Breakup as a tool to study exotic nuclear structures

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Outline

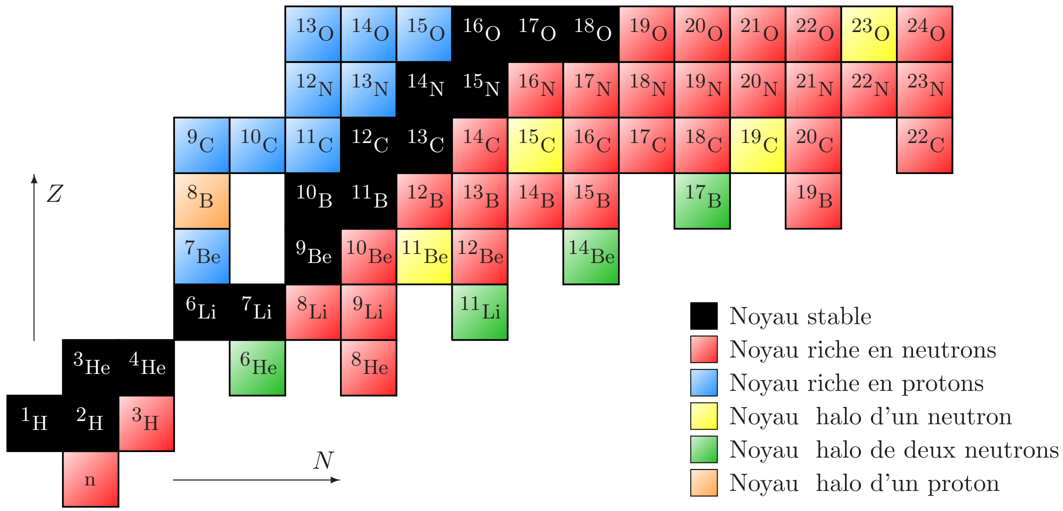
- Introduction: Halo nuclei
- Theoretical framework of reaction modelling
- Reaction models
  - Continuum-discretised coupled channel (CDCC)
  - Time-dependent technique (TDSE)
  - Dynamical eikonal approximation (DEA)
- New observable: Ratio technique
  - Similarity between angular distributions for elastic scattering and breakup
  - Ratio idea
- Summary

Introduction

Exotic nuclear structures are found far from stability

E.g. halo nuclei with peculiar quantal structure:

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



$\Rightarrow$ strongly clusterised system:
neutrons tunnel far from the core and form a halo

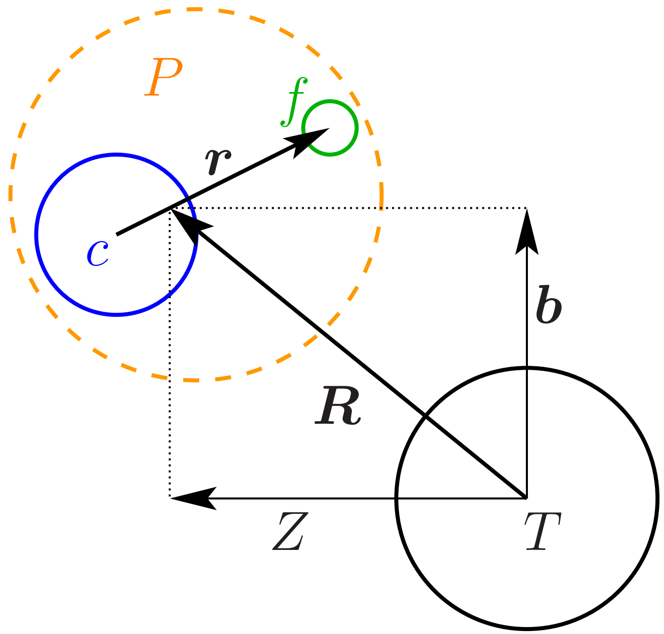
Far from stability nuclei are short-lived
$\Rightarrow$ studied in indirect ways, e.g. through reactions

$\Rightarrow$ need accurate reaction models
and observables sensitive to nuclear structure

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 state Φ_0 and resonances

Target T seen as structureless particle

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

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

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

CDCC

Solve the three-body scattering problem:

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

by expanding Ψ on eigenstates of H_0

$$\Psi(\boldsymbol{r},\boldsymbol{R}) = \sum_i \chi_i(\boldsymbol{R})\Phi_i(\boldsymbol{r}) \qquad \text{with } H_0\Phi_i = \epsilon_i\Phi_i$$

Leads to set of coupled-channel equations (hence CC)

$$[T_R + \epsilon_i + V_{ii}]\,\chi_i + \sum_{j\neq i} V_{ij}\chi_j = E_T\chi_i,$$

with $V_{ij} = \langle\Phi_i|V_{cT} + V_{fT}|\Phi_j\rangle$

The continuum has to be discretised (hence CD)

[Kamimura *et al*. Prog. Theor. Phys. Suppl. 89, 1 (1986)]

code FRESCO [Thompson, Comp. Phys. Rep. 7, 167 (1988)]

Fully quantal approximation

No approx. on P-T motion, nor restriction on energy

But expensive computationally (at high energies)

Time-dependent model

P-T motion described by classical trajectory $\boldsymbol{R}(t)$
Time-dependent potentials simulate P-T interaction
P structure described quantum-mechanically by H_0

$\Rightarrow$ Time-dependent Schrödinger equation (TDSE)

$$i\hbar\frac{\partial}{\partial t}\Psi(\boldsymbol{r},\boldsymbol{b},t) = [H_0 + V_{cT}(t) + V_{fT}(t)]\Psi(\boldsymbol{r},\boldsymbol{b},t)$$

solved for each $\boldsymbol{b}$ with initial condition $\Psi \underset{t\to-\infty}{\longrightarrow} \Phi_0$

Many codes have been written to solve TDSE
[Esbensen, Bertsch and Bertulani, NPA 581, 107 (1995)]
[Typel and Wolter, Z. Naturforsch. A54, 63 (1999)]
[P.C., Baye and Melezhik, PRC 68, 014612 (2003)]

Lacks quantum interferences between trajectories

Dynamical eikonal approximation

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 $\Psi \underset{Z\to-\infty}{\longrightarrow} e^{iKZ}\Phi_0$

Eikonal approximation: factorise $\Psi = e^{iKZ}\widehat{\Psi}$

$$T_R\Psi = e^{iKZ}[T_R + vP_Z + \frac{\mu_{PT}}{2}v^2]\widehat{\Psi}$$

Neglecting T_R vs P_Z and using $E_T = \frac{1}{2}\mu_{PT}v^2 + \epsilon_0$

$$i\hbar v\frac{\partial}{\partial Z}\widehat{\Psi}(\boldsymbol{r}, \boldsymbol{b}, Z) = [H_0 - \epsilon_0 + V_{cT} + V_{fT}]\widehat{\Psi}(\boldsymbol{r}, \boldsymbol{b}, Z)$$

solved for each $\boldsymbol{b}$ with condition $\widehat{\Psi} \underset{Z\to-\infty}{\longrightarrow} \Phi_0(\boldsymbol{r})$

This is the dynamical eikonal approximation (DEA)

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

Same equation as TDSE with straight line trajectories

DEA, TDSE and eikonal

$$i\hbar v \frac{\partial}{\partial Z}\widehat{\Psi}(\boldsymbol{r},\boldsymbol{b},Z) = [H_0 - \epsilon_0 + V_{cT} + V_{fT}]\widehat{\Psi}(\boldsymbol{r},\boldsymbol{b},Z)$$

DEA $\neq$ TDSE because $\boldsymbol{b}$ and Z are quantal

$\Rightarrow$ includes interference between *trajectories*

The usual eikonal uses adiabatic approx. $H_0 - \epsilon_0 \sim 0$

$\Rightarrow$ neglects internal dynamics of projectile

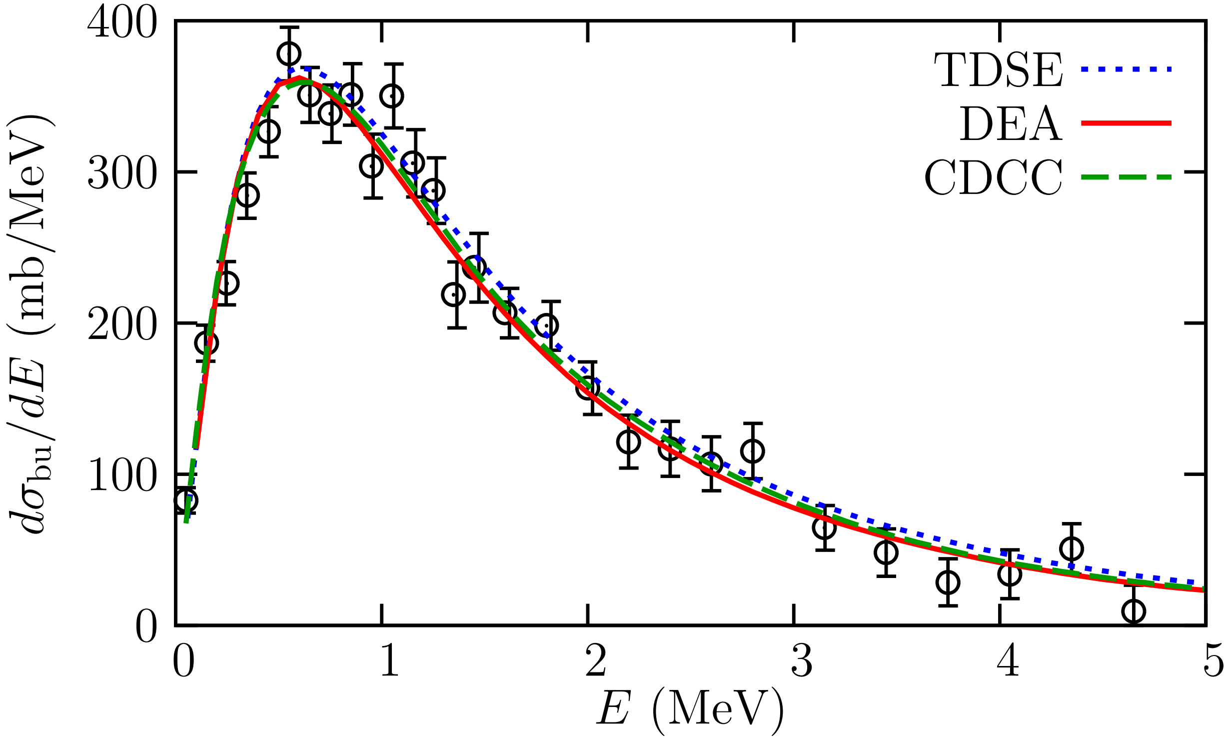
$$\widehat{\Psi}^{\rm eik}(\boldsymbol{r},\boldsymbol{b},Z) = e^{-\frac{i}{\hbar v}\int_{-\infty}^{Z} dZ'\left[V_{cT}(\boldsymbol{r},\boldsymbol{b},Z')+V_{fT}(\boldsymbol{r},\boldsymbol{b},Z')\right]}\Phi_0(\boldsymbol{r})$$

$\Rightarrow$ dynamical eikonal generalises TDSE and eikonal

- improves TDSE by including quantal interferences
- improves eikonal by including dynamical effects

How do CDCC, TDSE and DEA compare?

Energy distribution: ^{15}C+Pb @ $68A$MeV



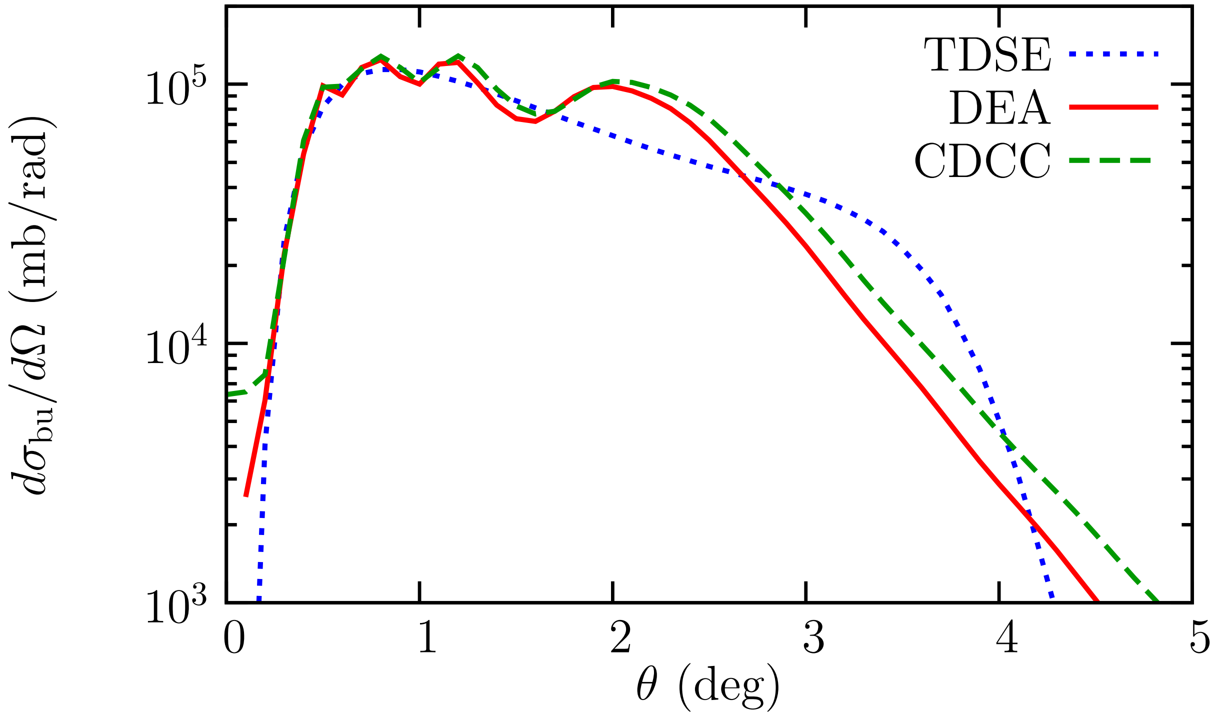
- Excellent agreement between all three models
- Excellent agreement with experiment

[Nakamura *et al.* PRC 79, 035805 (2009)]

$\Rightarrow$ Confirms the validity of the approximations

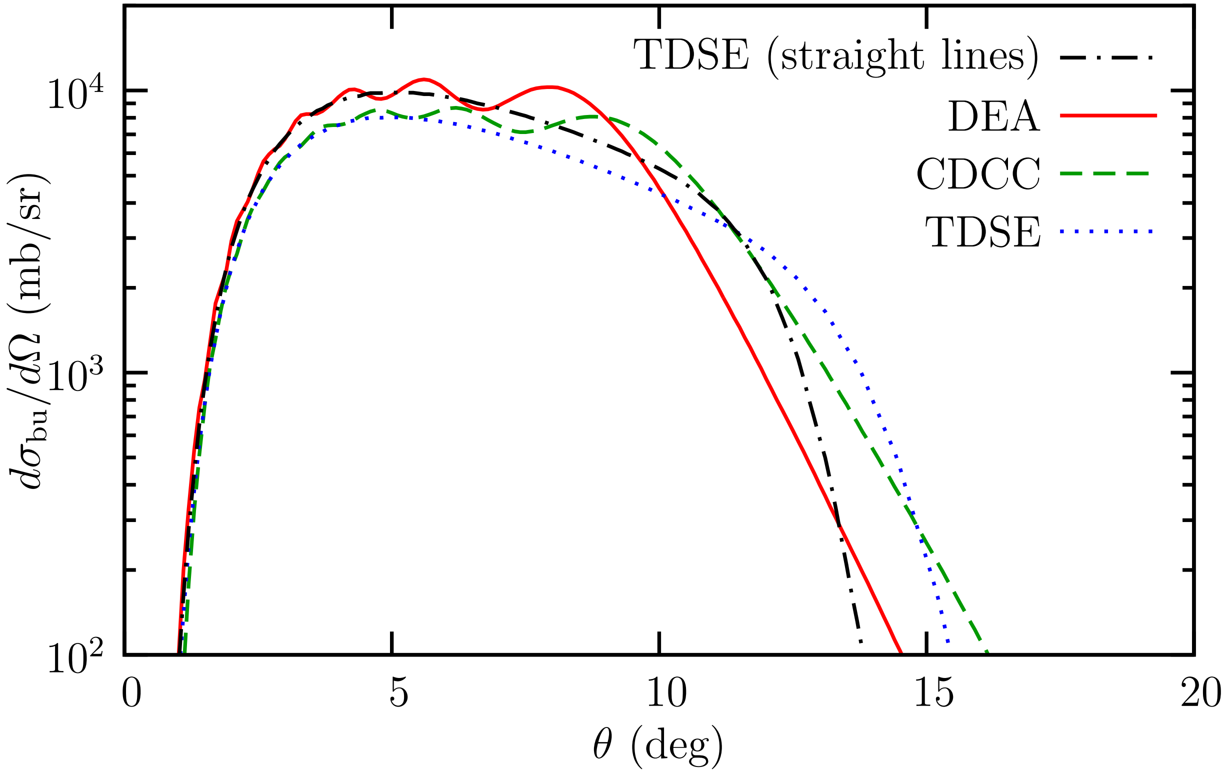
…and the two-body structure of ^{15}C

Angular distribution: ^{15}C+Pb @ $68A$MeV



- TDSE lacks quantum interferences
  but reproduces the general trend at small θ
  and observables integrated over angles
- DEA exhibits the quantum interferences
  much less time consuming than CDCC

^{15}C+Pb @ $20A$MeV



- Disagreement between DEA and CDCC increases
- With Coulomb trajectories TDSE follows CDCC
- With straight lines TDSE follows DEA

$\Rightarrow$ DEA lacks Coulomb deflection

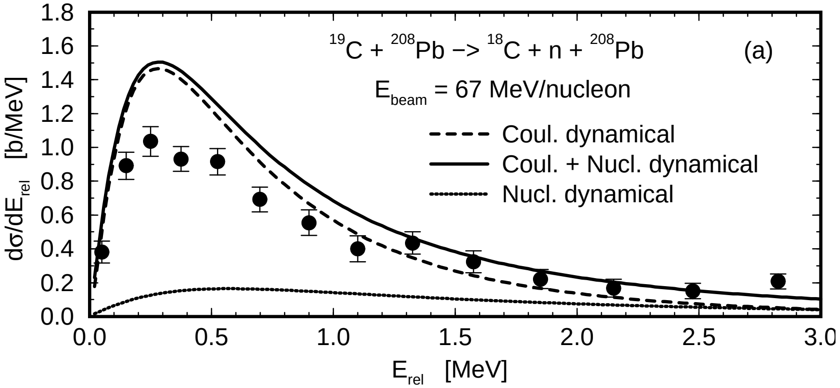
Conclusion of the comparison

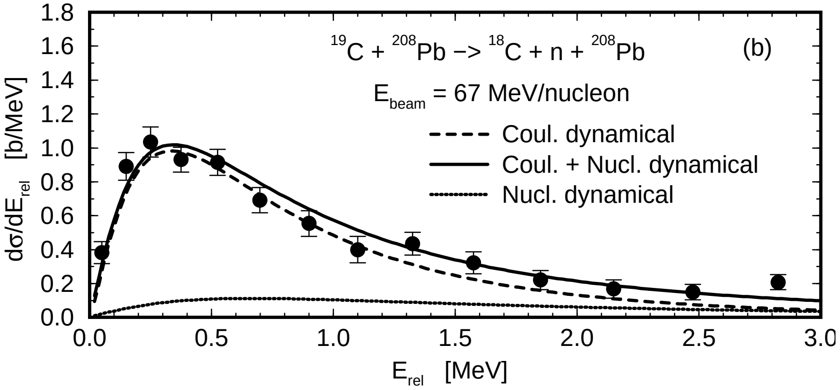
- Various nuclear-reaction models exist
  Built on simple description of nuclei
  using phenomenological potentials
  see review article [Baye, P.C. arXiv:1011.6427 (2010)]
- All models agree in energy distribution
  agree with exp. $\Rightarrow$ mechanism well understood
- TDSE lacks interferences in angular distribution
  because of semiclassical approximation
- DEA reproduces CDCC results
  while less time consuming
  but lacks Coulomb deflection

$\Rightarrow$ CDCC can be replaced by DEA at high energies

Study of halo nuclei (TDSE)

^{19}C on Pb @ 67AMeV

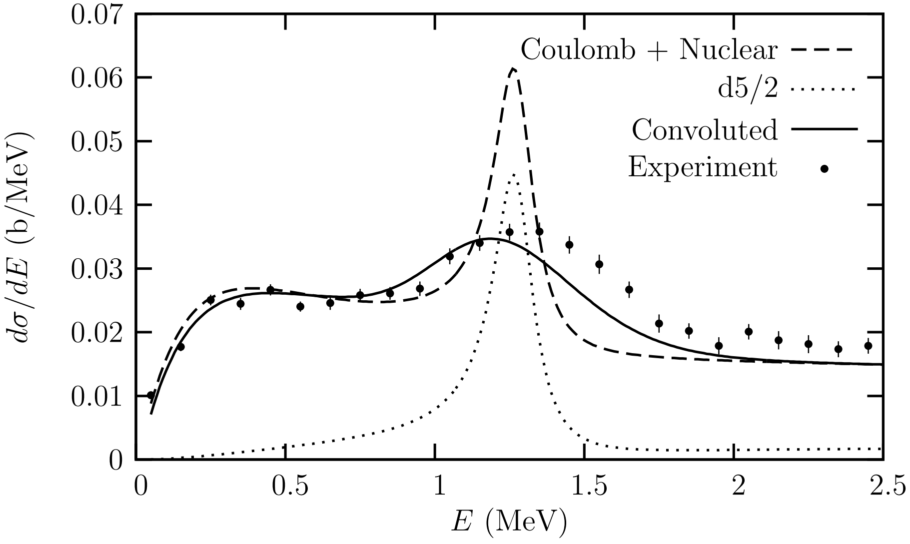




[Typel and Shyam, PRC 64, 024605 (2001)]

Exp. [Nakamura *et al.* , PRL 83, 1112 (1999)]

^{11}Be on C @ 67AMeV



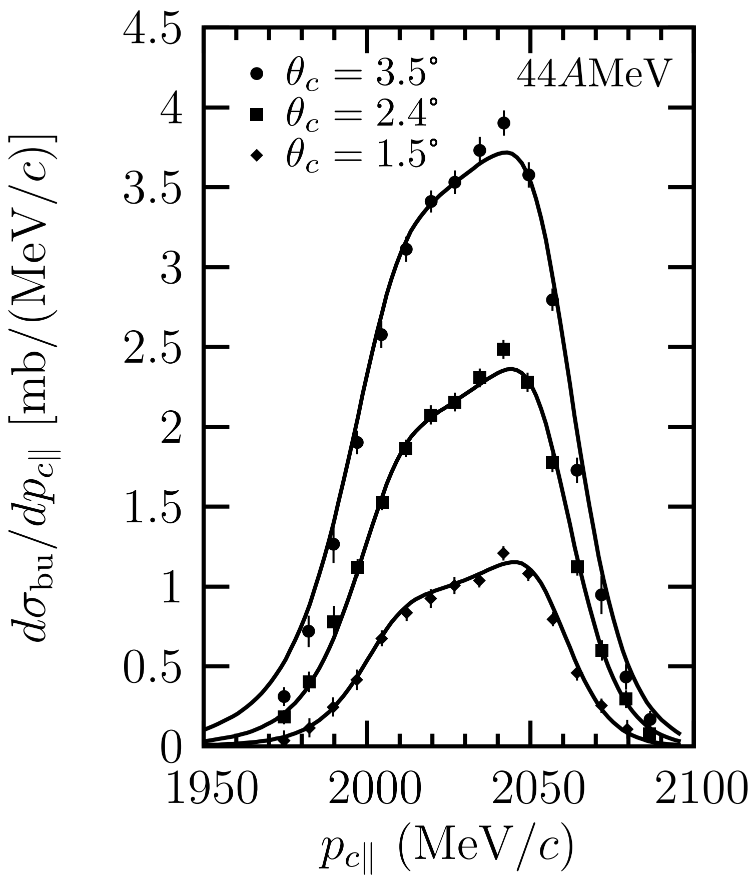
[P.C., Goldstein, Baye, PRC 70, 064605 (2004)]

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

- Sensitive to binding energy
  $S_{\mathrm{n}} =$ (a) 530keV; (b) 650keV
- Probes structure of continuum ($5/2^+$ resonance)

Reaction dynamics (DEA)

^{8}B on Pb @ $44A$MeV



DEA calculations

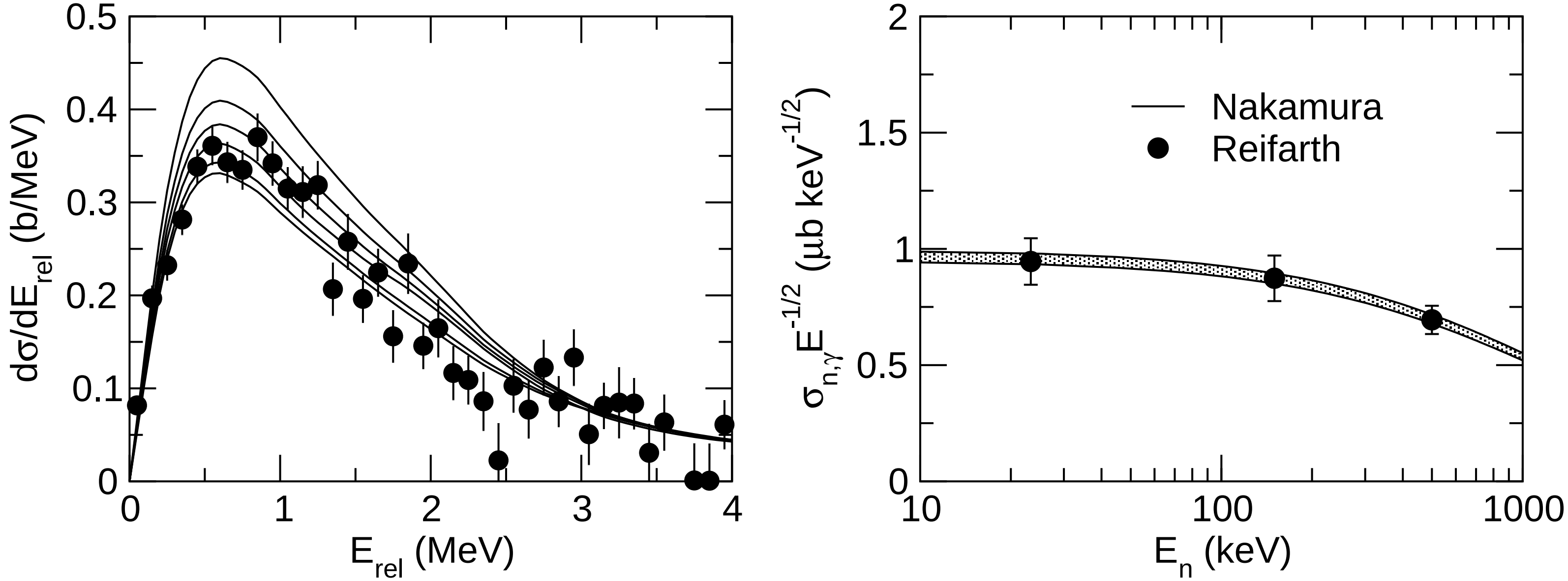
[Goldstein, P.C. and Baye, PRC 76, 024608 (2007)]

- agree with data
  [Davids *et al.* PRL 81, 2209 (98)]
- validate ^{7}Be + p structure of ^{8}B
- presence of E2 transitions
- higher-order effects (couplings in continuum)

⇒ significant reaction dynamics
⇒ attention when extracting info. from breakup data (e.g. $dB(\mathrm{E1})/dE$)

Application to astrophysics (CDCC)

^{15}C on Pb @ $68A$MeV



[Summers and Nunes, PRC 78, 011601(R) (2008)]

CDCC calculations with various ^{15}C models

Extract ANC from comparison with data

[Nakamura *et al.* PRC 79, 035805 (2009)]

Deduce σ_{capt} for $^{14}\mathrm{C}(\mathrm{n},\gamma)$, agrees with direct measure

Same analysis with TDSE [Esbensen PRC 80, 024608 ('09)]

Sensitivity to model inputs

Breakup is used to infer information about

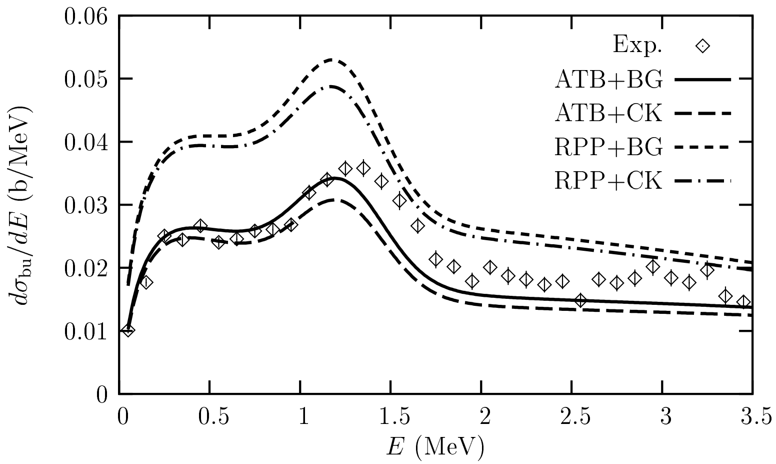
- exotic nuclear structure (halo nuclei)
- radiative capture of astrophysical interest

Reaction process is complex (E2, higher-orders…)

Calculations sensitive to optical potentials V_{PT}

Ex. ^{11}Be+C @ 69AMeV

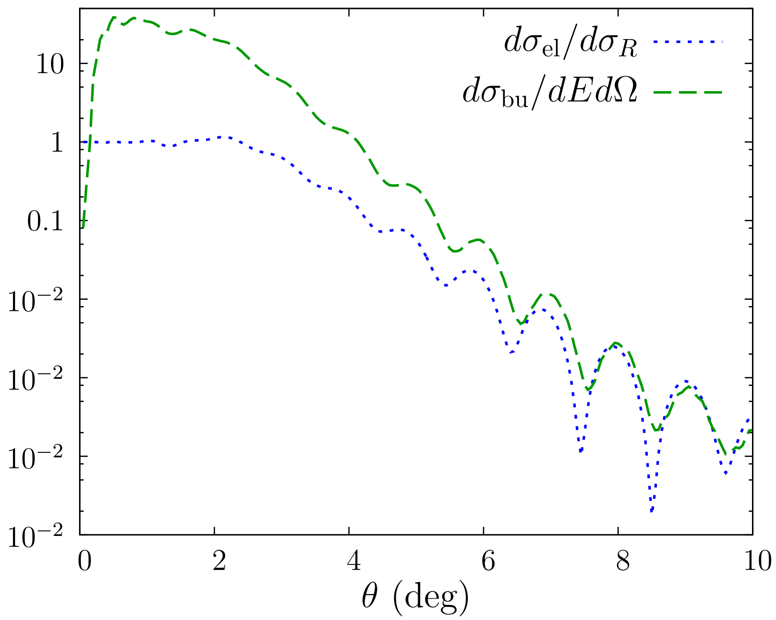
[P.C., Goldstein, Baye, PRC 70, 064605 (2004)]



Is there an observable insensitive to reaction process, V_{PT}, and that gives direct access to nuclear structure ?

Angular distributions

^{11}Be+Pb @ $69A$MeV [P. C., M. Hussein, D. Baye, PLB 693, 448 (2010)]



Very similar features for scattering and breakup:

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

$\Rightarrow$ projectile scattered similarly bound or broken up

Recoil Excitation and Breakup

Assumes [R. Johnson *et al.* PRL 79, 2771 (1997)]

- adiabatic approximation
- $V_{fT} = 0$

$\Rightarrow$ excitation and breakup due to recoil of the core

Elastic scattering: $\frac{d\sigma_{\rm el}}{d\Omega} = |F_{00}|^2 (\frac{d\sigma}{d\Omega})_{\rm pt}$

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

$\Rightarrow$ scattering of compound nucleus $\equiv$

form factor $\times$ scattering of pointlike nucleus

Similarly for breakup: $\frac{d\sigma_{\rm bu}}{dE d\Omega} = |F_{E,0}|^2 (\frac{d\sigma}{d\Omega})_{\rm pt}$

$$|F_{E,0}|^2 = \sum_{ljm} \left| \int \Phi_{ljm}(E) \Phi_0 e^{i\boldsymbol{Q}\cdot\boldsymbol{r}} d\boldsymbol{r} \right|^2$$

$\Rightarrow$ explains similarities in angular distributions

provides the idea for the ratio technique…

Ratio technique

$$d\sigma_{\text{bu}}/d\sigma_{\text{el}} = |F_{E,0}(\boldsymbol{Q})|^2/|F_{00}(\boldsymbol{Q})|^2$$

- completely independent of reaction process
  not affected by V_{cT}
- probes only projectile structure
- no need to normalise exp. cross sections

Test this using DEA

- without adiabatic approximation
- including V_{fT}

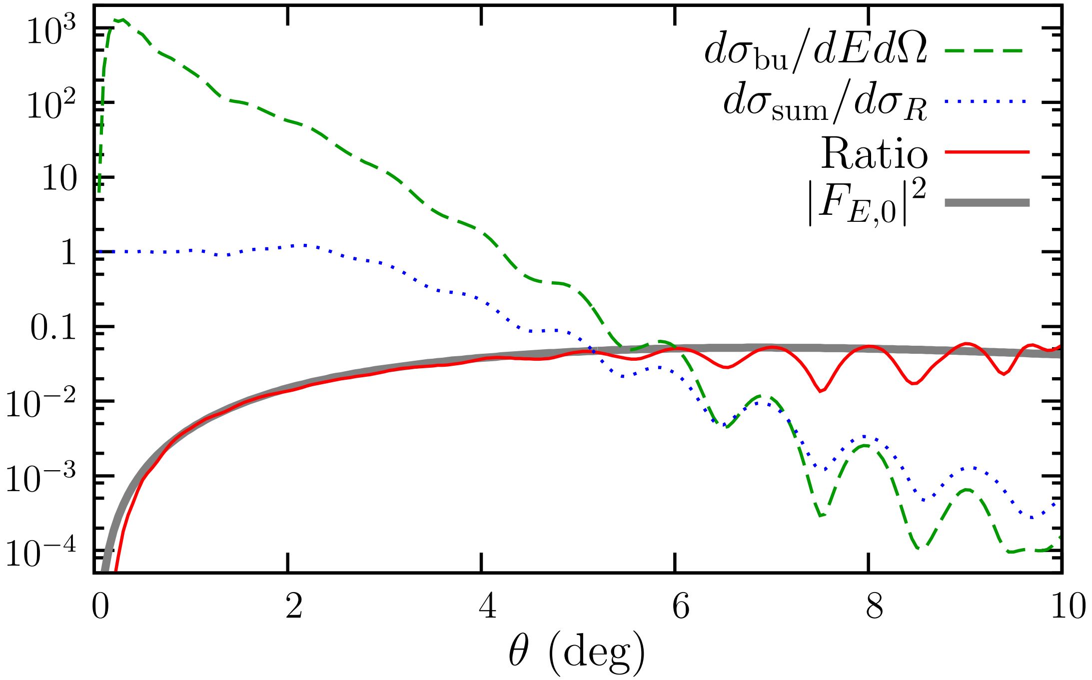
Alternative: $d\sigma_{\text{bu}}/d\sigma_{\text{sum}} = |F_{E,0}|^2$

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

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

Testing with DEA

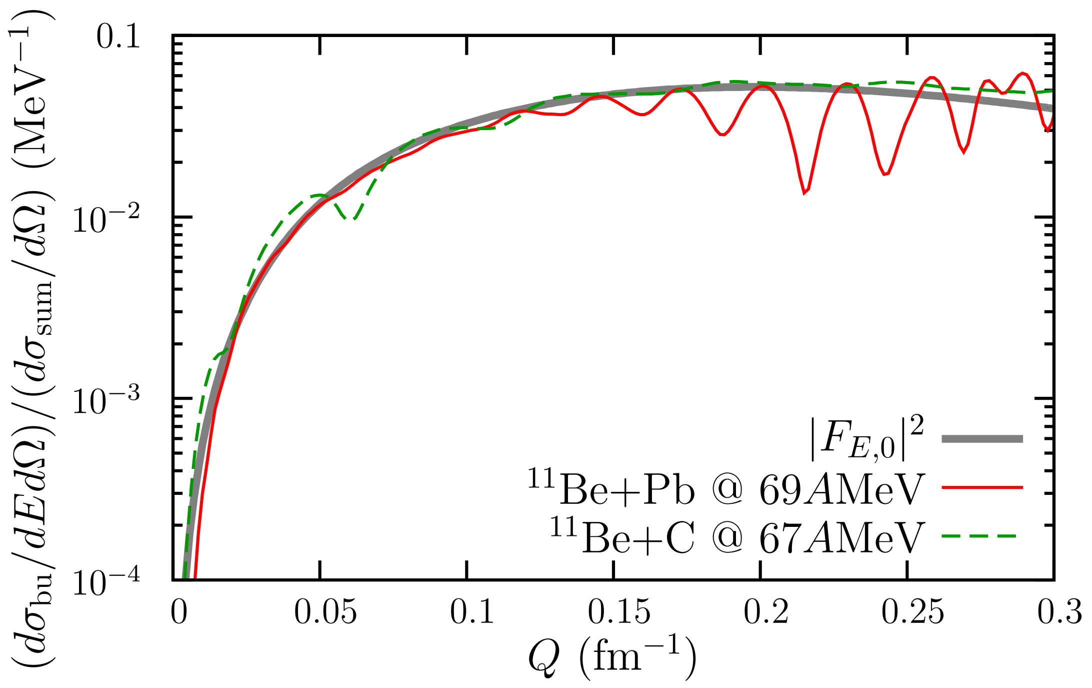
^{11}Be+Pb @ 69AMeV [P. C., R. Johnson, F. Nunes, arXiv:1104.2228 (2011)]



- removes most of the angular dependence
- REB predicts ratio $= |F_{E,0}|^2$
  confirmed by DEA calculations

$\Rightarrow$ probe structure with little dependence on reaction

(In)sensitivity to reaction process



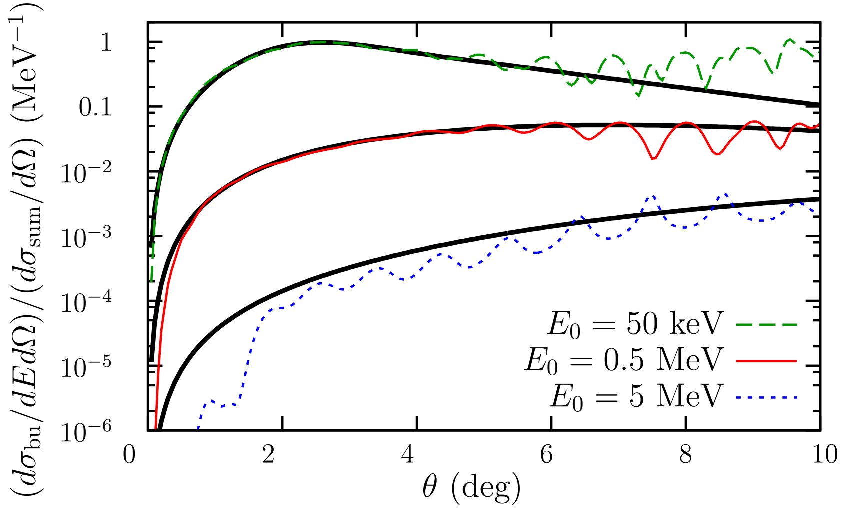
Similar for Coulomb and nuclear dominated collisions

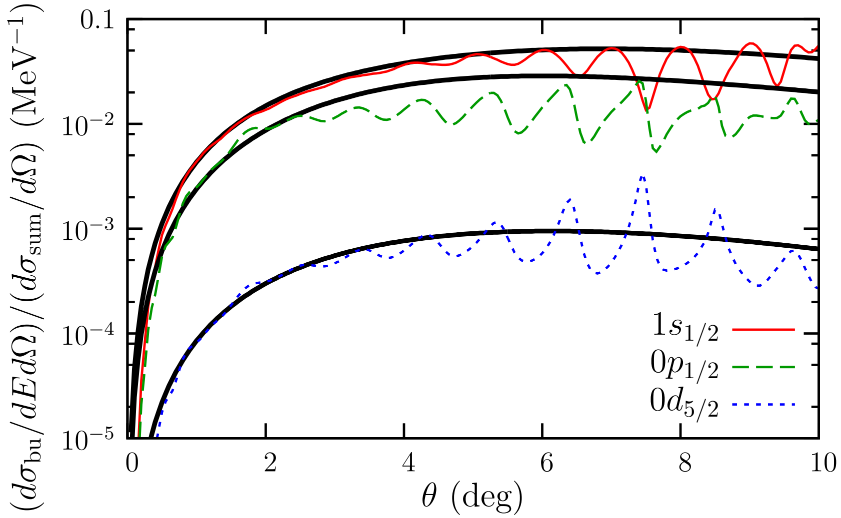
$\Rightarrow$ nearly independent of the reaction process

Sensitivity to projectile description

Study sensitivity to

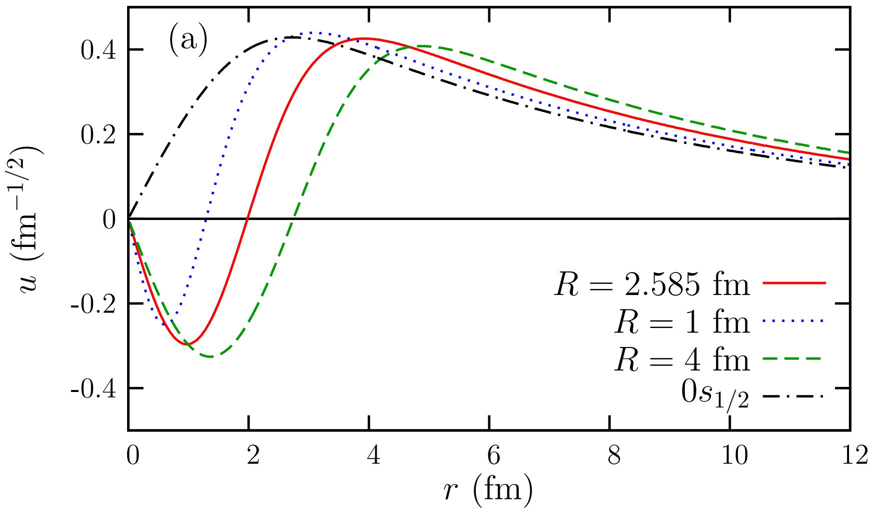
binding energy bound-state orbital

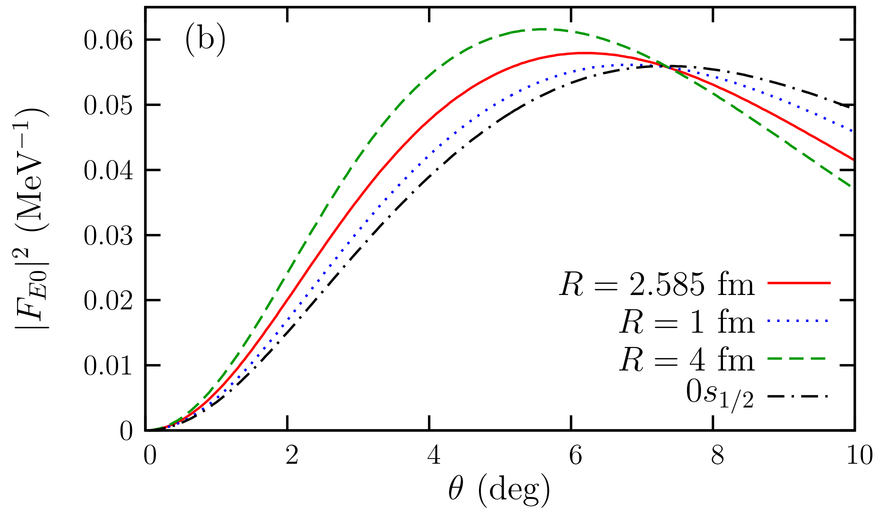




- Sensitive to both binding energy and orbital in both shape and magnitude
- Works better for loosely-bound projectile (adiabatic approximation ?)

Sensitivity to radial wave function





- Changes in $|F_{E,0}|^2$ similar to those in u_{lj}
- Forward angles probe asymptotics of u_{lj}
- Large angles probe the interior of u_{lj}
  may be difficult to distinguish experimentally

Summary of the ratio method

Breakup is a tool to study halo nuclei

Study hindered by reaction mechanism, $V_{PT}\ldots$

We propose a ratio of angular distributions

[P. C., R. Johnson, F. Nunes, arXiv:1104.2228 (2011)]

Removes most of the dependence on reaction process

Probes

- binding energy
- partial-wave configuration
- radial wave function

Open questions

- What happens for SF< 1 ?
- Is this valid for two-neutron haloes ?
- Can we extend this to proton haloes ?

Perspectives

Most reaction models built on
simple projectile description
using phenomenological V_{PT}

Ratio technique removes dependence on V_{PT}
$\Rightarrow$ gives access to finer information about projectile

Future: improve the description of projectile

- include configuration mixing
  - XCDCC [Summers *et al.* PRC 74, 014606 (2006)]
  - use DEA, as less expensive than CDCC
- three-body projectiles
  - CCE [Baye *et al.* PRC 79, 024607 (2009)]
  - CDCC [Rodrìguez-Gallardo *et al.* PRC 80, 051601 ('09)]

Thanks. . .

- to you for your attention
- to my collaborators

Filomena Nunes

Daniel Baye

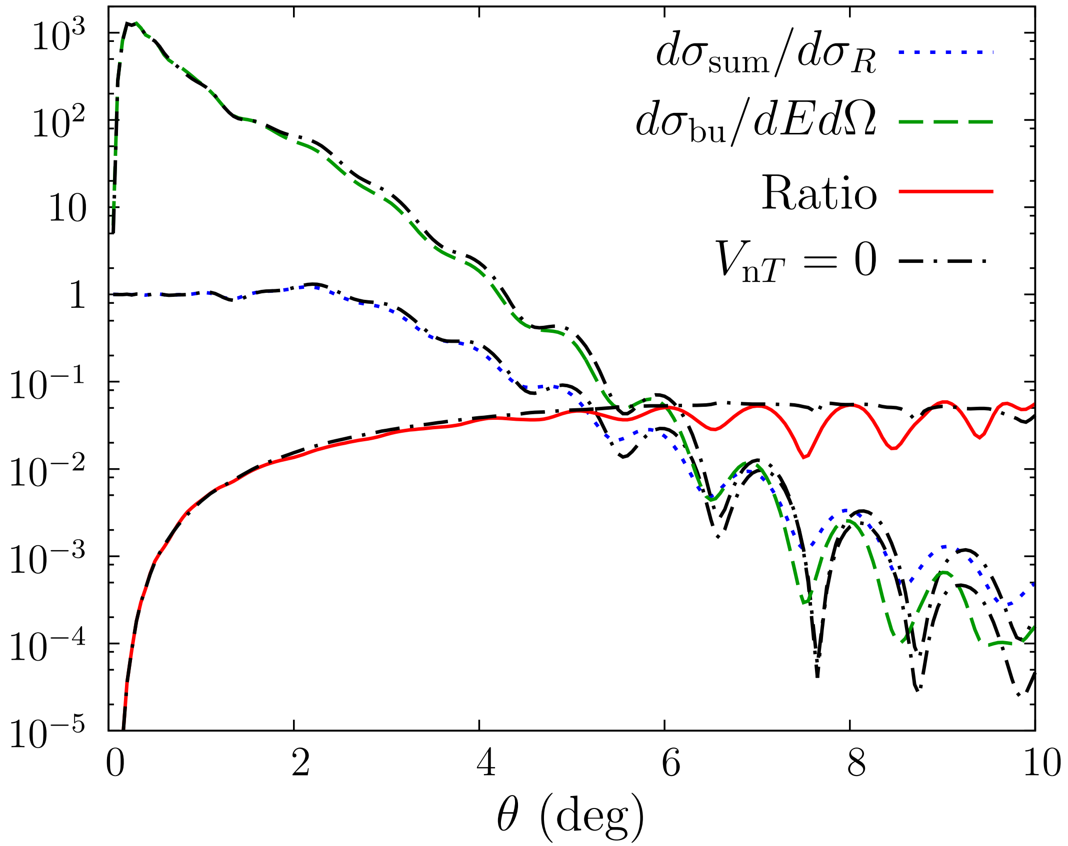
Mahir Hussein

Ron Johnson

Henning Esbensen

Ian Thompson

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



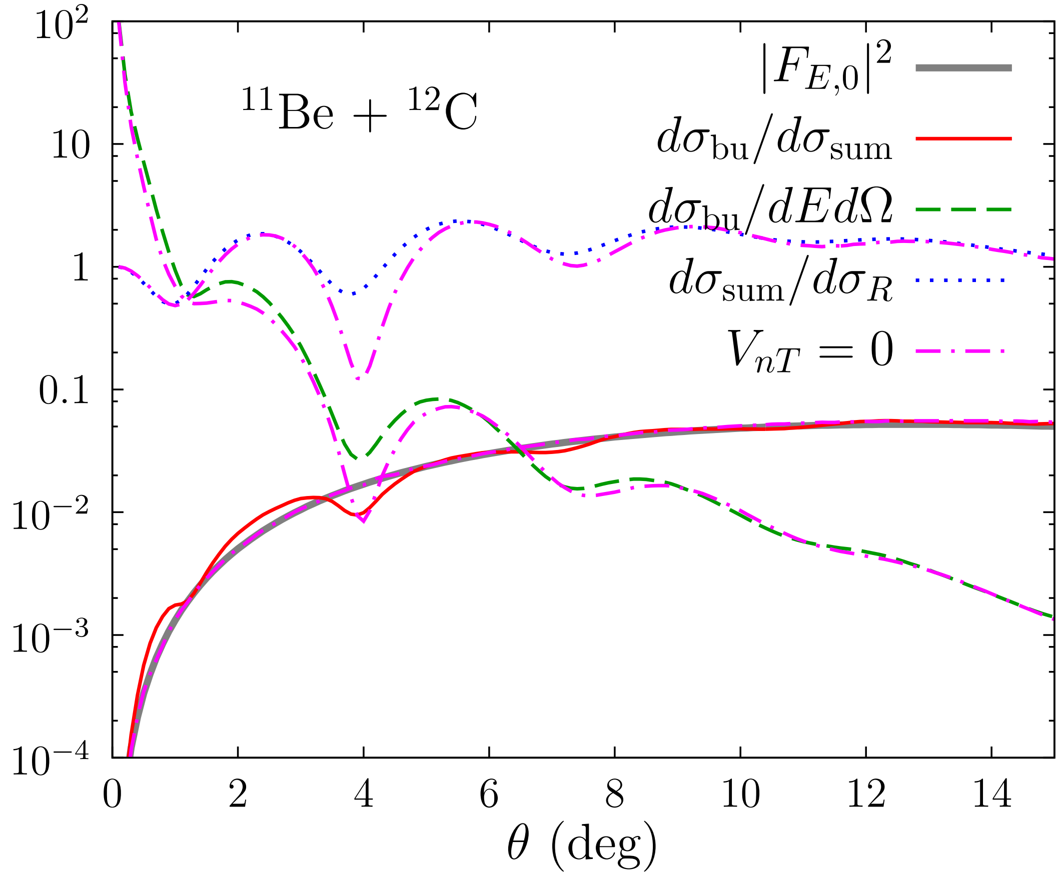
Large-angle oscillations due to $V_{\mathrm{n}T}$

$V_{\mathrm{n}T}$ shifts oscillations [R. Johnson *et al.* PRL 79, 2771 (97)]

shift vary with excitation energy E

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

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



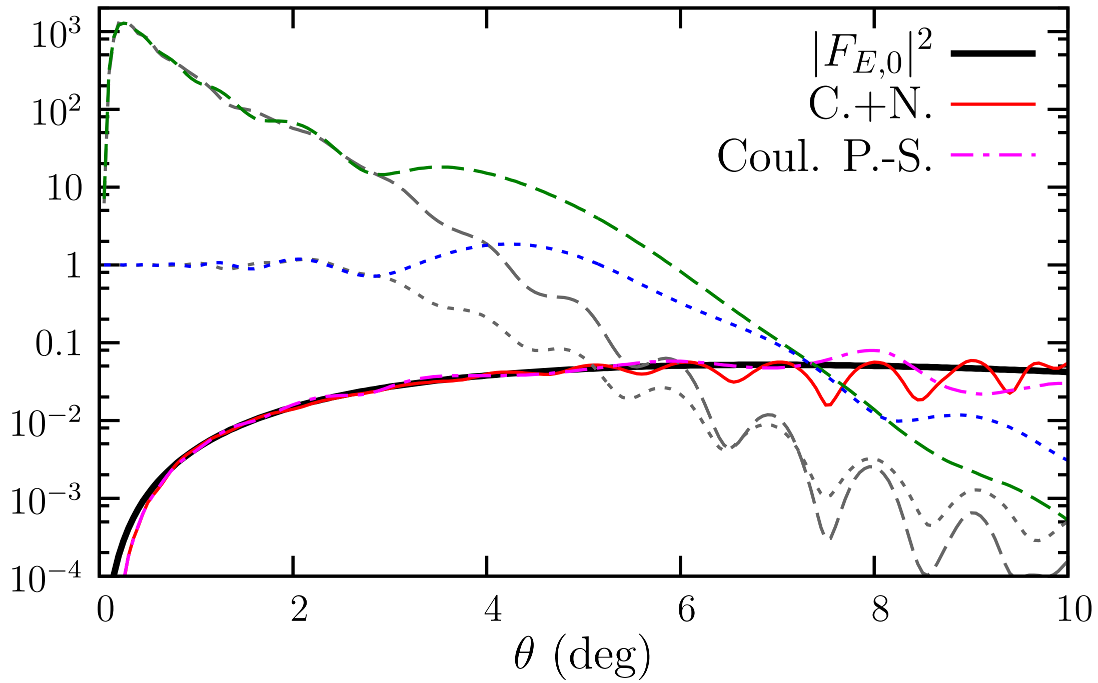
Oscillations at 2–4° due to $V_{\mathrm{n}T}$

$V_{\mathrm{n}T}$ shifts oscillations [R. Johnson *et al.* PRL 79, 2771 (97)]

shift vary with excitation energy E

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

Insensitivity to V_{PT} (1)

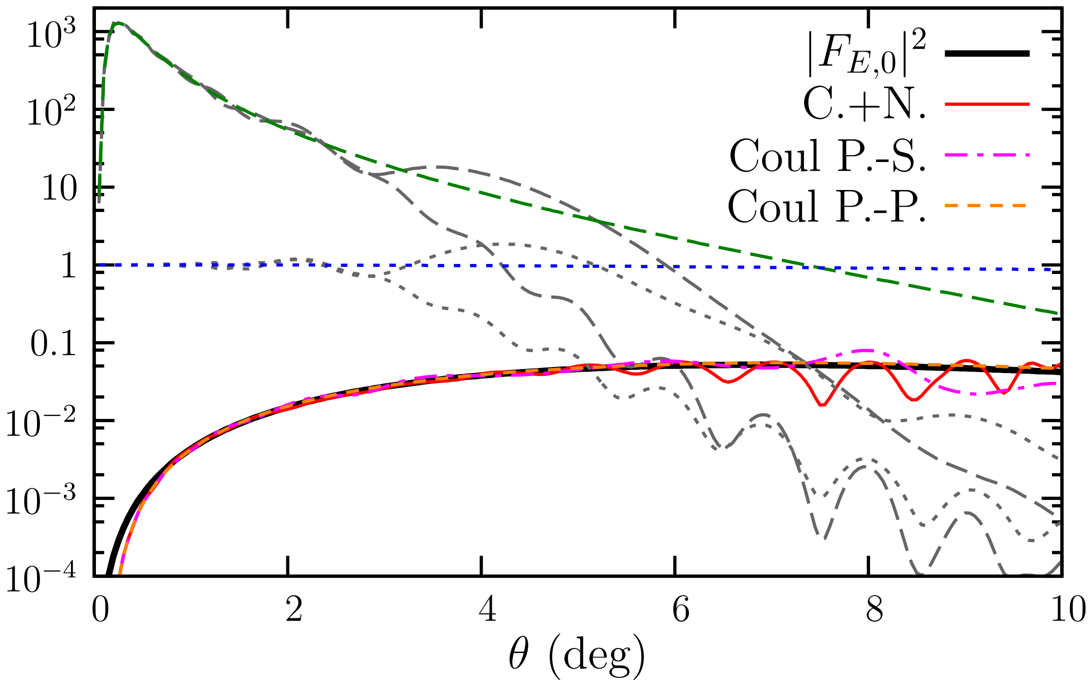


Without nuclear part of V_{PT}, different distributions:

- different Coulomb rainbow
- different oscillations

However, same ratio

Insensitivity to V_{PT} (2)

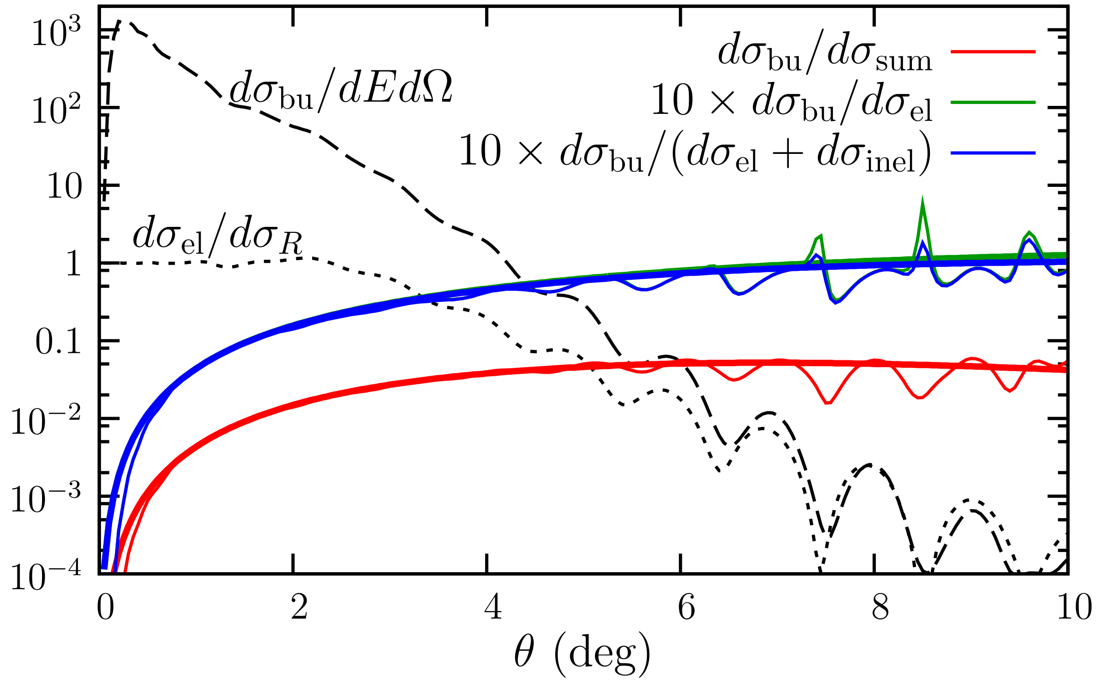


With $V_{PT} = \frac{Z_c Z_T e^2}{R_{cT}}$, very different distributions:

- No Coulomb rainbow
- No oscillations

However, same ratio

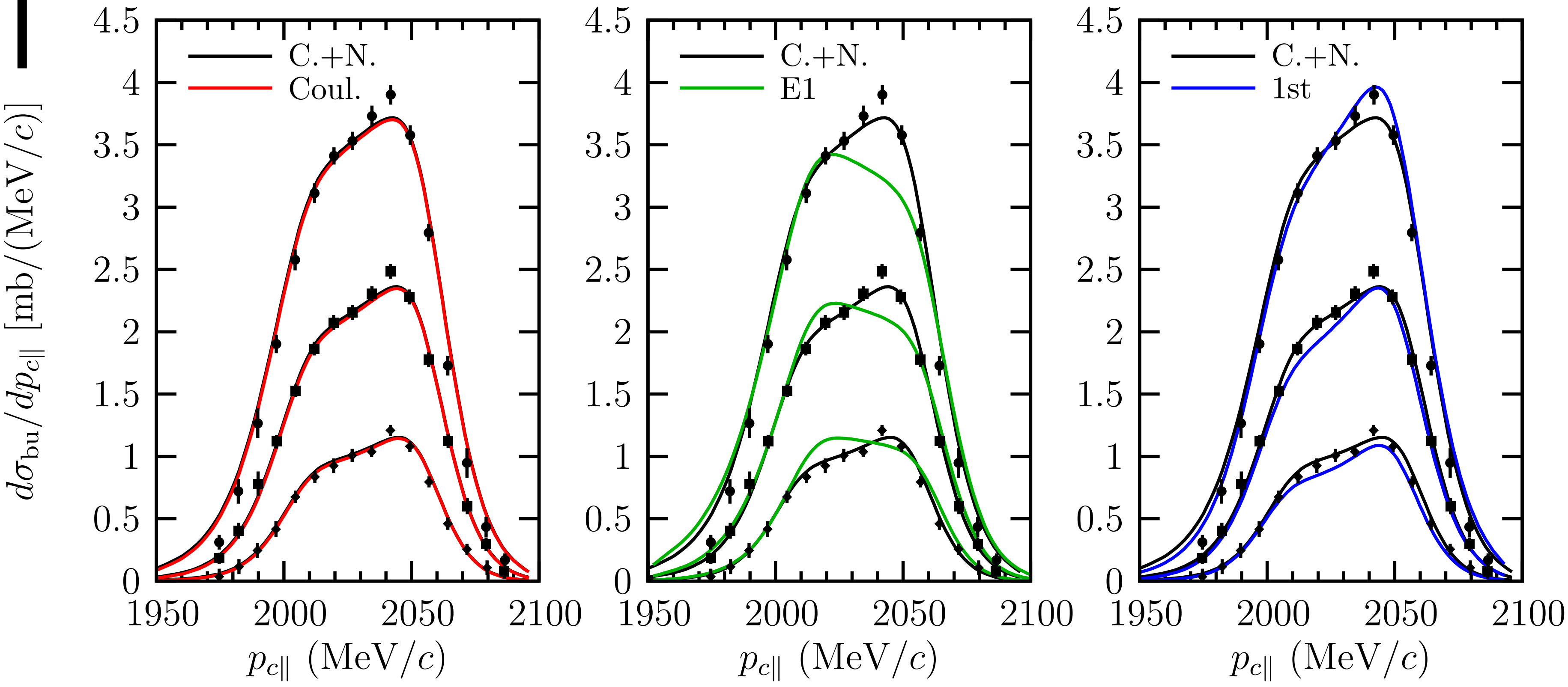
Other ratios



- $d\sigma_{\text{bu}}/d\sigma_{\text{sum}}$
- $d\sigma_{\text{bu}}/d\sigma_{\text{el}}$
- $d\sigma_{\text{bu}}/(d\sigma_{\text{el}} + d\sigma_{\text{inel}})$

Analysis

^{8}B + Pb @ 44 AMeV (MSU) [Davids PRL 81, 2209 (01)]



Nuclear interaction negligible at forward angles	Significant E1-E2 interference (asymmetry)	First-order: more asymmetric ⇒ higher-order