Breakup-Reaction Theory
Part IV: Application to Nuclear Astrophysics and Extension Beyond 2-b Projectiles

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11 August 2022

1. Nuclear Astrophysics
   - Astrophysical Application of Coulomb Breakup
2. Breakup of three-body projectiles
   - 4-body CDCC
   - Extension of the CCE to three-body projectiles
3. Core excitation
   - XCDCC
   - Adding an EFT 3-b force

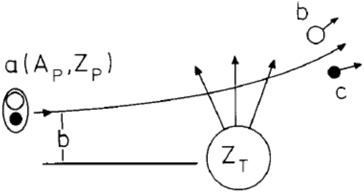
Coulomb Breakup Method

Radiative capture : $b + c \to a + \gamma$

Coulomb breakup : projectile breaks up colliding with a heavy target

$$a + T \to b + c + T$$

Coulomb dominated ⇒ due to exchange of virtual photons



Baur and Rebel Ann. Rev. Nucl. Part. Sc. 46, 321 (1996)

⇒ seen as the time-reversed reaction of the radiative capture
⇒ use Coulomb breakup to infer radiative-capture cross section
[Baur, Bertulani and Rebel NPA458, 188 (1986)]

Radiative Capture Cross Section

Radiative capture :

electromagnetic transition b-c continuum $\rightarrow a \equiv b + c$ bound state

At low energy, dominated by $\mathrm{E1}$ transitions

$$\sigma_{\mathrm{cap}}^{(\mathrm{E1})}(E) = \frac{2\pi^3}{3}\frac{E}{\hbar c}\frac{dB(\mathrm{E1})}{dE} \propto \frac{d\sigma_{\mathrm{bu}}^{(1)}(\mathrm{E1})}{dE}$$

$\Rightarrow$ Infer σ_{cap} from $d\sigma_{\mathrm{bu}}/dE$ [Baur, Bertulani and Rebel NPA458, 188 (1986)]

- easier to measure (above Coulomb barrier)
- higher cross sections

But :

- Nuclear interaction must be negligible
- Coulomb breakup must take place at first order
- and be dominated by E1 transitions

^{8}B

^{8}B has only one 2^+ loosely-bound state with $S_{\rm p} = 137$ keV
Often considered as a one-proton halo nucleus

Described as

$$\left|{}^8\mathrm{B}(2^+)\right\rangle = \left|{}^7\mathrm{Be}(3/2^-) \otimes \mathrm{p}(\mathrm{p}3/2)\right\rangle$$

Model of Esbensen & Bertsch [NPA 600, 37 (1996)] :

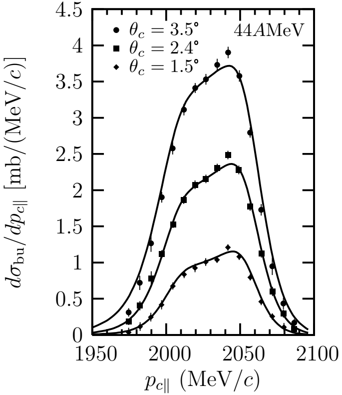
- ^{7}Be assumed spherical, its spin is neglected
- ^{7}Be-p potential has Woods-Saxon form factor (plus spin-orbit)

Parallel-momentum distribution

Parallel-momentum distribution is best to test this

see [Esbensen, Bertsch NPA 600, 37 (1996)]

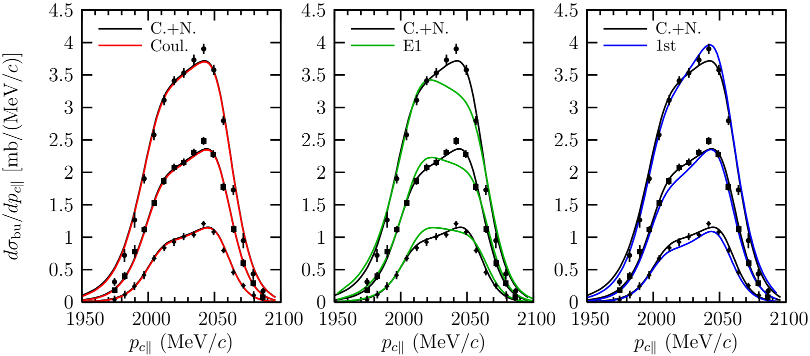
$^8\mathrm{B} + \mathrm{Pb}$ @ $44A$MeV   Exp : [Davids *et al.* PRL 81, 2209 (2001)]



Th : DEA [Goldstein, P.C., Baye, PRC 76, 064608 (2007)]

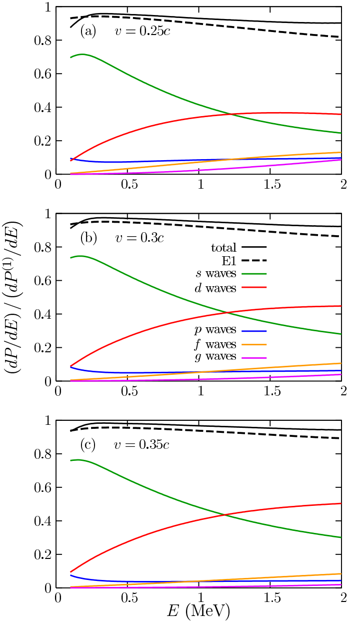
Excellent agreement with exp. (no fitting parameter)

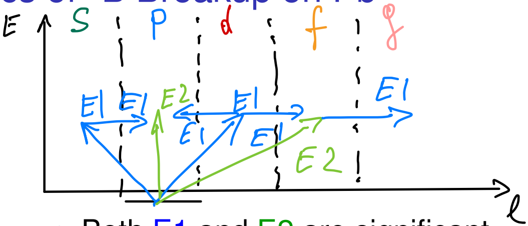
Reaction Dynamics



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

Analysis of the Dynamics of ^{8}B Breakup on Pb





- Both E1 and E2 are significant
- Higher-order effects :
  - presence of g components from a p ground state
  - $p + f >$ first-order E2
- Exact solution < first-order
  $\Rightarrow$ destructive interferences
  e.g. E1-E1 vs E2

$\Rightarrow$ be careful with first-order :
interesting qualitative tool
but inaccurate quantitative results

Interpretation

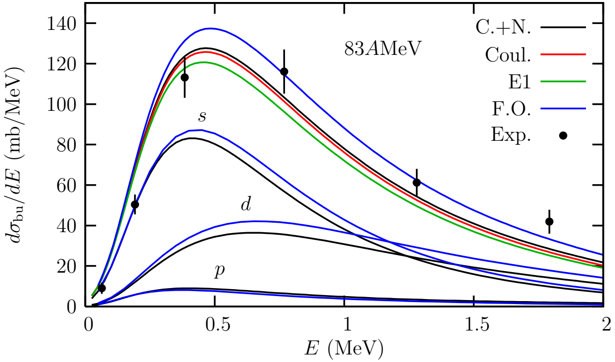
These results suggest the following mechanism

- at forward angle, reaction dominated by Coulomb
  $\Rightarrow$ removes sensitivity to nuclear interaction
- not only one-step E1 to continuum
- also one-step E2
- and two-step E1-E1
  which interfere with E2

$\Rightarrow$ direct extraction of $\sigma_{\rm capt}$ from $\sigma_{\rm bu}$ not that simple

Energy distribution

^{8}B + Pb @ 83AMeV (MSU) [Davids *et al.* PRL 83, 2750 (2001)]

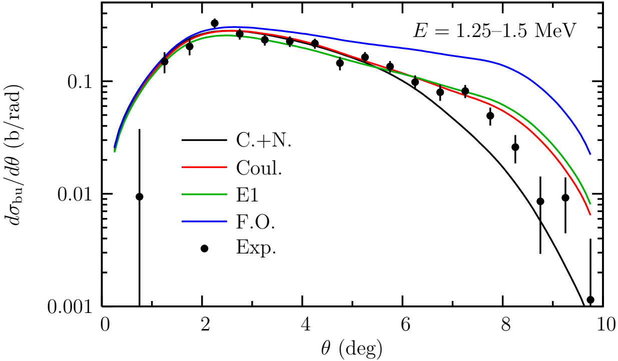


Th : DEA [Goldstein, P.C., Baye PRC 76, 024608 (2007)]

- Fair agreement with experiment
- Little influence of nuclear interaction
- Small influence of E2 $\Rightarrow$ no study of E2
- Higher-order effects (s and d $\searrow$, while p $\nearrow$)

Angular distribution

^{8}B + Pb @ 52AMeV (RIKEN) [Kikuchi *et al.* PLB 391, 261 (1997)]

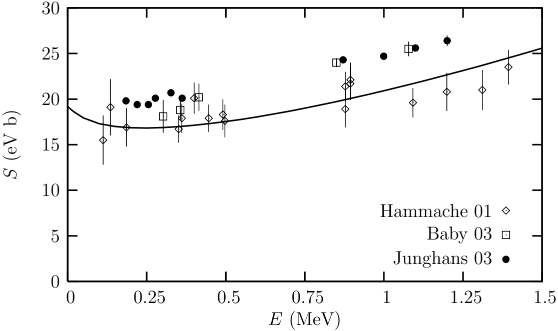


Th : DEA [Goldstein, P.C., Baye PRC 76, 024608 (2007)]

- Good agreement with experiment
- Nuclear interaction influent only at large angle
- Small influence of E2 ⇒ no study of E2
- First-order too large ⇒ higher-order effects

S_{17}

Using this $^{8}\mathrm{B}$ description, the $^{7}\mathrm{Be}(\mathrm{p},\gamma)^{8}\mathrm{B}$ S_{17} is



We obtain $S_{17} = 19.2$ b eV at $E = 0$

Good agreement with Hammache [PRL 86, 3985 (2001)]

Too low but good shape compared to Junghans [PRC 68, 065803 (03)]

Summers and Nunes suggest another idea . . .

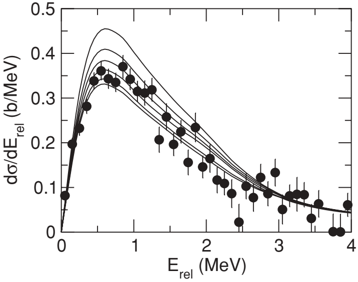
[Summers, Nunes PRC 78, 011601 (2008)]

Analysis by Summers & Nunes

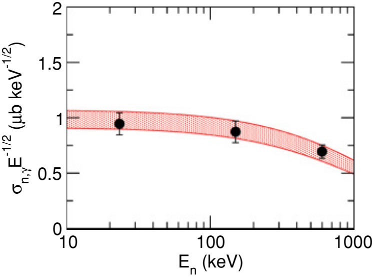
Summers and Nunes have calculated

$$^{15}\mathrm{C} + \mathrm{Pb} \rightarrow \ ^{14}\mathrm{C} + \mathrm{n} + \mathrm{Pb} \quad \text{at } 68A\text{MeV}$$

within CDCC using different $V_{^{14}\mathrm{C}-\mathrm{n}}$ [PRC 78, 011601 (2008)]



Exp. : Nakamura *et al.*
Th. : Summers, Nunes



Exp. : Reifarth *et al.*
Th. : Summers, Nunes

Significant dynamical effects ⇒ requires an accurate reaction model

From a χ^2 fit to the data, they extract an ANC they use to get $\sigma_{\mathrm{n},\gamma}$

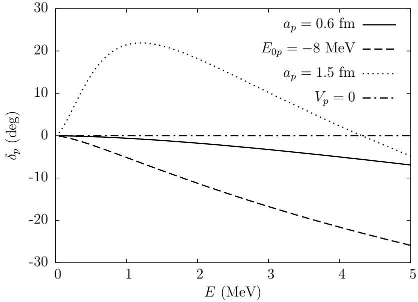
Influence of the ^{14}C-n continuum

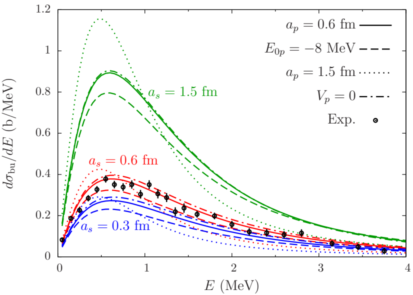
Breakup calculations are sensitive to ANC, but also to δ_l

Wat is the influence of the phaseshifts ?

We developed ^{14}C-n potentials with very different ANC and δ_p

[P.C., Nollet PRC 96, 015801 (2017)]





- Huge effect of ANC, but non-negligible effect of δ_p

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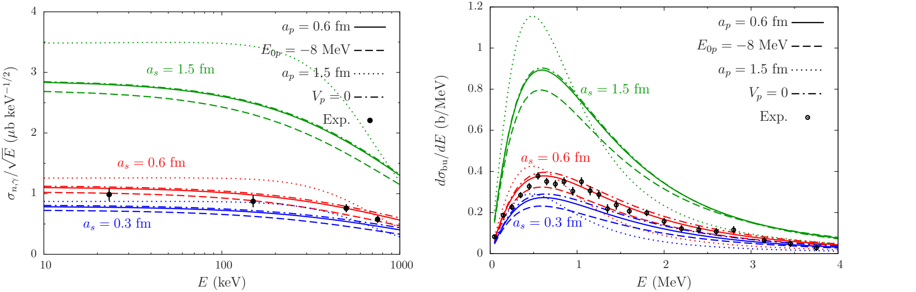

- Huge effect of ANC, but non-negligible effect of δ_p
- Same effect on $\sigma_{n,\gamma}$ $\Rightarrow$ sensitive ot the same inputs

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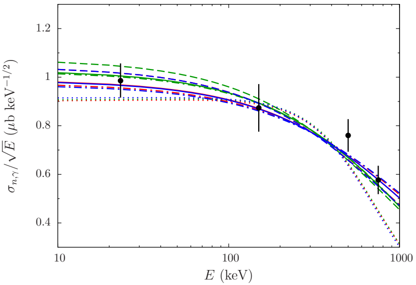
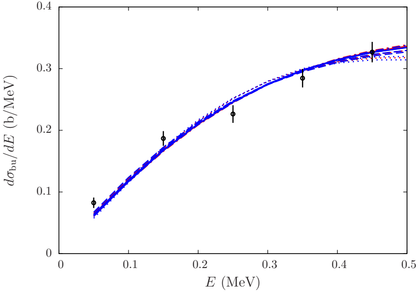




- Huge effect of ANC, but non-negligible effect of δ_p
- Same effect on $\sigma_{n,\gamma}$ $\Rightarrow$ sensitive ot the same inputs
- All potentials provide same $d\sigma_{\rm bu}/dE$ once scaled to data
- That scaling factor gives excellent agreement with capture data

Astrophysical Application of Coulomb Breakup

Initial idea : [Baur, Bertulani and Rebel NPA458, 188 (1986)]

See Coulomb breakup as time-reverse of radiative capture :

$$\sigma_{\rm cap}(E) \propto \frac{dB(\mathrm{E1})}{dE} \propto \frac{d\sigma^{(1)}_{\rm bu}(\mathrm{E1})}{dE}$$

But :

- Nuclear interaction (negligible at forward angles)
- E2 transitions
- higher orders

⇒ requires accurate reaction model [no direct extraction of $B(E1)$]

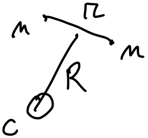
Nevertheless both reactions

- sensitive to same input (projectile description : ANC and δ_l)
- dominated by same interaction (Coulomb)

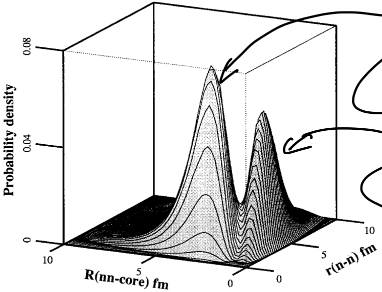
⇒ use breakup to constrain projectile model

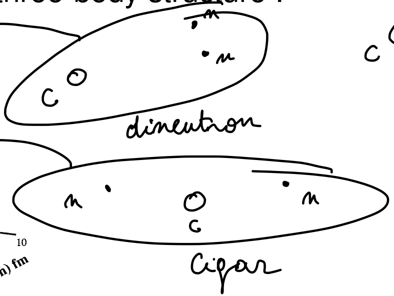
from which to calculate capture

Breakup of Borromean Nuclei



Borromean nuclei have a three-body structure :





[Zhukov *et al.* Phys. Rep. 231, 151 (1993)]

In first reaction models approached by a two-body model : $c + {}^2\mathrm{n}$

This is not appropriate, a three-body model is needed : $c + \mathrm{n} + \mathrm{n}$

Extension of CDCC have been proposed

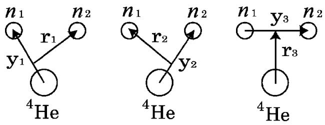
- Matsumoto *et al.* PRC 70, 061601(R) (2004) *ibid.* 73, 051602(R) (2006)]
- Rodríguez-Gallardo *et al.* PRC 77, 064609 (2008) *ibid.* 80, 051601(R) (2009)

Extension of CCE has been applied

- Baye *et al.* PRC 79, 024607 (2009)]

4-body CDCC

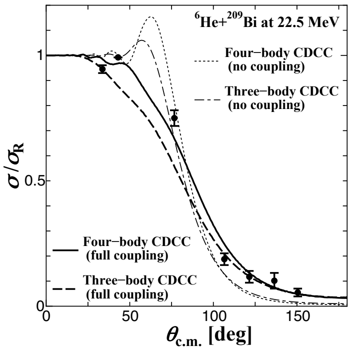
In Matsumoto *et al.* PRC 70, 061601(R) (2004)
the antisymmetrised 3-b wave function
is expanded in the 3 Jacobi sets of coordinates



$$\Phi_{nIM}(\xi) = \sum_{c=1}^{3} \psi_{nIM}^{(c)}(\xi)$$

To obtain a discretised continuum,
they diagonalise the Hamiltonian in a (finite) basis of Gaussians
to generate pseudostates

^{6}He+Bi elastic scattering @22.5~~A~~MeV



Th : [Matsumoto *et al.* 73, 051602(R) (2006)]

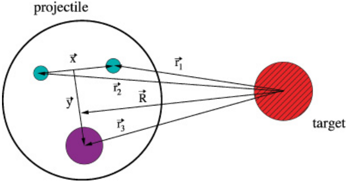
Exp : [Aguilera PRL 84, 5058 (2000)]

- breakup influences elastic scattering
- 3-b description of ^{6}He is needed to reproduce the data : dineutron model $c + {}^2\mathrm{n}$ does not agree with data
- Calculations limited (so far) to elastic scattering

Exension of Fresco

In Rodríguez-Gallardo *et al.* PRC 77, 064609 (2008)
the 3-b wave function is computed in hyperspherical harmonics

(see Nir's lectures)

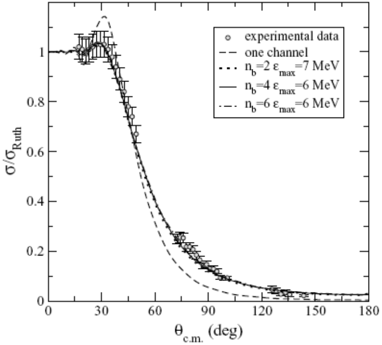


$$\Phi_{nIM}(\xi) = \sum_{\beta} R_{n\beta I}(\rho)\mathcal{Y}_{\beta IM}(\Omega_5)$$

- $\mathcal{Y}_{\beta IM}$ are the hyperspherical harmonics, known functions of $\Omega_5 \equiv \{\alpha, \hat{x}, \hat{y}\}$, which includes the hyperangle $\tan\alpha = x/y$
- $R_{n\beta I}$ are functions of the hyperradius $\rho = \sqrt{x^2 + y^2}$ that are determined by diagonalising the 3-b Hamiltonian

To obtain a discretised continuum, they generalise the THO method

^{6}He+Zn elastic scattering @13.6~~A~~MeV



Th : [Rodríguez-Gallardo *et al.* PRC 77, 064609 (2008)]

Exp : [Di Pietro *et al.* PRC 69, 044613 (2004)]

- breakup influences elastic scattering
- Note the convergence study shown in the figure. . .
- Size of the base limits the description of breakup

CCE for three-body projectiles

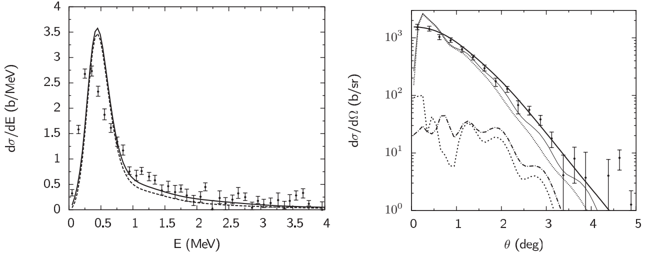
Coulomb-Corrected Eikonal model extended to three-body projectile

[Baye *et al.* PRC 79, 024607 (2009)]

Less computationally challenging than CDCC

$\Rightarrow$ gives access to finer breakup cross sections :

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



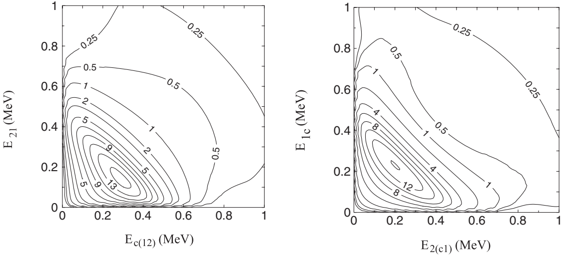
Th : [Pinilla PRC 85, 054610 (2012)] Exp : [Nakamura PRL 96, 252502 (2006)]

- Excellent agreement with experimental data
- Reaction dominated by E1 transition from ground state
  Narrow peak in energy distribution $\Rightarrow$ "1^-" resonance ?
- Convolution with experimental resolution is necessary

Structure of ^{11}Li continuum

CCE enables looking at how the energy is shared between the three bodies in the continuum (here in “1^-” contribution)

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



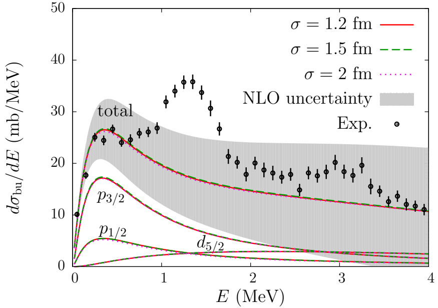
Th : [Pinilla PRC 85, 054610 (2012)]

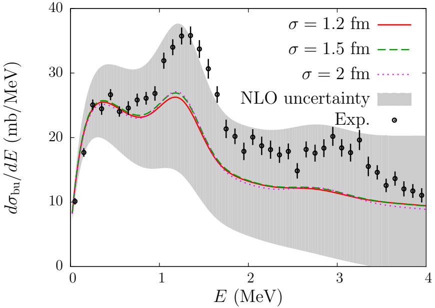
- Structure in the continuum ; confirms 1^- resonance ?
- Sign of ^{2}n virtual state in E_{21} ? ^{9}Li-n structure in E_{1c} ?
- More precise experimental data are needed to check this. . .

Core of the problem…

NLO analysis of ^{11}Be breakup on C
includes ^{10}Be-n interaction in s and p waves (not in d waves)
⇒ misses the resonant structures in data ($5/2^+$ and $3/2^+$ peaks)

^{11}Be+C→^{10}Be+n+C @ 67AMeV





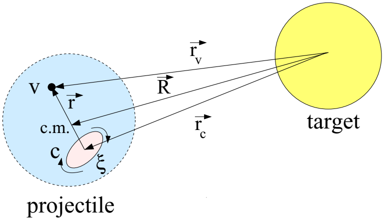
Exp. [Fukuda *et al.* PRC 70, 054606 (2004)]

Th. [P.C., Phillips & Hammer PRC 98, 034610 (2018)]

- Adding single-particle $d_{5/2}$ and $d_{3/2}$ resonances is not enough
  some degrees of freedom are missing…

Including the core excitation

Idea : consider that the core can be in an excited state :



[De Diego *et al.* PRC 89, 064609 (2014)]

$$H_0 = H_c(\xi_c) + T_r + V_{cn}(\xi_c, \boldsymbol{r})$$

[Summers, Nunes & Thompson PRC 73, 031603 (2006)]

[Lay, de Diego, Crespo, Moro, Arias & Johnson PRC 94, 021602 (2016)]

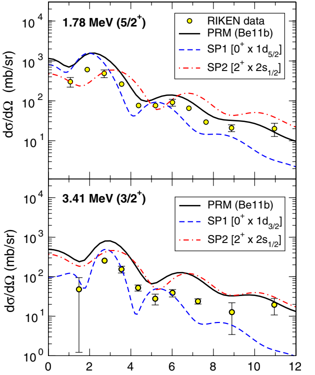
^{11}Be $\equiv$ ^{10}Be$(0^+) \otimes$ n$(1s_{1/2})$ + ^{10}Be$(2^+) \otimes$ n$(0d_{5/2})$+...

Core excitation in structure of the projectile & in reaction process

$\Rightarrow$ XCDCC (eXtended CDCC)

Role in resonant breakup

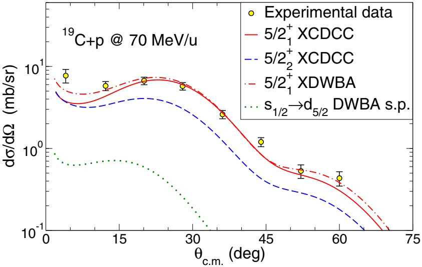
^{11}Be+C→^{10}Be+n+C @ 67AMeV



Th : DWBA [Moro& Lay PRL 109, 232502 (2012)]

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

^{19}C+p→^{18}C+n+p @ 70AMeV



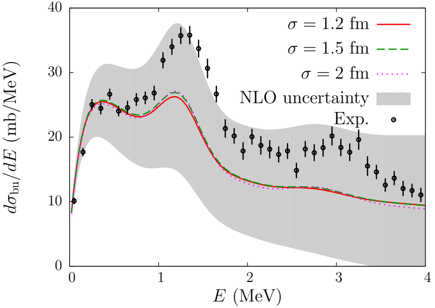
Th : XCDCC [Lay *et al.* PRC 94, 021602 (2016)]

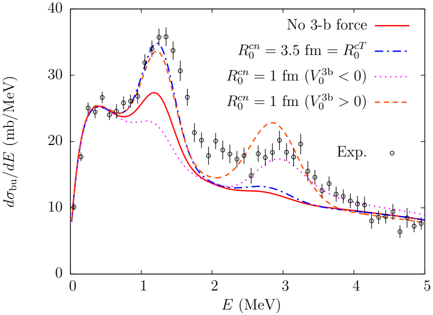
Exp. [Y. Satou *et al.* PLB 660, 320 (2008)]

- ^{11}Be+C : diffraction pattern reproduced only with core excitation
  $3/2^+$ dominated by ^{11}Be$(3/2^+) \equiv$ ^{10}Be$(2^+)\otimes$n$(d5/2)$
- Good agreement with data (no fitting parameter)
- Influence in resonant breakup confirmed on other systems

Including a 3-b force

^{11}Be+C→^{10}Be+n+C @ $67A$MeV (beyond NLO)





- Beyond NLO description is not sufficient : missing $^{10}\text{Be}(2^+)$
  [de Diego, Crespo & Moro, PRC 95, 044611 (2017)]
- Adding an effective 3-b force solves the issue
  Confirms role of the excitation of the core in reaction process

Summary

- Inferring B(E1) from breakup is risky
  - E2 contribution
  - Higher-order effect
- However radiative capture (n,γ) and breakup are sensitive to same structure inputs
- Extension of breakup models to Borromean systems :
  - 4-b CDCC
  - CCE
- Core degree of freedom of halo nuclei plays a role in resonant breakup