Workshop of the ESNT

Continuum effects in transfer reactions and core excitation in breakup

Antonio M. Moro

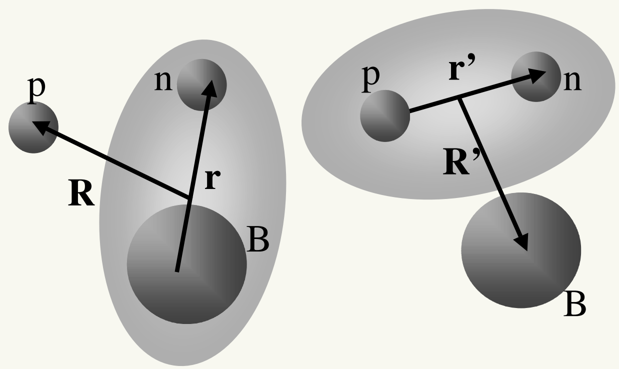
Planned content:

1. Continuum effects in transfer reactions
   - Beyond DWBA: CDCC-TR and "no-remnant" amplitudes
   - Post/prior equivalence
   - Comparison with Faddeev/AGS
2. Knock-out and QFS reactions.
   - Inelastic-like vs kock-out reactions
   - Role of p-n interaction in (p, pn) and $(p, 2p)$ reactions
   - Comparison with Faddeev/AGS
3. Core excitation in breakup

Part I: Continuum effects in transfer reactions

(work done with R. Johnson and F. Nunes)

One-nucleon transfer reaction in an effective three-body model



- Effective three-body model Hamiltonian for $A(p,d)B$ or $B(d,p)A$:

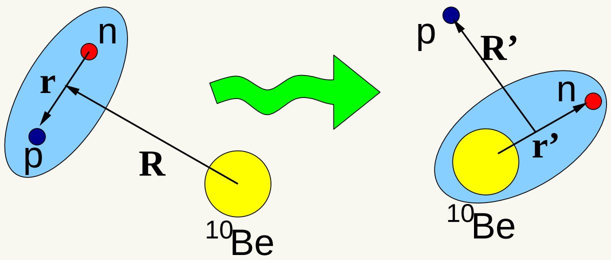
$$\boxed{H = K + V_{np} + V_{pn} + U_{nB} + U_{pB}}$$

- Internal d.o.f. of B not explicitly included $\Rightarrow$ all SF are 1.

Exact expression for the transtition amplitude (post form)

Test example: ^{10}Be(d,p)^{11}Be

$$\boxed{T_{\rm post}^{\rm exact} = \langle \Phi_\beta^{(-)} | V_{pn} + U_{\rm p^{10}Be} - U_\beta | \Psi_d^{(+)} \rangle}$$



- $U_{\rm p^{10}Be} - U_\beta \equiv U_{\rm rem}$ (remnant term)
- $\Psi_d^{(+)}$: exact 3-body WF (unknown)
- U_β: auxiliary arbitrary (even 0!)
- $\Phi_\beta^{(-)}$: 3-body WF, obtained as solution of the equation:

$$\left[E - i\epsilon - K - V_{\rm n^{10}Be} - U_\beta\right] \Phi_\beta^{(-)}(\mathbf{r}', \mathbf{R}') = 0$$

Post DWBA transfer amplitude

Approximations:

- $\Psi_d^{(+)} \approx \chi_d(\mathbf{R})\phi_d(\mathbf{r})$ ("product" approximation)
- $U_\beta = U_{opt}(\mathbf{R}') \Rightarrow \tilde{\Phi}_\beta^{(-)} \approx \chi_p(\mathbf{R}')\phi_{^{11}\mathrm{Be}}(\mathbf{r}')$

$$\boxed{T_{\mathrm{post}}^{\mathrm{DWBA}} = \langle \chi_p(\mathbf{R}')\phi_{^{11}\mathrm{Be}}(\mathbf{r}')|V_{pn} + U_{\mathrm{p}^{10}\mathrm{Be}} - U_\beta|\chi_d(\mathbf{R})\phi_d(\mathbf{r})\rangle}$$

✘ Only first order

✘ Ignores coupling to breakup channels

✘ Results can be very much dependent on $U_d(\mathbf{R})$ and $U_p(\mathbf{R}')$

Post CDCC-TR transfer amplitude

Approximations:

- $\Psi_d^{(+)} \approx \Psi_d^{\mathrm{CDCC}}(\mathbf{r},\mathbf{R}) = \sum_i \chi_d^i(\mathbf{R})\phi_d^i(\mathbf{r})$ (accurate within the range of $V_{pn}(\mathbf{r})$)
- $U_\beta = \langle \phi_{^{11}\mathrm{Be}} | V_{pn} + U_{\mathrm{p}^{10}\mathrm{Be}} | \phi_{^{11}\mathrm{Be}} \rangle \equiv U_{00}(\mathbf{R}')$

$$\boxed{T_{\mathrm{post}}^{\mathrm{CDCC}} = \langle \chi_p(\mathbf{R}')\phi_{^{11}\mathrm{Be}}(\mathbf{r}') | V_{pn} + U_{\mathrm{p}^{10}\mathrm{Be}} - U_{00}(\mathbf{R}') | \Psi_d^{CDCC} \rangle}$$

✔ Only two-body interactions needed

✔ Continuum effects in entrance channel explicitly included

✘ ^{11}Be continuum not explicitly included

✘ $\Psi_d^{\mathrm{CDCC}}(\mathbf{r},\mathbf{R})$ accurate within V_{pn} range but, what about $V_{pn} + U_{\mathrm{rem}}$?

An exact "no-remnant" amplitude

Timofeyuk-Johnson amplitude: *N.T. and R.C.J, PRC59, 1545 (1999)*

In the exact expression: $U_\beta \equiv U_{\mathrm{p}^{10}\mathrm{Be}}(\mathbf{r}_{\mathrm{p}^{10}\mathrm{Be}}) \Rightarrow U_{rem} = 0$

$$\boxed{T^{\mathrm{TJ}}_{\mathrm{post}} = \langle \tilde{\Phi}^{(-)}_\beta | V_{pn} | \Psi^{(+)}_d \rangle}$$

- $\left[E - i\epsilon - K - V_{\mathrm{n}^{10}\mathrm{Be}} - U_{\mathrm{p}^{10}\mathrm{Be}}\right] \tilde{\Phi}^{(-)}_\beta(\mathbf{r}', \mathbf{R}') = 0$

✔ Only binary interactions are needed (n-p, p-^{10}Be and n-^{10}Be)

✔ $\Psi^{(+)}_d(\mathbf{r}, \mathbf{R})$ is only required at small n-p separations ($r \approx 0$)

✘ $\tilde{\Phi}^{(-)}_\beta$ and $\Psi^{(+)}_d(\mathbf{r}, \mathbf{R})$ difficult to calculate.

Evaluation of “no-remnant” amplitude in the adiabatic approximation

Timofeyuk and Johnson, Phys.Rev. C59, 1545 (1999)

$$T^{\mathrm{TJ}}_{\mathrm{post}} = \langle \tilde{\Phi}^{(-)}_{\beta} | V_{pn} | \Psi^{(+)}_{d} \rangle$$

If $\epsilon_x \ll E_{\mathrm{c.m.}}$:

- $\tilde{\Phi}^{(-)}_{\beta} \approx \tilde{\Phi}^{ad}_{\beta} = \chi_{\mathrm{p}^{10}\mathrm{Be}}(\mathbf{r}_{\mathrm{p}^{10}\mathrm{Be}})\phi_{^{11}\mathrm{Be}}(\mathbf{r}')e^{-i\alpha\mathbf{k}_{\beta}\mathbf{r}'}$

  (Johnson, Al-Khalili and Tostevin, PRL79 (1997) 2771)

- $\Psi^{(+)}_{d} \approx \chi^{JS}_{d}(\mathbf{R})\phi_{d}(\mathbf{r})$

  ($\chi^{JS}_{d}(\mathbf{R})$ calculated with the Johnson-Soper potential)

  (Johnson and Soper, PRC1 (1979) 976)

Evaluation of "no-remnant" amplitude in the CDCC approximation

$$\boxed{T^{\mathrm{TJ}}_{\mathrm{post}} = \langle \tilde{\Phi}^{(-)}_{\beta} | V_{pn} | \Psi^{(+)}_{d} \rangle}$$

- $\tilde{\Phi}^{(-)}_{\beta}$ and $\Psi^{(+)}_{d}$ are approximated by CDCC expansions:
  - $\Psi^{(+)}_{d}$ expanded in p-n states
  - $\tilde{\Phi}^{(-)}_{\beta}$ expanded in n-^{10}Be states

Evaluation of "no-remnant" amplitude in the CDCC approximation

$$T_{\rm post}^{\rm TJ} = \langle \tilde{\Phi}_{\beta}^{(-)} | V_{pn} | \Psi_d^{(+)} \rangle$$

- $\tilde{\Phi}_{\beta}^{(-)}$ and $\Psi_d^{(+)}$ are approximated by CDCC expansions:
  - $\Psi_d^{(+)}$ expanded in p-n states
  - $\tilde{\Phi}_{\beta}^{(-)}$ expanded in n-^{10}Be states

✔ No adiabatic approximation is involved

✔ Short-ranged ransition potential (V_{pn})

✔ $\Psi_d^{(+)}$ accurate within V_{pn}.

Summary of transfer amplitudes

- Post DWBA:

$$\boxed{T_{\rm post}^{\rm DWBA} = \langle \chi_p(\mathbf{R}')\phi_{^{11}\rm Be}(\mathbf{r}')|V_{pn} + U_{\rm p^{10}Be} - U_p|\chi_d(\mathbf{R})\phi_d(\mathbf{r})\rangle}$$

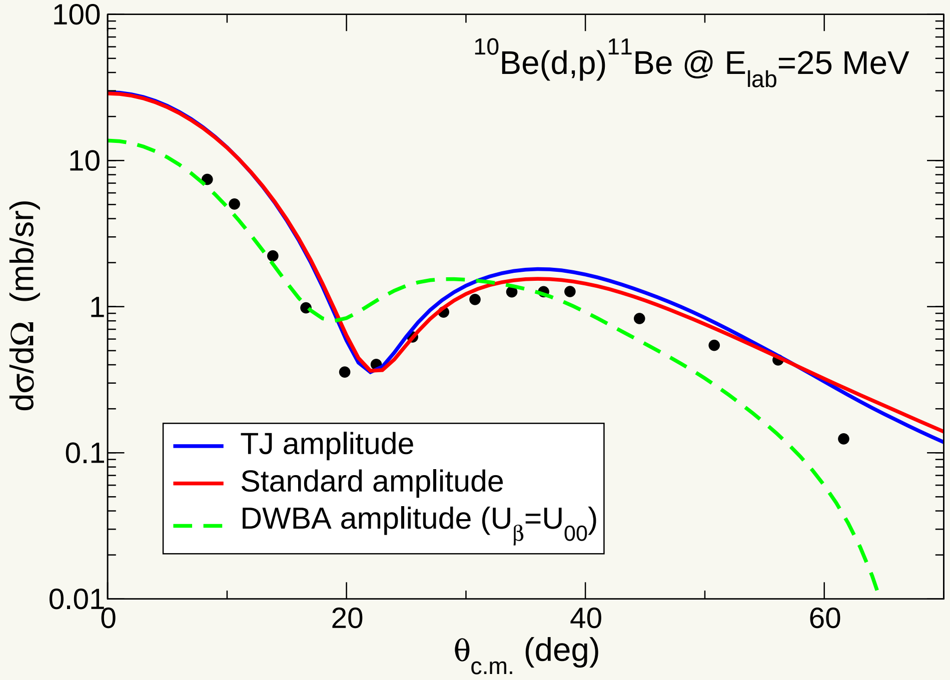
- Post CDCC-TR amplitude:

$$\boxed{T_{\rm post}^{\rm CDCC} = \langle \chi_p(\mathbf{R}')\phi_{^{11}\rm Be}(\mathbf{r}')|V_{pn} + U_{\rm p^{10}Be} - U_{00}(\mathbf{R}')|\Psi_d^{\rm CDCC}\rangle}$$

- “No-remnant” TJ amplitude:

$$\boxed{T_{\rm post}^{\rm TJ} = \langle \tilde{\Phi}_\beta^{\rm CDCC}|V_{pn}|\Psi_d^{\rm CDCC}\rangle}$$

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



Data:

Zwieglinski et al, NPA315, 124 (1979)

Calculations:

A.M.M, Nunes, Johnson, PRC80, 064606(20009

- ☞ The TJ and "standard" amplitudes provide consistent results
- ☞ The data are overestimated $\Rightarrow S_f < 1$
- ☞ DWBA out of phase and very dependent on U_β

Post/prior equivalence

- Exact prior transition amplitude:

$$T^{\text{exact}}_{\text{prior}} = \langle \Psi_p^{(-)} | V_{\text{n}^{10}\text{Be}} + U_{\text{p}^{10}\text{Be}} - U_\alpha | \Phi_\alpha^{(+)} \rangle$$

- DWBA approximation:

$$T^{\text{DWBA}}_{\text{prior}} = \langle \chi_p(\mathbf{R}') \phi_{^{11}\text{Be}}(\mathbf{r}') | V_{\text{n}^{10}\text{Be}} + U_{\text{p}^{10}\text{Be}} - U_d | \chi_d(\mathbf{R}) \phi_d(\mathbf{r}) \rangle$$

- CDCC-TR approximation:

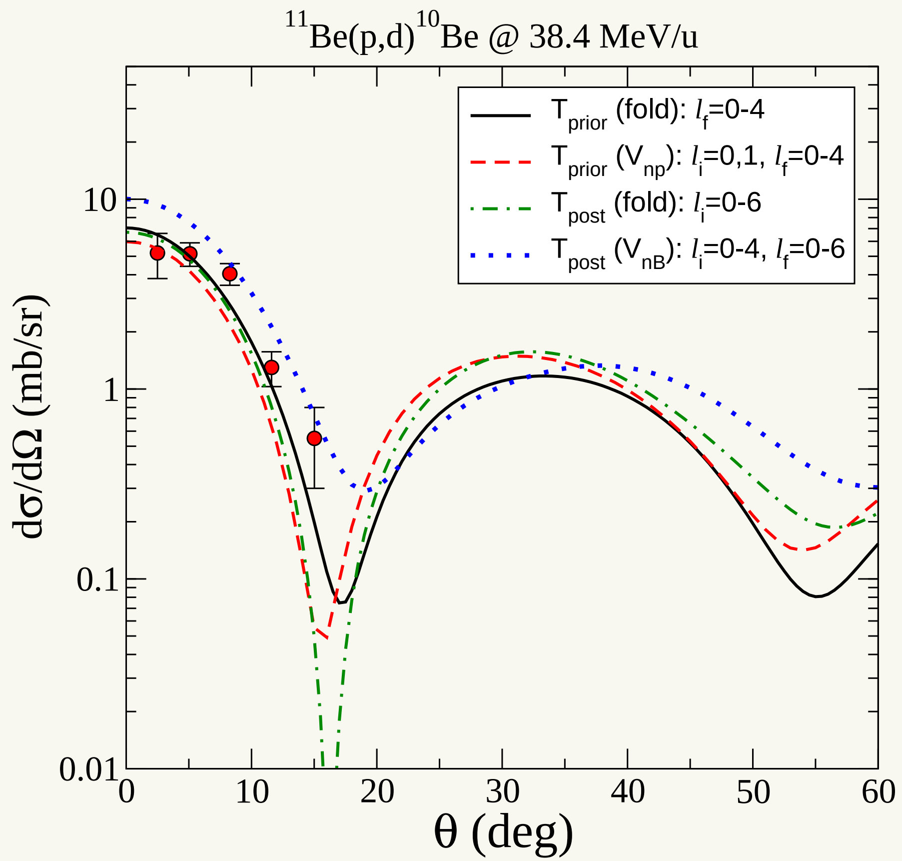
$$T^{\text{CDCC}}_{\text{prior}} = \langle \Psi_p^{\text{CDCC}} | V_{\text{n}^{10}\text{Be}} + U_{\text{p}^{10}\text{Be}} - U_d^{fold} | \chi_d(\mathbf{R}) \phi_d(\mathbf{r}) \rangle$$

- “No-remnant” approximation:

$$T^{\text{TJ}}_{\text{prior}} = \langle \Psi_p^{\text{CDCC}} | V_{\text{n}^{10}\text{Be}} | \tilde{\Phi}_\alpha^{(+)} \rangle$$

Comparison of post/prior amplitudes

☞ Same effective Hamiltonian: $H = K + V_{np} + V_{pn} + U_{\mathrm{p}^{10}\mathrm{Be}} + V_{\mathrm{n}^{10}\mathrm{Be}}$



Data:
Winfield et al, Nucl. Phys. A683, 48 (2001)

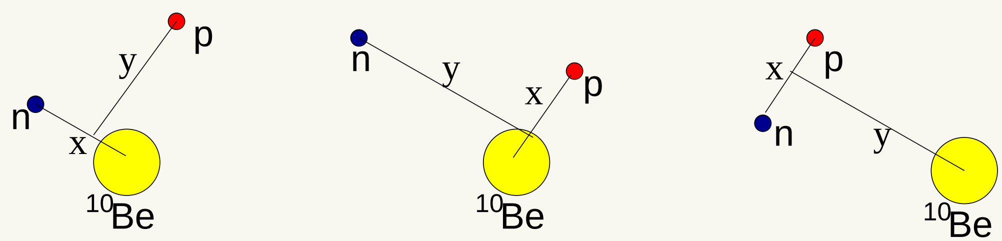
Calculations:
A.M.M, Nunes, Johnson, PRC80, 064606(20009

☞ Consistent results

☞ Slow convergence of **post CDCC-TR** ($V_{\mathrm{n}^{10}\mathrm{Be}}$ vs V_{pn})

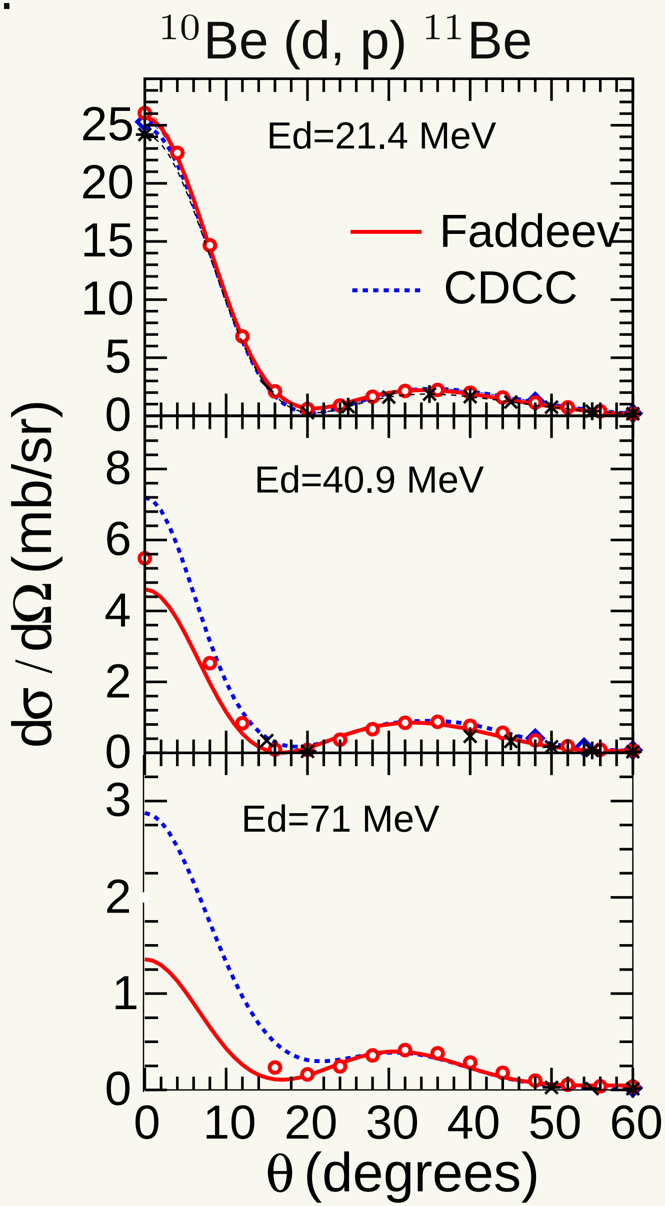
Faddeev approach for 3-body scattering problems

- The *exact* solution of a three-body scattering problem is formally given by the Faddeev equations.
- The 3-body WF is expanded in the (overcomplete) basis formed by the three Jacobi sets $\Rightarrow$ includes breakup and rearrangement channels on equal footing.



- Numerical complexities has limited its application to few-body problems (eg. n+d)
- Recent developments (eg. inclusion of Coulomb) permits its application to heavier systems within the momentum-space formulation of Alt, Grassberger and Sandhas (AGS).

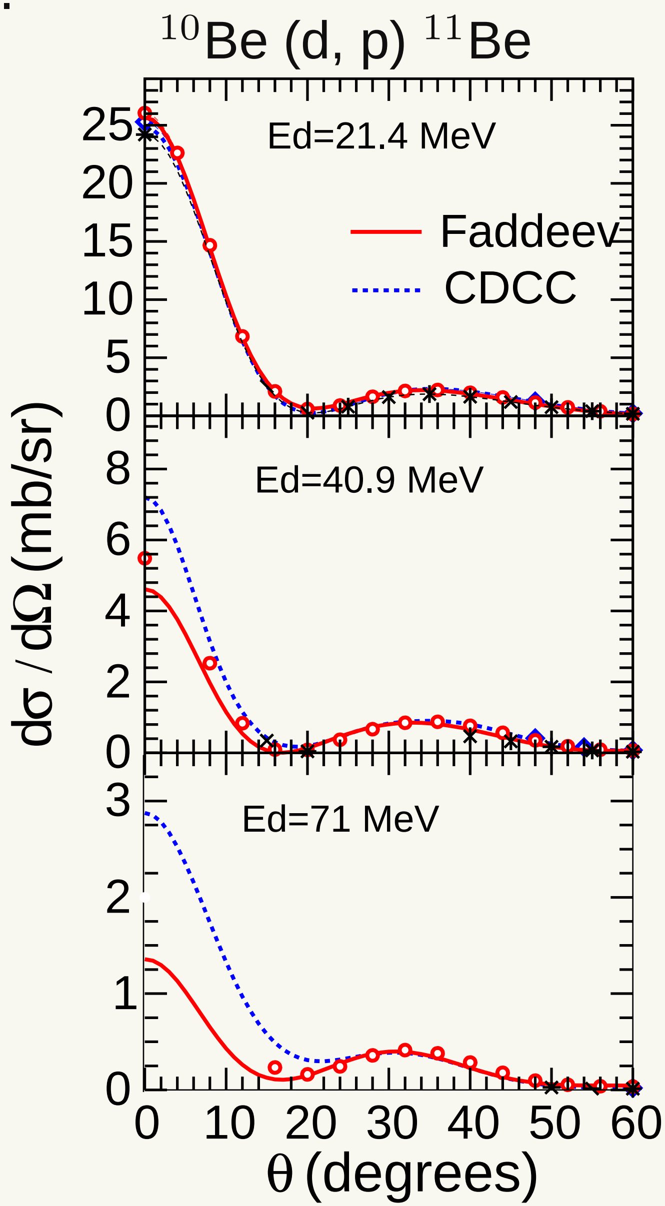
However...



N.J. Upadhyay, A. Deltuva, F.M. Nunes, PRC85, 054621 (2012)

☞ Good agreement at low energies (10 MeV/u) but differences become more and more important as the incident energy increases.

However...



N.J. Upadhyay, A. Deltuva, F.M. Nunes, PRC85, 054621 (2012)

☞ Good agreement at low energies (10 MeV/u) but differences become more and more important as the incident energy increases.

Further investigation is required!

Conclusions from this part

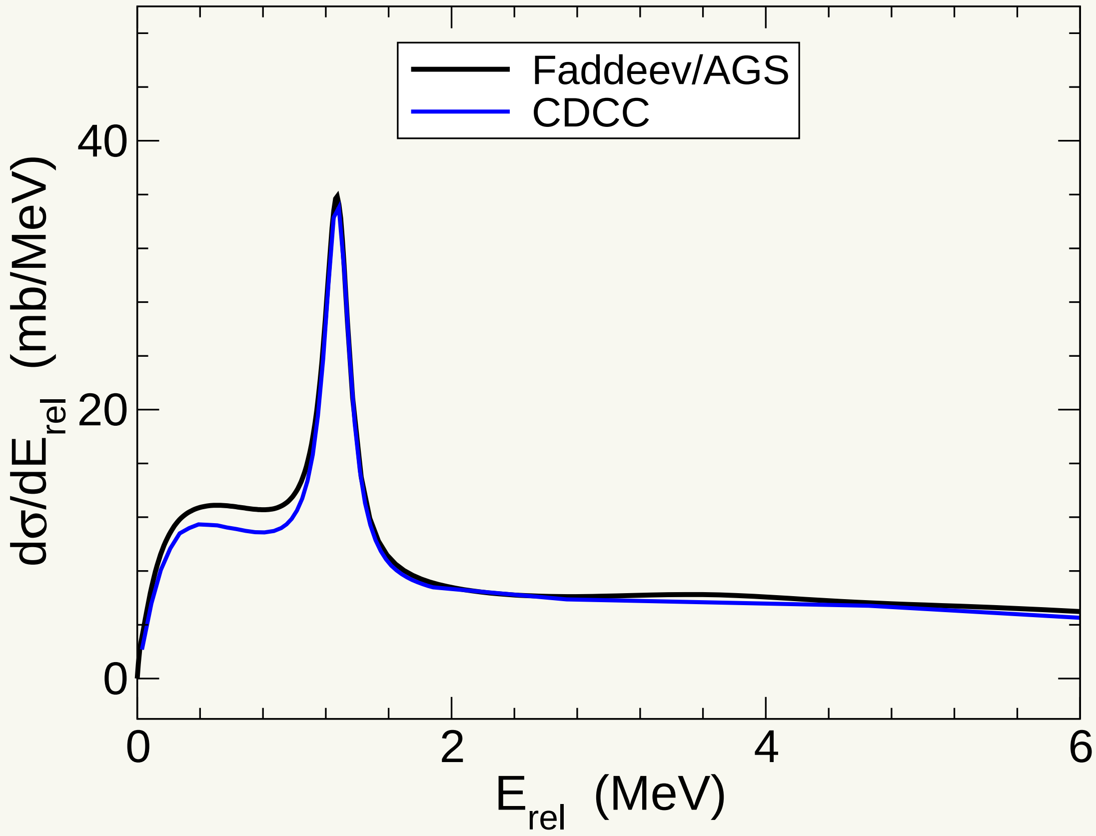
- Starting with a few-body effective Hamiltonian, scattering theory provide a series of alternative and formally equivalent transfer amplitudes.
- Continuum effects can be naturally incorporated approximating the exact wfs by CDCC counterparts.
- Benchmark calculations for ^{10}Be(d,p)^{11}Be confirm the practical equivalence of these expressions, when the CDCC wfs are used to approximate the exact wfs.
- Post/prior equivalence is hold but one of the representations is clearly preferable.
- To compare with data, additional degrees of freedom should be incorporated (eg. core excitation).
- Comparison with the “exact” solution (Faddeev/AGS) shows an excellent agreement at low energies, but as the energy increases worrying discrepancies appear.

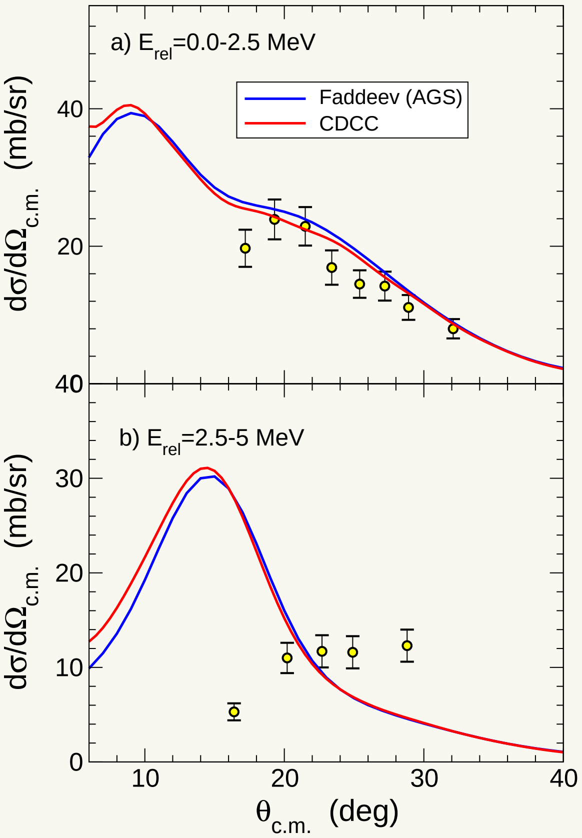
Part II: Application of CDCC to knock-out and QFS

(collaboration with R. Crespo, A. Deltuva and F. Nunes)

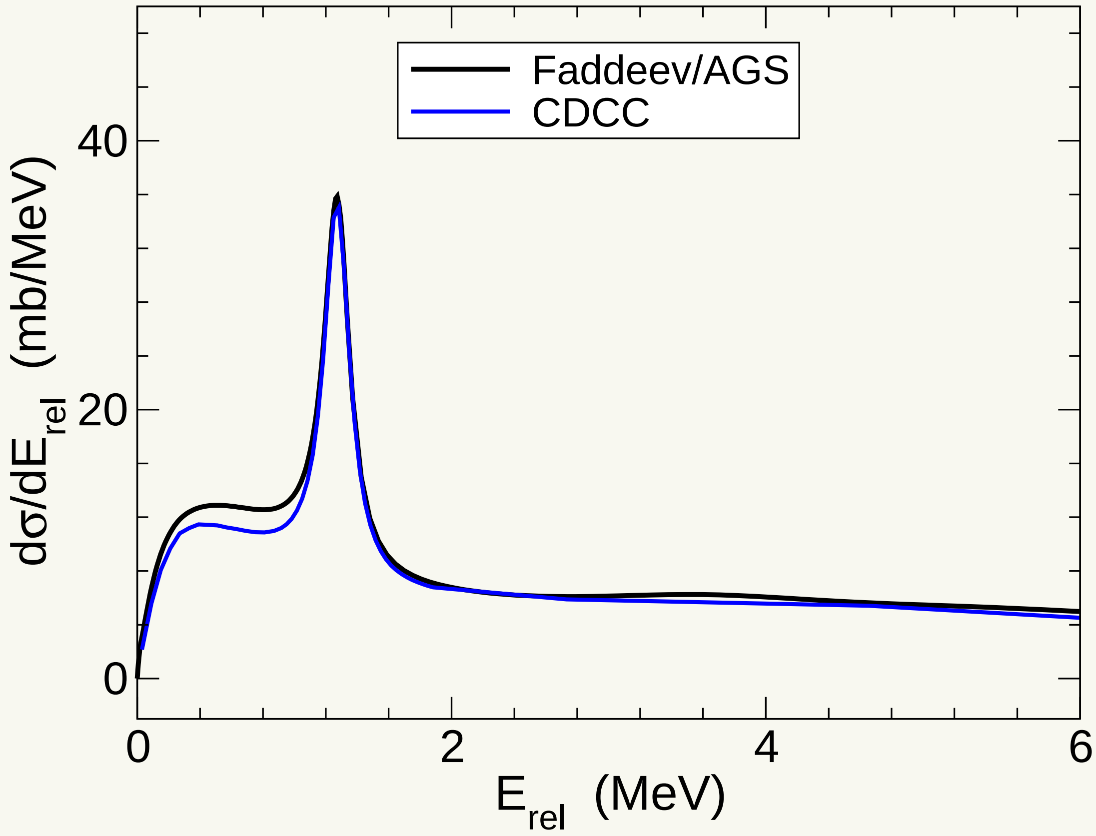
- Different breakup reactions explore different regions of the continuum:
  - Inelastic-like exclusive breakup: ^{11}Be + A $\rightarrow$ (^{10}Be + n) + A
  - Knock-out / QFS: ^{10}Be + p $\rightarrow$ ^{10}Be + (np)
  - Inclusive breakup: ^{11}Be + A $\rightarrow$ + ^{10}Be + anything
- Ideally, one should be able to treat all these processes within a common consistent framework $\Rightarrow$ Faddeev?
- In practice, approximate methods are tailored to specific processes, so their range of validity needs to be carefully assessed.

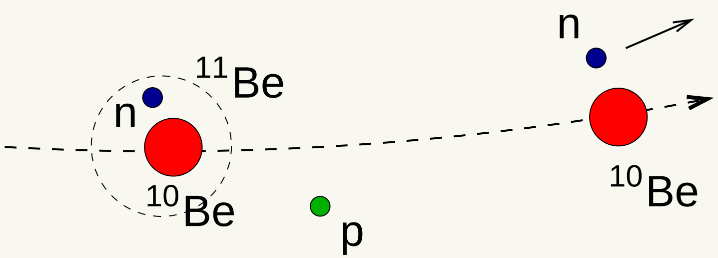
Exclusive direct breakup for ^{11}Be + p $\rightarrow$ (^{10}Be+n) +p @ $E \simeq 70$ MeV/u





Exclusive direct breakup for ^{11}Be + p $\rightarrow$ (^{10}Be+n) +p @ $E \simeq 70$ MeV/u

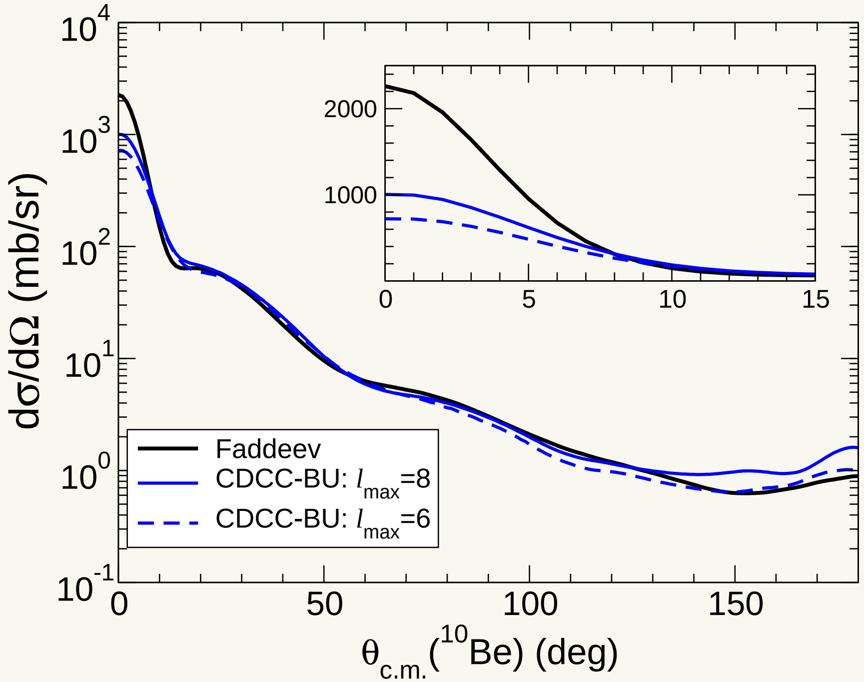


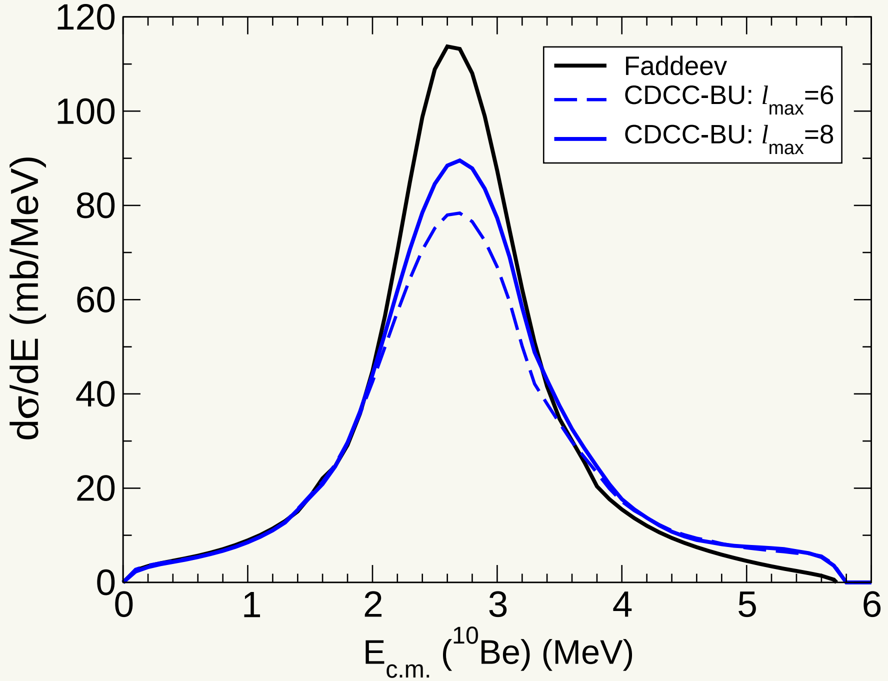


☞ *Good agreement between CDCC and Faddeev/AGS*

☞ *The reaction is dominated by small ^{10}Be+n energy/angular momenta, where CDCC is at it best*

Inclusive breakup for ^{11}Be + p $\rightarrow$ ^{10}Be +p +n





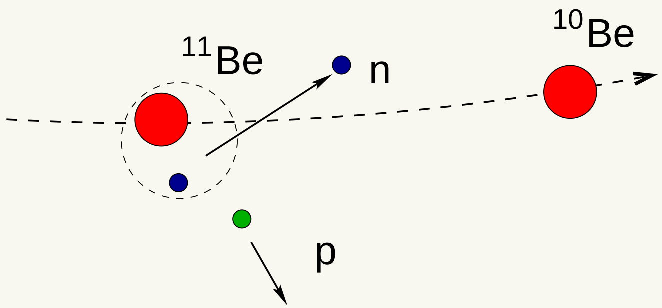
☞ CDCC converges very slowly to the *exact* solution.

- Backward angles: dominated by ^{11}Be low lying continuum $\Rightarrow$ inelastic-like picture (direct breakup).
- Forward angles: dominated by p-n interaction (quasi-free scattering) $\Rightarrow$ best described in terms of p-n states

Practical implementation of CDCC-TR*

Prior form of transition amplitude

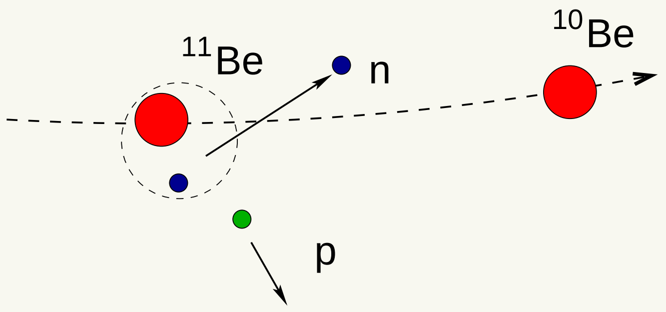
$$T_{if} = \langle \Psi_f^{(-)} | V_{\mathrm{p-n}} + U_{\mathrm{p+}^{10}\mathrm{Be}} - U_\alpha | \chi_p^{(+)} \phi_{^{11}\mathrm{Be}} \rangle$$



- Three-body wf expanded in target (p-n) internal states.
- Breakup formally treated as transfer to n+p continuum.
- Provides transfer to bound and unbound states (ie, breakup)

Prior form of transition amplitude

$$T_{if} = \langle \underbrace{\Psi_f^{(-)}} | V_{\mathrm{p-n}} + U_{\mathrm{p+^{10}Be}} - U_\alpha | \chi_p^{(+)} \phi_{^{11}\mathrm{Be}} \rangle$$

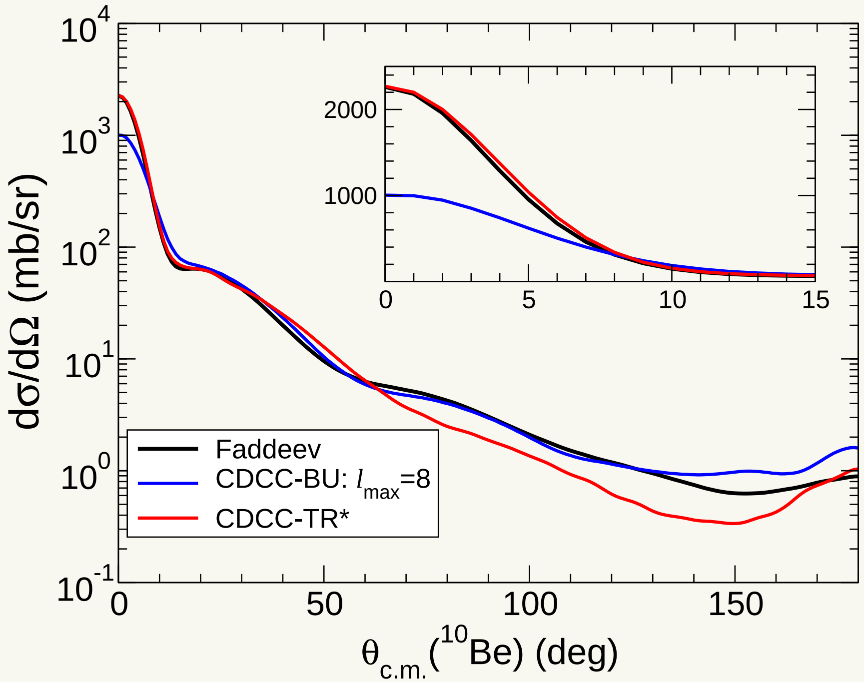


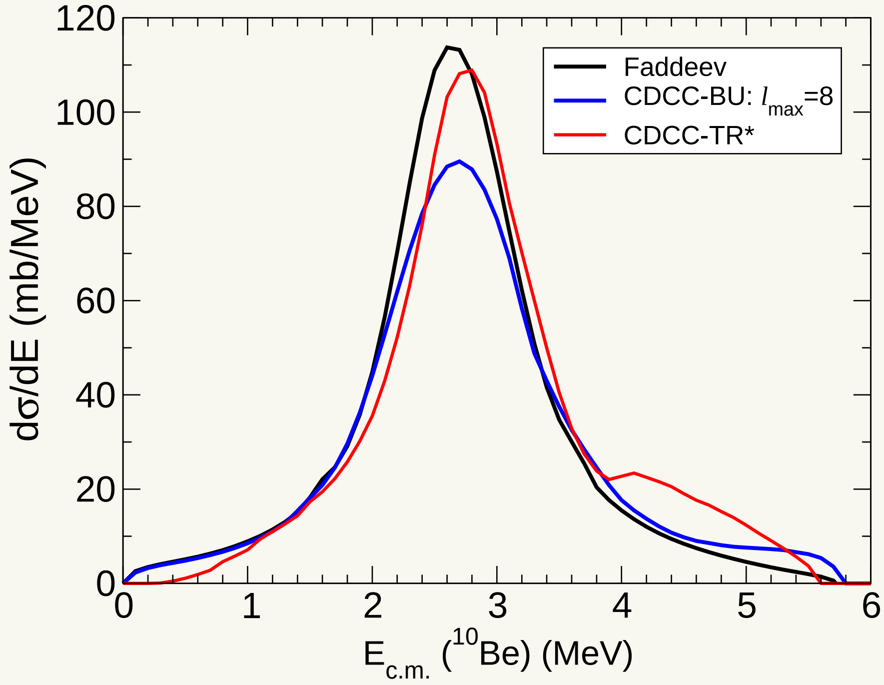
$$\Psi_f^{(-)} \approx \Psi_d^{\mathrm{CDCC}} = \sum_i \chi_d^i(\mathbf{R}) \phi_d^i(\mathbf{r})$$

- Three-body wf expanded in target (p-n) internal states.
- Breakup formally treated as transfer to n+p continuum.
- Provides transfer to bound and unbound states (ie, breakup)

CDCC vs Faddeev: inclusive breakup x-sections

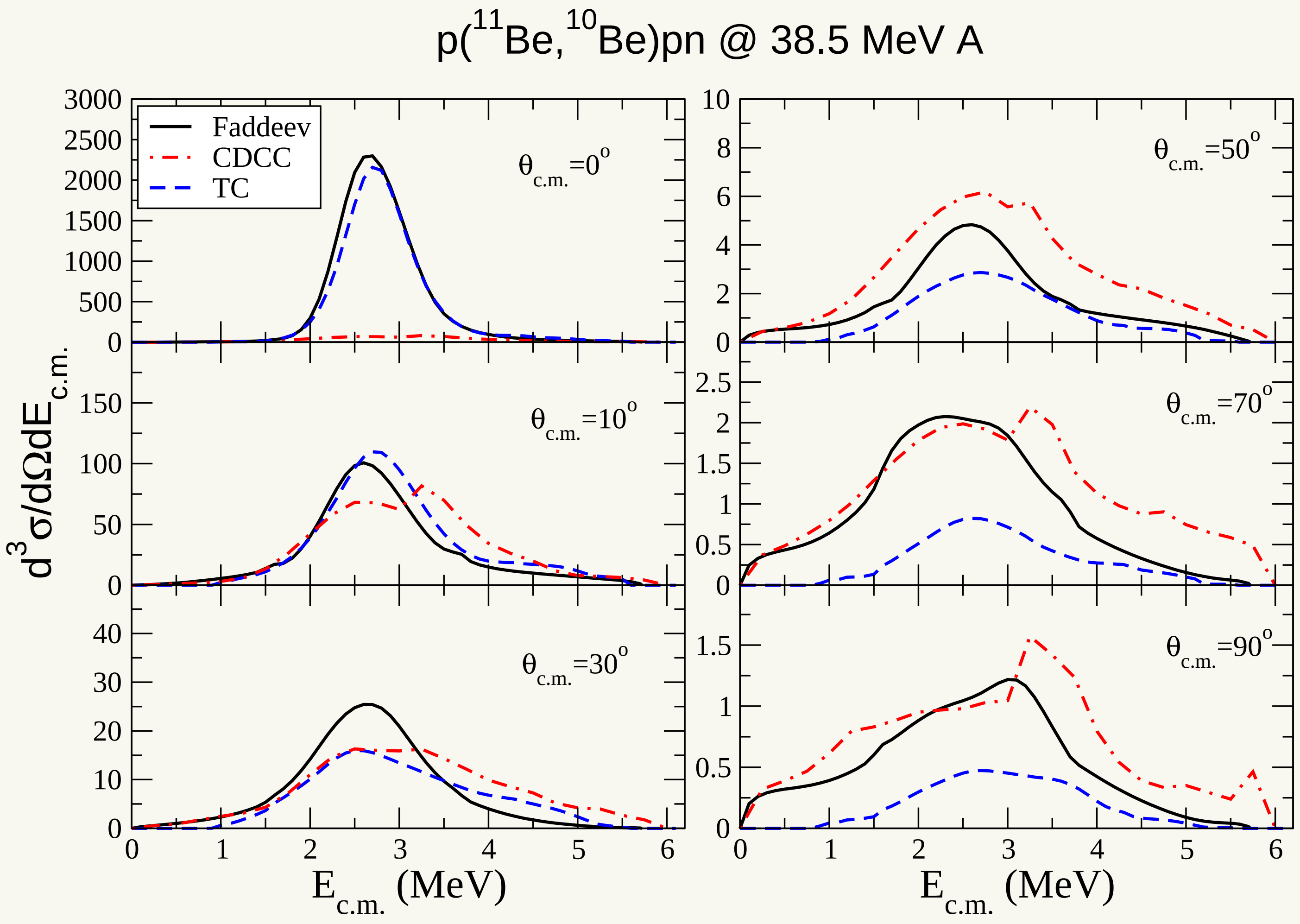
^{11}Be + p $\rightarrow$ ^{10}Be + p+n





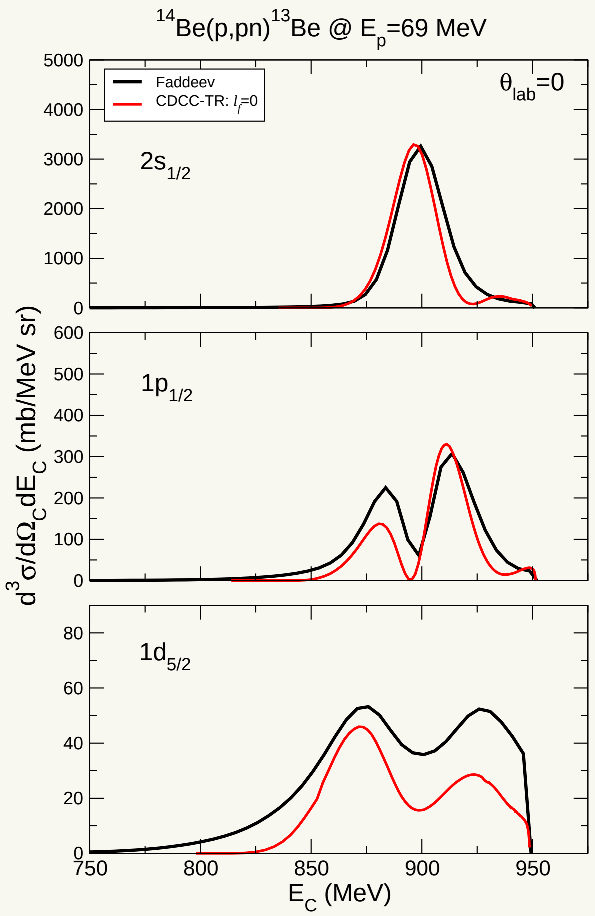
- Forward angles: dominated by p-n interaction (QFS) $\Rightarrow$ CDCC-TR*
- Backward angles: dominated by ^{11}Be low lying continuum $\Rightarrow$ CDCC-BU

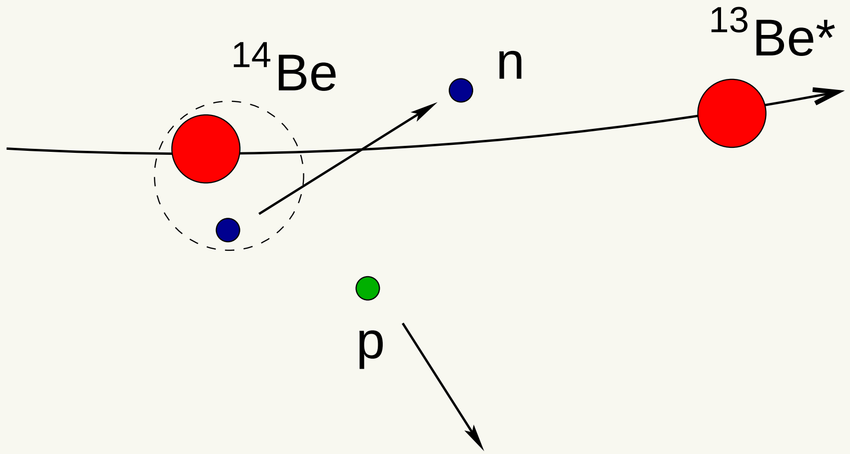
CDCC vs Faddeev: inclusive breakup x-sections



☞ *Forward angles are dominated by* quasi-free *p-n scattering*

CDCC vs Faddeev: inclusive breakup x-sections

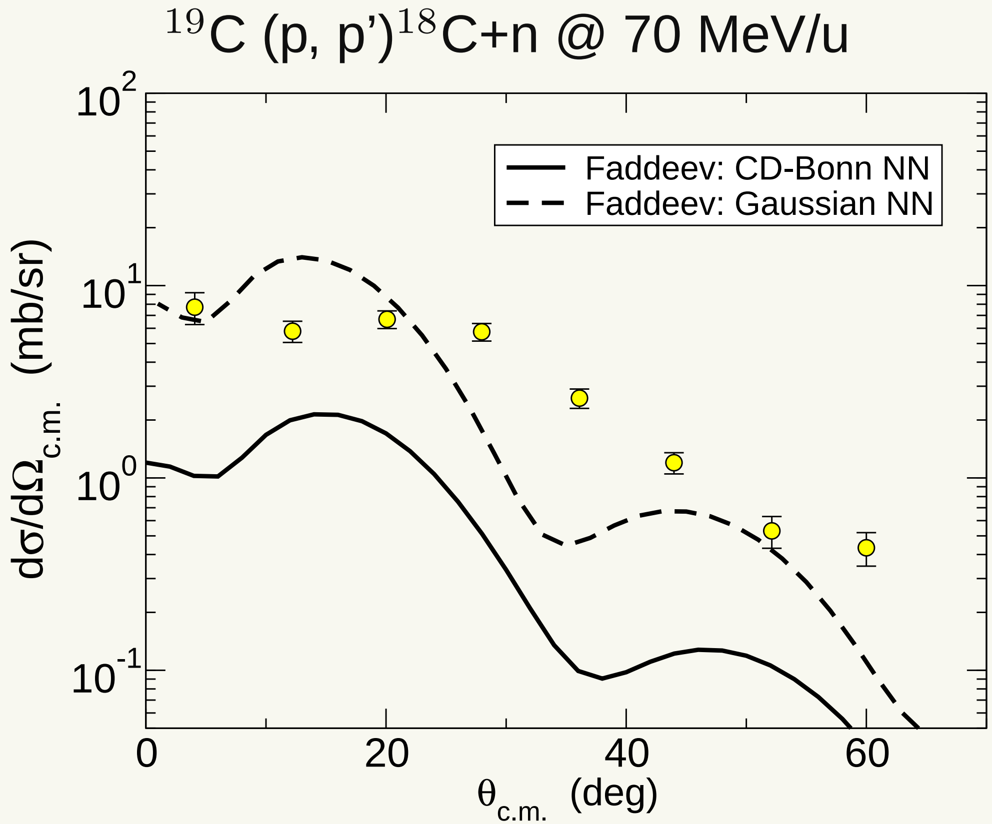


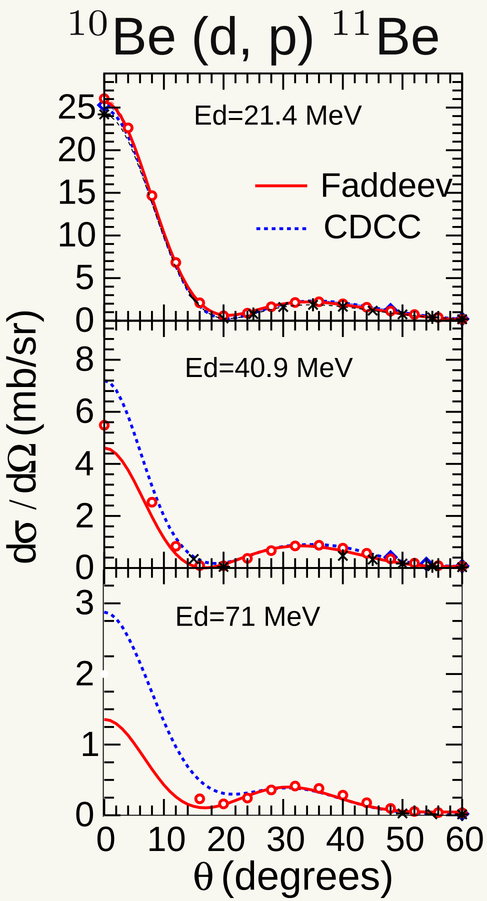


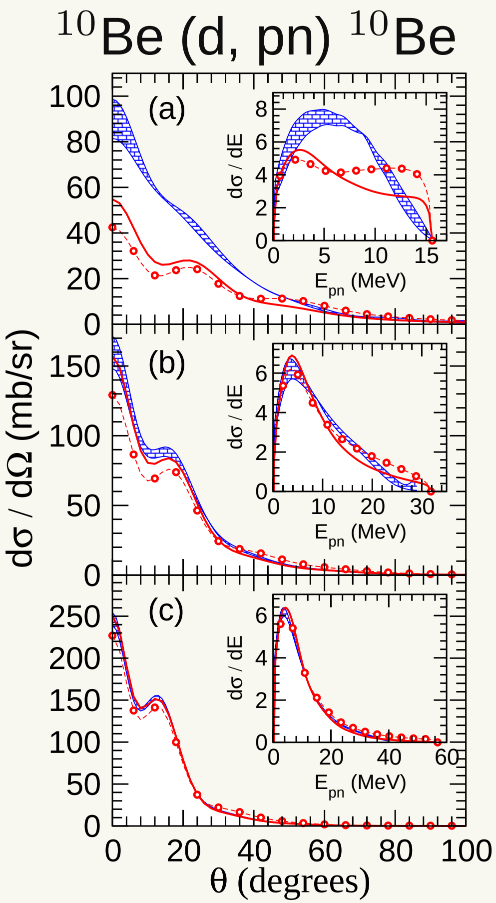
- ☞ *Forward angles are dominated by* quasi-free *p-n scattering*
- ☞ *CDCC-TR* with just $\ell = 0$ between p-n gives a reasonable account of the AGS result*

Sensitivity on p-n interaction

- (d,p) and (p,d) reactions are mostly sensitive to the $^3S_1$ part of the V_{pn} potential.
- This is no longer true for (p,pn) reactions!





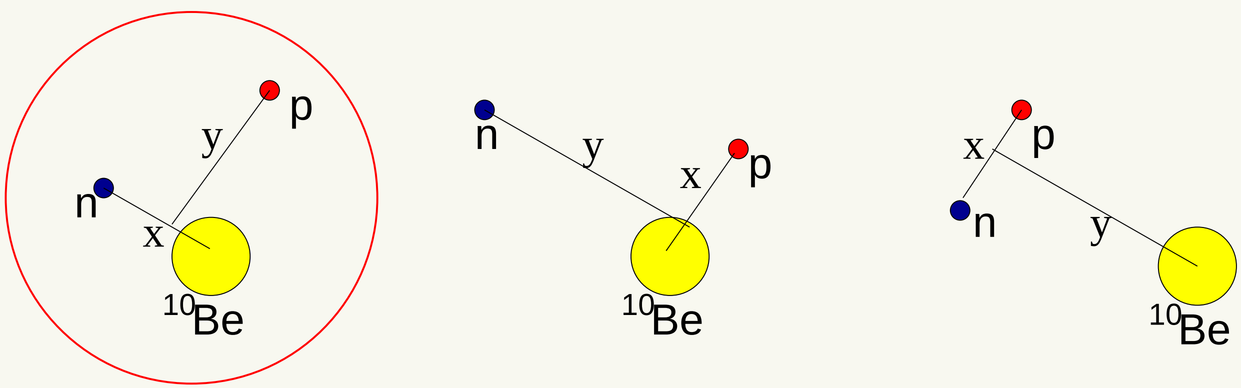


☞ Differences have been recently reported for breakup (low energies) and transfer (high energies) in ^{10}Be+d reaction (*N.J. Upadhyay, A. Deltuva, F.M. Nunes, PRC85, 054621 (2012)*)

☞ *Further investigation is required!*

Beyond CDCC: few-body CRC

- For a three-body problem, there are three possible rearrangement (Jacobi sets): α, β, γ



- In Faddeev: $\Psi = \Phi_\alpha + \Phi_\beta + \Phi_\gamma$
- In CDCC only the α set is used:

$$\Psi^{3b} \approx \Psi^{CDCC} = \sum_n^N \phi_{\alpha,n}(\mathbf{r})\chi(\mathbf{R})$$

Beyond CDCC: few-body CRC

- LS form of (CD)CC method: $H = K_\alpha + h_\alpha + V_\alpha$

$$T = V_\alpha + V_\alpha G_0 T$$

- Inserting a model-space set $\Pi_\alpha \equiv \sum_n^N |\alpha n\rangle\langle\alpha n|$

$$\boxed{T_{fi}^{CC} = \langle f\alpha|T^{CC}|\alpha i\rangle = \langle \alpha_f|V_\alpha|\alpha i\rangle + \sum_n^N \langle \alpha f|V_\alpha|\alpha n\rangle\langle\alpha n|G_0|\alpha n\rangle\langle\alpha n|T^{\mathrm{CC}}|\alpha i\rangle}$$

- A more accurate solution should be obtained using the augmented space $\Pi_\alpha \oplus \Pi_\beta \oplus \Pi_\beta$ (*Kuruoglu, PRC43, 1061 (1991)*)

$$\boxed{T_{\beta f;\alpha i}^{\mathrm{CRC}} = \langle \beta_f|V_\beta^{CRC}|\alpha i\rangle + \sum_{\gamma=1}^{3}\sum_n^N \langle \beta f|V_\beta^{CRC}|\gamma n\rangle\langle\gamma n|G_0|\gamma n\rangle\langle\gamma n|T^{\mathrm{CRC}}|\alpha i\rangle}$$

with

$$V_\beta^{CRC} = V_\beta + V_\beta^{NO}$$

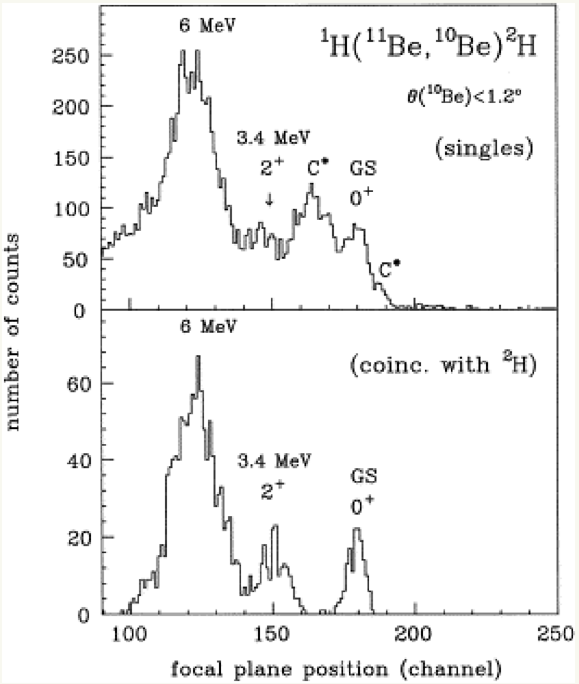
Conclusions

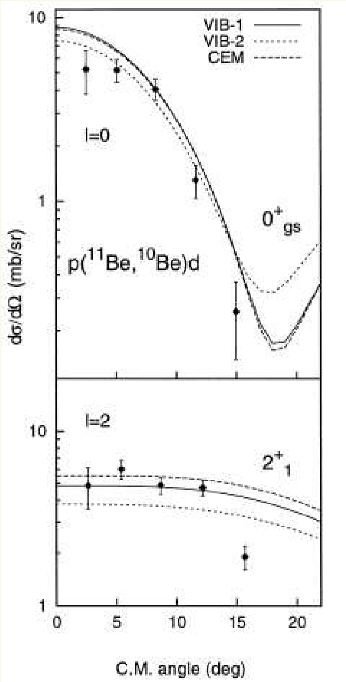
- Standard CDCC provides a good description of breakup in "direct breakup" (*inelastic-like*) processes.
- QFS is not well described by standard CDCC, but it can be modeled within the CDCC-TR* method.
- Scattering of halo nuclei on protons is very sensitive to the p-n interaction on several partial waves.
- A more general CC framework is probably needed in situations in which CDCC fails $\Rightarrow$ few-body CRC?

Part III: Core excitations effects in breakup reactions

Core excitation in transfer

^{1}H(^{11}Be,^{10}Be)^{2}H *Fortier et al, PLB461, 22 (1999)*





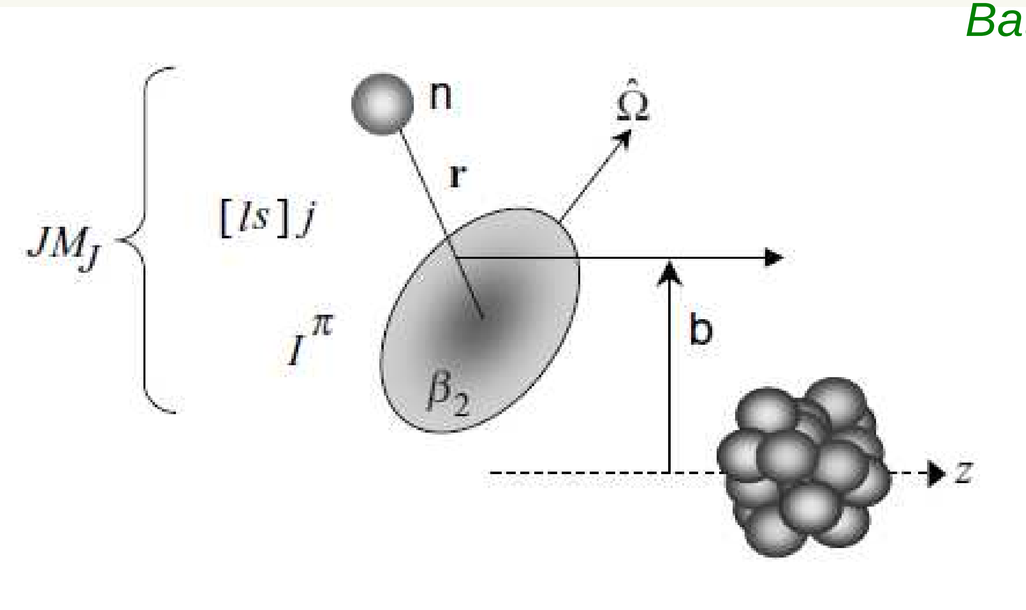
☛*Transfer experiments provide information on the amount of core excitation*

$$|^{11}\mathrm{Be}\rangle = \alpha\ |^{10}\ \mathrm{Be}(0^{+}) \otimes \nu 2s_{1/2}\rangle + \beta\ |^{10}\ \mathrm{Be}(2^{+}) \otimes \nu 1d_{5/2}\rangle + \dots$$

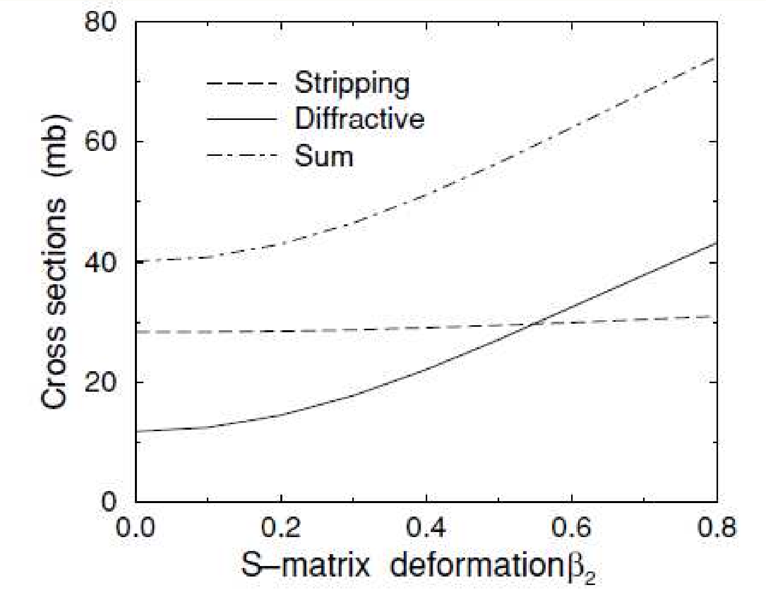
☛ In DWBA:

$$\sigma(0^{+}) \propto |\alpha|^{2}; \quad \sigma(2^{+}) \propto |\beta|^{2}$$

Core excitation in knock-out experiments



Batham et al, PRC71, 064608 (2005)

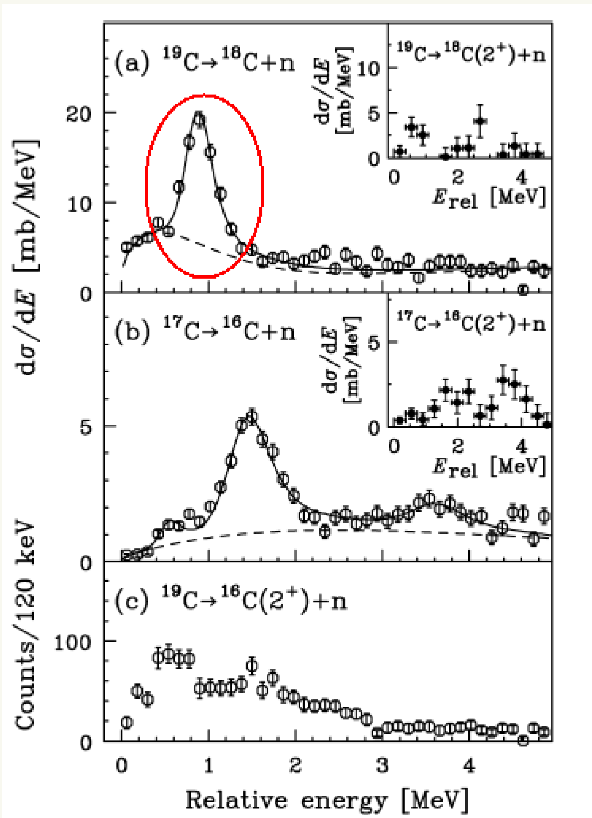


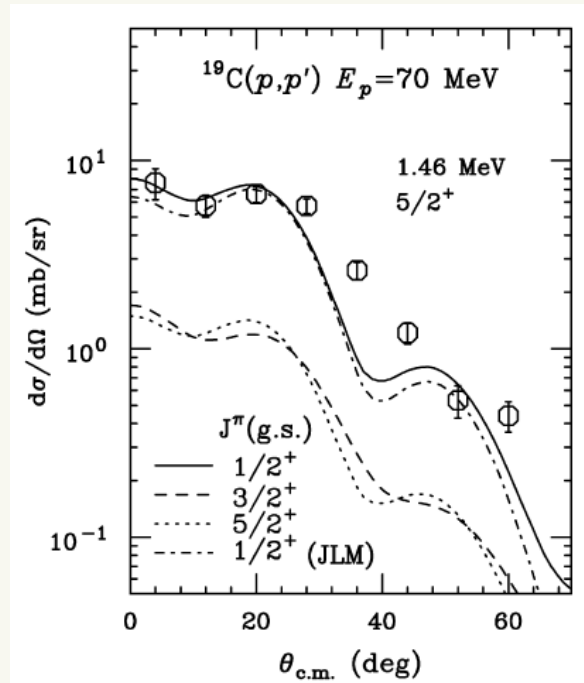
☞ Enhancement of diffractive breakup

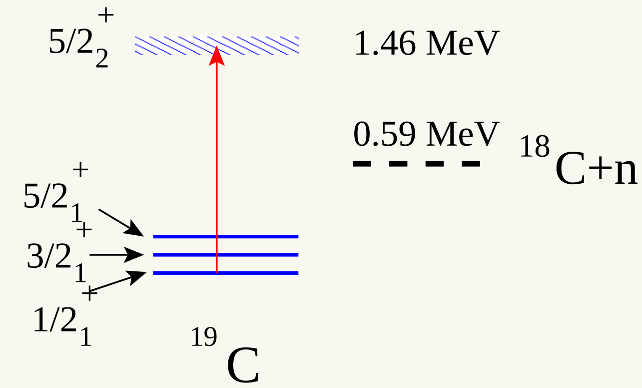
Open questions:

- How does deformation affect the momentum distributions?
- Effect in exclusive cross sections?

$^{19}\mathrm{C} + p$ @ $E/A = 69$ MeV (RIKEN), *Satou* et el., *PLB 660 (2008) 320*.



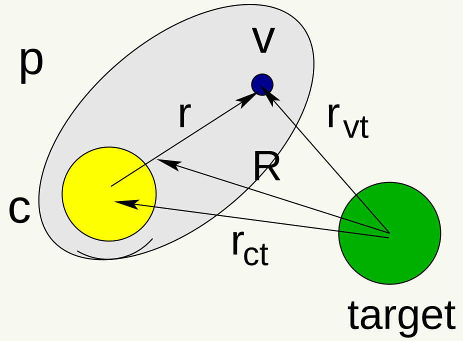




☞ *Microscopic DWBA calculations suggest a* $1/2^+ \rightarrow 5/2^+$ *transition.*

Few-body DWBA approach to inelastic scattering

Standard DWBA model for inelastic scattering:



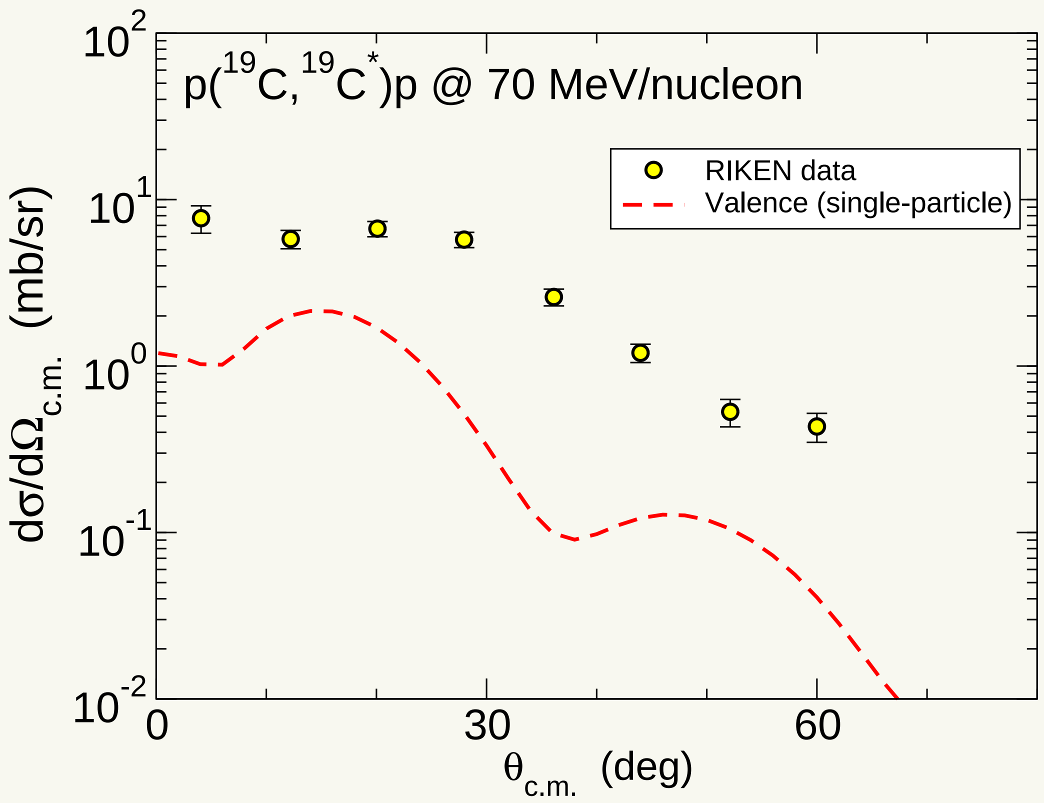
$$\boxed{T_{if}^{JM,J'M'} = \langle \chi_f^{(-)}(\vec{R}) \Psi^f_{J'M'}(\vec{r}) | V_{vt}(\vec{r}_{vt}) + V_{ct}(\vec{r}_{ct}) | \chi_i^{(+)}(\vec{R}) \Psi^i_{JM}(\vec{r}) \rangle}$$

- $\chi_f^{(-)}(\vec{R})$, $\chi_i^{(+)}(\vec{R})$ describe projectile-target relative motion
- $\Psi^i_{JM}(\vec{r})$, $\Psi^f_{J'M'}(\vec{r})$ projectile single-particle states

^{19}C+p within a three-body reaction model

- ^{19}C states treated as s.p. configurations on top of the ^{18}C(g.s.).

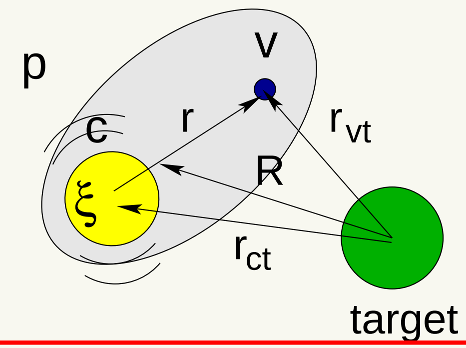
  - $^{19}\mathrm{C}(1/2^+) = |^{18}\mathrm{C}(0^+) \otimes \nu s_{1/2}\rangle$
  - $^{19}\mathrm{C}(5/2^+) = |^{18}\mathrm{C}(0^+) \otimes \nu d_{5/2}\rangle$



☞ *The valence excitation mechanism does not explain the observed x-sections*

☞ *Core excitation?*

A DWBA model for core excitation in inelastic and breakup



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

- Core excitation affects in two ways:

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

☞ $\Psi_{JM}(\vec{r},\vec{\xi})$ = projectile states ⇒ "static" deformation effect.

$$\Psi_{JM}(\vec{r},\vec{\xi}) = \sum_{\ell,j,I} \left[\varphi^J_{\ell,j,I}(\vec{r}) \otimes \Phi_I(\vec{\xi})\right]_{JM}$$

Structure part: particle-rotor model (PRM)

- Particle-rotor Hamiltonian:

$$H_{\text{proj}} = T_r + h_{\text{core}}(\vec{\xi}) + V_{vc}(\vec{r}, \vec{\xi})$$

- Projectile states expanded in $|\alpha;\ JM\rangle \equiv |(\ell s)j, I; JM\rangle$ basis:

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

- The unknowns $R^J_{\ell,j,I}(r)$ can be obtained by direct integration of the Schrödinger equation or by diagonalization in a suitable discrete basis (pseudo-state method).

Core-target interaction

1. Deformed potential:

$$V_{ct}(\vec{r}_{ct},\vec{\xi}) \simeq \underbrace{V_{ct}^{(0)}(r_{ct})}_{\text{Valence excitation}} + \underbrace{V_{ct}^{\text{def}}(\vec{r}_{ct},\hat{\xi})}_{\text{Core excitation}}$$

2. Double-folding with microscopic (AMD) transition densities

$$\langle I'||V_{ct}(\vec{r}_{ct},\vec{\xi})||I\rangle = \int d\mathbf{r}_p \int d\mathbf{r}_t \langle I'||\rho_p(r_p)||I\rangle \rho_t(r_t) v_{NN}(|\mathbf{R}-\mathbf{r}_p+\mathbf{r}_t|),$$

☞ *AMD densities provide by Y. Kanada En'yo*

Transition amplitude

- Multipole expansion for the core-target potential

$$V_{ct}(\vec{r}_{ct},\vec{\xi}) \simeq \underbrace{V_{ct}^{(0)}(r_{ct})}_{\text{Valence excitation}} + \underbrace{V_{ct}^{\text{tran}}(\vec{r}_{ct},\hat{\xi})}_{\text{Core excitation}}$$

- Replacing $V_{ct}(\vec{r}_{ct},\vec{\xi})$ in the transition amplitude:

$$\boxed{T^{if} = T^{if}_{\text{val}} + T^{if}_{\text{corex}}}$$

- Valence excitation amplitude:

$$T^{if}_{\text{val}} = \langle \chi_f^{(-)}(\vec{R})\Psi^f_{J'M'}(\vec{r},\vec{\xi})|V_{vt}(r_{vt}) + V_{ct}^{(0)}(r_{ct})|\chi_i^{(+)}(\vec{R})\Psi^i_{JM}(\vec{r},\vec{\xi})\rangle$$

- Core excitation amplitude:

$$T^{if}_{\text{corex}} = \langle \chi_f^{(-)}(\vec{R})\Psi^f_{J'M'}(\vec{r},\vec{\xi})|V_{ct}^{\text{tran}}(\vec{r}_{ct},\hat{\xi})|\chi_i^{(+)}(\vec{R})\Psi^i_{JM}(\vec{r},\vec{\xi})\rangle$$

Evaluation of the core contribution in the no-recoil limit

Neglecting core-recoil effects ($\vec{r}_{ct} \approx \vec{R}$):

$$\boxed{T^{JM,J'M'}_{\text{corex}} = \sum_{\lambda>0,\mu} \langle J'M'|JM\lambda\mu\rangle \sum_{\alpha,\alpha'} \langle R^{J'}_{\alpha'}|R^{J}_{\alpha}\rangle G^{(\lambda)}_{\alpha J,\alpha' J'} \widetilde{T}^{(\lambda\mu)}_{\text{ct}}(I \to I')}$$

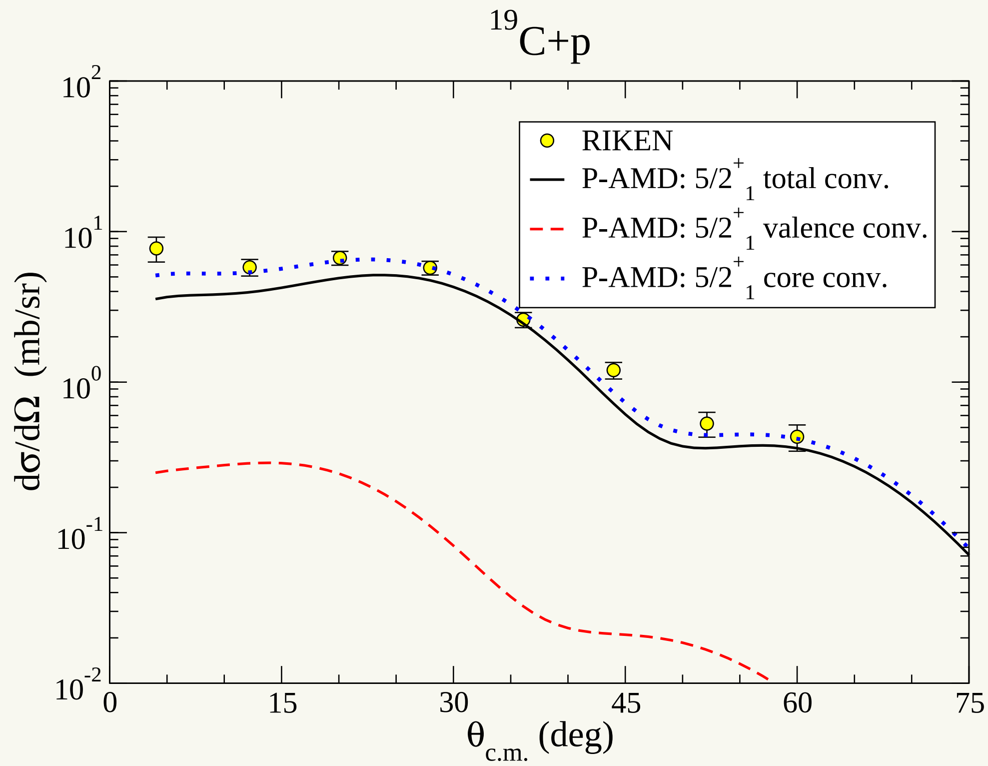
- $\widetilde{T}^{(\lambda\mu)}_{\text{ct}}(I \to I')$ is related to the free core-target inelastic amplitude for a core transition $IM_I \to IM'_I$:

$$\widetilde{T}^{(\lambda\mu)}_{\text{ct}}(I \to I') = T^{IM_I,IM'_I}_{ct} / \langle I'M'_I|IM_I\lambda\mu\rangle$$

- $G^{(\lambda)}_{\alpha J,\alpha',J'} \equiv \delta_{j,j'}(-1)^{\lambda+j+J'+I}\,\hat{J}\hat{I}' \left\{ \begin{array}{ccc} J' & J & \lambda \\ I & I' & j \end{array} \right\}$

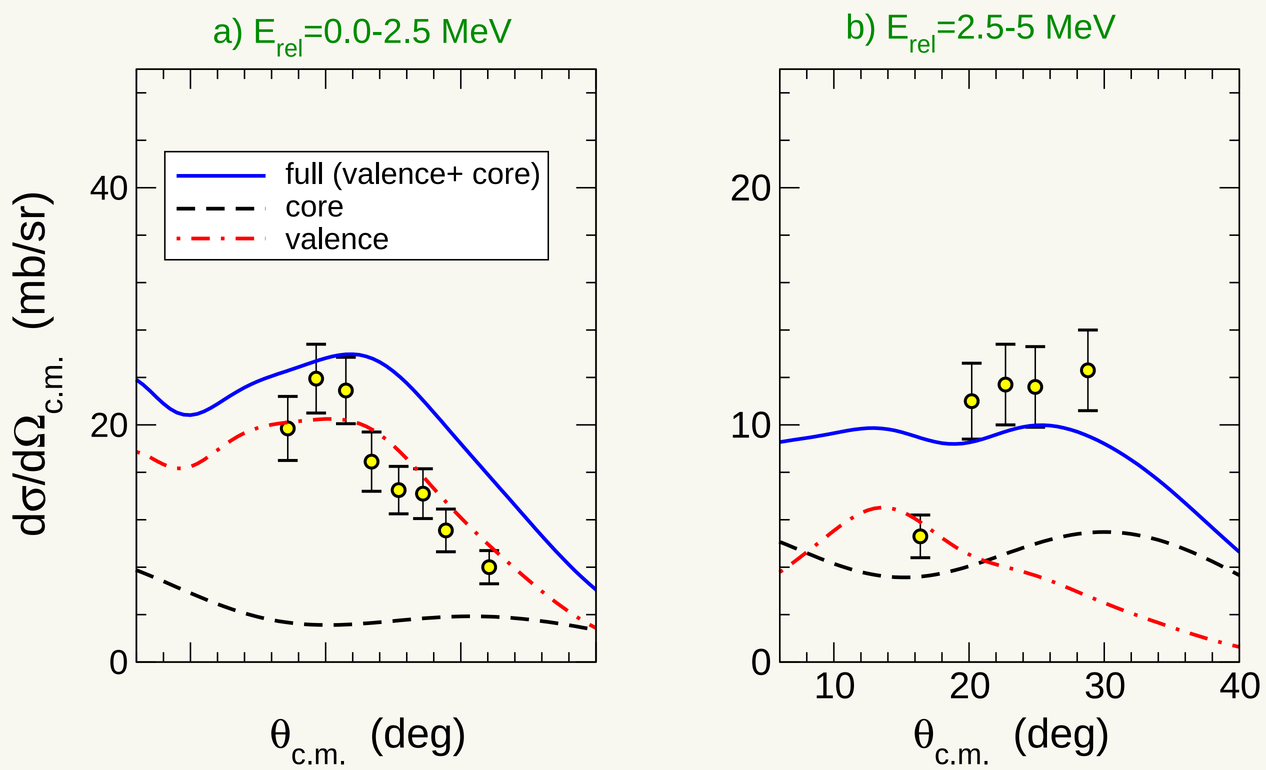
A.M.M. and R. Crespo, Phys. Rev. C 85, 054613 (2012)

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



- *The core-excitation mechanism gives the dominant contribution to the cross section.*
- *Inclusion of core excitation essential to extract reliable spectroscopic information*

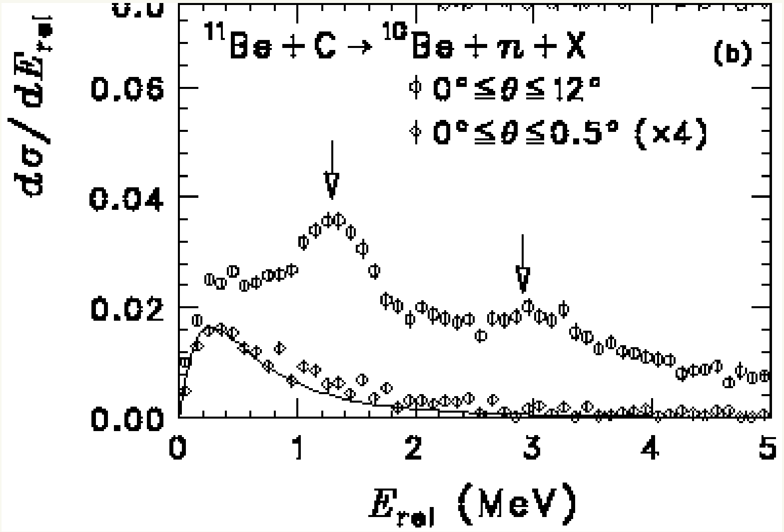
Application to ^{11}Be+p $\rightarrow$ ^{10}Be +n +p

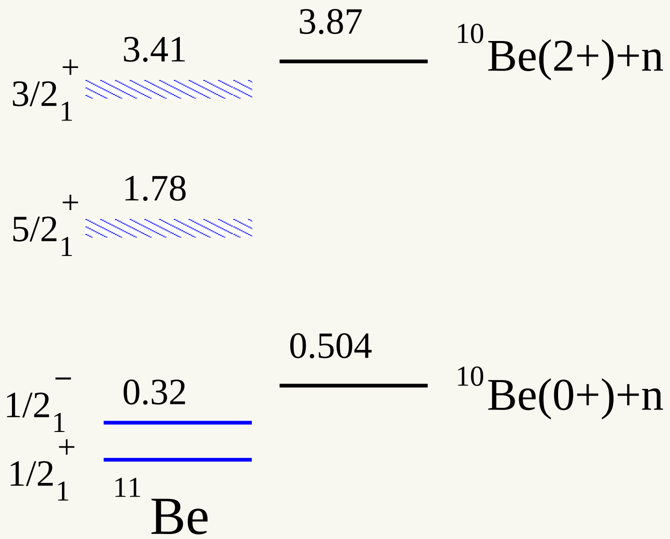


(*A.M.M. and R. Crespo, to be published in PRC*)

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

Application to $^{11}\mathrm{Be} + ^{12}\mathrm{C}$





- Nuclear effects dominant (EPM model not valid!)
- At these energies the DWBA approximation should be valid, so we use the *core-excitation* model:

$$\boxed{T_{if} = T_{if}^{(val)} + T_{if}^{(corex)}}$$

Application to $^{11}\mathrm{Be} + ^{12}\mathrm{C}$

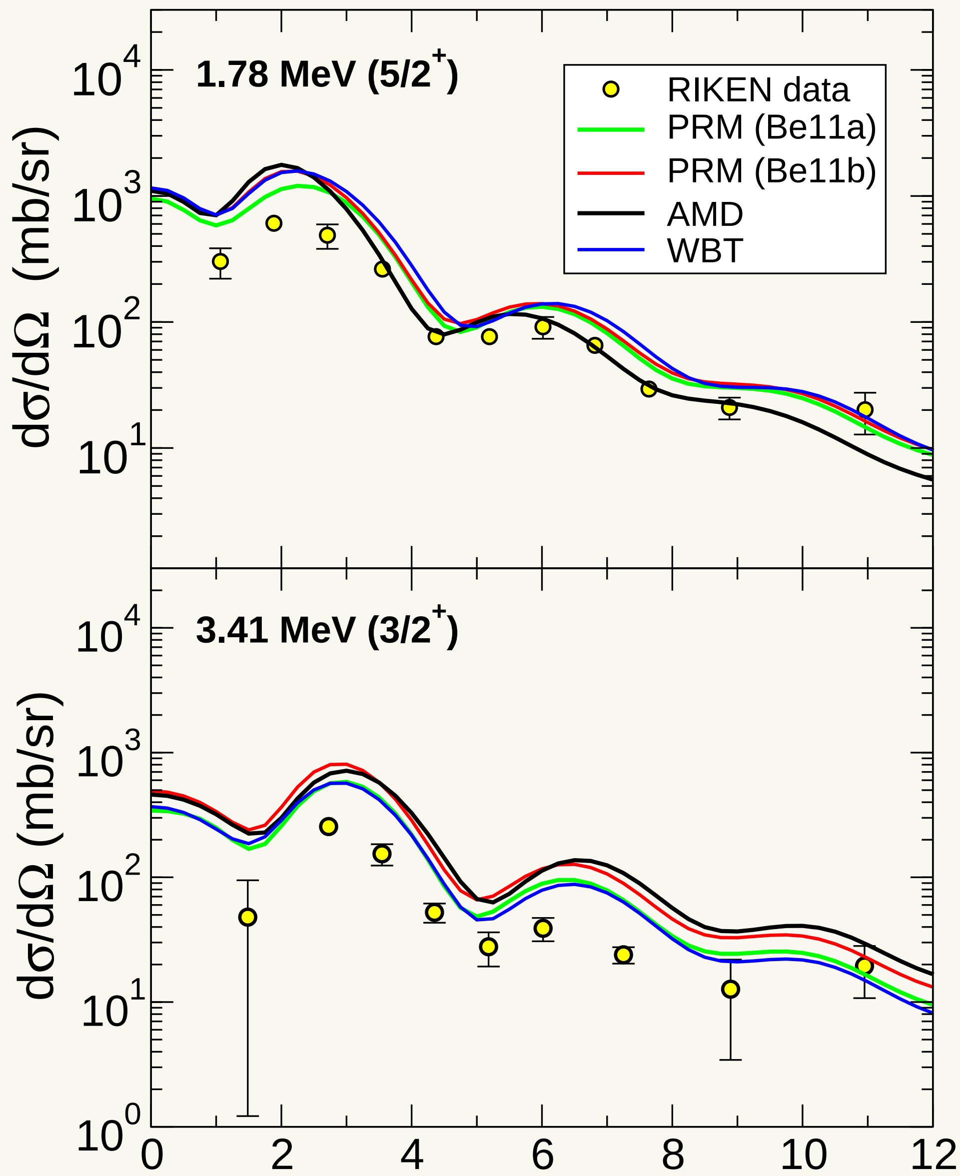
State	Model	$\|0^+ \otimes (\ell s)j\rangle$	$\|2^+ \otimes s_{1/2}\rangle$	$\|2^+ \otimes d_{5/2}\rangle$
$1/2^+$ (g.s.)	PRM (Be11-a)	0.799	–	0.187
	PRM (Be11-b)	0.857	–	0.121
	AMD	0.972	–	0.021
	WBT	0.76	–	0.184
$5/2^+$ (1.78 MeV)	PRM (Be11-a)	0.741	0.126	0.143
	PRM (Be11-b)	0.702	0.177	0.112
	AMD	0.895	0.055	0.047
	WBT	0.682	0.177	0.095
$3/2^+$ (3.41 MeV)	PRM (Be11-a)	0.088	0.633	0.274
	PRM (Be11-b)	0.165	0.737	0.081
	AMD	0.070	0.890	0.025
	WBT	0.068	0.534	0.167

PRM: Particle-rotor model with $\beta_2 = 0.67$ (*Nunes et al, NPA609, 43 (1996)*)

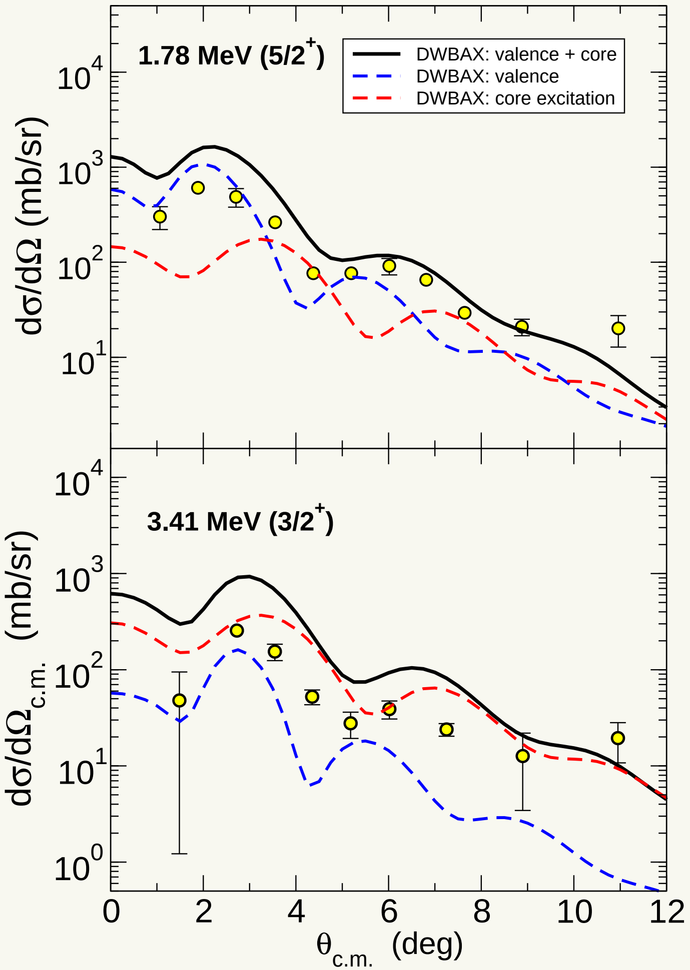
AMD: Semi-microscopic model with ^{10}Be AMD densities.

WBT: Shell-model calculation with WBT interaction

Application to $^{11}\mathrm{Be} + ^{12}\mathrm{C}$



Application to $^{11}\mathrm{Be} + ^{12}\mathrm{C}$



- Neither the valence nor core excitation alone describe the shape of the data
- $5/2^+$ x-section dominated by s.p. excitation
- $3/2^+$ x-section dominated by core excitation mechanism
- Interference effects between valence & core mechanisms are essential to explain the shape.

- For the $3/2^+$ state, the magnitude is overestimated (?)

A.M.M. and J.A. Lay, PRL109, 232502 (2012)

Full CDCC calculations with core excitation

- DWBA only valid for intermediate and high energies.
- Does not provide elastics

Full CDCC calculations with core excitation

- DWBA only valid for intermediate and high energies.
- Does not provide elastics

☞ *In more general situations, one needs to solve full coupled-channels calculations (CDCC)*

- Standard CDCC. $\Rightarrow$ use coupling potentials:

$$\boxed{V_{\alpha;\alpha'}(\mathbf{R}) = \langle \Psi^{\alpha'}_{J'M'}(\vec{r}) | V_{vt}(r_{vt}) + V_{ct}(r_{ct}) | \Psi^{\alpha}_{JM}(\vec{r}) \rangle}$$

- Extended CDCC $\Rightarrow$ use generalized coupling potentials

$$\boxed{V_{\alpha;\alpha'}(\mathbf{R}) = \langle \Psi^{\alpha'}_{J'M'}(\vec{r}, \vec{\xi}) | V_{vt}(r_{vt}) + V_{ct}(r_{ct}, \vec{\xi}) | \Psi^{\alpha}_{JM}(\vec{r}, \vec{\xi}) \rangle}$$

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