma_{\rm el}}{d\Omega}$ dominated by $\frac{d\sigma_{\rm el}^{cT}}{d\Omega}$,
perturbed by $F(\boldsymbol{Q})$ that includes structure effects

^{11}Be+C @ $49.3A$MeV

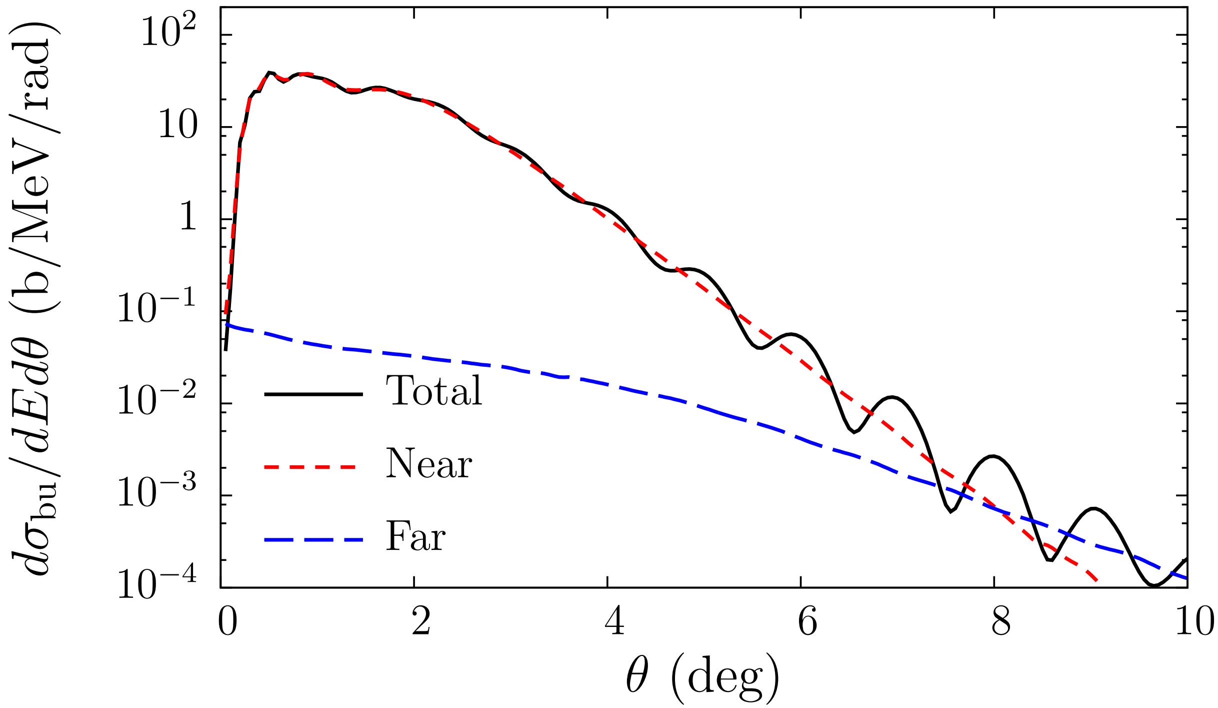
Including V_{fT}, they obtain



[PRL 79, 2771 (1997)]

$\Rightarrow$ concludes also that radius of halo influences $\frac{d\sigma_{\rm el}}{d\Omega}$ at large angles

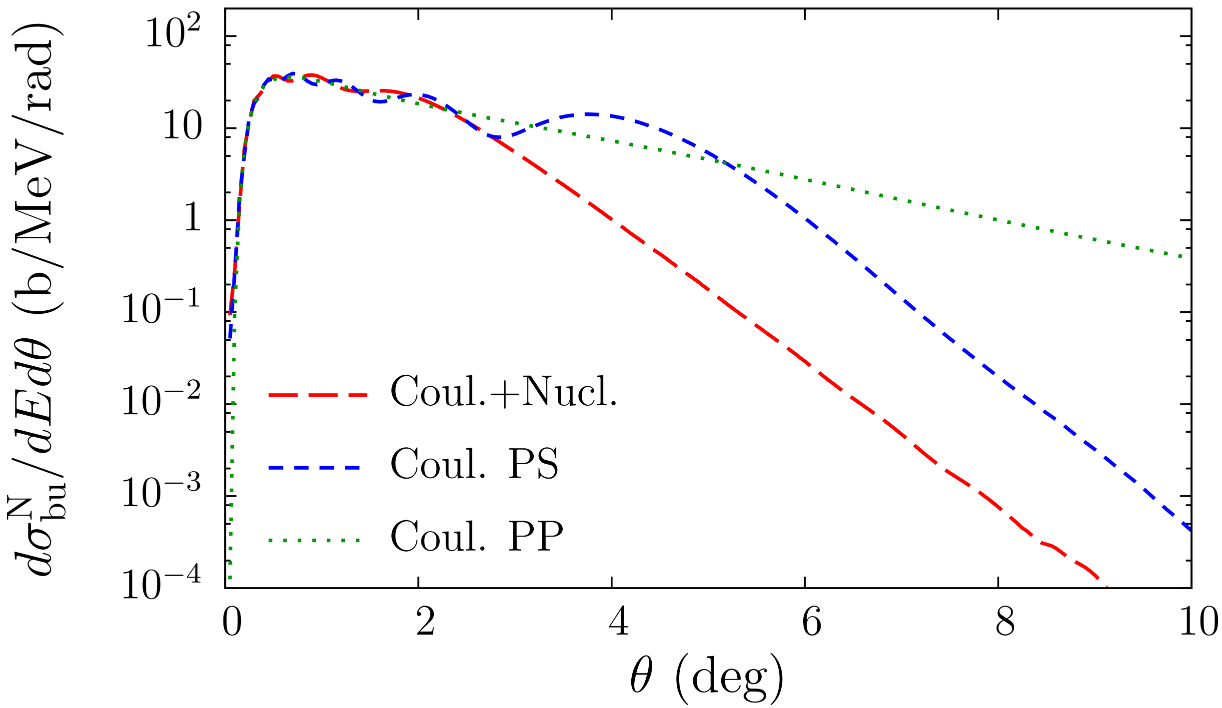
Elastic breakup



Similar results as for elastic scattering:

- Near side dominates at forwar angles
- Near/Far interferences at large angles

Influence of P-T interaction

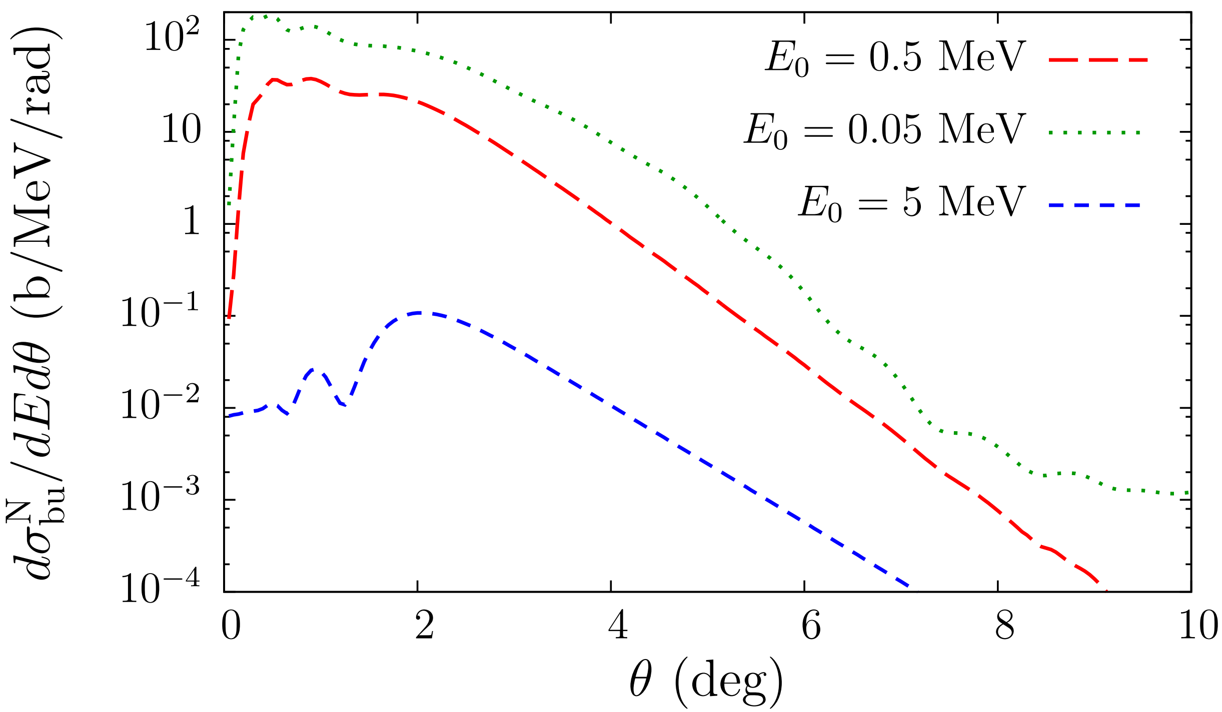


Same features as for elastic scattering:

- C.+N. and PS present a rainbow. Not PP.
- Explain larger σ_{bu} for PP

$\Rightarrow$ confirms there is no direct link between drop and loss of flux towards breakup

Influence of size of the halo



E_0	σ_{bu}
0.5 MeV	1.70 b
0.05 MeV	23.6 b
5 MeV	0.07 b

- Confirms the large dependence of σ_{bu} on E_0
- Same dependence of the slope on E_0 as in elastic scattering

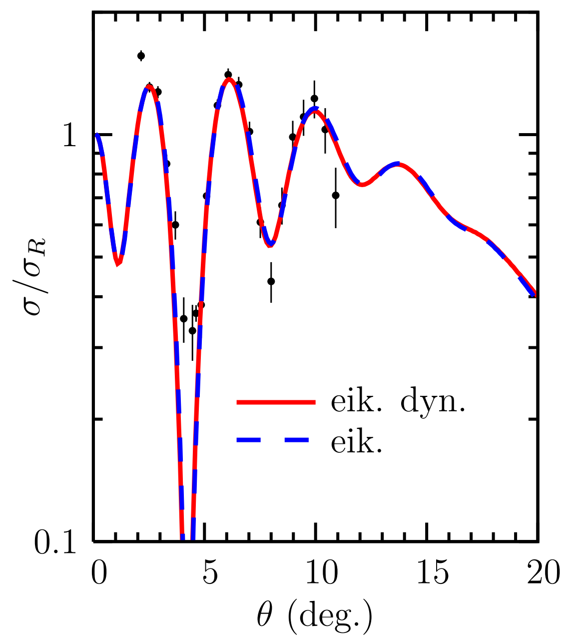
$\Rightarrow$ suggests angular distributions for elastic scattering and breakup are sensitive to same inputs

Conclusion

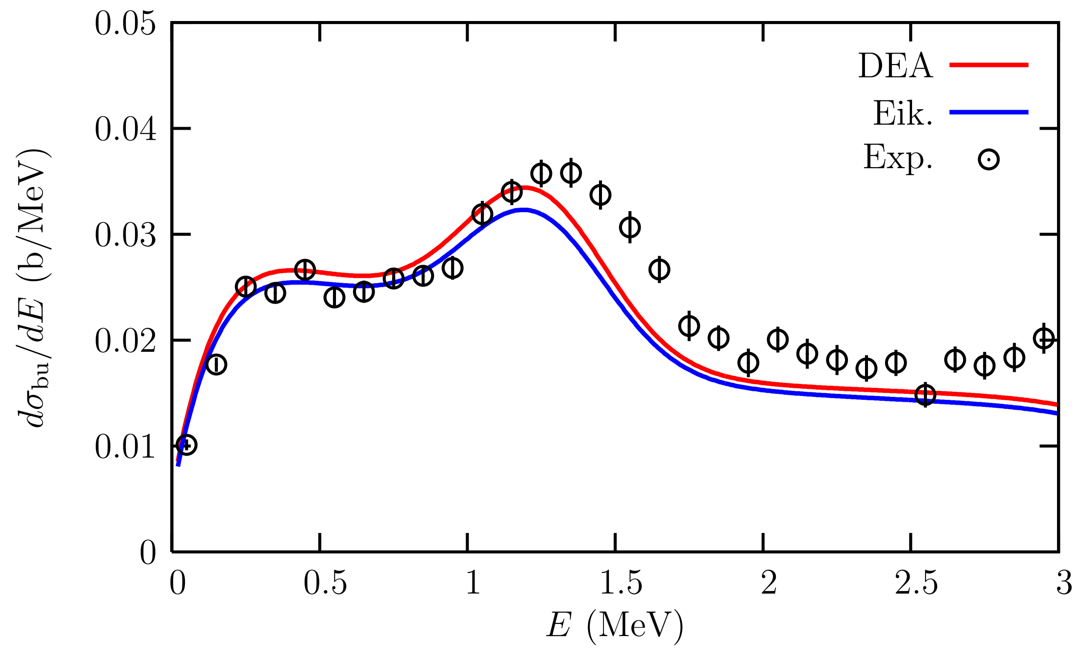
- DEA is a reaction model that treats coherently elastic scattering and breakup
- Used to study angular distributions for elastic scattering and breakup
- Very similar berhaviour for both processes:
  - Both present a Coulomb rainbow
  - sensitive to V_{PT}
  - with a slope slightly sensitive to E_0 or radius
- Breakup affects elastic scattering (and vice versa), but decrease in elastic scattering cannot be interpreted as a mere loss of flux towards breakup
- Angular distributions sensitive to c-f structure

DEA for light targets

^{11}Be on C @ 49.3AMeV
[Cortina-Gil, PhD (1996)]



^{11}Be+C $\rightarrow$ ^{10}Be+n+C @ 67AMeV
[Fukuda PRC 70, 054606 (2004)]



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

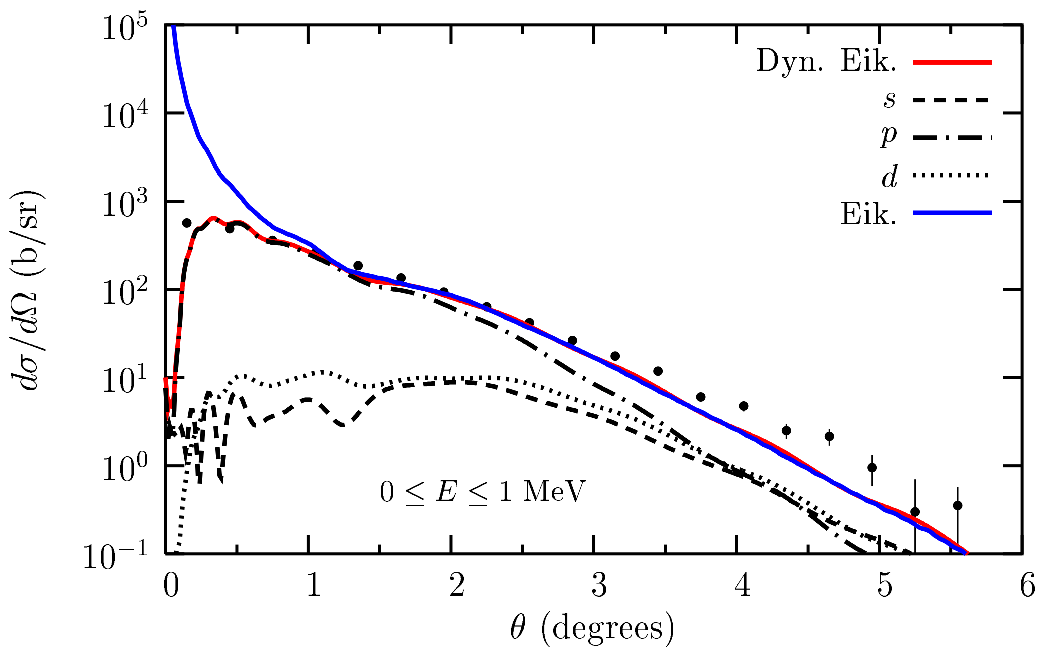
Both DEA and usual eikonal are in good agreement with experiment

DEA improves TDSE including interferences

DEA for heavy targets

^{11}Be + Pb @ 69AMeV

[Fukuda PRC 70, 054606 (2004)]



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

DEA in excellent agreement with experiment

Eikonal diverges because of Coulomb

$\Rightarrow$ DEA valid for both light and heavy targets