QFS from halo nuclei

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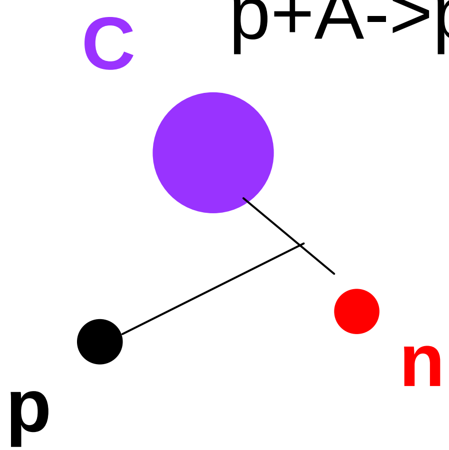
Synopsis

- **Breakup observables**
- **Kinematics (QFS)**
- **Formalism:** Faddeev/AGS multiple scattering reaction framework
- **Results I:** Breakup observables for p-^{11}Be, at QFS: a test of DWIA/PWIA
- **Results II:** Breakup observables for p-^{14}Be, at QFS: ^{13}Be spectroscopy
- **Conclusions**

Breakup observables



p+A->p+C+n

3 particles in the final state:

-> 9 kinematical variables

Momentum and energy conservation:

-> - 4 kinematical variables

Fully exclusive cross section: 5 variables

$$d^5\sigma / d\Omega_C d\Omega_n dS (mb/MeV.sr^2)$$

$$dS = (dE_C^2 + dE_n^2)^{1/2}$$

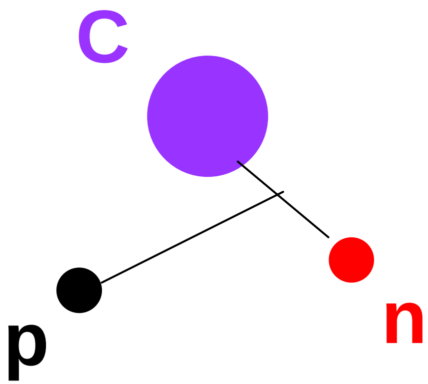
Semi-inclusive cross section:

$$d^3\sigma / d\Omega_C dE_C (mb/MeV.sr)$$

Inclusive momentum distributions:

$$d\sigma / dp_C^x (mb/MeV/c)$$

Kinematics



np QFS kinematics:

One of the particles acts as a spectator that is **C**

Direct kinematics: A(p,p)**Cn** $\Rightarrow \vec{k}_C^{LAB} = 0$

Inverse kinematics: p(A,**Cn**)p $\Rightarrow \vec{k}_C^{LAB} = \frac{m_C}{m_A}\vec{k}_A$

Standard assumption: DWIA

The probe (**p**) strucks the knocked particle (**n**) assumed free

The transition amplitude is disentagled into a reaction (σ_{pn}) and a structure term ϕ_{Cn}

How good is this assumption ?

Goal

- Calculation of fully excusive, semi-inclusive and inclusive breakup observables in QFS kinematics for few-body **halo nuclei**.
- **Formalism:** Faddeev/AGS multiple scattering reaction framework that treats all open channels (elastic, transfer, breakup) on equal footing

➡ Adequate to describe the scattering of halo nuclei where breakup thresholds are close to the ground state

Formalism: Faddeev/AGS

Let 3 particles interact by means of 2-body potentials.

Define the pair transition amplitudes

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

$G_0 = (E + i0 - H_0)^{-1}$ $\quad H_0$ Kinetic energy operator of the system

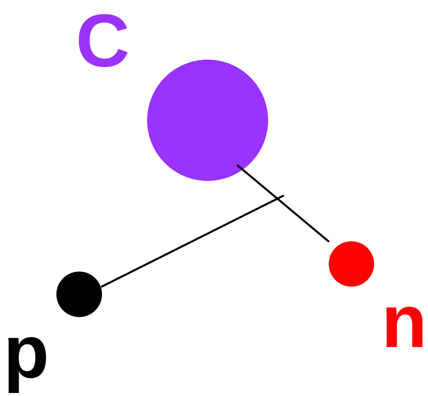
E is the total energy of the system

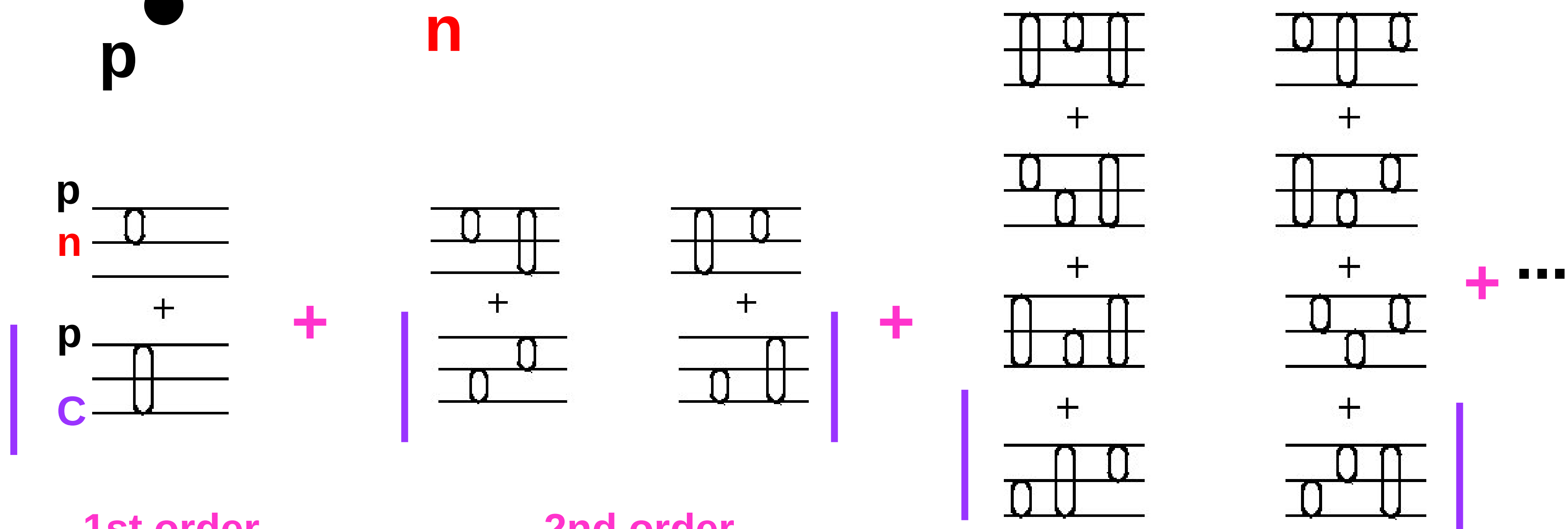
The Faddeev/AGS equations are a series expansion in terms of the pair operators

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

For breakup (β=0 in the final state) $\Longrightarrow$ $U^{0\alpha} = G_0^{-1} + \sum_\gamma t_\gamma G_0 U^{\gamma\alpha}$

Formalism: Faddeev/AGS breakup series





1st order
Single Scattering

2nd order
Double Scattering

3rd order

⟹ **Calculation to nth order OR Summing of the series** using Padé

Formalism: Faddeev/AGS

- We solve the Faddeev/AGS equations in momentum space using the Partial Wave Decomposition
- For intermediate energies many p-^{10}Be partial waves contribute and calculations need to be handled with care. Thus, we are limited in the range of energy
- We include Coulomb in one interacting pair using the method of screening of the Coulomb interaction plus renormalization

Results I: p(^{11}Be,^{10}Be)np

Pair interactions:

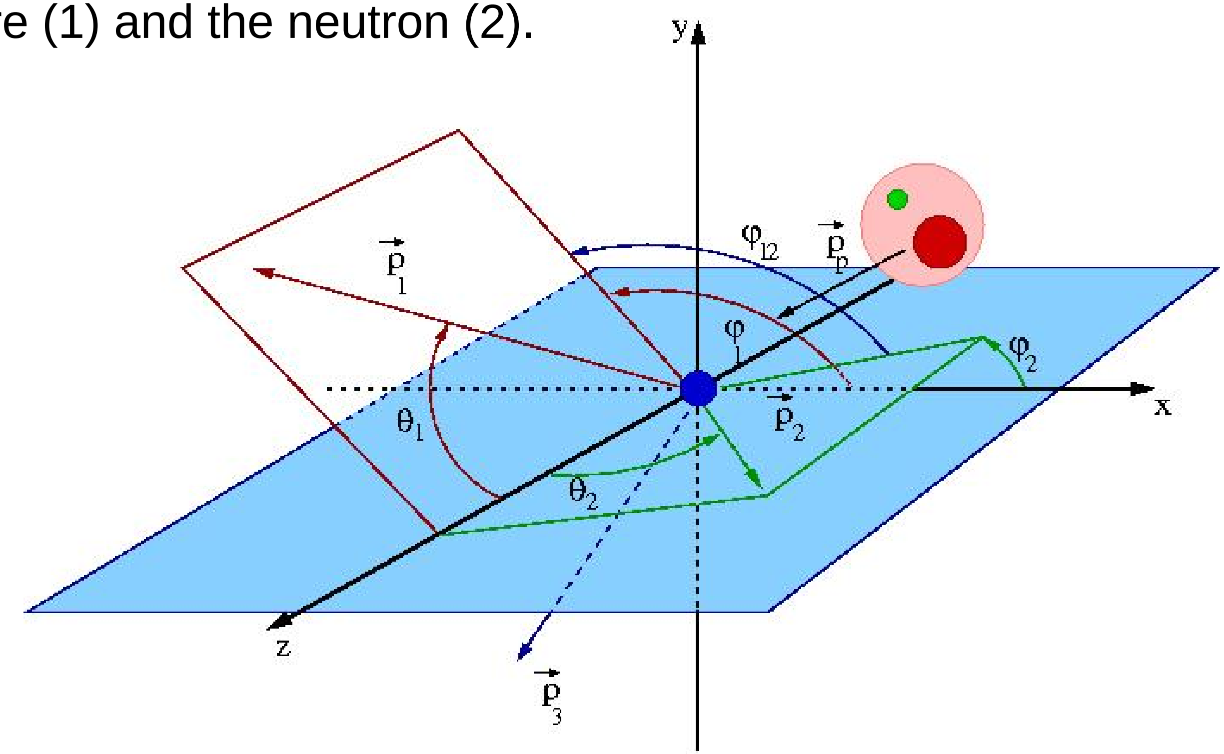
- Realistic NN CD Bonn interaction
- L dependent n-^{10}Be interaction

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

- Optical potential for the p-^{10}Be interactions with parameters taken from the Watson parametrization

Results I: $p(^{11}Be,^{10}Be)np$

The kinematical configurations are characterized by the polar and azimuthal angles (θ_i,ϕ_i) of the two detected particles. We assume those particles to be ^{10}Be core (1) and the neutron (2).

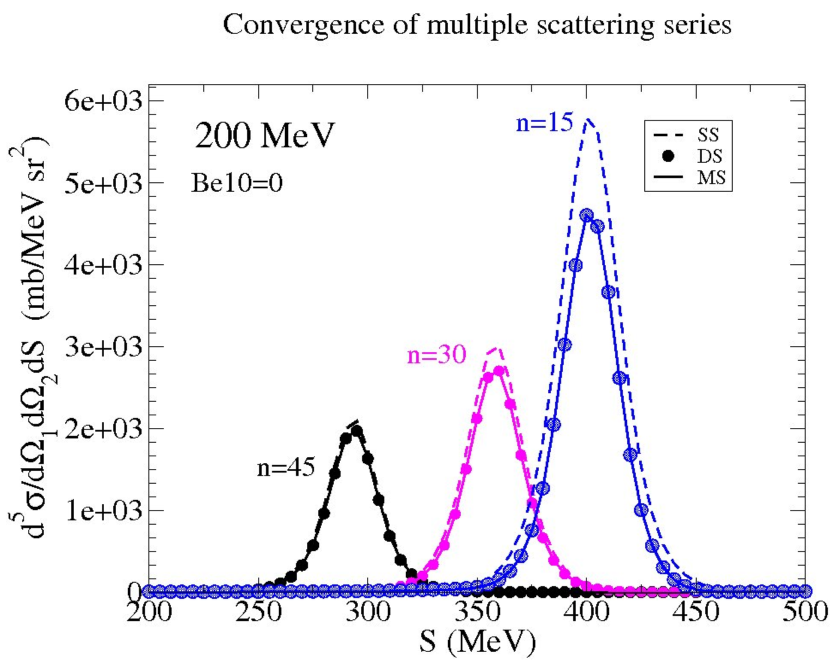


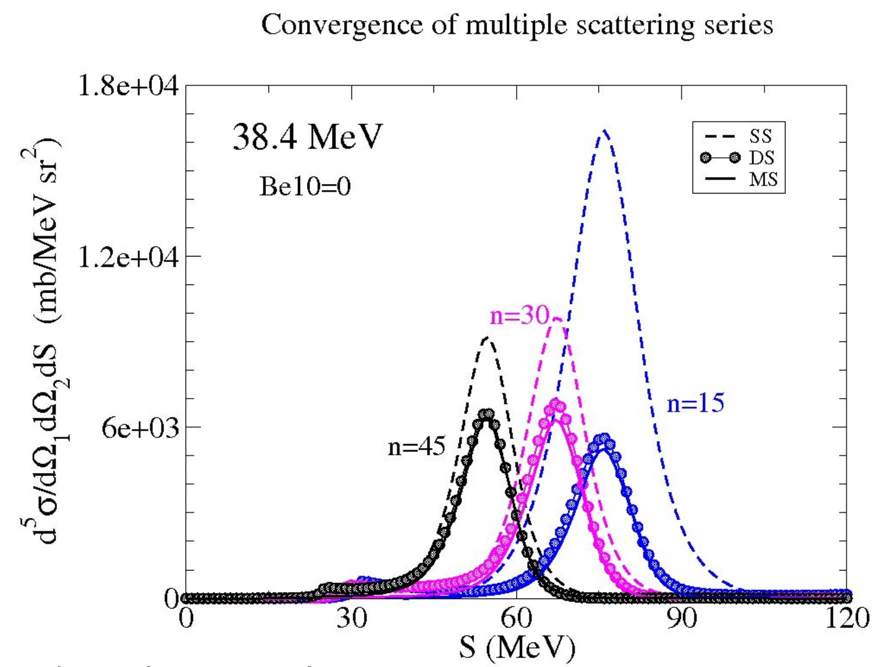
We take the **quasi-free kinematical conditions** (θ_1,ϕ_1)=(0,0) to study of the multiple scattering convergence.

We take 3 configurations:

conf1: (θ_2,ϕ_2)=(45,180) ; conf2: (θ_2,ϕ_2)=(30,180) ;
conf3: (θ_2,ϕ_2)=(15,180)

Results I: Fully exclusive $^{11}Be(p,^{10}Be)np$





S is the arclenght of the energy $dS = \sqrt{dE_{Be}^2 + dE_n^2}$

$\Rightarrow$ The convergence of the multiple scattering series depends upon the configuration and energy

$\Rightarrow$ The **double** scattering term reproduces well the calculated multiple scattering observable

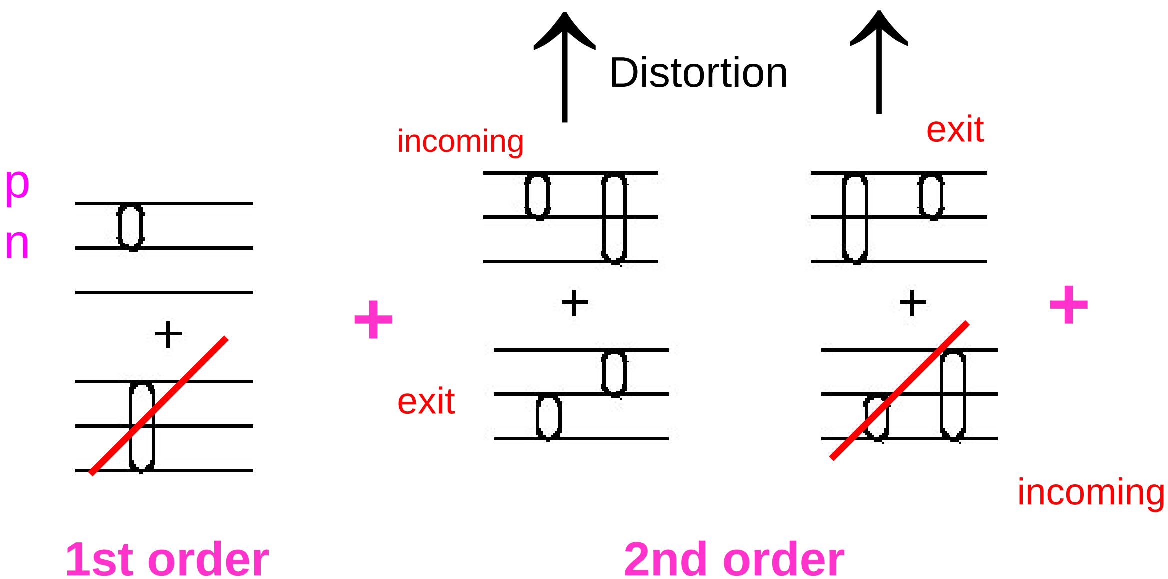
R. Crespo, A. Deltuva, E. Cravo, M. Rodríguez-Gallardo, A.C. Fonseca, *Multiple scattering effects in quasi free scattering from halo nuclei: a test to the Distorted Wave Impulse Approximation, Phys Rev C 77, 024601 (2008)*

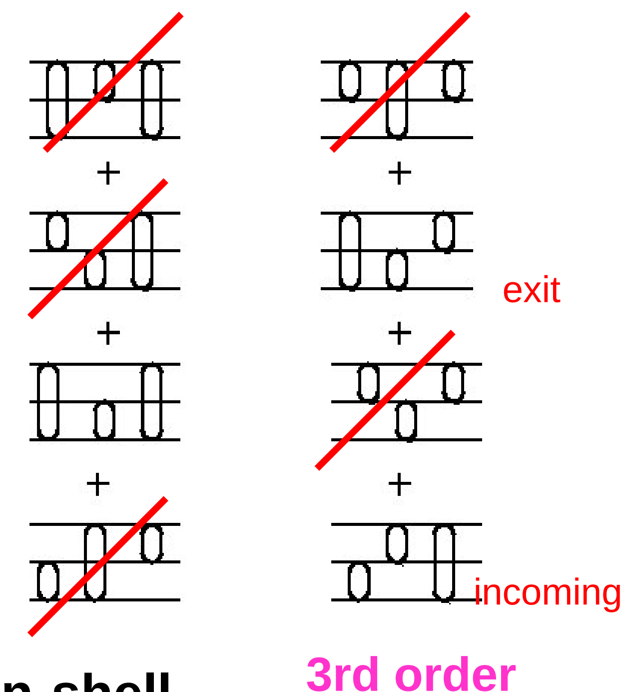
Results I: A test of DWIA-full

$$A(a,ab)B \longrightarrow {}^{11}Be(p,pn)^{10}Be$$

Chant and Roos, Phys. Rev C15, 57 (1977)

$$\langle \eta_{abB} \mid t_{ab} \mid \eta_{Aa}\phi_{bB} \rangle \approx \langle \eta_{aB}\eta_{bB} \mid t_{ab} \mid \eta_{Aa}\phi_{bB} \rangle \longrightarrow \langle \eta_{p^{10}Be}\eta_{n^{10}Be} \mid t_{pn} \mid \eta_{p^{11}Be}\phi_{n^{10}Be} \rangle$$

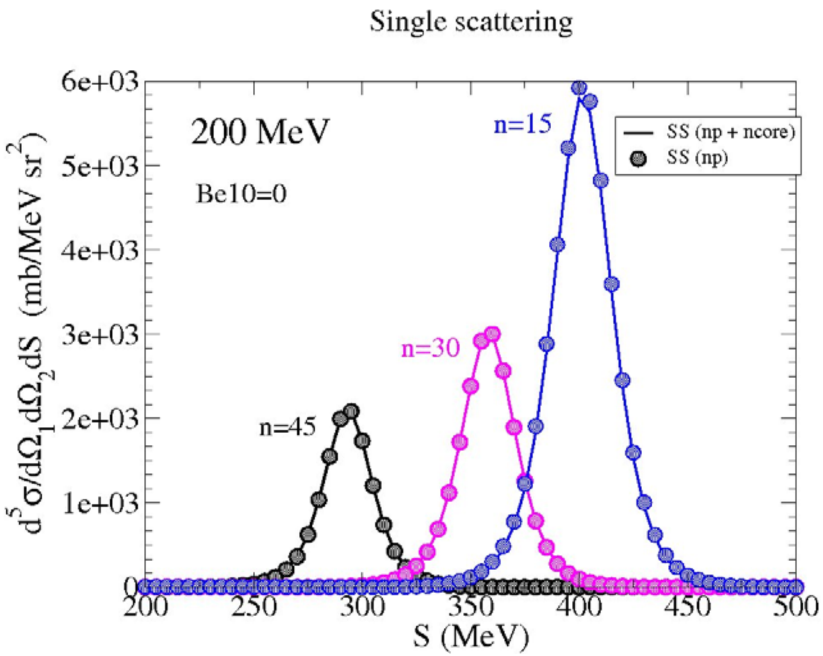


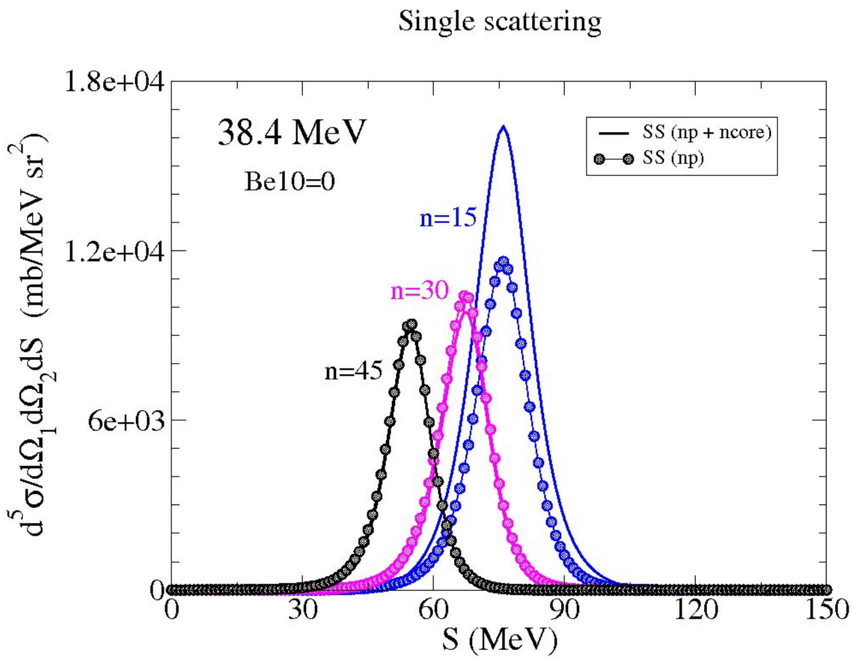


$\Longrightarrow$ **DWIA-Full: truncated incomplete series**

$\Longrightarrow$ **DWIA-Standard: DWIA-Full+factorization+on-shell**

Results I: A test of DWIA-full

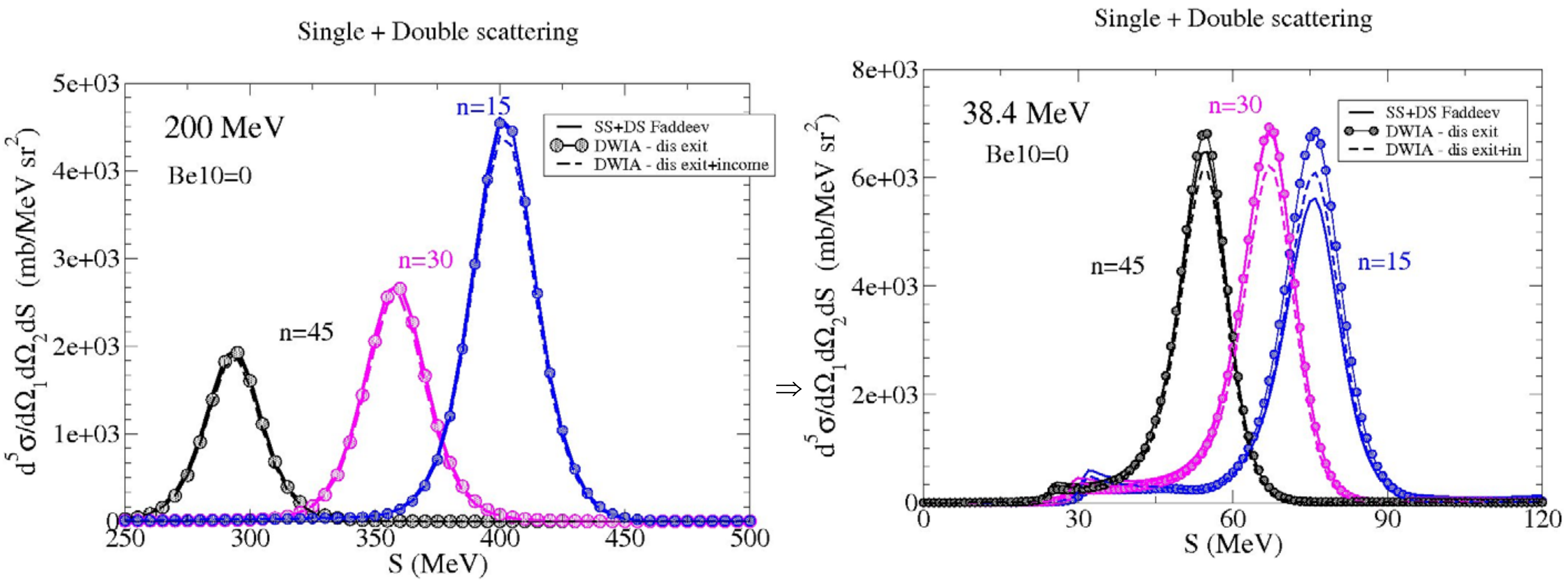




n-p single scattering is a bad approximation in some configurations at low energies

R. Crespo, A. Deltuva, E. Cravo, M. Rodríguez-Gallardo, A.C. Fonseca, *Multiple scattering effects in quasi free scattering from halo nuclei: a test to the Distorted Wave Impulse Approximation, Phys Rev C77, 024601 (2008)*

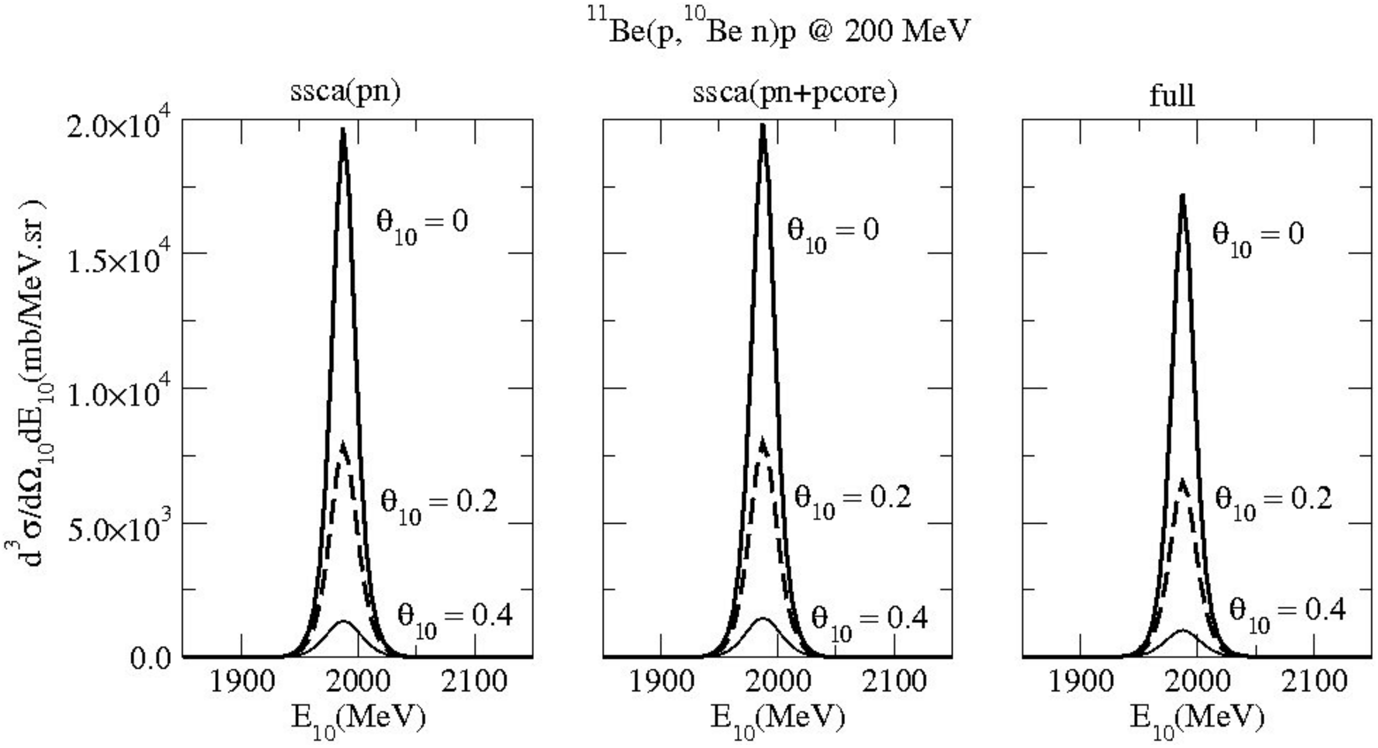
Results I: A test of DWIA-full



The DWIA-full is a bad approximation at low energies in any configuration

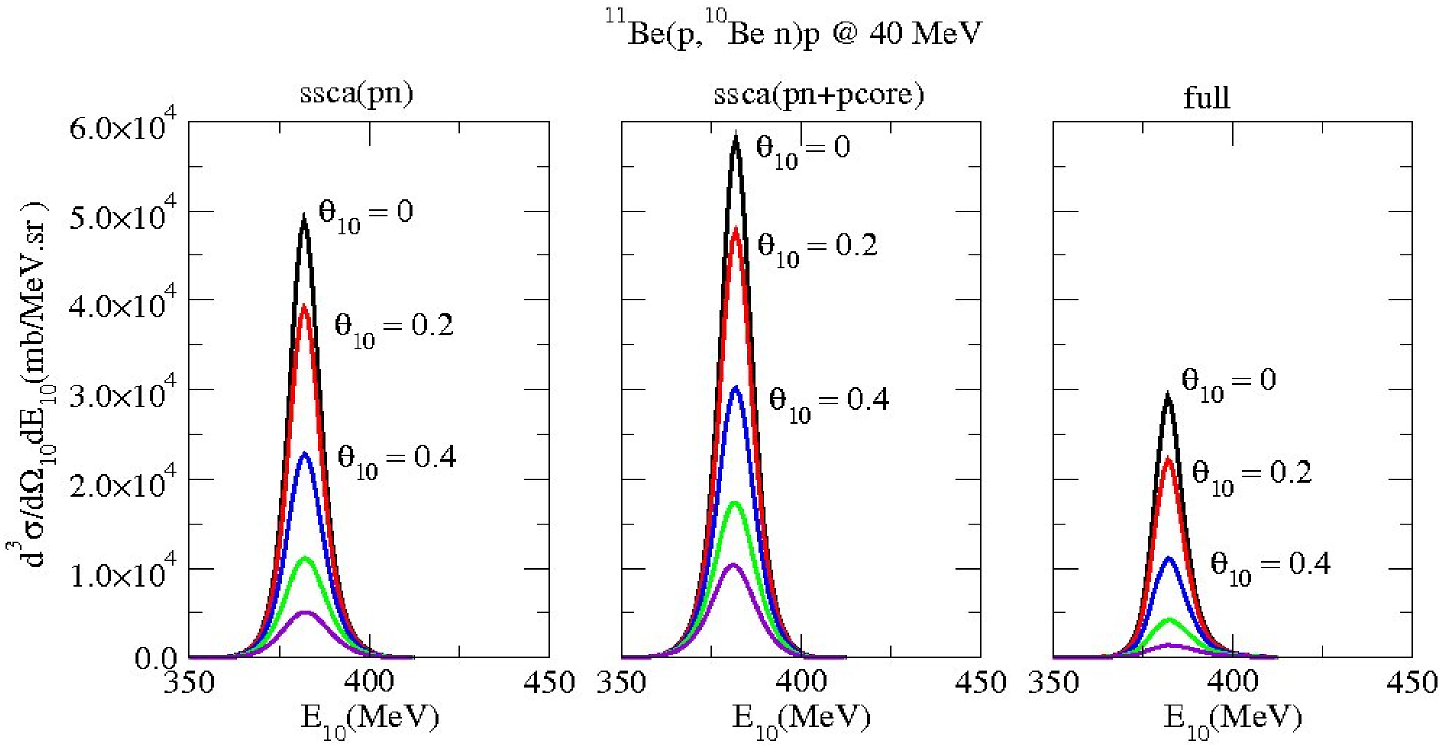
R. Crespo, A. Deltuva, E. Cravo, M. Rodríguez-Gallardo, A.C. Fonseca, *Multiple scattering effects in quasi free scattering from halo nuclei: a test to the Distorted Wave Impulse Approximation, Phys Rev C77, 024601 (2008)*

Results I: Semi-inclusive $p(^{11}Be,^{10}Be)np$



- Single Scattering (**SSA**) approaches the **full** calculation at **higher energies** (with an error os ~12%)
- Contribution to SSA from the scattering of the core is small in this case

Results I: Semi-inclusive $p(^{11}Be,^{10}Be)np$



- Single Scattering (**SSA**) overestimates the **full** calculation at **smaller** energies with an error of ~50%
- Contribution to SSA from the scattering of the core is more important in this case

Results II: $p(^{14}Be,^{13}Be)np$

We adopt the convention that the ground state of ^{14}Be has the following single-particle configuration:

$$|^{14}Be(0^+_{g.s.})\rangle = \alpha_0 |^{13}Be(1/2^+)\otimes\nu(2s_{1/2})\rangle + \alpha_1 |^{13}Be(1/2^-)\otimes\nu(1p_{1/2})\rangle + \alpha_2 |^{13}Be(5/2^+)\otimes\nu(1d_{5/2})\rangle$$

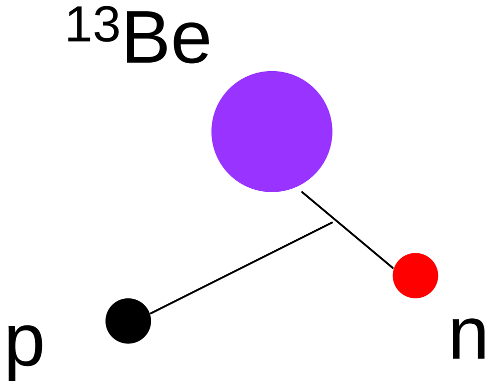
We consider each configuration of ^{14}Be separately. The binding energy of each configuration is taken to be:

$$\varepsilon = E_{rel} + S_{2n}$$

Where S_{2n}=1.26 MeV is the two-neutron separation energy of ^{14}Be

Results II: p(^{14}Be,^{13}Be)np

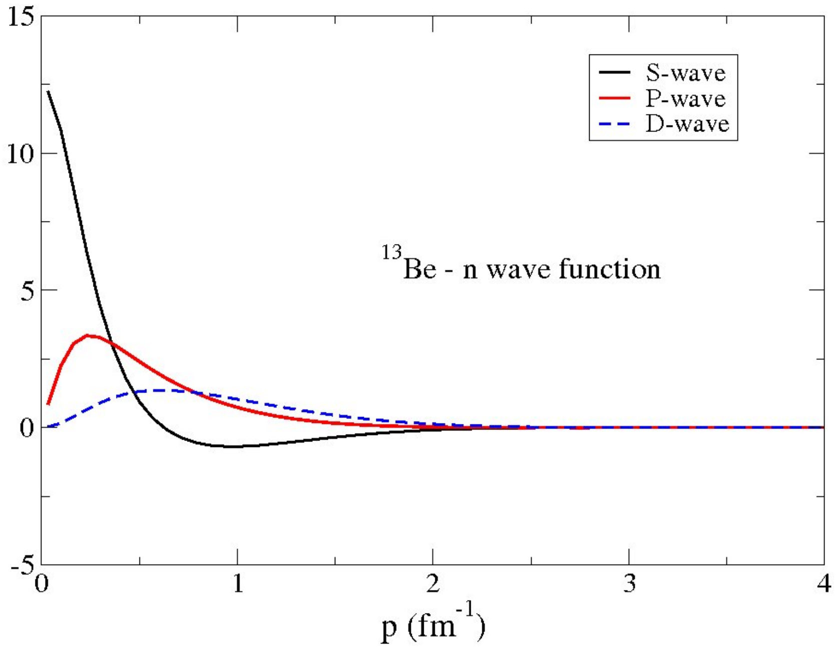
Pair interactions:



^{13}Be-n interaction:

$$V(r) = V_0 f(r, R_0, a_0)$$

- (**1p$_{1/2}$**): ε=-1.71, V_0=-32.922, R_0=1.2 $A^{1/3}$, a_0=0.6
- (**2s$_{1/2}$**): ε=-1.98, V_0=-60.105, R_0=1.2 $A^{1/3}$, a_0=0.6
- (**1d$_{5/2}$**): ε=-3.14, V_0=-67.962, R_0=1.2 $A^{1/3}$, a_0=0.6



Results II: p(^{14}Be,^{13}Be)np

p-^{13}Be interaction:

Optical potential with parameters taken from the Watson parametrization with a volume and surface term

NN interaction:

- Gaussian
- Bonn

Results II: p(^{14}Be,^{13}Be)np

Glauber/MOMDIS:

1) The scattering matrix

$$S(b) = \exp[i\chi(b)] \qquad \chi(b) = -\frac{1}{\hbar v}\int_{-\infty}^{+\infty} dz U_{opt}(r) \quad \Longrightarrow \quad S(b) = S_c(b_c) S_v(b_v)$$

2) The ^{13}Be-n bound wave function

Faddeev/AGS

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

Calculation of the sum of the series using Padé