Microscopic description of $^6$He elastic scattering

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6. Discussion of the $^6$He+$^{208}$Pb potential
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1. Introduction

Presentation of the $^6$He nucleus
- Simplest halo 3-body nucleus
- Well described by an $\alpha+n+n$ structure
- Many theoretical calculations: rms radius, energy spectrum, E1 strength, etc.
- Challenge: describing reactions involving $^6$He

Many data
- Essentially elastic scattering around the Coulomb barrier: $^{208}$Pb, $^{120}$Sn, $^{64}$Ni, $^{209}$Bi, etc.

$^6$He$+^{58}$Ni
V. Morcelle et al., PLB 732 (2014) 228
1. Introduction

Other cross sections (non elastic)
Example: Alpha production

\[ ^6\text{He} + ^{208}\text{Pb}, 22 \text{ MeV} \]

\[ \sigma (\text{mb/}\Omega) \]

\[ \theta_{\text{c.m.}} (\text{deg}) \]

\[ ^{6}\text{He} + ^{208}\text{Pb} \]
A. Sanchez Benitez et al., JPG31 (2005) S1953

Fusion: more difficult (must include transfer)

\[ ^{6}\text{He} + ^{64}\text{Zn} \]
V. Scuderi et al., PRC 84 (2011) 064604
1. Introduction

Current status of reactions with $^6\text{He}$

- Optical model: several parameters $\rightarrow$ predictive power? (used to fit data)

- CDCC (Continuum Discretized Coupled Channels)

**Solution of 3-body (4-body) scattering problem**

M. Kamimura et al, Prog. Theor. Phys. Suppl. 89 (1986) 1

- Projectile initially assumed to be described by two clusters

- Introduced for deuteron-induced reactions (breakup important) $\rightarrow$ well adapted to exotic nuclei

- Various cross sections: elastic, breakup, fusion, etc. (**Energy near the Coulomb barrier**)

- Recently extended to 3-body projectiles ($^6\text{He}=\alpha+n+n$, $^9\text{Be}=\alpha+\alpha+n$)
1. Introduction

Current status of reactions with $^6\text{He}$

- Non microscopic CDCC (Continuum Discretized Coupled Channel)

\[ \alpha+n+n \text{ description of } ^6\text{He} \]
\[ ^6\text{He}+^{209}\text{Bi} \]
T. Matsumoto et al., PRC 73 (2006) 051602(R)

\[ ^6\text{He}+^{58}\text{Ni} \]
V. Morcelle et al., PLB 732 (2014) 228

\[ \alpha+2n \text{ description of } ^6\text{He} \]
\[ ^6\text{He}+^{58}\text{Ni} \]
V. Morcelle et al., PLB 732 (2014) 228

→ Need for n+Target, $\alpha$+Target, 2n+Target optical potentials
1. Introduction

Here: 6-nucleon description of $^6$He +cluster approximation

RGM: $\psi_{0,k}^{j\pi} = A \varphi_\alpha \varphi_n \varphi_n g_k^{j\pi}(r_1, r_2)$

$j=$spin of the $^6$He system (here: $0^+$ to $3^-$)

$k=$excitation level

$\varphi_\alpha=$0s shell-model wave function

Microscopic CDCC
P.D., M. Hussein, PRL 111 (2013) 082701 ($^7$Li=$\alpha+t$)

- Antisymmetrization included in $^6$He
- Only nucleon-target potential
- Breakup included
Total Hamiltonian: \[ H = H_0 + T_R + \sum_{i=1}^{6} v_{i-T}(r_i - R) \]

With \[ H_0 = \sum_i t_i + \sum_{i<j} v_{ij} \] = microscopic Hamiltonian of $^6$He

\[ v_{i-T}(r) = \text{optical potential neutron/proton + target (includes Coulomb)} \]

Wave function: \[ \Psi^{JM\pi}(R, r_i) = \sum_{jLk} u^{J\pi}_{jLk}(R) \left[ \psi_{0,k}^{j\pi}(r_i) \otimes Y_L(\Omega_R) \right]^{JM} \]

To be determined \( \rightarrow \) scattering matrices

Angular functions

$^6$He wave functions
Several steps:

1. Solve the $^6$He problem: $H_0 \psi_{0,k}^{j\pi} = E_k^{j\pi} \psi_{0,k}^{j\pi}$
   $\rightarrow$ Generator Coordinate Method (GCM)

2. Compute the coupling potentials $V_{k,k'}^{j\pi,j'\pi'}(R) = \langle \psi_{0,k}^{j\pi} | \sum_i v_{i-T} (r_i - R) | \psi_{0,k'}^{j'\pi'} \rangle$
   $\rightarrow$ densities + folding method
   $\rightarrow$ multipole expansion

3. Solve the coupled-channel system for each $j\pi$
   $\rightarrow$ R-matrix method (provides the scattering matrices)

4. Compute the cross sections from the scattering matrices (standard formula)
First step:

Microscopic description of $^{6}\text{He}$
2. Microscopic description of $^6$He

References


6-body Hamiltonian: $H_0 = \sum_i t_i + \sum_{i<j} (v_{ij}^N + v_{ij}^C)$

$v_{ij}^C$ = Coulomb interaction (exact)

$v_{ij}^N$ = Minnesota (parameter u) + zero-range spin-orbit (parameter $S_0$)

RGM approximation (clusters): $\psi_{0,k}^{j\pi} = A\varphi_\alpha\varphi_n\varphi_n g_k^{j\pi}(r_1, r_2)$

GCM: $\psi_{0,k}^{j\pi} = \sum_{i,i'} f_k^{j\pi}(R_{1i}, R_{2i'}) \Phi^{jm\pi}(R_{1i}, R_{2i'})$

$R_{1i}, R_{2i'}$ = generator coordinates associated with $r_1, r_2$

$\Phi^{jm\pi}(R_{1i}, R_{2i'})$ = projected Slater determinant
2. Microscopic description of $^6$He

Hyperspherical coordinates

\[ X = \frac{R_2}{\sqrt{\mu_{12}}} \]
\[ Y = \frac{R_1}{\sqrt{\mu(12)3}} \]

→ Hyperradius $\rho = \sqrt{X^2 + Y^2}$

→ A single generator coordinate, associated with the hyperradius $\rho$

→ The $^6$He wave function is expanded as

\[ \psi_{0,k}^{jm\pi} = \sum_{K=0}^{\infty} \sum_{l_x,l_y,L,S}^N \sum_{i=1}^{f_{\gamma K}} (\rho_i) \Phi_{\gamma K}^{jm\pi} (\rho_i) \]

$K=$hypermoment (truncated at $K_{max}$)

$\gamma = (l_x, l_y, L, S)$
with $K = l_x + l_y + 2n \ (n > 0)$
the number of $\gamma$ values depends on $K_{max}$

$\rho_i$: values of the generator coordinate ($N \approx 10 - 15$)
2. Microscopic description of $^6$He

$$\psi_{0,k}^{jm\pi} = \sum_{K=0}^{\infty} \sum_{l_x,l_y,L,S} \sum_{i=1}^{N} f^{j\pi}_{\gamma K,k}(\rho_i) \Phi^{jm\pi}_{\gamma K}(\rho_i)$$

$\Phi^{jm\pi}_{\gamma K}(\rho_i)$=projected Slater determinant

$f^{j\pi}_{\gamma K}(\rho_i)$=generator function

Standard variational problem

$$\sum_{\gamma,K,i} f^{j\pi}_{\gamma K,k}(\rho_i) \left( H^{j\pi}_{\gamma K,\gamma',K'}(\rho_i,\rho_{i'}) - E^{j\pi}_{0,k} H^{j\pi}_{\gamma K,\gamma',K'}(\rho_i,\rho_{i'}) \right) = 0$$

With

$$H^{j\pi}_{\gamma K,\gamma',K'}(\rho_i,\rho_{i'}) = \langle \Phi^{j\pi}_{\gamma K}(\rho_i) | H | \Phi^{j\pi}_{\gamma',K'}(\rho_{i'}) \rangle$$

$$N^{j\pi}_{\gamma K,\gamma',K'}(\rho_i,\rho_{i'}) = \langle \Phi^{j\pi}_{\gamma K}(\rho_i) | 1 | \Phi^{j\pi}_{\gamma',K'}(\rho_{i'}) \rangle$$

7-dimension integrals

Also needed: densities $\langle \Phi^{j\pi}_{\gamma K}(\rho_i) | \sum_n \delta(\mathbf{r} - \mathbf{r}_n) | \Phi^{j\pi}_{\gamma',K'}(\rho_{i'}) \rangle$ (expanded in multipoles)
2. Microscopic description of $^6$He

Projected matrix elements: 7-dimension integrals

5 angles: $\theta_1, \phi_1, \theta_2, \phi_2, \theta$
2 hyperangles: $\alpha_1, \alpha_2$

For each $(\rho, \rho')$
2. Microscopic description of $^6\text{He}$

Conditions of the calculations

- NN interaction: Minnesota with $u=1.050$, $S_0=30 \rightarrow$ reproduce $^6\text{He}$ binding energy, and $\alpha+n$ phase shifts
- $j=0^+,1^-,2^+,3^-$
- $K_{\text{max}}=18$
- $\rho_i$: from 1.5 fm to 12 fm (by step of 1.5 fm)
### 2. Microscopic description of $^6\text{He}$

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<th>GCM</th>
<th>exp</th>
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<td></td>
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<tr>
<td>$\sqrt{&lt; r^2 &gt;_n}$</td>
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<tr>
<td>$\sqrt{&lt; r^2 &gt;}$</td>
<td>2.39</td>
<td>$2.33 \pm 0.04$</td>
</tr>
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#### Ground-state densities

- **Protons**
- **Neutrons**

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**Note:** The ground-state densities are plotted on a logarithmic scale for clarity.
Second step:

Calculation of the coupling potentials
3. Coupling potentials

Coupling potentials $V^{jm, j'm'}_{k,k'}(R) = \langle \psi_{0,k}^{jm\pi} | \sum_i v_{i-T}(r_i - R) | \psi_{0,k'}^{jm'\pi'} \rangle$

- $\psi_{0,k}^{jm\pi}$ = combination of projected Slater determinants
- $v_{i-T}(r_i - R)$ = nucleon-target interaction (including Coulomb)

→ Standard one-body matrix element (such as kinetic energy, rms radius...)
→ Must be expanded in multipoles:

$$V^{jm, j'm'}_{k,k'}(R) = \sum_{\lambda} < jm \lambda m' - m| j'm' > V^{j'\lambda}_{k,k'}(\lambda, R) Y_{\lambda}^{m'-m}(\Omega_R)$$
3. Coupling potentials

→ Two calculation methods:

1) Brink’s formula for Slater determinants

One-body matrix elements (kinetic energy, rms radius, densities, etc.)

• Matrix elements between individual orbitals \( \varphi_i : M_{ij} = < \varphi_i | v(r - R) | \varphi_j > \)
• Overlap matrix \( B_{ij} = < \varphi_i | \varphi_j > \)
• Angular momentum projection

2) Folding procedure

\[
V_{k,k'}^{j m, j' m'} (R) = < \psi_{0,k}^j \sum_i v(r_i - R) \psi_{0,k'}^{j'} > 
\]

\[
= \int dS \nu(S - R) < \psi_{0,k}^j \sum_i \delta(r_i - S) \psi_{0,k'}^{j'} > 
\]

\[
= \int dS \nu(S - R) \rho_{k,k'}^{j m, j' m'} (S) 
\]

With \( \rho_{k,k'}^{j m, j' m'} (S) = < \psi_{0,k}^j \sum_i \delta(r_i - S) \psi_{0,k'}^{j'} > = \text{nuclear densities} \)

expanded in multipoles as \( \rho_{k,k'}^{j m, j' m'} (S) = \sum_\lambda < jm \lambda m' - m | j' m' > \rho_{k,k'}^{jj' \lambda} (S) Y_{\lambda}^{m'-m} (\Omega_S) \)

→ Test of the calculation
→ 2\textsuperscript{nd} method more efficient since changing the potential is a minor work
3. Coupling potentials

**In practice:** folding potentials are computed with Fourier transforms

If $V(r) = \int v(r - S) \rho(S) dS$ → $\tilde{V}(q) = \tilde{v}(q) F(q)$

- $\tilde{v}(q)$=Fourier transform of the nucleon-target interaction
- $F(q)$=form factor (=Fourier transform of the density)
- Must be done for protons and neutrons
- For pseudostates: densities extend to large distances → numerical problems
tests with the Coulomb interaction: analytical calculations possible

All couplings are needed
→ many possibilities
Third step:
Solving the coupled-channel equations
4. Solving the coupled-channel equations

Hamiltonian: $H = H_0 + T_R + \sum_i v_{i-T}(r_i - R)$

Wave function: $\Psi^{JM\pi}(R, r_i) = \sum_{jLk} u^{J\pi}_{jLk}(R) \left[ \psi^{\pi}_{0,k}(r_i) \otimes Y_L(\Omega_R) \right]^{JM}$

$\rightarrow$ Set of coupled equations

$$\left[ -\frac{\hbar^2}{2\mu} \left( \frac{d^2}{dR^2} - \frac{L(L+1)}{R^2} \right) + E_c - E \right] u^{J\pi}_c(R) + \sum_{c'} V^{J\pi}_{cc'}(R) u^{J\pi}_{c'}(R) = 0$$

$V^{J\pi}_{cc'}(R)$ obtained from $V^{jm, j'm'}_{k,k'}(R)$ with additional angular momentum couplings

Channel $c=j$: projectile quantum numbers $k$: excitation level of the projectile [physical state ($E < 0$) or pseudostate ($E > 0$)] $L$: orbital angular momentum between projectile and target
4. Solving the coupled-channel equations

\[
\left[ -\frac{\hbar^2}{2\mu} \left( \frac{d^2}{dR^2} - \frac{L(L + 1)}{R^2} \right) + E_c - E \right] u_c^{J\pi}(R) + \sum_{c'} V_{cc'}^{J\pi}(R) u_{c'}^{J\pi}(R) = 0
\]

- Common to all CDCC variants
  - Solved with: Numerov algorithm / \textbf{R-matrix method}

At large distances
- Nuclear potential negligible, only Coulomb remains
- Wave function \( u_c^{J\pi}(R) \rightarrow I_c(k_cR)\delta_{\omega c} - U_{\omega c}^{J\pi} O_c(k_cR) \)
  - with \( \omega \) = entrance channel
  - \( I_c(x), O_c(x) \) = incoming and outgoing Coulomb functions
  - \( U_{\omega c}^{J\pi} \) = scattering matrix \( \rightarrow \) various cross sections (elastic, breakup, etc)

\( ^6\text{He ground state:} \ j=0^+, k=1 \)

\( \alpha+n+n \) pseudostates
  - Simulate BU effects
  - \( j=0^+ (k>1), 1^-, 2^+, 3^- \)
4. Solving the coupled-channel equations

Solving the coupled-channel system

**R-matrix theory:** based on 2 regions (channel radius a)

- A.M. Lane and R.G. Thomas, Rev. Mod. Phys. 30 (1958) 257

Internal region: \( R \leq a \)

External region: \( R \geq a \)

**Full Hamiltonian**

\[ u^{J\pi}_c(R) \] expanded over a basis (N functions)

\[ u^{J\pi}_{c,\text{int}}(R) = \sum_{i=1}^{N} c_i \phi_i(R) \]

**Only Coulomb**

\[ V_{cc'}^{J\pi}(R) = \frac{Z_pZ_te^2}{R} \delta_{cc'} \]

\[ u^{J\pi}_c(R) \] has its asymptotic form

\[ u^{J\pi}_{c,\text{ext}}(R) = I_c(kR)\delta_{c\omega} - O_c(kR)U^{J\pi}_{c\omega} \]

matching at \( R=a \) provides: scattering matrices \( U^{J\pi} \) \( \rightarrow \) cross sections
4. Solving the coupled-channel equations


- Gauss approximation: \( \int_0^a g(x)dx \approx \sum_{k=1}^{N} \lambda_k g(x_k) \)
  - N= order of the Gauss approximation
  - \( x_k \) = roots of an orthogonal polynomial \( P_N(x) \), \( l_k \) = weights
  - If interval \([0,a]\): Legendre polynomials
    \([0,\infty]\): Laguerre polynomials

- Lagrange functions for \([0,1]\): \( f_i(x) \sim \frac{P_N(2x-1)}{(x-x_i)} \)
  - \( x_i \) are roots of \( P_N(2x-1) = 0 \)
  - with the Lagrange property: \( f_i(x_j) = \lambda_i^{-1/2} \)

- Matrix elements with Lagrange functions: Gauss approximation is used
  \[ <f_i|f_j> = \int f_i(x)f_j(x)dx \approx \delta_{ij} \]
  \[ <f_i|T|f_j> \] analytical
  \[ <f_i|V|f_j> = \int f_i(x)V(x)f_j(x)dx \approx V(x_i)\delta_{ij} \Rightarrow \text{no integral needed} \]
Propagation techniques

Computer time: 2 main parts

- **Matrix elements**: very fast with Lagrange functions
- **Inversion of a complex matrix** $C \rightarrow R$-matrix (long times for large matrices)

For reactions involving halo nuclei:

- Long range of the potentials (Coulomb)

\[
\frac{Z_1 Z_t e^2}{R + \frac{A_2}{A_p} r} + \frac{Z_2 Z_t e^2}{R - \frac{A_1}{A_p} r} = \sum_{\lambda} V_\lambda(r, R) P_\lambda(\cos \theta_{Rr})
\]

\[
V_{cc'}(R) \approx \frac{Z_p Z_t e^2}{R^2} + \frac{Z_t Q_p}{R^3} + \ldots
\]

- Radius $a$ must be large
- Many basis functions ($N$ large)
- Even stronger for dipole terms ($\sim 1/R^2$)

- **Distorted Coulomb functions (FRESCO)**
- **Propagation techniques in the R-matrix** (well known in atomic physics)
  
  Well adapted to Lagrange-mesh calculations
Applications:

$^6\text{He}$ scattering on $^{58}\text{Ni}$, $^{120}\text{Sn}$, $^{208}\text{Pb}$
5. Applications

$^6$He scattering on $^{58}$Ni, $^{120}$Sn, $^{208}$Pb

- Optical potentials n-T, p-T: taken from Koning and Delaroche, NPA 713 (2003) 231
  - Complex potentials (simulate the excitation of the target)
  - $^{58}$Ni, $^{120}$Sn, $^{208}$Pb: “local” potentials (specific fits)
- Convergence problems: truncation on $E_{max}, j_{max}$
5. Applications

\(^{6}\text{He} + ^{58}\text{Ni}: \) V. Morcelle et al., PLB 732 (2014) 228

Coulomb barrier \( V_B \sim 7.3 \) MeV

Convergence with \( E_{\text{max}} \)
\( j_{\text{max}} = 3 \)

Convergence with \( j_{\text{max}} \)
\( E_{\text{max}} = 15 \) MeV

→ 1- important
5. Applications

Convergence with $E_{\text{max}}$

$E_{\text{max}} = 15$ MeV

$\theta$ (deg)

$\sigma/\sigma_R$

Convergence with $j_{\text{max}}$

$E_{\text{max}} = 15$ MeV

$\theta$ (deg)

$\sigma/\sigma_R$

$^6\text{He} + ^{58}\text{Ni}$
5. Applications

$^6\text{He} + ^{120}\text{Sn}$:

Ref: P. N. de Faria et al., PRC 81 (2010) 044605

Coulomb barrier: VB~12 MeV

\[ \text{σ/σ}_R \] versus \( \theta \) (deg)

- Elab=17.4
- $^3\text{He}$ + $^{120}\text{Sn}$

\[ \text{σ/σ}_R \] at different \( j_{max} \) and $E_{max}$ values:

- $j_{max}=0$, $E=15$
- $j_{max}=1$, $E=15$
- $j_{max}=2$, $E=15$
- $J=3$, $E=15$
- $J=3$, $E_{max}=5$
- $J=3$, $E_{max}=10$
- $J=3$, $E=15$
5. Applications

$^6$He $+^{120}$Sn: VB $\sim$ 12 MeV

\[ \frac{\sigma}{\sigma_R} \]

$\theta$ (deg)

$\frac{\sigma}{\sigma_R}$

- $\text{gs}$
- $j_{\text{max}}=0, E=15$
- $j_{\text{max}}=1, E=15$
- $j_{\text{max}}=2, E=15$
- $j_{\text{max}}=3, E=15$

$\text{He}^6 + ^{120}\text{Sn}$: VB $\sim$ 12 MeV
$^6\text{He} + ^{208}\text{Pb}$: L. Acosta et al., PRC 84 (2011) 044604
Coulomb barrier VB~18.4 MeV

\begin{align*}
\text{Elab}=18 \text{ MeV} & \\
\text{Elab}=22 \text{ MeV} & \\
\text{Elab}=27 \text{ MeV} & 
\end{align*}
5. Applications

\(^6\text{He} + ^{208}\text{Pb}: \text{reaction cross sections}\\

\[ \sigma_R (\text{mb}) \]

\[ E_{\text{cm}} \text{ (MeV)} \]

- **BU channels yield a larger reaction cross section**
- **Stable with \( j_{\text{max}} \) and \( E_{\text{max}} \)**
Discussion of the $^6$He-$^{208}$Pb potential
6. Discussion of the $^6$He-$^{208}$Pb potential

Goals:
• Sensitivity with respect to the p-$^{208}$Pb and n-$^{208}$Pb optical potentials
• Equivalent potentials (full CDCC $\rightarrow$ single-channel)

1. Sensitivity

\[ H = H_0 + T_R + \sum_{i=1}^{6} \left( \frac{1}{2} - t_{iz} \right) \left[ v_p(r_i - R) + v_C(r_i - R) \right] + \left( \frac{1}{2} + t_{iz} \right) v_n(r_i - R) \]

Proton-target Optical potential

Neutron-target Optical potential

$v_p$ and $v_n$ are taken from Koning-Delaroche, NPA 713 (2003) 231
• Include real and imaginary parts
• Fit nucleon elastic scattering

$\rightarrow$ How sensitive are the $^6$He-$^{208}$Pb cross sections?
$\rightarrow$ Multiplicative factors $F_p$ and $F_n$
6. Discussion of the $^6$He-$^{208}$Pb potential

Single channel

- Negligible role of the p-$^{208}$Pb optical potential
  $E_{\text{lab}}(^6\text{He})=22$ MeV $\rightarrow E_{\text{lab}}(p)\sim 3.7$ MeV: much lower than the Coulomb barrier ($\sim 10$ MeV)

- Role of n-$^{208}$Pb: not very strong
  Consistent with R.C. Johnson et al., PRL 79 (1997) 2771

For halo nuclei: $\frac{d\sigma}{d\Omega} \approx |F(q)| \left(\frac{d\sigma}{d\Omega}\right)_{\text{core-target}}$

several conditions: adiabatic, core-target potential dominant, etc.
6. Discussion of the $^6$He-$^{208}$Pb potential

Multi channel

→ Similar conclusions for the p/n optical potentials
→ Importance of Coulomb couplings (difference between SC and MC)
6. Discussion of the $^{6}\text{He}-^{208}\text{Pb}$ potential

2. Equivalent potentials

Question: can we find a single-channel equivalent potential?

a) J-dependent potential

For the elastic channel: $(T_R + V_1^J(R) - E)u_1^J(R) = -\sum_{c\neq 1} V_{1c}^J(R)u_c^J(R)$

Equivalent to $(T_R + V_1^J(R) + V_{pol}^J(R) - E)u_1^J(R) = 0$

with $V_{pol}^J(R) = -\frac{\sum_{c\neq 1} V_{1c}^J(R)u_c^J(R)}{u_1^J(R)}$

Problems: J dependent
contains singularities (nodes of the wave function)

→ Construction of a J-independent potential
6. Discussion of the $^6$He-$^{208}$Pb potential

b) J-independent potential

$$V_{pol}(R) = \frac{\sum_J V_{pol}^J(R) \omega^J(R)}{\sum_J \omega^J(R)}$$

With $\omega^J(R)=$ weight function
- reduces the influence of the nodes
- gives more weight to the dominant J-values

$$\omega^J(R) = (2J + 1) \left( 1 - |U_{11}^J|^2 \right) |u_1^J(R)|^2$$

Test: verify that $V_{pol}(R)$ reproduces the full calculation
6. Discussion of the $^6$He-$^{208}$Pb potential
6. Discussion of the $^6\text{He} - ^{208}\text{Pb}$ potential

$^6\text{He} - ^{208}\text{Pb}$, 22 MeV

- Long range of the polarization
- Real part repulsive
- Imaginary part negative (consistent with the reaction cross section)
Conclusion
7. Conclusion

- **Microscopic CDCC**: Combination of CDCC and microscopic cluster model for the projectile
- Continuum simulated by pseudostates
- Extension to three-cluster projectiles (still in progress!)
- Only a nucleon-target is necessary (no free parameter)
- Application to $^6$He + target
  - $^6$He is well described by a microscopic $\alpha$n+n structure
  - $^6$He+$^{58}$Ni, $^6$He+$^{120}$Sn, $^6$He+$^{208}$Pb are investigated near the Coulomb barrier
  - Good agreement with experiment
  - Importance of break-up channels (poor agreement when they are neglected)
- $^6$He+$^{208}$Pb potential
  - Equivalent potentials can be obtained
  - Break-up channels make the real part more repulsive
  - Imaginary part has a long range