Interfaces between structure and reactions for rare isotopes and nuclear astrophysics

The effect of core excitation if the scattering of two-body halo nuclei

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Outline:

1. Benchmark calculations for CDCC vs Faddeev.
   - d+^{12}C at 56 MeV: elastic scattering and exclusive breakup.

2. Application to the scattering of two-body halo nuclei.
   - ^{19}C+p at 70 MeV: CDCC vs Faddeev
   - Effect of core excitation.

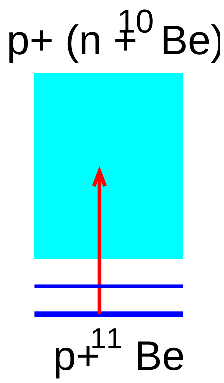
Part I: The effect of core excitation in the scattering of weakly bound nuclei

(work done with A. Deltuva, E. Cravo, F.M. Nunes and A. Fonseca)

Remainder of the CDCC method

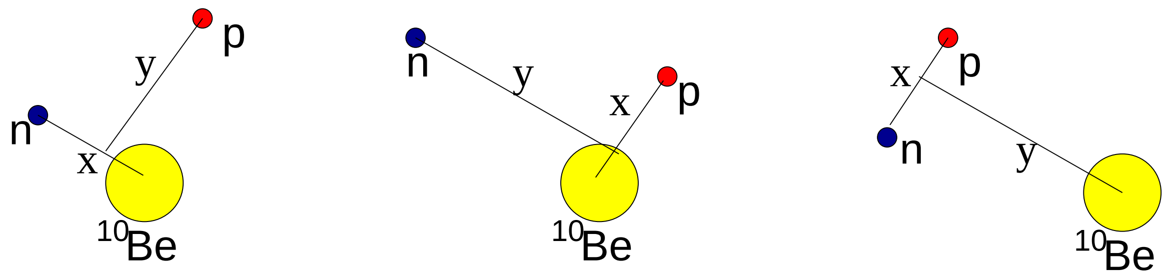
Example: ^{11}Be+p $\rightarrow$ (^{10}Be + n) + p

- 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.



CDCC versus Faddeev

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



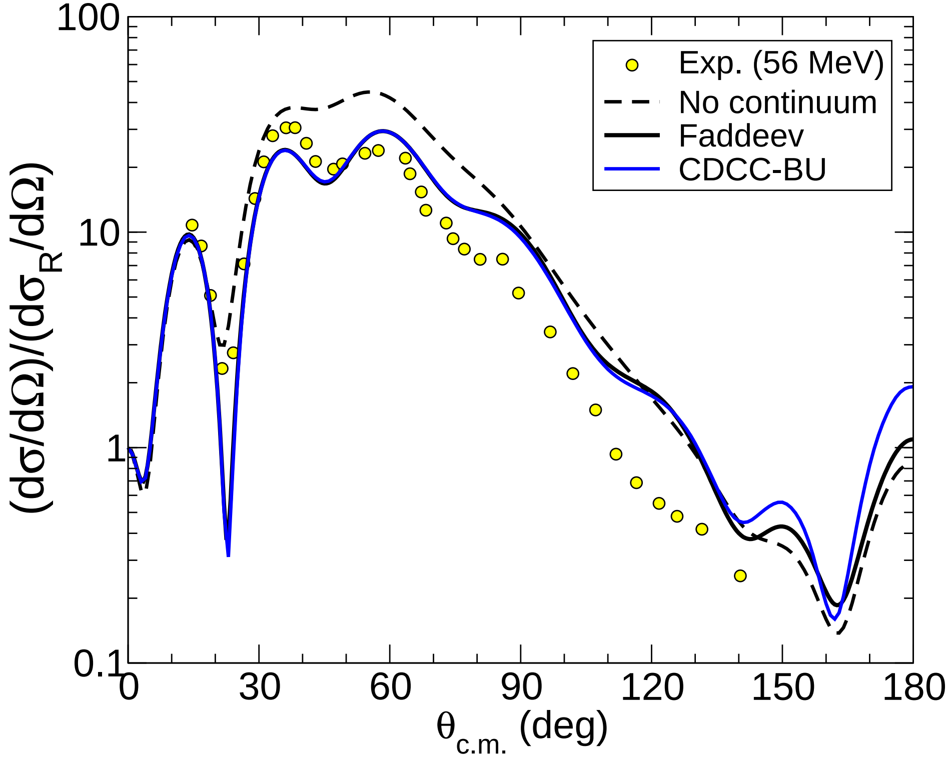
- The CDCC method can be derived as an approximated solution of the Faddeev equations in a trucated model space (Austern,Yahiro,Kawai, PRL63 (1989) 2649)
- For light systems, Faddeev equations can be now solved, so a comparison with CDCC is possible.

Benchmark calculations for CDCC vs Faddeev

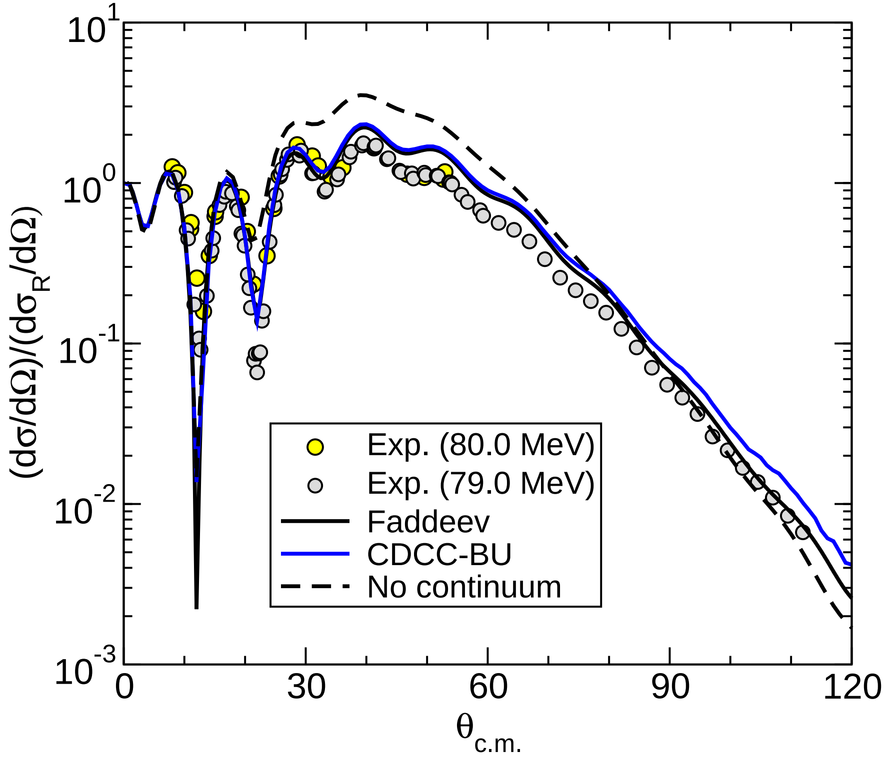
- Systems:
  - d+^{12}C @ E_d=56 MeV
  - d+^{58}Ni @ E_d=80 MeV
- Faddeev: Alt, Grass, Sandas (AGS) formulation
  - Solves Faddeev eqs in momentum space
  - Coulomb included by means of screening procedure

CDCC vs Faddeev: elastic scattering

d+^{12}C at 56 MeV

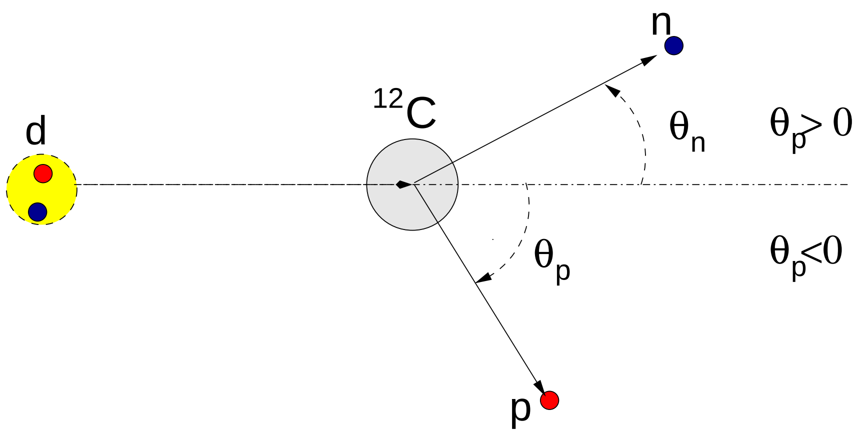


d+^{58}Ni at 80 MeV



☞ CDCC and Faddeev are in perfect agreement!

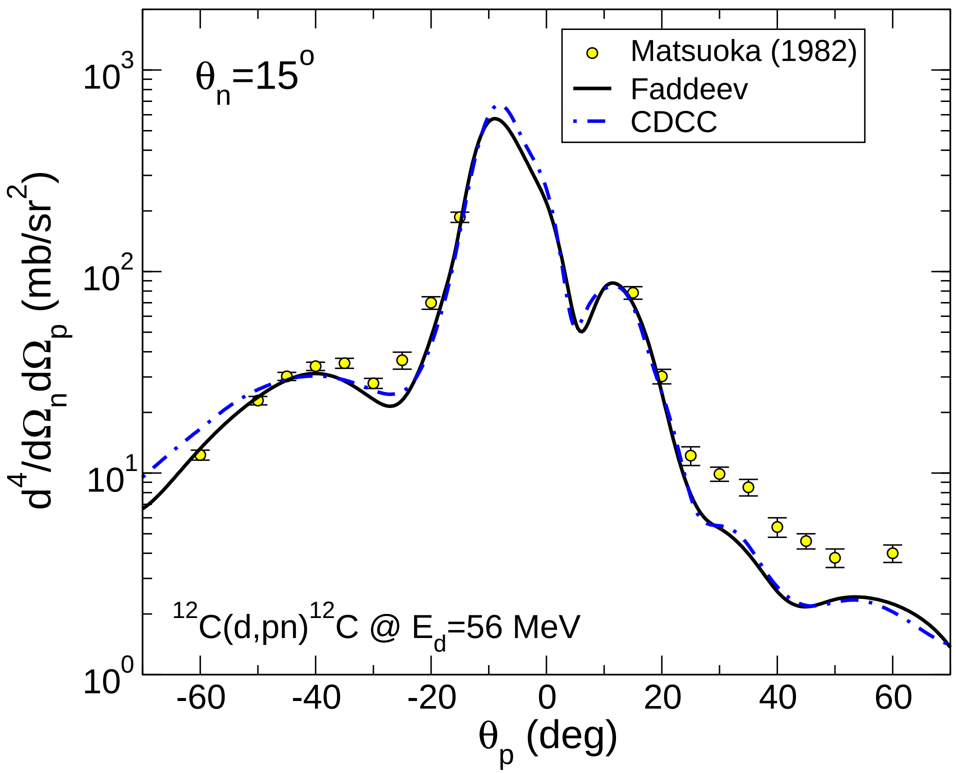
CDCC vs Faddeev: exclusive breakup x-sections



N. Matsuoka *et al.*, Nucl. Phys. **A 391**, 357 (1986).

Application of the CDCC formalism: d+ ^{12}C

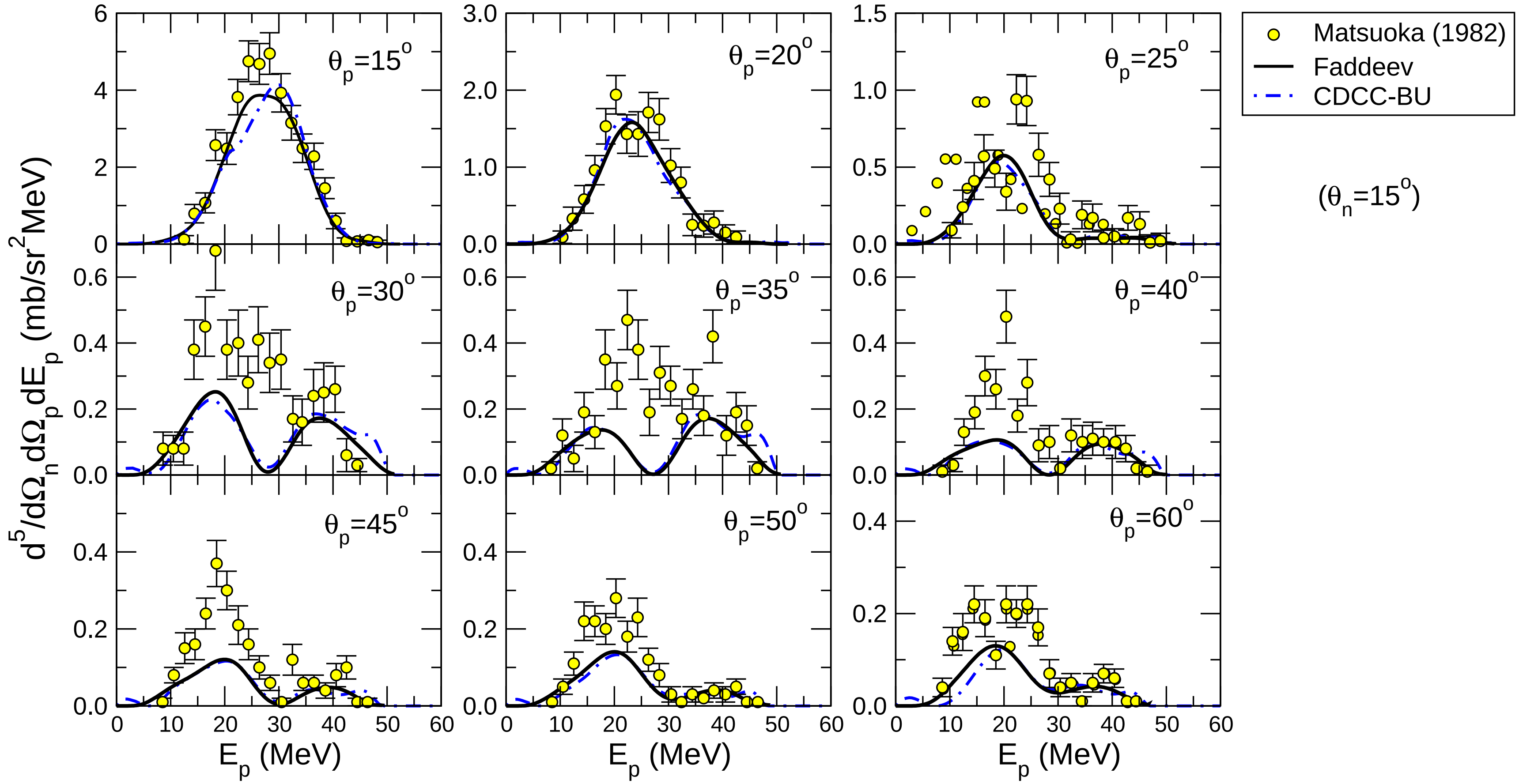
Observables for exclusive breakup: proton angular distribution



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

Application of the CDCC formalism: d+ ^{12}C

Observables for exclusive breakup: proton energy distribution for fixed θ_n and θ_p

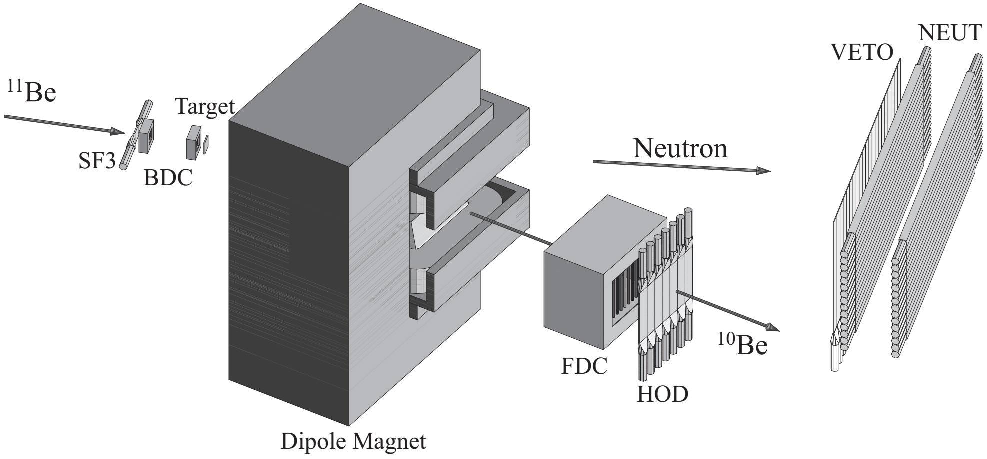


Part II: The effect of core excitation in the scattering of weakly bound nuclei

(work done with R. Crespo)

Exclusive breakup measurements of halo nuclei

Example: ^{19}C+p at RIKEN (Satou *et el.*, PLB660 (2008) 320



☞ Excitation energy can be reconstructed from core-neutron coincidences (*invariant mass method*)

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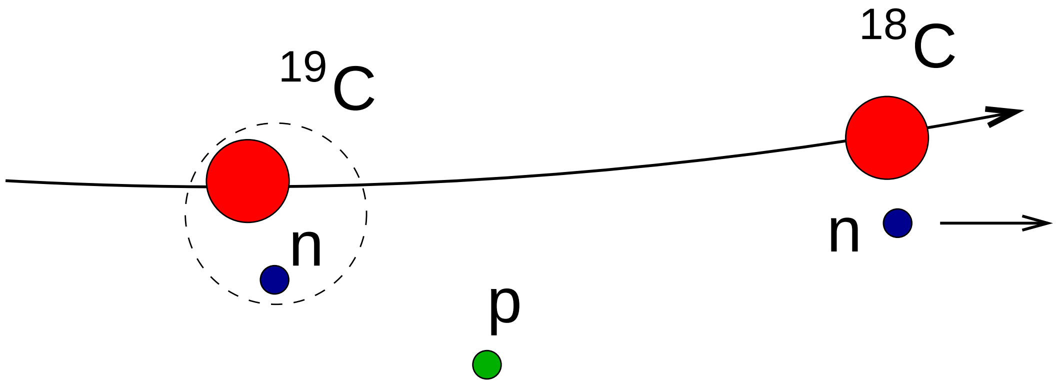

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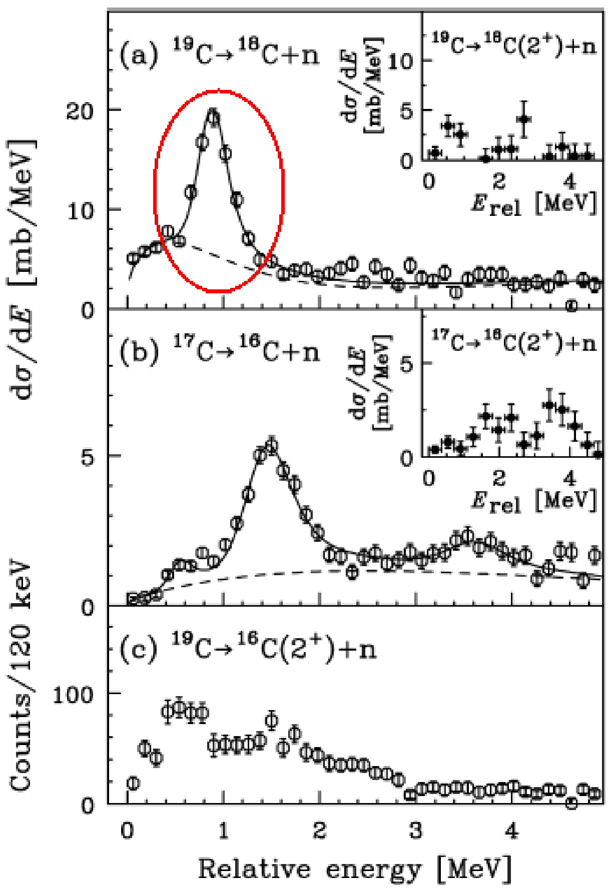
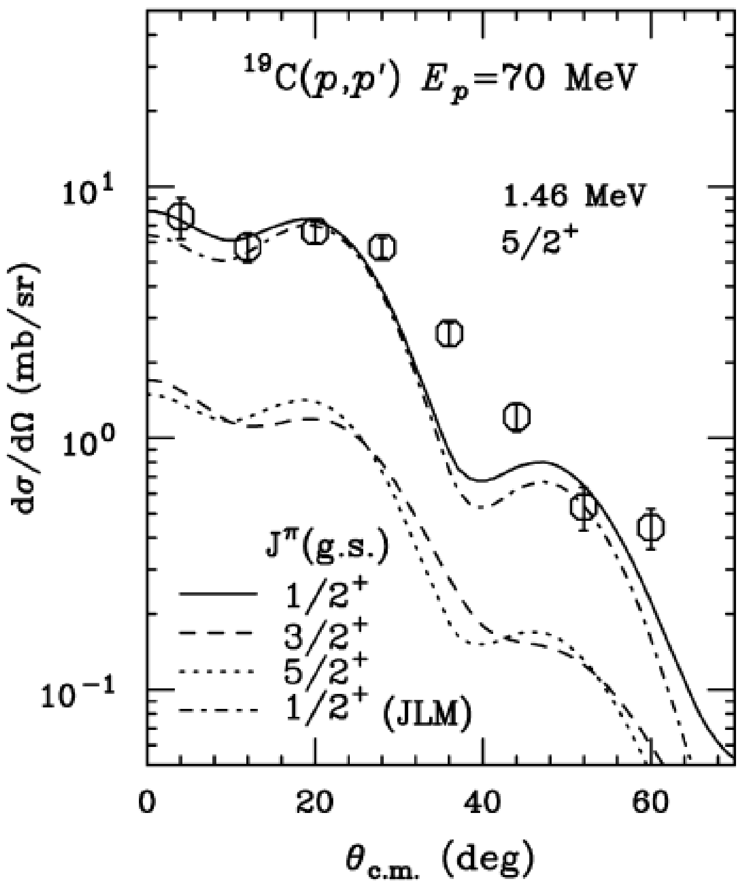
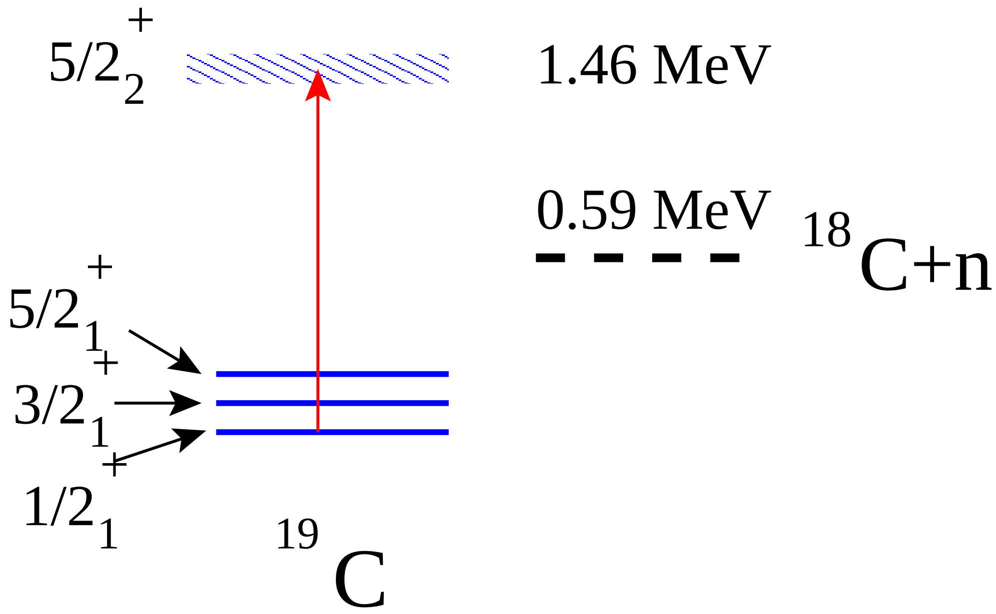
Experimental data





☞ Microscopic DWBA calculations, support a $1/2^+ \rightarrow 5/2^+$ mechanism Satou et el., PLB660 (2008) 320.

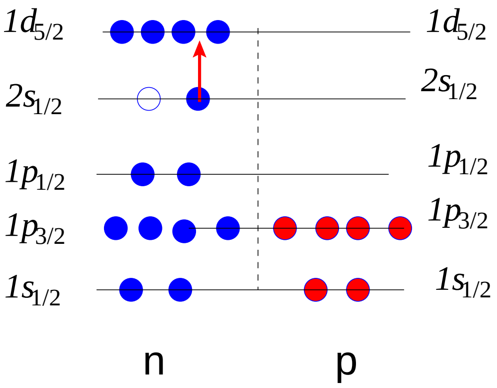
^{19}C spectrum



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

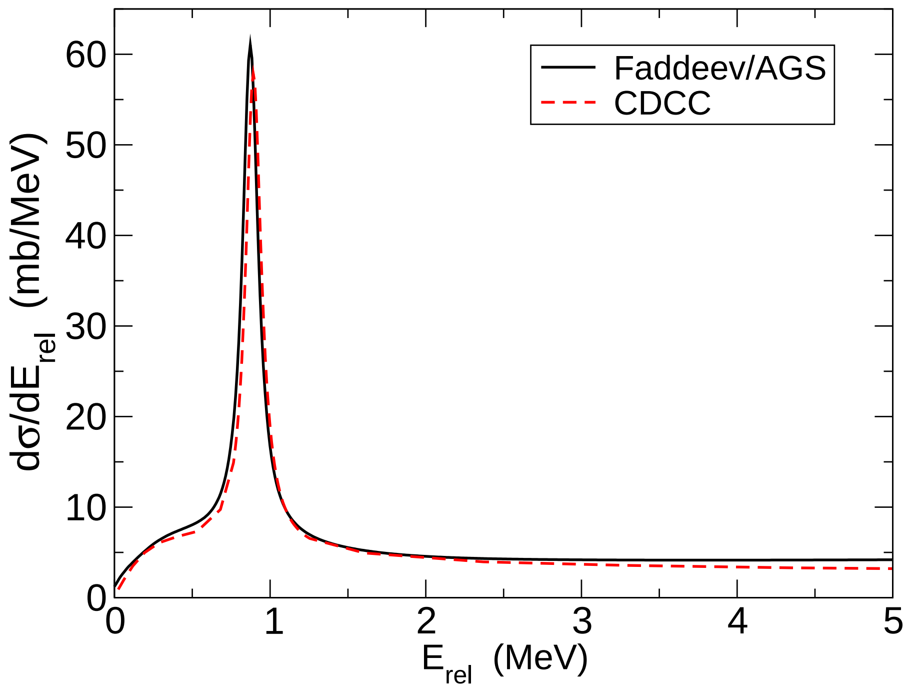
- ^{19}C states treated as s.p. configurations with the ^{18}C in the g.s.

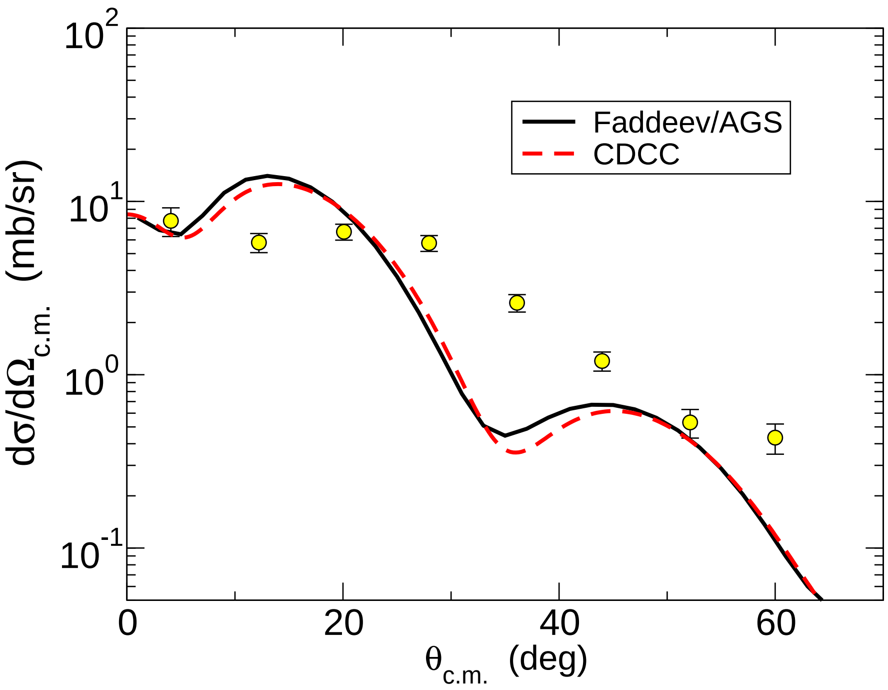
  - $^{19}\mathrm{C}(1/2^+) = |^{18}\mathrm{C}(0^+) \otimes \nu 2s_{1/2}\rangle$
  - $^{19}\mathrm{C}(5/2^+) = |^{18}\mathrm{C}(0^+) \otimes \nu 1d_{5/2}\rangle$



- Reaction mechanism ⇒ CDCC and Faddeev (AGS) methods.
- Interactions:
  - $n{-}^{18}$C: WS potential
  - $p{-}^{18}$C: global optical potential (Watson *et al*, PR182 (1969) 182)
  - $p-n$: central Gaussian potential reproducing the deuteron gs and $^3S_1$ phase-shifts

Comparison of calculations with the data

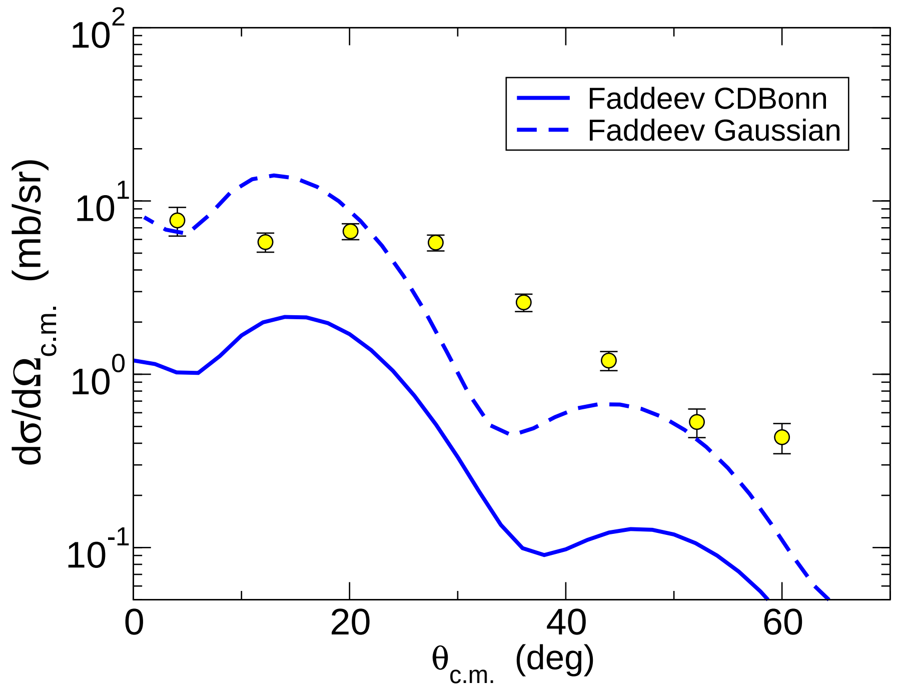




- ✔ Faddeev and CDCC provide consistent results
- ✘ The calculations reproduce the magnitude, but not the shape.
  - Pair interactions?
  - Structure model?

Effect of the p-n interaction

Faddeev calculations with the realistic CD-Bonn interaction shows that the p-n Gaussian potential is too simple



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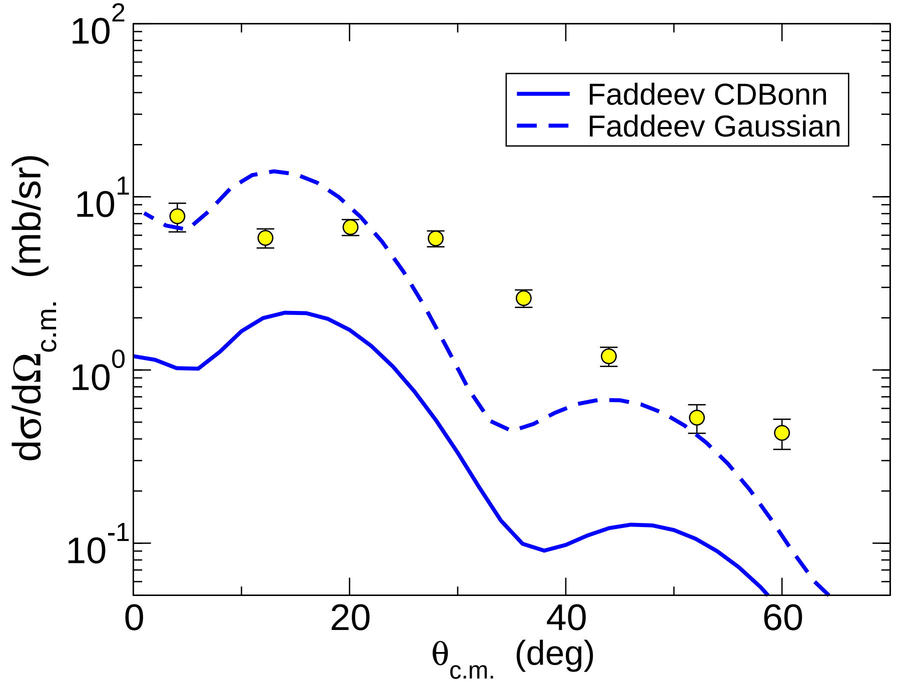

☞ *A simple single-particle excitation mechanism cannot explain the data!*

Structure model

Shell-model spectroscopic factors (WBP) for $^{19}\mathrm{C} = ^{18}\mathrm{C} + n$

$^{19}\mathrm{C}(1/2_1^+)$ g.s.

Core state	$2s_{1/2}$	$1d_{5/2}$	$1d_{3/2}$
0_1^+	0.58	–	–
2_1^+	–	0.47	0.0085
0_2^+	0.32	–	–
2_2^+	–	0.018	0.086
3_1^+	–	1.52	–
$(\ldots)$	$(\ldots)$	$(\ldots)$	$(\ldots)$

$^{19}\mathrm{C}(5/2_2^+)$ resonance

Core state	$1d_{5/2}$	$1d_{3/2}$	$2s_{1/2}$
0_1^+	0.035	–	–
2_1^+	0.29	0.0087	0.61
0_2^+	0.25	–	–
2_2^+	0.37	0.0053	0.0077
3_1^+	0.094	0.11	0.37
$(\ldots)$	$(\ldots)$	$(\ldots)$	$(\ldots)$

Structure model

- ☞ *Shell-model calculations predict a significant admixture of core excitation in both states.*
- ☞ *These core excited admixtures should be taken into account in the structure model and in the reaction model*

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- Faddeev: core-excitation not included in present implementations.
- CDCC: Summers et al, PRC74 (2006) 014606 Extended version of CDCC with core excitation (XCDCC)

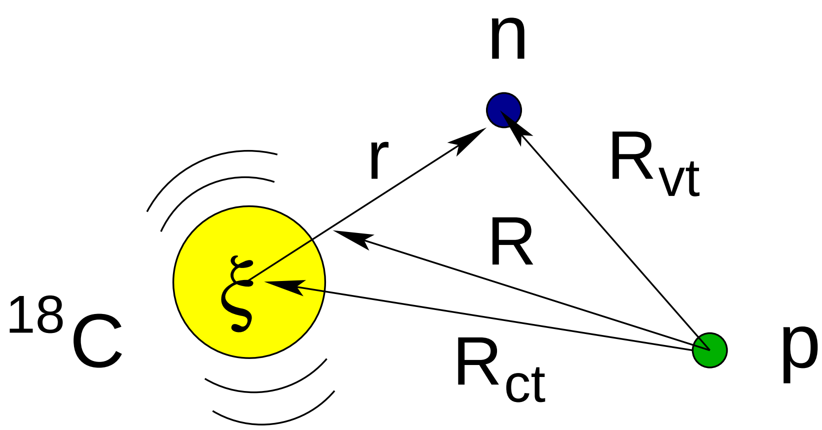
DWBA amplitude with core excitation

- DWBA amplitude with core degrees of freedom:

$$A^{JM,J'M'} = \langle \chi_f^{(-)}(\vec{R})\Psi_{J'M'}(\vec{r},\vec{\xi})|\hat{V}_T|\chi_i^{(+)}(\vec{R})\Psi_{JM}(\vec{r},\vec{\xi})\rangle$$

- Transition operator

$$\hat{V}_T = V_{vt}(\vec{R}_{vt}) + V_{ct}(\vec{R}_{ct},\vec{\xi}) - U_{\rm aux}(\vec{R})$$



Rotor model for the ^{19}C nucleus

- ^{18}C+n states calculated in a deformed potential:

$$V_{vc}(r,\vec{\xi}) \simeq V_{vc}^{(0)}(r) + \sum_{\lambda>0,\mu} V_{ct}^{(\lambda)}(r) Y_{\lambda\mu}(\hat{r}) Y^{*}_{\lambda\mu}(\hat{\xi})$$

- Internal (projectile) states:

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

State	$\|0^+ \otimes s_{1/2}\rangle$	$\|0^+ \otimes d_{5/2}\rangle$	$\|2^+ \otimes s_{1/2}\rangle$	$\|2^+ \otimes d_{5/2}\rangle$
Ground state	73%	–	–	24%
$5/2^+$ resonance	–	26%	74%	$\ll$

Scattering amplitude

- Multipole expansion for the core-target potential

$$V_{ct}(\vec{R}_{ct},\vec{\xi}) \simeq V_{ct}^{(0)}(R_{ct}) + V_{ct}^{(\lambda)}(R_{ct})Y_{\lambda\mu}(\hat{r}_{ct})Y_{\lambda\mu}^{*}(\hat{\xi})$$

- Scattering amplitude

$$A_{if} = A_{if}^{(val)} + A_{if}^{(core)}$$

- *Valence* excitation amplitude:

$$A_{if}^{(val)} = \langle \chi_f^{(-)}(\vec{R})\Psi_{J'M'}(\vec{r},\vec{\xi})|V_{vc}(\vec{r})+V_{ct}^{(0)}(R_{ct})-U_{\rm aux}(\vec{R})|\chi_i^{(+)}(\vec{R})\Psi_{JM}(\vec{R},\vec{\xi})\rangle$$

- Core excitation amplitude:

$$A_{if}^{(core)} = \langle \chi_f^{(-)}(\vec{R})\Psi^{f}_{J'M'}(\vec{r},\vec{\xi})|V_{ct}^{(\lambda)}(R_{ct})Y_{\lambda\mu}(\hat{r}_{ct})Y_{\lambda\mu}^{*}(\hat{\xi})|\chi_i^{(+)}(\vec{R})\Psi^{i}_{JM}(\vec{r},\vec{\xi})\rangle$$

Evaluation of the core contribution (no-recoil)

- Consider the free scattering amplitude for a core-target inelastic scattering:

$$A_{ct}(IM_I, IM_I') = \langle \chi^{(-)}(\vec{R}_{ct})\Phi_{I'M_I'}(\vec{\xi})|V_{ct}^{(\lambda)}(R_{ct})Y_{\lambda\mu}(\hat{R}_{ct})Y^*_{\lambda\mu}(\hat{\xi})|\Phi_{IM_I}(\vec{\xi})\chi^{(+)}(\vec{R}_{ct}$$

- In the no-recoil approximation ($\vec{R}_{ct} \approx \vec{R}$):

$$A_{if}^{(core)}(JM \to J'M') = \frac{\langle J'M'|JM\lambda\mu\rangle}{\langle I'M_c'|IM_c\lambda\mu\rangle} \sum_{\alpha,\alpha'} \langle R_{\alpha'}|R_\alpha\rangle G_{\alpha,\alpha'}^{(\lambda)} A_{ct}(IM_c \to I'M_c')$$

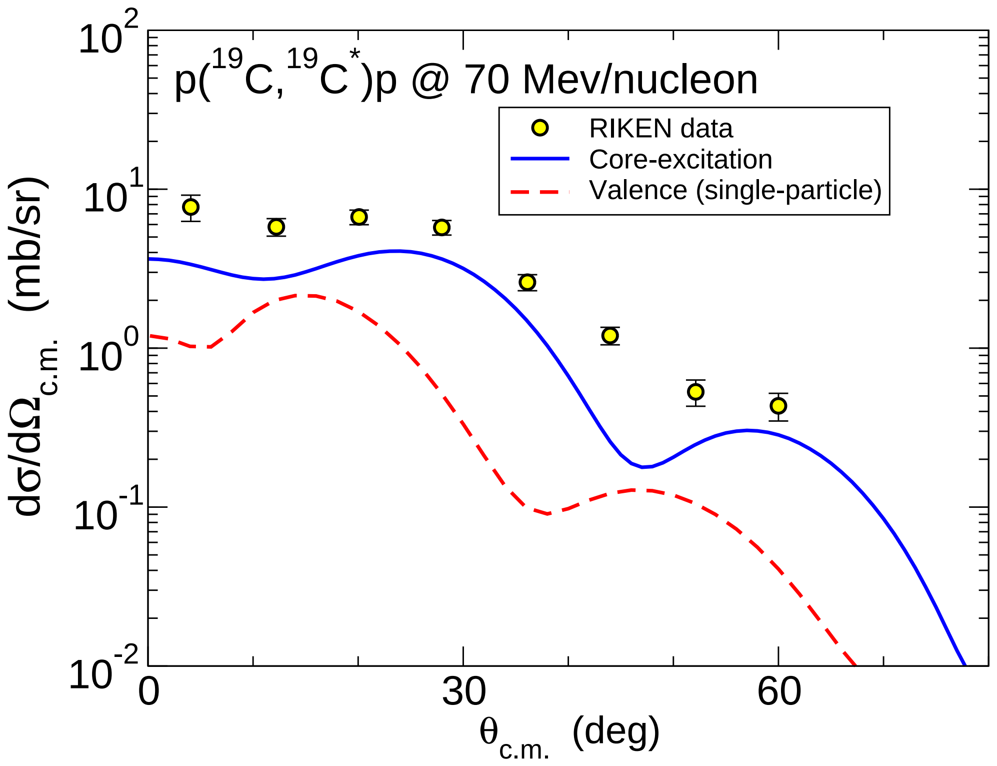
$$\alpha \equiv \{\ell, s, j, I\}$$

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

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

- ^{18}C treated in a rotor model with $I = 0^+, 2^+$ states
- ^{18}C+n and ^{18}C+p calculated with a deformed potential
- Breakup calculated in first order (Born approximation)
- Recoil effects ignored.

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



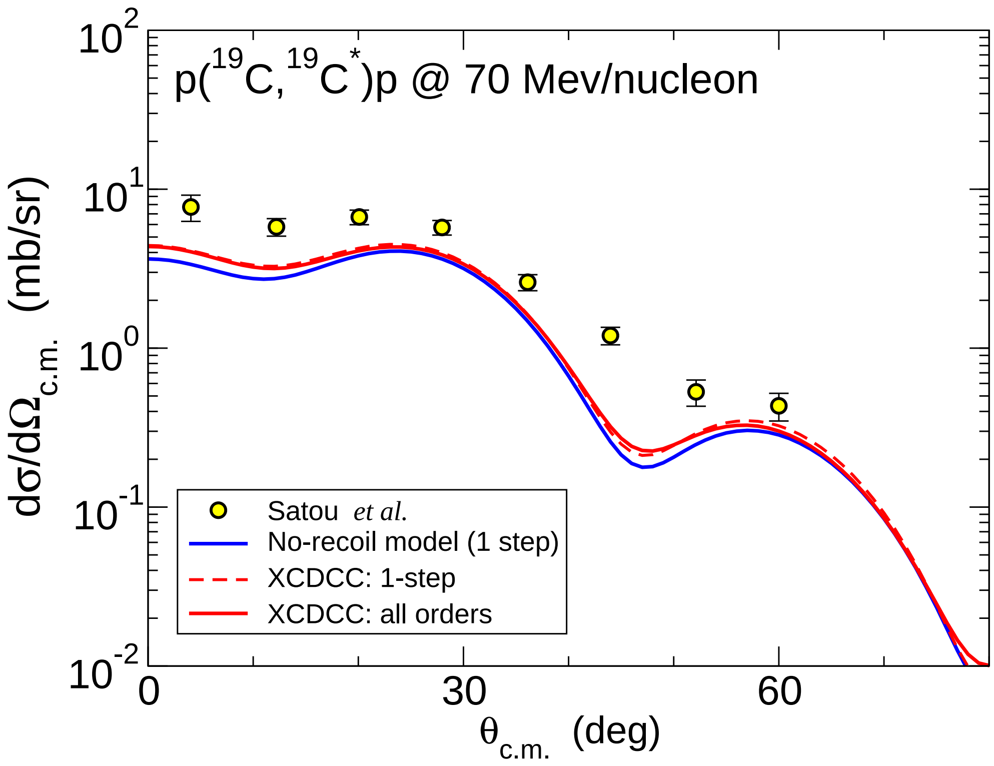
- ☞ *The core-excitation mechanism gives a significant contribution to the cross section.*
- ☞ improved description of the shape.

Conclusions

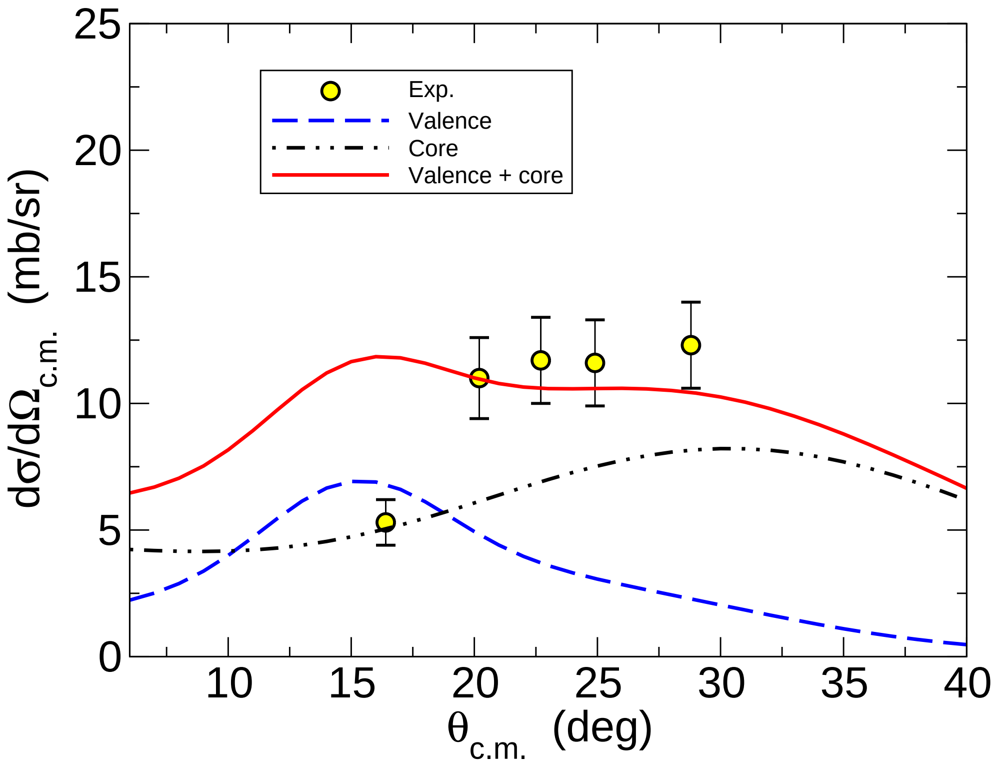
- For elastic and (exclusive) breakup observables, the CDCC method has proven to be a very accurate approximation to the full Faddeev equations.
- For the scattering of a core+neutron system on a proton target, the breakup is very sensitive to the p-n interaction $\Rightarrow$ needs to be incorporated in existing implementations of the CDCC method.
- Core excitation plays a very important role in the resonant breakup of halo nuclei with deformed core.


Thanks!

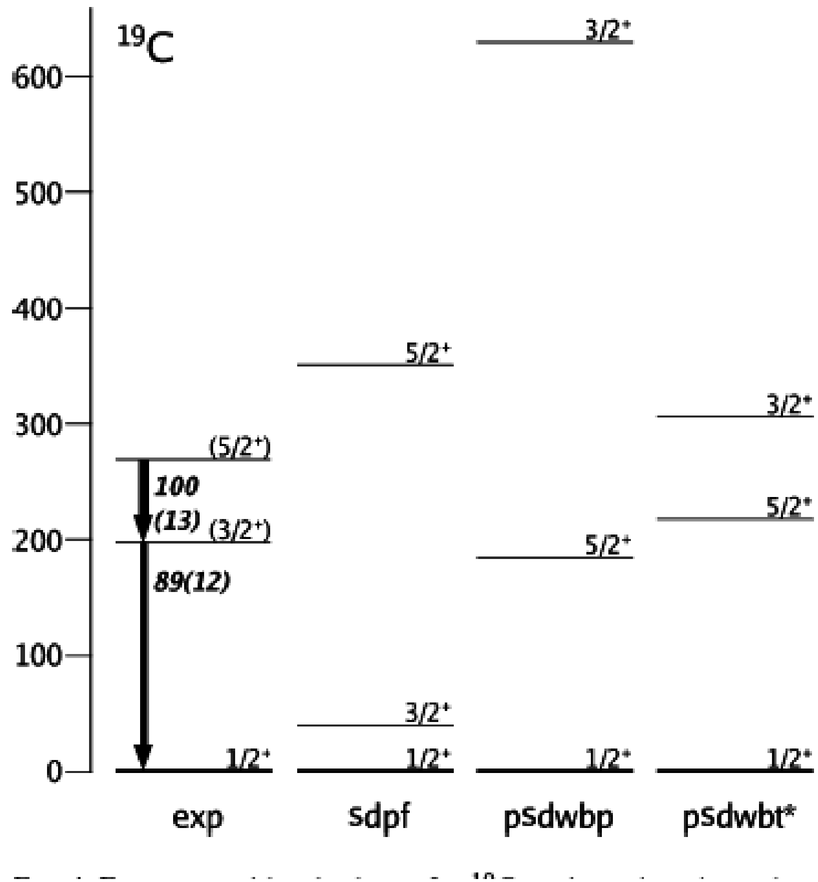
Application to ^{19}*C+p* $\rightarrow$ ^{18}*C +n +p*



Core excitation in ^{11}Be+p



^{19}*C spectrum from shell-model calculations*

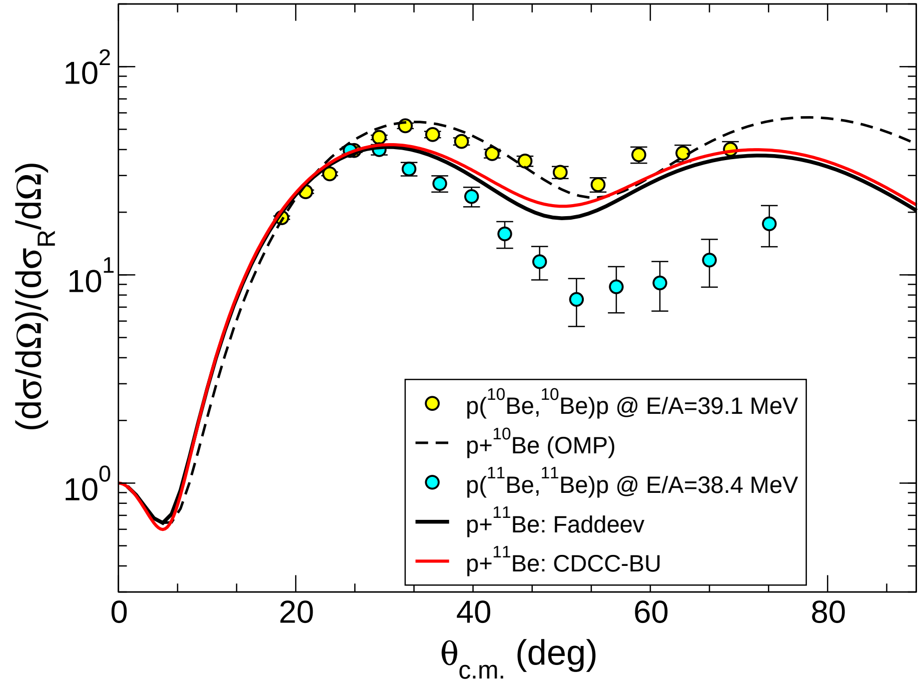


From Elekes *et al*, PLB 614 (2005) 174)

Benchmark calculations for ^{11}Be+p

- Can we understand the ^{11}Be+p elastic and transfer (p, d) data within a three-body model (p+n^{10}Be)?
- DBU vs TC: what approach is more appropriate for inclusive breakup cross sections?

CDCC versus Faddeev: ^{11}Be + p elastic scattering



- Good agreement betwen Faddeev and DBU (CDCC)
- Significant disagreement with data! $\Rightarrow$ interactions?

CDCC vs Faddeev: transfer to bound states

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