Elastic and Inelastic scattering from halo nuclei

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Outlook

- Multiple scattering reaction frameworks: MST and MSO
- Applications in elastic scattering from halo nuclei (differential cross sections and analysing powers)
- Applications in inelastic scattering from halo nuclei (differential cross sections and energy spectrums)

Theory: The Total transition amplitude.

We consider the scattering of a projectile (p) from a few-body target consisting of n sub-systems weakly bound to each other. The total transition operator, T, for the scattering is

$$T = V + VG_0T = \sum_{i=1}^{n} v_i + \sum_{i=1}^{n} v_i G_0 T$$

$$G_0 = (E + i\varepsilon - K_p - H_0)^{-1}$$

$\Rightarrow$ **n+1 body problem**

E - Total energy in the cm frame

K_p - Kinetic energy operator of the projectile

H_0 - Internal Hamiltonian of the n-body target

Theory: The multiple scattering expansion of the Total transition amplitude-MST.

Defining the projectile-ith constituent many body (**n+1**) transition operator

$$\tau_i = v_i + v_i G_0 \tau_i$$

$$T = V + VG_0T \quad \Longrightarrow \quad T = \sum_{i=1}^{n} T_i$$

$$T_i = \tau_i + \tau_i G_0 1 \sum_{j \neq i} \tau_j + \ldots$$

$$\Uparrow$$

$$1 = P_0 + Q_0$$

Ground state and excited states are treated in equal footing **!**

Theory: The multiple scattering expansion of the Total transition amplitude-MST.

$$T_i = \tau_i + \tau_i G_0 1 \sum_{j \neq i} \tau_j + \ldots$$

This is a complicated many body n+1 problem and several approximations can be made in the high energy regime that lead to equivalent (**n+1**) scattering frameworks (although differing in detail where the expansion is truncated):

- Glauber many body of Al-Khalili and Tostevin
- Adiabatic of Johnson
- MST impulse approximation of Crespo and Johnson

Theory: The multiple scattering expansion of the Optical potential-MSO

Underlying idea: the contribution from the excited states space (Q_0) can be handled perturbatively

Defining the projectile-ith constituent many body **(n+1)** transition operator

$$\tau_i' = v_i + v_i G_0 Q_0 \tau_i'$$

$$T = V + V G_0 T \quad \Longrightarrow \quad T = \hat{U} + \hat{U} G_0 P_0 T$$

$$\hat{U} = \sum_i \hat{U}_i$$

$$\hat{U}_i = \tau_i' + \tau_i' G_0 Q_0 \sum_{j \neq i} \hat{U}_j$$

Theory: MSO-Single Scattering approximation

The contribution from the excited states space (Q_0) is neglected

$$\hat{U}_i = \tau_i' + \tau_i' G_0 Q_0 \sum_{j \neq i} \hat{U}_j \quad \Rightarrow \quad T = \sum_i T_i^{SSA}$$

$$T_i^{SSA} = \tau_i + \tau_i G_0 P_0 \sum_{j \neq i} \tau_j + \ldots$$

In the MSO-SSA the contribution from the excited states to the total transition amplitude is neglected

Theory: MSO-´$t_{NN}\rho$´

- The **SSA** $\hat{U}_i = \tau_i$´
- All the nucleons are treated in equal footing and the many body transition amplitude is replaced by the **FREE nucleon-nucleon** transition amplitude

$$\tau_i{}' \rightarrow t_{NN}^{free}$$

(n+1)-many body is replaced by a **2**-body problem **!**

Theory: MSO-´$t_{NN}\rho$´

For the elastic scattering problem for proton scattering from a cluster of nucleons

$$U_{opt} = \langle \phi_0 \mid t_{NN}^{free} \mid \phi_0 \rangle$$

In momentum space configuration

$$\langle \vec{k}' | U_{opt} | \vec{k} \rangle = \sum_{i=1}^{n} \rho_p^i \bar{t}_{pp}(\omega, q, Q, \phi) + \rho_n^i \bar{t}_{pn}(\omega, q, Q, \phi)$$

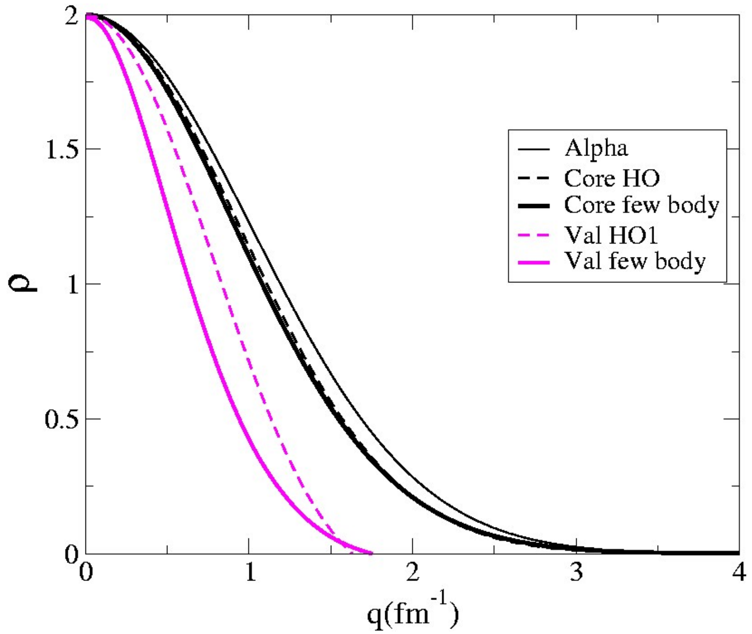
Target <u>density</u> **X** component <u>NN scattering amplitude</u>

Elastic scattering

What can we learn for proton elastic scattering from halo nuclei **?**

Elastic scattering p-^{6}He: SSA/MSO.

^{6}He matter density distributions

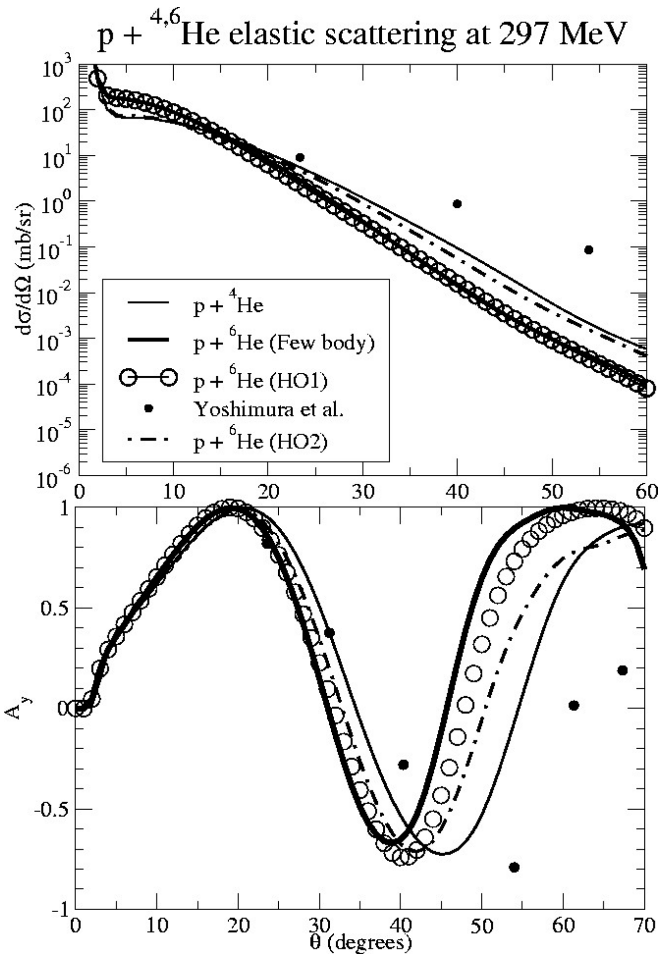


$\Rightarrow$

The HO1 core density distribution is similar than the Fewbody

Elastic scattering p-^{6}He: SSA/MSO.

Elastic scattering observables



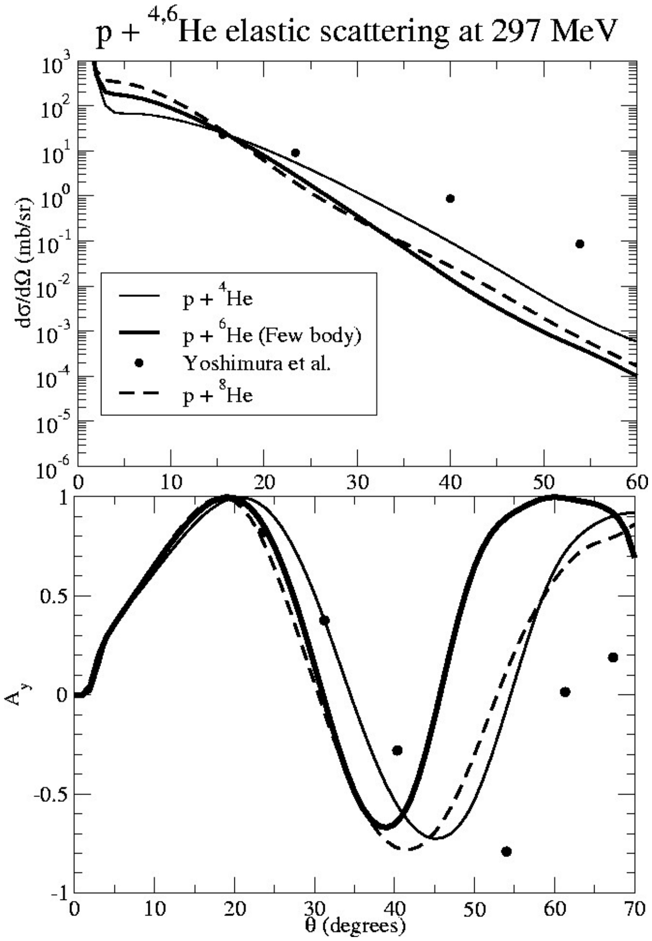
$\Rightarrow$

The observables for p-**4,6**He with HO1 and FB are similar

The observables probe essentially probe that part of information contained in the core contribution of the optical potential

Elastic scattering p-^{6}He: SSA/MSO.

Elastic scattering observables



⟹ The polarization observables for p-^{4,6,8}He are similar

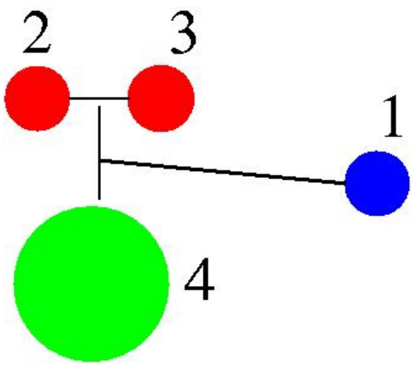
Elastic scattering p-^{6}He: SSA/MSO

- **Conclusion:** At intermediate energies the polarization observable is NOT a god tool to obtain information from the valence neutrons
- **However ....**

This contradicts the LATEST Riken experimental results at 72 Mev that show significant differences for the A_y in p-^{4,6}He

Elastic scattering p-^{6}He:MST

Let us consider a 3-body target. Within MST the transition amplitude is:



$$T_{(n=3)} = \sum_{i=1}^{3} T_i \qquad T_i = \tau_i + \tau_i G_0 1 \sum_{j \neq i} \tau_j + \ldots$$

The elastic scattering amplitude is written:

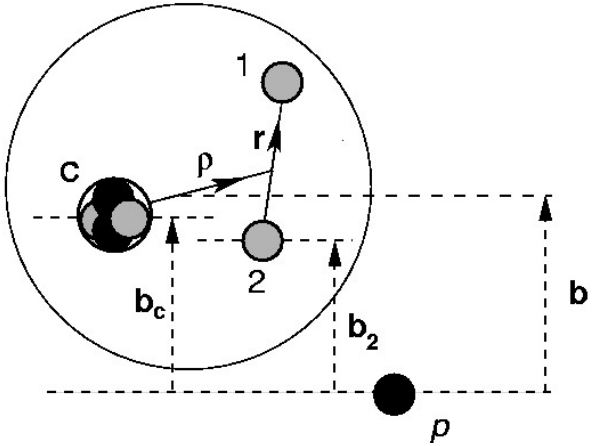
$$F_{(n)}(q) = \frac{-\mu}{2\pi\hbar^2} \langle \vec{k}' \phi^{(n)} \mid T_{(n)} \mid \vec{k} \phi^{(n)} \rangle$$

Elastic scattering p-^{6}He:MST

Glauber Multiple Scattering (Al-Khalili *et al*) :

- Adiabatic (or sudden) approximation
- Eikonal (or straight line) assumption

$$F_{(n)}^{GL}(q) = \frac{ik}{2\pi}\int d^2\vec{b}\, e^{i\vec{q}.\vec{b}}\,\underleftarrow{(1-S(b))}$$



$$1-S(b) = \langle \phi^{(n)} \,|\, 1 - S_c(b_c)S_1(b_1)S_2(b_2) \,|\, \phi^{(n)} \rangle$$

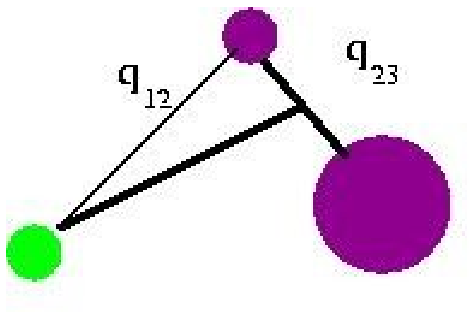
$$\begin{aligned}
&= \langle \phi^{(n)} \,|\, ((1-S_c(b_c)) + (1-S_1(b_1)) + (1-S_2(b_2)) \\
&-(1-S_c(b_c))(1-S_1(b_1)) - (1-S_c(b_c))(1-S_2(b_2)) - (1-S_1(b_1))(1-S_2(b_2)) \\
&+(1-S_c(b_c))(1-S_1(b_1))(1-S_2(b_2)) \,|\, \phi^{(n)} \rangle
\end{aligned}$$

$\Longrightarrow$ Forward approximation

Elastic scattering p-^{6}He:MST

The MST factorized Impulse approximation (Crespo & Johnson):

- The interaction between the clusters is neglected in the transition amplitude
- The initial relative momenta between the clusters is neglected



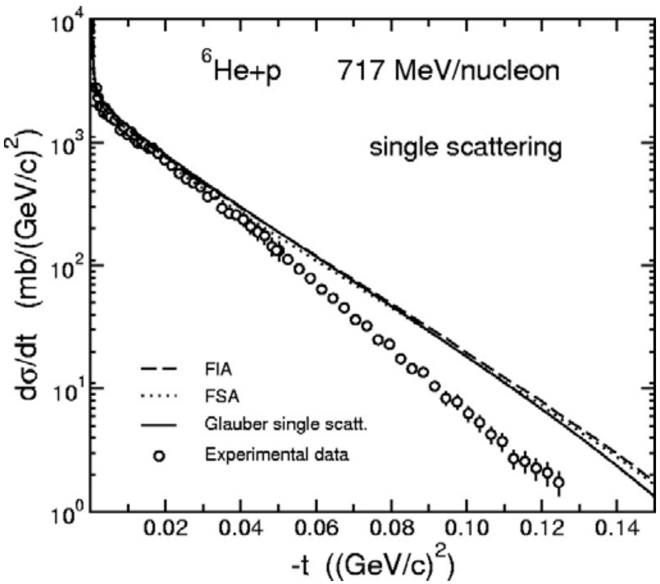
SSA $\Rightarrow$

$$T^{FIA}_{(n=3)} = \langle \vec{Q}'_1 | t_1(\omega_1) | \vec{Q}_1 \rangle \rho_{12,3}\left(\frac{m_2}{M_{12}}\vec{q}, \frac{m_3}{M_{123}}\vec{q}\right)$$

$$+ \langle \vec{Q}'_2 | t_2(\omega_2) | \vec{Q}_2 \rangle \rho_{12,3}\left(\frac{m_1}{M_{12}}\vec{q}, \frac{m_3}{M_{123}}\vec{q}\right)$$

$$+ \langle \vec{Q}'_3 | t_3(\omega_3) | \vec{Q}_3 \rangle \rho_{12,3}\left(0, \frac{M_{12}}{M_{123}}\vec{q}\right)$$

Elastic scattering p-^{6}He-MST



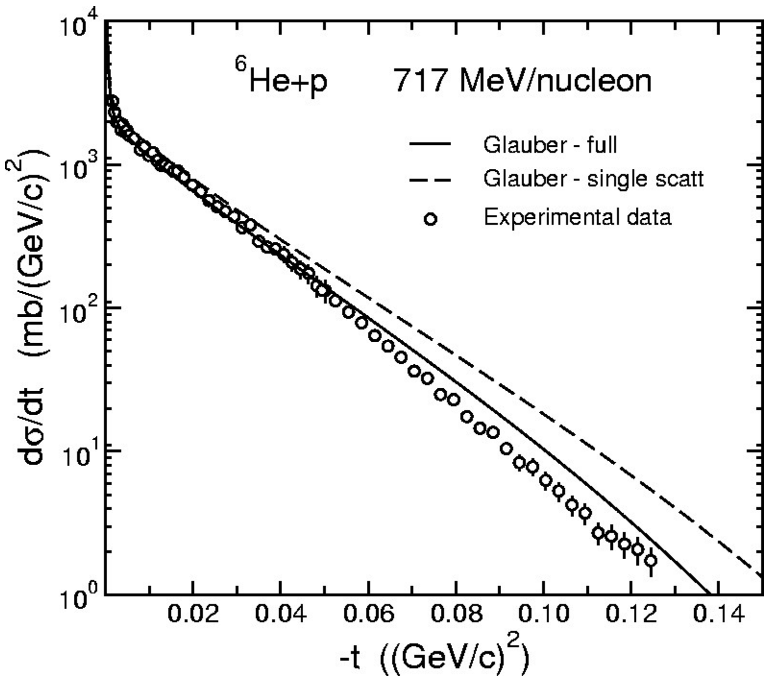
GSI Data from P. Egelhof, Nucl. Phys A 722 (2002) C260

- **Good agreement** between the Glauber and Factorized impulse MST and FSA

J.S. Al-Khalili, R. Crespo, A.M. Moro, I.J. Thompson, *Few body multiple scattering calculations for 6He on protons*, submitted for publication

Elastic scattering p-^{6}He-MST

Higher order contributions



⇒ Higer order effetcs are important to describe the HIGH momentum transfer

⇒ Structure effects **?**

⇒ Breakdown of the forward approximation **?**

J.S. Al-Khalili, R. Crespo, A.M. Moro, I.J. Thompson, *Few body multiple scattering calculations for 6He on protons*, submitted for publication

GSI Data from P. Egelhof, Nucl. Phys A 722 (2002) C260

Inelastic scattering:

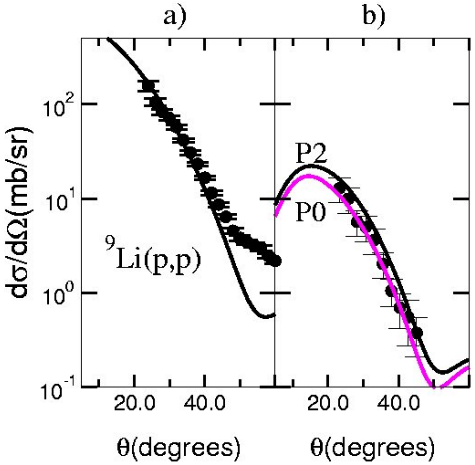
- Various structure theories predict a variety of excitation/resonance modes at the low energies in the continuum of Borromean nuclei
- Experimental studies often lead to contradictory results

$\Rightarrow$ Our knowledge of the Borromean resonant continuum sea is today **very inconclusive**

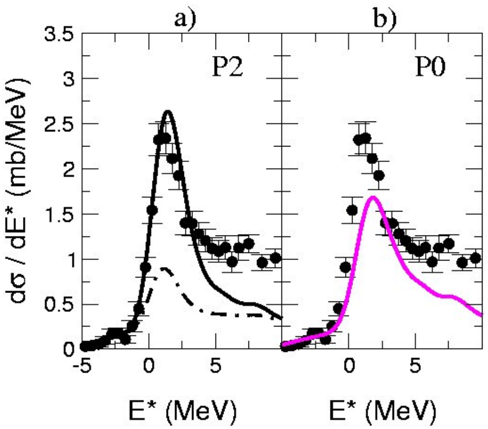
$\Rightarrow$ Inelastic scattering may be useful tool to study the excitation modes if it is possible to single out particular multipole excitations.

Inelastic scattering:

^{11}Li(p,p´) at 72MeV



⇒ The angular distribution does not distinguish between the two structure models



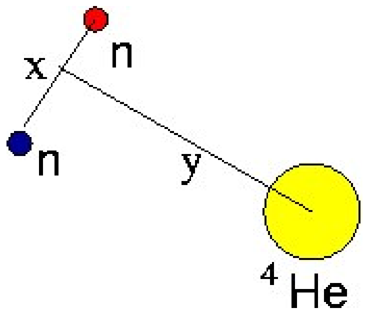
⇒ The energy spectrum is very sensitive to the structure models

R. Crespo, I.J. Thompson and A.A. Korsheninnikov, Phys. Rev. C 66 (20002), 021002 (R).

Inelastic scattering:Structure

The Pseudo state (PS) method:

The eigenstates are obtained by diagonalization of the Hamiltonian in a basis of normalizable states

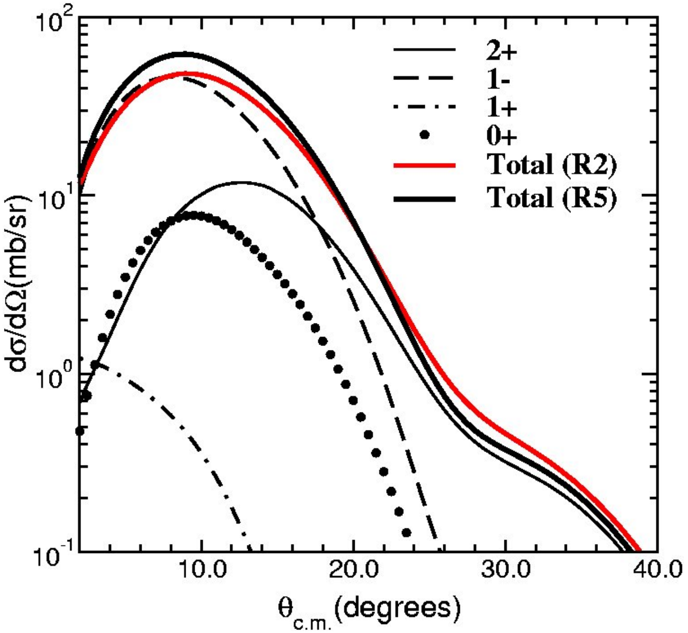


$$\psi_{n\beta}^{JM}(\vec{r},\vec{R}) = R_{n\beta}(\rho)\Upsilon_{\beta}^{JM}(\Omega_5)$$

$$\varphi_{\varepsilon}^{JM}(\vec{r},\vec{R}) = \sum_{n\beta} C_{n\beta}^{J\varepsilon}\psi_{n\beta}^{JM}(\vec{r},\vec{R})$$

Inelastic scattering: ^{6}He(p.p´)

Inelastic differential xs at 700 Mev



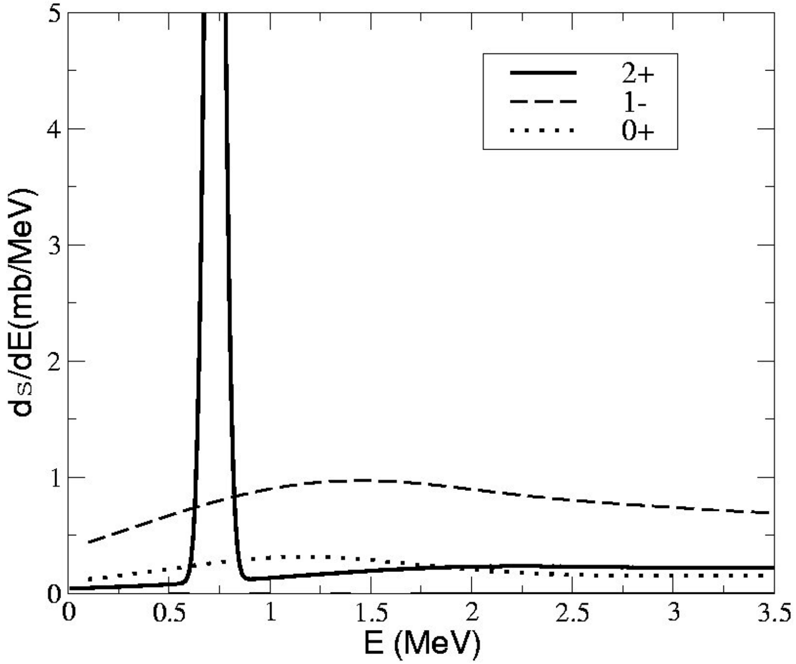
⇒ The non-resonant 1^- excitation is dominant at small angles and the 2^+ becomes dominant at larger angles

⇒ Spin flip transitions give a small contribution to the scattering at these energies

⇒ Smaller Rms gives a slightly broader xs

R. Crespo, I.J. Thompson and A.M. Moro, *Excitation modes of ^{6}He from proton collisions*, to be published in Phys Rev C

Inelastic scattering:^{6}He(p.p´)

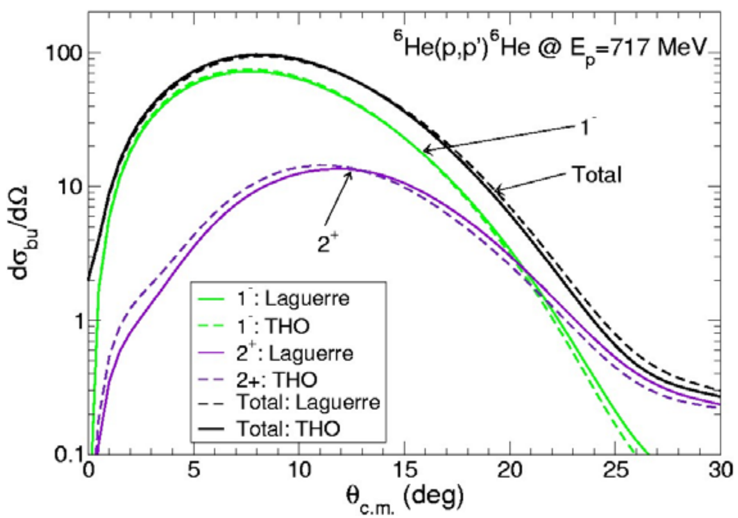


⇒ Some low lying strenght accumulation for tne transition to the 1^{-} state.

R. Crespo, I.J. Thompson and A.M. Moro, *Excitation modes of ^{6}He from proton collisions*, to be published in Phys Rev C

Inelastic scattering:^{6}He(p.p´)

The pseudo state basis



⇒ Provided that enough states are included, both bases predict essentially the **same inelastic cross section**

⇒ **Reliability of the pseudo states method** as a convenient method to treat inelastic scattering problems

A.M. Moro, M. Rodriguez-Gallardo, R. Crespo, I.J. Thompon, *The continuum description with Pseudo-State wave functions*, submitted for publication

Near future

- Benchmark calculations between Multiple scattering frameworks and Faddeev calculations at an appropriate energy are needed in order to check multiple scattering convergence

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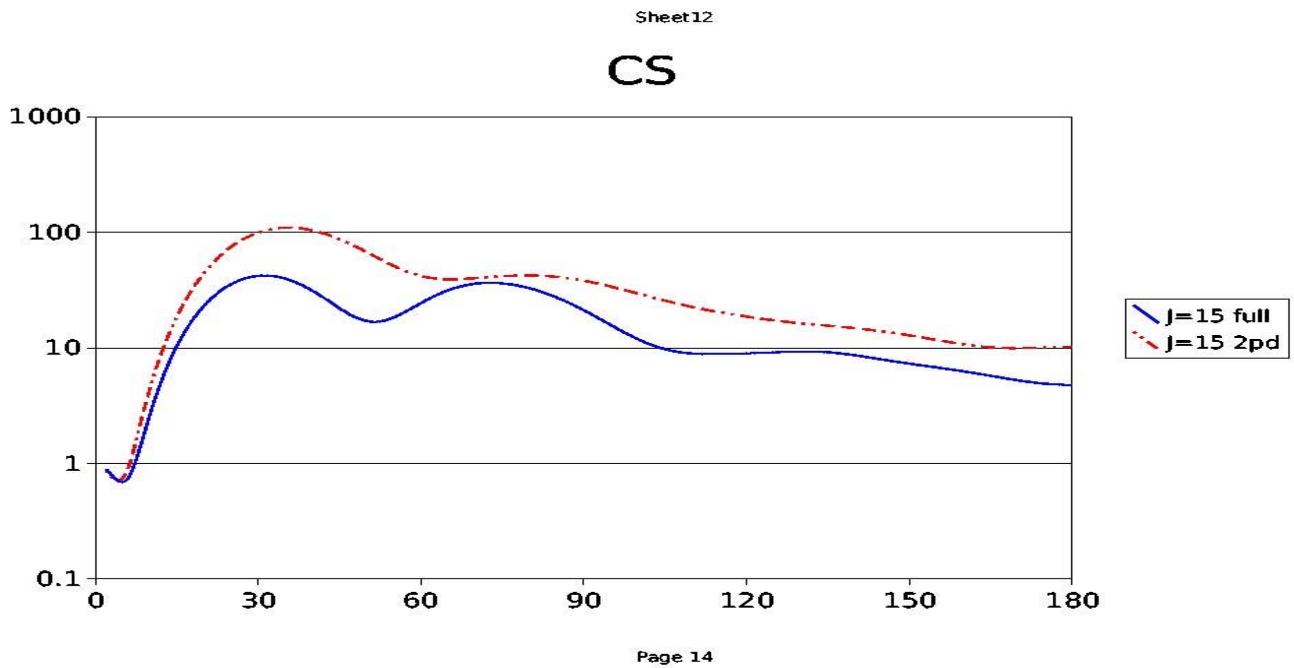
Near future

- Multiple scattering convergence: Xs



Near future

- Multiple scattering convergence: A_y