Nucleon knockout: reaction and structure

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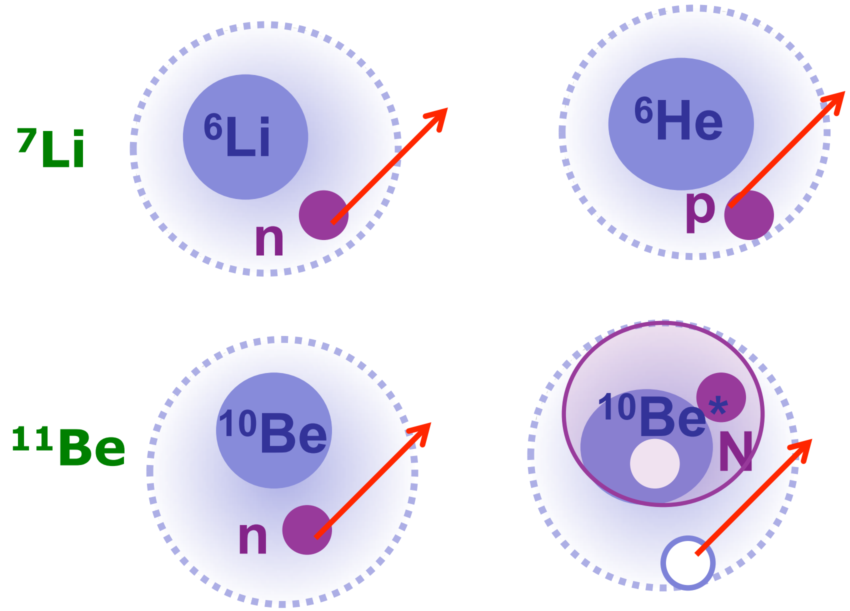
Questions to be adressed:

1) What is the **accuracy** of current standard Fewbody DR approaches **?**

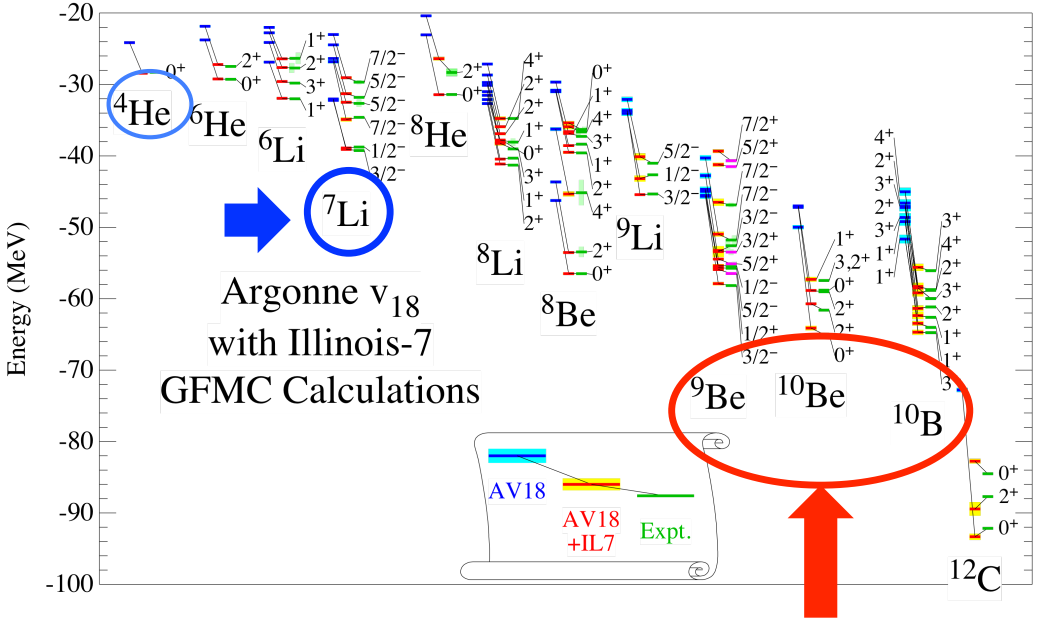
2) What are the role of the **many body degrees of freedom** in the scattering process**?**



Structure break through: *Ab initio* models

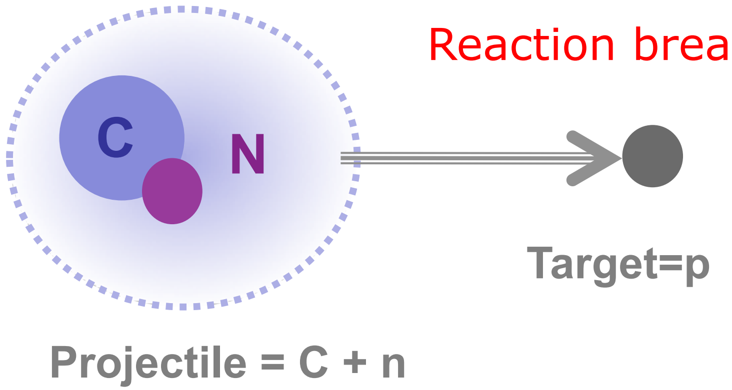
- *O*ffer the unique possibility to get insight on effects beyond truncated model space approches, that might include the role of ***NNN***, ***continuum effects***.

- Ex1: Variational and Green´s function Monte Carlo (VMC, GFMC) techniques (Argonne group: R.B. Wiringa, S.C. Pieper,)



$$H = \sum_i K_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} v_{ijk}$$

- Ex2: NCSM/RGM (S. Quaglioni, P. Navratil, Phys Rev Lett 101, 092501 (2008))



Reaction break through: Exact reaction fewbody frameworks

- Nonrelativistic
- Treats all 3 particles on an equal footing
- *Treats* ***all open channels simultaneously***

- Formulated in terms of the transition amplitude for each interacting pair:

$$t_\gamma = v_\gamma + v_\gamma \; G_0 \; t_\gamma$$

Pair transition operators

$$G_0 = (E + i0 - H_0)^{-1}$$

Free propagator

$$U^{\beta\alpha} = \bar{\delta}_{\beta\alpha} G_0^{-1} + \sum_\gamma \bar{\delta}_{\beta\gamma} t_\gamma G_0 U^{\gamma\alpha}$$

$$\bar{\delta}_{\beta\alpha} = 1 - \delta_{\beta\alpha}$$ integral equations

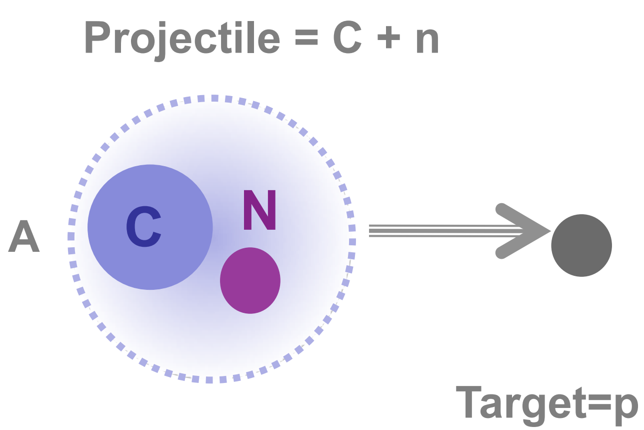
elastic,inelastic,transfer, breakup/knockout

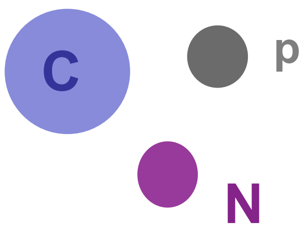
Tool for investigating:

- ✓ Single particle properties
- ✓ Spectroscopic factors

- Note: Spectroscopic factors are not observables: extracted from data *under the assumption of the validity of a reaction theory and a structure model*

Revisiting ***standard*** pair interactions



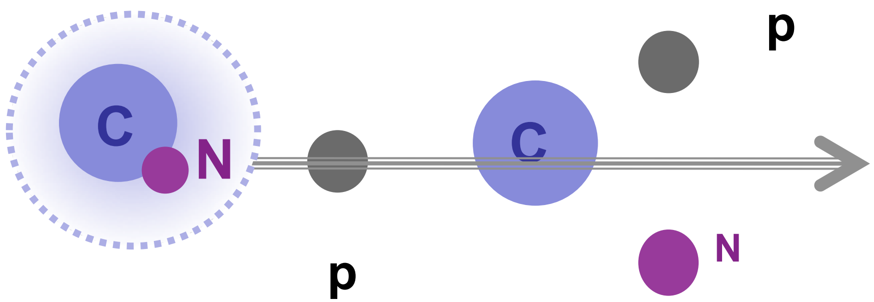


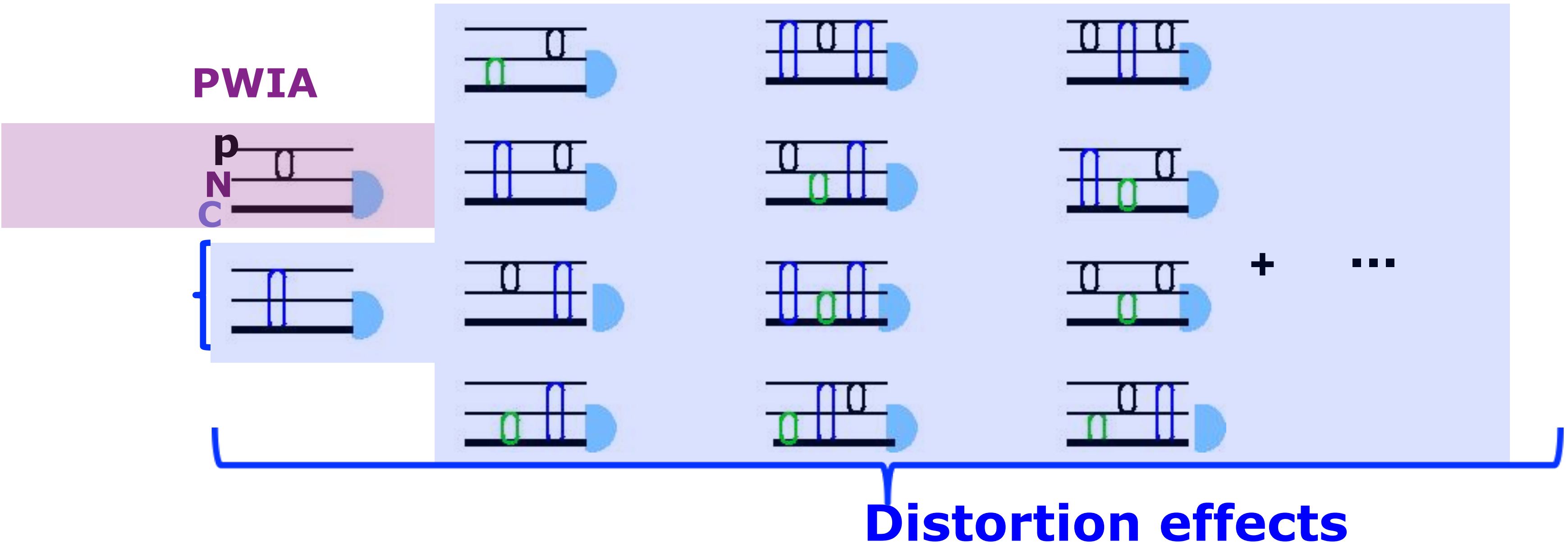
- N-C pair interaction:
  - Bound and scattering states are treated *inconsistently*
  - L-dependent and local interaction for bound and excited states

$$V(r) = -V_c f(r, R_0, a_0) + 4\vec{L}.\vec{S} V_{SO} \frac{1}{r} \frac{d}{dr} f(r, R_{SO}, a_{SO})$$

  - Energy independent optical potential for all other states in the continuum, with very limited validity (example Koning-Delaroche)
  - Properties of the projectile (NC) system taken into account:
    - Separation energies
    - Some low lying states and resonances

- p-C optical potential often unknown

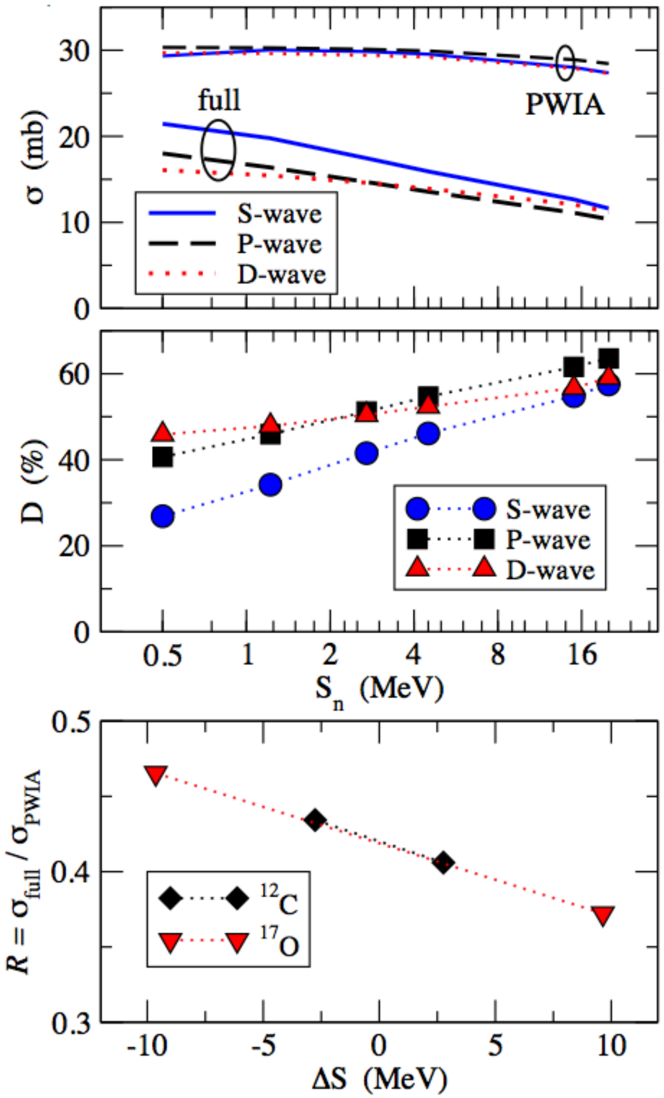




Interplay in acessing **the accuracy of distortion effects**:

Dynamics: accurate treament of terms involving **N-C rescattering contributions**

Structure: requires a good description of the N-C interaction



$$D = \frac{\sigma(pn) - \sigma(full)}{\sigma(pn)}$$

E. Cravo, R. Crespo, A. Deltuva, Distortion effects on the neutron knockout from exotic nuclei in the collision with a proton target, PRC 93, 054612 (2016).

breakup/N-knockout observables

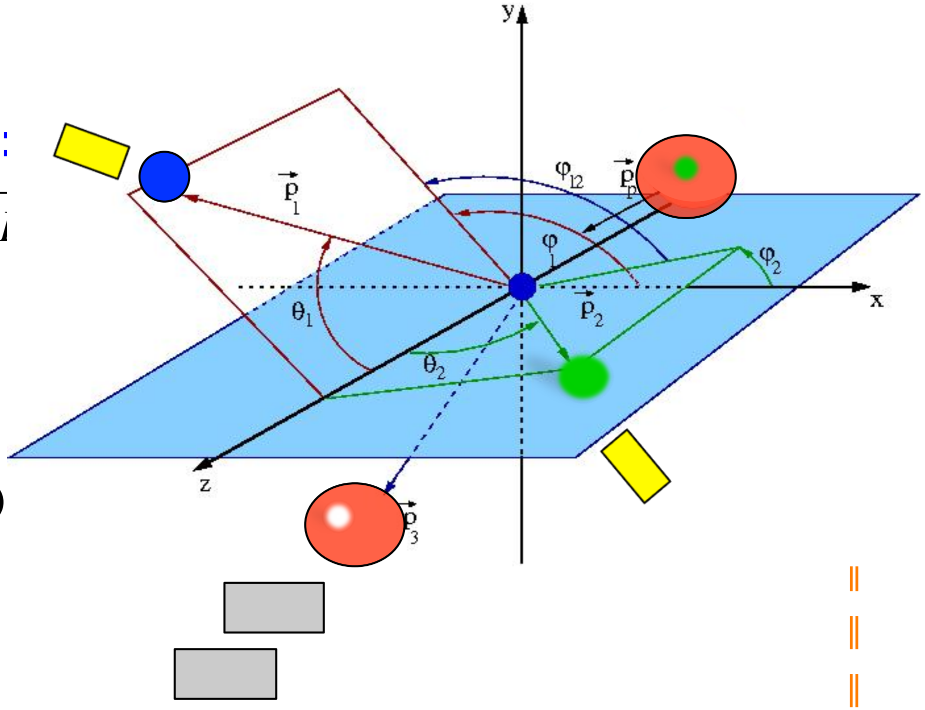
- Kinematically fully exclusive cross sections :

$d^5\sigma/dSd\Omega_Z d\Omega_N (mb/MeV\, sr^2)$ $dS = \sqrt{dE_N^2 + d}$

- Double cross sections: $Z = C$ or p

$d^2\sigma/dE_p d\theta_p$ (mb/MeV rad)

$d^2\sigma/dE_N d\theta_N$ (mb/MeV rad) $d^2\sigma/\theta_p d\theta_N$ (mb/ rad^2)



- Semi-inclusive cross sections:

$d\sigma/d\theta_Z (mb/sr)$ ✧ Angular distributions

$d\sigma/dE_{rel} (mb/MeV)$ ✧ Energy spectrum

$d\sigma/dp_Z^x (mb/MeV/c)$ ✧ Transverse momentum distribution

$d\sigma/dp_Z^z (mb/MeV/c)$ ✧ Longitudinal momentum distribution

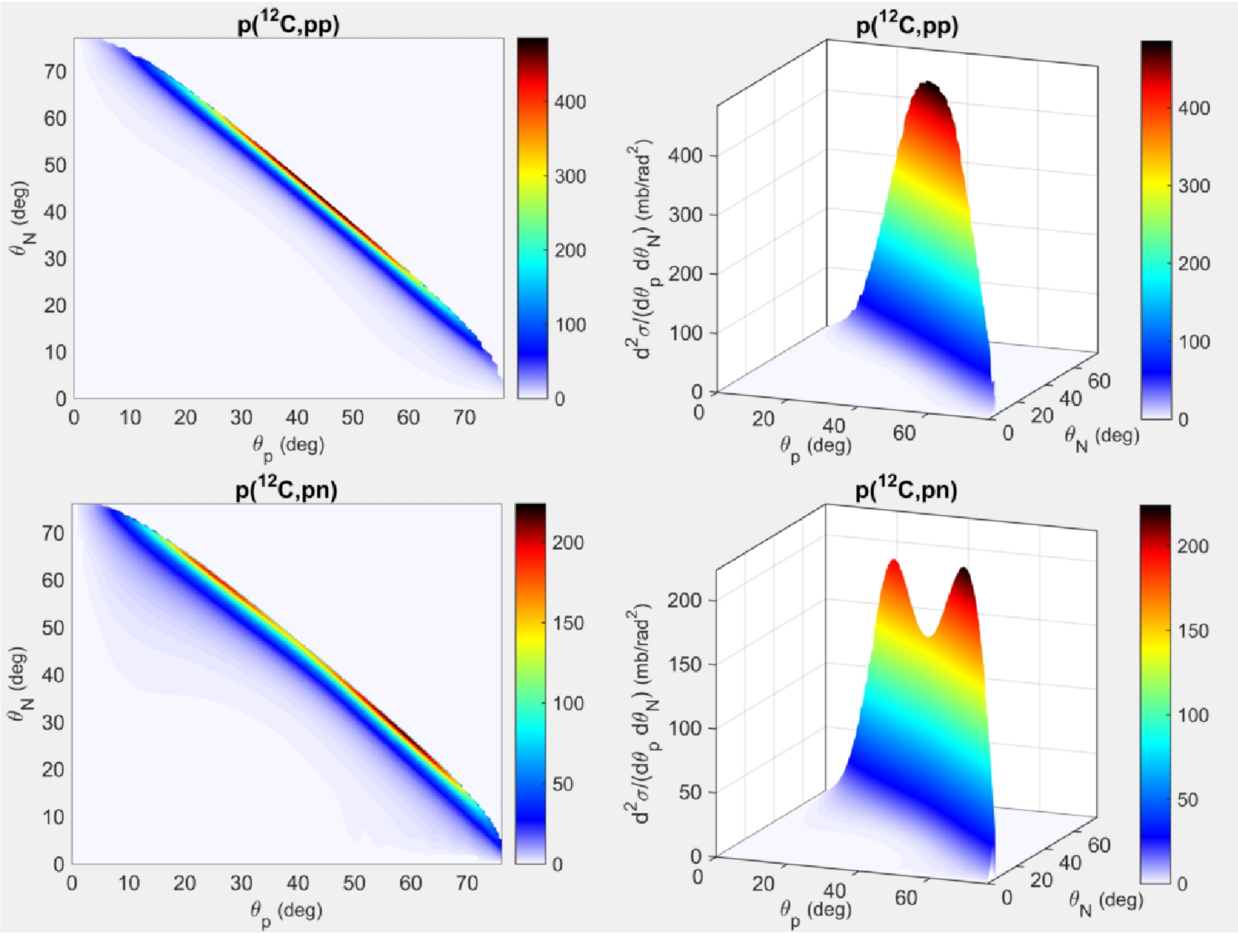
- Inclusive: Total cross sections: σ(PWIA) ; σ(FADD)

Kinematic Integration

Physics information **lost**

Kinematically Semi-inclusive and Inclusive breakup/N-knockout observables @ Current RIB facilities presently

- Double cross sections: $d^2\sigma/\theta_p d\theta_N \,(\text{mb/ rad}^2)$



R. Crespo, E. Cravo, A. Deltuva, A. Deltuva, submitted PRC

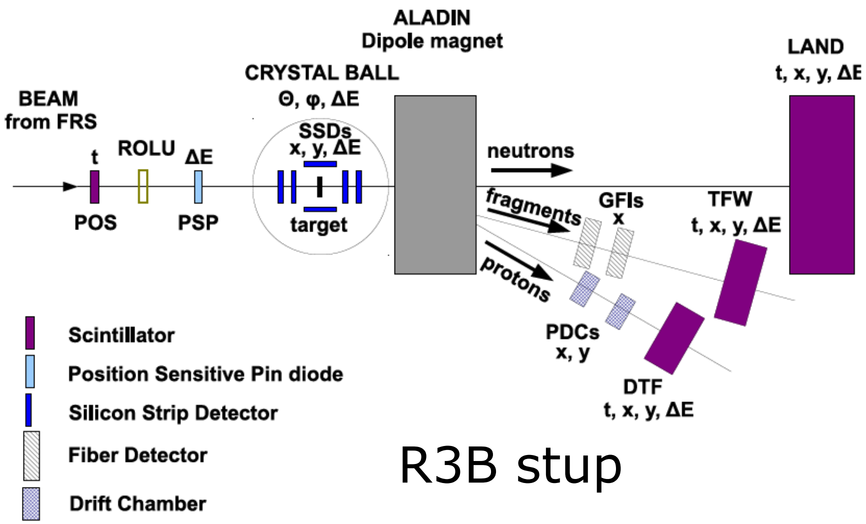
Faddeev/AGS is well suited for studying reaction mechanisms:

Particle fully exclusive (named (p,pN)/QFS): p,N and ^{A-1}X are measured

Particle inclusive (named N-knockout): Only ^{A-1}X is measured

Complementary reaction tools

Need to be investigated simultaneoulsy (theoretically & experimentally)

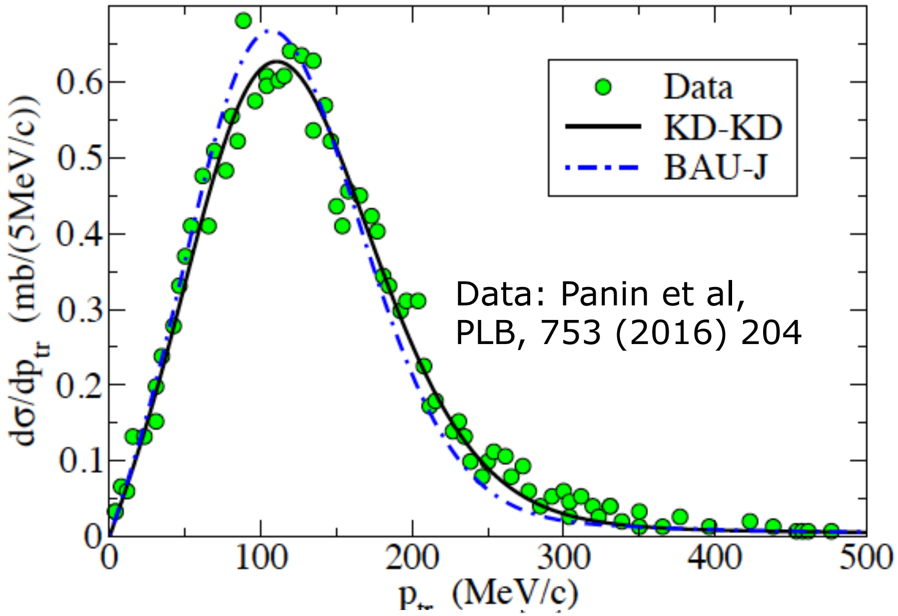


R3B stup

A. Henriques, *Nucleon knockout of ^{11}Be, from the collision with a proton target at high energies* (PhD thesis, Lisboa 2017): **both** particle fully exclusive and particle inclusive were analysed simultaneously.

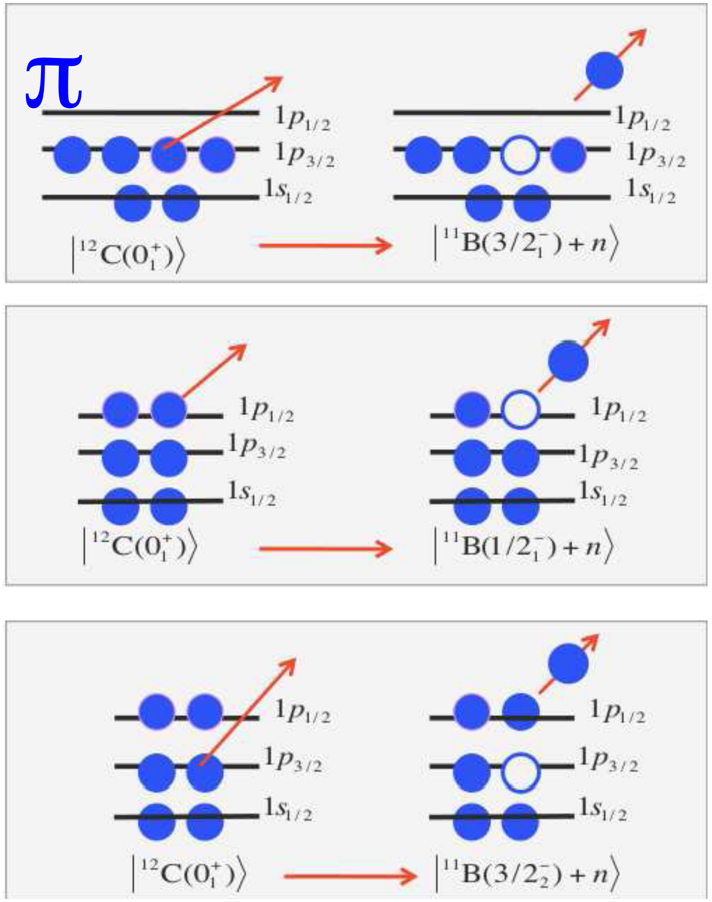
p-knockout form ^{12}C @ 400 MeV/u

$$|^{A}X\rangle = \mathcal{Z}(3/2_1^-)\,|^{A-1}X(3/2_1^-)\otimes 1p_{3/2}\rangle + \mathcal{Z}(3/2_2^-)\,|^{A-1}X(3/2_2^-)\otimes 1p_{3/2}\rangle + \mathcal{Z}(1/2_1^-)\,|^{A-1}X(1/2_1^-)\otimes 1p_{1/2}\rangle$$



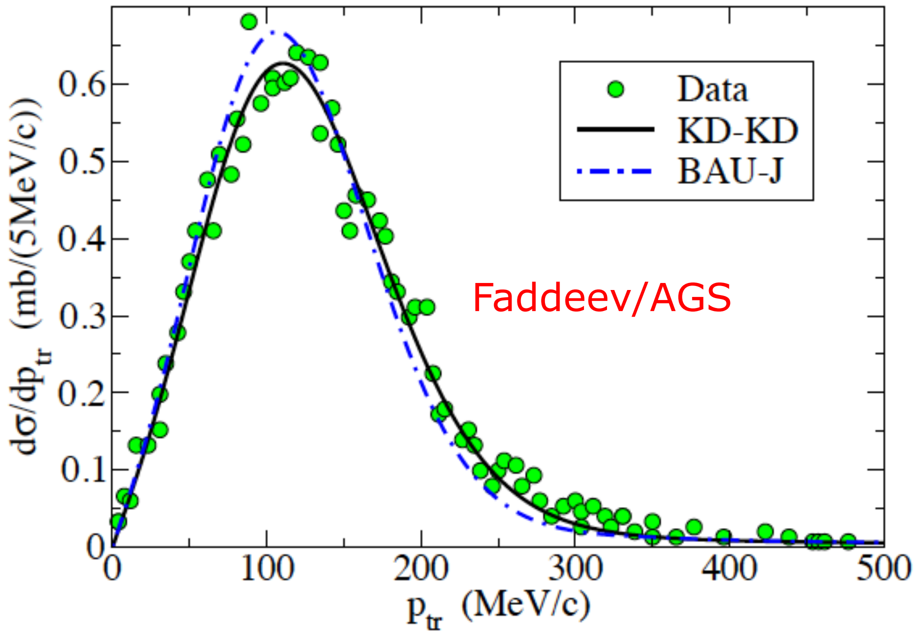
V	I_C^π	nlj	σ_{sp}(mb)	σ_{exp}(mb)	$\mathcal{Z}$
BAU-J	$3/2_1^-$	$1p3/2_1$	6.02	15.18(18)	2.52
	$1/2_1^-$	$1p1/2_1$	5.90	1.92(2)	0.31
	$3/2_2^-$	$1p3/2_1$	5.43	1.5(2)	0.28
					$\Sigma = 3.11$
KD-KD	$3/2_1^-$	$1p3/2_1$	8.54	15.18(18)	1.85
	$1/2_1^-$	$1p1/2_1$	8.50	1.92(2)	0.23
	$3/2_2^-$	$1p3/2_1$	7.90	1.5(2)	0.19
					$\Sigma = 2.27$

R. Crespo, E. Cravo, A. Deltuva, A. Deltuva, submitted PRC

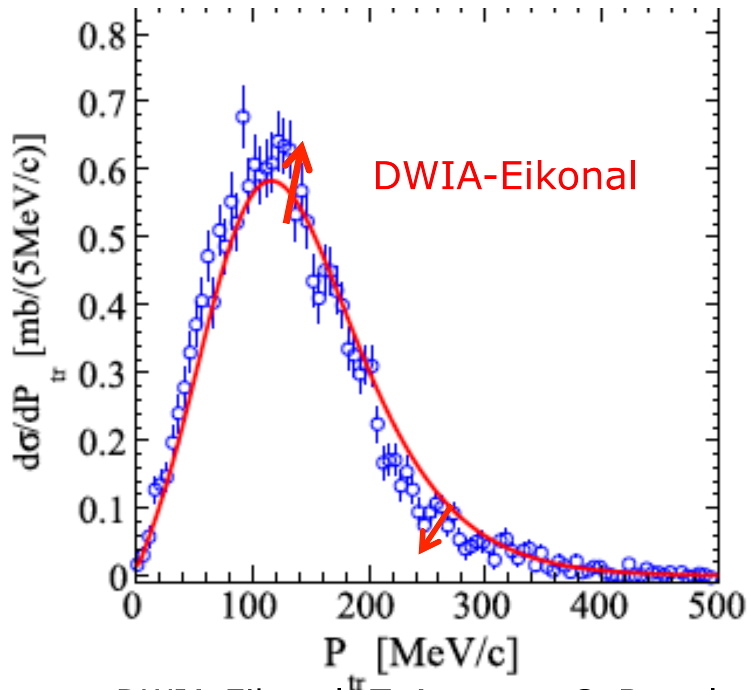


- *Uncertainty N-Core interactions*

p-knockout form ^{12}C @ 400 MeV/u



R. Crespo, E. Cravo, A. Deltuva, submitted PRC

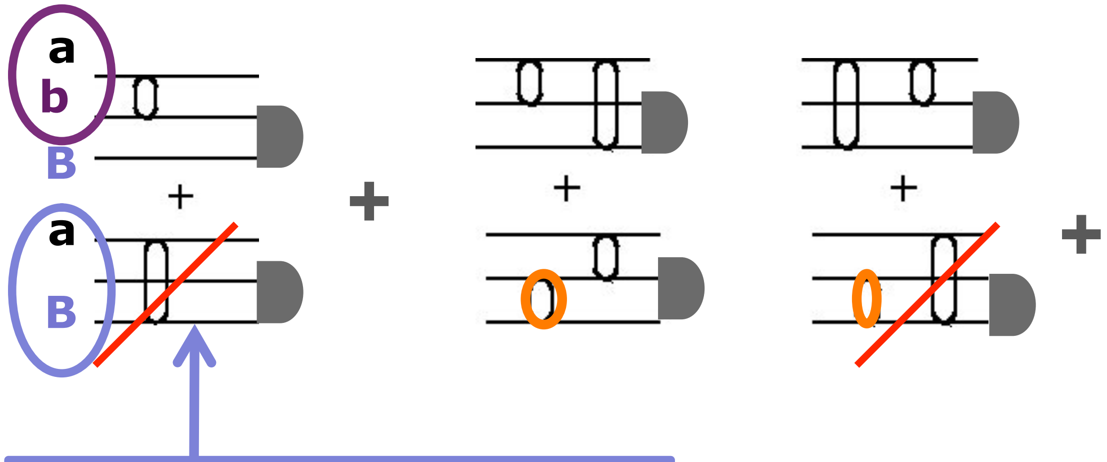


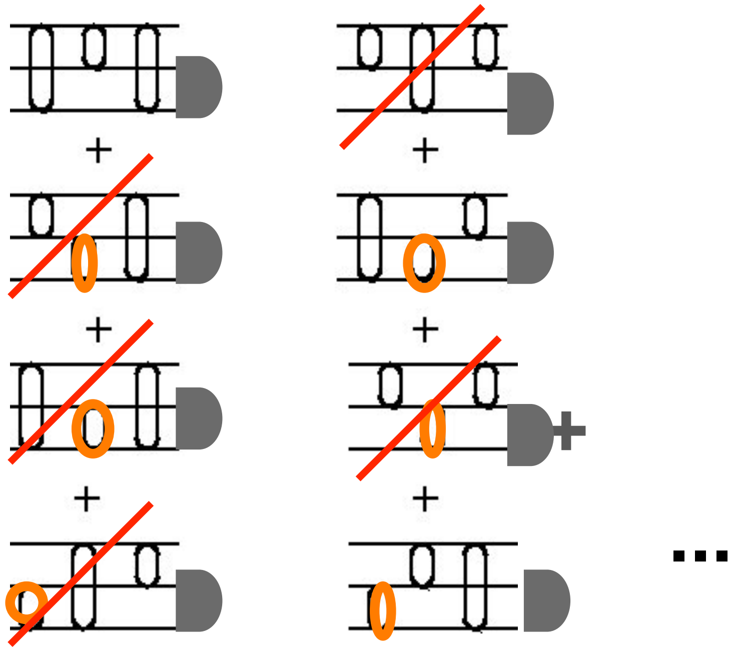
DWIA-Eikonal: T. Aumann, C. Bertulani, Ryckebush, PRC 88 (2013) 064610.

Reaction framework	$Z(3/2_1^-)$	$Z(1/2_1^-)$	$Z(3/2_2^-)$
FADD/BAU-J	2.52	0.31	0.28
FADD/KD-KD	1.85	0.23	0.19
DWIA-EIK	2.11	0.26	0.21

- Interaction uncertainty: Δ_{max}=50%
- Reaction model uncertainty: Δ_{max}=30%

DWIA: $A(a,ab)B$ $\quad \langle \eta_{abB} \,|\, t_{ab} \,|\, \eta_{Aa}\phi_{bB} \rangle \approx \langle \eta_{aB}\eta_{bB} \,|\, t_{ab} \,|\, \eta_{Aa}\phi_{bB} \rangle$





- The single scattering between particle a and the core B, t_{aB} *is* ***assumed to be exactly cancelled by higher order terms***

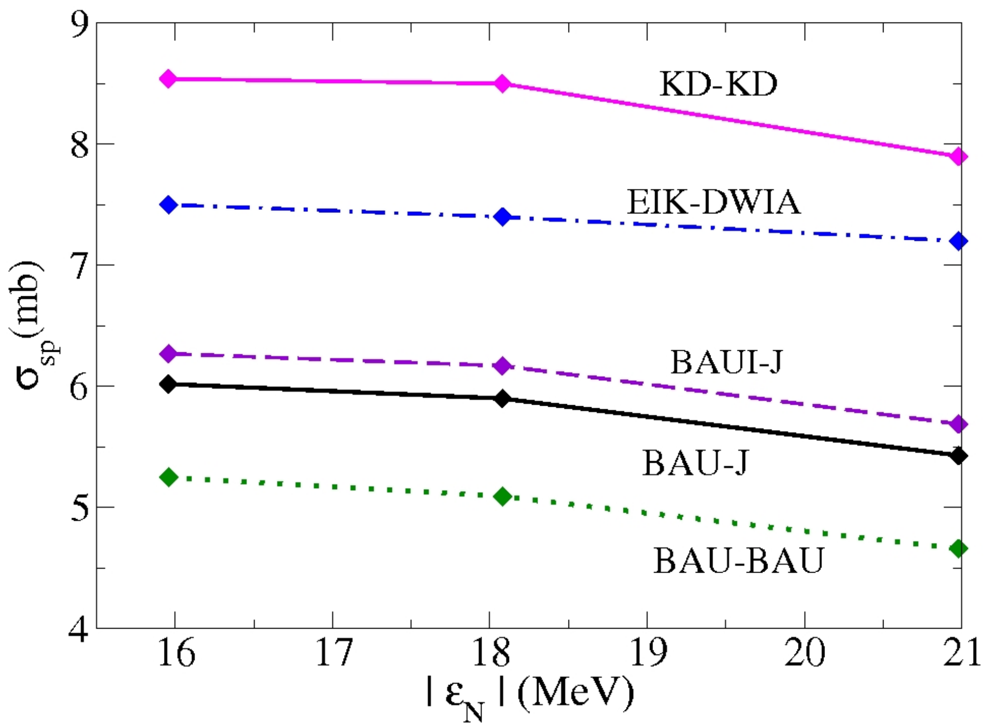
- Diagrams where t_{ab} ***does not occur*** *or* ***appear more than once*** are not taken into account

Glauber + adiabatic: rescatering terms are treated approximately

- Insight on the approximations using the AGS/Faddeev formalism

R. Crespo, A. Deltuva and E. Cravo, PRC 90, 044606 (2014).

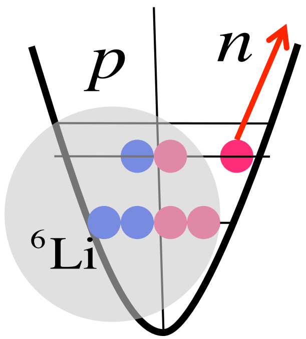
p-knockout form ^{12}C @ 400 MeV/u



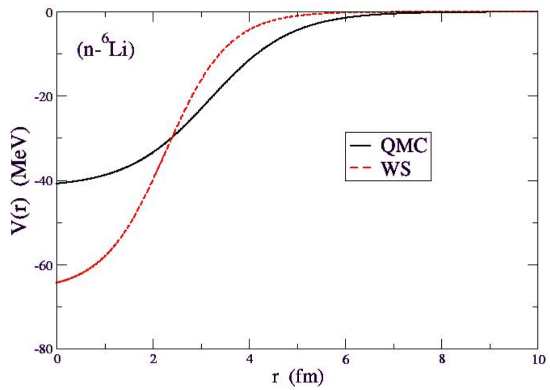
Faddeev/AFS: R. Crespo, E. Cravo, A. Deltuva, submitted PRC

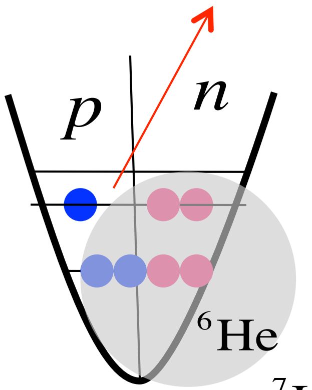
DWIA-Eikonal: T. Aumann, C. Bertulani, Ryckebush, PRC 88 (2013) 064610.

Q2a) what are the structure effects on the description of the gs ?

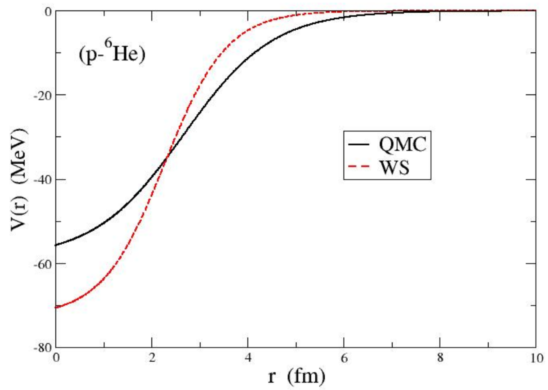


^{7}Li(p,pn)





^{7}Li(p,2p)

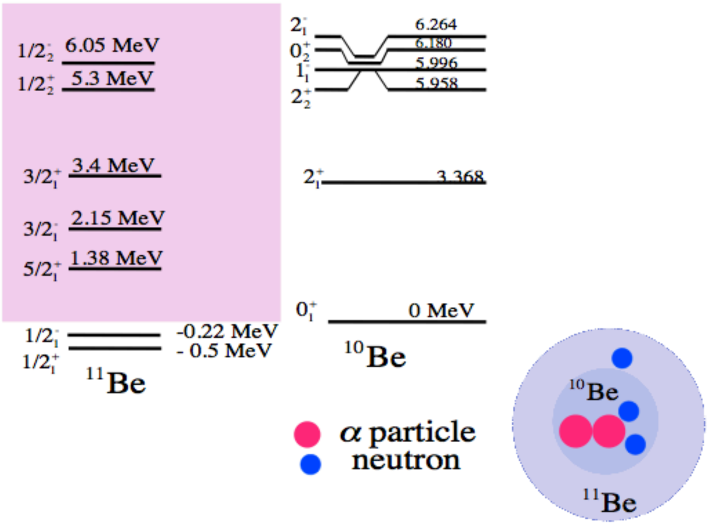


Reaction	σ_{th}^{QMC} (mb)	σ_{th}^{IPM} (mb)	Δ_{th}(%)
^{7}Li(p,pn)^{6}Li	15.4	16.9	9
^{7}Li(p,2p)^{6}He	5.08	7.84	54

R. Crespo E. Cravo, A. Deltuva, A. Arriaga, R. Wiringa, R. Diego, to be published in Journal Physics G (2018).

Valence- shell knockout from ^{11}Be to the ^{10}Be ground state

Inner -shell knockout from ^{11}Be to the ^{10}Be core excited state



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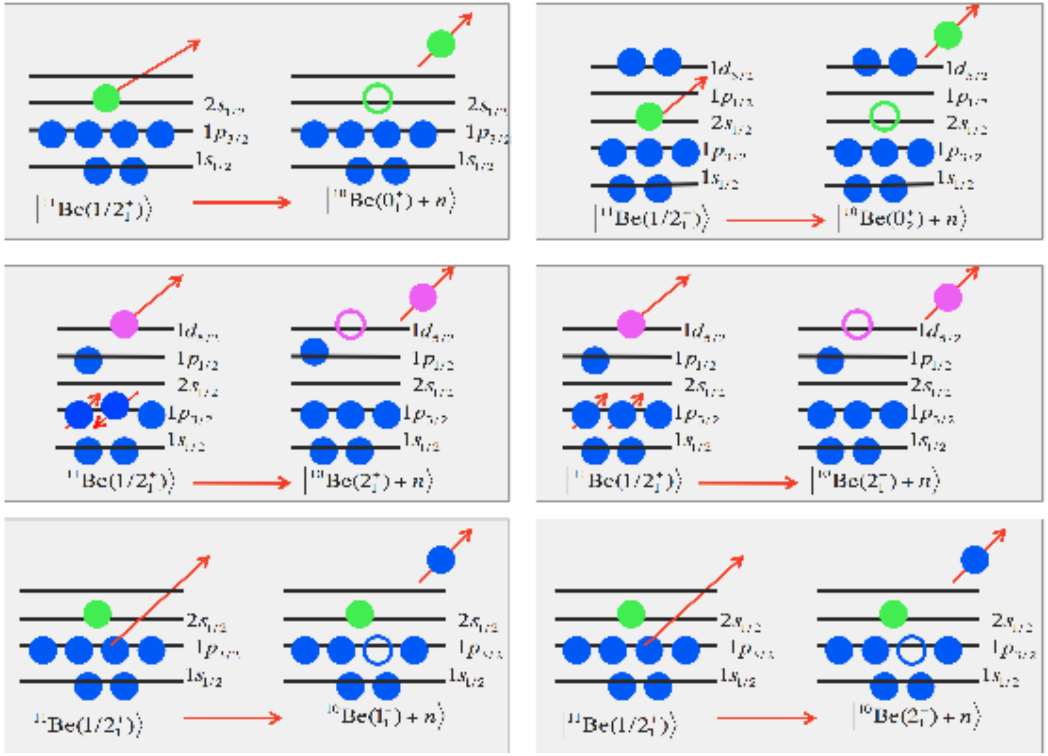
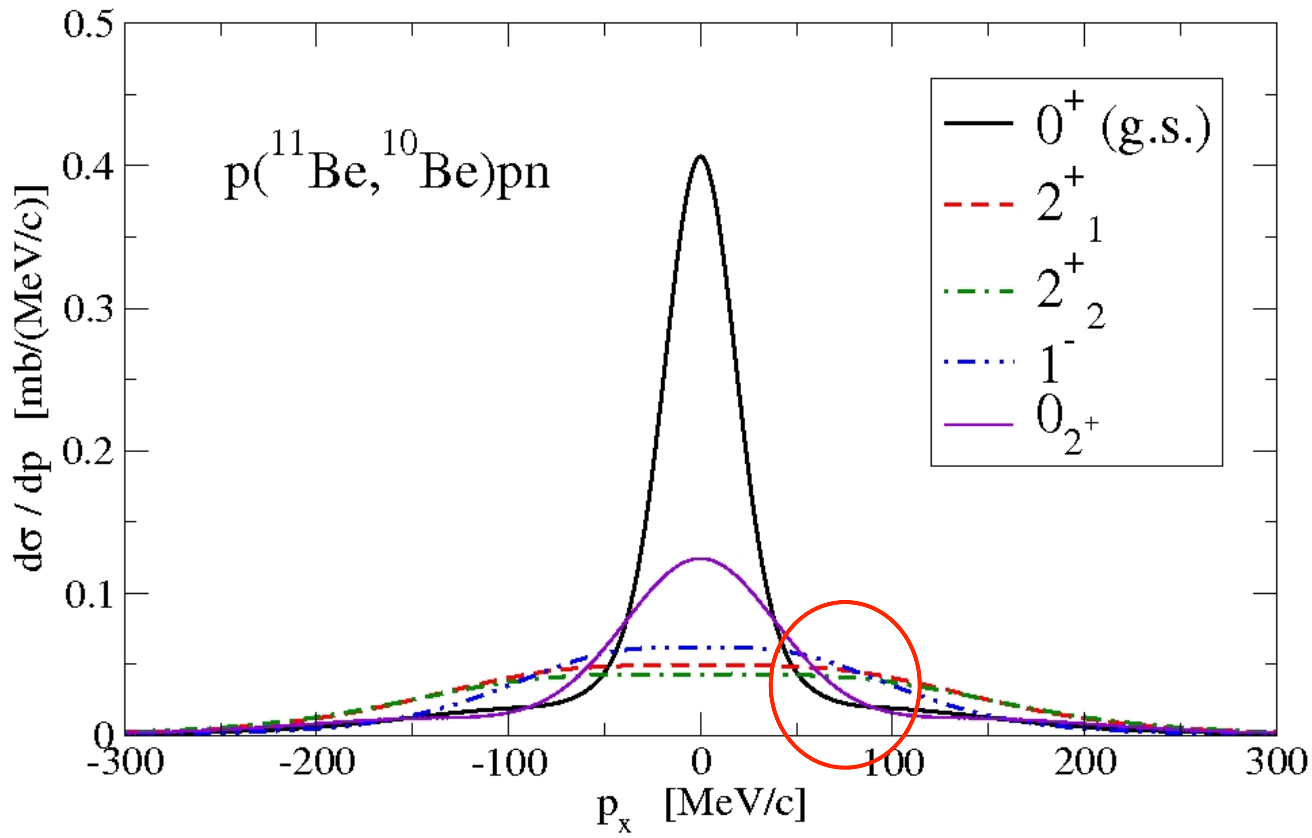


R. Crespo and E. Cravo, *Critical phenomena: Coexistence of valence single particle- and core-excitations in the ^{11}Be halo nucleus*, published in Fewbody systems, Springer (2018).



Structure information is needed !

R. Crespo and E. Cravo, *Critical phenomena: Coexistence of valence single particle- and core-excitations in the* ^{11}*Be halo nucleus*, published in Fewbody systems, Springe (2018).

Nucleon knockout: reaction and structure

Answer to the Questions:

1) What is the **accuracy** of current standard Fewbody DR approaches **?**

   R: Uncertainties on the potential describing the interactions are large and need to be reduced

2) What are the role of the **many body degrees of freedom** in the scattering process**?**

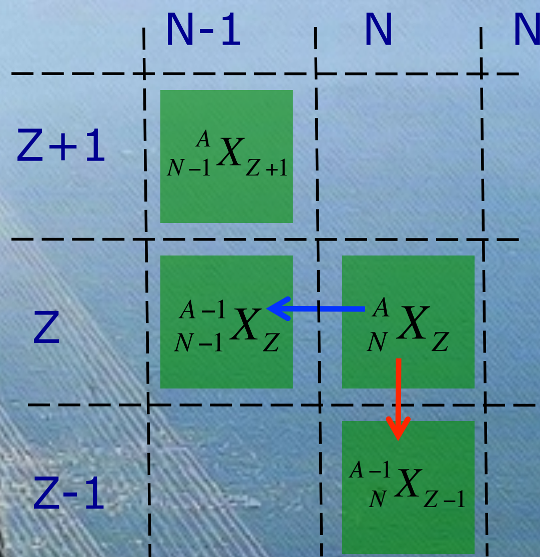
   R: Many body degrees of freedom need to be taken into account

- TASK FORCE:

- Full understanding of the reaction mechanisms

- Consistent measurement & theoretical analysis of all possible channels

Ex: p(A,pp $_{N}X_{Z-1}$), p(A,pn $_{N-1}X_{Z}$), p(A,$_{N}X_{Z-1}$), p(A, $_{N-1}X_{Z}$)



- Merging microscopic structure information into reactions

THANK YOU !