Consistent description for ^{11}Li scattering from light to heavy targets

Manuela Rodríguez-Gallardo
José Antonio Lay **Antonio Moro**
Joaquín Gómez-Camacho

Universidad de Sevilla

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Outline

- Motivation: Borromean nucleus ^{11}Li
- Continuum-Discretized Coupled-Channels (CDCC)
  - Discretization methods
- $B(E1)$ using different structure models
- Four-body CDCC applied to:
  - ^{11}Li+^{208}Pb at 29 MeV
    - Dipolar resonance at low energies
  - ^{11}Li+^{64}Zn at 22.5 MeV
  - ^{11}Li+d at 55.3 MeV
  - ^{11}Li+p at 66 MeV
- $B(E1)$ vs $B(E1)_{iso}$?
- Summary and future work

Motivation

Consistent description for ^{11}Li scattering from light to heavy targets

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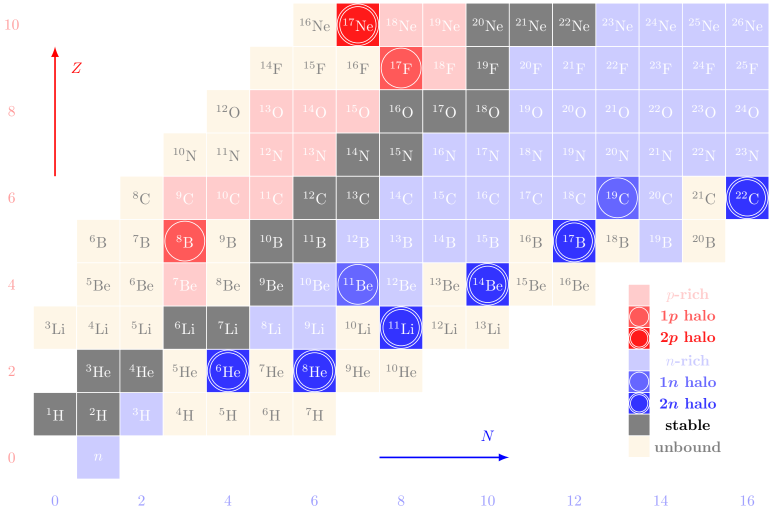

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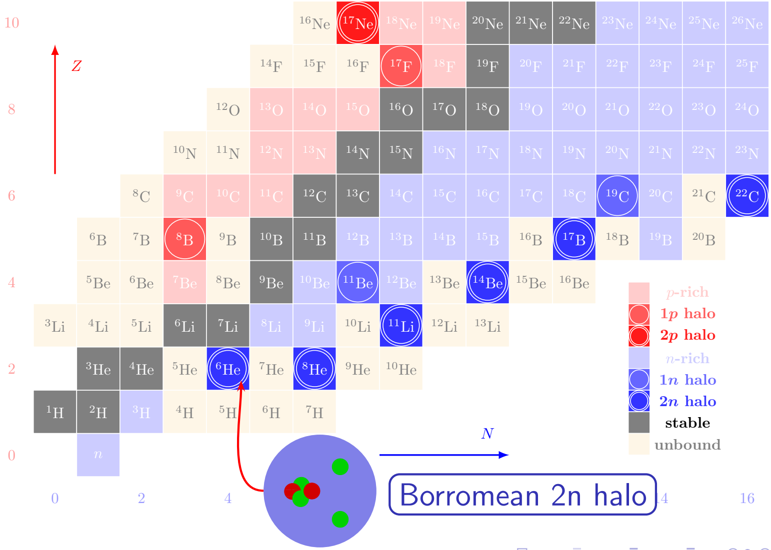

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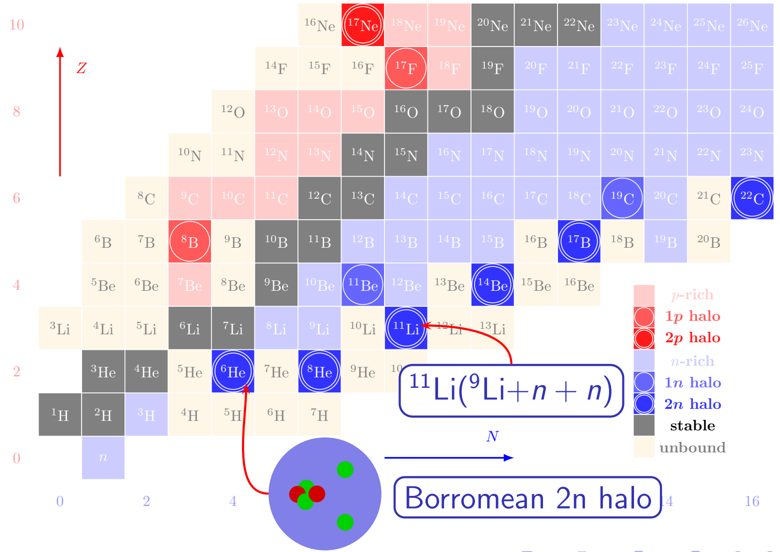
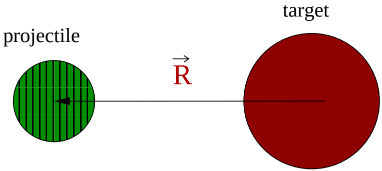
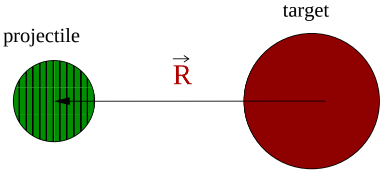


CDCC formalism

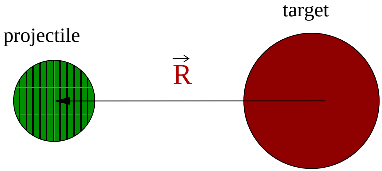


CDCC formalism



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

CDCC formalism

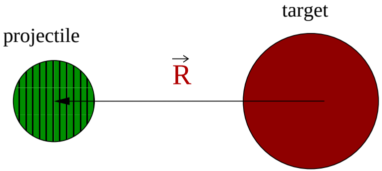


$$\Psi_J^M(\vec{R},\xi) = \sum \phi_{jn}^{\mu}(\xi)\langle L M_L j \mu | JM \rangle \frac{i^L}{R} Y_L^{M_L}(\widehat{R}) f_{Lnj}^J(R)$$

$\Uparrow$

1, 2, 3 $\cdots$ n particles

CDCC formalism



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

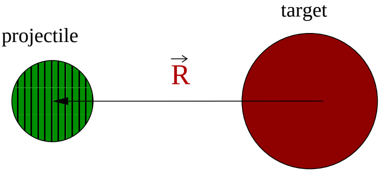
Coupled-channels system

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

⇑

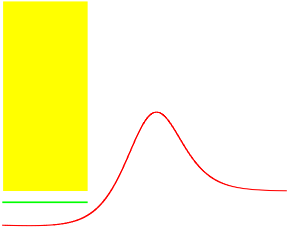
$1,\ 2,\ 3\cdots n$ particles

CDCC formalism

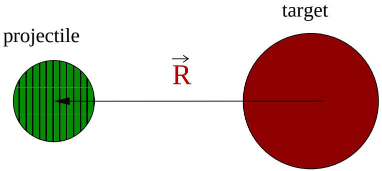


$$\Psi_J^M(\vec{R},\xi) = \sum \phi_{jn}^{\mu}(\xi)\langle L M_L j \mu | J M\rangle \frac{i^L}{R} Y_L^{M_L}(\widehat{R}) f_{Lnj}^{J}(R)$$

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



CDCC formalism



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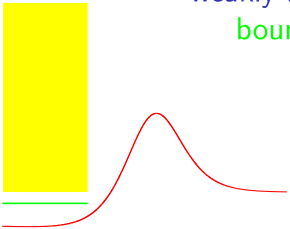
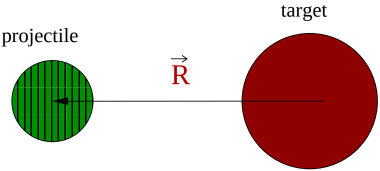
weakly-bound systems

bound+continuum

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



CDCC formalism



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

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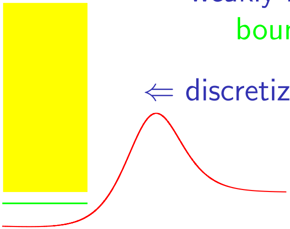
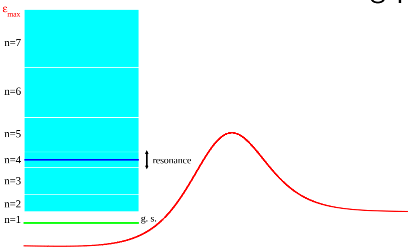


$\Leftarrow$ discretization methods

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
   - ✏ Transformed Harmonic Oscillator (THO) method
2. Binning procedure: It consists in calculating the true continuum states and making packages of energy



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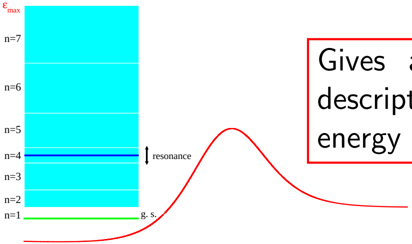
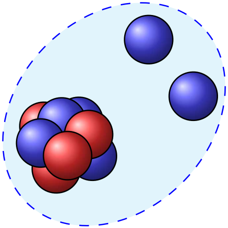


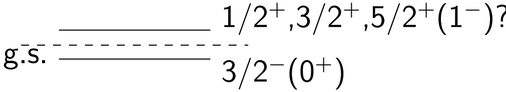
Gives a more precise description of the low-energy continuum

Application to ^{11}Li

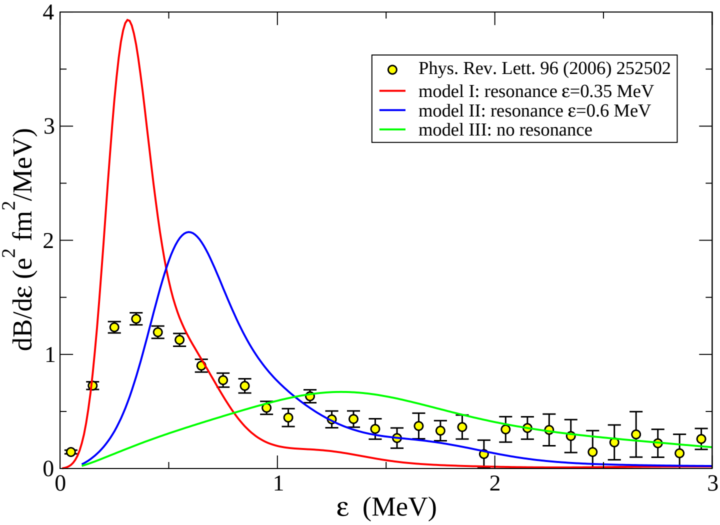
$$\boxed{^{11}\text{Li}(^{9}\text{Li}+n+n)}$$

$$\boxed{\varepsilon_{gs} = -0.369 \text{ MeV}}$$

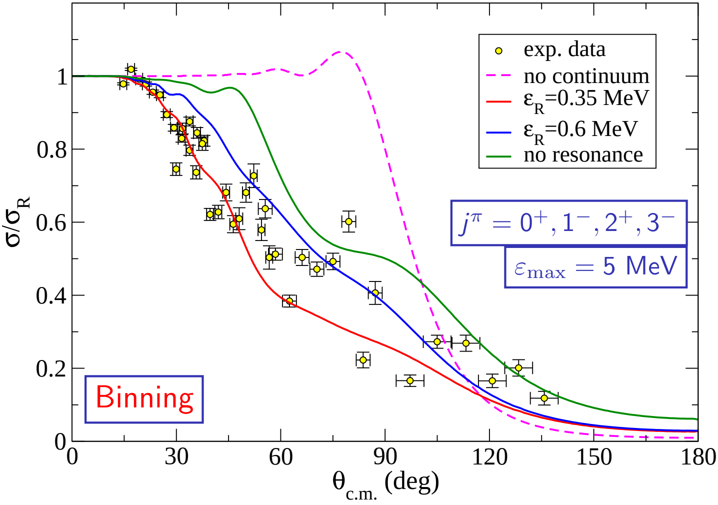




$B(E1)$ distribution



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



Cubero et al., PRL 109 (2012) 262701

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

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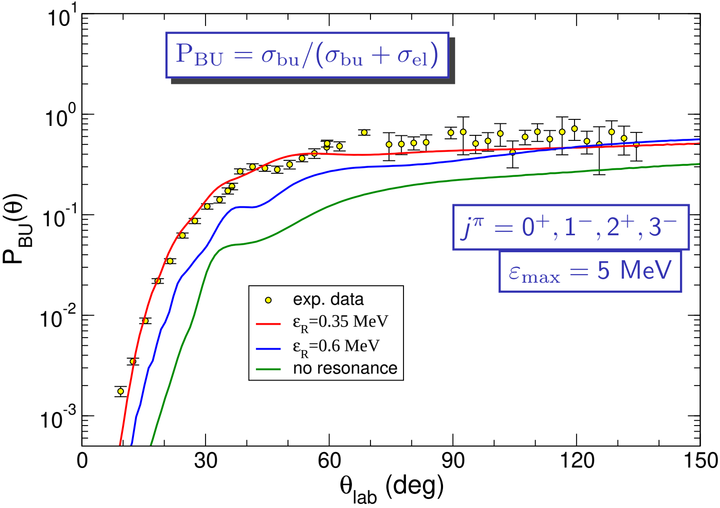
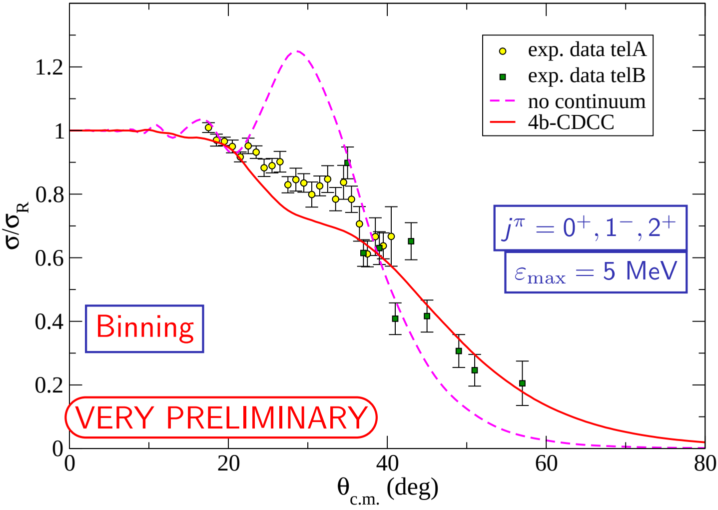


✉ Fernández-García et al., PRL 110 (2013) 142701

^{11}Li+^{64}Zn at 22.5 MeV (elastic)



S1847 (TRIUMF, Canada): A. di Pietro, J.P. Fernández et al.

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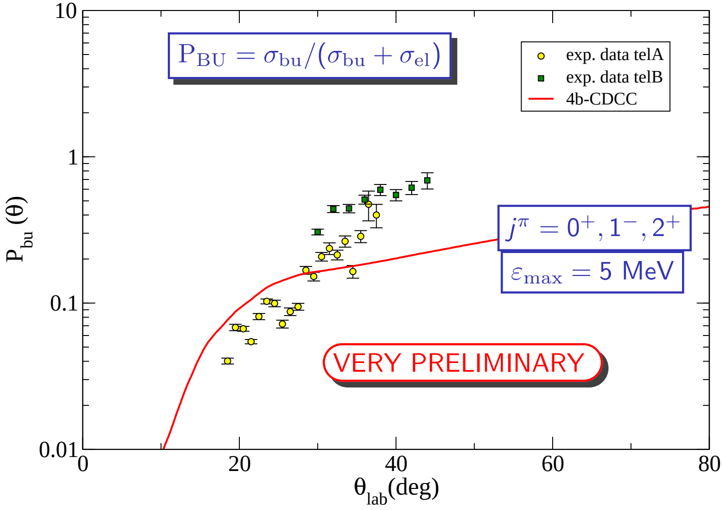

S1847 (TRIUMF, Canada): A. di Pietro, J.P. Fernández et al.

What about light targets?

- ^{11}Li+^{208}Pb,^{64}Zn at eneregies around the Coulomb barrier are Coulomb-dominated reactions.
- These reactions can be then understood as an isovectorial type excitation, being due mainly to the dipolar electric excitation ($B(E1)$).
- However, the reactions on light targets like p and more specially d are not Coulomb-dominated reactions so the excitations can be undesrtood more as an isoscalar excitation.
- What happens if we apply the same ^{11}Li structure model reproducing the data on ^{208}Pb,^{64}Zn to the reactions on p and d published more recently?

^{11}Li+d at 55.3 MeV (elastic)

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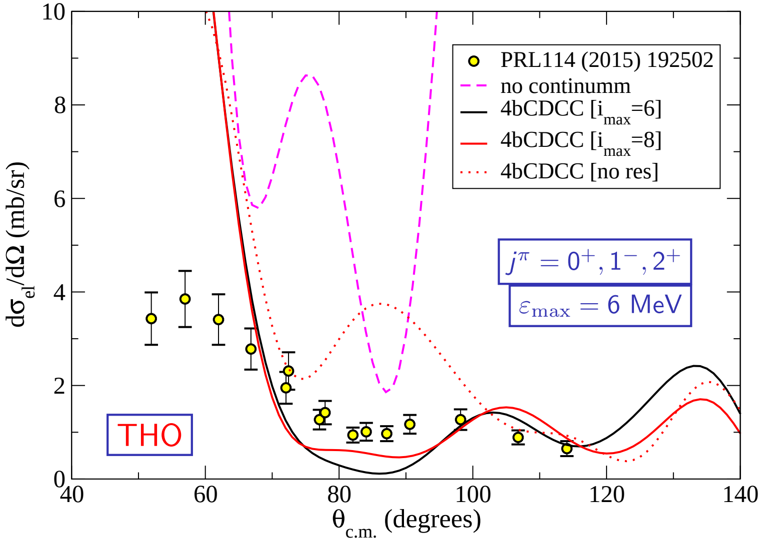
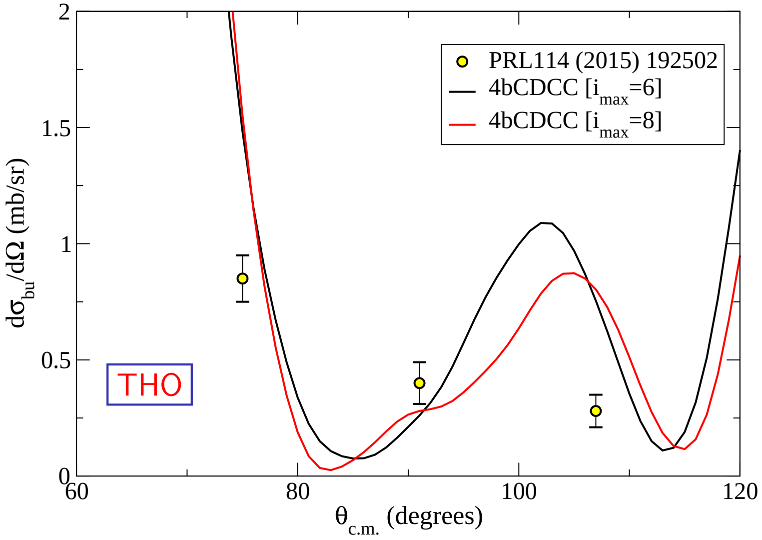
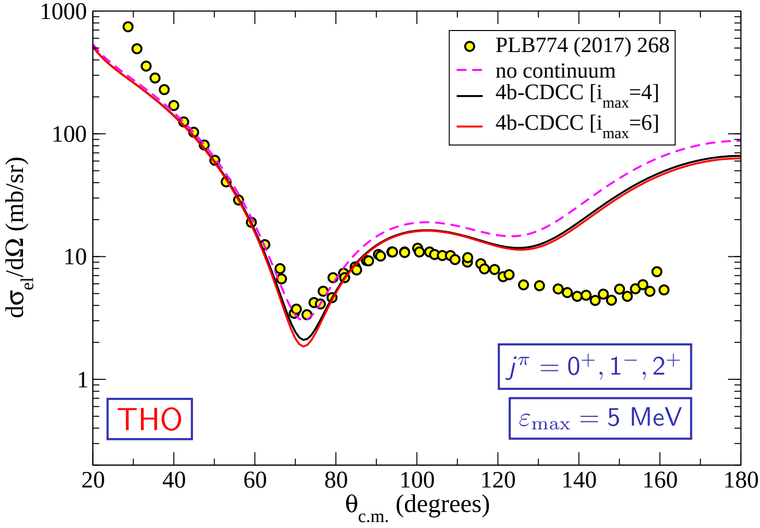


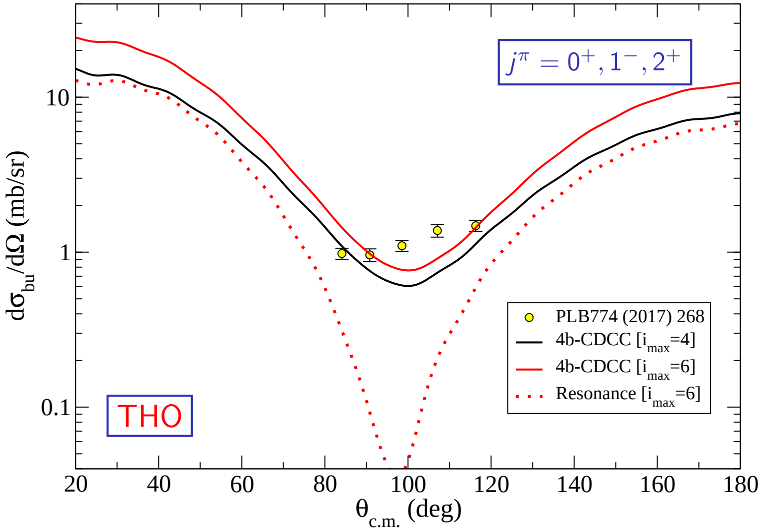
^{11}Li+d at 55.3 MeV (bu to resonance)



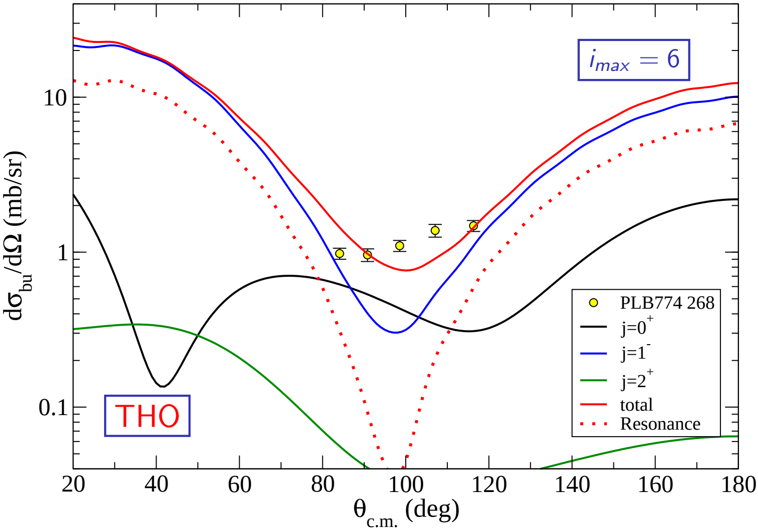
^{11}Li+p at 66 MeV (elastic)



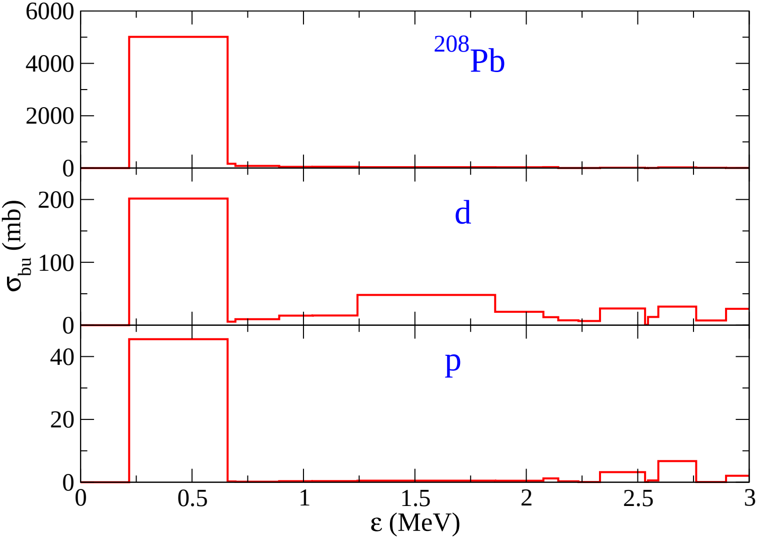
^{11}Li+p at 66 MeV (bu up to 3 MeV)



^{11}Li+p at 66 MeV (bu up to 3 MeV)



Energy distributions states $j = 1^-$



$B(E1)$ vs $B(E1)_{iso}$

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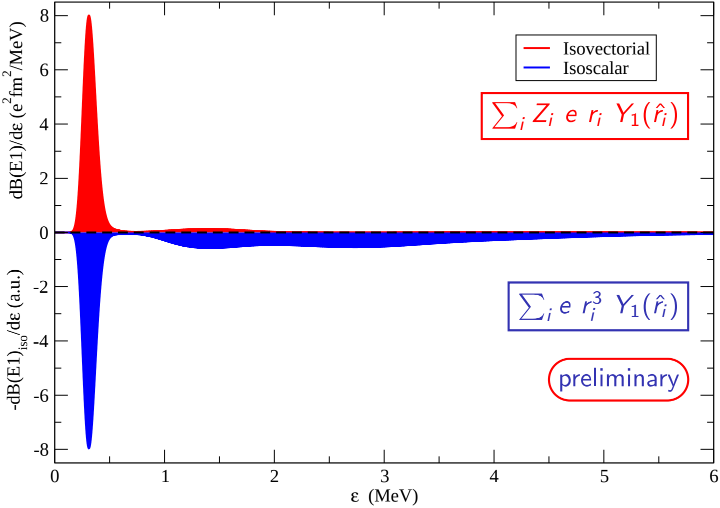

- Thanks to E. Lanza for discussions on the isoscalar part.

Summary and conclusions

- Systmatic analysis of existing ^{11}Li elastic and bu data on light and heavy targets have been performed in terms of the 4-body CDCC formalism.
- The comparison between experimental data (elastic and bu) and 4b-CDCC calculations for ^{11}Li+^{208}Pb suggested the existence of a dipolar resonance at about 0.7 MeV over the g.s.
- The same structure model, with a dipolar resonance at low energies, can also explain reasonably well the experimental data for ^{11}Li+^{64}Zn at 22.5 MeV, ^{11}Li+d at 55.2 MeV and ^{11}Li+p at 66 MeV.
- The comparison (preliminary) between isovectorial and isoscalar $B(E1)$ distributions reveals a large coupling to the same resonant state.

Acknowledgments

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Unión Europea

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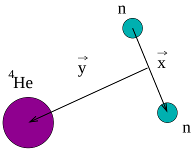
P20_01247

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



Optical potentials

- ^{9}Li+^{208}Pb,^{64}Zn from adjustment to experimental data from same experiment.
- ^{9}Li+p from folding with JLM nucleon-nucleon interaction (^{9}Li density as a simple Fermi distribution).
- ^{9}Li+d as a TELP from d breakup on ^{9}Li with n/p+^{9}Li optical potential with same folding with JLM.
- n+^{208}Pb,^{64}Zn Koning & Delaroche.
- $n + p$ effective Gaussian potential.
- $n + d$ as a TELP from previous $n + p$ interaction.

Experimental $B(E1)$

PRL **96**, 252502 (2006) PHYSICAL REVIEW LETTERS week ending 30 JUNE 2006

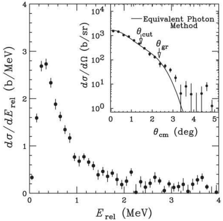


FIG. 2. Breakup cross sections for ^{11}Li + Pb at 70 MeV/nucleon as a function of the three-body relative energy for data with $\theta_{cm} \leq 5°$. Inset: Angular distribution of ^{11}Li (the ^{9}Li + n + n c.m.) scattered by the Pb target in the range $0 \leq E_{rel} \leq 4$ MeV. θ_{gr} denotes the grazing angle (2.34°). The calculation using the equivalent photon method is shown by the solid curve

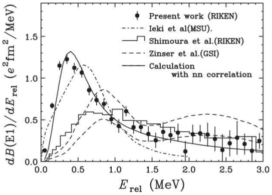


FIG. 3. The $B(E1)$ distribution obtained in the present work (solid circles) is compared with those from previous measurements [dotted-dashed line [13], solid histogram [14], dashed lines (zone) [15]]. The present data are also compared with the calculation (solid line) [20] which included the full n-n correlation.

- Indirec measurement: from Coulomb breakup data.
- Based on the Equivalent Photon Model (EPM).