Theory Discussion Session (DREB12)

Challenges and recent developments of the CDCC method

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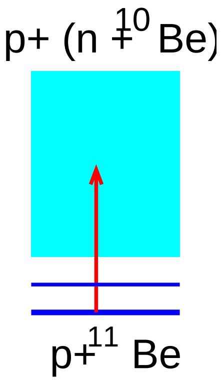
Outline:

1. Brief remainder of the “standard” CDCC method.
2. Testing the standard CDCC method against the Faddeev method.
3. Beyond the single-particle model: inclusion of core excitation.
4. Extension to three-body projectiles (4-body CDCC)

Remainder of the "standard" CDCC method (∼80s)

Example: ^{11}Be+p $\rightarrow$ (^{10}Be + n) + p

- Effective 3-body Hamiltonian with the 3 bodies in their g.s.
- Three-body wf expanded in projectile (^{11}Be) internal states
- Breakup treated as single-particle excitations to n+^{10}Be continuum
- Continuum is discretized in energy bins and truncated in energy and angular momentum
- Provides elastic and elastic breakup, but NOT transfer.



Restrictions and open issues of the standard CDCC method

Formal:

- Originally formulated for 3-body problems (2-body projectiles).
- Ignores possible excitations of the projectile constituents and target.
- Simple pair interactions (eg. central fragment-target interactions).
- Ignores transfer channels
- Relation with Faddeev formalism?

Computional:

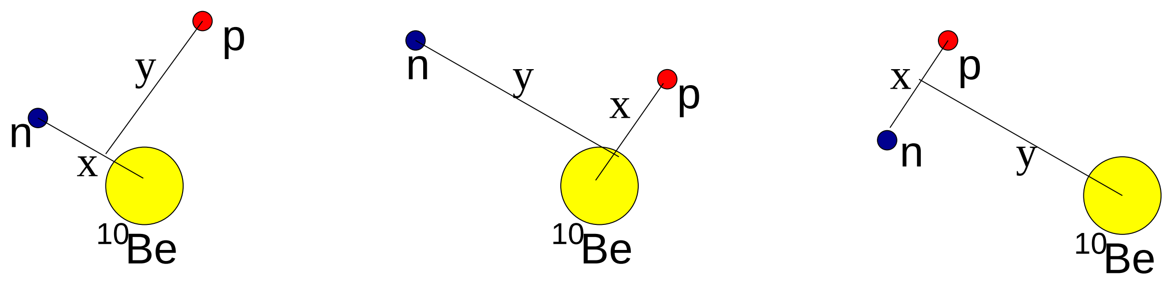
- Numerically demanding

Benchmark calculations CDCC versus Faddeev

CDCC versus Faddeev

- The *exact* solution of a three-body scattering problem is formally given by the Faddeev equations.

$$\Psi = \Psi_1 + \Psi_2 + \Psi_3$$

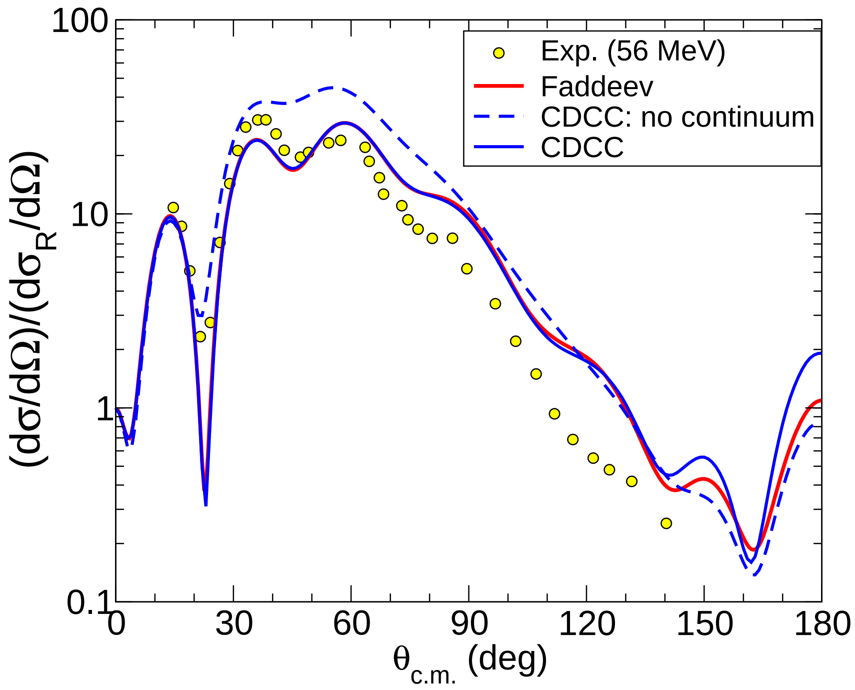


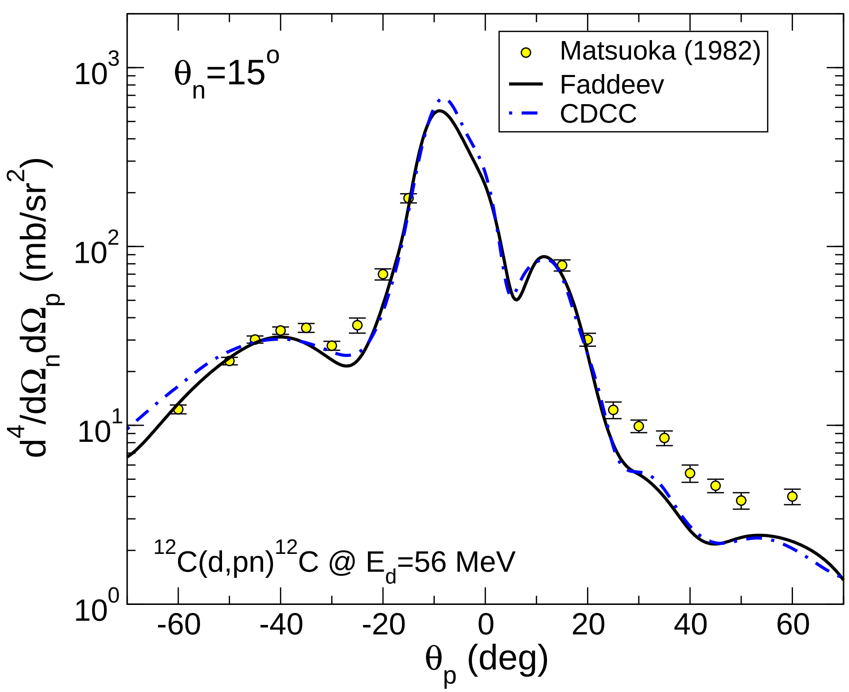
- The CDCC method can be derived as an approximated solution of the Faddeev equations in a truncated model space (Austern,Yahiro,Kawai, PRL63 (1989) 2649)
- For light systems, Faddeev equations can now be solved, so a comparison with CDCC is possible.

CDCC vs Faddeev: elastic scattering

$^{12}C(d,d)^{12}C$ at 56 MeV

$^{12}C(d,pn)^{12}C$





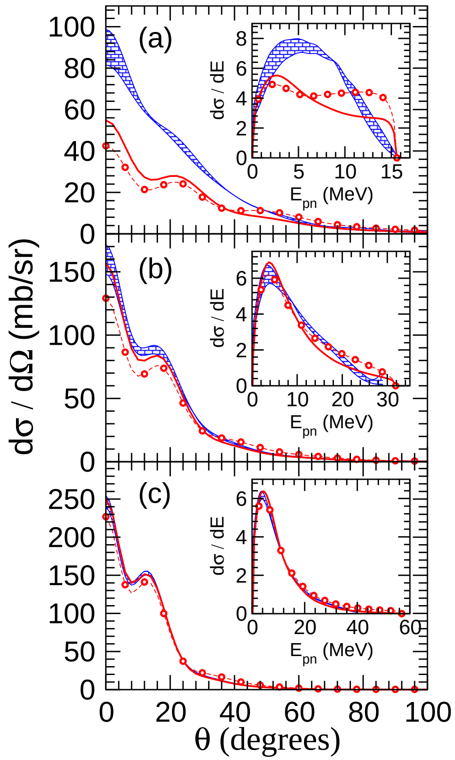
A. Deltuva, A.M.M., E. Cravo, F.M.Nunes, A.C. Fonseca, PRC76, 064602 (2007)

☞ *CDCC and Faddeev fully consistent!*

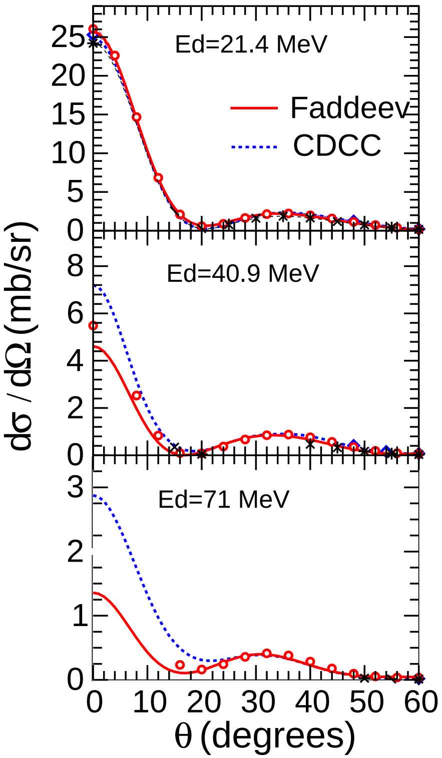
CDCC vs Faddeev

However...

^{10}Be (d, pn) ^{10}Be



^{10}Be (d, p) ^{11}Be



☞ Differences have been recently reported for breakup (low energies) and transfer (high energies) in ^{10}Be+d reaction (*N.J. Upadhyay, A. Deltuva, F.M. Nunes, arXiv:1112.5338*)

☞ *Further investigation is required!*

Beyond the standard CDCC method

Beyond the standard CDCC method

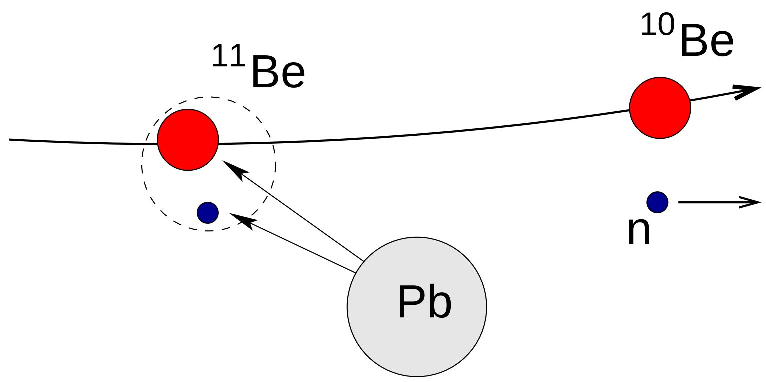
- Explicit inclusion of target excitation
  - ☞ *Yahiro* et al, *Prog. Theor. Phys. Suppl. 89 (1986)32*
- Explicit inclusion of core excitation
  - ☞ *Summers* et al, *PRC74 (2006) 014606, PRC76 (2007) 014611*
- Extension to three-body projectiles ($^6\mathrm{He}$).
  - ☞ *Matsumoto* et al, *NPA738 (2004) 471, PRC70 (2004) 061601(R)*.
  - ☞ *Rodríguez-Gallardo* et al, *PRC72 (2005) 024007, PRC77 (2008) 064609*.

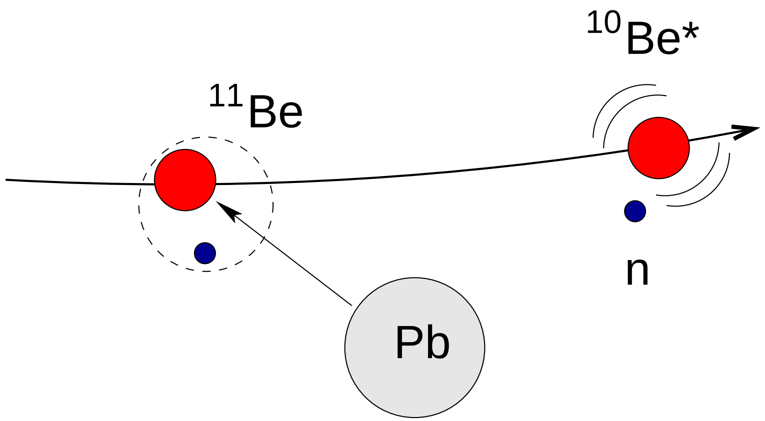
Part II: The effect of core excitation in the scattering of weakly bound nuclei

Why is important studying core excitation?

- Many nuclei of current interest (eg. exotic nuclei) are best studied within few-body models.
- The few-body constituents are frequently deformed clusters (eg. Be, C isotopes)
- Inclusion of the core degrees of freedom can be essential to:
  - understand the dynamics,
  - extract reliable structure information

^{11}Be+^{208}Pb





☞ Valence excitation mechanism.

☞ Core-excitation mechanism

Effect of core excitation in scattering observables

- Elastic scattering (adiabatic recoil model): *K. Horii* et al, *PRC81 (2010) 061602*

  ☞ *Some effects found in* $^8\mathrm{B}+^{12}\mathrm{C}$.

- Transfer (DWBA, CCBA): *Winfield* et al, *NPA 683 (2001) 48, Fortier* et al, *PLB 461 (1999) 22*

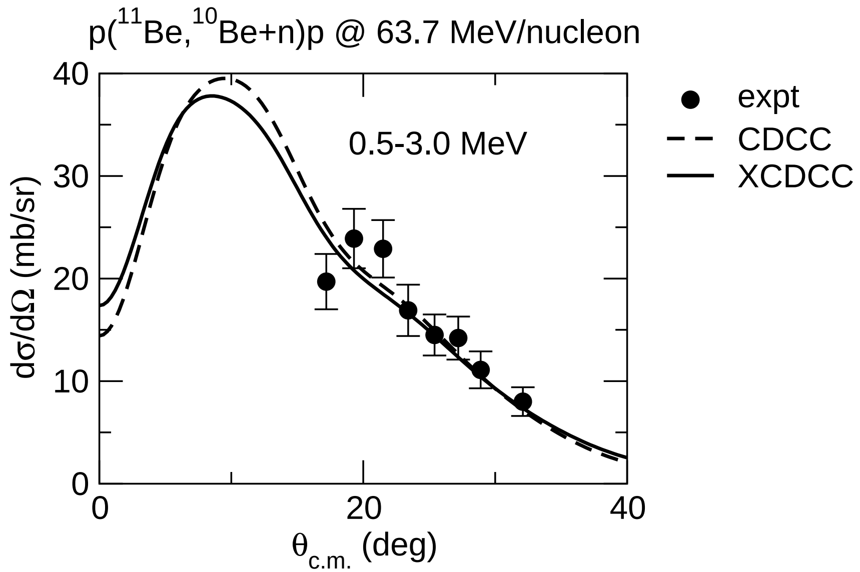
  ☞ *Very important to explain the production of* $^{10}\mathrm{Be}(2^+)$ *in* $^{11}\mathrm{Be}$*(p,d)*$^{10}\mathrm{Be}$

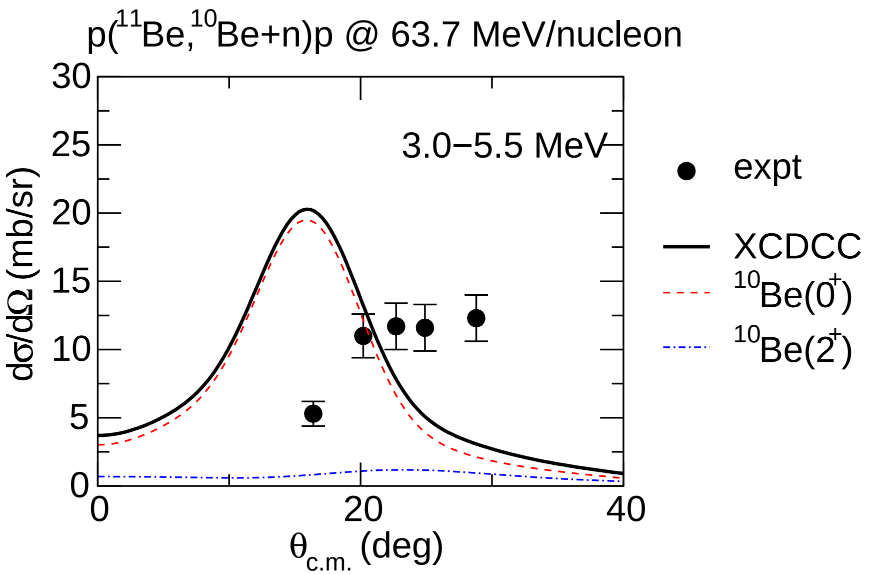
- Breakup (XCDCC) *Summers* et al, *PRC74 (2006) 014606, PRC76 (2007) 014611*

  ☞ *Very small effects in the cases studied (*$^{11}\mathrm{Be}$, $^{17}\mathrm{C}$*)*

Core excitation in nuclear breakup

Extended CDCC (XCDCC) calculations with core excitation:



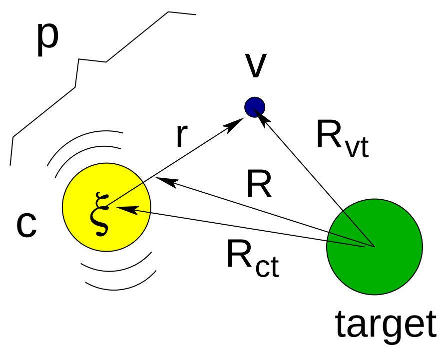


(Summers and Nunes, PRC76, 014611 (2007))

☞ *Very small core-excitation effect but...these calculations are currently under revision.*

Core excitation in a DWBA model

- Three-body model: two-body projectile (core+valence) + target



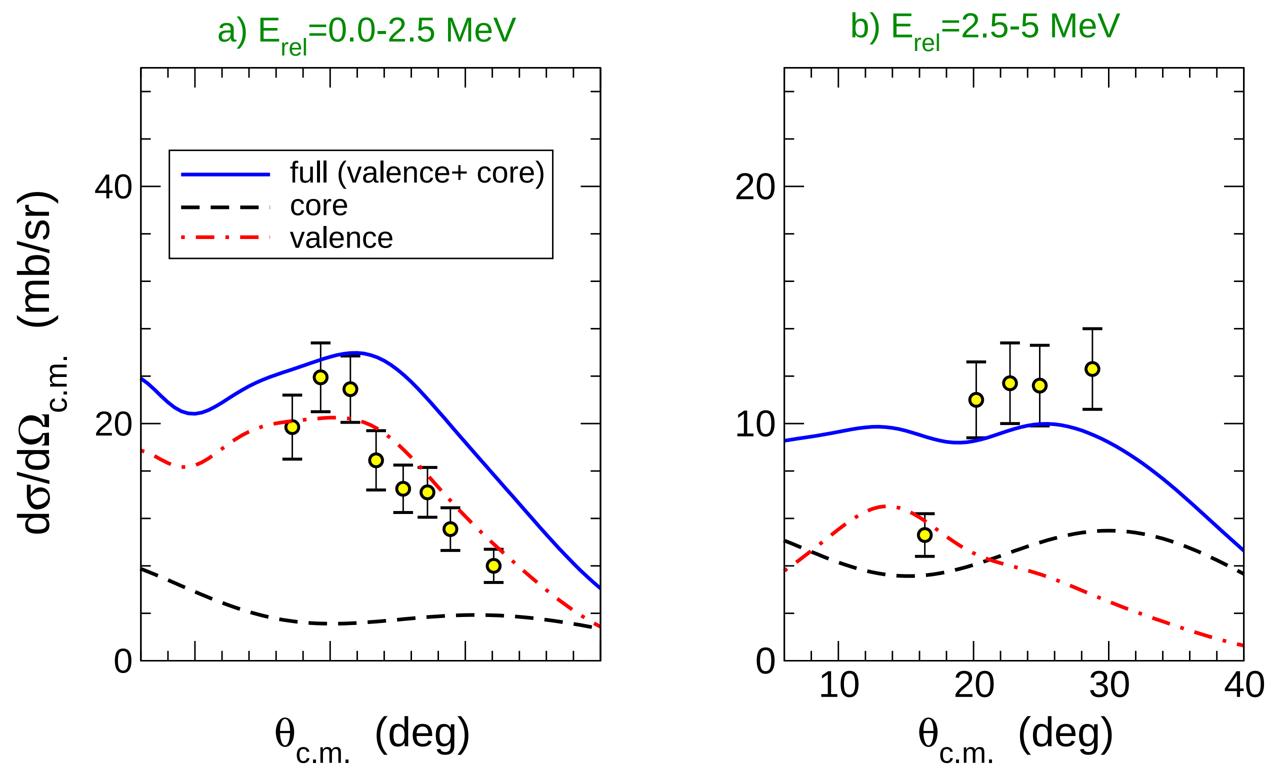
- DWBA amplitude with core excitation:

$$\boxed{T_{if}^{JM,J'M'} = \langle \chi_f^{(-)}(\vec{R})\Psi^f_{J'M'}(\vec{r},\vec{\xi})|V_{vt}(\vec{R}_{vt}) + V_{ct}(\vec{R}_{ct},\vec{\xi})|\chi_i^{(+)}(\vec{R})\Psi^i_{JM}(\vec{r},\vec{\xi})\rangle}$$

☞ $V_{ct}(\vec{R}_{ct},\vec{\xi})$ responsible for dynamic core excitation.

☞ $\Psi_{JM}(\vec{r},\vec{\xi}) = \sum_{\ell,j,I} R^J_{\ell,j,I}(r)\left[[Y_\ell(\hat{r})\otimes\chi_s]_j \otimes \Phi_I(\vec{\xi})\right]_{JM}$

Application to ^{11}Be+p $\rightarrow$ ^{10}Be +n +p



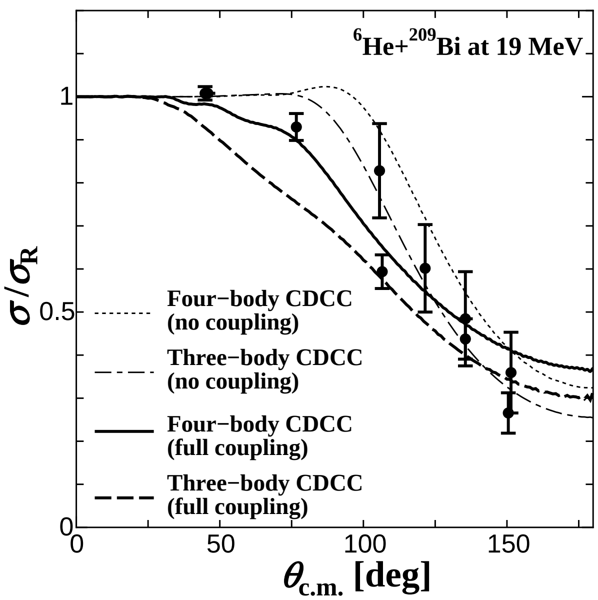
(*A.M.M. and R. Crespo, submitted to PRC*)

☞ *Core-excitation mechanism essential to explain observed cross sections!*

Part III: Extension to three-body projectiles (4-body CDCC)

Extension to three-body projectiles

- Kyushu group ⇒ Pseudo-state basis (Complex Gaussians) in Jacobi coordinates.
- Sevilla group ⇒ HH expansion using Pseudo-states (Transformed Harmonic Oscillator) or bins.
- Brussels group



Matsumoto et al, Phys.Rev. C 73, 051602 (2006)

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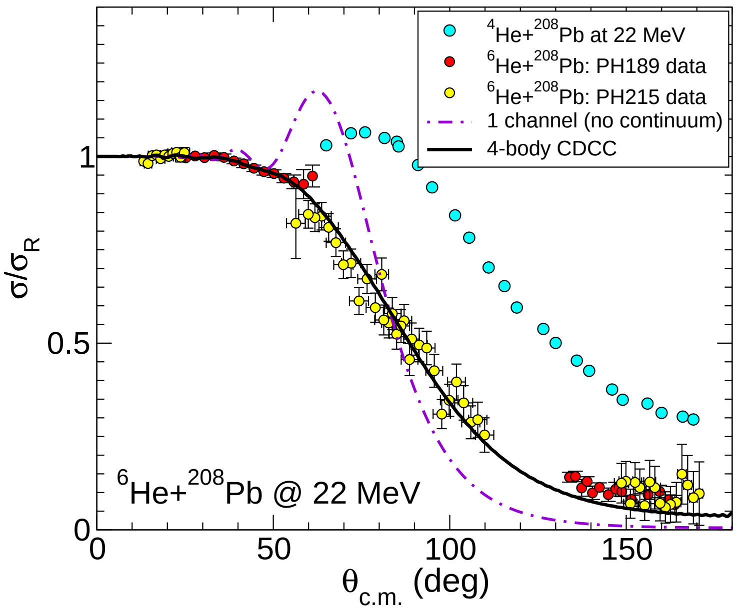


Rodríguez-Gallardo et al, PRC 80, 051601 (2009)

Extension of three-body projectiles

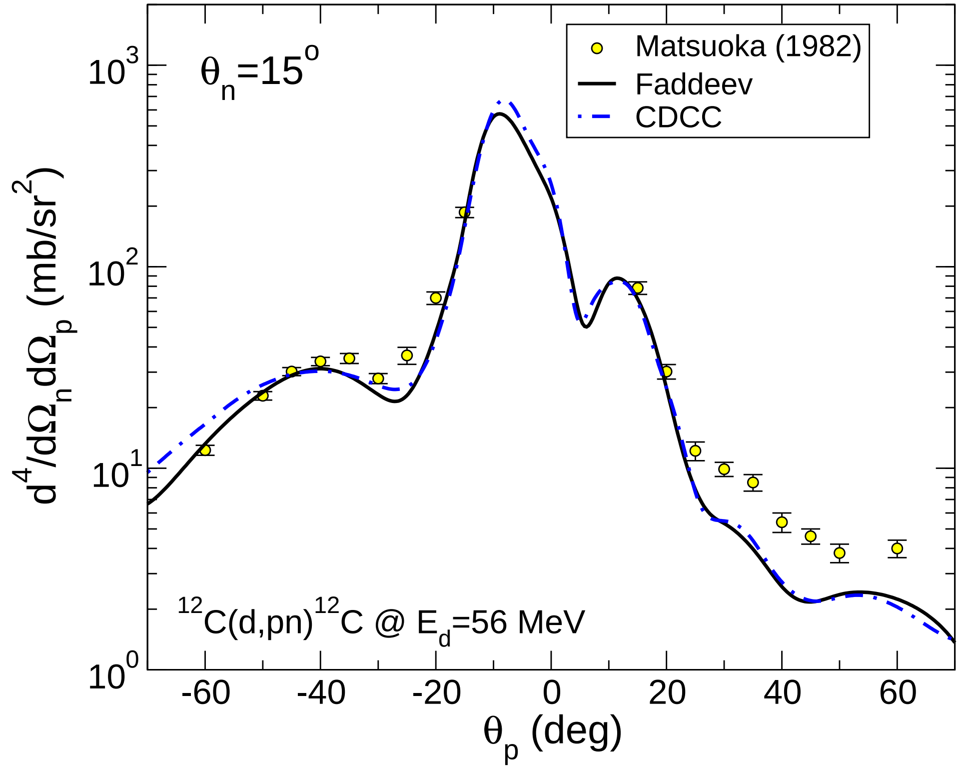
... but there are still many challenges. Eg:

- Extension to other 3-body projectiles other than ^{6}He (^{11}Li, ^{14}Be, etc)
  - ☞ *See talk by M. Rodríguez-Gallardo.*
- Computation and convergence of <u>breakup</u> observables
- Extension to $A > 4$ projectiles?
- Use of microscopic models instead of few-body models?

EXTRA SLIDES...

CDCC vs Faddeev: exclusive breakup

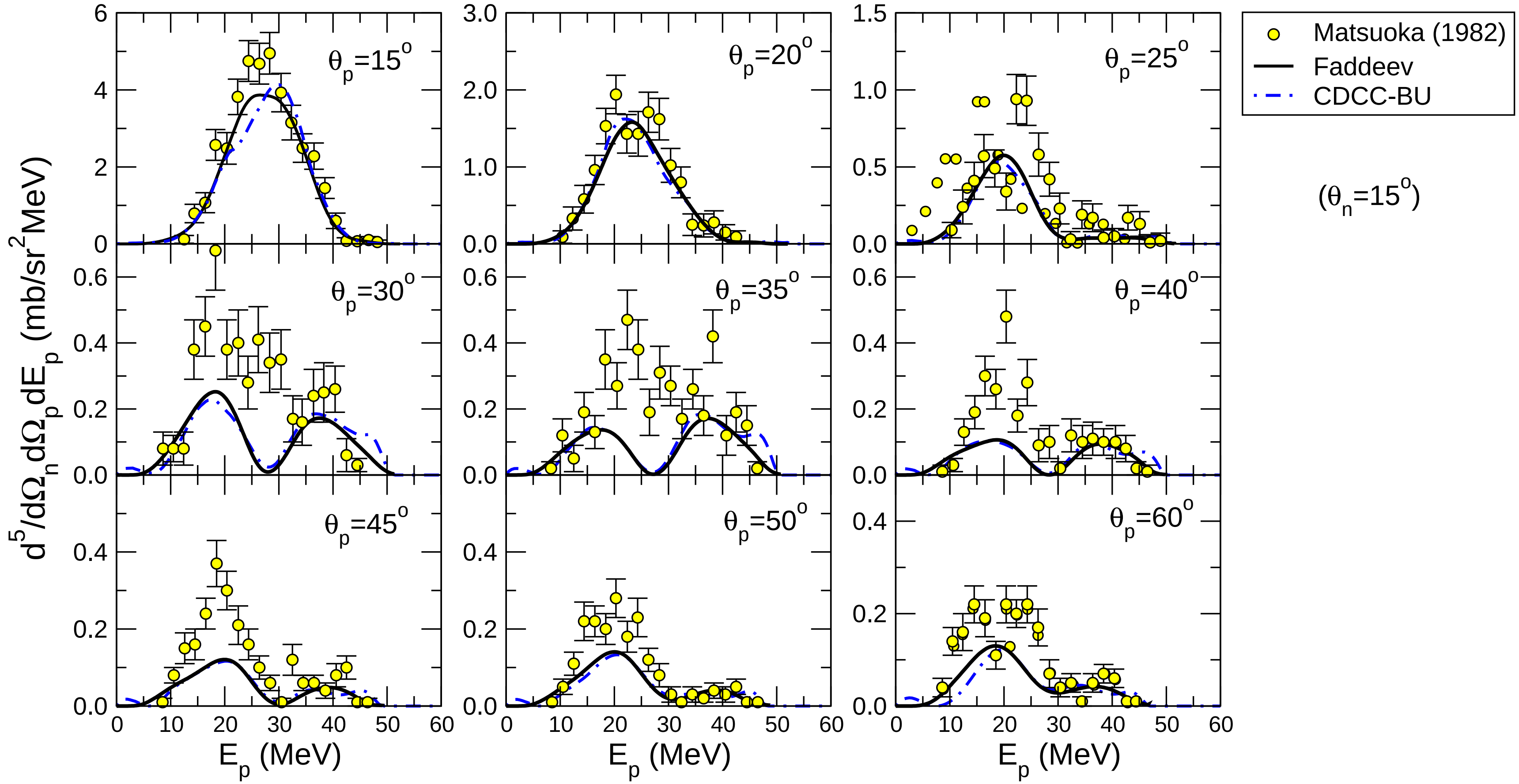
Proton angular distribution for fixed θ_n.



A.Deltuva, A.M.M., E.Cravo, F.M.Nunes, A.C.Fonseca, PRC76, 064602 (2007)

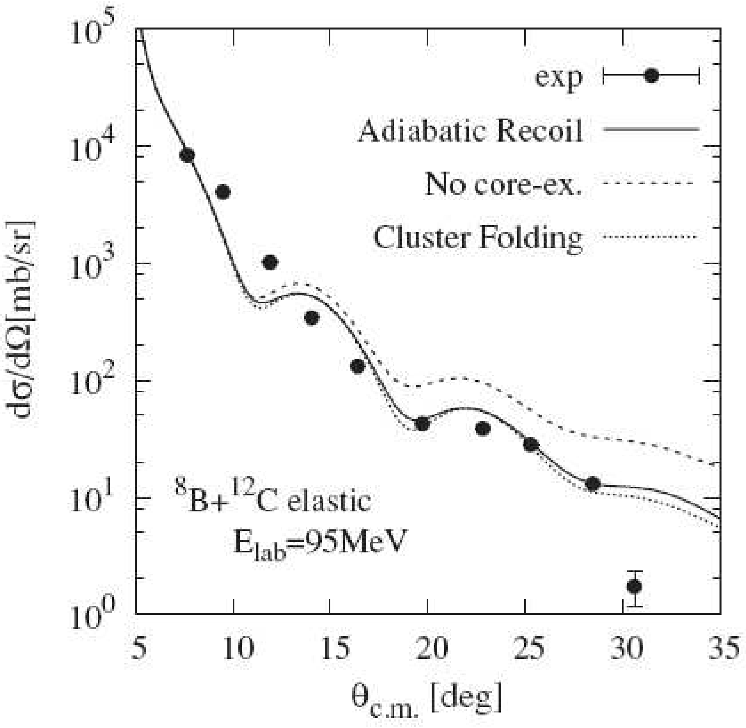
CDCC vs Faddeev: exclusive breakup

Proton energy distribution for fixed θ_n and θ_p



Core excitation in elastic scattering

Core excitation in ^{8}B+^{12}C elastic scattering:



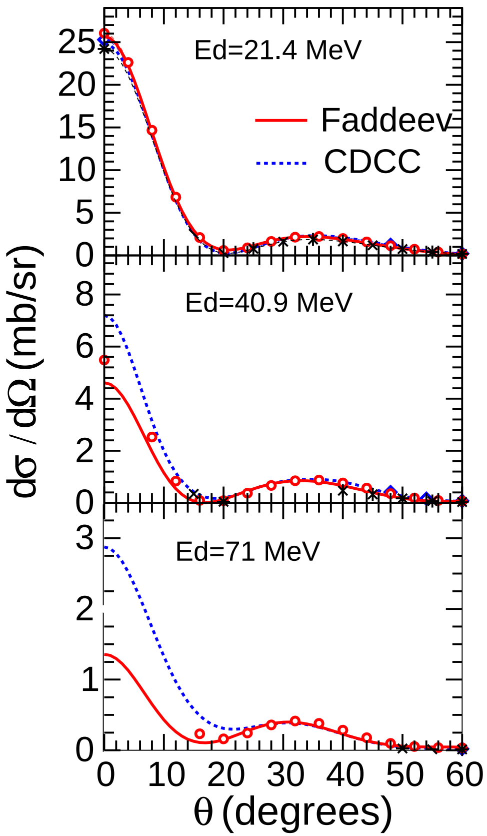
*

(quoted from *K. Horii* et al, *PRC81 (2010) 061602*)

CDCC vs Faddeev: transfer

☞ The CDCC does NOT provide the transfer cross section, but can be used to approximate the 3-body WF in the exact transfer amplitude:

Eg: $A(d,p)B \quad \Rightarrow \quad T \approx \langle \chi^{(-)}_{\mathrm{pB}} \, \phi_{\mathrm{nA}} \,|\, V_{\mathrm{pn}} + U_{\mathrm{pA}} - U_{\mathrm{pB}} \,|\, \Psi^{CDCC} \rangle$

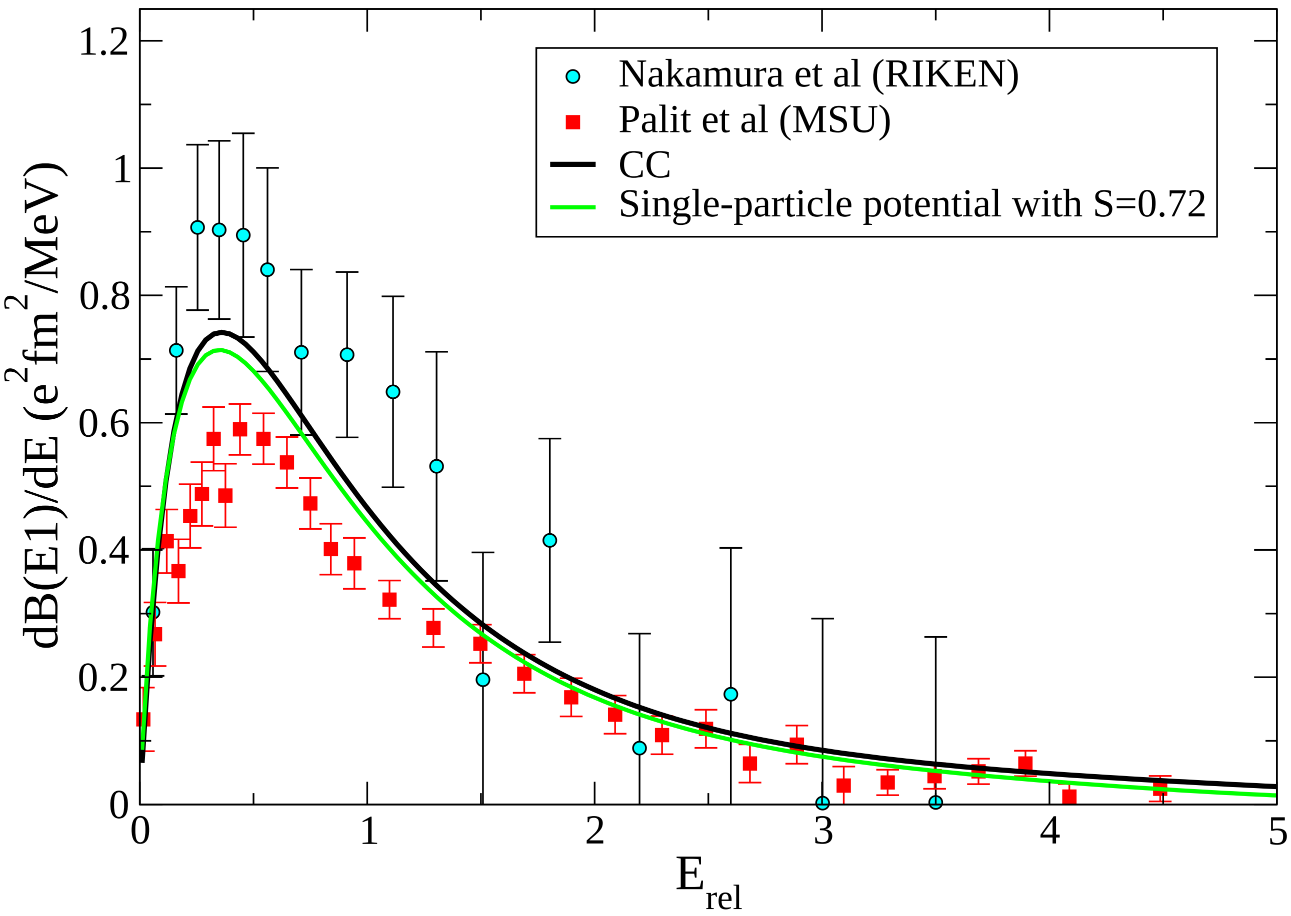


^{10}Be (d, p) ^{11}Be

☞ Good agreement at low energies
☞ Differences found at higher energies

N.J. Upadhyay, A. Deltuva and F.M. Nunes, arXiv:1112.5338

Core excitation in Coulomb breakup: $B(E1)$ response of $^{11}\mathrm{Be}$



Nakamura et al, NPA588 (1995) 81c (inclusive in ^{10}Be state)
Palit et al, PRC 68 (2003) 034318 (^{10}Be(g.s.) only)

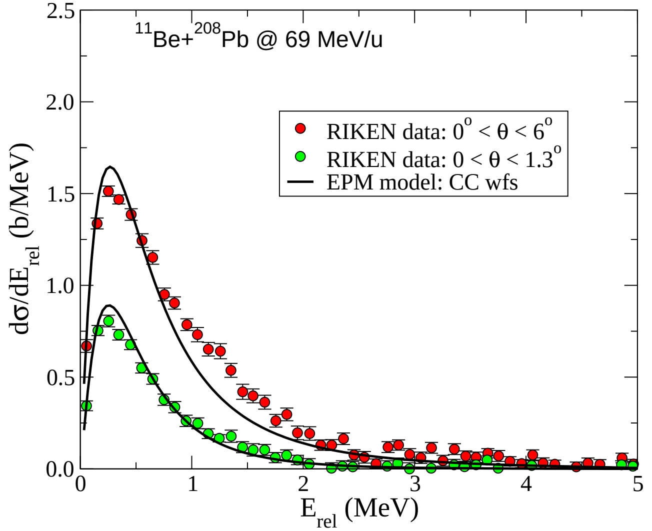
Core excitation in Coulomb breakup: $B(E1)$ response of ^{11}Be

$B(E1)$ extracted in a model-dependent way $\Rightarrow$ compare directly cross sections

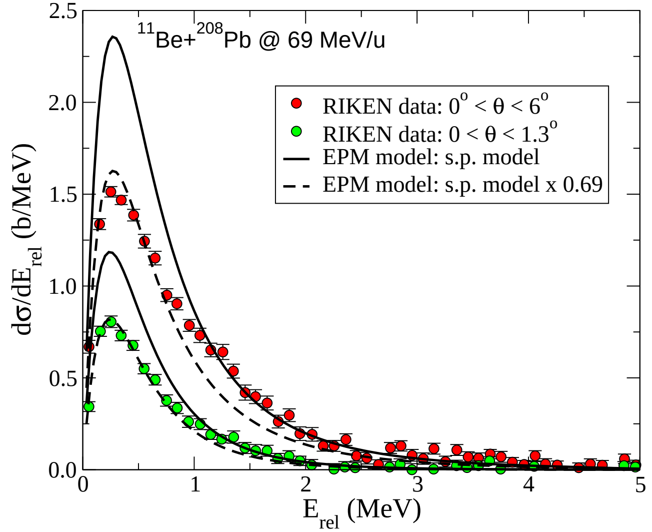
$$\boxed{\frac{d\sigma^2}{d\Omega dE_{\rm rel}} = \frac{16\pi^3}{9\hbar c}\frac{dN_{\rm E1}(\theta, E_{\rm x})}{d\Omega}\frac{dB({\rm E1})}{dE_{\rm rel}},}$$ (EPM)

Eg: ^{11}Be+^{208}Pb at RIKEN *Fukuda et al, PRC70, 054606 (2004))*

Deformed core model.

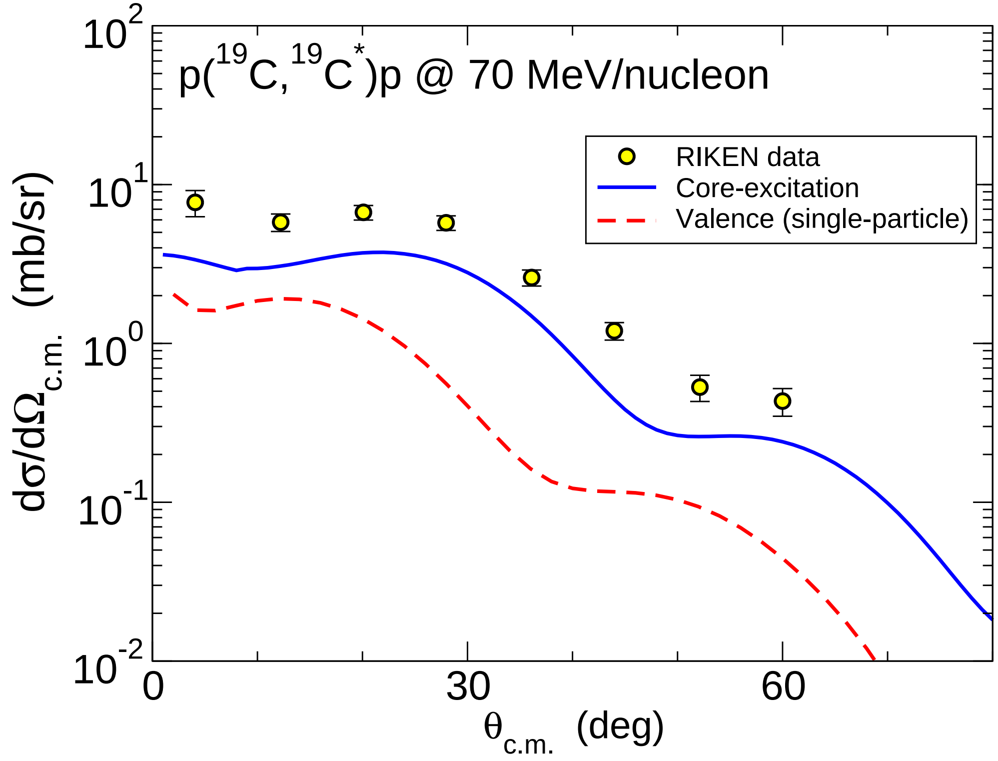


Single-particle model



Q: How good is the approximation $\sigma_{bu} = S\sigma_{sp}$?

Application to ^{19}C+p $\to$ ^{18}C +n +p



- *The core-excitation mechanism gives the dominant contribution to the cross section.*
- *This mechanism improves the description of the shape with respect to the single-particle calculation.*