Dynamics and Correlations in Exotic Nuclei (DCEN2011)

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

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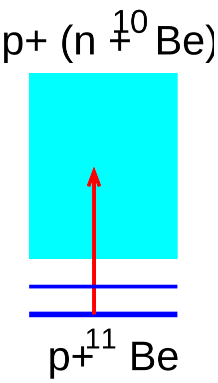
Outline:

1. Brief remainder of the “standard” CDCC method.
2. Testing the standard CDCC method against the Faddeev method.
   - d+^{12}C at 56 MeV: elastic scattering and exclusive breakup.
   - Scattering on protons: effect of NN interaction
3. Recent extensions of the standard CDCC method
   - Extension to three-body projectiles (4-body CDCC)
   - Beyond the *frozen core* approximation: inclusion of core-excitation.
4. A simple model for core excitation.
   - Application to ^{19}C+p at 70 MeV
   - Application $^{11}\mathrm{Be}$ scattering on $^{12}\mathrm{C}$ and $^{208}\mathrm{Pb}$

Remainder of the “standard” CDCC method

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

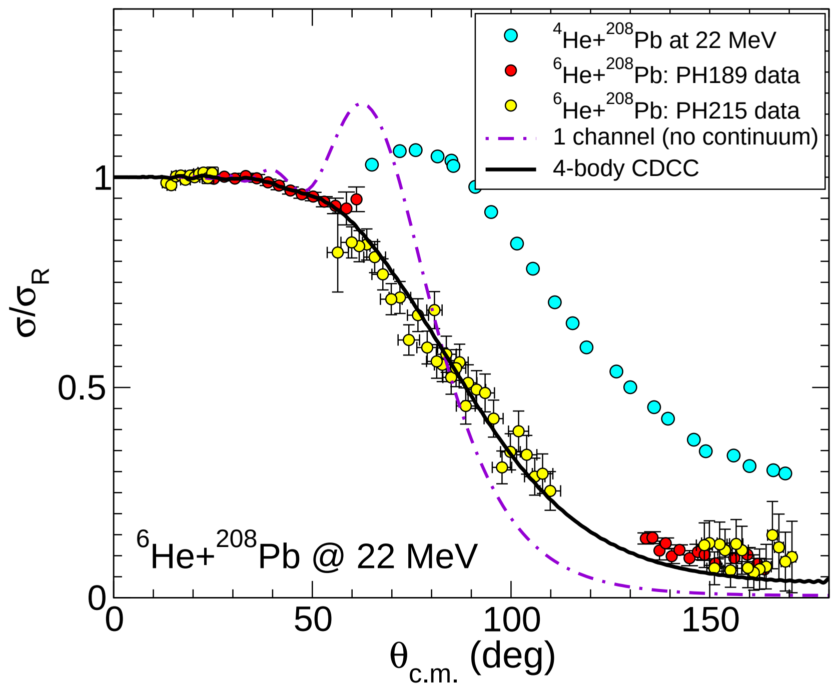
- Effective 3-body Hamiltonian with the cluster in g.s.
- Three-body wf expanded in projectile (^{11}Be) internal states
- Breakup treated as single-particle excitations to n+^{10}Be continuum
- Continuum is discretized in energy bins and truncated in energy and angular momentum
- Provides elastic and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

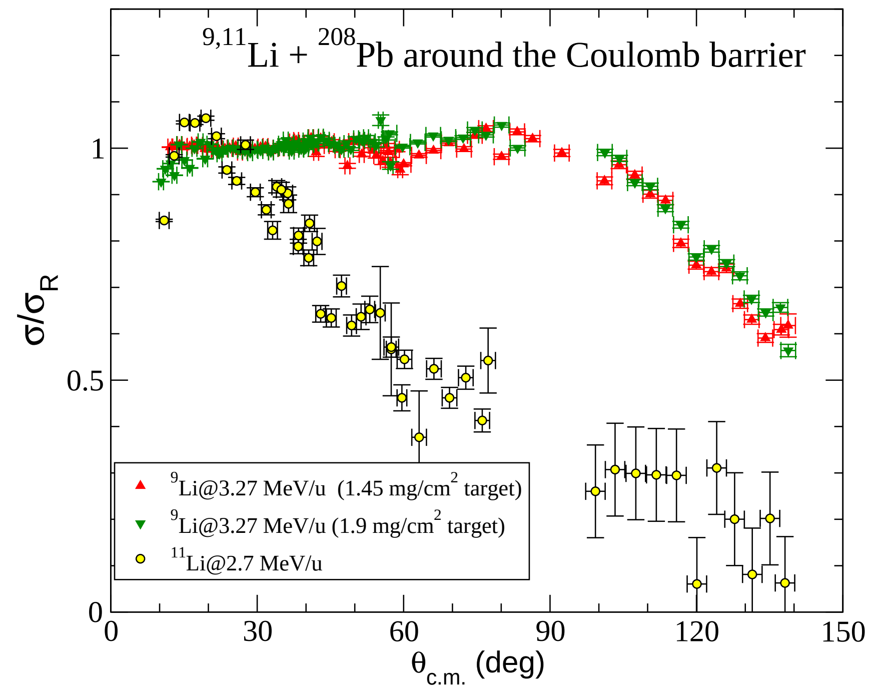


Generalizations of the standard CDCC method

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

Extension of three-body projectiles





Data (LLN): *Sánchez-Benítez et al, NPA 803, 30 (2008) L. Acosta et al, PRC 84, 044604 (2011)*
Calculations: *Rodríguez-Gallardo et al, PRC 80, 051601 (2009)*

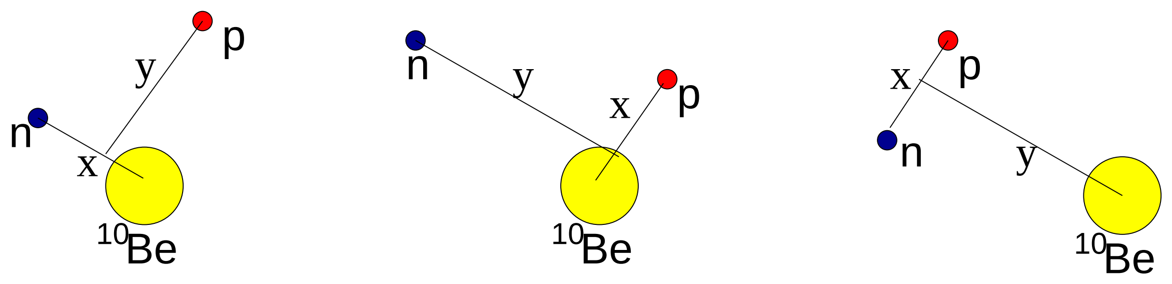
Data: TRIUMF (2008)

Benchmark calculations of the “standard” CDCC method against Faddeev within a pure three-body model.

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 be now solved, so a comparison with CDCC is possible.

CDCC versus Faddeev

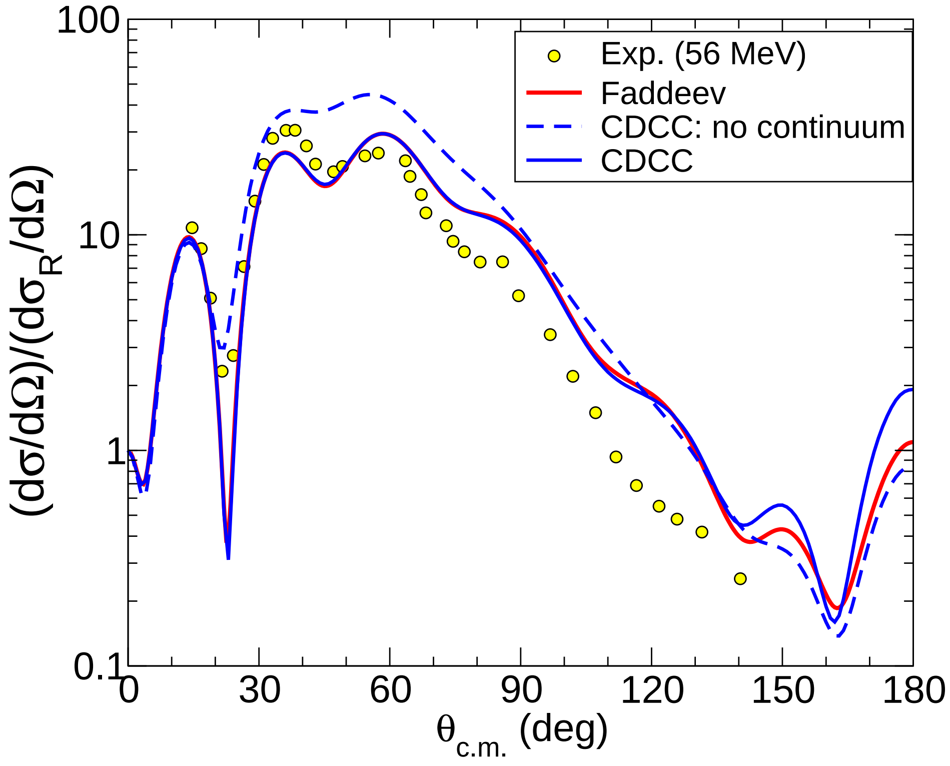
BENCHMARK CALCULATIONS FOR CDCC VS FADDEEV

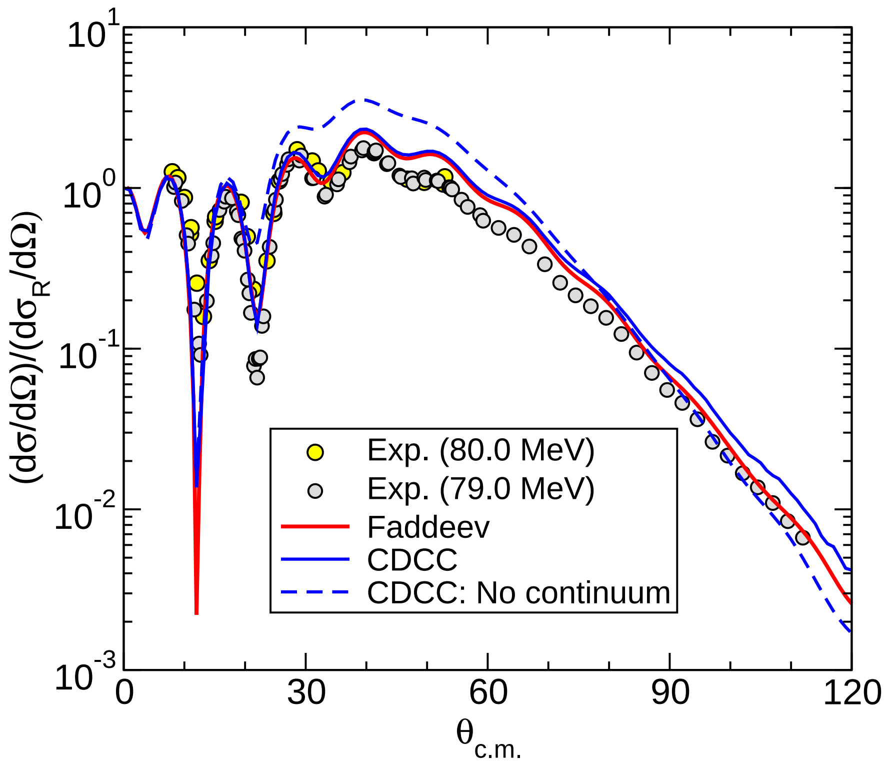
- Systems:
  - d+^{12}C @ E_d=56 MeV
  - d+^{58}Ni @ E_d=80 MeV
  - ^{19}C+p @ $E/A = 70$ MeV
- Faddeev: AGS formulation
  (*Alt, Grassberger, Sandas , Nuc. Phys. B 2(1967)167*)
  - Solves Faddeev equations in momentum space
  - Coulomb included by means of screening procedure
  - Does not require discretization of the continuum.

CDCC vs Faddeev: elastic scattering

d+^{12}C at 56 MeV

d+^{58}Ni at 80 MeV

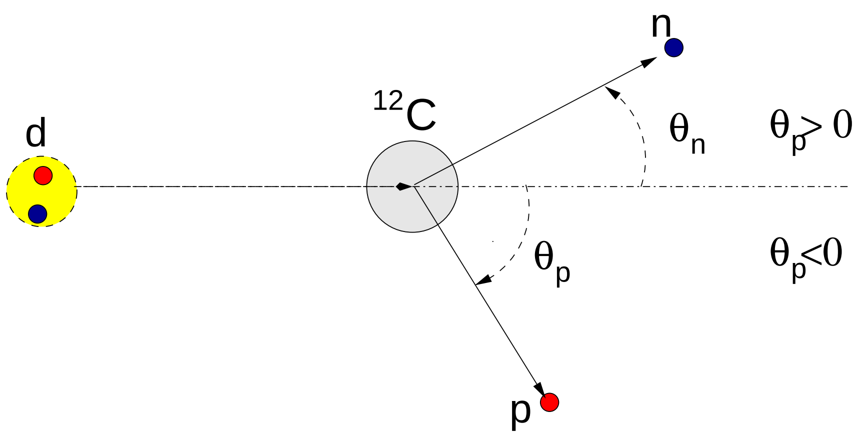




☞ CDCC and Faddeev fully consistent!

Example: d+^{12}C $\rightarrow$ p+n+ ^{12}C

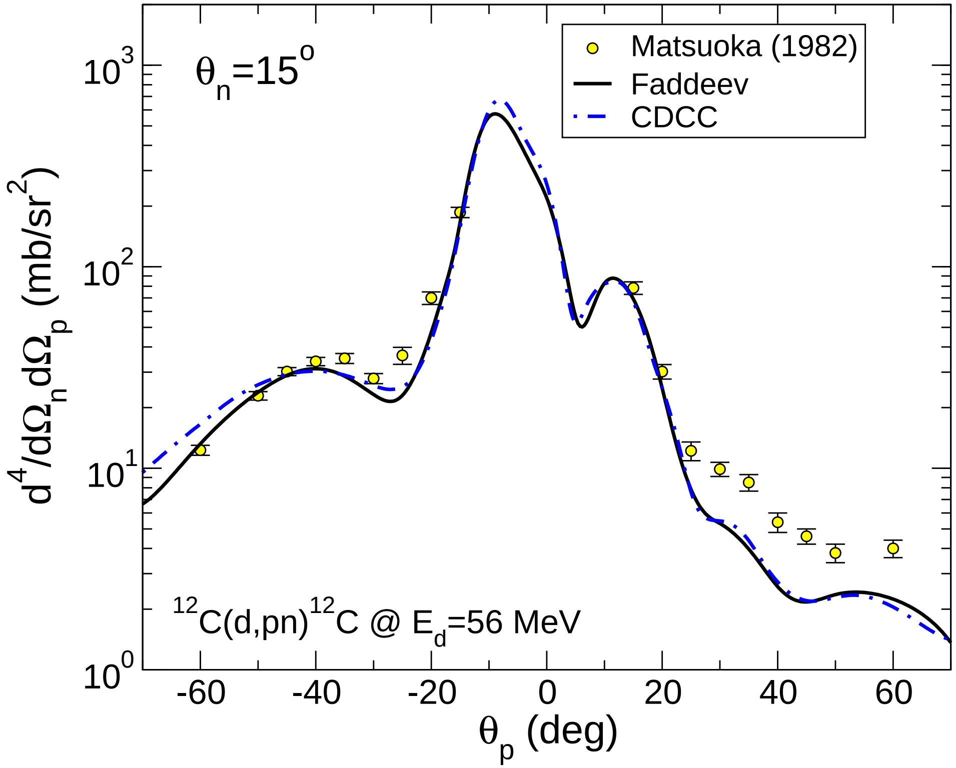
N. Matsuoka et al., Nucl. Phys. **A 391**, *357 (1986)*.



Protons and neutrons measured in coincidence.

CDCC vs Faddeev: exclusive breakup

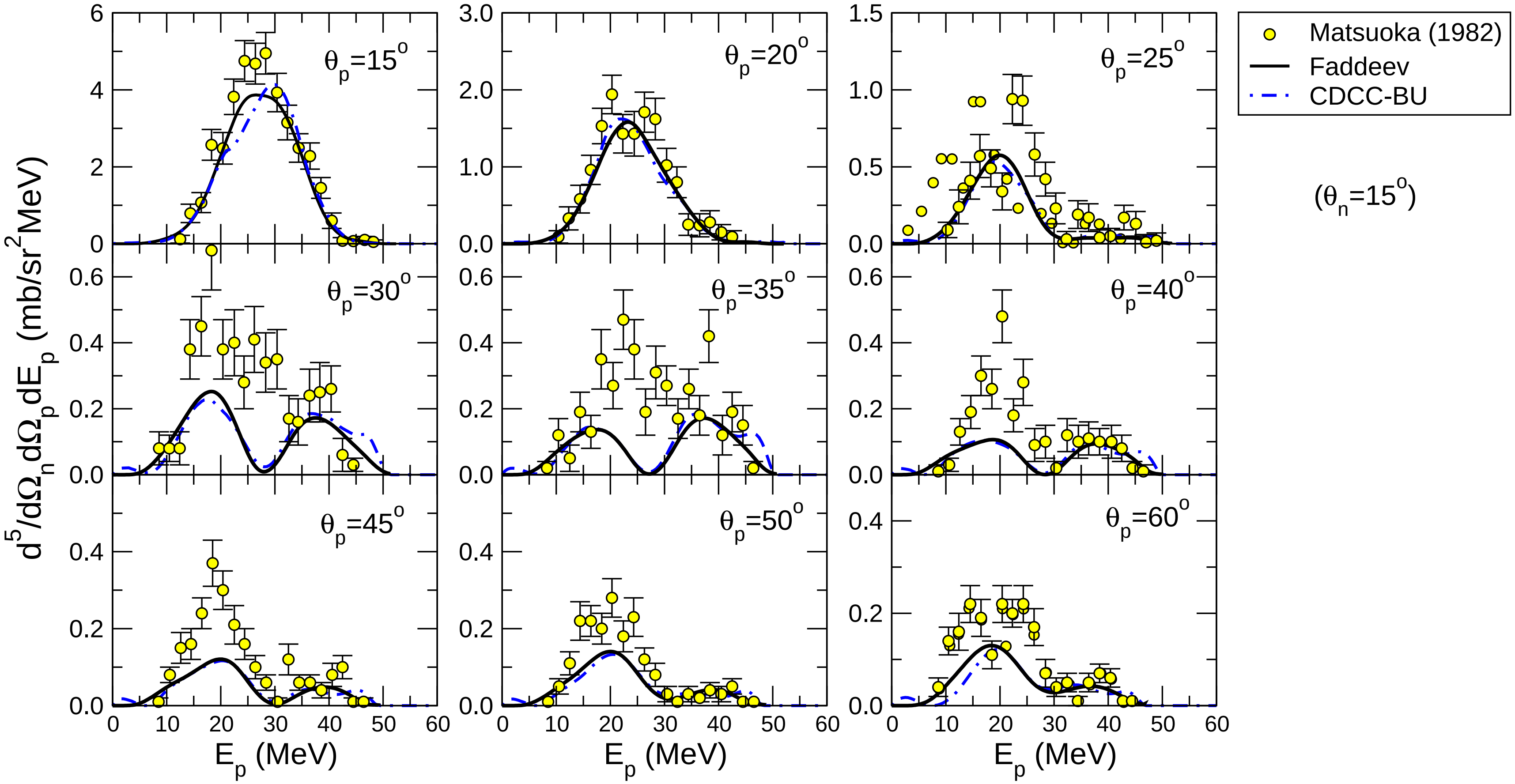
Proton angular distribution for fixed θ_n.



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

CDCC vs Faddeev: exclusive breakup

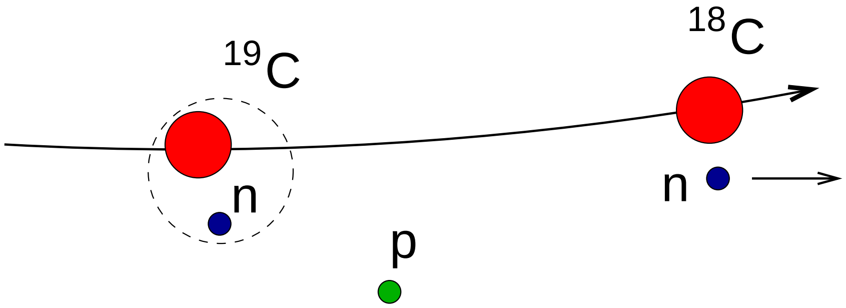
Proton energy distribution for fixed θ_n and θ_p



CDCC vs Faddeev: scattering on protons

Test case:

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



Test case:
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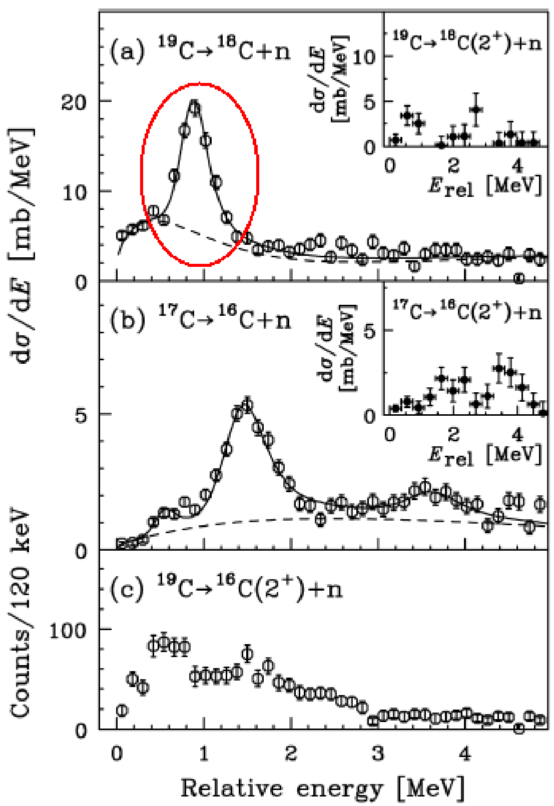
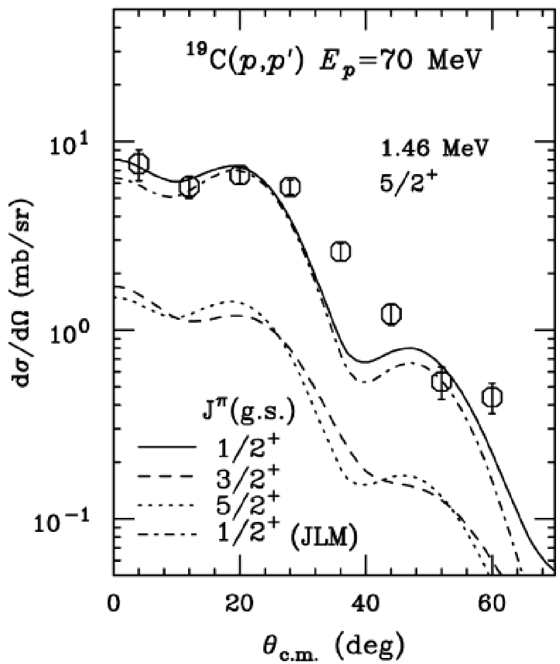
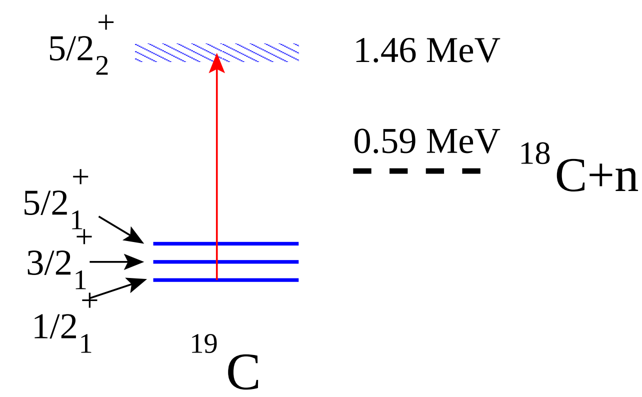






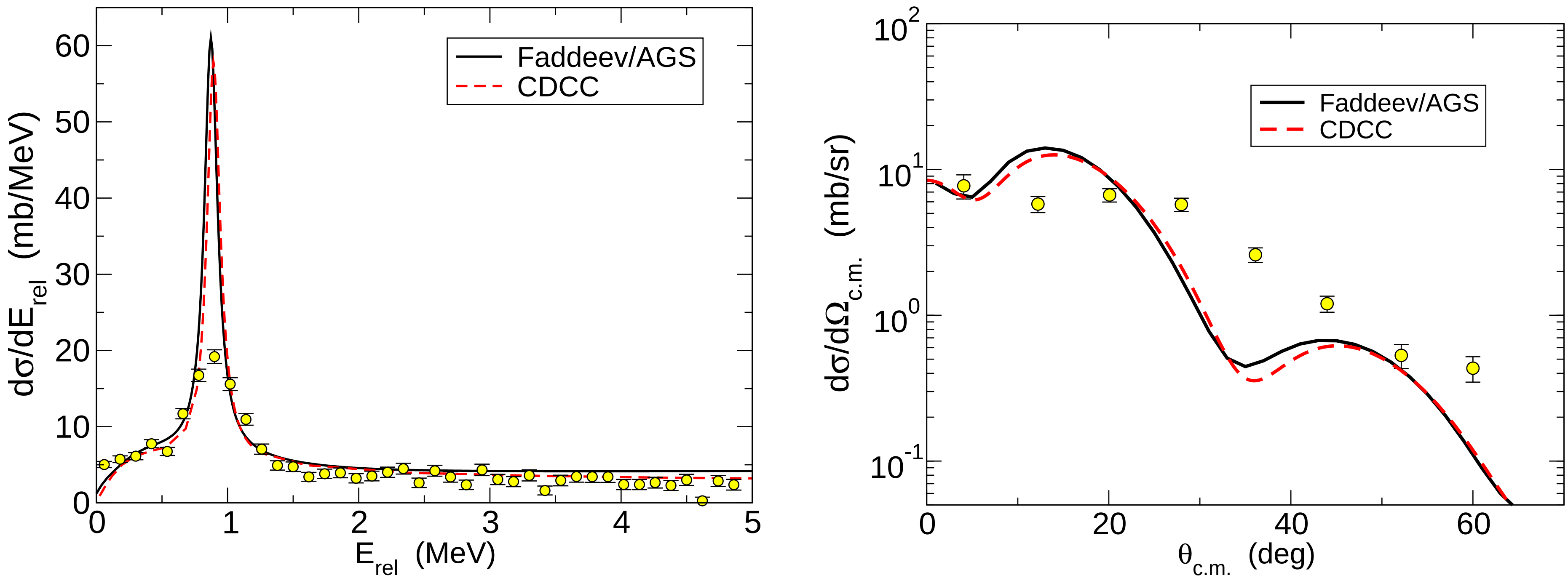
☞ *Microscopic DWBA calculations support a* $1/2^+ \to 5/2^+$ *transition.*

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

- ^{19}C states treated as s.p. configurations on top of the ^{18}C in the g.s.
  - $^{19}\mathrm{C}(1/2^+) = |^{18}\mathrm{C}(0^+) \otimes \nu s_{1/2}\rangle$
  - $^{19}\mathrm{C}(5/2^+) = |^{18}\mathrm{C}(0^+) \otimes \nu d_{5/2}\rangle$

- Pairwise interactions:
  - $n-^{18}$C: WS potentials reproducing $1/2^+_1$ b.s. and $5/2^+_2$ resonance.
  - $p-^{18}$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



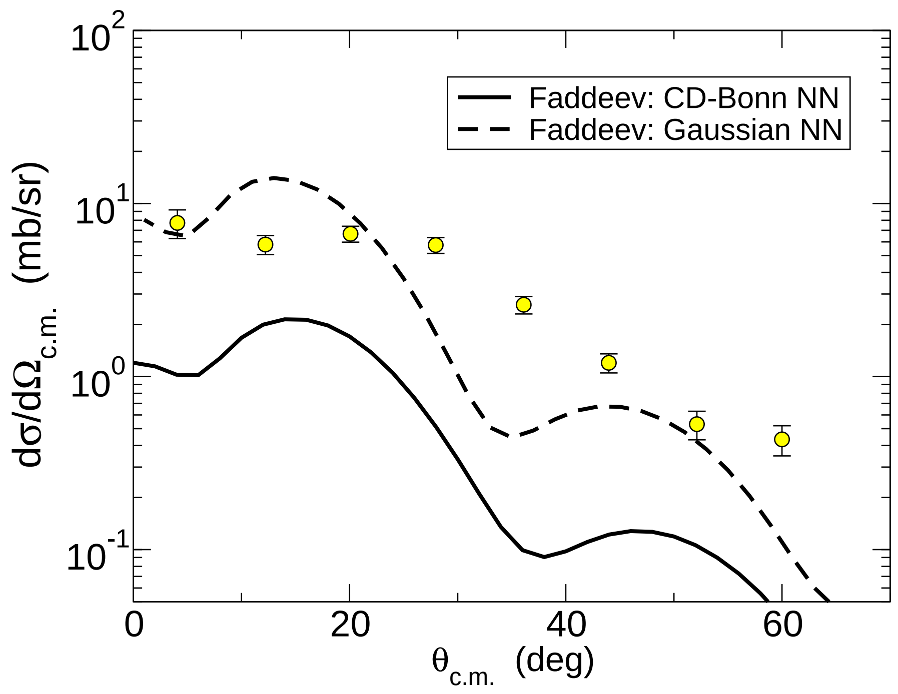
✔ Faddeev and CDCC provide fully consistent results

✘ The calculations reproduce the magnitude, but NOT the shape.

- Pair interactions?
- Structure model?

Effect of the p-n interaction

Replace simple p-n central interaction by the more realistic CD-Bonn:



Effect of the p-n interaction

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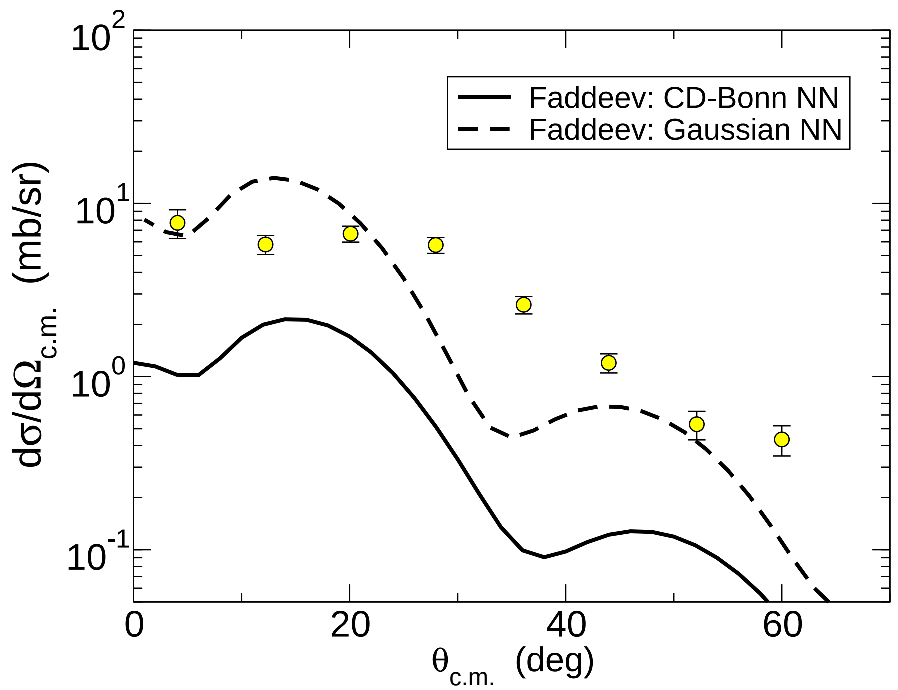


☞ *The inelastic cross section is extremely sensitive to the choice of the NN interaction.*

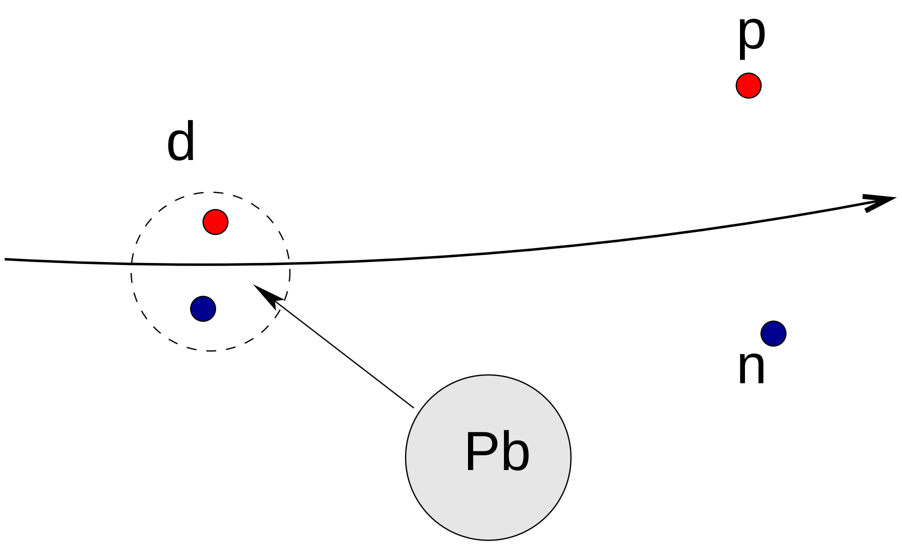
☞ *A simple single-particle excitation mechanism cannot explain the data!*

☞ *We need to go beyond the frozen core approximation* ⇒ *core excitation.*

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

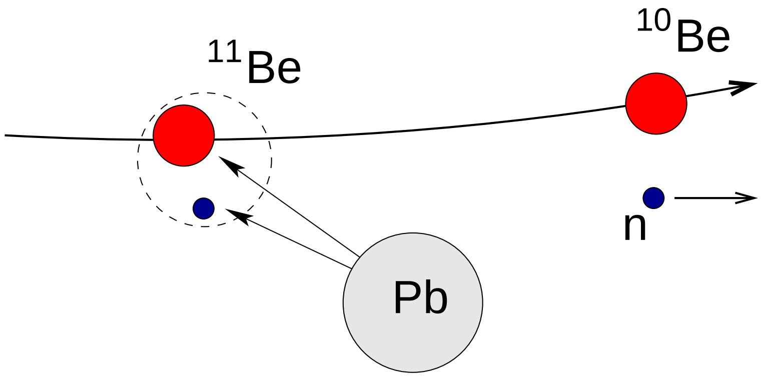
(work done with R. Crespo and R. C. Johnson)

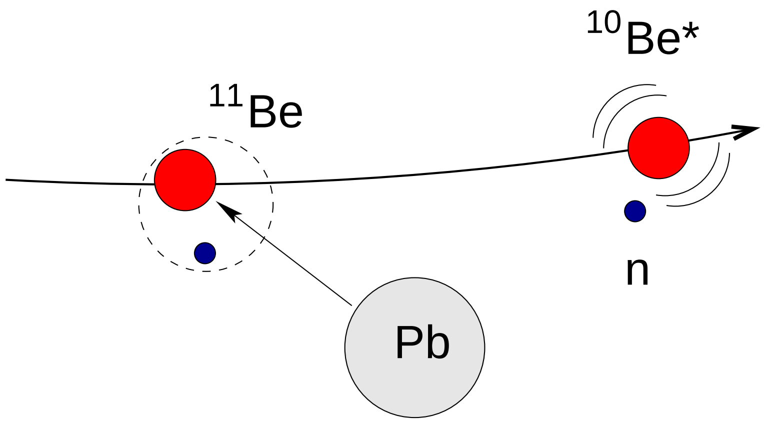
Deuteron scattering:



☞ If the target is inert, purely three-body scattering.

^{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 (*$^{11}\mathrm{Be}$, $^{17}\mathrm{C}$*)*

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

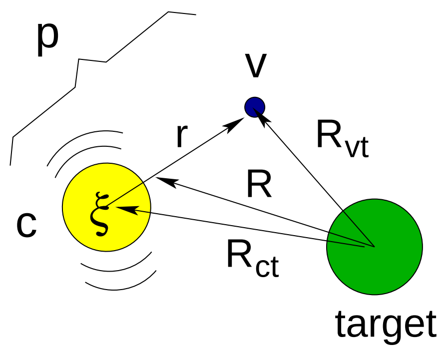
$^{19}\mathrm{C}(5/2^+_2)$ resonance

Core state	$1d_{5/2}$	$1d_{3/2}$	$2s_{1/2}$
0^+_1	0.035	–	–
2^+_1	0.29	0.0087	0.61
$(\ldots)$	$(\ldots)$	$(\ldots)$	$(\ldots)$

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

A DWBA model for core excitation in inelastic and breakup

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



- DWBA amplitude with core excitation:

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

- Transition operator:

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

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

- $\Psi_{JM}(\vec{r},\vec{\xi})$ = projectile states $\Rightarrow$ static core excitation.

Structure part: rotor model for the ^{19}C nucleus

- ^{18}C+n states calculated in a particle-rotor model:

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

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

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

- 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).

Scattering amplitude

- Multipole expansion for the core-target potential

$$V_{ct}(\vec{R}_{ct},\vec{\xi}) \simeq \underbrace{V_{ct}^{(0)}(R_{ct})}_{\text{Valence excitation}} + \underbrace{\sum_{\lambda>0,\mu} V_{ct}^{(\lambda)}(R_{ct}) Y_{\lambda\mu}(\hat{r}_{ct}) Y^{*}_{\lambda\mu}(\hat{\xi})}_{\text{Core excitation}}$$

- Replacing the $V_{ct}(\vec{R}_{ct},\vec{\xi})$ expansion in the scattering amplitude:

$$\boxed{T^{if} = T^{if}_{(\mathrm{val})} + T^{if}_{(\mathrm{corex})}}$$

- *Valence* excitation amplitude:

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

Evaluation of the core contribution (no-recoil)

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

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

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

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

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

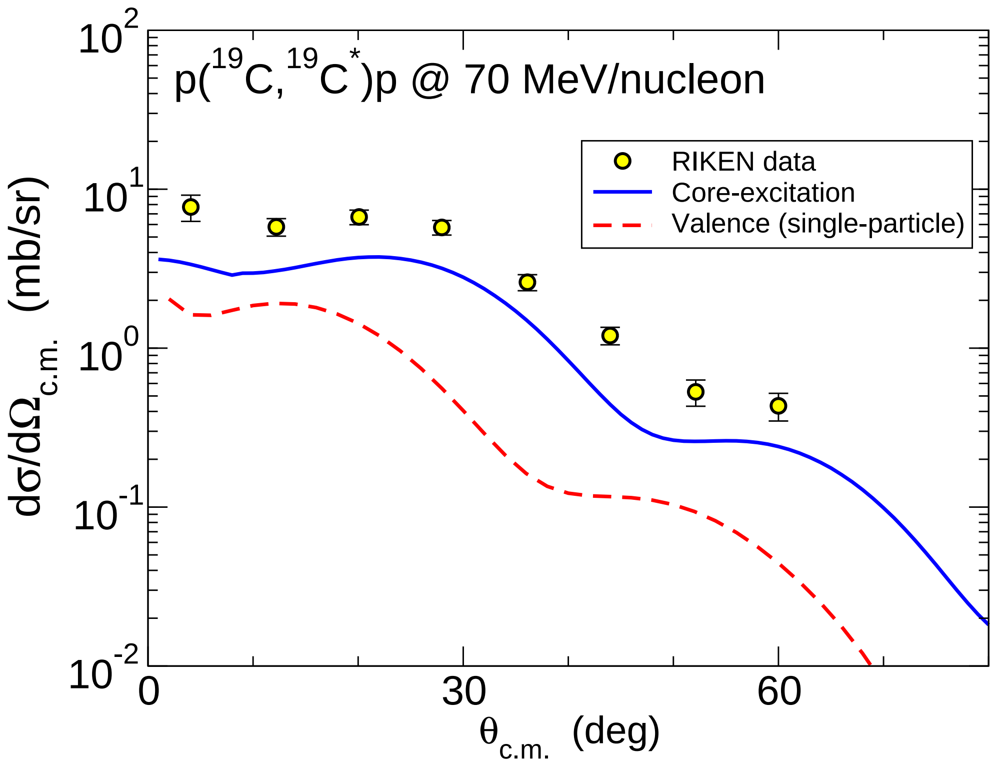
Application to ^{19}C+p $\rightarrow$ ^{18}C +n +p

- ^{18}C treated in a rotor model with $\beta = 0.5$
- Core states restricted to $I = 0^+, 2^+$

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%	$\ll$

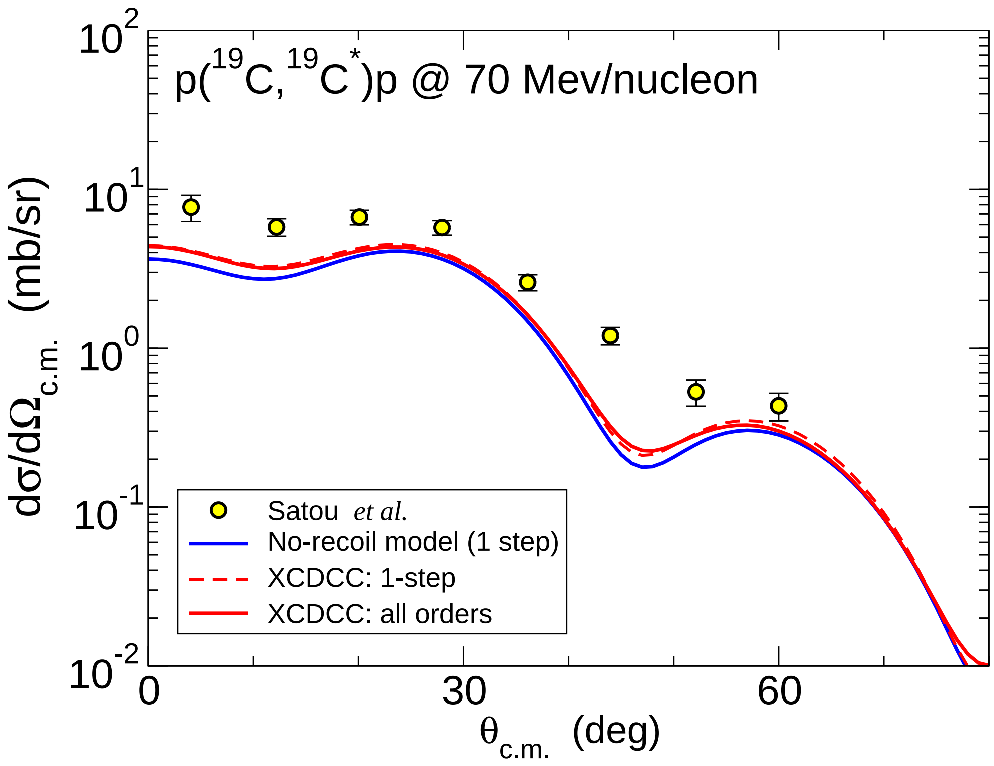
- ^{18}C+n and ^{18}C+p described with deformed potentials with $\beta_2 = 0.5$.

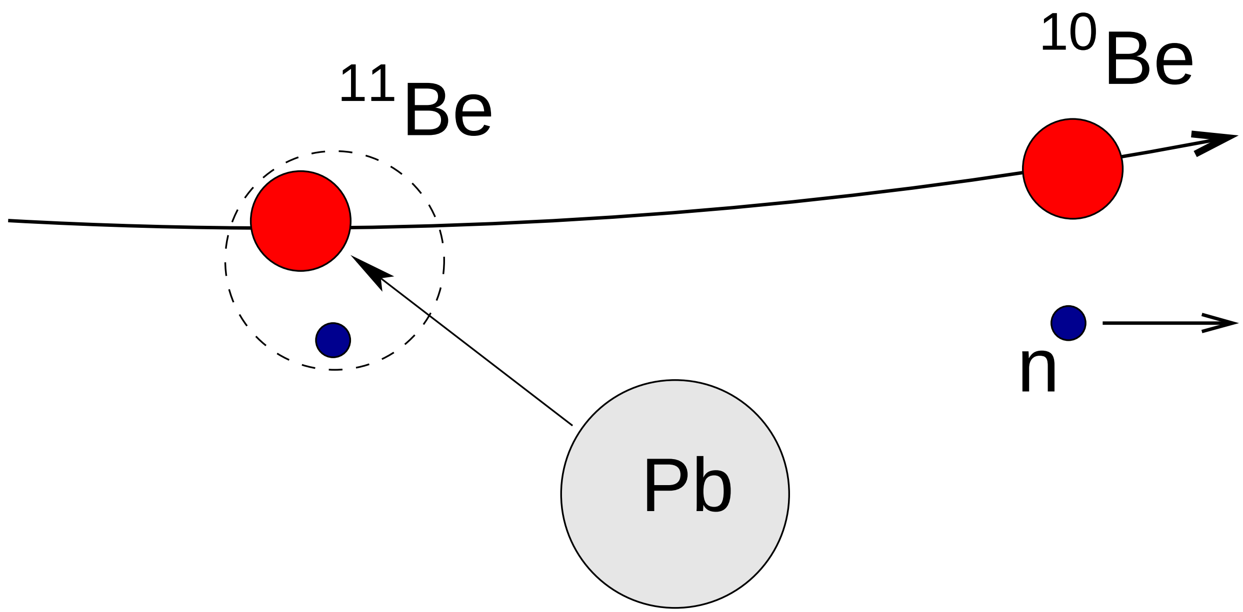
Application to ^{19}C+p $\to$ ^{18}C +n +p



- *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.*

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




11Be
10Be
n
Pb

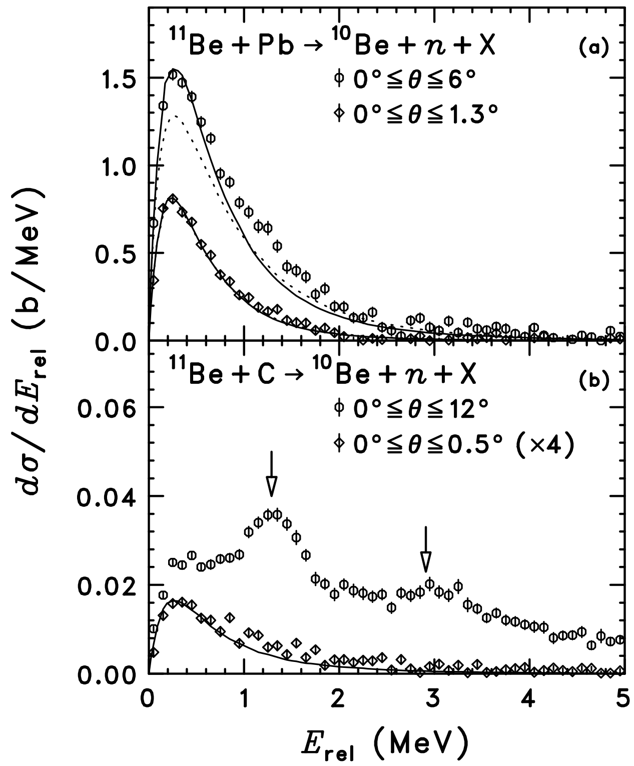
Core excitation in $^{11}\mathrm{Be}$ *scattering*

☞ $^{11}\mathrm{Be}$ states are known to contain significant admixtures of core-excited components.

	S($0^+ \otimes$ 2s)	S($2^+ \otimes$ 1d)
Analysis of ^{10}Be(d,p)^{11}Be [1]	0.44	-
Shell-model (Warburton & Brown [2])	0.74	0.19
Vibrational coupling (Vinh-Mau [3])	0.80	0.20
GCM (Descouvemont [4])	0.92	0.07
Coulomb breakup [5]	0.72	0.28

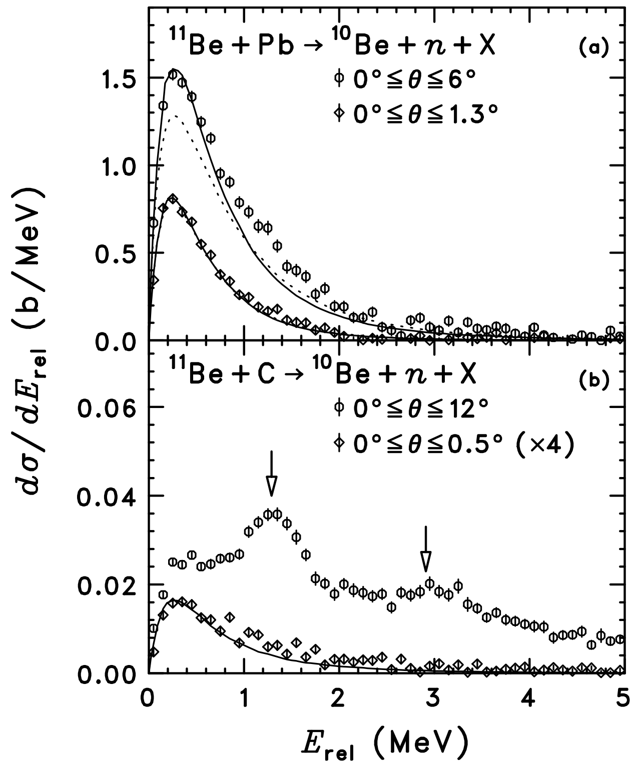
1. N.K. Timofeyuk and R.C. Johnson, Phys.Rev. C59 (1999)1545.
2. E.K. Warburton and B.A. Brown, Phys. Rev. C 46 (1992) 923.
3. N. Vinh Mau, Nucl. Phys. A 592 (1995) 33 N. Vinh Mau and J.C. Pacheco, Nucl. Phys. A 607 (1996) 163.
4. P. Descouvemont, Nucl. Phys. A 615 (1997) 261
5. Fukuda et al, PR C70 (2004) , 054606.

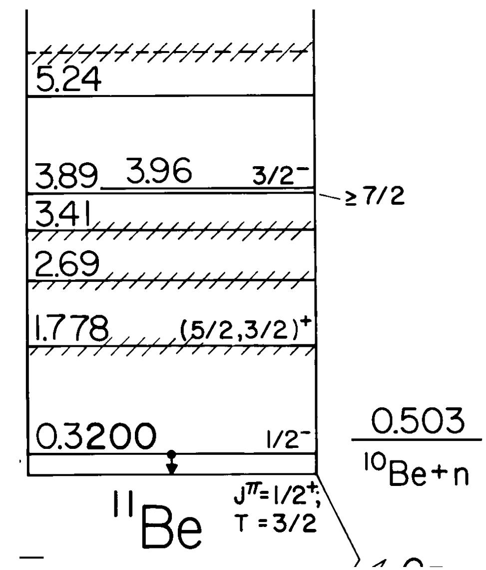
Application to ^{11}Be+^{12}C



Fukuda et al, Phys. Rev. C70 (2004) 054606)

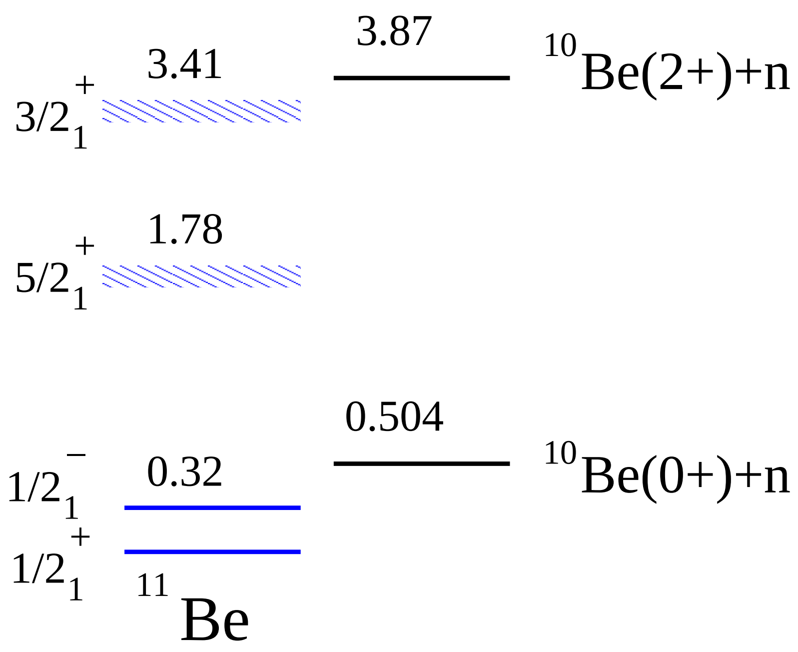
Application to ^{11}Be+^{12}C



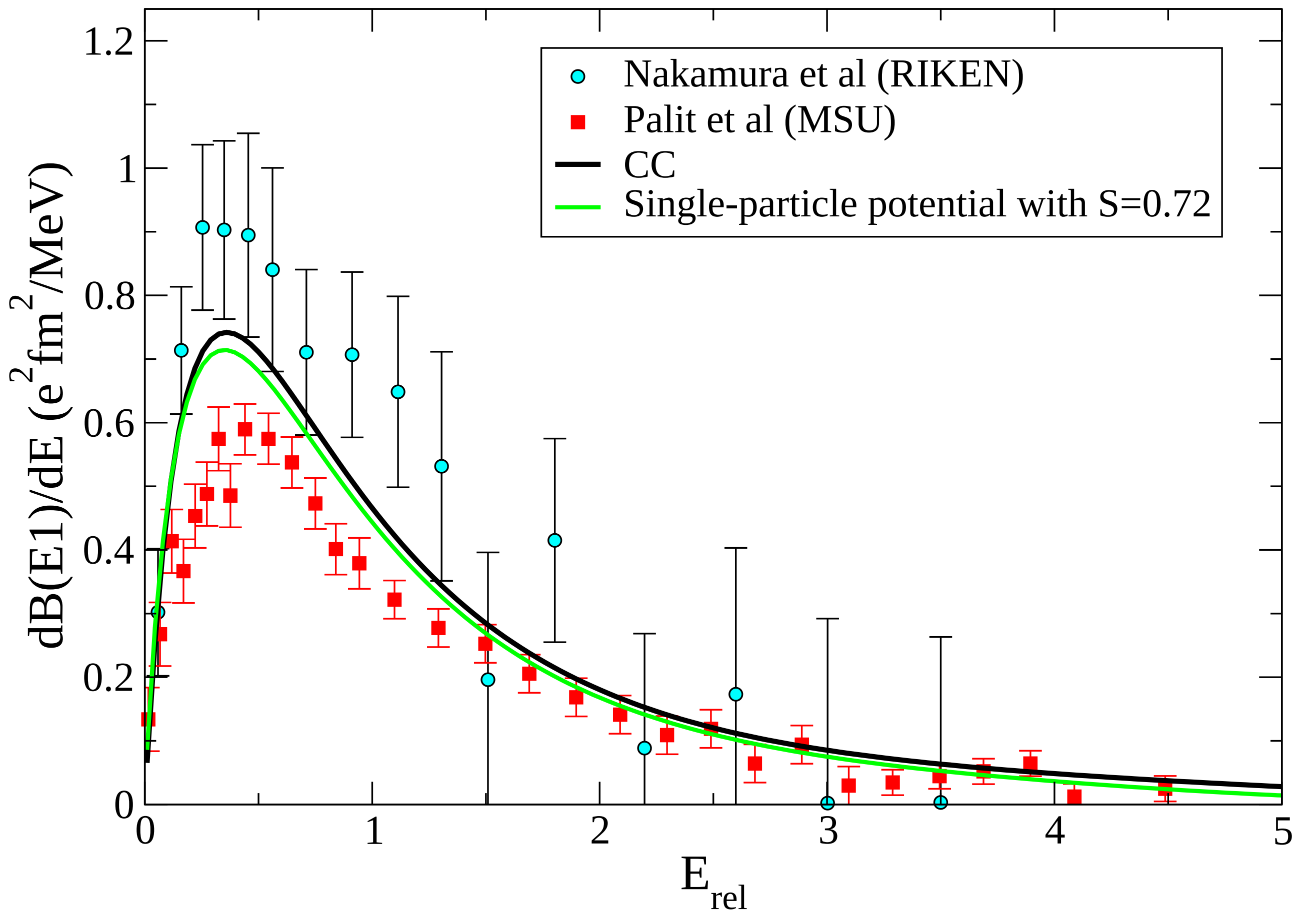


Fukuda et al, Phys. Rev. C70 (2004) 054606)

- Particle-rotor model of Nunes et al, NPA596 (1996) 171 ($\beta_2 = 0.67$).
- Only $^{10}\mathrm{Be}$ gs (0^+) and 1st excited state (2^+).
- Orbital angular momenta of the neutron restricted to $\ell \leq 2$.
- Reproduces $1/2^+$, $1/2^-$ bound states and $5/2^+$, $3/2^+$ resonances.



$B(E1)$ ***response of*** $^{11}\mathrm{Be}$



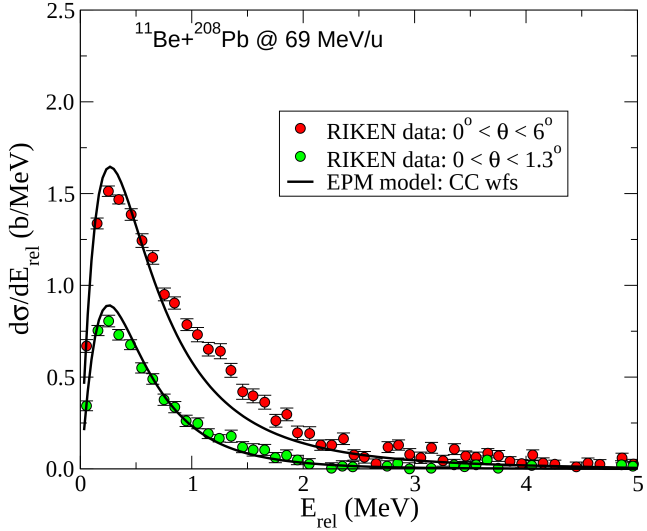
Nakamura et al, NPA588 (1995) 81c (inclusive in ^{10}Be state)
Palit et al, PRC 68 (2003) 034318 (^{10}Be(g.s.) only)

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

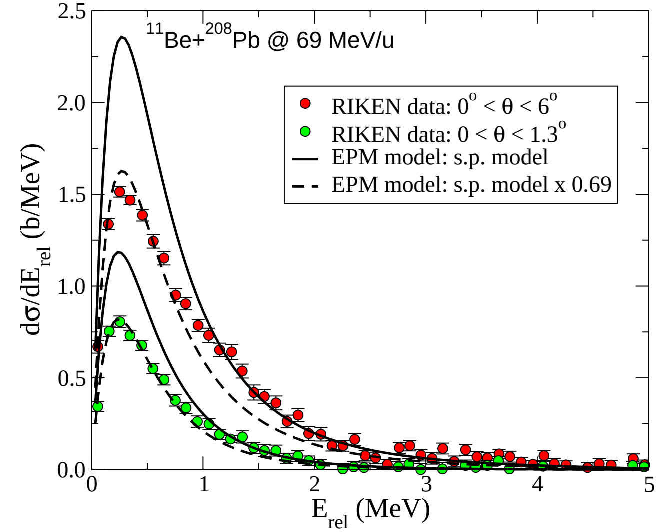
$$\boxed{\frac{d\sigma^2}{d\Omega dE_{\mathrm{rel}}} = \frac{16\pi^3}{9\hbar c}\frac{dN_{\mathrm{E1}}(\theta, E_{\mathrm{x}})}{d\Omega}\frac{dB(\mathrm{E1})}{dE_{\mathrm{rel}}},}$$ (EPM)

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

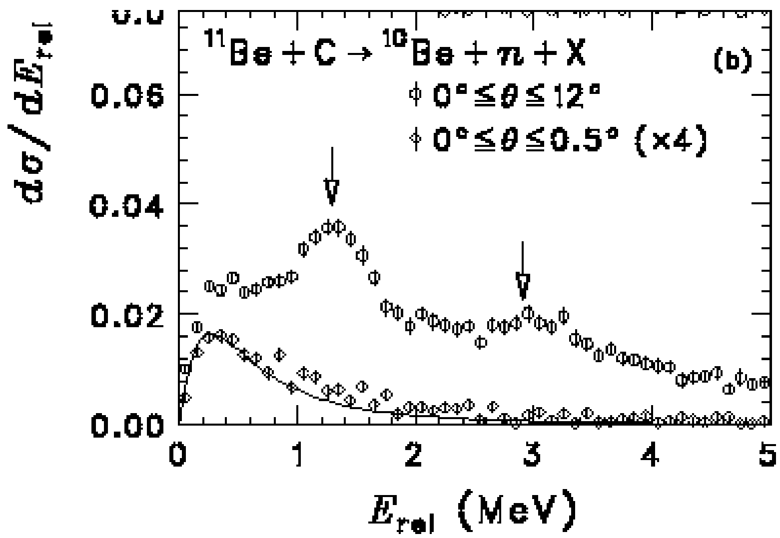
Deformed core model.

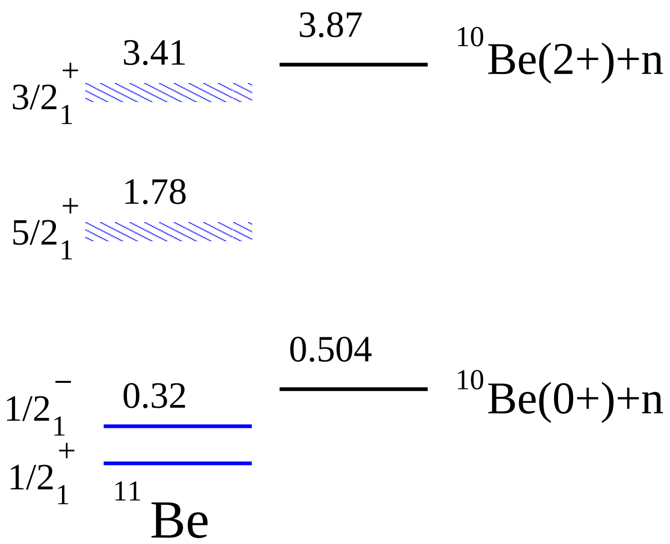


Single-particle model



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

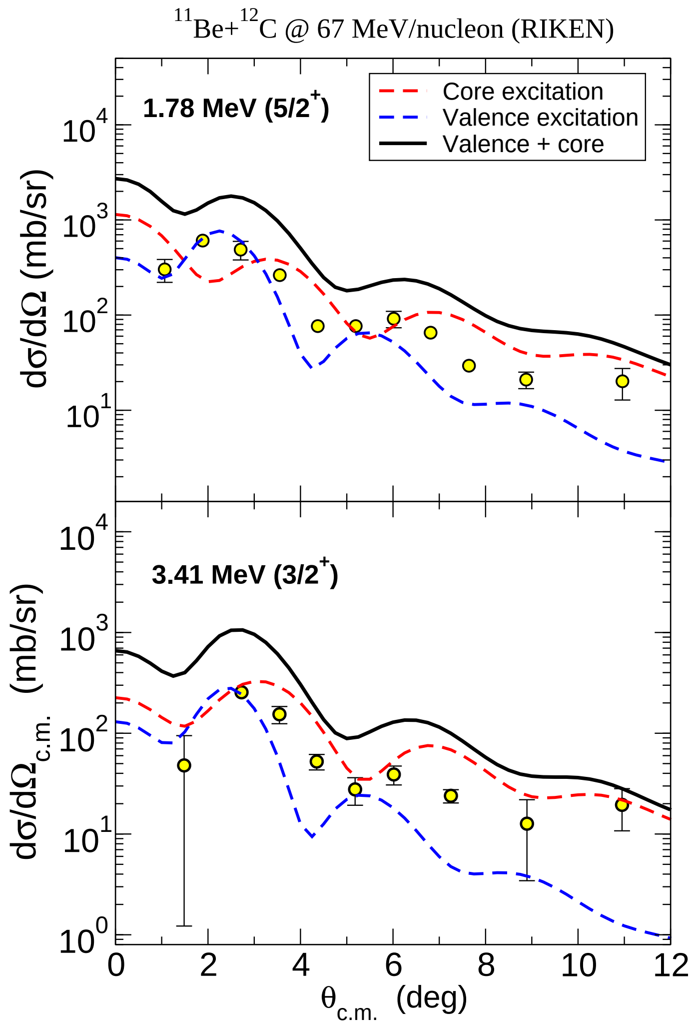




- Nuclear effects dominant (EPM model not valid!)
- At these energies the DWBA approximation should be valid, so we use the *core-excitation* model:

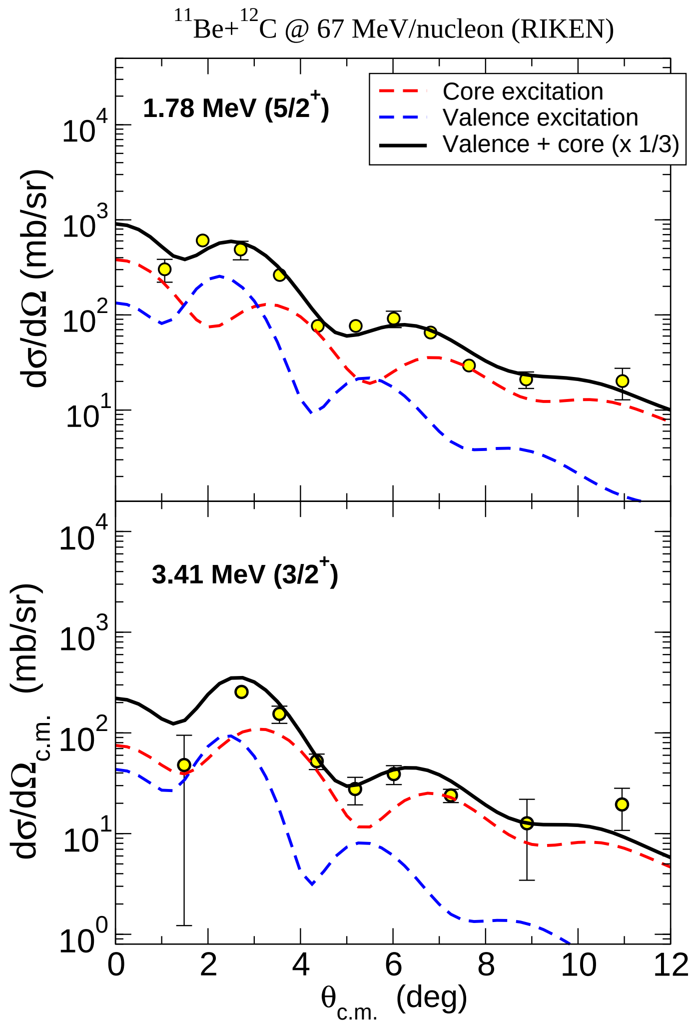
$$\boxed{T_{if} = T_{if}^{(val)} + T_{if}^{(corex)}}$$

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



- Neither the valence or core excitation describe the shape of the data
- Coherent superposition valence+core describes very well the shape.
- Magnitude overestimated by a factor of ~ 3!

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



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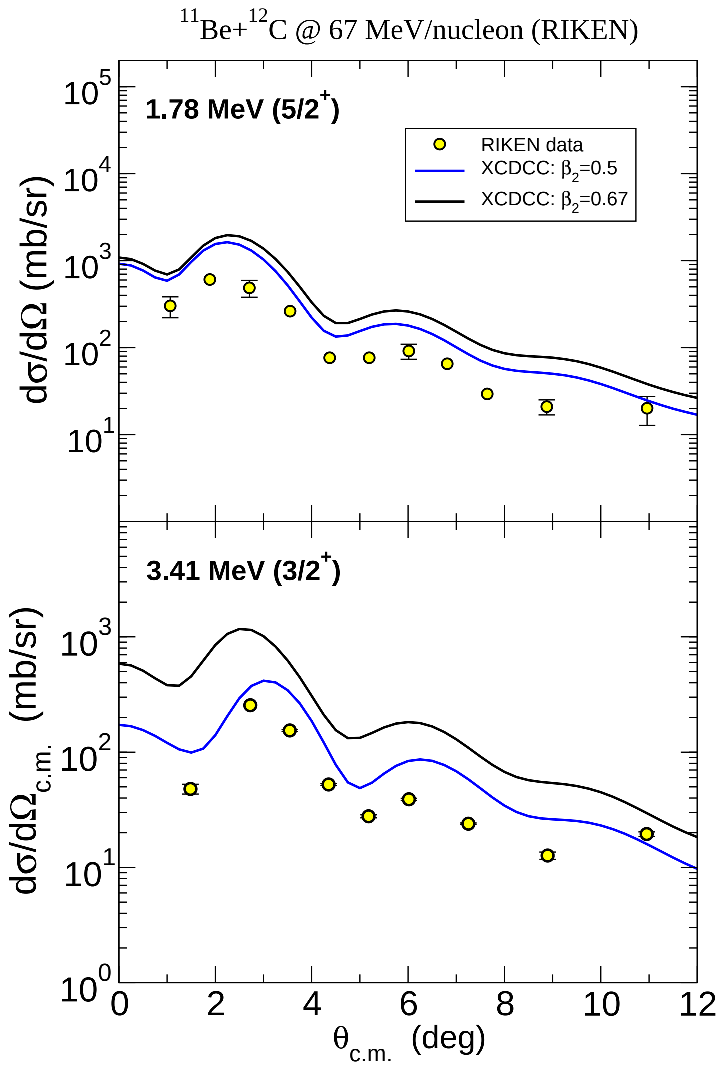
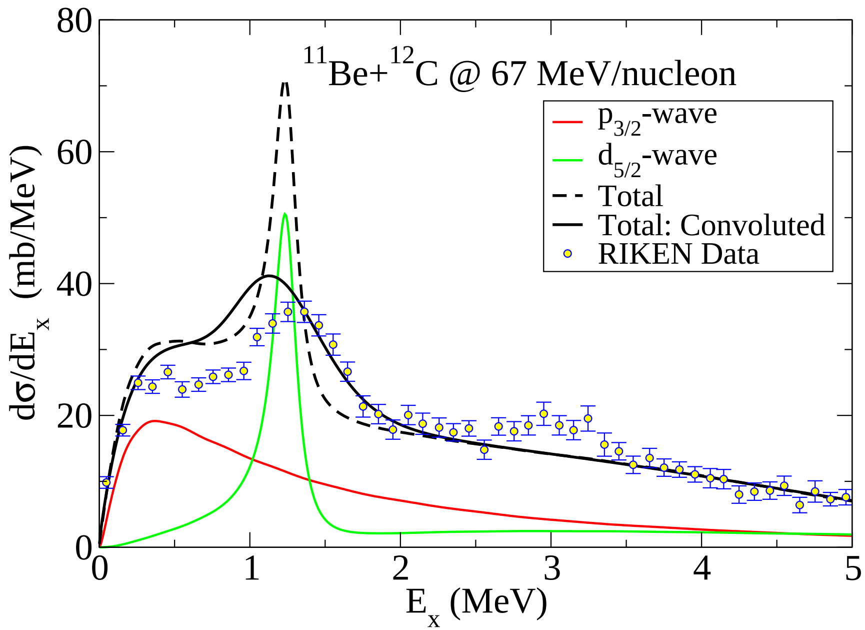
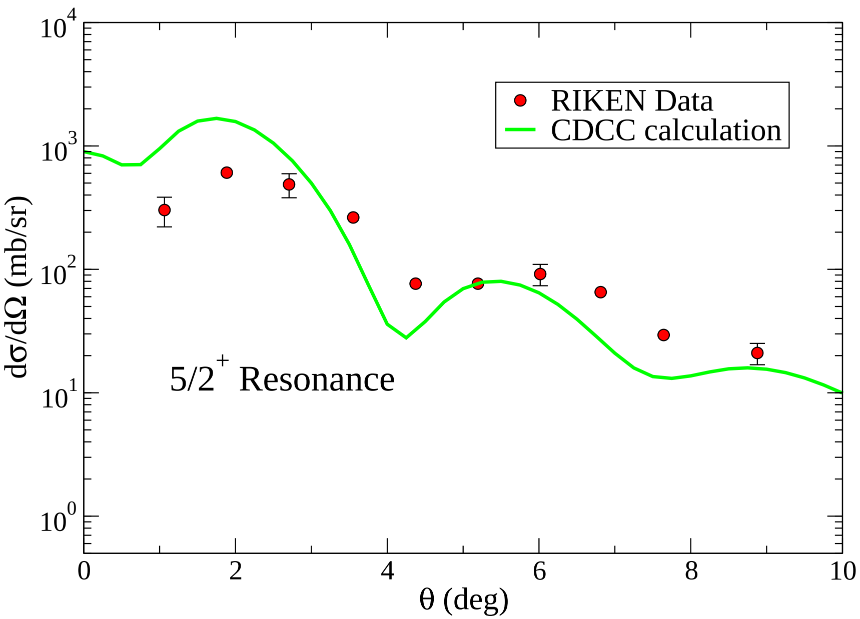
Application to $^{11}\mathrm{Be} + ^{12}\mathrm{C}$

The calculations are found to depend strongly on the deformation parameter:



Calculations without core excitation $^{11}\mathrm{Be} + ^{12}\mathrm{C}$





Conclusions

- For elastic and exclusive breakup observables, the CDCC method has proven to be an accurate approximation to the “exact” (Faddeev) solution.
- 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.
- CDCC calculations are often based on the frozen core approximation, but in many cases core excitation seems to play a very important role in the resonant breakup of halo nuclei with deformed core. These effects need to be taken into account to extract reliable structure information from these reactions.

Core excitation in structure

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Core Excitations in Nondeformed, Odd-A, Nuclei*

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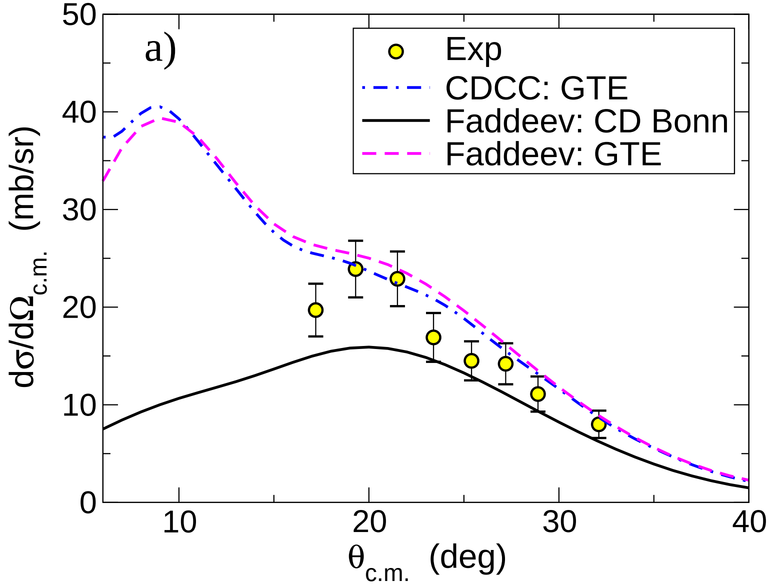
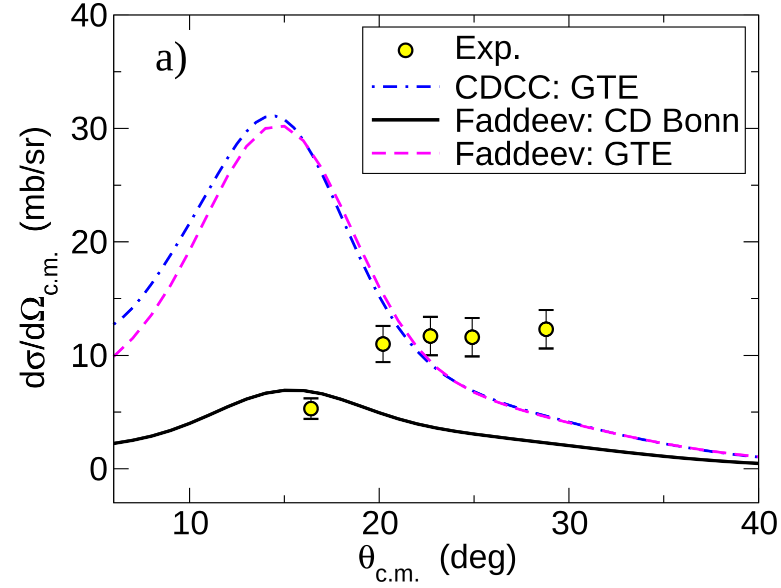
(Received January 16, 1961)

The possibility of describing some excited states of odd-A nuclei in terms of excitations of the even-even core is investigated. No assumption is made on the nature of the core excitation, but certain relations involving electromagnetic transitions and moments are deduced. These seem to fit well some data available on Ag^{107}, Ag^{109}, Au^{197}, Hg^{199}, Tl^{203}, and Tl^{205}. More experimental data are required to test the validity of this picture in other cases.

$$
\begin{aligned}
\langle J_c' j, J_f \| \boldsymbol{\Omega}_c^{(k)} + \boldsymbol{\Omega}_p^{(k)} \| J_c j, J_i \rangle
&= (-1)^{J_c'+j+J_f} [(2J_f+1)(2J_i+1)]^{\frac{1}{2}} \\
&\times \Bigg[\langle J_c' \| \Omega_c^{(k)} \| J_c \rangle \begin{Bmatrix} J_c' & J_f & j \\ J_i & J_c & k \end{Bmatrix} \\
&+ (-1)^{J_i - J_f} \langle j \| \Omega_p^{(k)} \| j \rangle \begin{Bmatrix} j & J_f & J_c \\ J_i & j & k \end{Bmatrix} \delta_{J_c J_c'} \Bigg]. \qquad (7)
\end{aligned}
$$

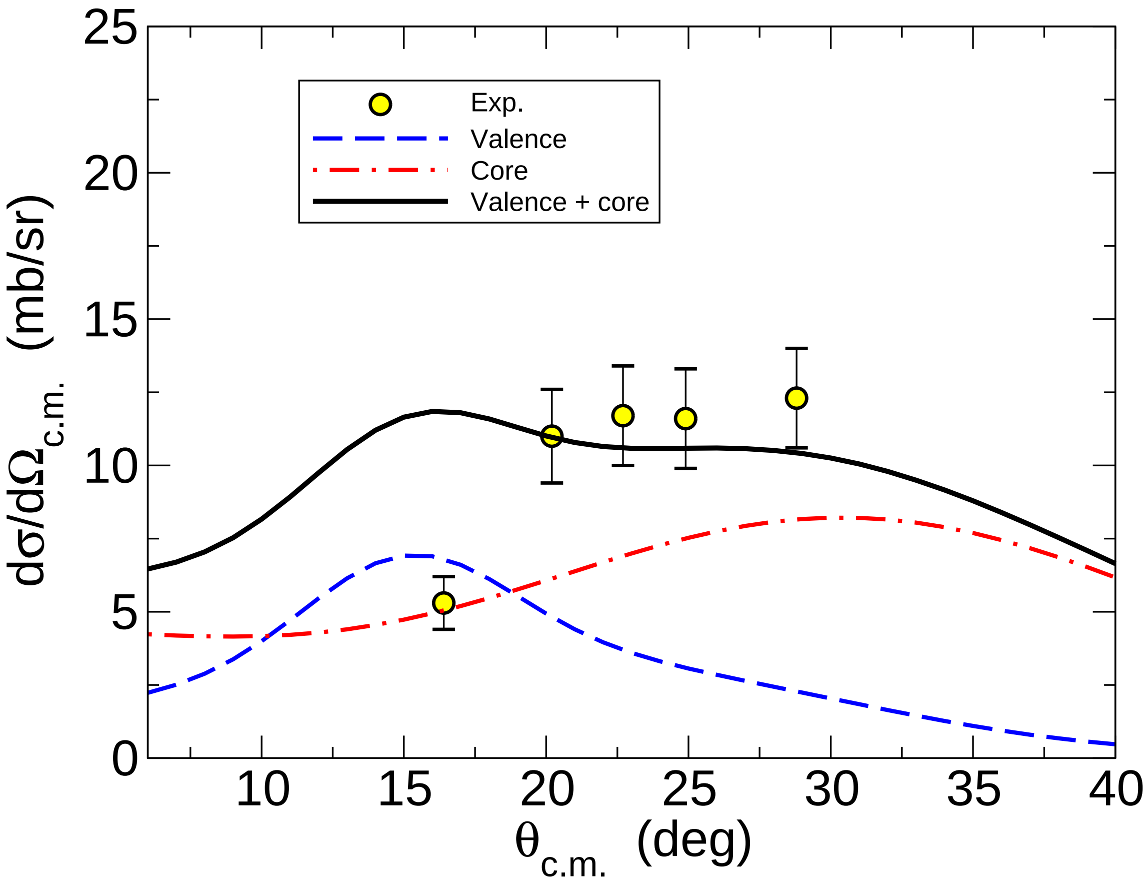
Eg: ^{11}Be +p


a)
Exp
CDCC: GTE
Faddeev: CD Bonn
Faddeev: GTE
dσ/dΩc.m. (mb/sr)
θc.m. (deg)
0
10
20
30
40
50
10
20
30
40


a)
Exp.
CDCC: GTE
Faddeev: CD Bonn
Faddeev: GTE
dσ/dΩc.m. (mb/sr)
θc.m. (deg)
0
10
20
30
40
10
20
30
40

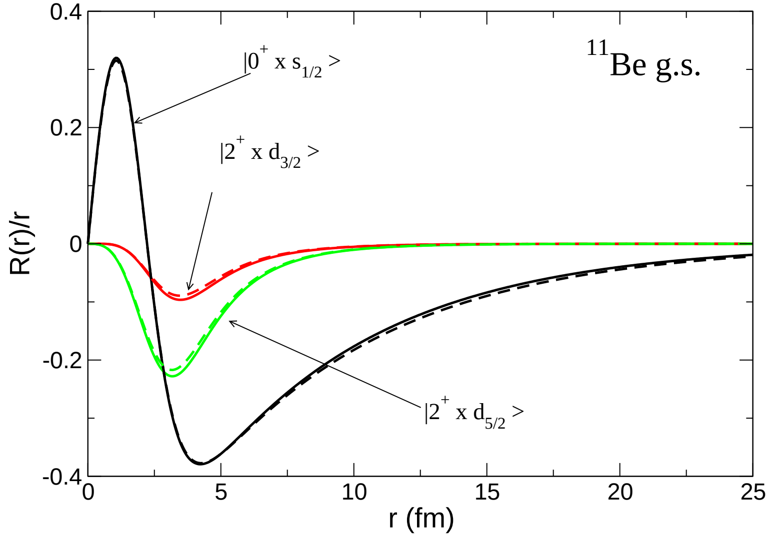
Core excitation in ^{11}Be+p breakup

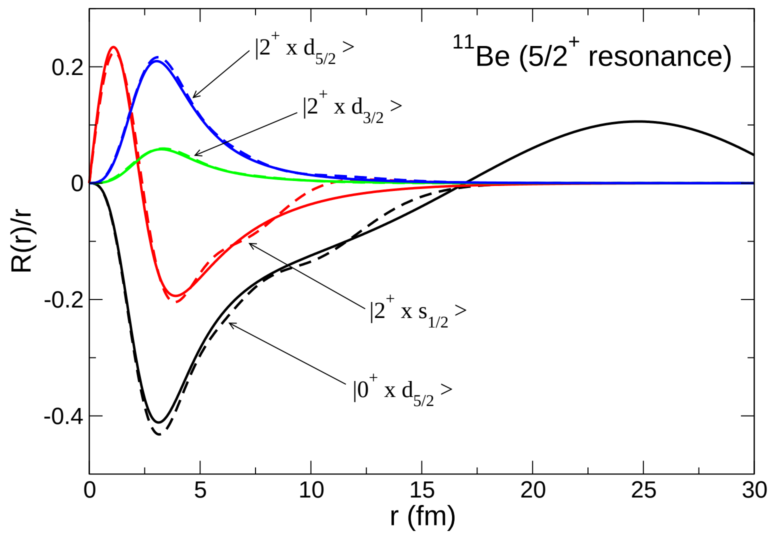
Eg: ^{11}Be +p



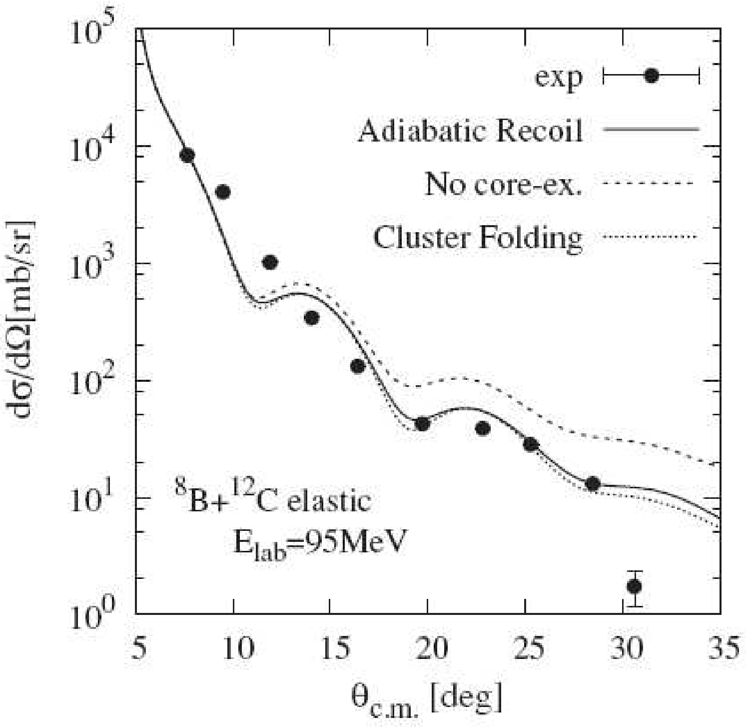
Scattering states vs Pseudostates

Eg: Ground-state and $5/2^+$ resonance in ^{11}Be





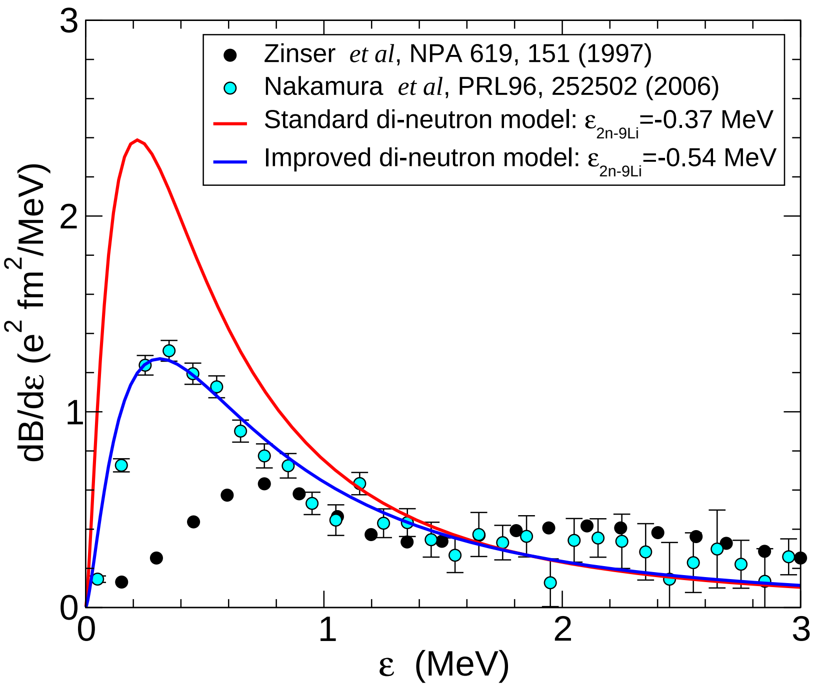
Core excitation in ^{8}B+^{12}C elastic scattering:



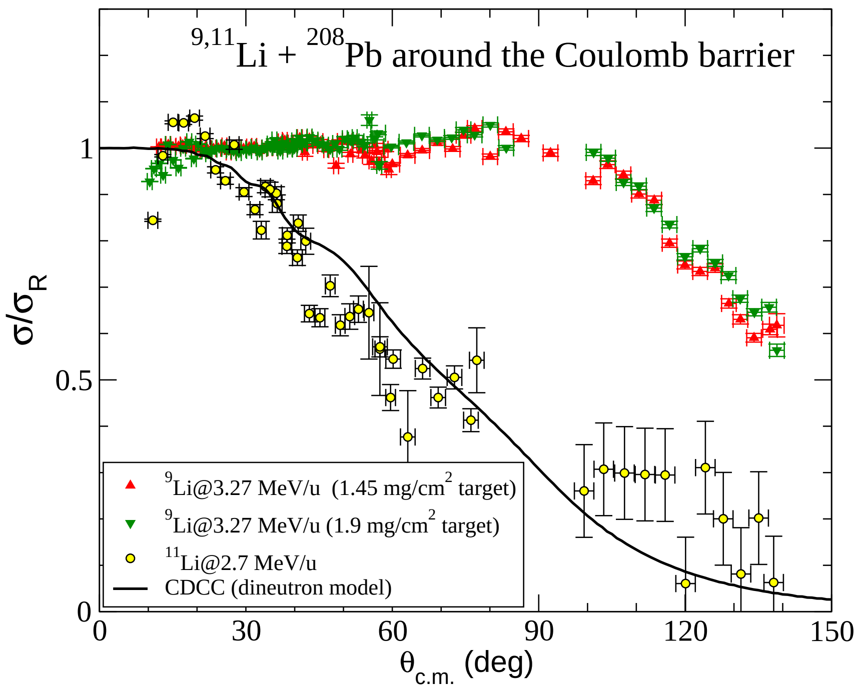
*

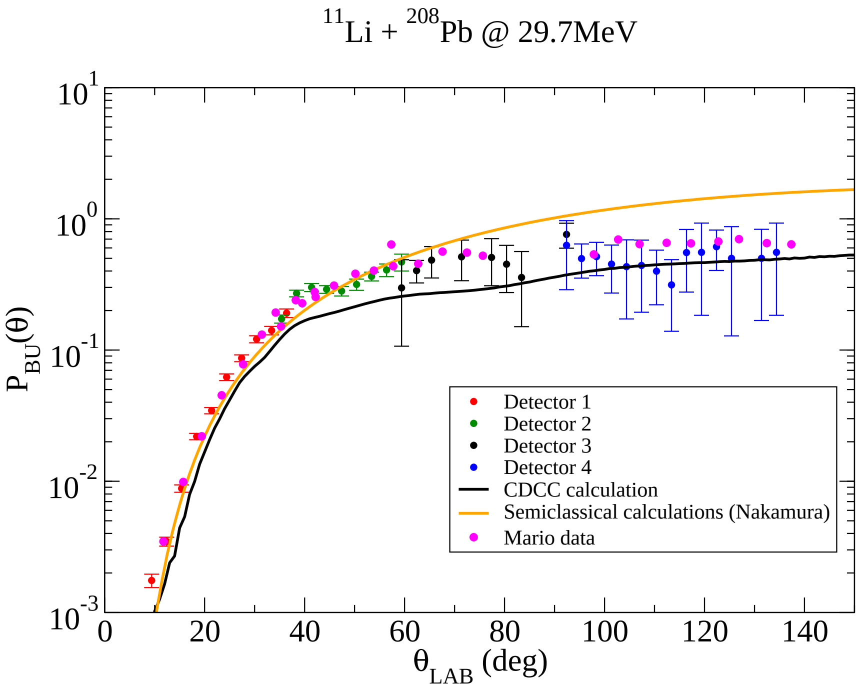
(quoted from *K. Horii* et al, *PRC81 (2010) 061602*)

Extension of three-body projectiles



Extension of three-body projectiles



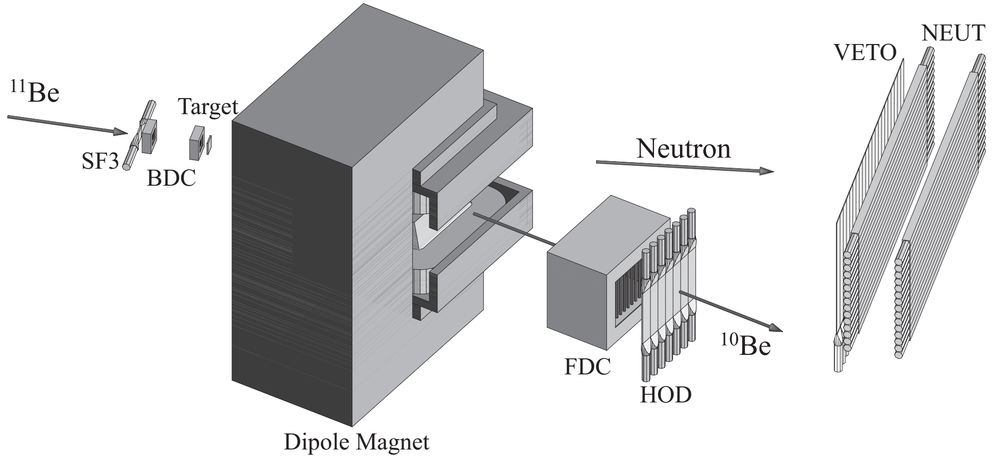


Why is important studying core excitation?

- 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

Why is important studying core excitation?

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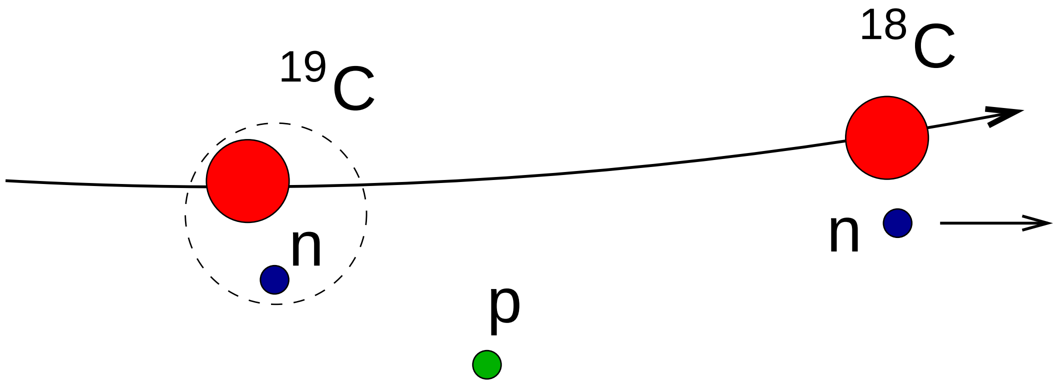
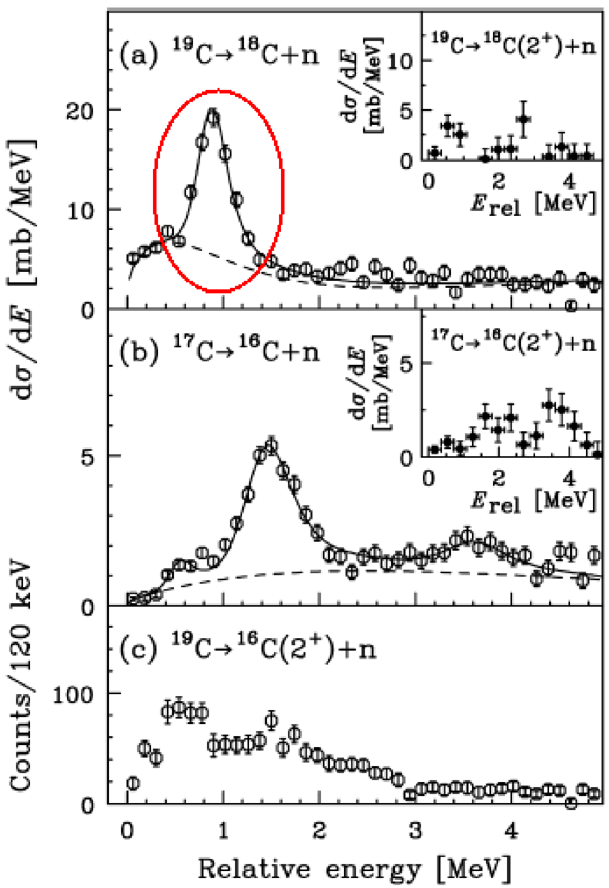
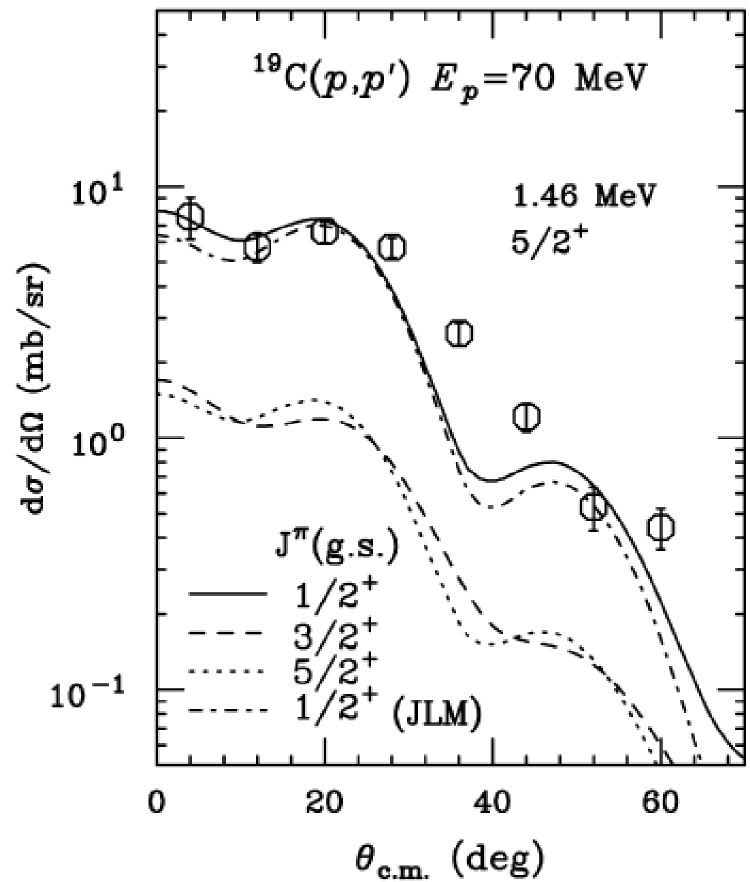
Example: ^{19}C+p at RIKEN (Satou *et el.*, PLB660 (2008) 320



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

Experimental data





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