Low-energy corrections to the eikonal description of elastic scattering and breakup of halo nuclei

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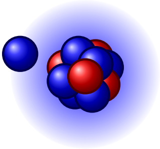
Introduction

- **Halo nuclei** exhibit a very large matter radius
  Compact core + one or two loosely-bound neutrons
  Ex : $^{11}\text{Be} \equiv {}^{10}\text{Be} + \text{n}$, $^{15}\text{C} \equiv {}^{14}\text{C} + \text{n}$



Short-lived : studied through **reactions processes**
(**elastic scattering**, **breakup**,...)

⇒ **Need an accurate reaction model to infer reliable information**

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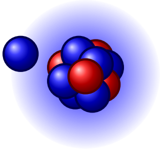


  Short-lived : studied through **reactions processes**
  (**elastic scattering**, **breakup**,...)
  ⇒ **Need an accurate reaction model to infer reliable information**

- **The eikonal approximation :**
  ⊕ reduced computational time
  ⊕ simple interpretation of the reaction

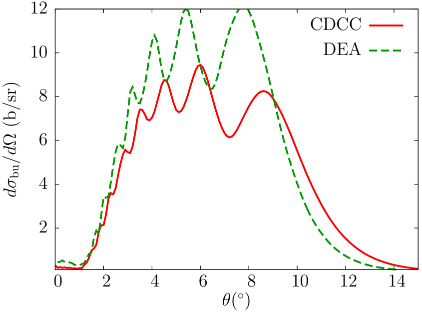
- Some experimental facilities will provide RIBs at ∼ $10A$ MeV
  (e.g. HIE-ISOLDE @ CERN and ReA12 @ MSU)

  ⇒**Is it valid at these energies ?**

Introduction

- **Coulomb dominated reactions :**

$$^{15}\mathrm{C} + {}^{208}\mathrm{Pb} \rightarrow {}^{14}\mathrm{C} + \mathrm{n} + {}^{208}\mathrm{Pb} \text{ @ } 20A \text{ MeV}$$



[T. Fukui, K. Ogata and P. Capel. PRC **90**, 034617 (2014)]

- **Coulomb dominated reactions :**
  Coulomb correction : $b \rightarrow b' = \frac{\eta + \sqrt{\eta^2 + b^2 k^2}}{k}$ $\Rightarrow$ valid at low energies

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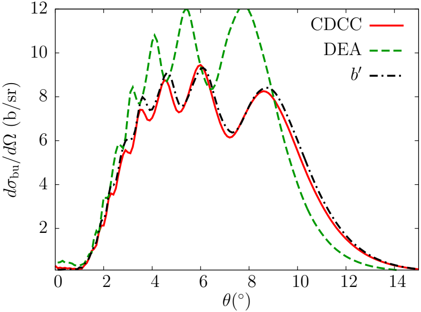

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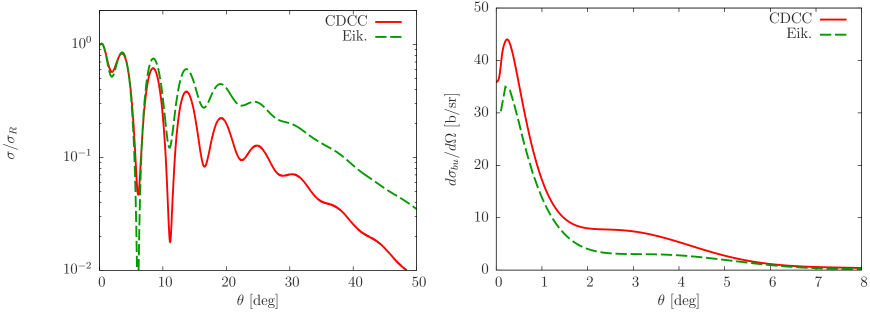

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→ Eikonal dampens the oscillations

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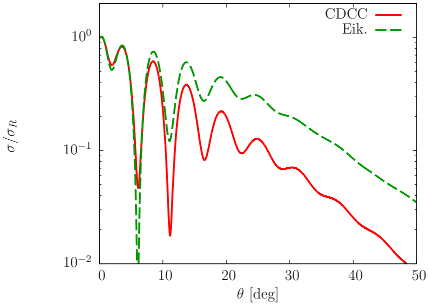

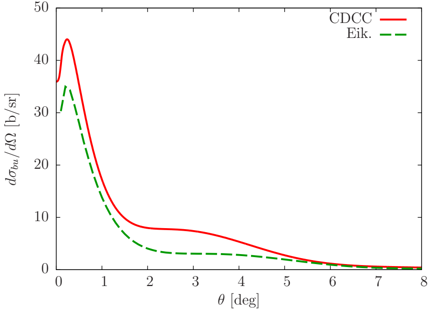

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⇒ **Can a nuclear correction fix these issues ?**

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1. Eikonal model
   - Usual eikonal model
   - Dynamical Eikonal Approximation (DEA)
2. Semi-classical correction
   - Implementation
   - Elastic scattering @ 10A MeV
   - Generalisation to the DEA
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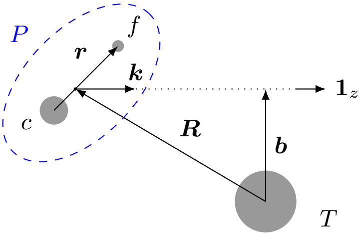
4. Extension to breakup
5. Sensitivity analyses of both corrections
   - Dependence on energy
   - Sensitivity to the potentials
6. Summary

Reaction model :

- Assumptions : - Spinless particles
  - Central potentials
- Two-body projectile (P) :
  $P \equiv$ core (c) + fragment (f)
  Internal Hamiltonian : $h_{cf} = T_r + V_{cf}(r)$
- Structureless target (T)



Three-body Schrödinger equation :

$$\left[T_R + h_{cf} + V_{cT} + V_{fT}\right]\Psi(\boldsymbol{R},\boldsymbol{r}) = E\,\Psi(\boldsymbol{R},\boldsymbol{r})$$

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

where Φ_0 is the ground state of P : $h_{cf}\Phi_0 = \epsilon_0\Phi_0$

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① Eikonal approximation : at high energy, $\Psi \approx$ plane wave (e^{ikZ})
Factorization : $\Psi(\boldsymbol{R},\boldsymbol{r}) = e^{ikZ}\,\widehat{\Psi}(\boldsymbol{R},\boldsymbol{r})$ with $|\Delta_{\mathbf{R}}\widehat{\Psi}| \ll k\left|\frac{\partial}{\partial Z}\widehat{\Psi}\right|$

Eikonal model

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Dynamical Eikonal Approximation (DEA) uses only ①

$$\Rightarrow i\hbar v\frac{\partial}{\partial Z}\widehat{\Psi}(\boldsymbol{b},Z,\boldsymbol{r}) = [h_{cf} - \epsilon_0 + V_{cT} + V_{fT}]\widehat{\Psi}(\boldsymbol{b},Z,\boldsymbol{r}),$$

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[D. Baye, P. Capel, and G. Goldstein, PRL **95**, 082502 (2005).]

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② Adiabatic approximation : $h_{cf} \approx \epsilon_0$

Usual eikonal model uses ①+② :

$$\boxed{\Psi^{\text{eik}}(\boldsymbol{b},Z,\boldsymbol{r}) = e^{ikZ}\,e^{i[\chi_{cT}(b_{cT})+\chi_{fT}(b_{fT})]}\,\Phi_0(\boldsymbol{r}),}$$

with $\chi_j(b_j) = -\frac{1}{\hbar v}\int_{-\infty}^{Z} V_j(\boldsymbol{b_j},Z')\,dZ'$

[R. J. Glauber, *High energy collision theory*, (1959).]

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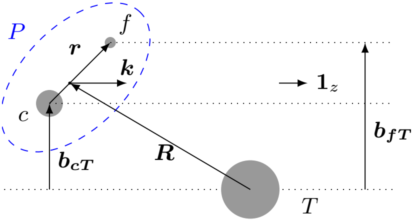

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⊖ Deflection and couplings between trajectories are neglected !

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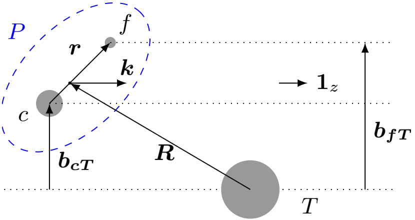

- ⊕ Simple interpretation : c and f follow **straight-line** trajectories
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⇒ **Extension to low energies through corrections to account for the deflection of P**

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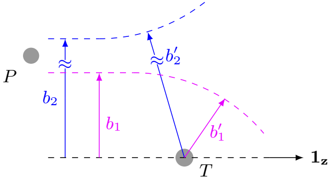
Idea : $\chi_j(b_j) \rightarrow \chi_j(b''_j)$, with b''_j the **complex** distances of closest approach [Analysis of two-body collisions in A. Vitturi *et al.* , PRC **56**, 1511, (1997).]

① Real part of the distances b'_j :



trajectories at b_1 is nuclear dominated
at b_2 is Coulomb dominated

$\rightarrow$ b'_j computed exactly

[CH, P. Capel, *Proc. of the 55th International Winter Meeting on Nuclear Physics*, (2017).]

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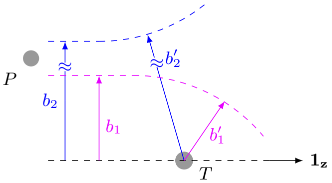

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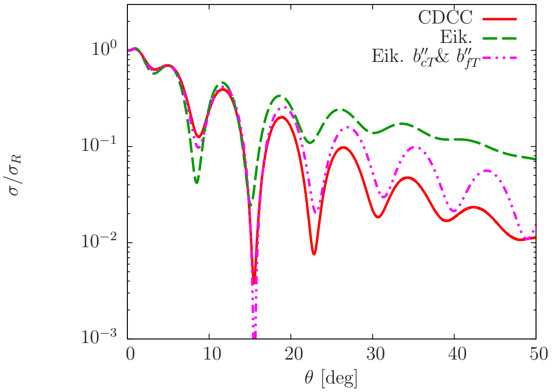
② Complex distances b''_j :

→ b''_j approximated by a **perturbation formula**

$$b''_j = b'_j - i\frac{\mathrm{Im}\{V_j(b')\}}{2\,E_0\,\frac{b^2}{b'^3} - \left[\frac{\partial}{\partial r}\left(\mathrm{Re}\{V_j\}\right)\right]_{r=b'}}$$

[D. M. Brink, *Semi-classical methods in nucleus-nucleus scattering*, (1985).]

Elastic scattering ^{11}Be+^{12}C @ 10A MeV



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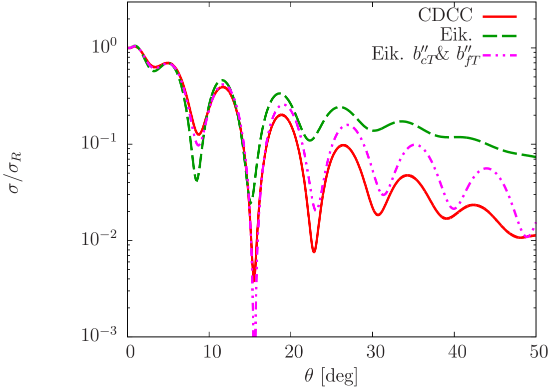

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⇒ **Influence of the dynamics of the projectile ?**

Generalisation of the semi-classical correction to the DEA

DEA : no eikonal phases
$\Rightarrow$ replace b_j by b''_j in the computation of the interaction

$$\boxed{V_j(b_j, z) \to V_j(b''_j, z)}$$

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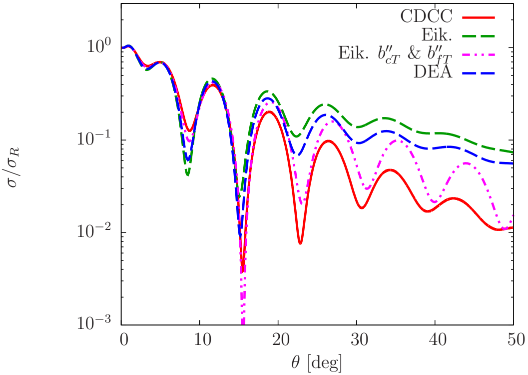

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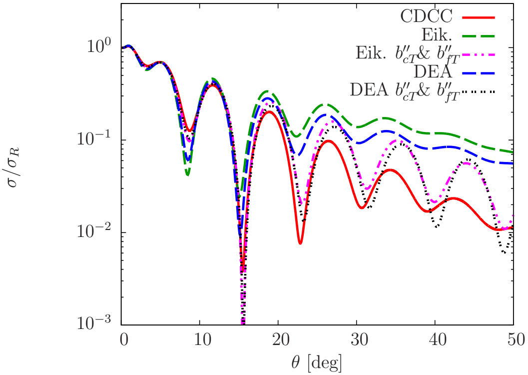

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- **Same behaviour** of the correction
  - ⊕ Accuracy gain
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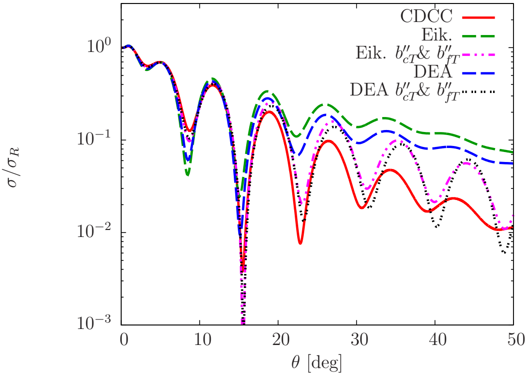

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$\Rightarrow$ **Use of another correction ?**

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Two-body collisions :

- Partial-wave expansion : $F(\theta) = \frac{1}{2ik}\sum_{l=0}^{+\infty}(2l+1)P_l(\cos(\theta))[\underbrace{e^{2i\delta_l}}_{S_l}-1]$
- Eikonal model : $f(\theta) = -ik\int_0^{+\infty} bJ_0(qb)[\underbrace{e^{i\chi(b)}}_{S(b)}-1]\mathrm{d}b$
- Relation between Legendre polynomial and Bessel function :

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→ **Exact continued S-matrix** :
use the exact S_l in the eikonal framework using $l = kb - 1/2$

$$\boxed{\bar{f}(\theta) = -ik\int_0^{+\infty} bJ_0(qb)[S_l - 1]\mathrm{d}b}$$

[J. M. Brooke *et al.* , PRC **59**, 1560, (1999).]

Exact continued S-matrix : three-body collisions

Generalisation to three-body collisions :

- Eikonal model : $f^{(2)}(\theta) = -ik\int_0^{+\infty} bdbJ_0(qb)[S^{(2)}(b_{cT}, b_{fT}) - 1]$
  with $S^{(2)}(b_{cT}, b_{fT}) = \langle\Phi_0|S(b_{cT})S(b_{fT})|\Phi_0\rangle$
- **Exact continued S-matrix** :

$$\boxed{\overline{f^{(2)}}(\theta) = -ik\int_0^{+\infty} bJ_0(qb)[S^{(2)}_{l_c,l_f} - 1]\mathrm{d}b}$$

with $S^{(2)}_{l_c,l_f} = \langle\Phi_0|S^c_{l_c}S^f_{l_f}|\Phi_0\rangle$ [J. M. Brooke *et al.* , PRC **59**, 1560, (1999).]

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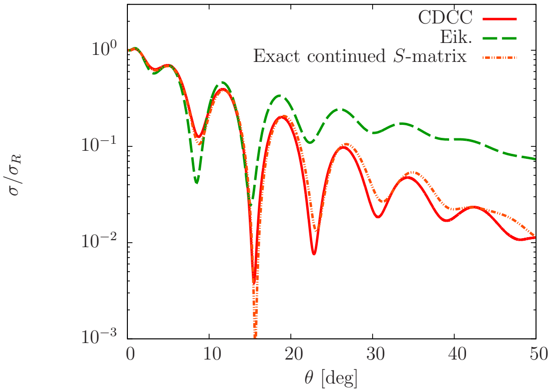

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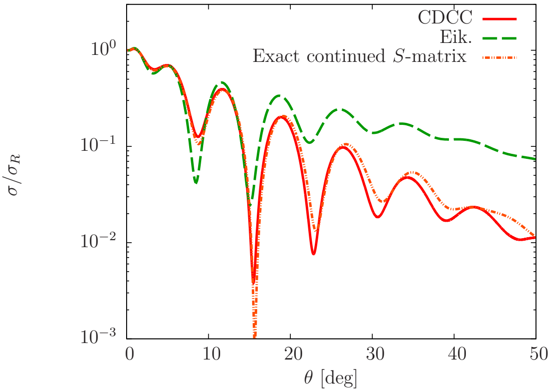

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What about breakup observables ?

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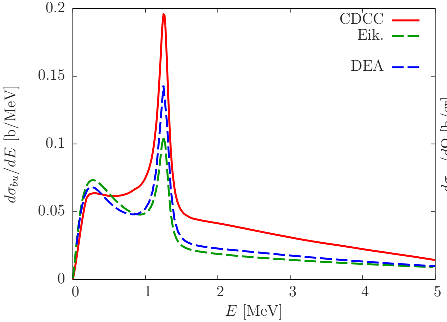

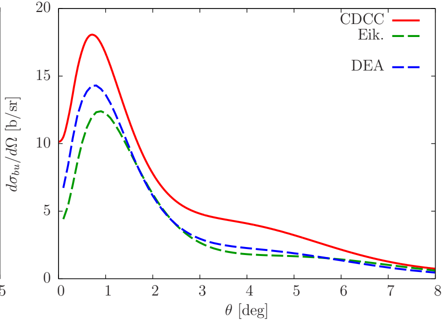

Small dynamical effects in breakup cross sections

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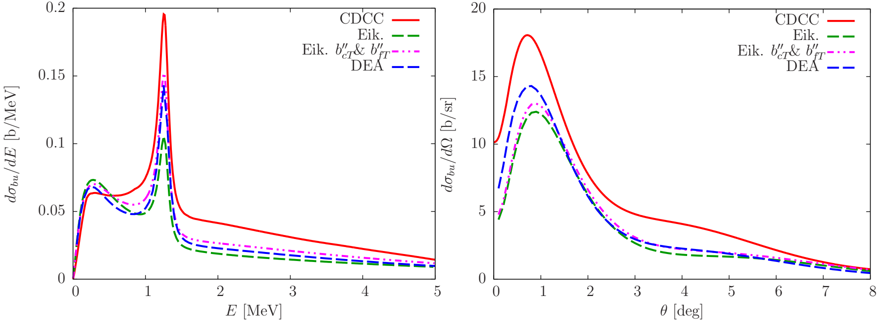

Small dynamical effects in breakup cross sections

① **Semi-classical correction :** small correction to the eikonal model

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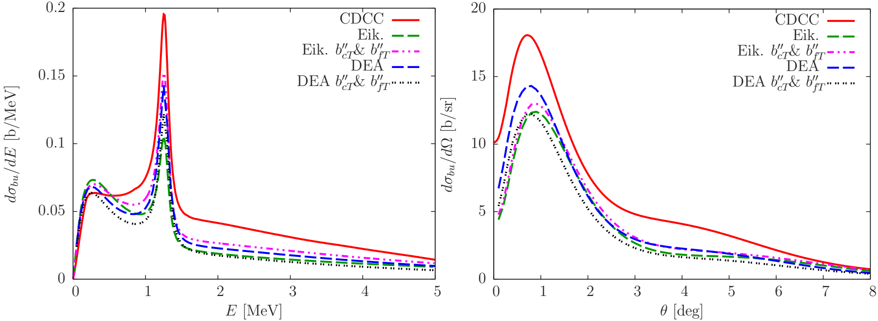

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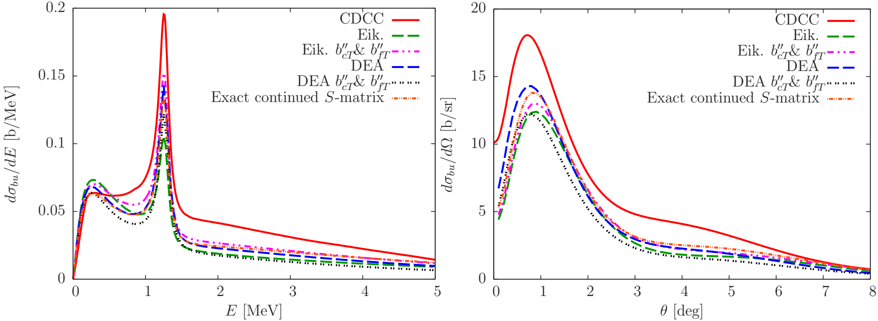

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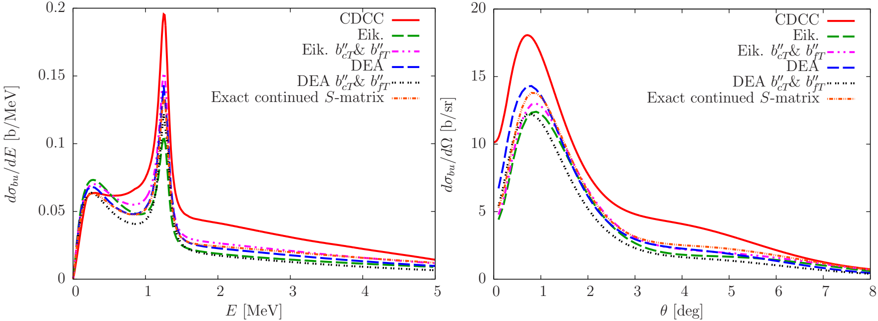

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How do both corrections vary with energy ?

How sensitive are they to the potential parameters ?

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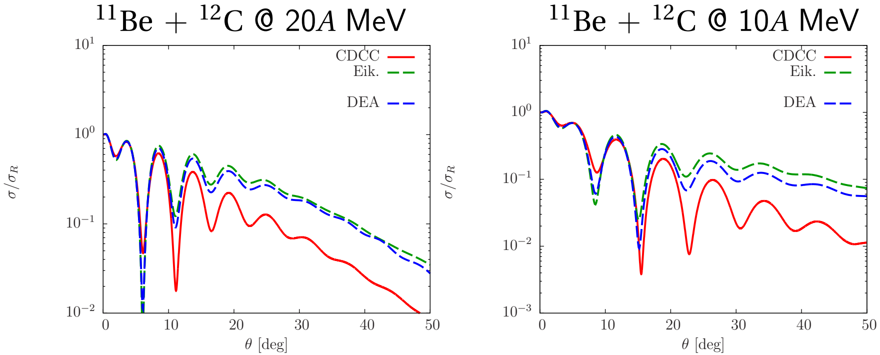
Dependence on energy : elastic scattering



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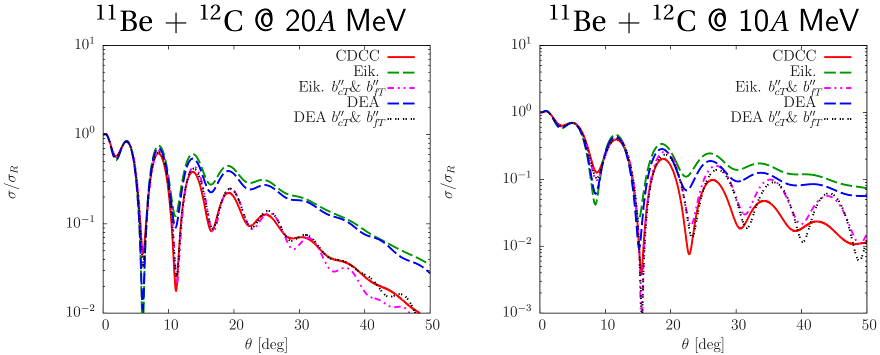
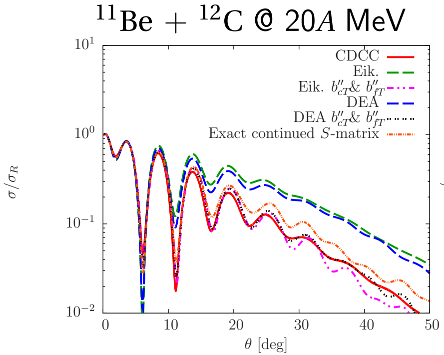
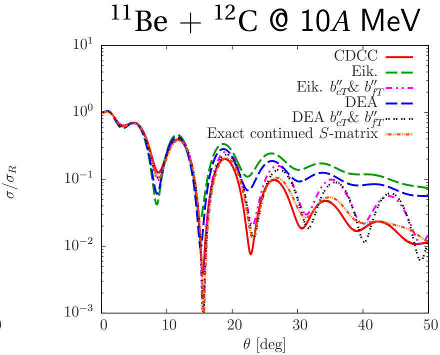


① **Semi-classical correction : more efficient at high energy**

Same accuracy in the eikonal model or the DEA

Dependence on energy : elastic scattering

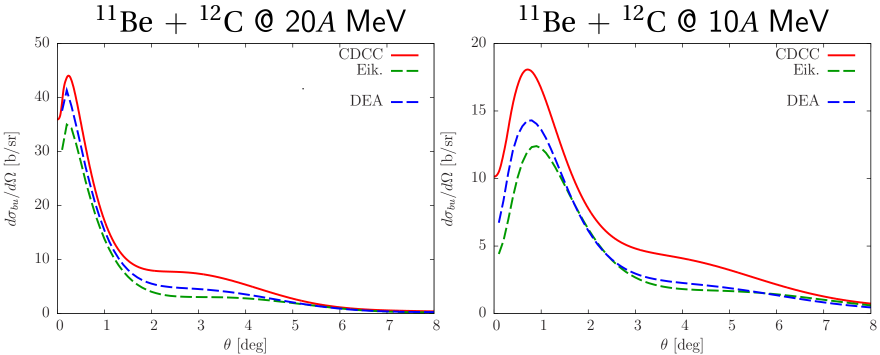




① **Semi-classical correction : more efficient at high energy**
Same accuracy in the eikonal model or the DEA

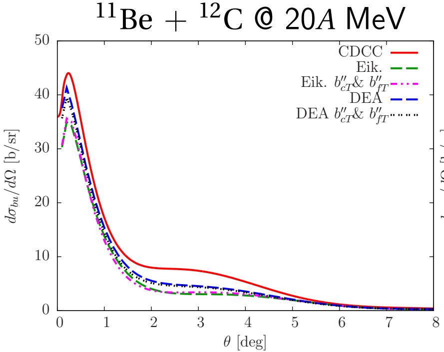
② **Exact continued S-matrix : more efficient at low energy**

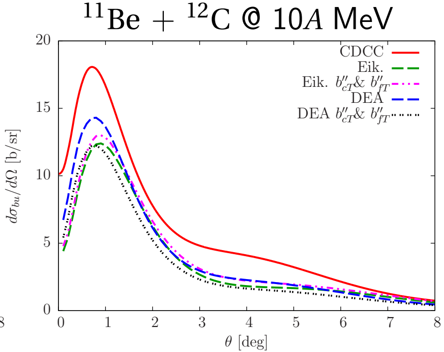
Dependence on energy : breakup



- Dynamical effects more important at lower energies

Dependence on energy : breakup





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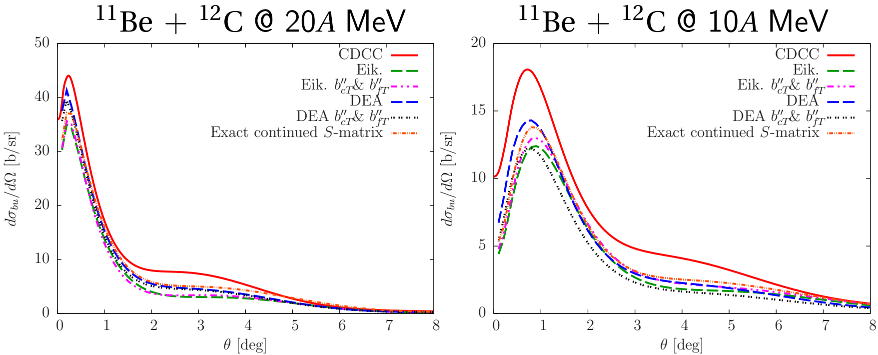

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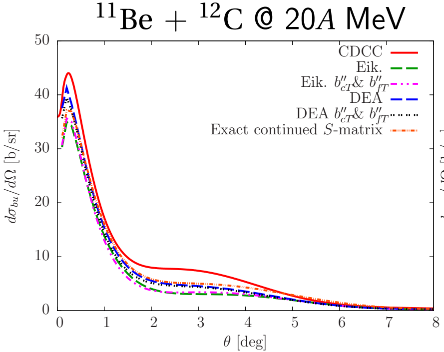

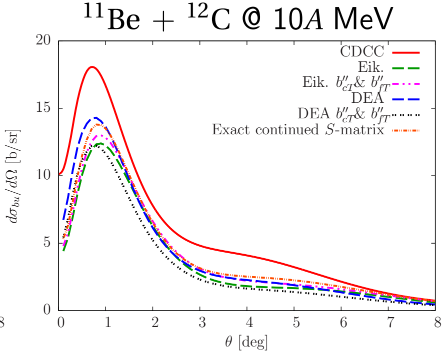

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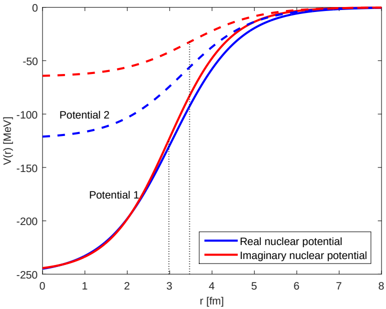
⇒ No significant accuracy gain at both energies

Ongoing analysis

Main influence of ^{10}Be-^{12}C potential → test on two potentials



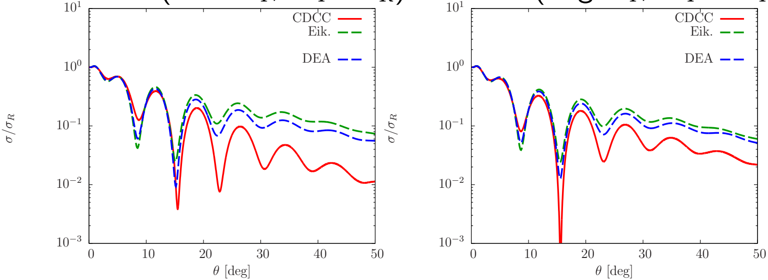
Different absorption parameters :

$$\left(\frac{W_I}{V_R}\right)_{\text{potential 1}} > \left(\frac{W_I}{V_R}\right)_{\text{potential 2}} \quad \text{but} \quad r_{I,\text{potential 1}} < r_{I,\text{potential 2}}$$

Sensitivity to interaction potentials : elastic scattering

Elastic scattering of ^{11}Be off ^{12}C at 10A MeV

Pot. 1 (small r_I, $W_I \sim V_R$) Pot. 2 (large r_I, $W_I \sim V_R/2$)



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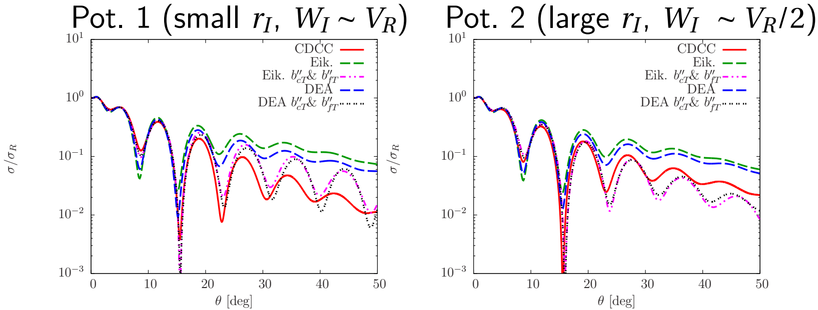

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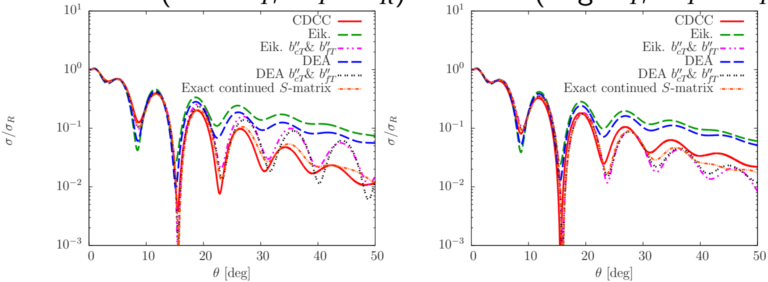

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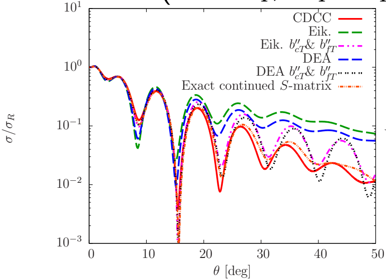

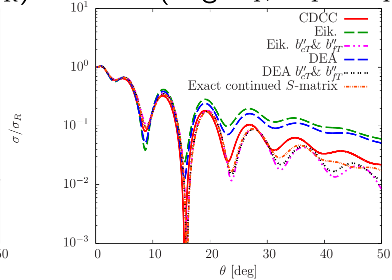

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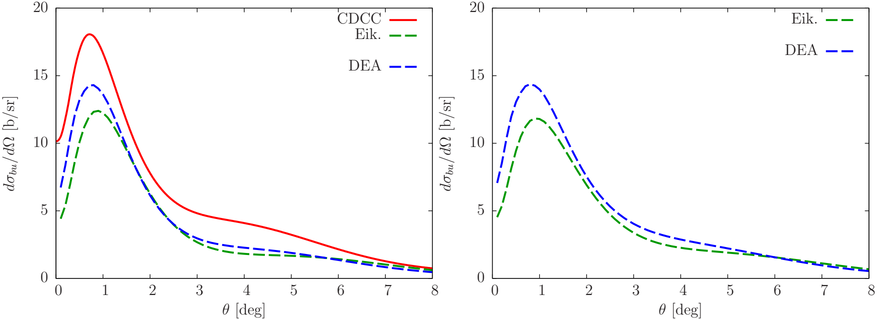

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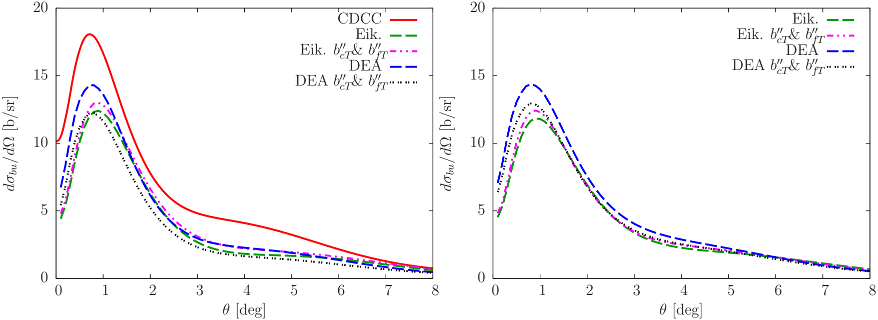

① **Semi-classical correction : insensitive to the potential**

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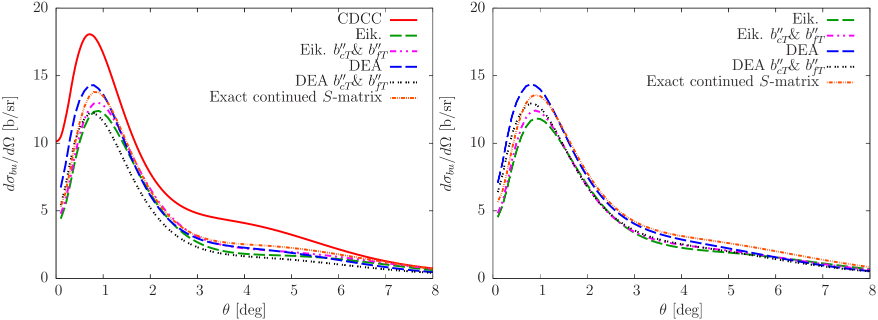

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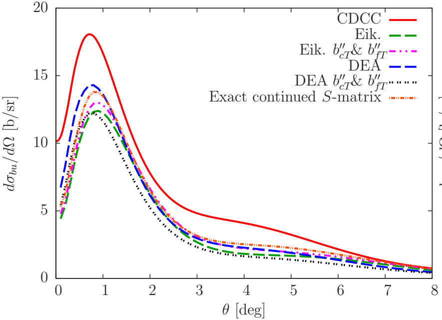
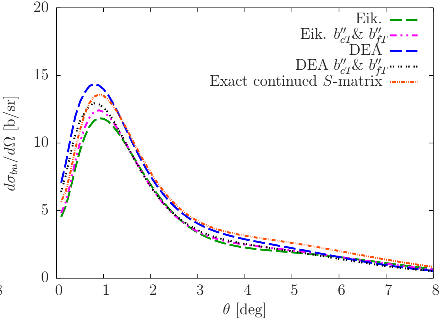


Pot. 2 (large r_I, $W_I \sim V_R/2$)



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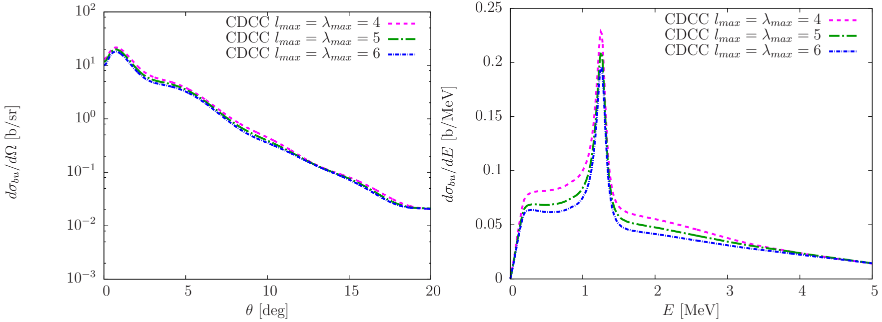
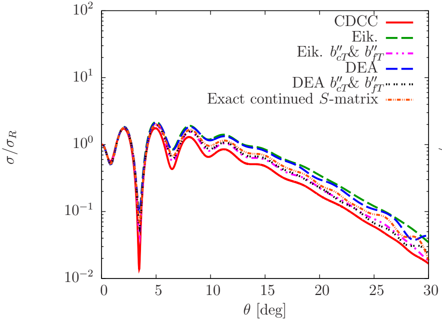
⇒ **Need to improve the couplings between the « trajectories » within the eikonal model**

Convergence of CDCC computations at 10A MeV

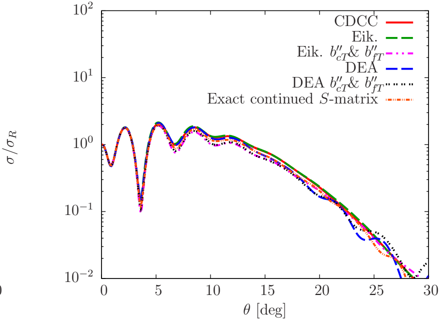


Elastic scattering of ^{11}Be off ^{12}C at 67A MeV

Pot. 1 (small r_I, $W_I \sim V_R$)



Pot. 2 (large r_I, $W_I \sim V_R/2$)



- **Sensitive to** r_I → undercorrection when r_I is small
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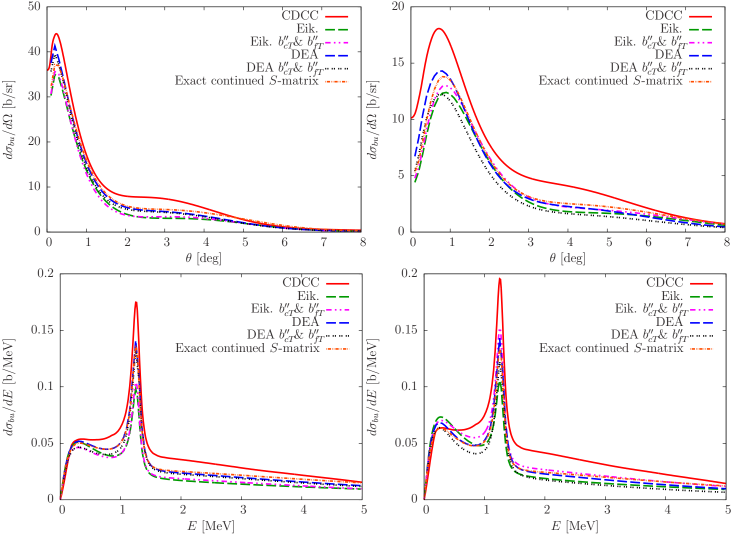
Dependence on energy of breakup distributions

^{11}Be + ^{12}C @ 20A MeV

^{11}Be + ^{12}C @ 10A MeV



Sensitivity of both corrections to interaction potentials

Breakup of ^{11}Be off ^{12}C at 10A MeV

Pot. 1 (small r_I, $W_I \sim V_R$)   Pot. 2 (large r_I, $W_I \sim V_R/2$)