Reaction dynamics of exotic and stable weakly-bound nuclei using a four-body CDCC formalism

Manuela Rodríguez-Gallardo
Jesús Casal

Universidad de Sevilla

15 May 2021

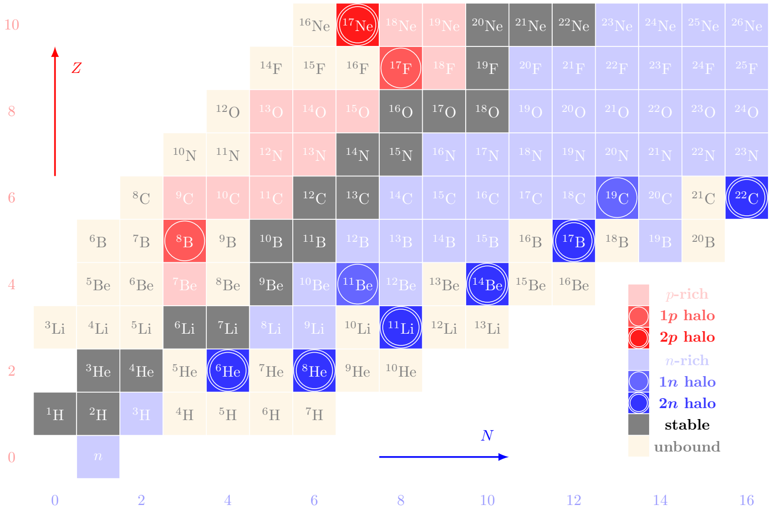
Outline

- Motivation: three-body weakly-bound systems
- Continuum-Discretized Coupled-Channels (CDCC)
  - Discretization methods
- ^{11}Li+^{208}Pb at Coulomb barrier energies
  - Dipolar resonance at low energies?
  - Elastic breakup?
- ^{6}He+^{120}Sn,^{208}Pb at Coulomb barrier energies
  - Elastic breakup?
  - Discretization methods?
- ^{9}Be+^{208}Pb,^{120}Sn,p
  - Is the coupling to the continuum still important?
- ^{10}C+^{208}Pb at 66 MeV
- Summary and future work

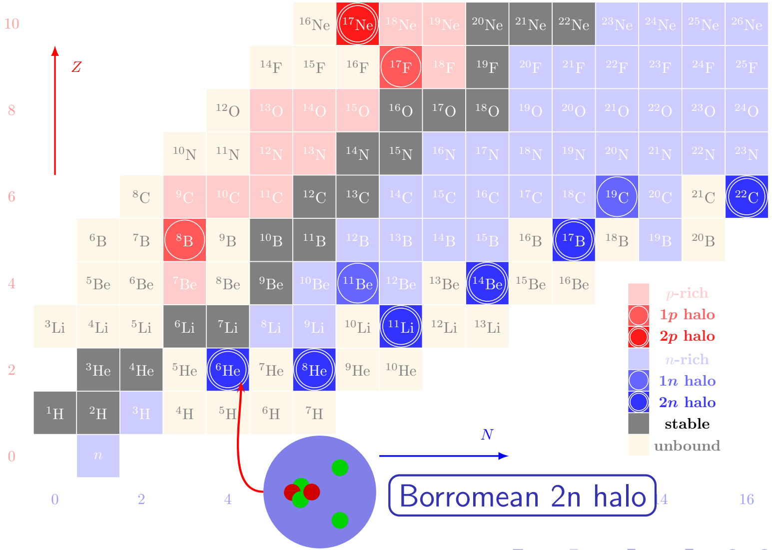
Motivation

Reaction dynamics of exotic and stable weakly-bound nuclei using a four-body CDCC formalism

Manuela Rodríguez Gallardo



Motivation

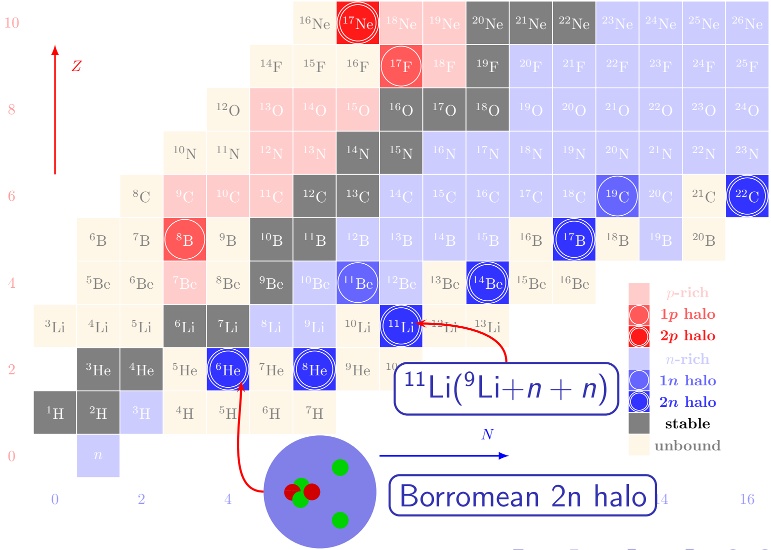


Z
N
0 2 4 6 8 10
0 2 4 14 16
^{16}Ne ^{17}Ne ^{18}Ne ^{19}Ne ^{20}Ne ^{21}Ne ^{22}Ne ^{23}Ne ^{24}Ne ^{25}Ne ^{26}Ne
^{14}F ^{15}F ^{16}F ^{17}F ^{18}F ^{19}F ^{20}F ^{21}F ^{22}F ^{23}F ^{24}F ^{25}F
^{12}O ^{13}O ^{14}O ^{15}O ^{16}O ^{17}O ^{18}O ^{19}O ^{20}O ^{21}O ^{22}O ^{23}O ^{24}O
^{10}N ^{11}N ^{12}N ^{13}N ^{14}N ^{15}N ^{16}N ^{17}N ^{18}N ^{19}N ^{20}N ^{21}N ^{22}N ^{23}N
^{8}C ^{9}C ^{10}C ^{11}C ^{12}C ^{13}C ^{14}C ^{15}C ^{16}C ^{17}C ^{18}C ^{19}C ^{20}C ^{21}C ^{22}C
^{6}B ^{7}B ^{8}B ^{9}B ^{10}B ^{11}B ^{12}B ^{13}B ^{14}B ^{15}B ^{16}B ^{17}B ^{18}B ^{19}B ^{20}B
^{5}Be ^{6}Be ^{7}Be ^{8}Be ^{9}Be ^{10}Be ^{11}Be ^{12}Be ^{13}Be ^{14}Be ^{15}Be ^{16}Be
^{3}Li ^{4}Li ^{5}Li ^{6}Li ^{7}Li ^{8}Li ^{9}Li ^{10}Li ^{11}Li ^{12}Li ^{13}Li
^{3}He ^{4}He ^{5}He ^{6}He ^{7}He ^{8}He ^{9}He ^{10}He
^{1}H ^{2}H ^{3}H ^{4}H ^{5}H ^{6}H ^{7}H
n
p-rich
1p halo
2p halo
n-rich
1n halo
2n halo
stable
unbound
Borromean 2n halo

Motivation

Reaction dynamics of exotic and stable weakly-bound nuclei using a four-body CDCC formalism

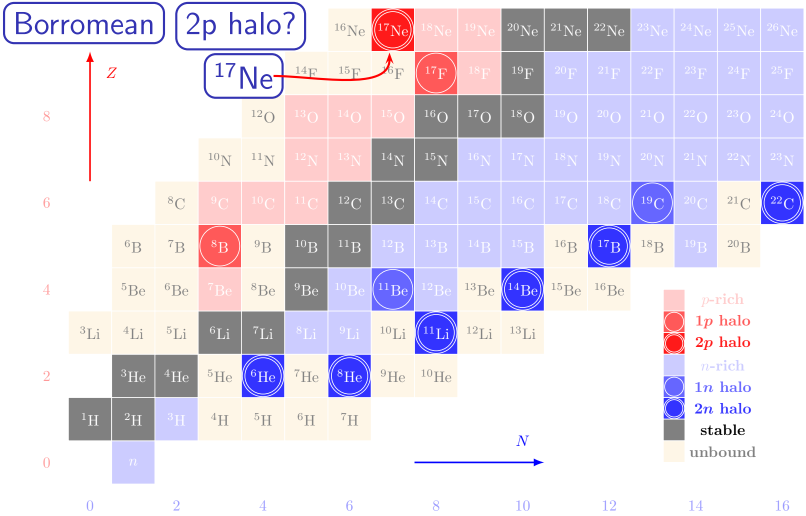
Manuela Rodríguez Gallardo



Motivation

Reaction dynamics of exotic and stable weakly-bound nuclei using a four-body CDCC formalism

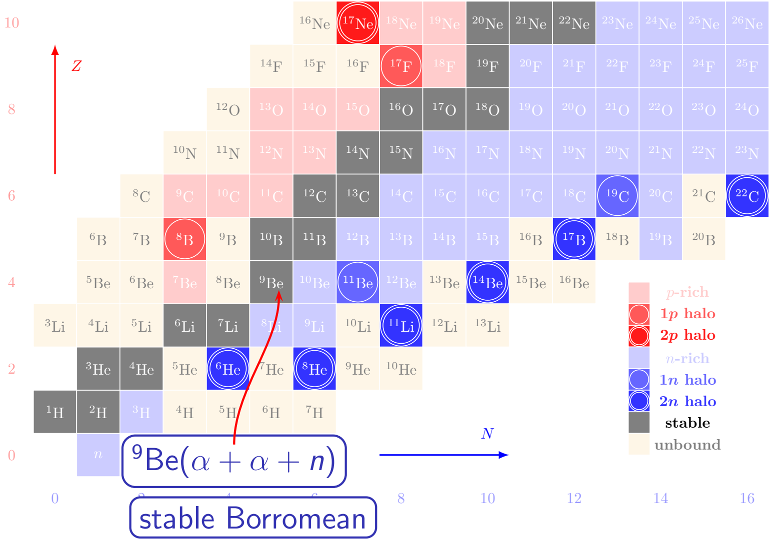
Manuela Rodríguez Gallardo



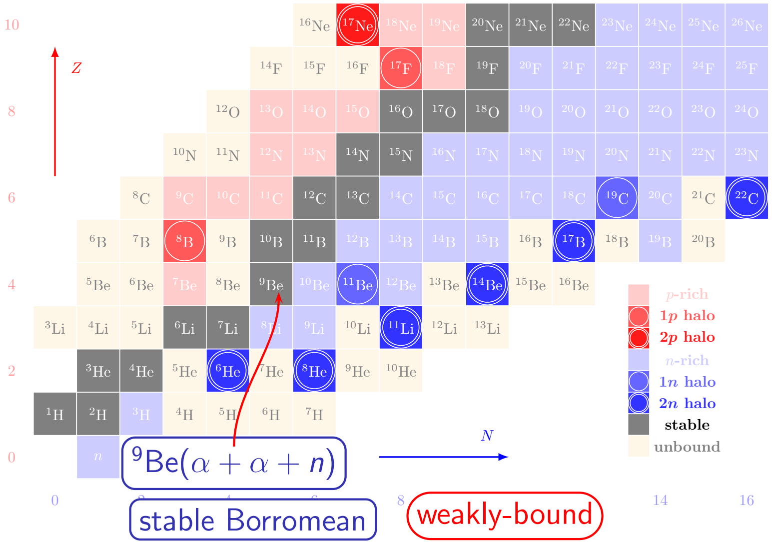
Motivation

Reaction dynamics of exotic and stable weakly-bound nuclei using a four-body CDCC formalism

Manuela Rodríguez Gallardo



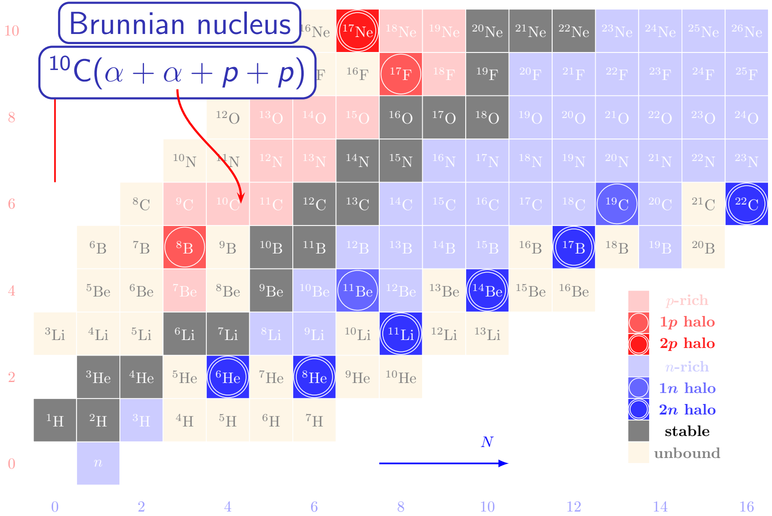
Motivation


Z
N
p-rich
1p halo
2p halo
n-rich
1n halo
2n halo
stable
unbound
^{9}Be($\alpha+\alpha+n$)
stable Borromean
weakly-bound

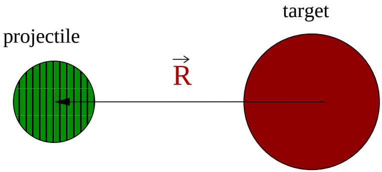
Motivation

Brunnian nucleus

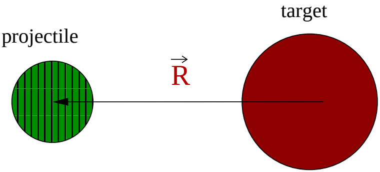
$^{10}\mathrm{C}(\alpha + \alpha + p + p)$



CDCC formalism

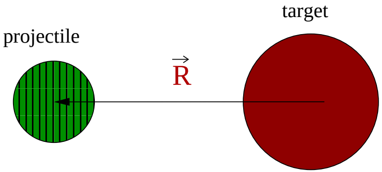


CDCC formalism



$$\Psi_J^M(\vec{R},\xi) = \sum \phi_{jn}^{\mu}(\xi)\langle L M_L j \mu | J M\rangle \frac{i^L}{R} Y_L^{M_L}(\widehat{R}) f_{Lnj}^J(R)$$

CDCC formalism

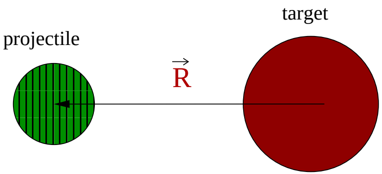


$$\Psi_J^M(\vec{R},\xi) = \sum \phi_{jn}^{\mu}(\xi)\langle L M_L j \mu | J M\rangle \frac{i^L}{R} Y_L^{M_L}(\widehat{R}) f_{Lnj}^J(R)$$

$\Uparrow$

1, 2, 3 $\cdots$ n particles

CDCC formalism



$$\Psi_J^M(\vec{R},\xi) = \sum \phi_{jn}^{\mu}(\xi)\langle L M_L j \mu | J M\rangle \frac{i^L}{R} Y_L^{M_L}(\widehat{R}) f_{Lnj}^J(R)$$

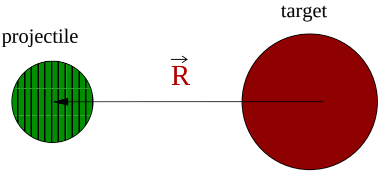
Coupled-channels system

$$\left[-\frac{\hbar^2}{2m_r}\left(\frac{d^2}{dR^2} - \frac{L(L+1)}{R^2}\right) + \varepsilon_{nj} - E\right] f_{Lnj}^J(R) + \sum_{L'n'j'} i^{L'-L} V_{Lnj,L'n'j'}^J(R) f_{L'n'j'}^J(R) = 0$$

⇑

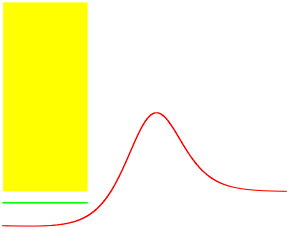
1, 2, $3 \cdots n$ particles

CDCC formalism

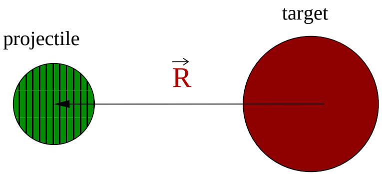


$$\Psi_J^M(\vec{R},\xi) = \sum \phi_{jn}^{\mu}(\xi)\langle L M_L j \mu | J M\rangle \frac{i^L}{R} Y_L^{M_L}(\widehat{R}) f_{Lnj}^J(R)$$

$\phi_n^{j\mu}(\xi)$?



CDCC formalism

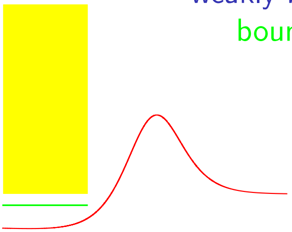


$$\Psi_J^M(\vec{R},\xi) = \sum \phi_{jn}^{\mu}(\xi)\langle L M_L j \mu | J M\rangle \frac{i^L}{R} Y_L^{M_L}(\widehat{R}) f_{Lnj}^{J}(R)$$

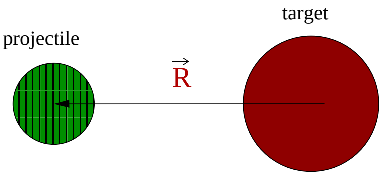
weakly-bound systems

bound+continuum

$\phi_n^{j\mu}(\xi)$?



CDCC formalism

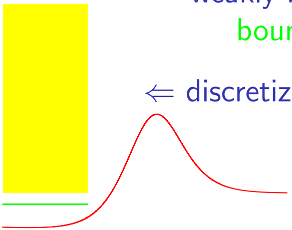


$$\Psi_J^M(\vec{R},\xi) = \sum \phi_{jn}^{\mu}(\xi)\langle L M_L j \mu | J M\rangle \frac{i^L}{R} Y_L^{M_L}(\widehat{R}) f_{Lnj}^J(R)$$

weakly-bound systems

bound+continuum

$\phi_n^{j\mu}(\xi)$?



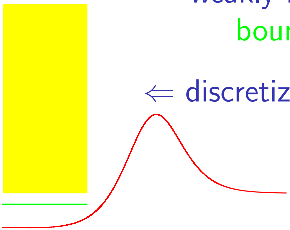
$\Leftarrow$ discretization methods

Discretization methods

weakly-bound systems

bound+continuum

$\phi_n^{j\mu}(\xi)$?



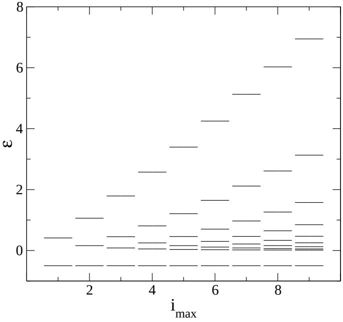
$\Leftarrow$ discretization methods

Discretization methods

1. Pseudo-State (PS) methods: They consist in diagonalizing the Hamiltonian in a complete discrete basis, truncated at a maximum number of states

Discretization methods

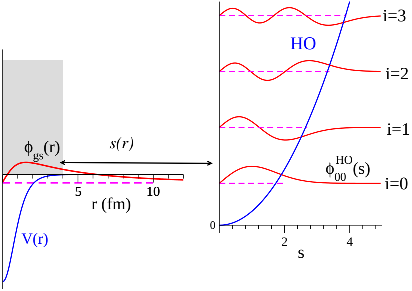
1. Pseudo-State (PS) methods: They consist in diagonalizing the Hamiltonian in a complete discrete basis, truncated at a maximum number of states



- PS $\varepsilon < 0 \rightarrow$ bound states
- PS $\varepsilon > 0 \rightarrow$ discrete representation of the energy continuum

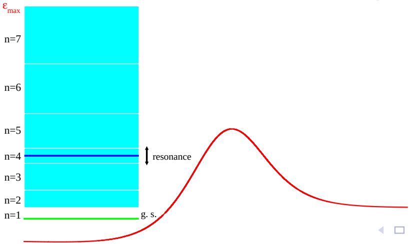
Discretization methods

1. Pseudo-State (PS) methods: They consist in diagonalizing the Hamiltonian in a complete discrete basis, truncated at a maximum number of states
   - ✏ The PS method can be used for systems with more than one charged particle
   - ✏ Transformed Harmonic Oscillator (THO) method



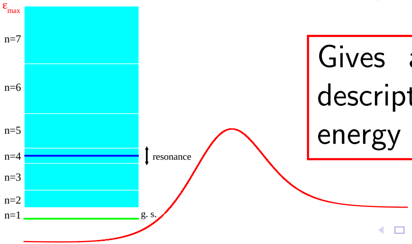
Discretization methods

1. Pseudo-State (PS) methods: They consist in diagonalizing the Hamiltonian in a complete discrete basis, truncated at a maximum number of states
   - ✏ The PS method can be used for systems with more than one charged particle
   - ✏ Transformed Harmonic Oscillator (THO) method
2. Binning procedure: It consists in calculating the true continuum states and making packages of energy



Discretization methods

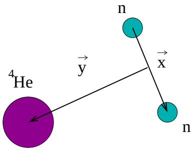
1. Pseudo-State (PS) methods: They consist in diagonalizing the Hamiltonian in a complete discrete basis, truncated at a maximum number of states
   - The PS method can be used for systems with more than one charged particle
   - Transformed Harmonic Oscillator (THO) method
2. Binning procedure: It consists in calculating the true continuum states and making packages of energy



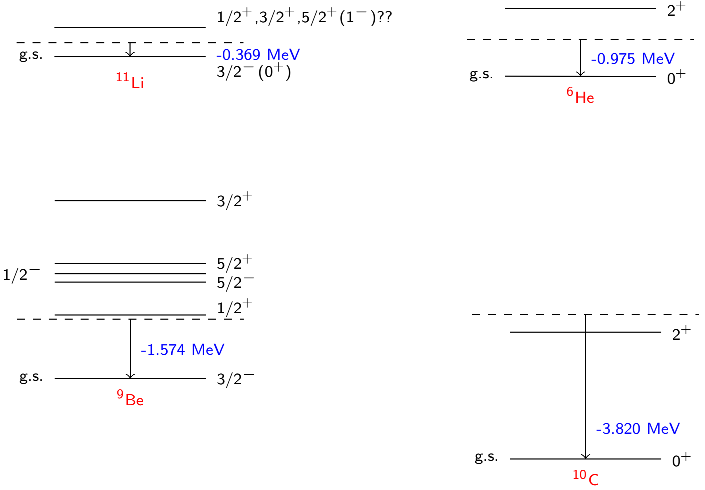
Gives a more precise description of the low-energy continuum

Four-body CDCC (three-body projectiles)

- Three-body THO:
  Rodríguez-Gallardo et al., PRC 72 (2005) 024007
- Four-body CDCC with THO method:
  Rodríguez-Gallardo et al., PRC 77 (2008) 064609
- Four-body CDCC with binning procedure:
  Rodríguez-Gallardo et al., PRC 80 (2009) 051601(R)
- Three-body Analytical THO (ATHO) method:
  Casal et al., PRC 88 (2013) 014327
- Four-body CDCC with ATHO:
  Casal et al., PRC 92 (2015) 054611

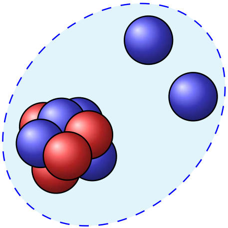


Application to ^{11}Li, ^{6}He, ^{9}Be and ^{10}C

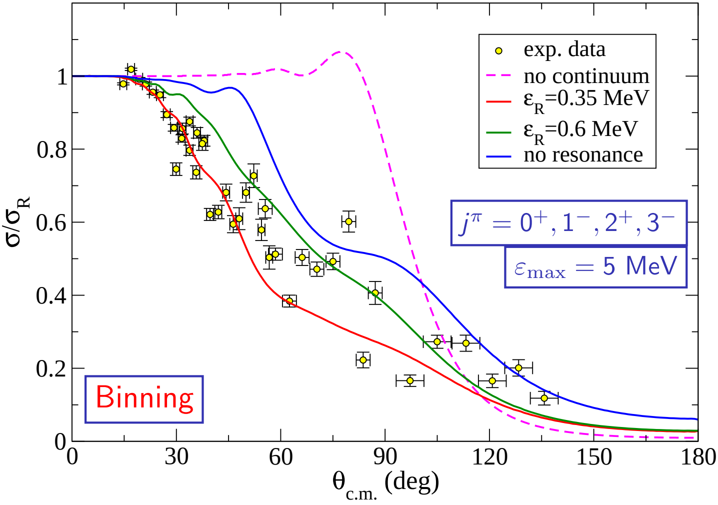


$$^{11}\mathrm{Li}(^{9}\mathrm{Li}{+}n+n)$$

$$\varepsilon_{gs} = -0.369\ \mathrm{MeV}$$

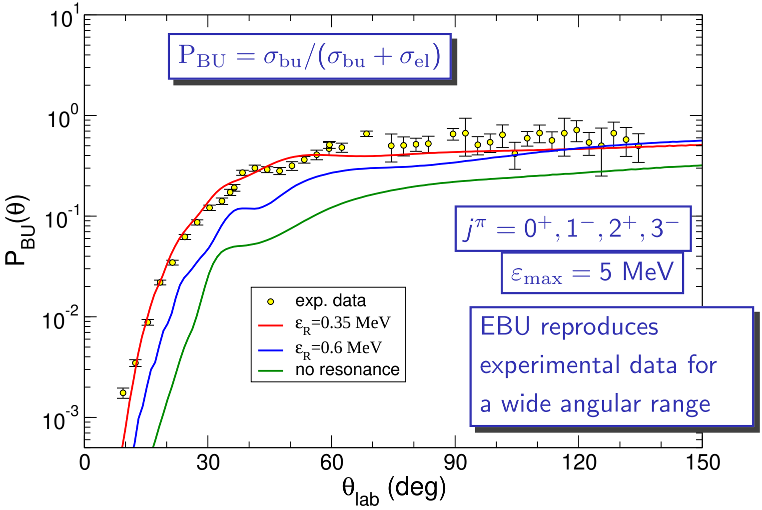


^{11}Li+^{208}Pb at 29.8 MeV (elastic)



Cubero et al., PRL 109 (2012) 262701

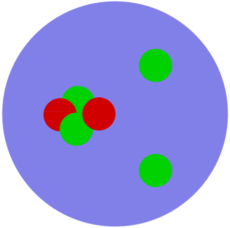
^{11}Li+^{208}Pb at 29 MeV (breakup)



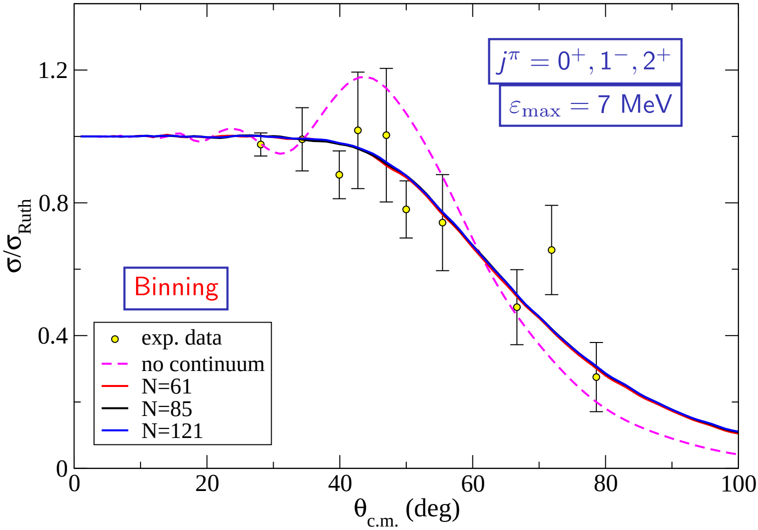
Fernández-García et al., PRL 110 (2013) 142701

$$^{6}\text{He}(^{4}\text{He}+n+n)$$

$$\varepsilon_{gs} = -0.975 \text{ MeV}$$

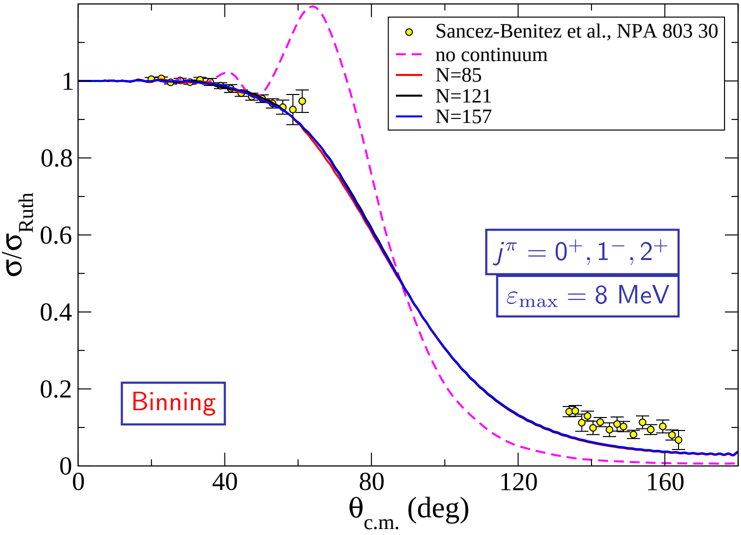


$^{6}He+^{120}Sn$ at 17.4MeV (elastic)

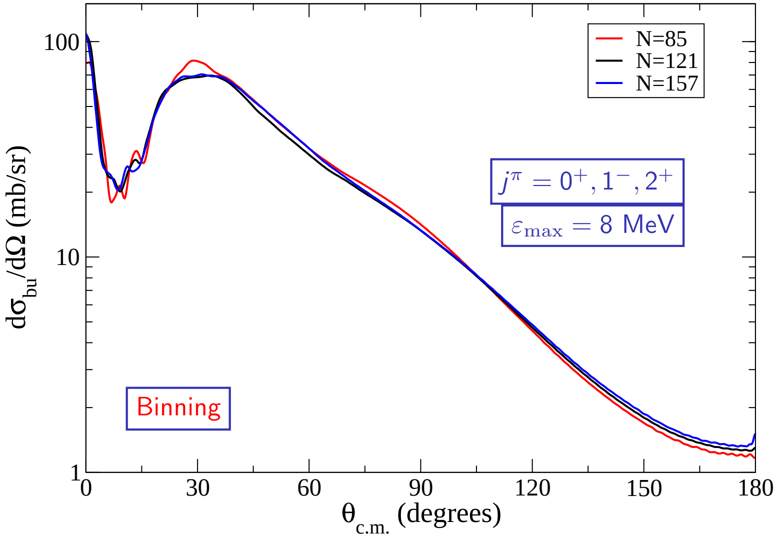


de Faria et al., PRC 81 (2010) 044605

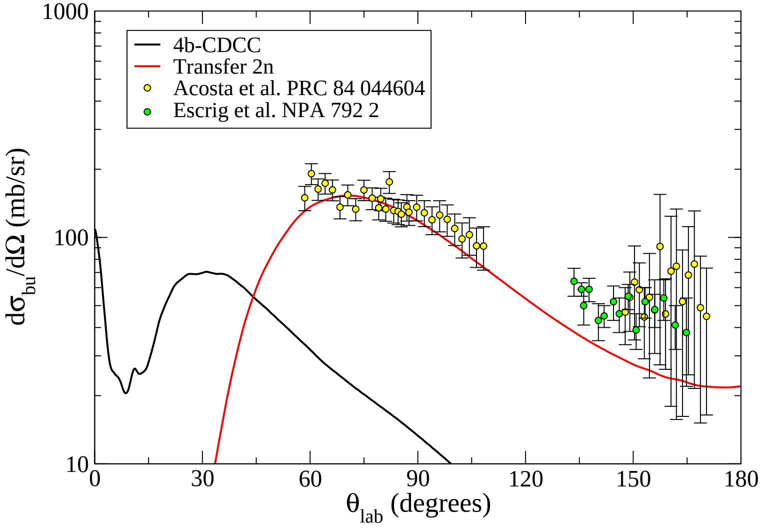
^{6}He+^{208}Pb at 22MeV (elastic)



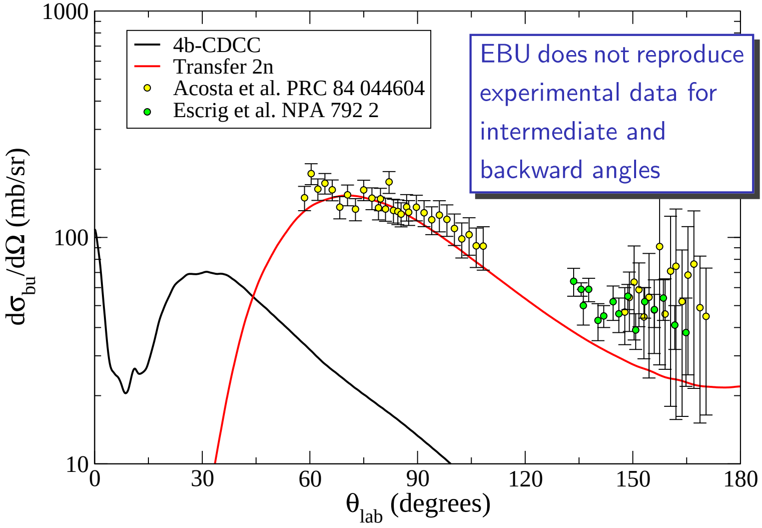
^{6}He+^{208}Pb at 22MeV (breakup)



^{6}He+^{208}Pb at 22 MeV: EBU vs transfer

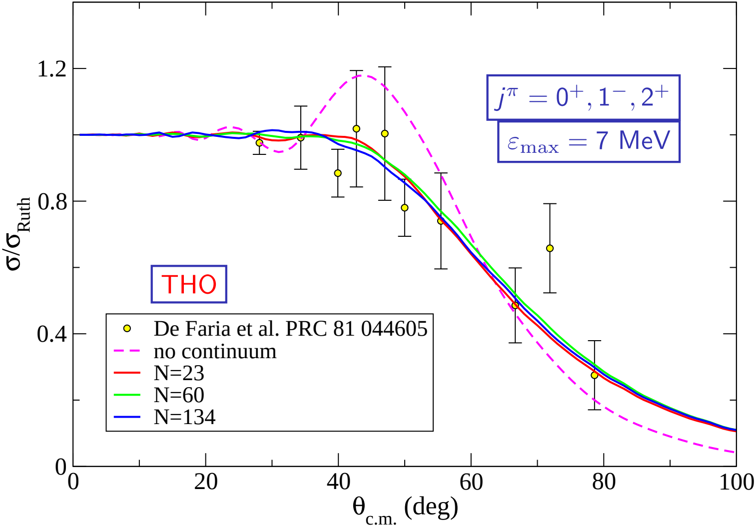


^{6}He+^{208}Pb at 22 MeV: EBU vs transfer



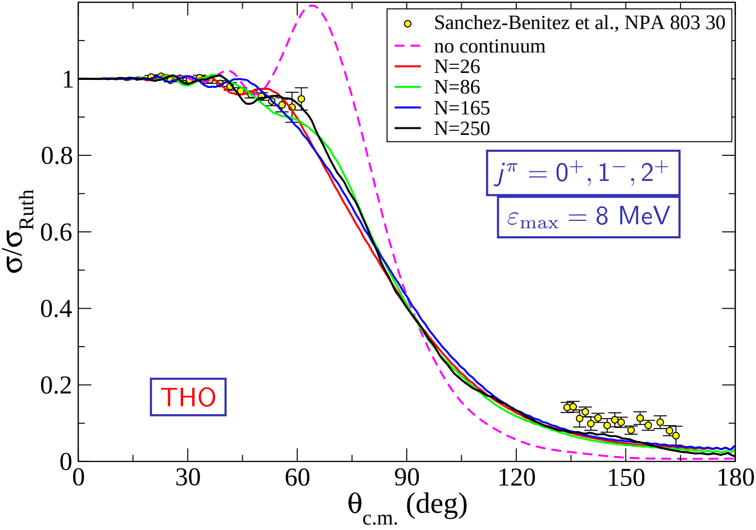
EBU does not reproduce experimental data for intermediate and backward angles

$^{6}He+^{120}Sn$ at 17.4 MeV (elastic)

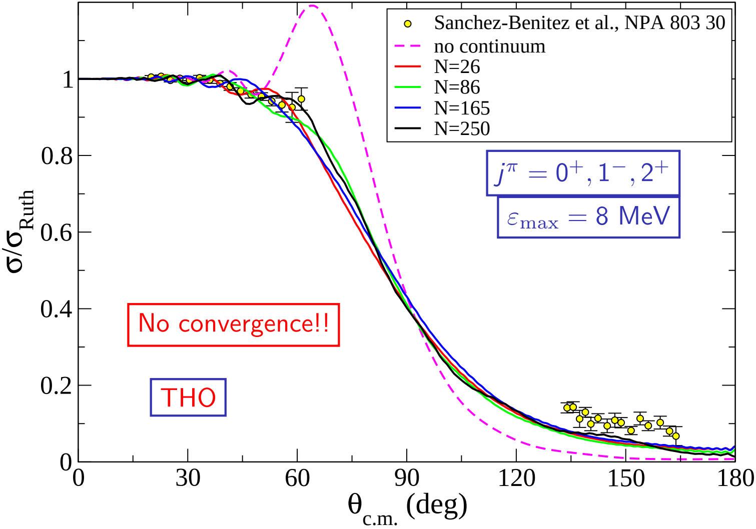


de Faria et al., PRC 81 (2010) 044605

^{6}He+^{208}Pb at 22 MeV (elastic)



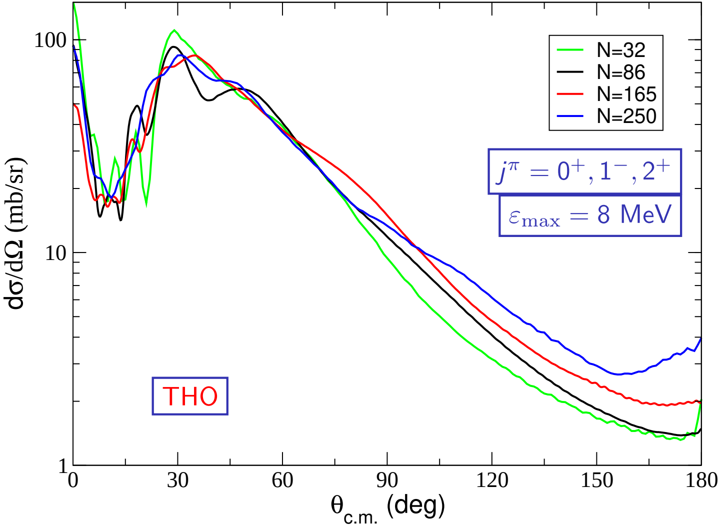
$^{6}He+^{208}Pb$ at 22 MeV (elastic)



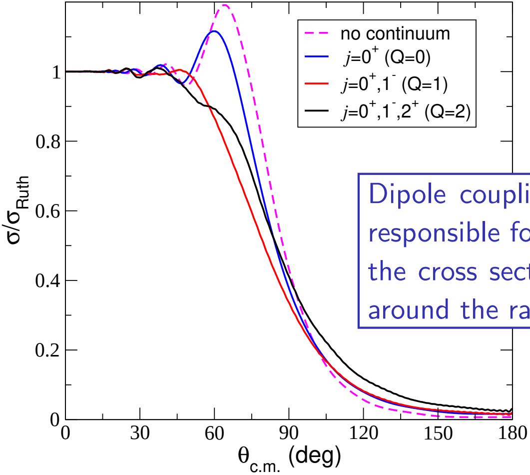
$^{6}He+^{208}Pb$ at 22 MeV (breakup)

Reaction dynamics of exotic and stable weakly-bound nuclei using a four-body CDCC formalism

Manuela Rodríguez Gallardo



$^{6}He+^{208}Pb$ at 22 MeV (multipoles)

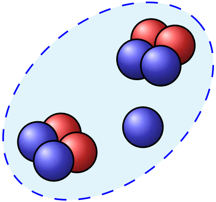


Dipole couplings are the main responsible for the reduction of the cross section at the angles around the rainbow

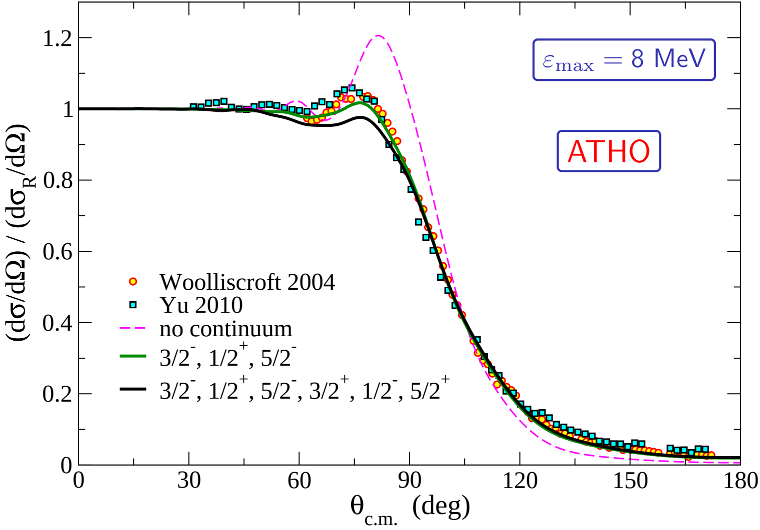
Rodríguez-Gallardo et al., PRC 80 (2009) 051601(R)

$$^{9}\mathrm{Be}(^{4}\mathrm{He}+^{4}\mathrm{He}+n)$$

$$\varepsilon_{gs} = -1.574 \text{ MeV}$$

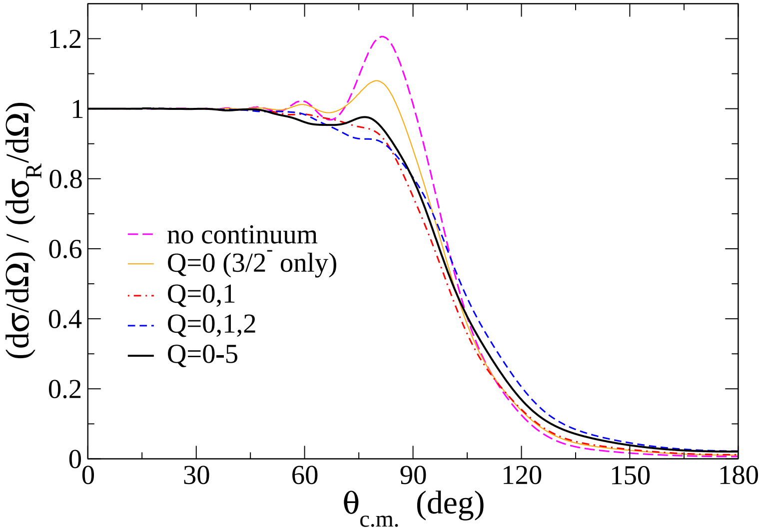


^{9}Be+^{208}Pb at 44 MeV (elastic)

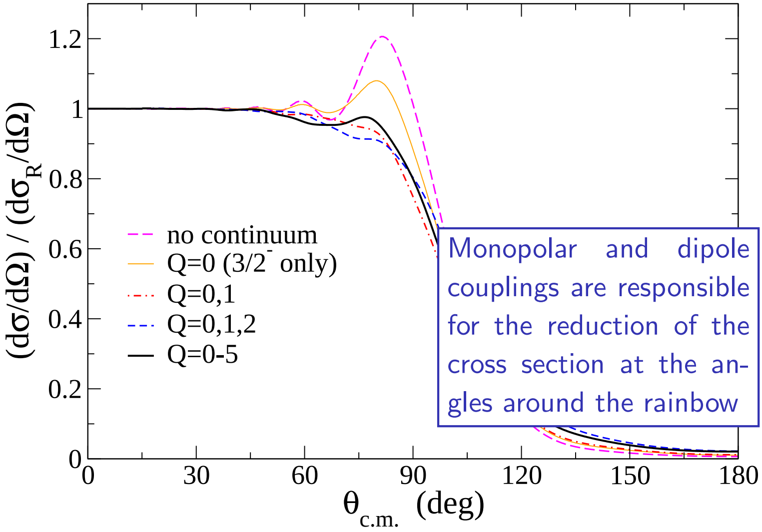


J. Casal et al., Phys. Rev. C 92 (2015) 054611

^{9}Be+^{208}Pb at 44 MeV (multipoles)

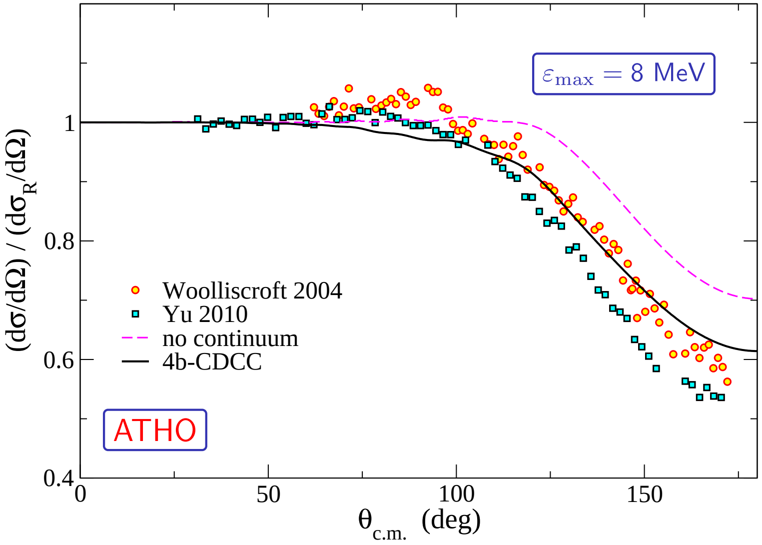


^{9}Be+^{208}Pb at 44 MeV (multipoles)

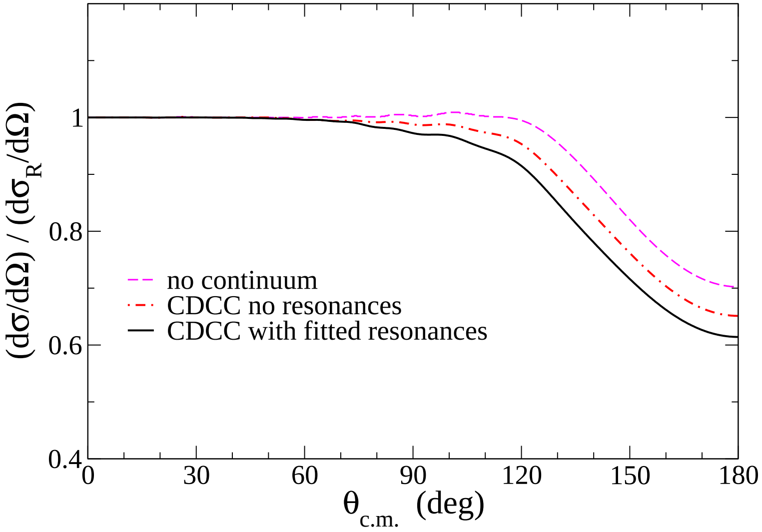


Monopolar and dipole couplings are responsible for the reduction of the cross section at the angles around the rainbow

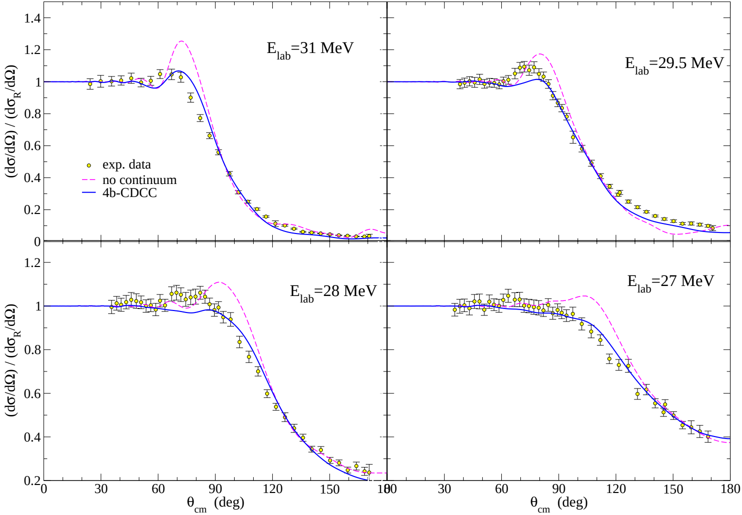
$^{9}Be+^{208}Pb$ at 38 MeV (elastic)



^{9}Be+^{208}Pb at 38 MeV (resonances)



^{9}Be+^{120}Sn at TANDAR (Argentina)

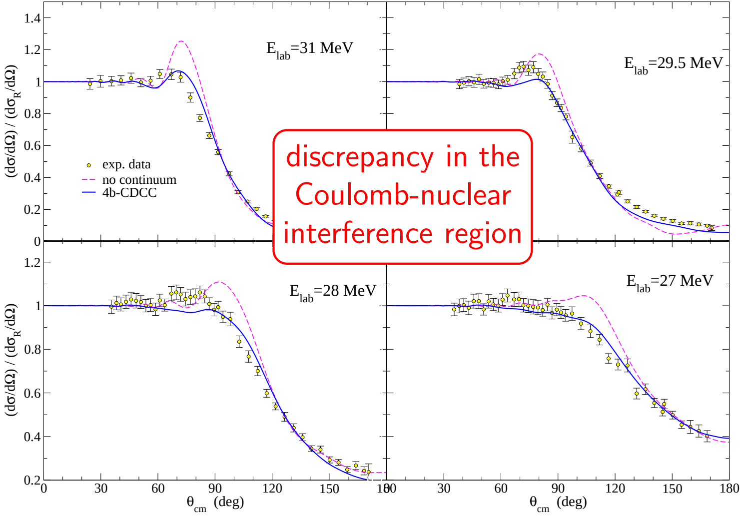


Arazi et al., PRC 97 (2018) 044609

$^{9}Be + ^{120}Sn$ at TANDAR (Argentina)

Reaction dynamics of exotic and stable weakly-bound nuclei using a four-body CDCC formalism

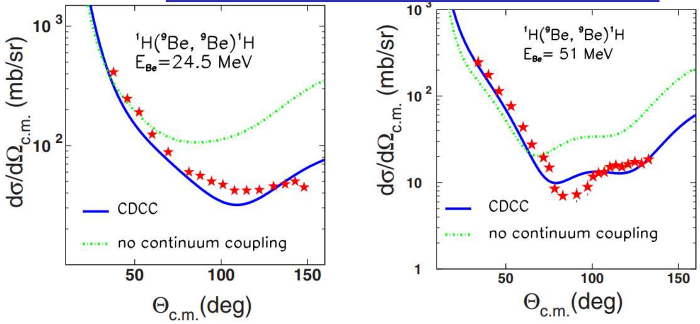
Manuela Rodríguez Gallardo



Arazi et al., PRC 97 (2018) 044609

^{9}Be$+p$ at 24.5 and 51 MeV (elastic)

$\varepsilon_{\max} = 8$ MeV; $j^{\pi} = 1/2^{\pm}, 3/2^{\pm}, 5/2^{\pm}$



$\sigma_{bu}^{exp} = 2.5 \pm 1$ mb
$\sigma_{bu}^{CDCC} = 3.67$ mb
coupling to near-threshold $1/2^{+}$ resonance

$\sigma_{bu}^{exp} = 142 \pm 20$ mb
$\sigma_{bu}^{CDCC} = 163$ mb
50% of σ_{bu} is due to the $5/2^{-}$ narrow resonance

Soukeras et al., PRC 102 (2020) 064622

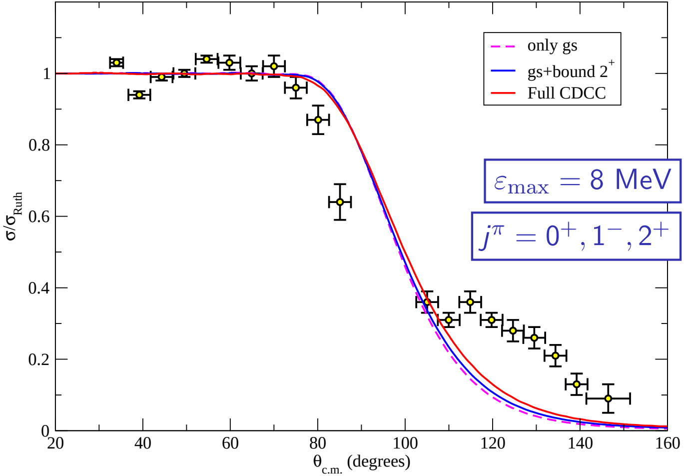
^{10}C(^{8}Be$+p+p$)

$\varepsilon_{gs} = -3.820$ MeV

$^{10}C+^{208}Pb$ at 66 MeV (elastic)

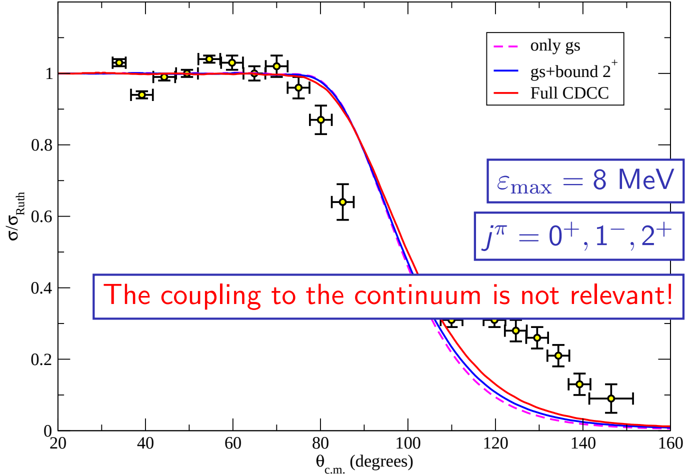
Reaction dynamics of exotic and stable weakly-bound nuclei using a four-body CDCC formalism

Manuela Rodríguez Gallardo



Linares et al., PRC 103 (2021) 044613

^{10}C+^{208}Pb at 66 MeV (elastic)



$\varepsilon_{\max} = 8$ MeV

$j^{\pi} = 0^+, 1^-, 2^+$

The coupling to the continuum is not relevant!

Linares et al., PRC 103 (2021) 044613

Summary

- We have studied the reactions induced by 3b weakly-bound nuclei using the 4b CDCC formalism.
- Some conclusions:
  - The coupling to the continuum is very important for low binding energy nuclei.
  - The reactions induced by halo nuclei (^{6}He, ^{11}Li) on heavy targets at energies around the Coulomb barrier have to be studied with a very precise description of the low-energy continuum (binning). In this case, ^{11}Li bu is dominated by EBU and ^{6}He is dominated by transfer.
  - For ^{9}Be, the suppression of the rainbow is due to monopolar and dipolar couplings and for ^{6}He and ^{11}Li, is due to dipolar couplings.
  - It is crutial to have a Hamiltonian with the correct positions of the resonances.
  - The halo nuclei ^{11}Li could have a dipolar resonance at around 0.35 MeV over the bu threshold.

Future work

- The application of the formalism to the Borromean pronton-rich nuclei ^{17}Ne(^{15}O$+p+p$),
- The application of the formalism to the 4-neutron halo nuclei ^{8}He(^{4}He$+n+n+n+n \equiv {}^{6}$He$+n+n$).
- The extension of the 4b-CDCC to include the core excitation of the projectile:
  - ^{8}He(^{6}He$+n+n$) with ^{6}He excitations;
  - ^{10}C(^{8}Be$+p+p$) with ^{8}Be excitations.

- Three-body radiative capture reaction rates of astrophysical interest, from the $B(O\lambda)$ distributions.