Inelastic scattering: the Coupled-Channels and DWBA methods

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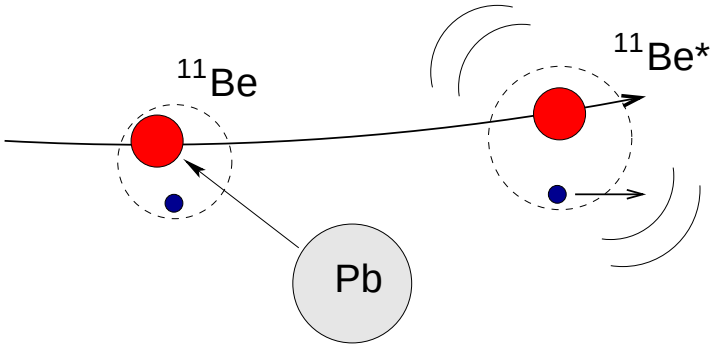
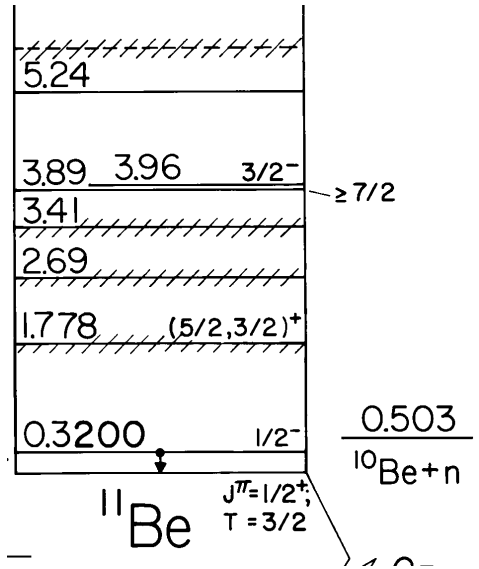
Material available at: `https://github.com/ammoro/padova`

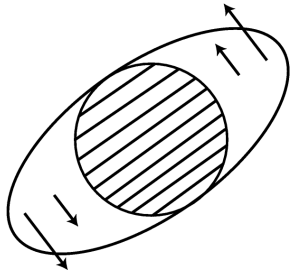
Inelastic scattering to bound states

- Nuclei are not inert or *frozen* objects; they do have an internal structure of protons and neutrons that can be modified (excited) during the collision.
- Quantum systems exhibit, in general, an energy spectrum with bound and unbound levels.

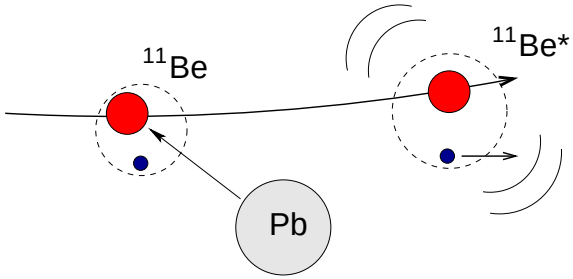




1. COLLECTIVE: Involve a collective motion of several nucleons which can be interpreted macroscopically as rotations or surface vibrations of the nucleus.



2. FEW-BODY/SINGLE-PARTICLE: Involve the excitation of a nucleon or cluster.



- **Goal:** Determine the differential cross section for an inelastic process of the form: $a + A \rightarrow a + A^*$

- The scattering wavefunction $\Psi^{(+)}_{\mathbf{K}_0}(\mathbf{R}, \xi)$ must contain, besides the elastic scattering component, additional components associated to excited states.

- Asymptotically:

$$\Psi^{(+)}_{\mathbf{K}_0}(\mathbf{R}, \xi) \xrightarrow{R\gg} \underbrace{e^{i\mathbf{K}_0\cdot\mathbf{R}}\phi_0(\xi)}_{\text{incident}} + \underbrace{f_{0,0}(\theta)\frac{e^{iK_0R}}{R}\phi_0(\xi)}_{\text{elastic}} + \underbrace{\sum_{n>0} f_{n,0}(\theta)\frac{e^{iK_nR}}{R}\phi_n(\xi)}_{\text{inelastic}}$$

  where $\phi_n(\xi)$ are internal wfs of the nuclei being excited in some model.

- Cross sections:

$$\left(\frac{d\sigma(\theta)}{d\Omega}\right)_{0\rightarrow n} = \frac{K_n}{K_0}|f_{n,0}(\theta)|^2$$

The coupled-channels method

We need to incorporate explicitly in the Hamiltonian the internal structure of the nucleus being excited (e.g. projectile).

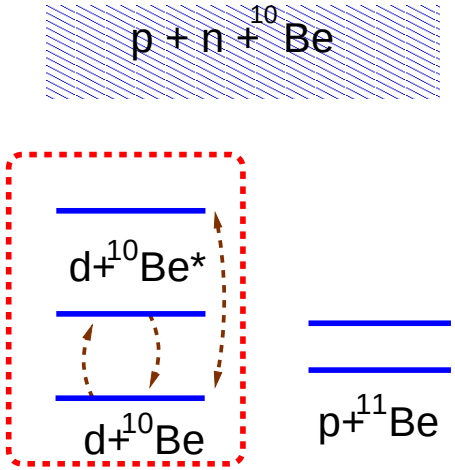
$$H = T_R + h(\xi) + V(\mathbf{R}, \xi)$$

- T_R: Kinetic energy for projectile-target relative motion.
- $\{\xi\}$: Internal degrees of freedom of the projectile (depend on the model).
- $V(\mathbf{R}, \xi)$: Projectile-target interaction.
- $h(\xi)$: Internal Hamiltonian of the projectile.

$$h(\xi)\phi_n(\xi) = \varepsilon_n \phi_n(\xi)$$

- $\phi_n(\xi)$: internal states of the projectile.

Modelscape and scattering wavefunction: d+^{10}Be → d+^{10}Be* example



☞ The modelspace is composed by ground states (elastic channel) and some excited states (inelastic scattering)

Boundary conditions for scattering wavefunction:

$$\Psi^{(+)}_{\mathbf{K}_0}(\mathbf{R},\xi) \xrightarrow{R\gg} \underbrace{e^{i\mathbf{K}_0\cdot\mathbf{R}}\phi_0(\xi)}_{\text{incident}} + \underbrace{f_{0,0}(\theta)\frac{e^{iK_0R}}{R}\phi_0(\xi)}_{\text{elastic}} + \underbrace{\sum_{n>0} f_{n,0}(\theta)\frac{e^{iK_nR}}{R}\phi_n(\xi)}_{\text{inelastic}}$$

Cross sections:

$$\left(\frac{d\sigma(\theta)}{d\Omega}\right)_{0\to n} = \frac{K_n}{K_0}|f_{n,0}(\theta)|^2 \qquad f_{n,0}(\theta) = \text{scattering amplitude}$$

CC model wavefunction (target excitation)

The total wave function is expanded in a subset of internal states representing the adopted modelspace:

$$\Psi_{\text{model}}(\mathbf{R},\xi) = \phi_0(\xi)\chi_0(\mathbf{K}_0,\mathbf{R}) + \sum_{n>0} \phi_n(\xi)\chi_n(\mathbf{K}_n,\mathbf{R})$$

and impose the boundary conditions for the (unknown) $\chi_n(\mathbf{R})$:

$$\chi_0^{(+)}(\mathbf{K}_0,\mathbf{R}) \to e^{i\mathbf{K}_0\cdot\mathbf{R}} + f_{0,0}(\theta)\frac{e^{iK_0R}}{R} \qquad \text{for n=0 (elastic)}$$

$$\chi_n^{(+)}(\mathbf{K}_n,\mathbf{R}) \to f_{n,0}(\theta)\frac{e^{iK_nR}}{R} \qquad \text{for n>0 (non-elastic)}$$

Calculation of $\chi_n^{(+)}(\mathbf{R})$: the coupled equations

- The model wavefunction must satisfy the Schrödinger equation:

$$[H - E]\Psi^{(+)}_{\text{model}}(\mathbf{R}, \xi) = 0$$

- Multiply on the left by each $\phi_n^*(\xi)$, and integrate over $\xi \Rightarrow$ coupled channels equations for $\{\chi_n(\mathbf{R})\}$:

$$\boxed{[E - \varepsilon_n - T_R - V_{n,n}(\mathbf{R})]\chi_n(\mathbf{R}) = \sum_{n' \neq n} V_{n,n'}(\mathbf{R})\chi_{n'}(\mathbf{R})}$$

- The structure information is embedded in the coupling potentials:

$$\boxed{V_{n,n'}(\mathbf{R}) = \int d\xi \phi^*_{n'}(\xi) V(\mathbf{R}, \xi)\phi_n(\xi)}$$

☞ *$\phi_n(\xi)$ will depend on the assumed structure model (collective, few-body, etc).*

Optical Model

- The Hamiltonian:
  $H = T_R + V(\mathbf{R})$
- Internal states: Just $\phi_0(\xi)$
- Model wavefunction:
  $\Psi_{\rm mod}(\mathbf{R}, \xi) \equiv \chi_0(\mathbf{K}, \mathbf{R})\phi_0(\xi)$
- Schrödinger equation:
  $[H - E]\chi_0(\mathbf{K}, \mathbf{R}) = 0$

Optical Model vs. Coupled-Channels method

Optical Model

- The Hamiltonian:
  $H = T_R + V(\mathbf{R})$
- Internal states: Just $\phi_0(\xi)$
- Model wavefunction:
  $\Psi_{\rm mod}(\mathbf{R},\xi) \equiv \chi_0(\mathbf{K},\mathbf{R})\phi_0(\xi)$
- Schrödinger equation:
  $[H-E]\chi_0(\mathbf{K},\mathbf{R}) = 0$

Coupled-channels method

- The Hamiltonian:
  $H = T_R + h(\xi) + V(\mathbf{R},\xi)$
- Internal states:
  $h(\xi)\phi_n(\xi) = \varepsilon_n\phi_n(\xi)$
- Model wavefunction:
  $\Psi_{\rm model}(\mathbf{R},\xi) = \phi_0(\xi)\chi_0(\mathbf{K},\mathbf{R}) + \sum_{n>0}\phi_n(\xi)\chi_n(\mathbf{K},\mathbf{R})$
- Schrödinger equation:

$$[H-E]\Psi_{\rm model}(\mathbf{R},\xi) = 0$$

$$\Downarrow$$

$$[E-\varepsilon_n - T_R - V_{n,n}(\mathbf{R})]\chi_n(\mathbf{K},\mathbf{R}) = \sum_{n'\neq n} V_{n,n'}(\mathbf{R})\chi_{n'}(\mathbf{K},\mathbf{R})$$

The DWBA approximation for inelastic scattering

- Assume that we can write the p-t interaction as: $V(\mathbf{R},\xi) = V_0(R) + \Delta V(\mathbf{R},\xi)$
- Use central $V_0(R)$ part to calculate the (distorted) waves for p-t relative motion:

$$\left[\hat{T}_{\mathbf{R}} + V_0(R) - E_i\right]\chi_i^{(+)}(\mathbf{K}_i,\mathbf{R}) = 0 \qquad (E_i = \text{c.m. energy})$$

$$\left[\hat{T}_{\mathbf{R}} + V_0(R) - E_f\right]\chi_f^{(+)}(\mathbf{K}_f,\mathbf{R}) = 0 \qquad (E_f = E_i + Q = E_i - E_x)$$

- In first order of $\Delta V(\mathbf{R},\xi)$ (DWBA) :

$$f_{i\to f}^{\text{DWBA}}(\theta) = -\frac{\mu}{2\pi\hbar^2}\int \chi_f^{(-)*}(\mathbf{K}_f,\mathbf{R})\,\Delta V_{if}(\mathbf{R})\,\chi_i^{(+)}(\mathbf{K}_i,\mathbf{R})\,d\mathbf{R}$$

with the transition potential:

$$\Delta V_{if}(\mathbf{R}) \equiv \int \phi_f^*(\xi)\,\Delta V(\mathbf{R},\xi)\,\phi_i(\xi)\,d\xi$$

Multipole expansion of the interaction: reduced matrix elements

- In actual calculations, the internal states will have definite spin/parity:

$$\phi_i(\xi) = |I_i M_i\rangle \qquad \text{and} \qquad \phi_f(\xi) = |I_f M_f\rangle$$

- The projectile-target interaction can be expanded in multipoles:

$$V(\mathbf{R}, \xi) = \sum_{\lambda,\mu} V_{\lambda\mu}(R, \xi) Y_{\lambda\mu}(\hat{R}) \equiv V_0(\mathbf{R}) + \Delta V(\mathbf{R}, \xi)$$

- In many practical (and important) situations:

$$\Delta V(\mathbf{R}, \xi) = \sum_{\lambda>0} \underbrace{\mathcal{F}_\lambda(R)}_{\text{formfactor}} \sum_{\mu} \underbrace{\mathcal{T}_{\lambda,\mu}(\xi)}_{\text{structure}} Y_{\lambda\mu}(\hat{R})$$

- DWBA and CC calculations require the coupling potentials

$$\langle I_f M_f | \Delta V(\mathbf{R}, \xi) | I_i M_i \rangle = \sum_{\lambda>0} \mathcal{F}_\lambda(R) \langle I_f M_f | \mathcal{T}_{\lambda\mu}(\xi) | I_i M_i \rangle Y_{\lambda\mu}(\hat{R})$$

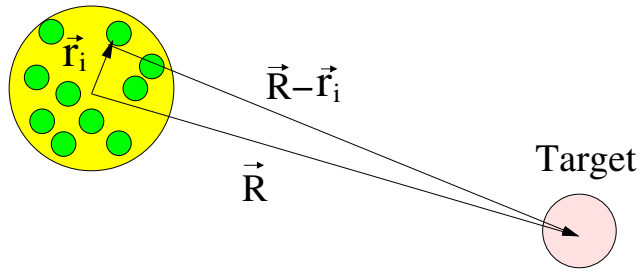
- Wigner-Eckart theorem → reduced matrix elements (r.m.e.)*:

$$\langle I_f M_f | \mathcal{T}_{\lambda\mu}(\xi) | I_i M_i \rangle = (2I_f + 1)^{-1/2} \langle I_f M_f | I_i M_i \lambda\mu \rangle \underbrace{\langle I_f || \mathcal{T}_\lambda(\xi) || I_i \rangle_{\text{BM}}}_{\text{r.m.e}}$$

Inelastic scattering: Coulomb excitation

- Projectile-target Coulomb interaction:

$$V_C(\mathbf{R},\xi) = \frac{e^2}{4\pi\varepsilon_0}\sum_i^{Z_p}\frac{Z_t e^2}{|\mathbf{R}-\mathbf{r}_i|}; \qquad \xi \equiv \{\mathbf{r}_i\}$$



- Multipolar expansion:

$$\frac{1}{|\mathbf{R}-\mathbf{r}_i|} = \sum_{\lambda\mu}\frac{4\pi}{2\lambda+1}\frac{r_i^\lambda}{R^{\lambda+1}}Y^*_{\lambda\mu}(\hat{r}_i)Y_{\lambda\mu}(\hat{R}) \qquad (R > r_i)$$

- Electric multipole operator: $\mathcal{M}(E\lambda,\mu) \equiv e\sum_i^{Z_p} r_i^\lambda Y^*_{\lambda\mu}(\hat{r}_i) \equiv \mathcal{T}_{\lambda,\mu}(\xi)$

$$V_C(\mathbf{R},\xi) = \kappa\frac{Z_t Z_p e^2}{R} + \sum_{\lambda>0,\mu}\underbrace{\frac{4\pi\kappa}{2\lambda+1}\frac{Z_t e}{R^{\lambda+1}}}_{\mathcal{F}_\lambda(\mathcal{R})}\underbrace{\mathcal{M}(E\lambda,\mu)}_{\mathcal{T}_{\lambda,\mu}}Y_{\lambda\mu}(\hat{R}) \equiv V_0(R) + \Delta V(\mathbf{R},\xi)$$

Coupling potentials for Coulomb excitation

- Transition potentials:

$$\Delta V_{if}(\mathbf{R}) \equiv \langle f; I_f M_f | \Delta V | i; I_i M_i \rangle = \sum_{\lambda>0,\mu} \frac{4\pi\kappa}{2\lambda+1} \frac{Z_t e}{R^{\lambda+1}} \langle f; I_f M_f | \mathcal{M}(E\lambda,\mu) | i; I_i M_i \rangle Y_{\lambda\mu}(\hat{R})$$

- Wigner-Eckart theorem⇒ reduced matrix elements (BM convention):

$$\langle f; I_f M_f | \mathcal{M}(E\lambda,\mu) | i; I_i M_i \rangle = (2I_f+1)^{-1/2} \langle I_i M_i \lambda\mu | I_f M_f \rangle \langle f; I_f || \mathcal{M}(E\lambda,\mu) || i; I_i \rangle$$

- Relation to physical quantities (Coulomb case)

$$B(E\lambda; I_i \to I_f) = (2I_i+1)^{-1} \, |\langle f; I_f || \mathcal{M}(E\lambda,\mu) || i; I_i \rangle|^2 \qquad (I_i \neq I_f)$$

$$Q_2 = \sqrt{16\pi/5} \, (2I+1)^{-1/2} \, \langle II20|II\rangle \, \langle I||M(E2||I\rangle \qquad (I_i = I_f \equiv I)$$

DWBA scattering amplitude for a transition of multipolarity λ:

$$f(\theta)_{iM_i\to fM_f} = -\frac{\mu}{2\pi\hbar^2}\frac{4\pi\kappa Z_t e}{2\lambda+1}\langle f; I_f M_f|\mathcal{M}(E\lambda,\mu)|i; I_i M_i\rangle \int d\mathbf{R}\,\chi_f^{(-)*}(\mathbf{K}_f,\mathbf{R})\frac{Y_{\lambda\mu}(\hat{R})}{R^{\lambda+1}}\chi_i^{(+)}(\mathbf{K}_i,\mathbf{R})$$

Cross sections:

$$\left(\frac{d\sigma}{d\Omega}\right)_{iM_i\to fM_f} = \frac{K_f}{K_i}\left|f(\theta)_{iM_i\to fM_f}\right|^2$$

Unpolarized cross section:

$$\left(\frac{d\sigma}{d\Omega}\right)_{I_i\to I_f} = \frac{1}{(2I_i+1)}\frac{K_f}{K_i}\sum_{M_i,M_f}\left|f(\theta)_{iM_i\to fM_f}\right|^2$$

What can we learn measuring Coulomb excitation?

☞ For a inelastic excitation $i \to f$ of multipolarity λ the differential cross section is proportional to the electric transition probability $B(E\lambda; I_i \to I_f)$ because

$$B(E\lambda; i \to f) = \frac{1}{2I_i + 1} |\langle f\ I_f || \mathcal{M}(E\lambda) || i\ I_i \rangle_{\rm BM}|^2$$

$$\Downarrow$$

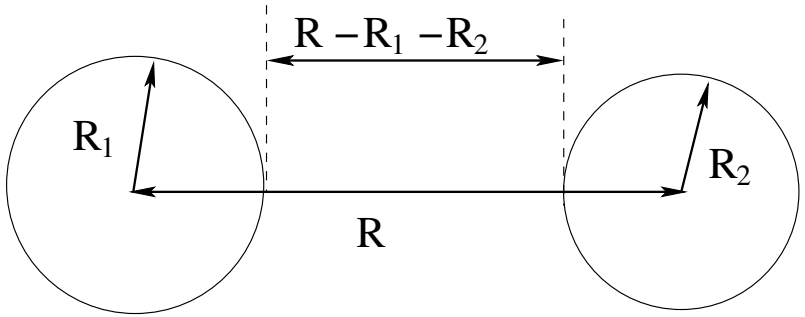
$$\frac{d\sigma}{d\Omega} \propto |\langle f\ I_f || \mathcal{M}(E\lambda) || i\ I_i \rangle|^2 \propto B(E\lambda; I_i \to I_f)$$

☞ *If the approximations involved in the derivation of the DWBA approximation are valid, the transition probabilities $B(E\lambda; I_f \to I_f)$ can be obtained comparing the magnitude of the inelastic cross sections with DWBA calculations.*

- Central potential: Typically $U_{\rm nuc}(\mathbf{R}) = V(R - R_0), \quad R_0 = R_1 + R_2.$

☞ Eg: Woods-Saxon parametrization

$$U_{\rm nuc}(R) = -\frac{V_0}{1+\exp\left(\frac{R-R_0}{a_r}\right)} - i\frac{W_0}{1+\exp\left(\frac{R-R_i}{a_i}\right)}$$



Deformed potential

- Deformed radius: $r(\theta,\phi) = R_0 + \sum_{\lambda,\mu} \delta_{\lambda,\mu} Y_{\lambda,\mu}(\theta,\phi)$
- Deformed potential: $V(R - R_0) \rightarrow V(R - r(\theta,\phi)) \equiv V(\mathbf{R},\xi)$
- Multipole expansion of the potential:

$$V(\mathbf{R},\xi) = V(R - R_0) - \sum_{\lambda,\mu} \hat{\delta}_{\lambda\mu} \frac{dV(R-R_0)}{dR} Y_{\lambda\mu}(\theta,\phi) + \ldots$$

($\hat{\delta}_\lambda$=deformation length operators)

- Transition potentials for a multipole λ:

$$V_{if}(\mathbf{R}) \equiv \langle f|V|i\rangle = -\frac{dV(R-R_0)}{dR} \langle f; I_f M_f|\hat{\delta}_{\lambda\mu}|i; I_i M_i\rangle Y_{\lambda\mu}(\hat{R})$$

☞*The nuclear transition potentials are proportional to the matrix element of the deformation length operator*.

DWBA scattering amplitude:

$$f(\mathbf{K}',\mathbf{K})_{iM_i\to fM_f} = -\frac{\mu}{2\pi\hbar^2}\langle f; I_f M_f|\hat{\delta}_{\lambda\mu}|i; I_i M_i\rangle \int d\mathbf{R}\,\chi_f^{(-)*}(\mathbf{K}',\mathbf{R})\frac{dV}{dR}Y_{\lambda\mu}(\hat{\mathbf{R}})\chi_i^{(+)}(\mathbf{K},\mathbf{R})$$

Cross sections:

$$\left(\frac{d\sigma(\theta)}{d\Omega}\right)_{iM_i\to fM_f} = \frac{K_f}{K_i}\left(\frac{\mu}{2\pi\hbar^2}\right)^2 \left|\langle f; I_f M_f|\hat{\delta}_{\lambda\mu}|i; I_i M_i\rangle\right|^2$$
$$\times\left|\int d\mathbf{R}\,\chi_f^{(-)*}(\mathbf{K}',\mathbf{R})\frac{dV}{dR}Y_{\lambda\mu}(\hat{\mathbf{R}})\chi_i^{(+)}(\mathbf{K},\mathbf{R})\right|^2$$

- *The differential cross section is proportional to the deformation parameters*
- *If the approximations are valid, the deformation parameters can be obtained comparing the magnitude of the inelastic cross sections with DWBA calculations.*

Summary of physical ingredients for collective excitations

In general, we have both Coulomb and nuclear couplings

$$\boxed{V_{if}(\mathbf{R}) = V^C_{if}(\mathbf{R}) + V^N_{if}(\mathbf{R})}$$

1. Coulomb excitation → electric reduced matrix elements

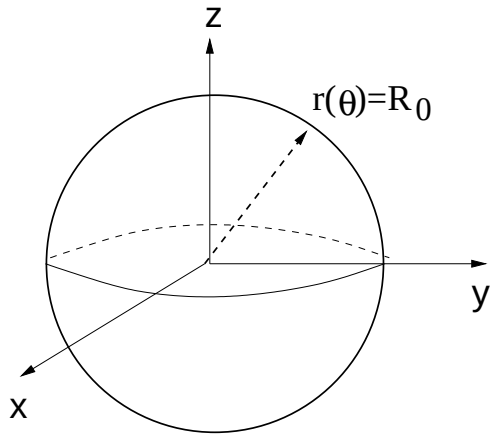
$$V^C_{if}(\mathbf{R}) = \sum_{\lambda>0} \frac{4\pi\kappa}{2\lambda+1} \frac{Z_t e}{R^{\lambda+1}} \langle f; I_f M_f | \mathcal{M}(E\lambda,\mu) | i; I_i M_i \rangle Y_{\lambda\mu}(\hat{R})$$

2. Nuclear excitation (collective model) → reduced deformation lengths

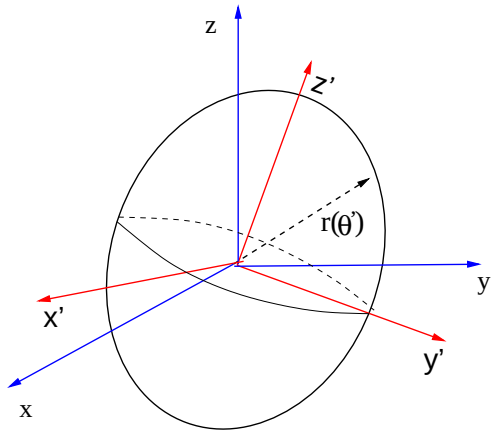
$$V^N_{if}(\mathbf{R}) = -\frac{dV_0}{dR} \sum_{\lambda} \langle f; I_f M_f | \hat{\delta}_{\lambda\mu} | i; I_i M_i \rangle Y_{\lambda\mu}(\hat{R})$$

Collective excitations in the rotor model

Spherical nucleus ($\beta = 0$)



Deformed nucleus ($\beta \neq 0$)

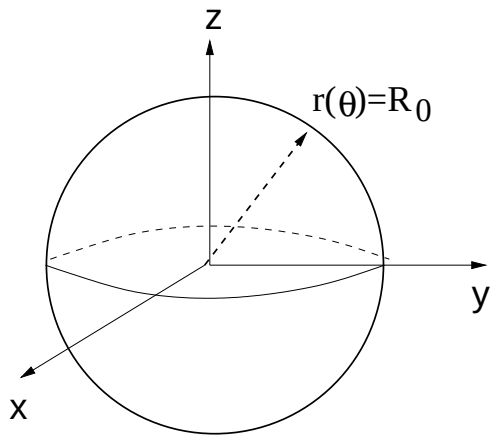


$$r(\theta') = R_0 \left[1 + \beta_2 Y_{20}(\theta', 0)\right]$$

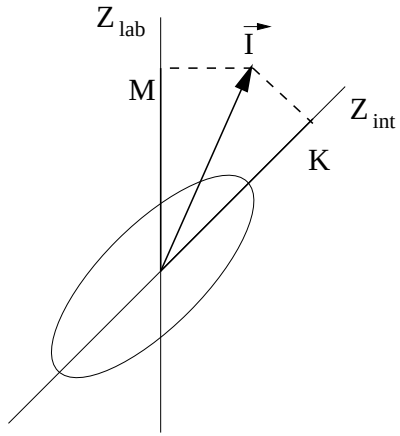
⇨ For a permanent deformed nucleus (or for a nucleus with surface vibrations) the nucleus-nucleus potential will not be longer central.

Collective excitations in the rotor model

Spherical nucleus ($\beta = 0$)



Deformed nucleus ($\beta \neq 0$)



⇨ For a permanent deformed nucleus (or for a nucleus with surface vibrations) the nucleus-nucleus potential will not be longer central.

⇨ States are characterized by their spin (I) and its projection of the angular momentum along the symmetry axis (K).

Reduced matrix elements in the rotor model

⇨ For axial deformation, the charge and matter deformations can be characterized by the deformation parameters β_λ^C and β_λ^N. For quadrupole deformations:

$$r^C(\theta') = R_c\left[1+\beta_2^C Y_{20}(\theta',0)\right]; \qquad r^N(\theta') = R_0\left[1+\beta_2^N Y_{20}(\theta',0)\right]$$

⇨ Considering for simplicity the case of even-even nucleus ($K=0$) and $I_i = 0 \rightarrow I_f$ transitions:

1. **Coulomb excitation:**

$$\langle f; K\ I_f||\mathcal{M}(E\lambda)||i; K\ I_i\rangle_{\rm BM} = \sqrt{B(E\lambda; I_i \rightarrow I_f)} = \frac{3Z_p\, e\, R_c^{\lambda-1}}{4\pi}\beta_\lambda^C R_c$$

β_λ^C=Coulomb deformation parameter

2. **Nuclear excitation:**

$$\langle f; KI_f||\hat{\delta}_\lambda||i; KI_i\rangle_{\rm BM} = (-1)^\lambda \beta_\lambda^N R_0$$

β_λ^N=nuclear deformation parameter

$$V_{ij}^{(\lambda)}(\mathbf{R}) = \frac{1}{\sqrt{2I_f+1}}\left[F_\lambda^C(R)+F_\lambda^N(R)\right]\langle f; I_f M_f | I_i M_i \lambda\mu\rangle Y_{\lambda,\mu}(\hat{R})$$

with the radial *form factors*:

1. Coulomb:
$$F_\lambda^C(R) = \frac{4\pi Z_t e}{2\lambda+1}\sqrt{B(E\lambda; I_i \to I_f)}\frac{1}{R^{\lambda+1}}$$
2. Nuclear:
$$F_\lambda^N(R) = -\beta_\lambda^N R_0 \frac{dU}{dR}$$

☞ *The Coulomb form factor, being of longer range, dominates at higher partial waves (large distances) and hence to smaller angles*

Coulomb + nuclear potential

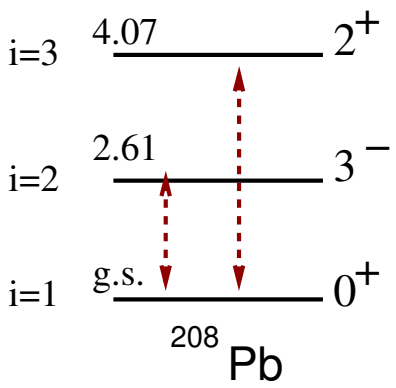
- We expect the Coulomb excitation to be more important when:
  - The projectile and/or target charges are large (i.e. large $Z_1 Z_2 \gg 1$)
  - At energies below the Coulomb barrier (where nuclear effects are less important).
  - At very forward angles (large impact parameters).

- If both Coulomb and nuclear contributions are important the scattering *amplitudes* for both processes should be added:

$$\left(\frac{d\sigma}{d\Omega}\right)_{i\to f} = \frac{K_f}{K_i}\left|f_{if}^{\rm coul} + f_{if}^{\rm nucl}\right|^2$$

☞ *In this case, interferences effects will appear!*

Physical example: $^{16}O + {}^{208}Pb \rightarrow {}^{16}O + {}^{208}Pb(3^-, 2^+)$



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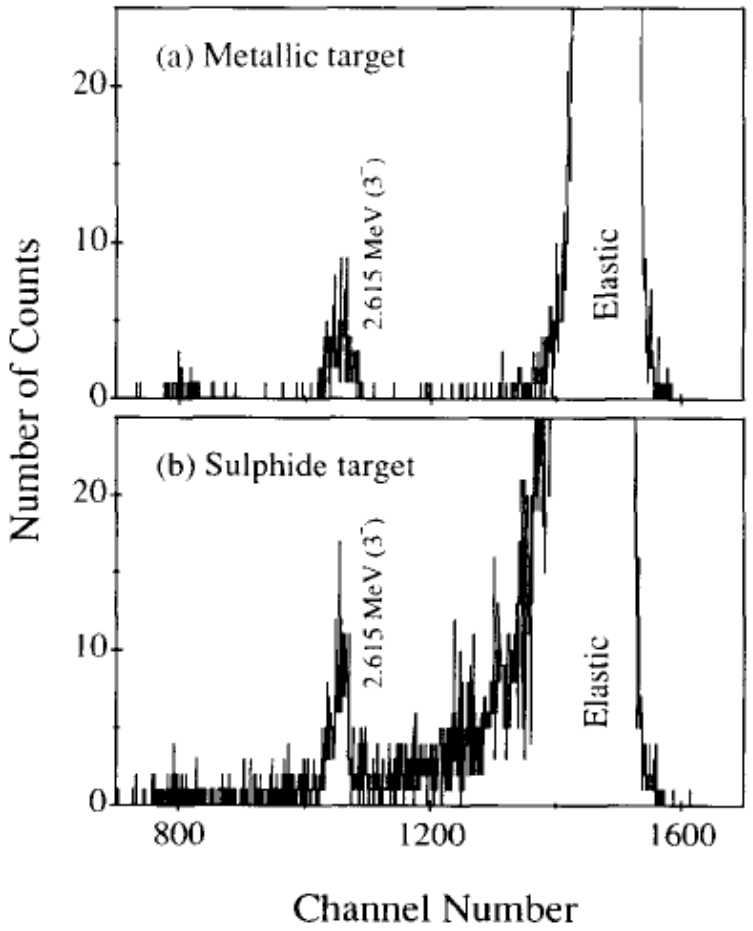
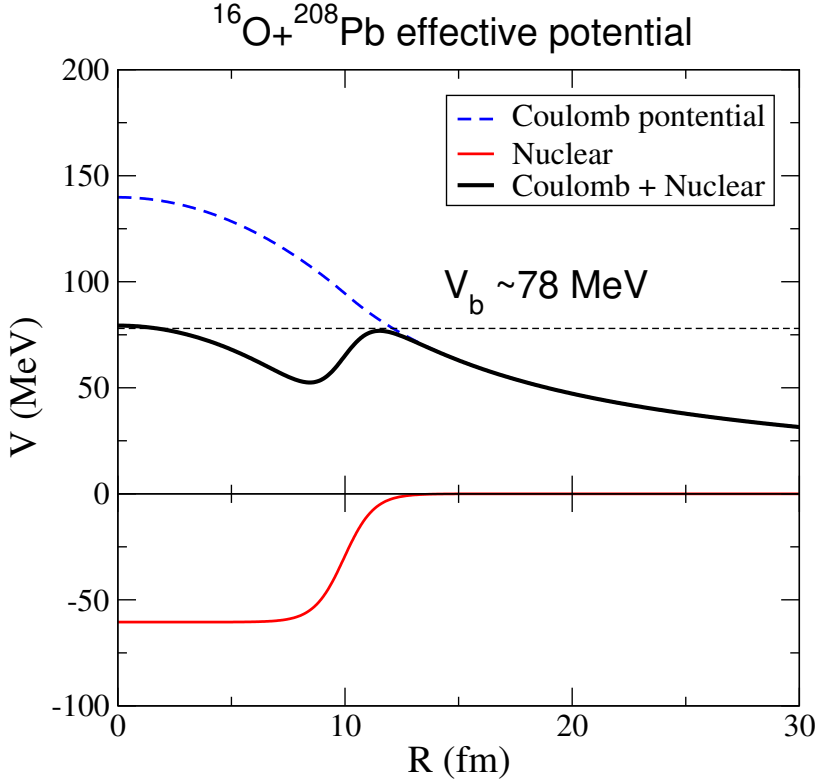
Outgoing ^{16}O energy:



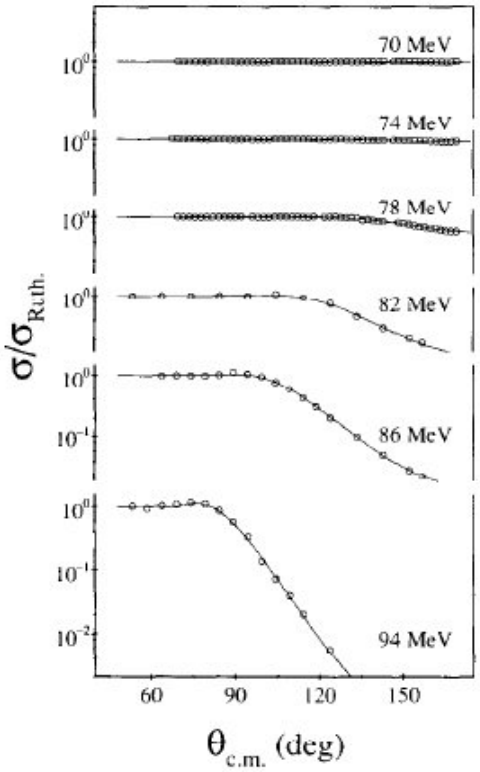
^{16}O+^{208}Pb effective interaction

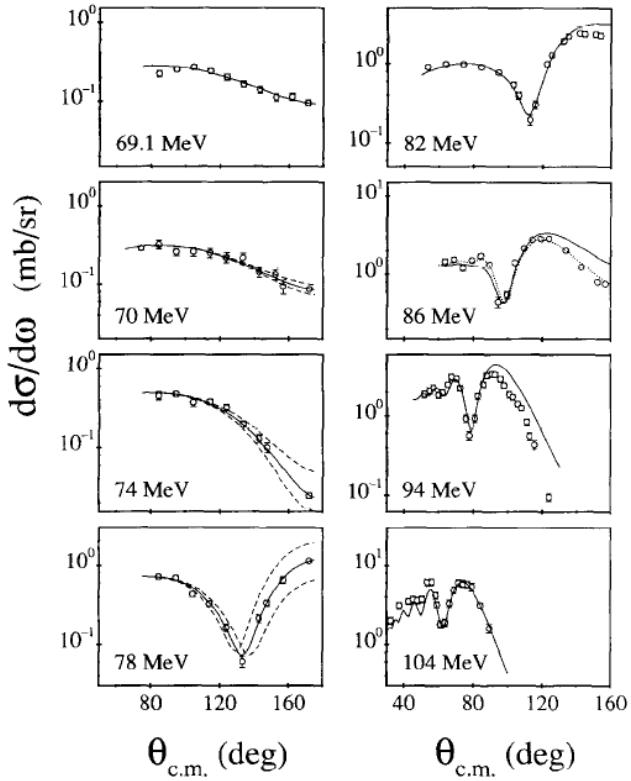


☞ Coulomb barrier:

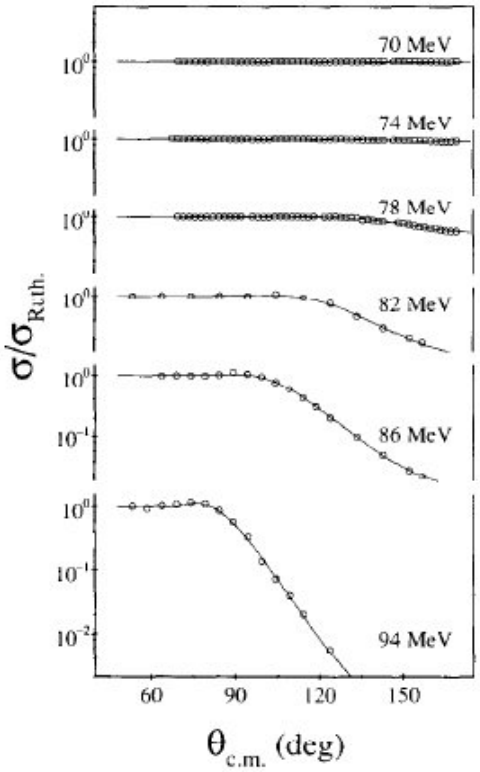
$$V_{\text{barrier}} \approx \kappa \frac{Z_p Z_t e^2}{1.44(A_p^{1/3} + A_t^{1/3})} \simeq 78 \text{ MeV}$$

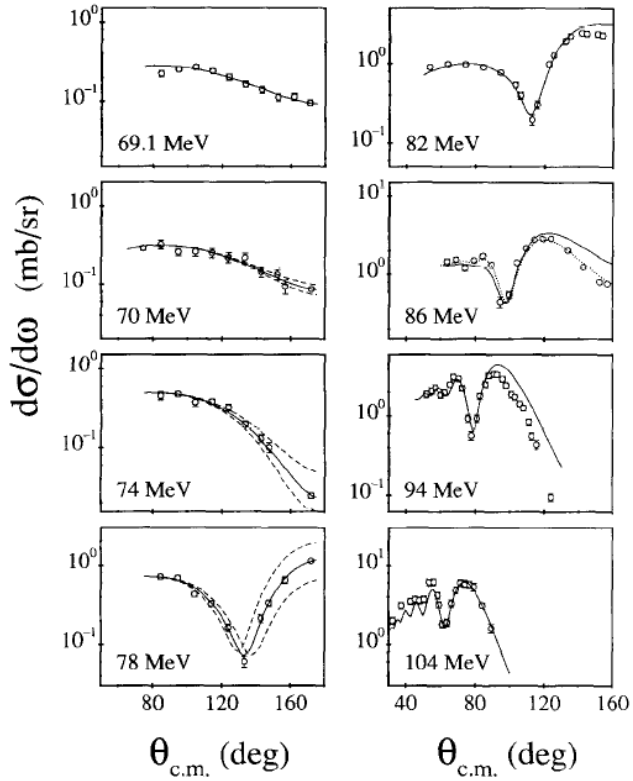
Collective excitations: example





Collective excitations: example

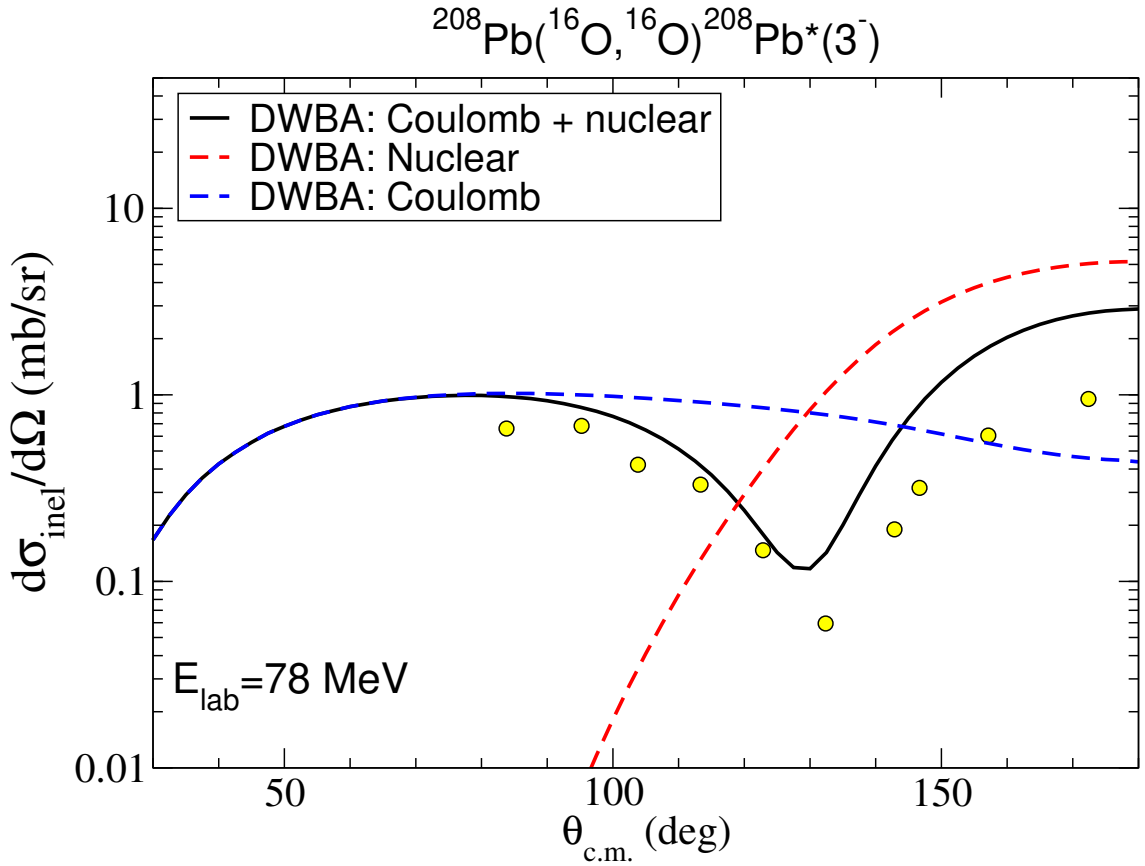




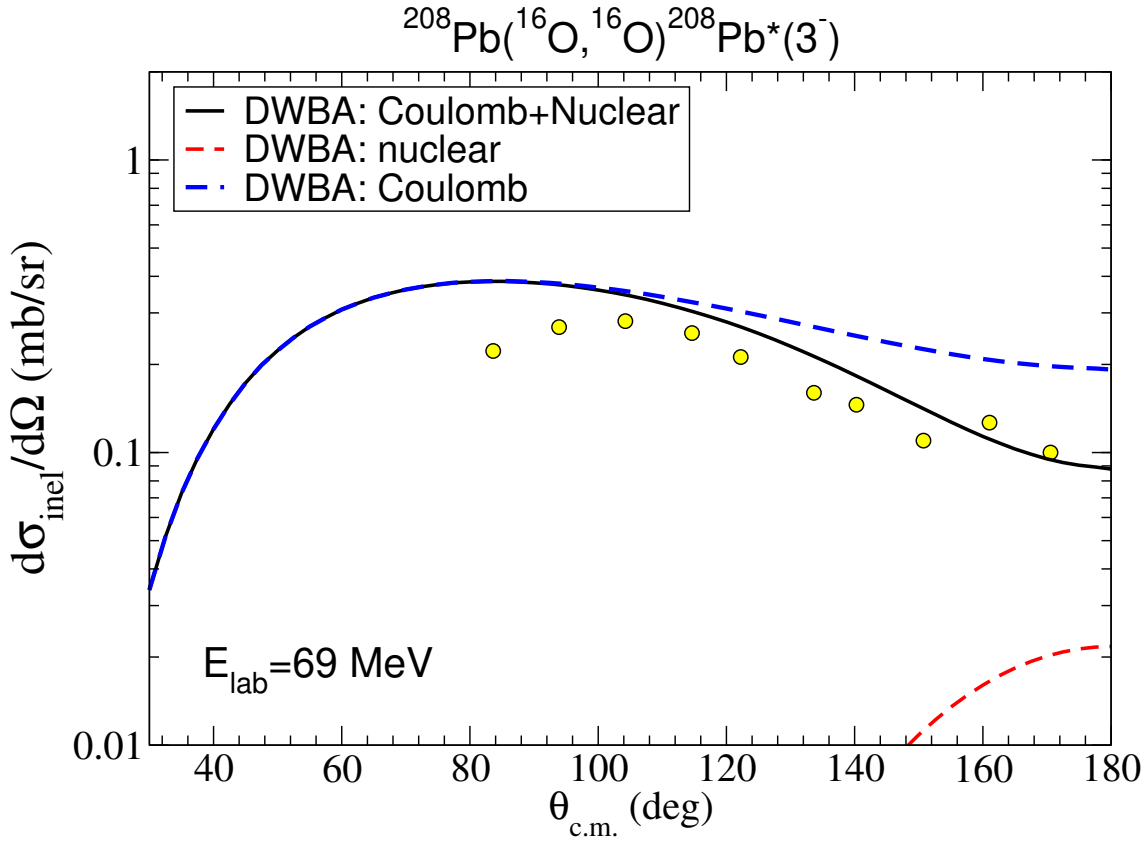
☞ Coulomb barrier:

$$V_{\text{barrier}} = \frac{Z_p Z_t e^2}{R_b} \approx \frac{Z_p Z_t e^2}{1.44(A_p^{1/3} + A_t^{1/3})} \simeq 78 \text{ MeV}$$

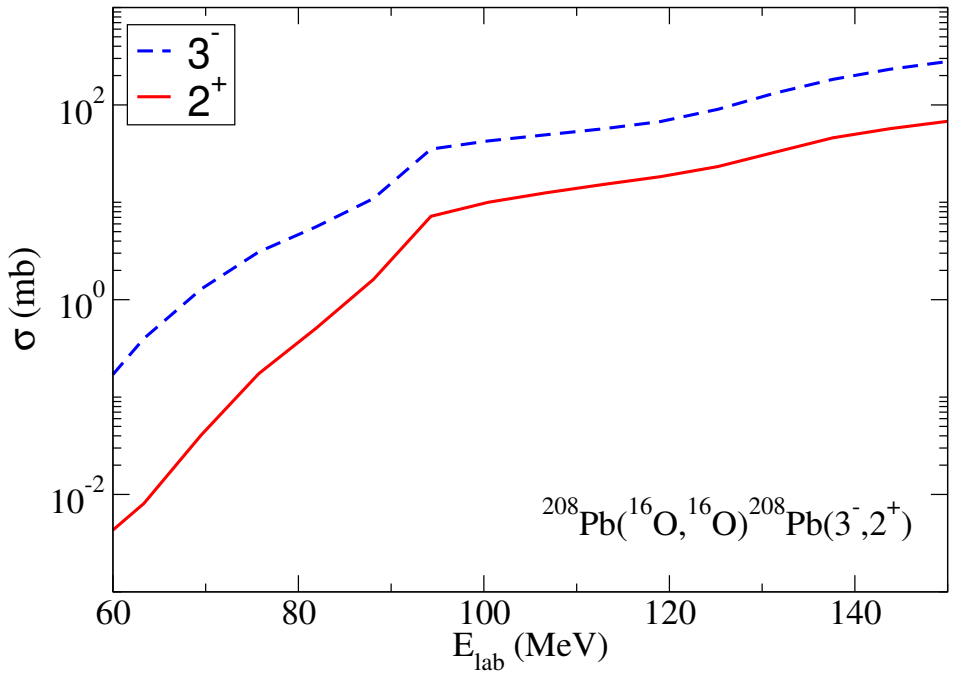
Coulomb and Nuclear excitations can produce constructive or destructive interference:



Below the barrier, the Coulomb excitation is dominant, and the interference is smaller:

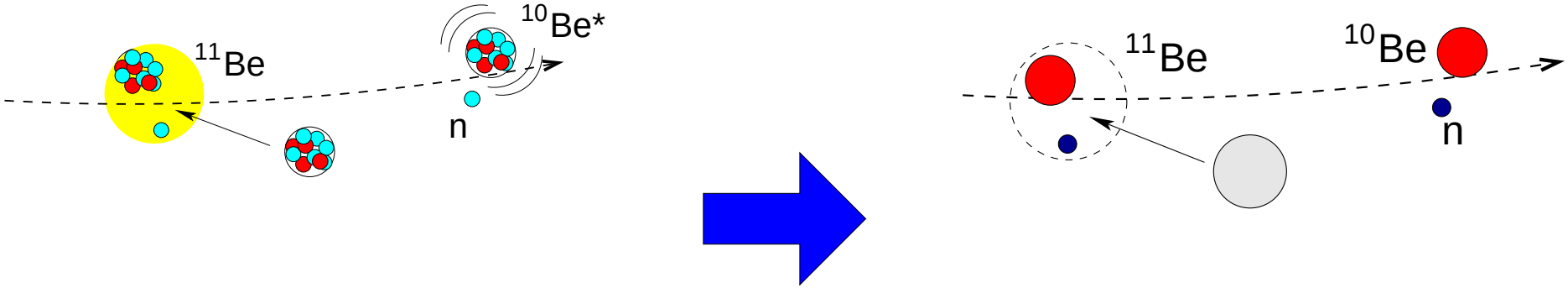


Effect of the incident energy:



Single-particle and cluster excitations

Many-body to few-body reduction



$$\mathcal{V}_{pt} = \sum_{ij} V_{ij}(\mathbf{r}_{ij})$$

$$\mathcal{V}_{pt} = U_{ct}(\mathbf{r}_{ct}) + U_{nt}(\mathbf{r}_{nt})$$

- Effective three-body Hamiltonian:

$$H = T_{\mathbf{R}} + h_r(\mathbf{r}) + U_{ct}(\mathbf{r}_{ct}) + U_{nt}(\mathbf{r}_{nt})$$

- $U_{ct}(\mathbf{r}_{ct})$, $U_{nt}(\mathbf{r}_{nt})$ are optical potentials describing fragment-target elastic scattering (eg. target excitation is treated effectively, through absorption)

Inelastic scattering in a few-body model

- Some nuclei allow a description in terms of two or more clusters: d=p+n, ^{6}Li=α+d, ^{7}Li=α+^{3}H.
- Projectile-target interaction:

$$V(\mathbf{R},\xi) \equiv V(\mathbf{R},\mathbf{r}) = U_1(\mathbf{r}_1) + U_2(\mathbf{r}_2)$$

- Transition potentials:

$$V_{n,n'}(\mathbf{R}) = \int d\mathbf{r}\phi_n^*(\mathbf{r})\left[U_1(\mathbf{r}_1) + U_2(\mathbf{r}_2)\right]\phi_{n'}(\mathbf{r})$$

- Some nuclei allow a description in terms of two or more clusters: d=p+n, ^{6}Li=α+d, ^{7}Li=α+^{3}H.
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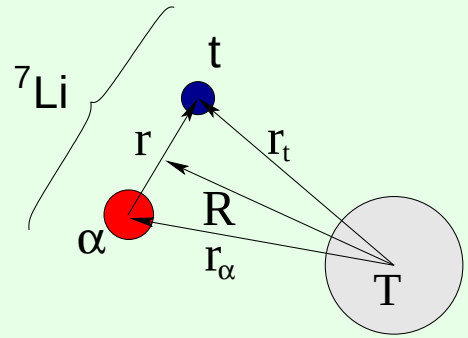
- Transition potentials:

$$V_{n,n'}(\mathbf{R}) = \int d\mathbf{r}\phi_n^*(\mathbf{r})\left[U_1(\mathbf{r}_1) + U_2(\mathbf{r}_2)\right]\phi_{n'}(\mathbf{r})$$

Example: ^{7}Li=α+t

$$\mathbf{r}_\alpha = \mathbf{R} - \frac{m_t}{m_\alpha + m_t}\mathbf{r}; \quad \mathbf{r}_t = \mathbf{R} + \frac{m_\alpha}{m_\alpha + m_t}\mathbf{r}$$

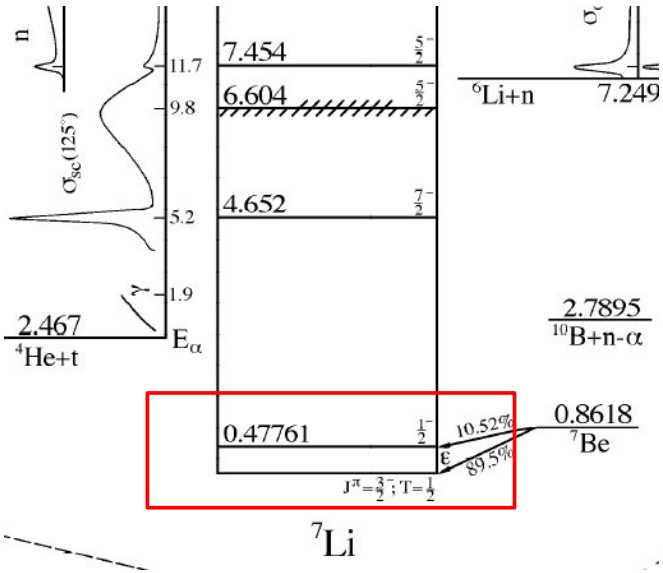


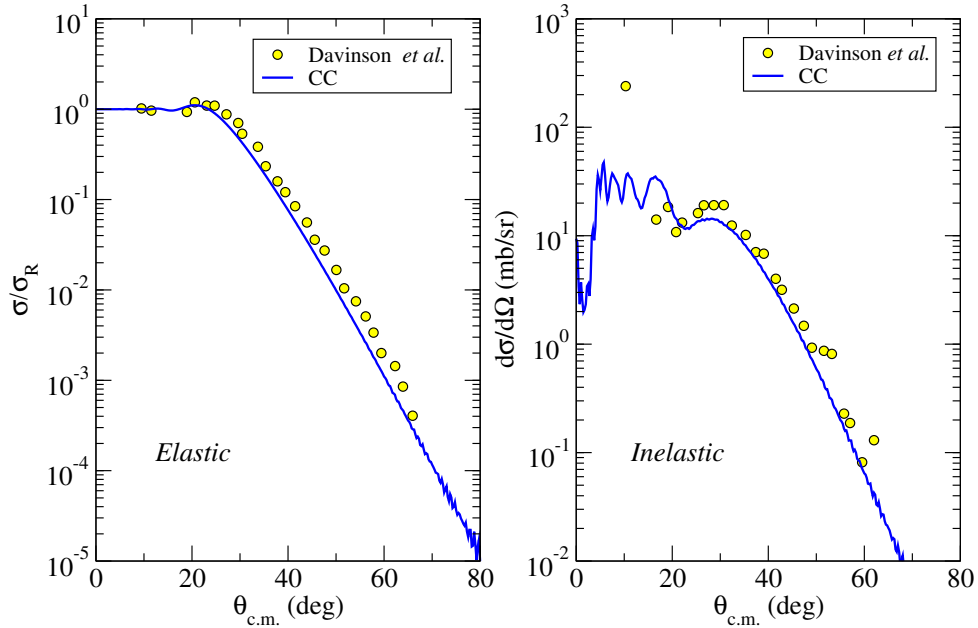
Internal states: (two-body cluster model)

$$[T_\mathbf{r} + V_{\alpha-t}(\mathbf{r}) - \varepsilon_n]\phi_n(\mathbf{r}) = 0$$

Example: ^{7}Li(α+t) +^{208}Pb at 68 MeV

⇨ CC calculation with 2 channels ($3/2^-$, $1/2^-$):



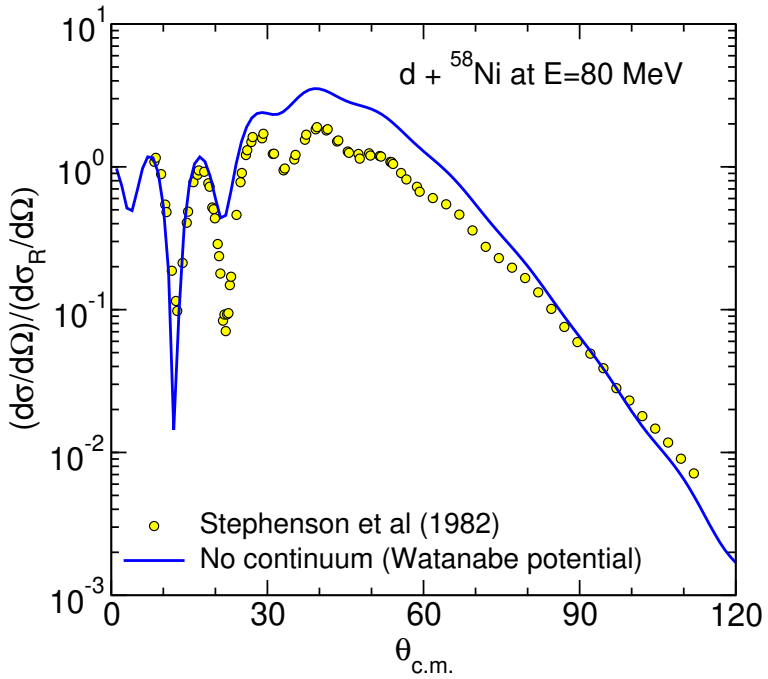


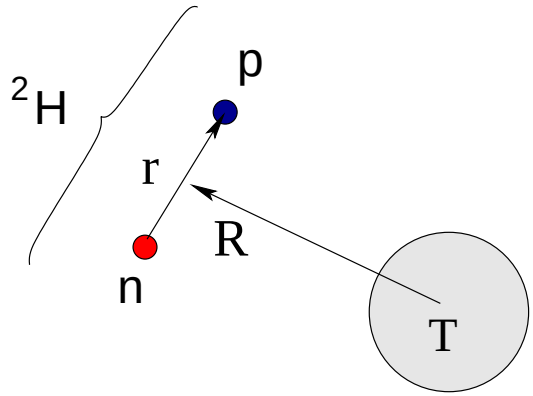
Data from Davinson et al, Phys. Lett. 139B (1984) 150)

☞ Fresco input available at `https://github.com/ammoro/RAON`

Example: Three-body calculation (p+n+^{58}Ni) with Watanabe potential:

$$V_{dt}(\mathbf{R}) = \int d\mathbf{r}\phi^*_{\rm gs}(\mathbf{r})\left\{V_{pt}(\mathbf{r}_{pt}) + V_{nt}(\mathbf{r}_{nt})\right\}\phi_{\rm gs}(\mathbf{r})$$

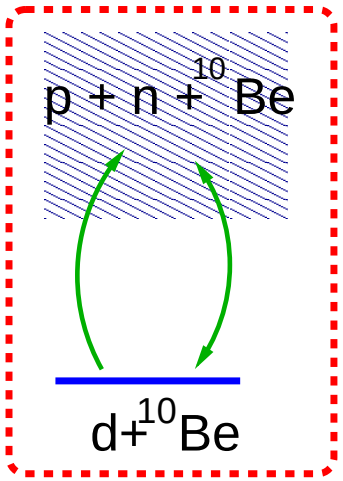




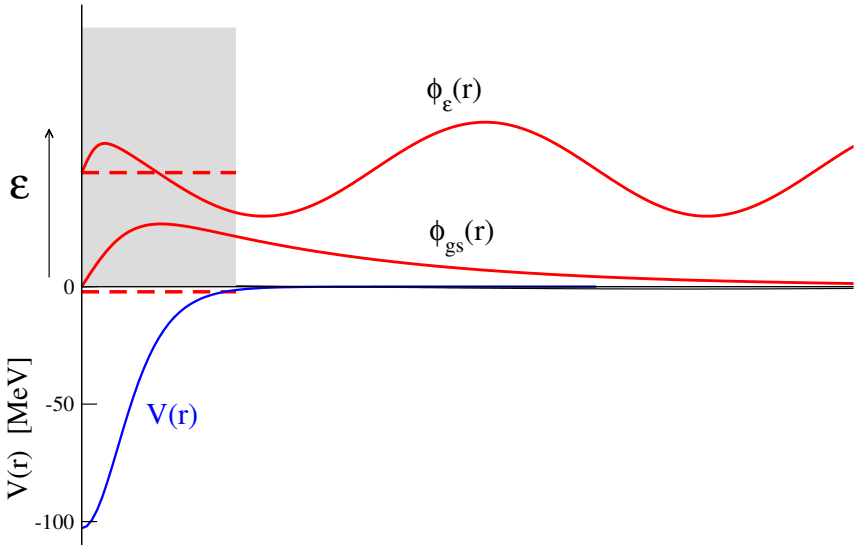
☞*Three-body calculations omitting breakup channels fail to describe the experimental data.*

Inclusion of breakup channels

- In collisions involving weakly bound nuclei, excitation of unbound states (breakup channels) of the weakly-bound nucleus plays an important role.
- Reaction formalisms (DWBA, CC...) must be conveniently extended in order to incorporate the possibility of coupling to these breakup channels.



Bound versus scattering states

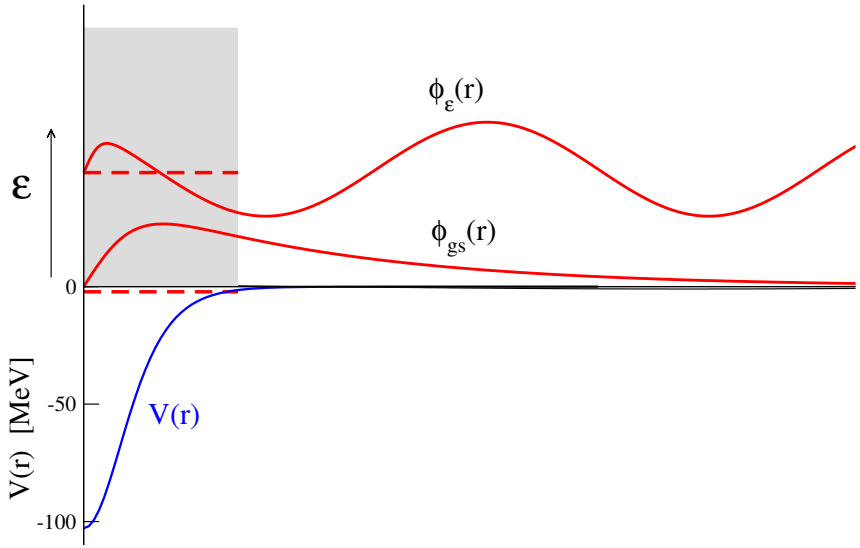


Continuum wavefunctions:

$$\varphi_{k,\ell jm}(\mathbf{r}) = \frac{u_{k,\ell j}(r)}{r}[Y_\ell(\hat{r}) \otimes \chi_s]_{jm}$$

$$\varepsilon = \frac{\hbar^2 k^2}{2\mu}$$

Bound versus scattering states



Continuum wavefunctions:

$$\varphi_{k,\ell jm}(\mathbf{r}) = \frac{u_{k,\ell j}(r)}{r}[Y_\ell(\hat{r}) \otimes \chi_s]_{jm}$$

$$\varepsilon = \frac{\hbar^2 k^2}{2\mu}$$

Unbound states are not suitable for CC calculations:

- They have a continuous (infinite) distribution in energy.
- Non-normalizable: $\langle u_{k,\ell sj}(r) | u_{k',\ell sj}(r) \rangle \propto \delta(k - k')$

SOLUTION $\Rightarrow$ continuum discretization

The origins of CDCC

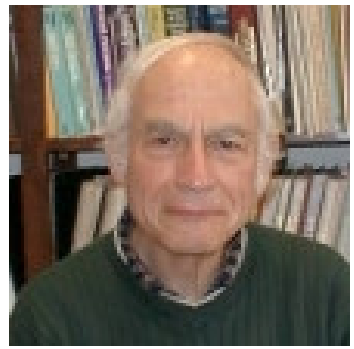
- Continuum discretization method proposed by G.H. Rawitscher [*PRC9, 2210 (1974)*] and Farrell, Vincent and Austern [*Ann.Phys.(New York) 96, 333 (1976)*] to describe deuteron scattering as an effective three-body problem $p + n + A$.

PHYSICAL REVIEW C VOLUME 9, NUMBER 6 JUNE 1974

Effect of deuteron breakup on elastic deuteron-nucleus scattering

George H. Rawitscher*
Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139,†
and Department of Physics, University of Surrey, Guildford, Surrey, England
(Received 1 October 1973; revised manuscript received 4 March 1974)

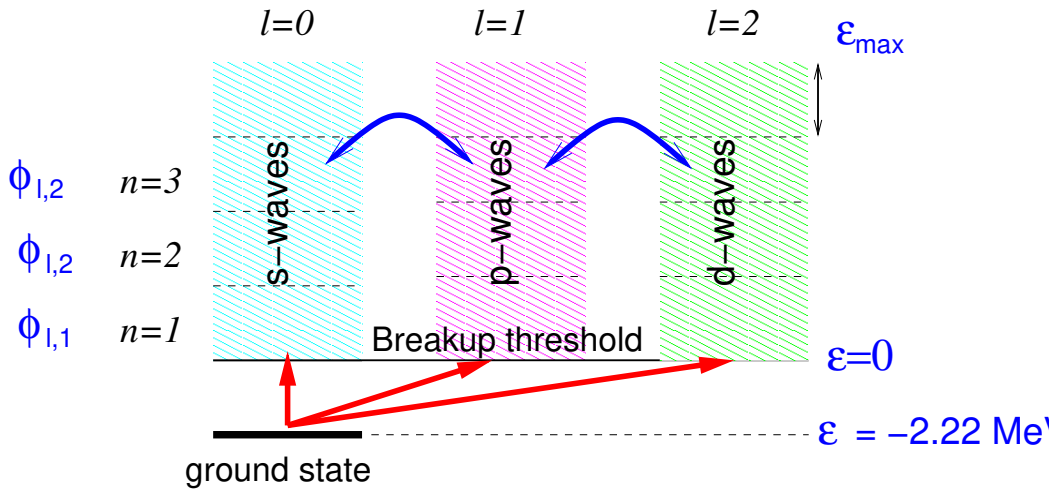
The properties of the transition matrix elements $V_{ab}(R)$ of the breakup potential V_N taken between states $\phi_a(\vec{r})$ and $\phi_b(r)$ are examined. Here $\phi_a(\vec{r})$ are eigenstates of the neutron-proton relative-motion Hamiltonian, and the eigenvalues of the energy ϵ_a are positive (continuum states) or negative (bound deuteron); $V_N(\vec{r}, \vec{R})$ is the sum of the phenomenological proton nucleus $V_{p-A}(|\vec{R}-\frac{1}{2}\vec{r}|)$ and neutron nucleus $V_{n-A}(|\vec{R}+\frac{1}{2}\vec{r}|)$ optical potentials evaluated for nucleon energies equal to half the incident deuteron energy. The bound-to-continuum transition matrix element for relative neutron-proton angular momenta $l=2$ are found to be comparable in magnitude to the ones for $l=0$ for values of ϵ_a larger than about 3 MeV, and both decrease only slowly with ϵ_a, suggesting that a large breakup spectrum is involved in deuteron-nucleus collisions. The effect of the various breakup transitions on the elastic phase shifts is estimated by numerically solving a set of coupled equations. These equations couple the functions $\chi_a(\vec{R})$ which are the coefficients of the expansion of the neutron-proton-nucleus wave function in a set of the $\phi_a(\vec{r})$'s. The equations are rendered manageable by performing a (rather crude) discretization in the neutron-proton relative-momentum variable k_a. Numer-



George Rawitscher (1928-2018)

- Full numerical implementation by Kyushu group (Sakuragi, Yahiro, Kamimura, and co.): *Prog. Theor. Phys.(Kyoto) 68, 322 (1982)*

Continuum discretization for deuteron scattering



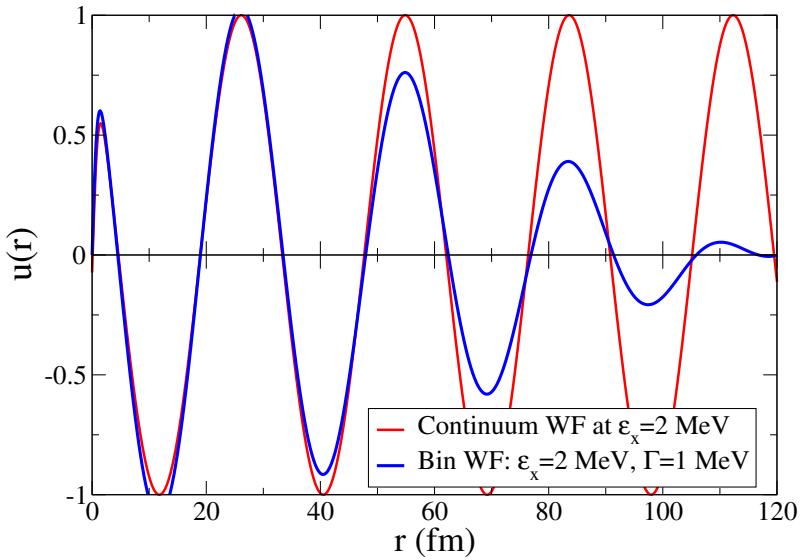
- Select a number of angular momenta ($\ell = 0, \ldots, \ell_{\max}$).
- For each ℓ, set a maximum excitation energy $\varepsilon_{\max}$.
- Divide the interval $\varepsilon = 0 - \varepsilon_{\max}$ in a set of sub-intervals (*bins*).
- For each bin, calculate a representative wavefunction $\phi_{\ell m}(\mathbf{r})$.

Bin wavefunction:

$$\phi^{[k_1,k_2]}_{\ell jm}(\mathbf{r}) = \frac{u^{[k_1,k_2]}_{\ell j}(r)}{r}[Y_\ell(\hat{r}) \otimes \chi_s]_{jm} \qquad [k_1, k_2] = \text{bin interval}$$

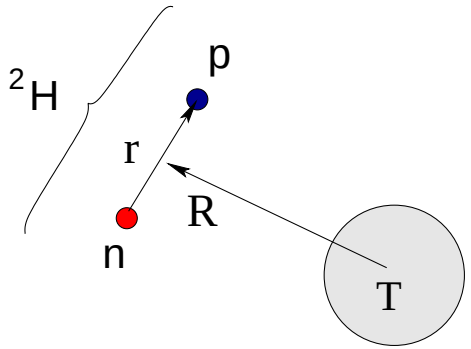
$$u^{[k_1,k_2]}_{\ell sjm}(r) = \sqrt{\frac{2}{\pi N}} \int_{k_1}^{k_2} w(k) u_{k,\ell sj}(r) dk$$

- k: linear momentum
- $u_{k,\ell sj}(r)$: scattering states (radial part)
- $w(k)$: weight function



CDCC formalism for deuteron scattering

- Hamiltonian: $H = T_{\mathbf{R}} + h_r(\mathbf{r}) + V_{pt}(\mathbf{r}_{pt}) + V_{nt}(\mathbf{r}_{nt})$
- Model wavefunction:



$$\Psi^{(+)}(\mathbf{R},\mathbf{r}) = \underbrace{\phi_{gs}(\mathbf{r})\chi_0(\mathbf{R})}_{\text{bound state}} + \underbrace{\sum_{n>0}^{N} \phi_n(\mathbf{r})\chi_n(\mathbf{R})}_{\text{discretized contimuum}}$$

- Coupled equations: $[H - E]\Psi(\mathbf{R},\mathbf{r}) = 0$

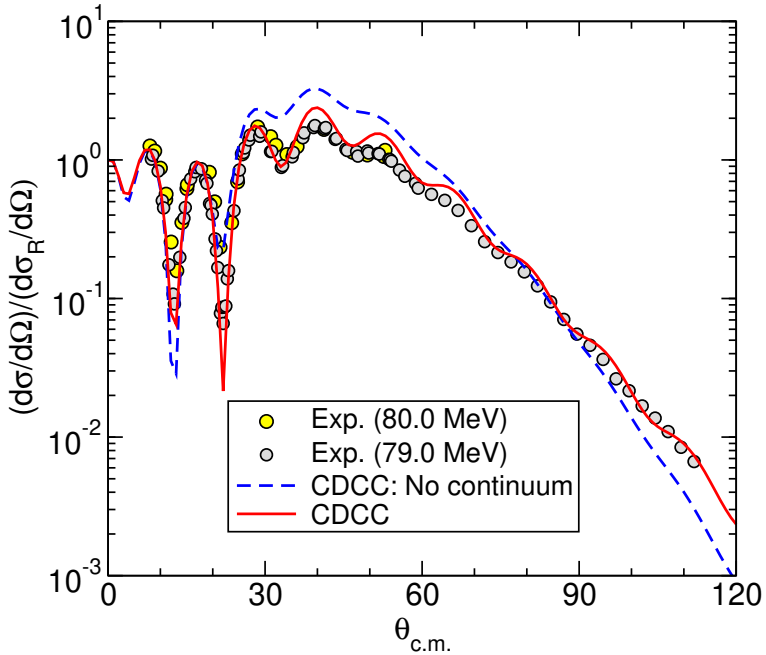
$$\left[E - \varepsilon_n - T_R - V_{n,n}(\mathbf{R})\right]\chi_n(\mathbf{R}) = \sum_{n' \neq n} V_{n,n'}(\mathbf{R})\chi_{n'}(\mathbf{R})$$

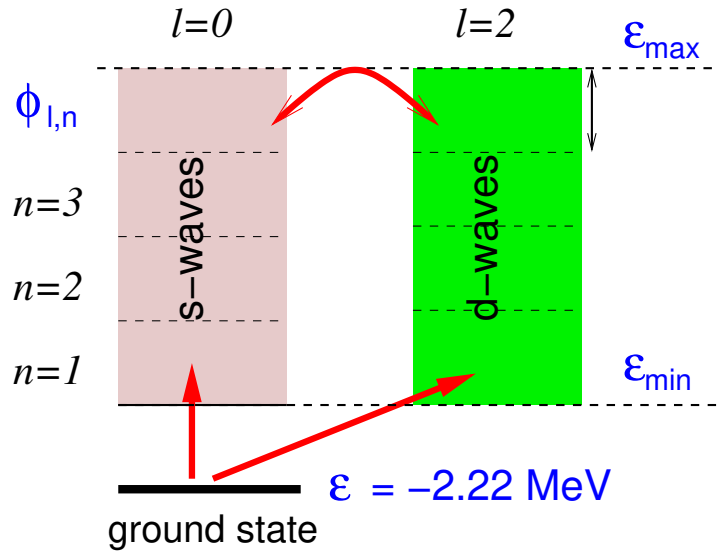
- Coupling potentials:

$$V_{n;n'}(\mathbf{R}) = \int d\mathbf{r}\, \phi_n^*(\mathbf{r}) \left[V_{pt}(\mathbf{R} + \frac{\mathbf{r}}{2}) + V_{nt}(\mathbf{R} - \frac{\mathbf{r}}{2})\right] \phi_{n'}(\mathbf{r})$$

Coupling to continuum states produce:

- Polarization of the projectile (modification of real part)
- Flux removal (absorption) from the elastic channel (imaginary part)





☞ No continuum ⇒ retain only the Watanabe potential:

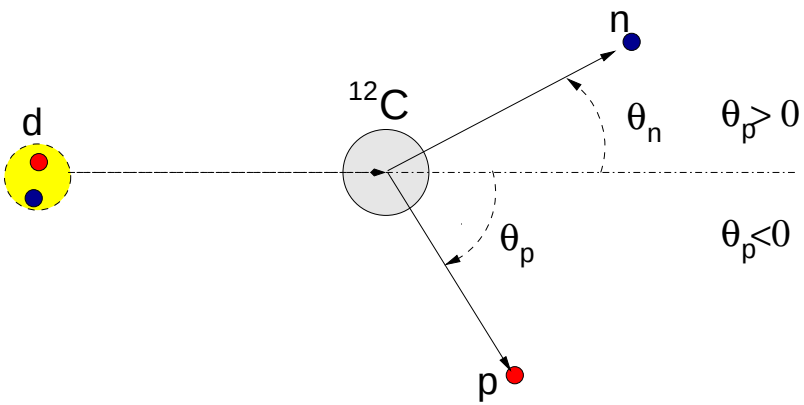
$$V_{00}(\mathbf{R}) = \int d\mathbf{r}\, \phi^*_{\rm gs}(\mathbf{r}) \left(V_{pt} + V_{nt}\right) \phi_{\rm gs}(\mathbf{r})$$

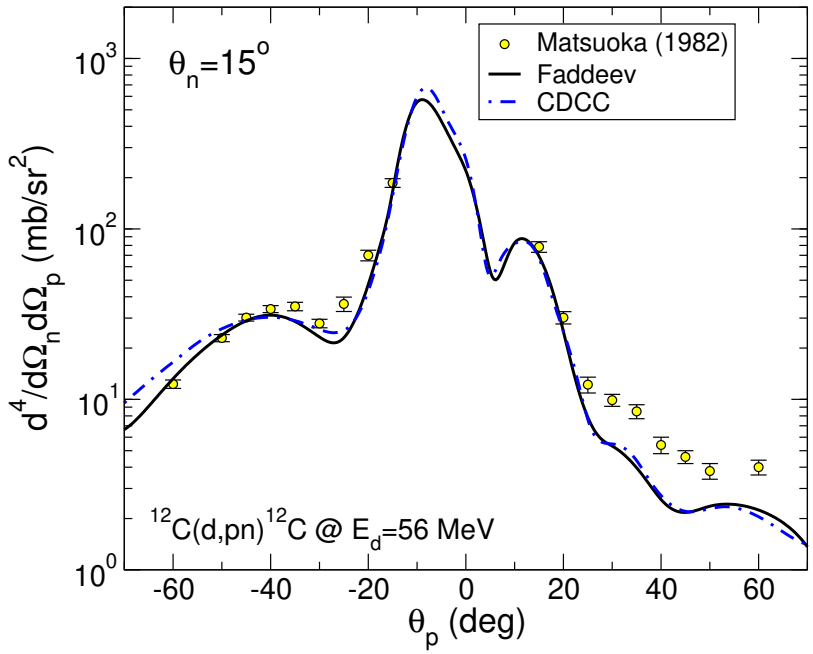
Breakup observables with CDCC: exclusive breakup of d+ ^{12}C → p+n+^{12}C

CDCC calculations for **d+ ^{12}C** at 56 MeV:

- Continuum states with $\ell \leq 8$ and ε_{max}=46 MeV.
- Proton and neutron intrinsic spins ignored
- p/n+ ^{58}Ni from Watson global optical potential
- p+n simple Gaussian interaction describing deuteron g.s.

Data: *Matsuoka et al., NPA391, 357 (1982).*

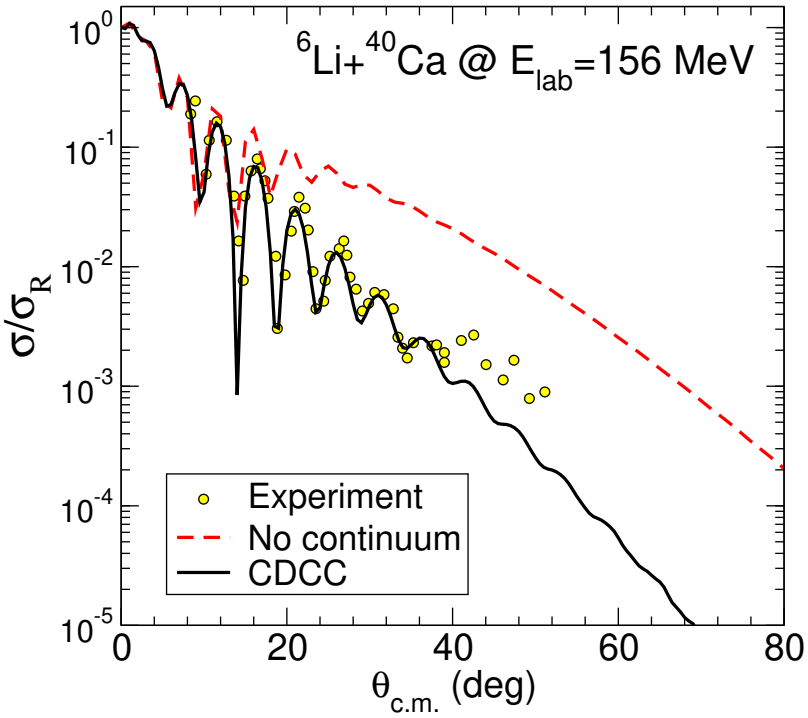


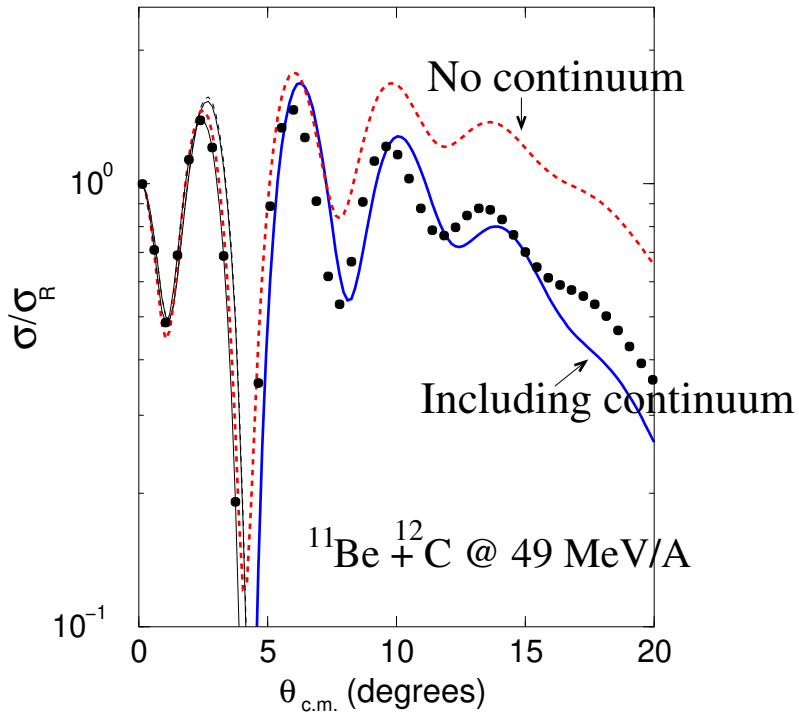


A. Deltuva et al, PRC 76, 064602 (2007)

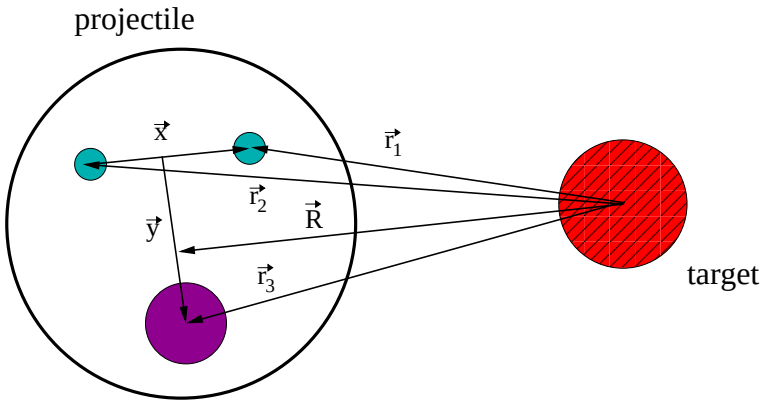
Application of the CDCC method: ^{6}Li and ^{6}He scattering

- The CDCC method has been also applied to nuclei with a cluster structure:
  - ^{6}Li=α + d ($S_{\alpha,d}$=1.47 MeV)
  - ^{11}Be=^{10}Be + n (S_n=0.504 MeV)





Extension to 3-body projectiles

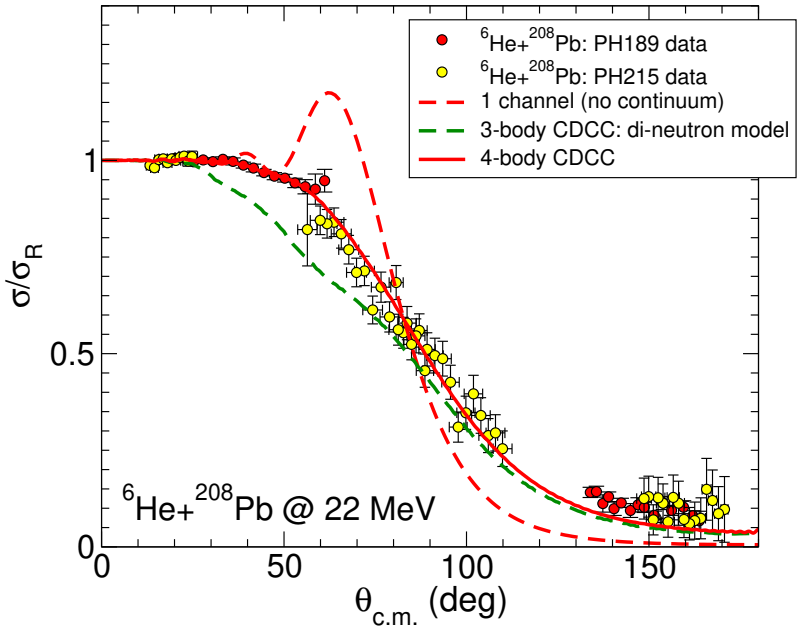


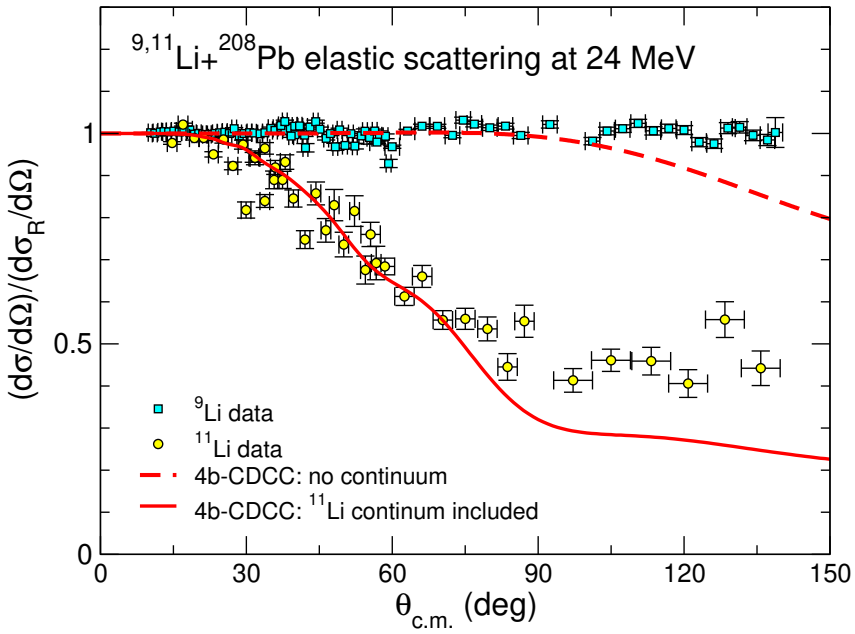
To extend the CDCC formalism, one needs to evaluate the new coupling potentials:

$$V_{n;n'}(\mathbf{R}) = \int d\mathbf{r}\, \phi^*_n(\mathbf{x},\mathbf{y}) \{V_{nt}(\mathbf{r}_1) + V_{nt}(\mathbf{r}_2) + V_{\alpha t}(\mathbf{r}_3)\} \phi_{n'}(\mathbf{x},\mathbf{y})$$

- $\phi_n(\mathbf{x},\mathbf{y})$ three-body WFs for bound and continuum states: hyperspherical coordinates, Faddeev, etc (difficult to calculate!)
- 4b-CDCC calculations not included in FRESCO; require separate codes to compute the $\phi_n(\mathbf{x},\mathbf{y})$ wfs (e.g. FACE) and $V_{n;n'}(\mathbf{R})$ potentials

Four-body CDCC calculations for ^{6}He and ^{11}Li scattering





Data (LLN): NPA803, 30 (2008);PRC 84, 044604 (2011)
Calculations: PRC 80, 051601 (2009)

M Cubero et al, PRL109, 262701 (2012)

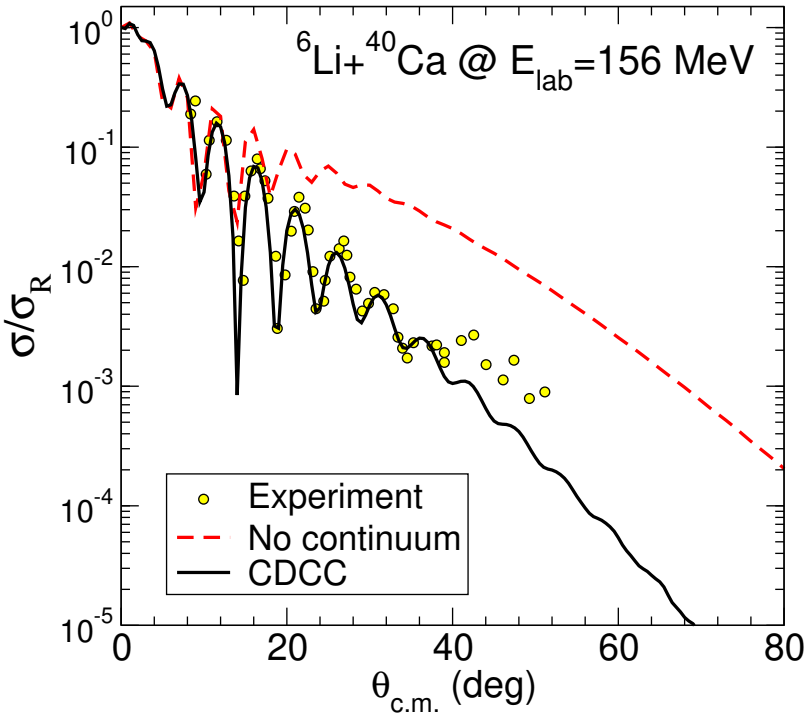
N.b.: 1-channel potential considers only g.s. → g.s. coupling potential:

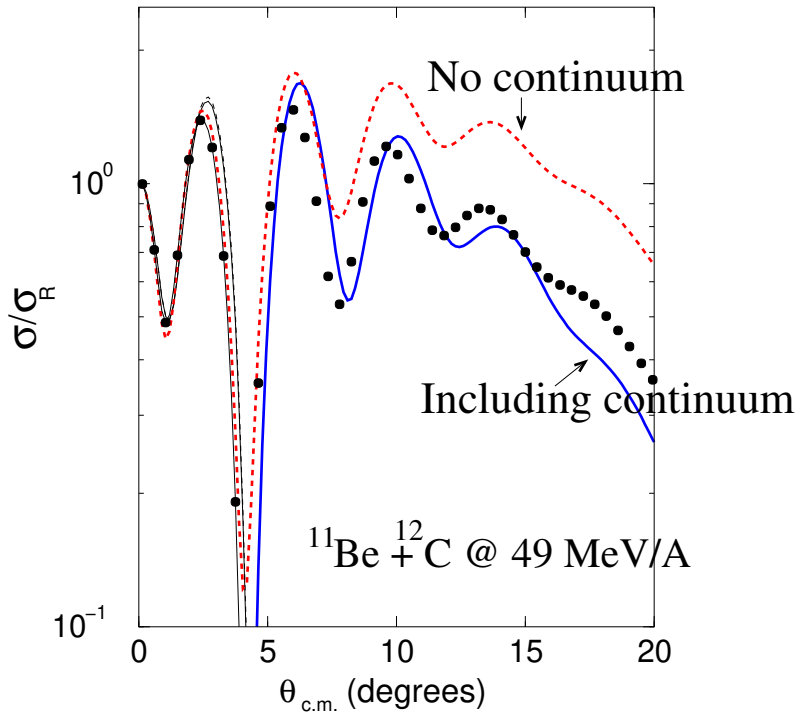
$$V_{00}(\mathbf{R}) = \int d\mathbf{r}\, \phi^{*}_{\text{g.s.}}(\mathbf{x},\mathbf{y})\,\{V_{nt}(\mathbf{r}_1) + V_{nt}(\mathbf{r}_2) + V_{ct}(\mathbf{r}_3)\}\,\phi_{\text{g.s.}}(\mathbf{x},\mathbf{y})$$

Application of the CDCC method: ^{6}Li and ^{6}He scattering

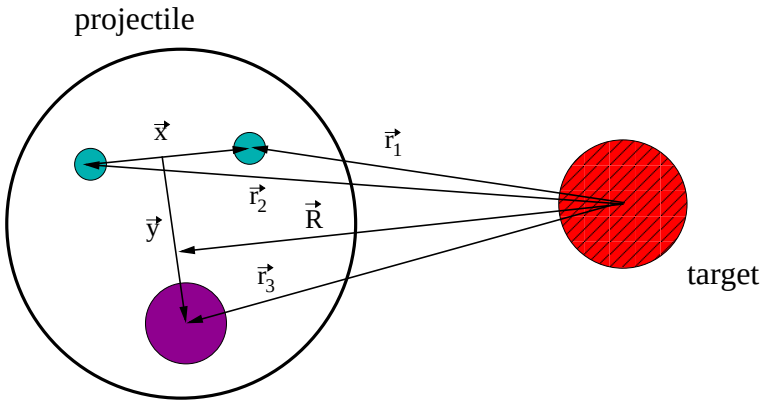
☞ The CDCC method has been also applied to nuclei with a cluster structure:

- ^{6}Li=α + d ($S_{\alpha,d}$=1.47 MeV)
- ^{11}Be=^{10}Be + n (S_n=0.504 MeV)





Extension to 3-body projectiles

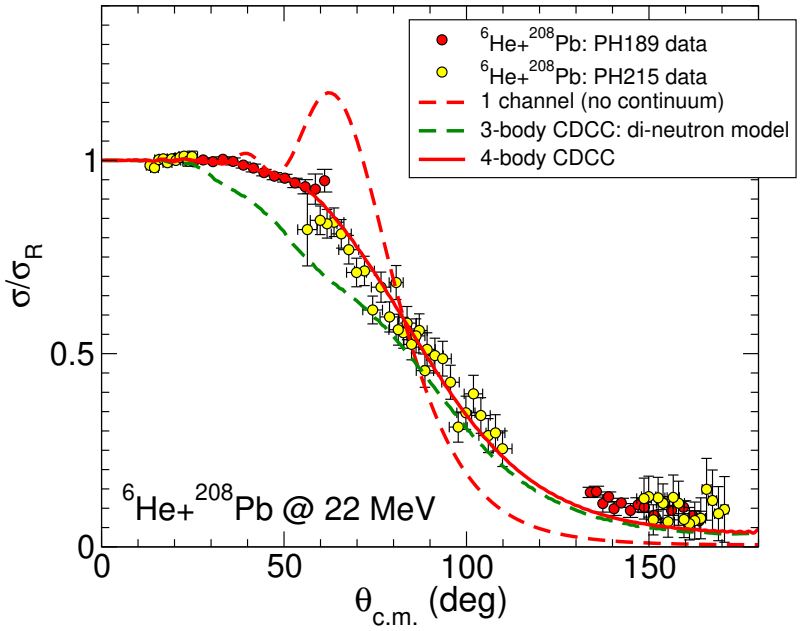


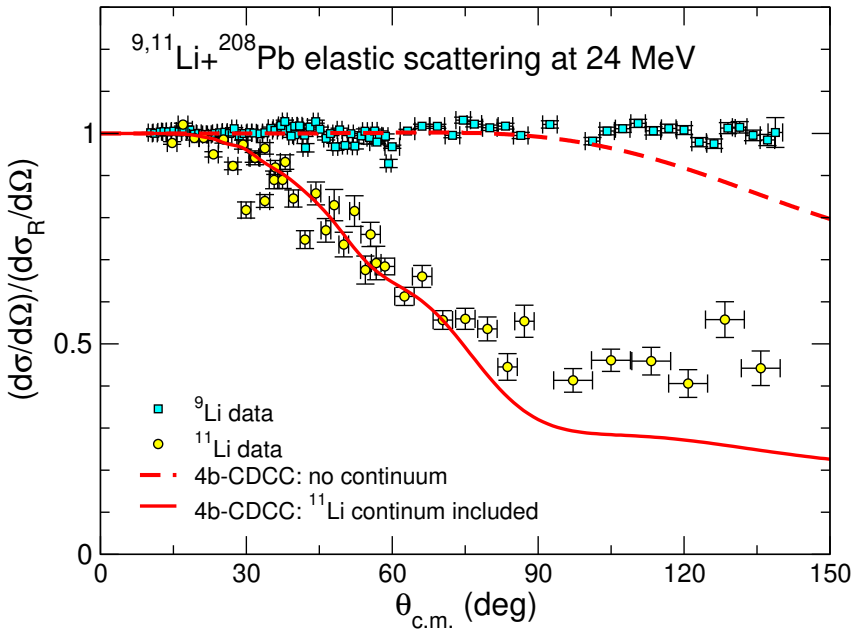
To extend the CDCC formalism, one needs to evaluate the new coupling potentials:

$$V_{n;n'}(\mathbf{R}) = \int d\mathbf{r}\, \phi^*_n(\mathbf{x},\mathbf{y}) \{V_{nt}(\mathbf{r}_1) + V_{nt}(\mathbf{r}_2) + V_{\alpha t}(\mathbf{r}_3)\} \phi_{n'}(\mathbf{x},\mathbf{y})$$

- $\phi_n(\mathbf{x},\mathbf{y})$ three-body WFs for bound and continuum states: hyperspherical coordinates, Faddeev, etc (difficult to calculate!)
- 4b-CDCC calculations not included in FRESCO; require separate codes to compute the $\phi_n(\mathbf{x},\mathbf{y})$ wfs (e.g. FACE) and $V_{n;n'}(\mathbf{R})$ potentials

Four-body CDCC calculations for ^{6}He and ^{11}Li scattering





Data (LLN): NPA803, 30 (2008);PRC 84, 044604 (2011)
Calculations: PRC 80, 051601 (2009)

M Cubero et al, PRL109, 262701 (2012)

N.b.: 1-channel potential considers only g.s. → g.s. coupling potential:

$$V_{00}(\mathbf{R}) = \int d\mathbf{r}\, \phi^{*}_{\text{g.s.}}(\mathbf{x},\mathbf{y})\,\{V_{nt}(\mathbf{r}_1) + V_{nt}(\mathbf{r}_2) + V_{ct}(\mathbf{r}_3)\}\,\phi_{\text{g.s.}}(\mathbf{x},\mathbf{y})$$