Application of Three-Body methods in Direct Nuclear Reactions: ^{6}He (p,p) ^{6}He

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8/9/2011

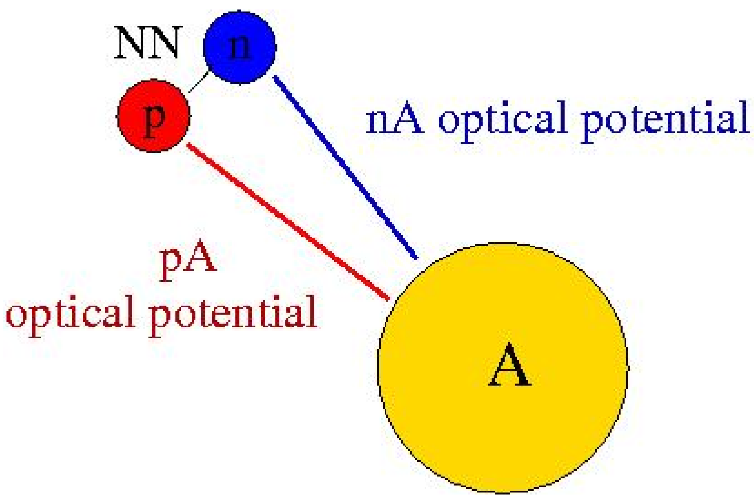
Supported by: U.S. DOE & TORUS

Direct Reactions:

- Elastic & inelastic scattering
- Few-particle transfer
  (stripping, pick-up)
- Charge exchange
- Knockout

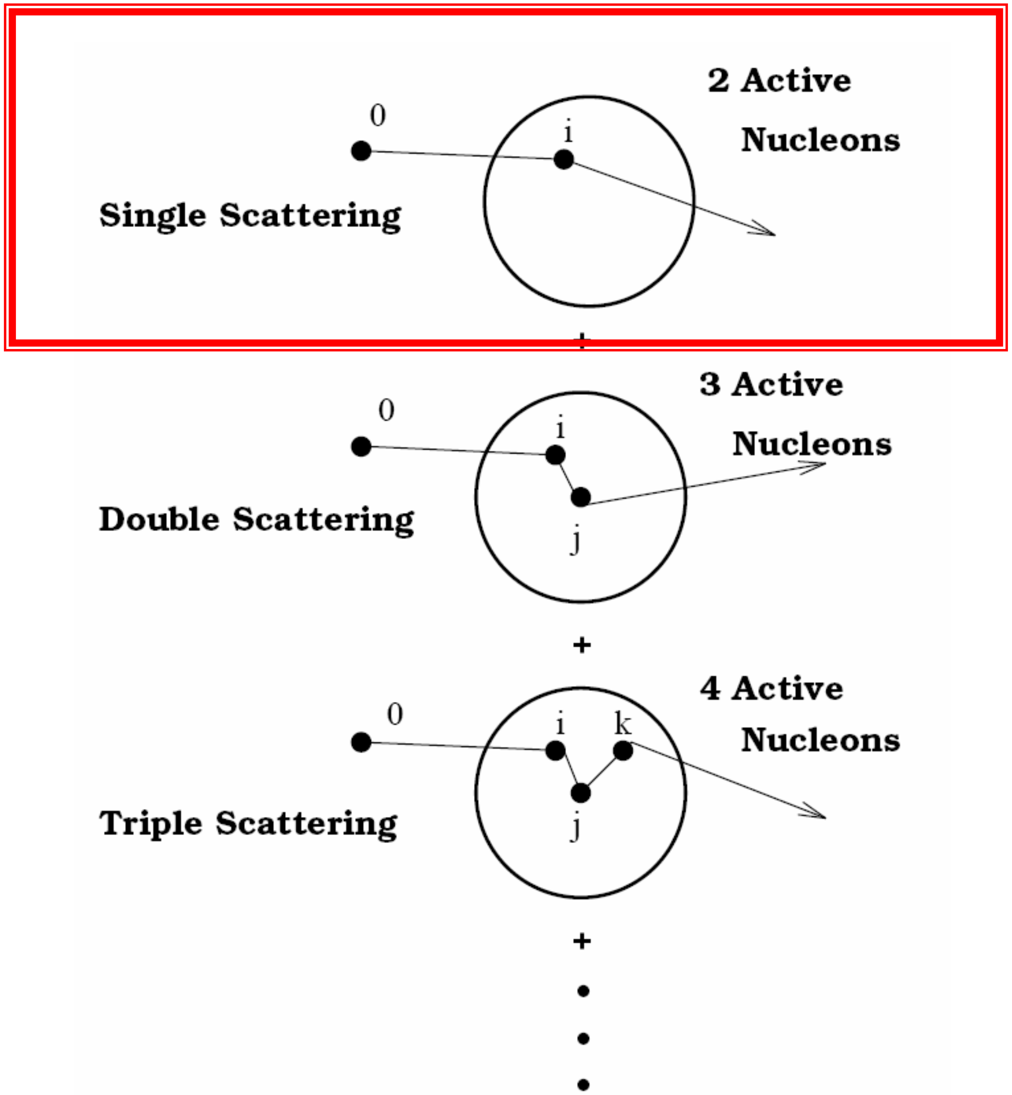
(d,p) reaction

Three-Body Problem



p+A Scattering

Spectator Expansion:

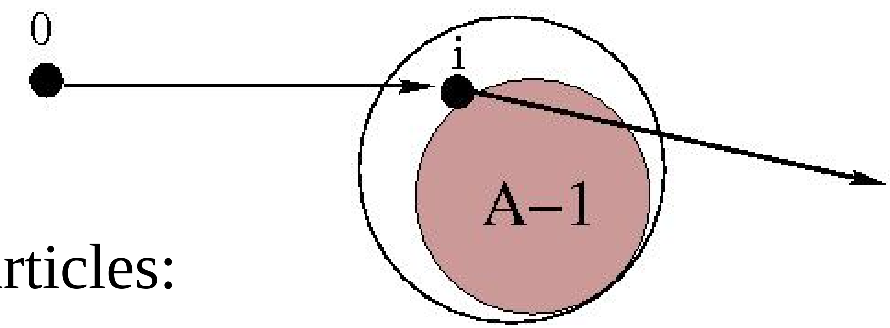


Written down by

Siciliano, Thaler (1977)

Picklesimer, Thaler (1981)

Single Scattering



Three-body problem with particles:

o – i – (A-1)-core

o – i : NN interaction

i – (A-1) core : e.g. mean field force

Phenomenological Optical Potentials parameterize single scattering term

Microscopic Optical Potentials

"Folding Models" for closed shell nuclei

- Watson Multiple Scattering
  - Elster, Weppner, Chinn, Thaler, Tandy, Redish
    - Separation of p-A and n-A optical potential
    - Based on NN t-matrix as interaction input
    - Treating of interaction with (A-1)-core via mean field and as implicit three-body problem
- Kerman-McManus-Thaler (KMT)
  - Crespo, Johnson, Tostevin, Thompson
    - Based on NN t-matrix as input
    - Couple explicitly to (A-1) core
    - Introduce cluster ansatz for halo targets within coupled channels
- G-matrix folding
  - Arellano, Brieva, Love
    - Based on NN g-matrix
    - Improving local density approximation
  - Picked up by Amos, Karataglidis and extended to exotic nuclei

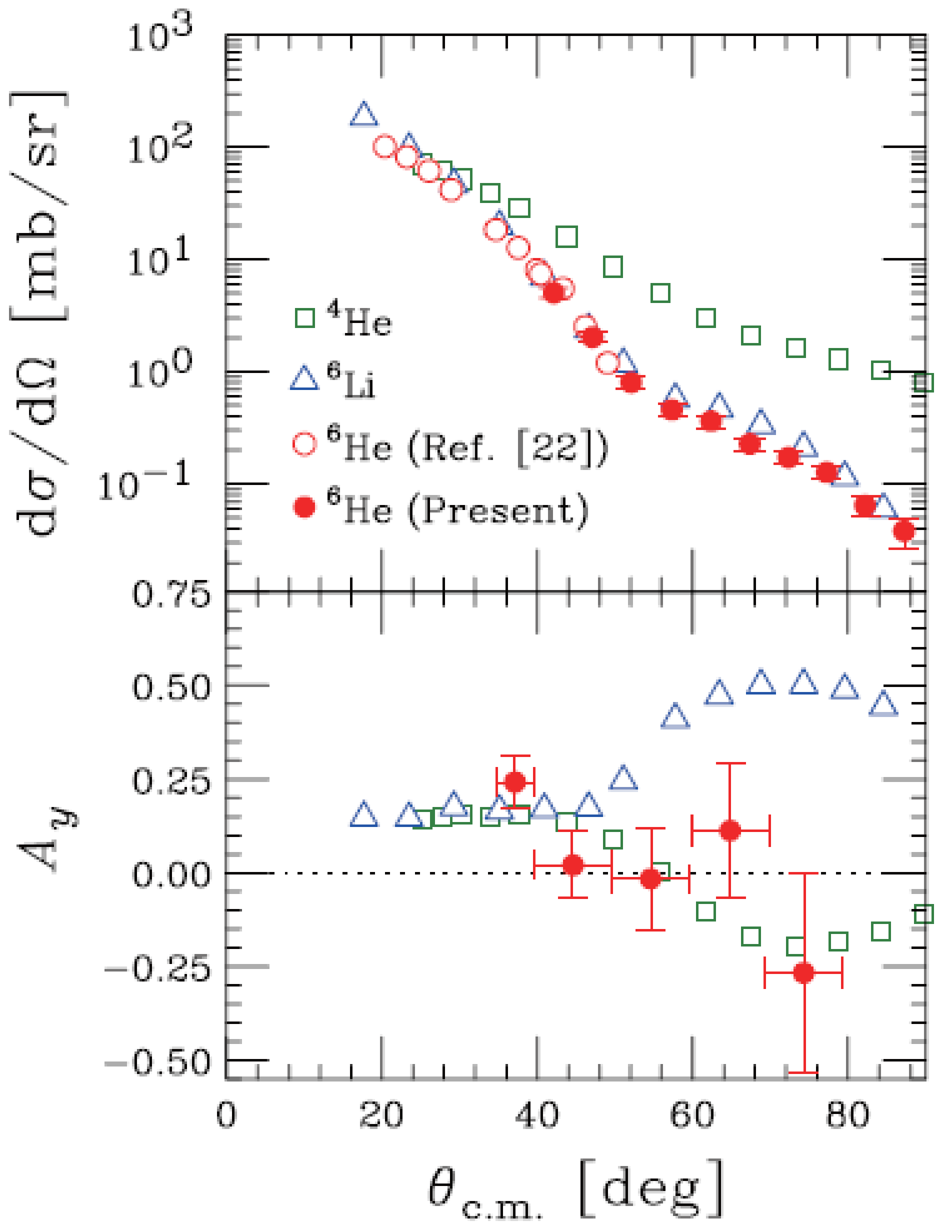
RIKEN:
$^6He(p,p)^6He$
@ 71 MeV

S. Sakaguchi et al.

arXiv: 1106.3903

[nucl-exp]

Task:
Optical Potential
for Halo Nucleus



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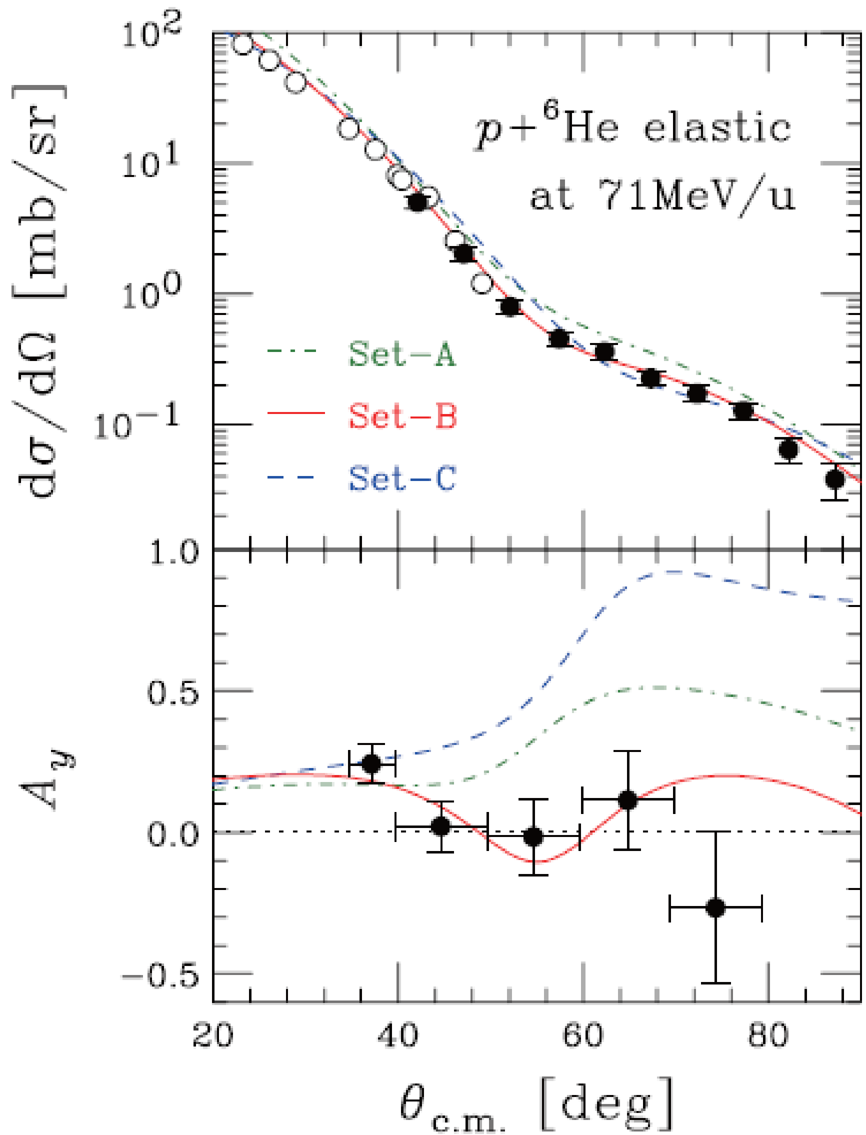
We adopted a standard Woods-Saxon optical potential with a spin-orbit term of the Thomas form:

$$U_{\rm OM}(R) = -\ V_0\, f_r(R) - i\, W_0\, f_i(R) + 4i\, a_{id}\, W_d \frac{d}{dR} f_{id}(R) + V_s \frac{2}{R}\frac{d}{dR} f_s(R)\, \boldsymbol{L}\cdot\boldsymbol{\sigma}_p + V_{\rm C}(R) \quad (1)$$

with

$$f_x(R) = \left[1+\exp\left(\frac{R - r_{0x}A^{1/3}}{a_x}\right)\right]^{-1} \quad (2)$$

$$(x = r, i, id, \text{ or } s).$$



Scattering: Lippmann-Schwinger Equation

- LSE: $T = V + V\, G_0\, T$
- Hamiltonian: $H = H_0 + V$
- Free Hamiltonian: $H_0 = h_0 + H_A$
  - h_0: kinetic energy of projectile '0'
  - H_A: target hamiltonian with $H_A\, |\Phi\rangle = E_A\, |\Phi\rangle$
- V: interactions between projectile '0' and target nucleons 'i' $V = \Sigma^A_{i=0}\, v_{0i}$
- Propagator is (A+1) body operator
  - $G_0(E) = (E - h_0 - H_A + i\varepsilon)^{-1}$

Elastic Scattering

- In- and Out-States have the target in ground state Φ_0
- Projector on ground state $P = |\Phi_0\rangle\langle\Phi_0|$
  - With $1=P+Q$ and $[P,G_0]=0$
- For elastic scattering one needs
- $P\,T\,P = P\,U\,P + P\,U\,P\,G0(E)\,P\,T\,P$
- Or
  - $\boxed{T = U + U\,G_0(E)\,P\,T}$
  - $\boxed{U = V + V\,G_0(E)\,Q\,U}$ $\Leftarrow$ **optical potential**

Standard: $\mathbf{U^{(1)}} \approx \Sigma^{A}_{i=0}\, \boldsymbol{\tau}_{0i}$ (1st order)

with $\boxed{\tau_{0i} = v_{0i} + v_{0i}\, G_0(E)\, Q\, \tau_{0i}}$

$$\boxed{\tau_{0i} = v_{0i} + v_{0i}\, G_0(E)\, Q\, \tau_{0i}}$$

- $G_0(E) = (E - h_0 - H_A + i\varepsilon)^{-1}$ == (A+1) body operator
  - Standard **"impulse approximation":**
  - Average over $H_A \Rightarrow$ c-number
  - $\rightarrow G_0(e)$ ==: two body operator
- Deal with **Q**
  - Define "two-body" operator $\mathbf{t_{0i}^{free}}$ by
  - $\mathbf{t_{0i}^{free} = v_{0i} + v_{0i}\, G_0(e)\, t_{0i}^{free}}$
  - and relate via integral equation to τ_{oi}
  - $\boxed{\tau_{oi} = t_{0i}^{free} - t_{0i}^{free}\, G_0(e)\, \tau_{oi} \quad \text{[integral equation]}}$
  - Important for keeping correct iso-spin character of optical potential
  - $\boxed{U^{(1)} = \Sigma^{A}_{i=1}\, \tau_{oi} =: N\, \tau_n + Z\, \tau_p}$

First order Watson optical potential

$$U^{(1)} = \Sigma^{A}_{i=1}\, \tau_{oi} =: \Sigma^{N}_{i=1}\, \tau_{n} + \Sigma^{P}_{i=1}\, \tau_{p}$$

- Important for treating N≠Z nuclei
- Be sensitive to proton vs. neutron scattering
- In general
  - $t_{pp} \neq t_{np}$ **and** $\rho_p \neq \rho_n$
- These differences enter in a non-linear fashion into first order Watson optical potential

$$\tau_\alpha = t_\alpha - t_\alpha\, G_0^{\alpha}(e)\, \tau_\alpha\,, \quad \alpha = n,p$$

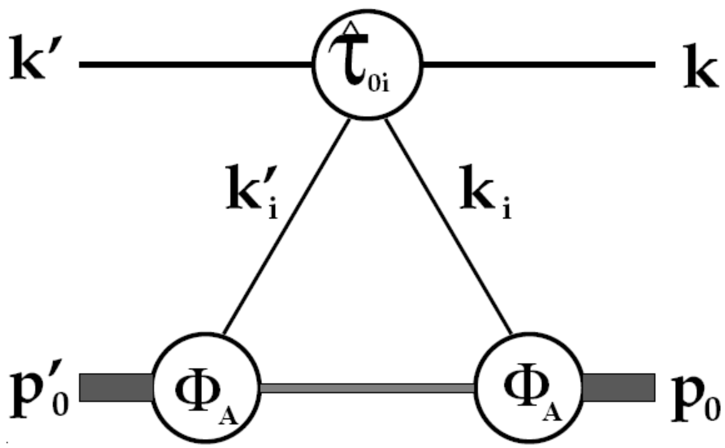
- **The Watson ansatz allows introducing a cluster ansatz for a nucleus very naturally**

Isospin effects in elastic p+A scattering, Chinn, Elster, Thaler, PRC47, 2242 (1993)

More formal:

- Elastic scattering : $$T_{el} = PUP + PUPG_0(E)PT_{el}.$$
- First order Watson O.P.:

$$\langle \mathbf{k}' | \langle \phi_A | PUP | \phi_A \rangle \mathbf{k} \rangle \equiv U_{el}(\mathbf{k}', \mathbf{k}) = \sum_{i=n,p} \langle \mathbf{k}' | \langle \phi_A | \hat{\tau}_{0i}(\mathcal{E}) | \phi_A \rangle \mathbf{k} \rangle$$



$$\langle \hat{\tau}_{01} \rangle \equiv \langle \mathbf{k}' | \langle \phi_A | \hat{\tau}_{01}(\mathcal{E}) | \phi_A \rangle \mathbf{k} \rangle$$

Proton scattering: $$U_{el}(\mathbf{k}', \mathbf{k}) = Z \langle \hat{\tau}_{01}^{pp} \rangle + N \langle \hat{\tau}_{01}^{np} \rangle$$

Calculate: $\langle \hat{\tau}_{01} \rangle \equiv \langle \mathbf{k}' | \langle \phi_A | \hat{\tau}_{01}(\mathcal{E}) | \phi_A \rangle \mathbf{k} \rangle$

$$\langle \mathbf{k}_1 \mathbf{k}_2 \mathbf{k}_3 \mathbf{k}_4 ... \mathbf{k}_A | \phi_A \rangle = \delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 + \mathbf{k}_4 ... + \mathbf{k}_A - \mathbf{p}_0) \langle \zeta_{\mathbf{1}} \zeta_{\mathbf{2}} \zeta_{\mathbf{3}} \zeta_{\mathbf{4}} ... \zeta_{\mathbf{A-1}} | \phi_A \rangle.$$

$$\langle \hat{\tau}_{01} \rangle = \int \prod_{j=1}^{A} d\mathbf{k}'_j \int \prod_{l=1}^{A} d\mathbf{k}_l \; \langle \phi_A | \zeta'_1 \zeta'_2 \zeta'_3 \zeta'_4 ... \zeta'_{A-1} \rangle \delta(\mathbf{p}' - \mathbf{p}'_0) \; \langle \mathbf{k}' \mathbf{k}'_1 | \hat{\tau}_{01}(\mathcal{E}) | \mathbf{k} \mathbf{k}_1 \rangle$$
$$\prod_{j=2}^{A} \delta(\mathbf{k}'_j - \mathbf{k}_j) \delta(\mathbf{p} - \mathbf{p}_0) \; \langle \zeta_1 \zeta_2 \zeta_3 \zeta_4 ... \zeta_{A-1} | \phi_A \rangle, \qquad (2.48)$$

With single particle density matrix :

$$\rho(\zeta'_{\mathbf{1}}, \zeta_{\mathbf{1}}) \equiv \int \prod_{l=2}^{A-1} d\zeta'_{\mathbf{l}} \int \prod_{j=2}^{A-1} d\zeta_{\mathbf{j}} \langle \phi_A | \zeta'_1 \zeta'_2 \zeta'_3 \zeta'_4 ... \zeta'_{A-1} \rangle \; \langle \zeta_1 \zeta_2 \zeta_3 \zeta_4 ... \zeta_{A-1} | \phi_A \rangle.$$

$$\boxed{\begin{aligned} \langle \hat{\tau}_{01} \rangle = & \int d\zeta'_{\mathbf{1}} \int d\zeta_{\mathbf{1}} \langle \mathbf{k}' \; \zeta'_{\mathbf{1}} + \frac{\mathbf{p}'_0}{A} | \hat{\tau}_{01}(\mathcal{E}) | \mathbf{k} \; \zeta_{\mathbf{1}} + \frac{\mathbf{p}_0}{A} \rangle \; \rho(\zeta'_{\mathbf{1}}, \zeta_{\mathbf{1}}) \\ & \delta(\frac{A-1}{A} \mathbf{p}'_0 - \zeta'_{\mathbf{1}} - \frac{A-1}{A} \mathbf{p}_0 + \zeta_{\mathbf{1}}). \end{aligned}}$$

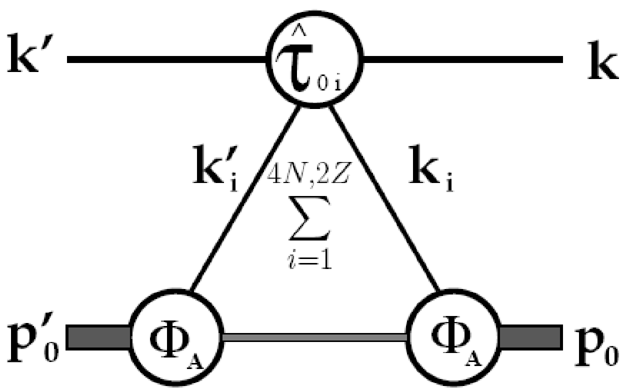
Better Variables:

$$\mathbf{k} = \mathbf{K} - \frac{1}{2}\mathbf{q} \qquad \zeta_1 = \mathbf{P} + \frac{A-1}{2A}\mathbf{q}$$

$$\mathbf{k}' = \mathbf{K} + \frac{1}{2}\mathbf{q} \qquad \zeta_1' = \mathbf{P} - \frac{A-1}{2A}\mathbf{q}.$$

$$\langle \hat{\tau}_{01} \rangle = \langle \frac{1}{2}(\mathbf{K} - \mathbf{P} + \frac{2A-1}{2A}\mathbf{q} - \frac{\mathbf{p}_0'}{A}) | \hat{\tau}_{01}(\hat{\mathcal{E}}) | \frac{1}{2}(\mathbf{K} - \mathbf{P} - \frac{2A-1}{2A}\mathbf{q} - \frac{\mathbf{p}_0}{A}) \rangle$$
$$\rho(\mathbf{P} - \frac{A-1}{2A}\mathbf{q}, \mathbf{P} + \frac{A-1}{2A}\mathbf{q}). \tag{2.59}$$

$$U_{el}(\mathbf{q}, \mathbf{K}) = \sum_{i=n,p} \int d\mathbf{P} \hat{\tau}_{0i}(\mathbf{q}, \frac{1}{2}(\frac{A+1}{A}\mathbf{K} - \mathbf{P}), \hat{\mathcal{E}})\ \rho_i(\mathbf{P} - \frac{A-1}{2A}\mathbf{q}, \mathbf{P} + \frac{A-1}{2A}\mathbf{q})$$



$$\hat{\mathcal{E}} = E_{NA} - \frac{(\mathbf{k} + \mathbf{k}_1)^2}{4m} = E_{NA} - (\frac{(\frac{A-1}{A}\mathbf{K} + \mathbf{P})^2}{4m})$$

Cluster Folding Optical Potential (n+n+α)

Jacobi momenta

$$\mathbf{p}_{j_i} = \frac{1}{A}(A_{si}\mathbf{p}_i - A_i\mathbf{p}_{\mathbf{s}i})$$

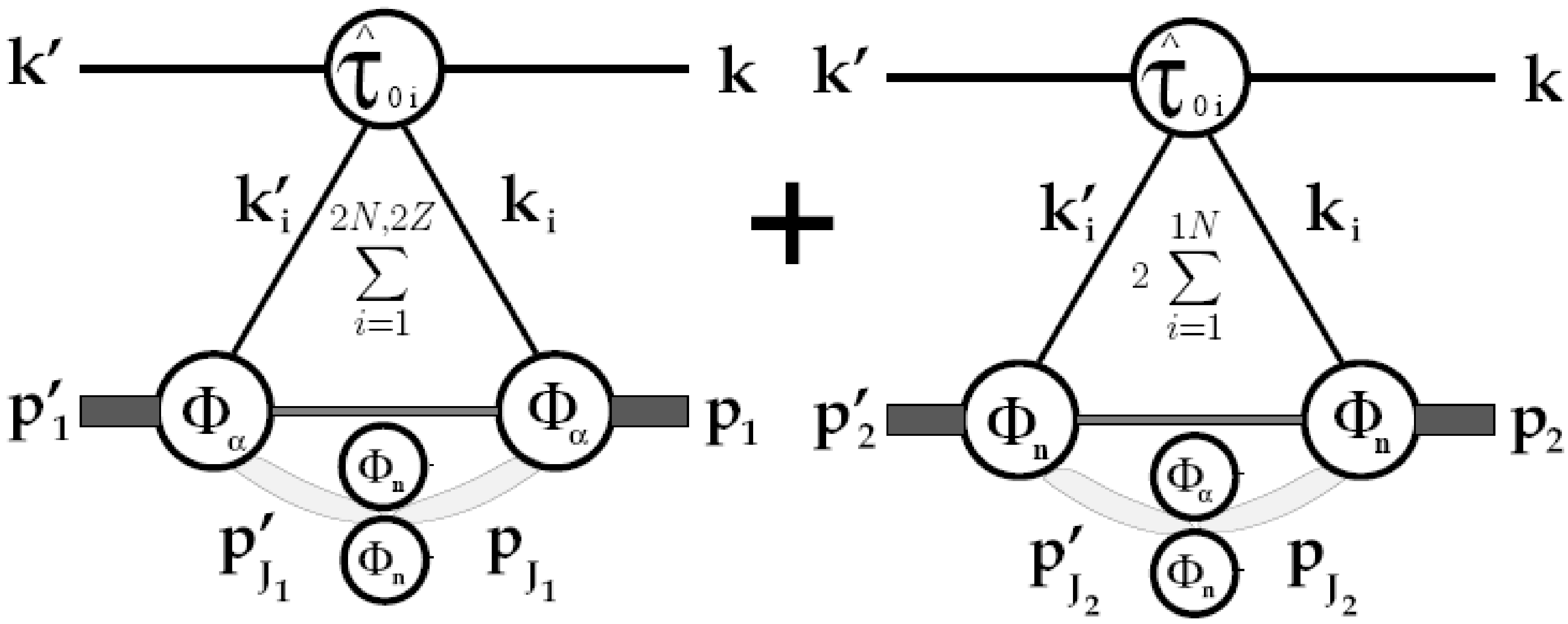
Correlation Density

$$\rho_{corr}(\mathbf{p}_{j_1}, \mathbf{p}_{j_1}') \equiv \int \prod_{l=2}^{N_c} d\mathbf{p}_{j_l}' \int \prod_{m=2}^{N_c} d\mathbf{p}_{j_m} \langle \phi_A | \mathbf{p}_{\mathbf{j}_1}' \mathbf{p}_{\mathbf{j}_2}' \cdots \mathbf{p}_{\mathbf{j}_{N_c}}' \rangle \, \langle \mathbf{p}_{\mathbf{j}_1} \mathbf{p}_{\mathbf{j}_2} \cdots \mathbf{p}_{\mathbf{j}_{N_c}} | \phi_A \rangle$$

Cluster optical potential

$$U_{el}(\mathbf{q}, \mathbf{K}) = \sum_{c=1,N_c} \sum_{i=n_c,p_c} \int d\mathbf{P} \, d\mathcal{P}_{j_c} \, \rho_{corr}(\mathcal{P}_{j_c}) \\ \hat{\tau}_{0i}\left(\mathbf{q}, \frac{1}{2}\left(\frac{A+1}{A}\mathbf{K} - \mathbf{P}\right), \mathcal{E}\right) \; \rho_{ci}\left(\mathbf{P} - \frac{A-1}{2A}\mathbf{q}, \mathbf{P} + \frac{A-1}{2A}\mathbf{q}\right)$$

Optical Potential for
^{6}He as cluster α+n+n



Cluster folding potential for ^{6}He+p

$$
{}^{^6\mathrm{He}}U_{el}(\mathbf{q},\mathbf{K}) = U_\alpha + 2U_n =
$$

$$
\sum_{i=n,p} \int d\mathbf{P}\, d\mathcal{P}_{j_\alpha}\, \rho_{corr}(\mathcal{P}_{j_\alpha})\, \hat{\tau}_{0i} \left(\mathbf{q}, \frac{1}{2}\left(\frac{A+1}{A}\mathbf{K} - \mathbf{P}\right), \mathcal{E}\right)\, \rho_{\alpha i}\left(\mathbf{P} - \frac{A-1}{2A}\mathbf{q}, \mathbf{P} + \frac{A-1}{2A}\mathbf{q}\right)
$$

$$
+2\int d\mathbf{P}\, d\mathcal{P}_{j_n}\, \rho_{corr}(\mathcal{P}_{j_n})\, \hat{\tau}_{0n} \left(\mathbf{q}, \frac{1}{2}(\frac{A+1}{A}\mathbf{K} - \mathbf{P}), \mathcal{E}\right)\, \rho_n\left(\mathbf{P} - \frac{A-1}{2A}\mathbf{q}, \mathbf{P} + \frac{A-1}{2A}\mathbf{q}\right).
$$

For calculation:

NN t-matrix: Nijmegen II potential

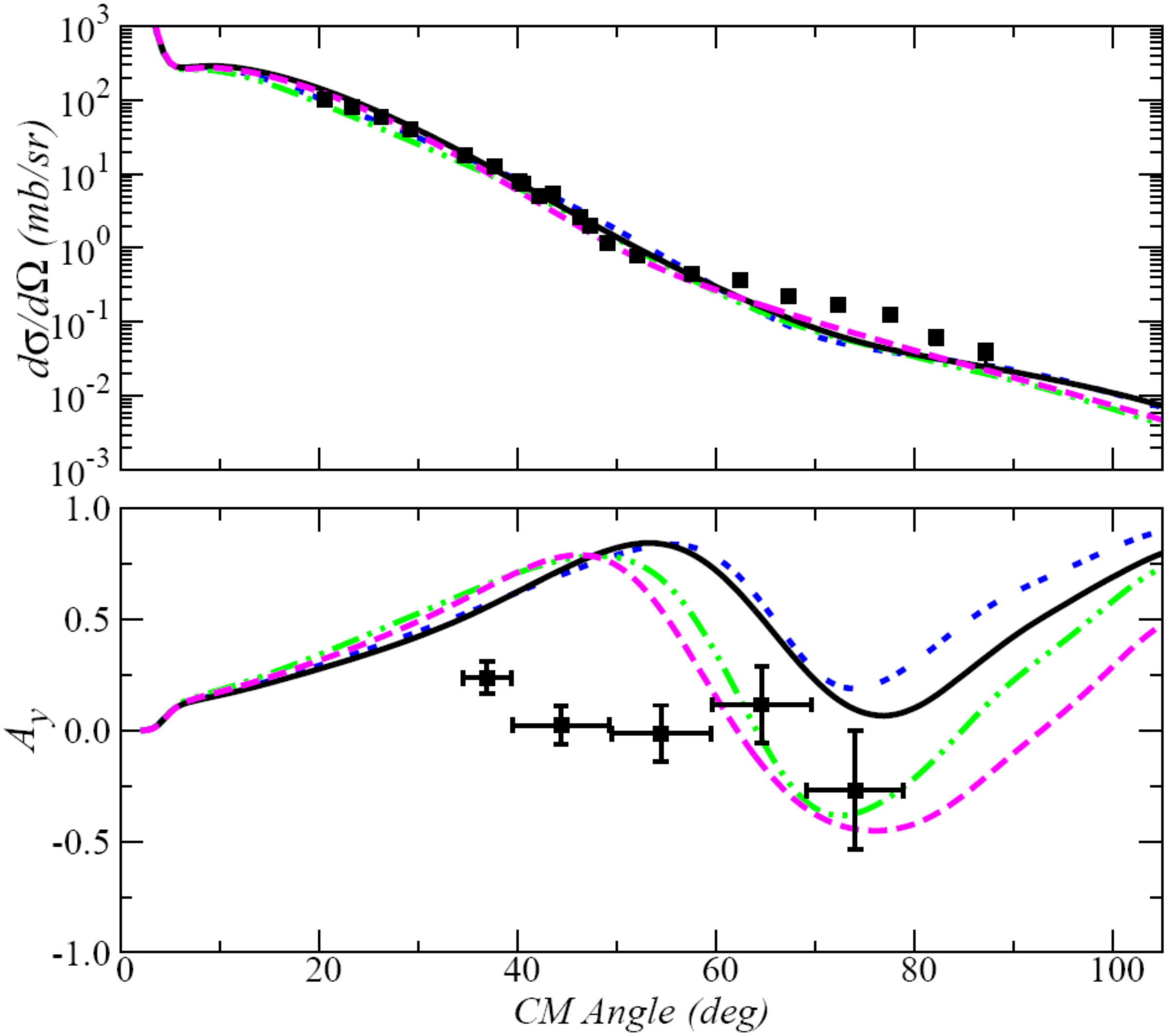
Densities:

COSMA density == s & p- shell harmonic oscillator wave functions

Fitted to give rms radius of ^{6}He

and for ^{4}He: Gogny density

^{6}He (p,p) ^{6}He @ 71 MeV



COSMA single particle OP

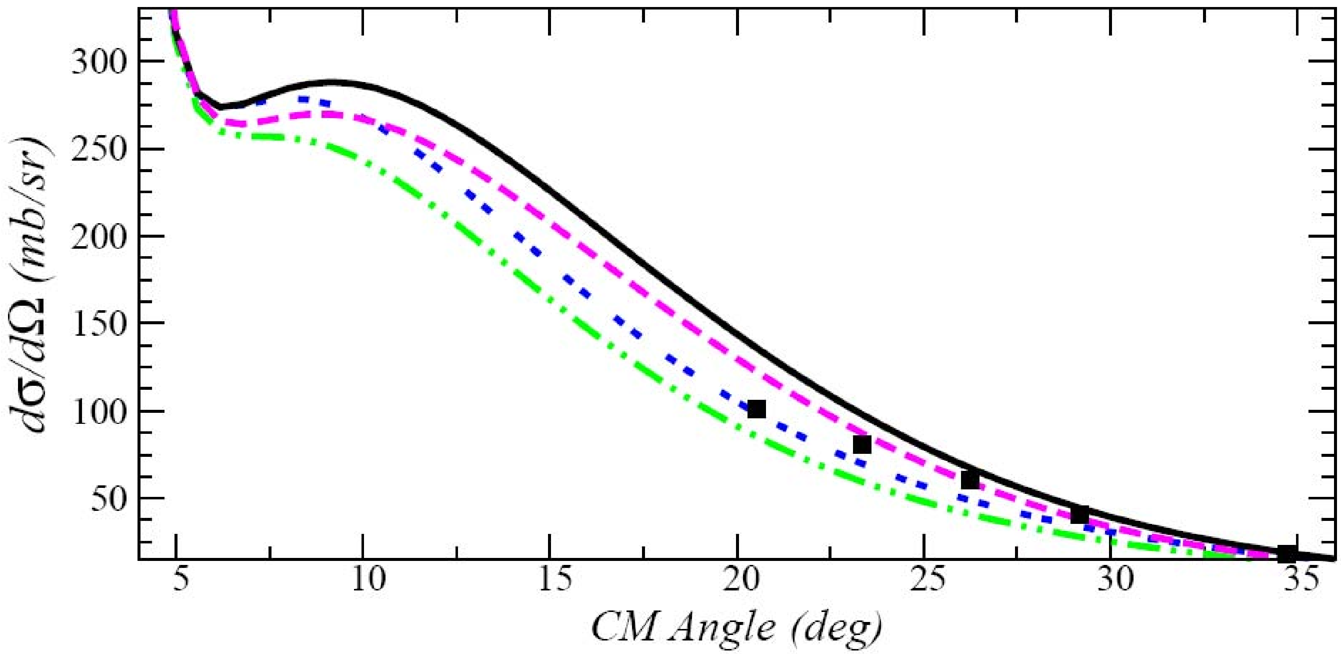
COSMA cluster OP

α- HFB

n - COSMA

α - HFB
n – COSMA
no correlations

^{6}He (p,p) ^{6}He @ 71 MeV



COSMA single particle OP

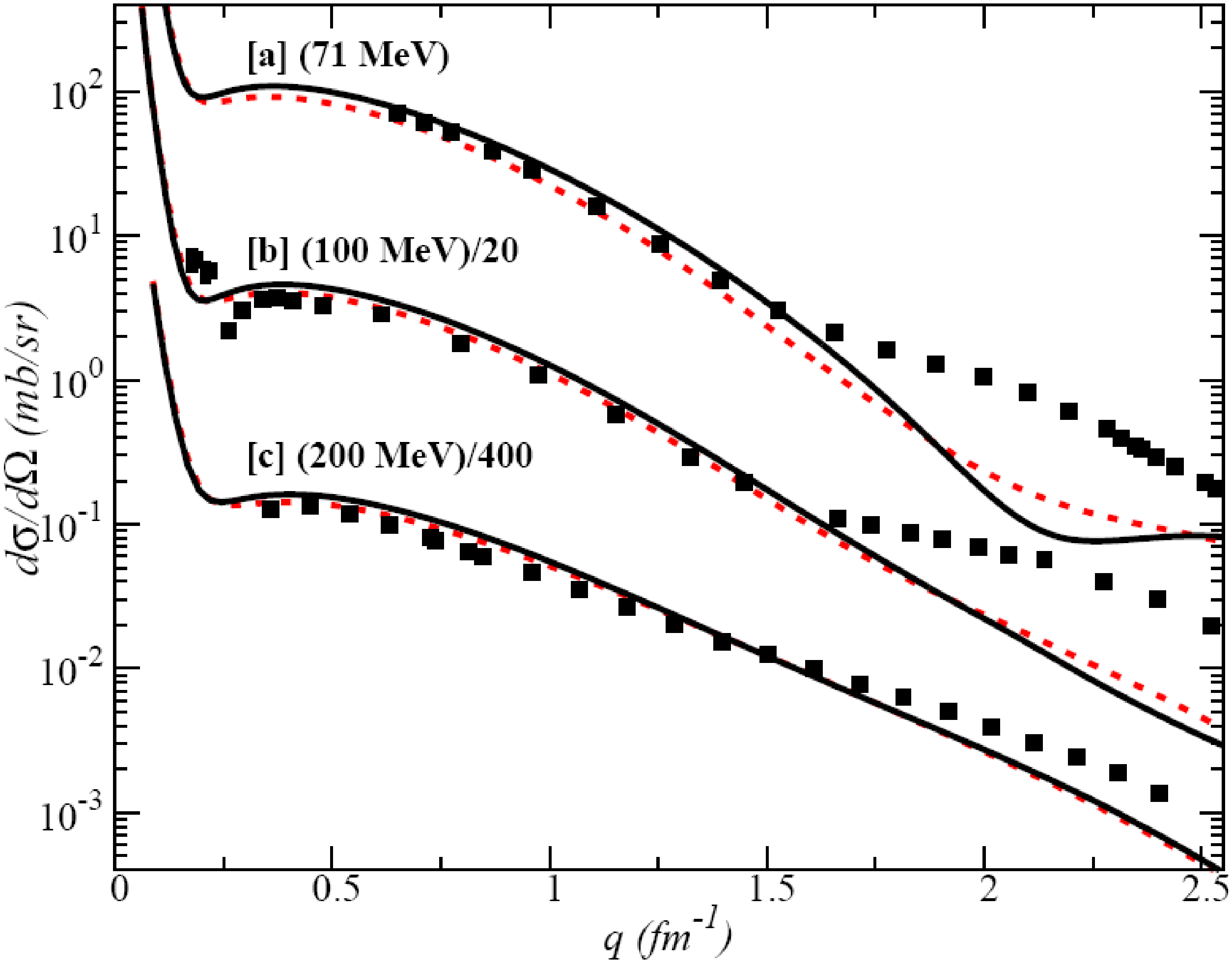
COSMA cluster OP

α- HFB

n - COSMA

α - HFB
n – COSMA
no correlations

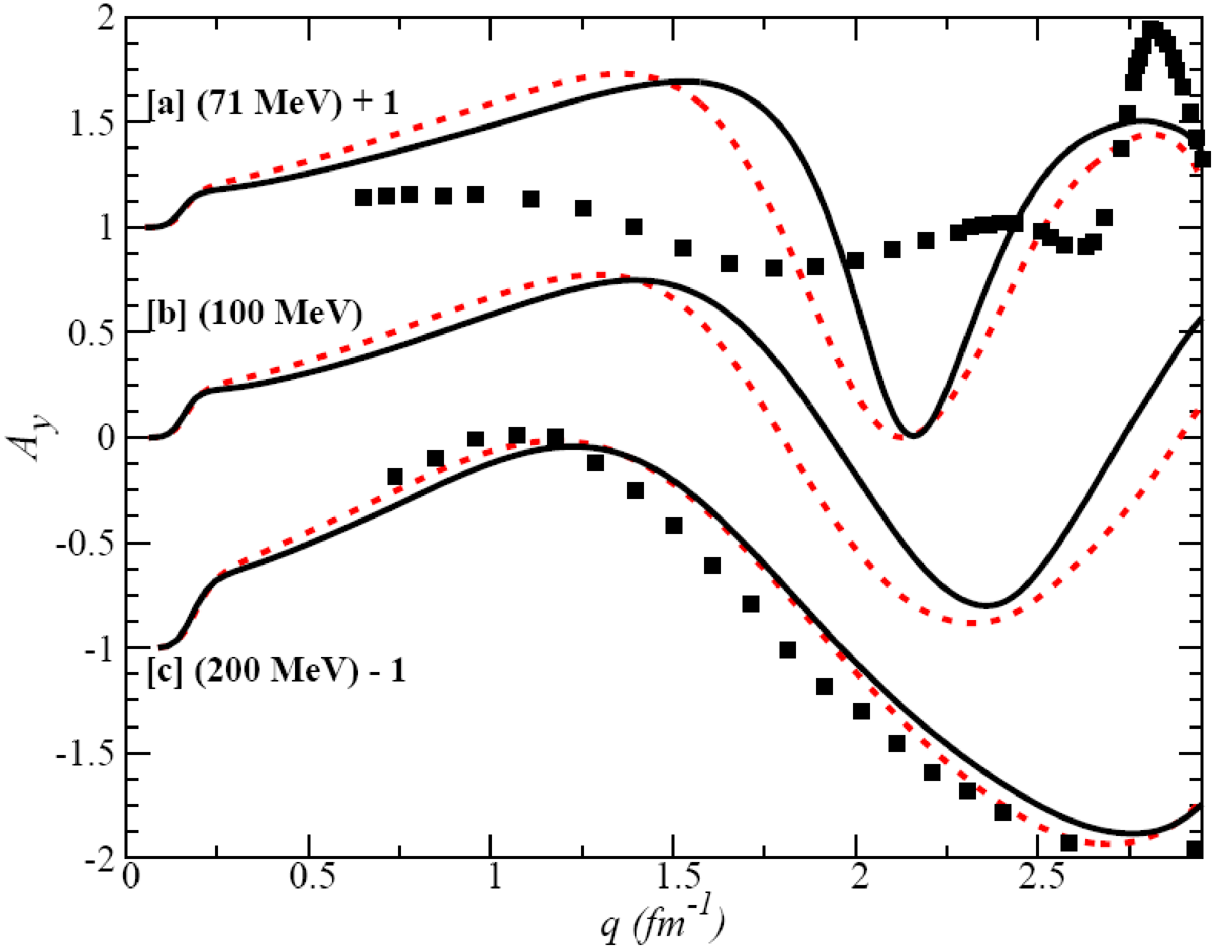
^{4}He (p,p) ^{4}He



Black: Free NN-tmatrix

Red: HFB mean field included

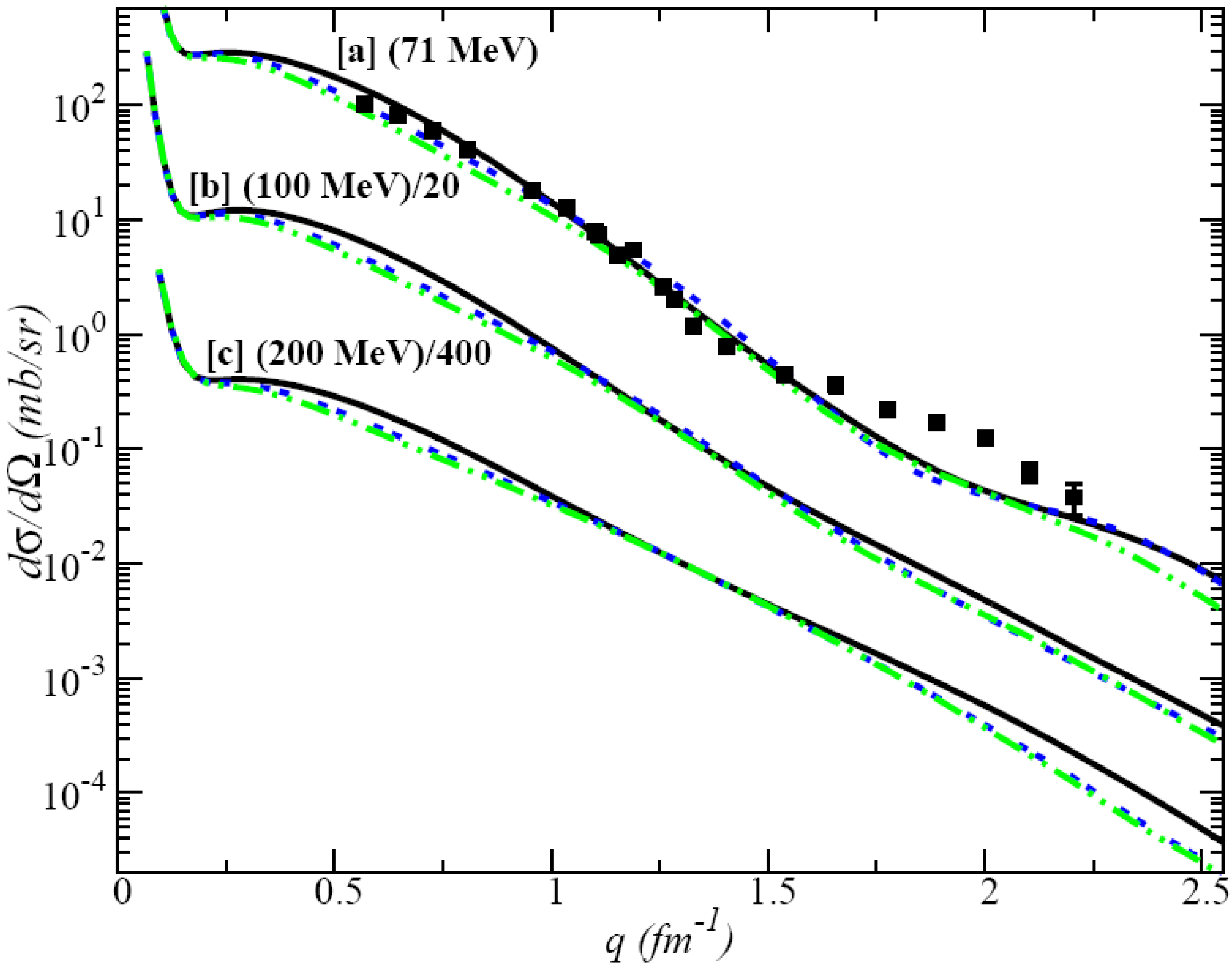
^{4}He (p,p) ^{4}He



Black: Free NN-tmatrix

Red: HFB mean field included

^6He (p,p) ^6He

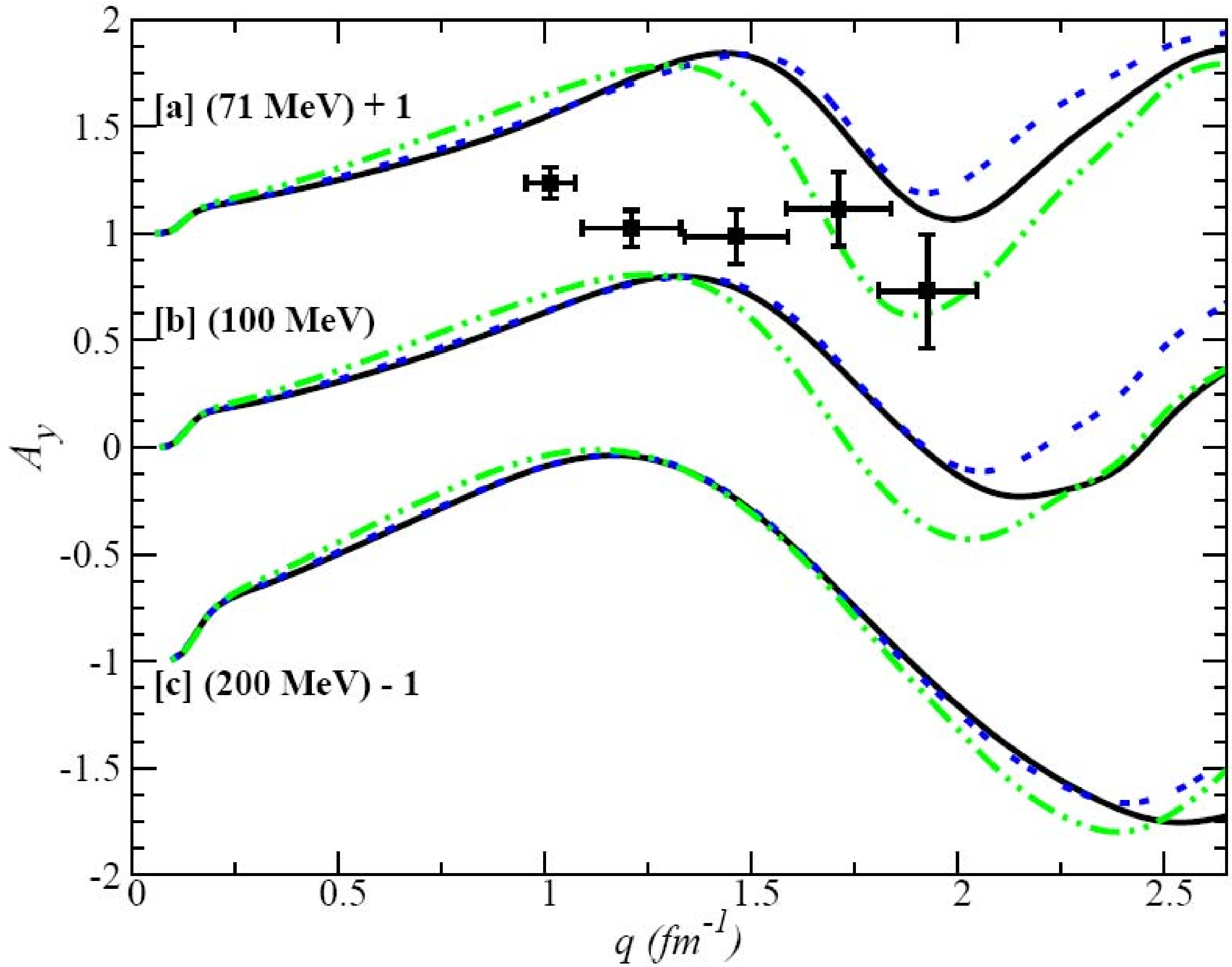


Black: COSMA single particle

Blue: Cosma Cluster

Green: ^4He - HFB

^{6}He (p,p) ^{6}He



[a] (71 MeV) + 1
[b] (100 MeV)
[c] (200 MeV) - 1
A_y
q (fm^{-1})
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
0.5
1
1.5
2
2.5

RIKEN: ^{6}He(p,p)^{6}He

S. Sakaguchi et al.

arXiv: 1106.3903

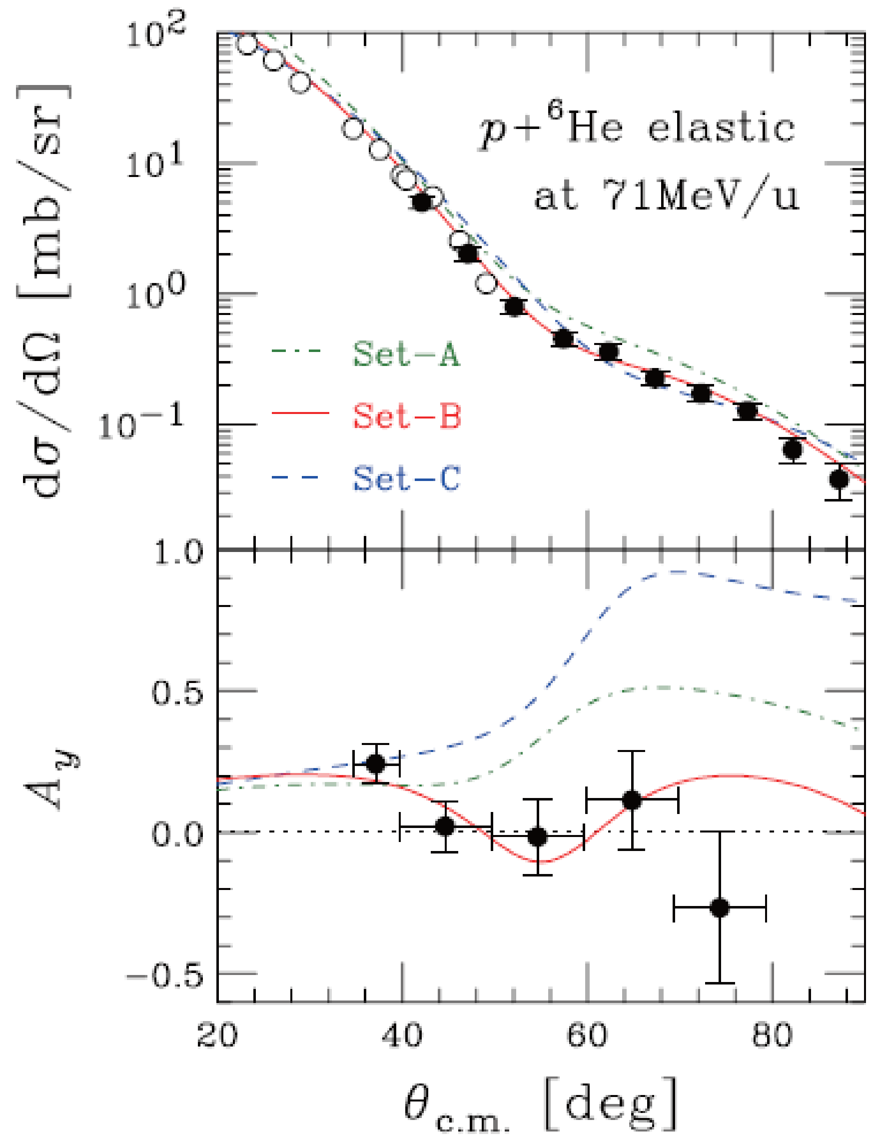
We adopted a standard Woods-Saxon optical potential with a spin-orbit term of the Thomas form:

$$\begin{aligned} U_{\mathrm{OM}}(R) = & - V_0\, f_r(R) - i\, W_0\, f_i(R) \\ & + 4i\, a_{id}\, W_d \frac{d}{dR} f_{id}(R) \\ & + V_s \frac{2}{R} \frac{d}{dR} f_s(R)\, \boldsymbol{L} \cdot \boldsymbol{\sigma}_p + V_{\mathrm{C}}(R) \end{aligned} \qquad (1)$$

with

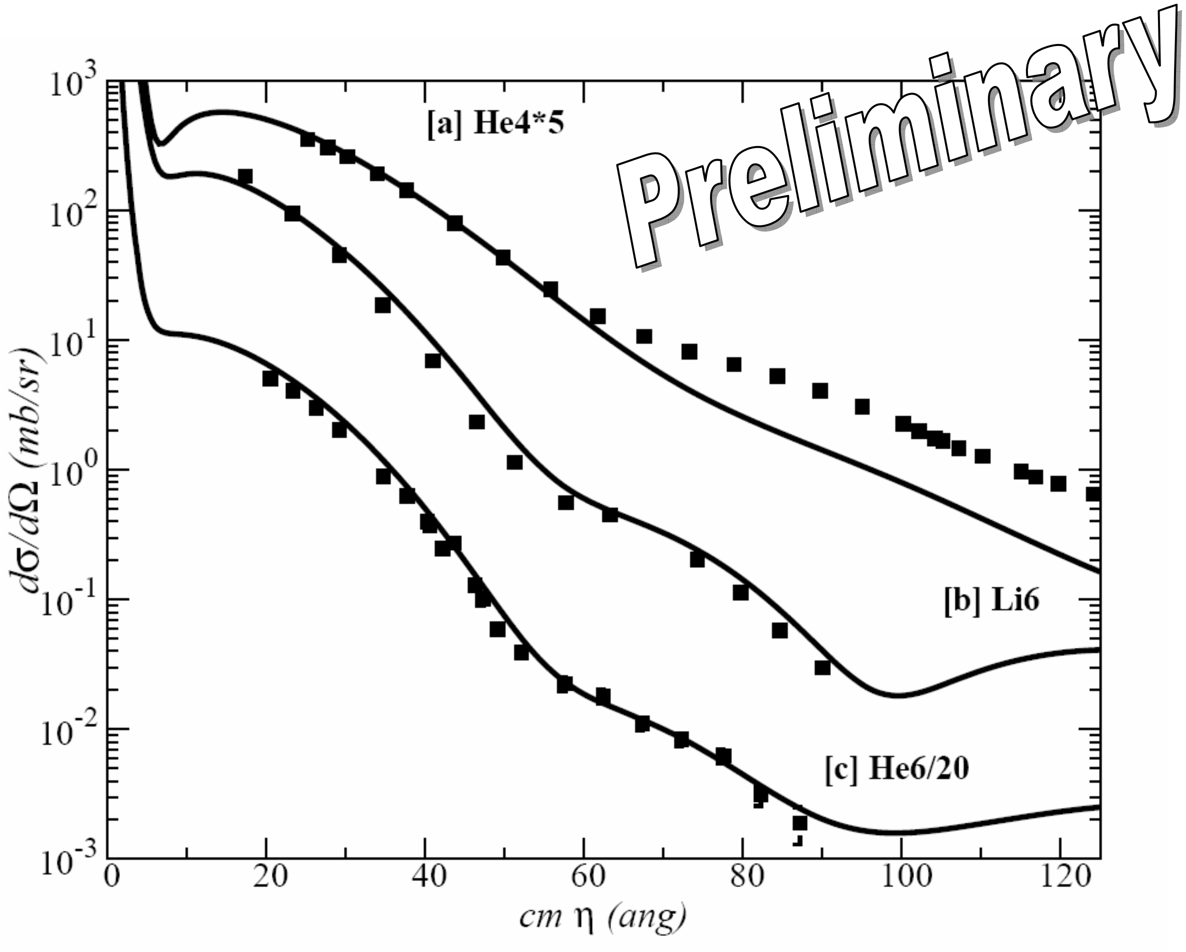
$$f_x(R) = \left[1 + \exp\left(\frac{R - r_{0x} A^{1/3}}{a_x}\right)\right]^{-1} \qquad (2)$$

$$(x = r, i, id, \text{ or } s).$$



S.P. Weppner (preliminary): Phenomenological OP for ^{4}He, ^{6}Li, ^{6}He

Ansatz for parameters: $V_i \rightarrow V_i\,(A_0 + (A\text{-}4)\,B_0 + (N\text{-}Z)C_0)$



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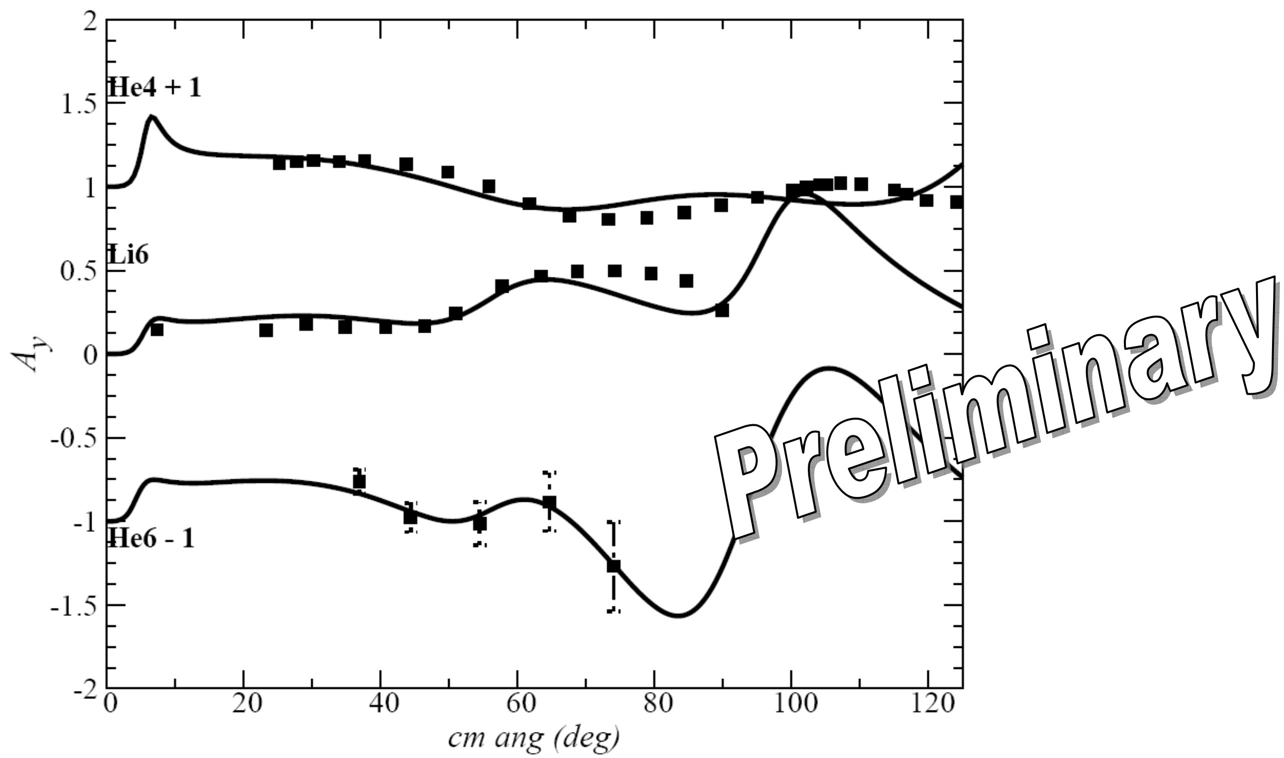


Finding: surface term for ^{6}He is negative.

Non-standard

Back to derivation of optical potential:

NN amplitude $f_{NN}(k'k;E) \approx \langle k' | t_{NN}(E) | k \rangle$

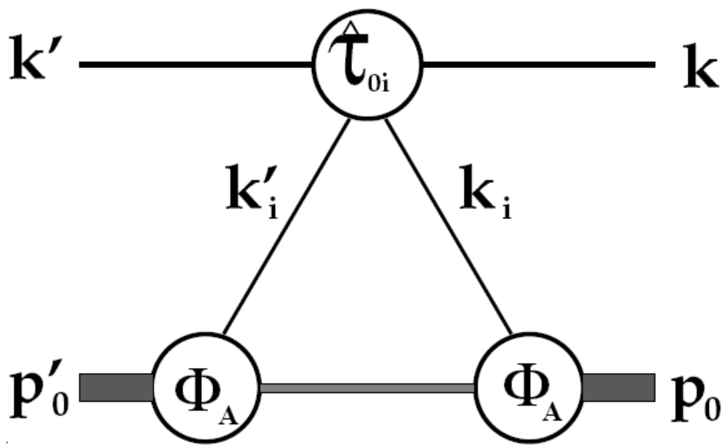
Invariant $\mathcal{I}_\alpha$	Amplitude A_α
$\mathbb{1}$	$A\ (q, \mathcal{K}, \vec{q}\cdot\vec{\mathcal{K}})$
$(\vec{\sigma}_1 + \vec{\sigma}_2)\cdot\vec{w}$	$C\ (q, \mathcal{K}, \vec{q}\cdot\vec{\mathcal{K}})$

How do those enter the optical potential ?

More formal:

- Elastic scattering : $$T_{el} = PUP + PUPG_0(E)PT_{el}.$$
- First order Watson O.P.:

$$\langle \mathbf{k}'|\langle\phi_A|PUP|\phi_A\rangle\mathbf{k}\rangle \equiv U_{el}(\mathbf{k}',\mathbf{k}) = \sum_{i=n,p}\langle\mathbf{k}'|\langle\phi_A|\hat{\tau}_{0i}(\mathcal{E})|\phi_A\rangle\mathbf{k}\rangle$$



$$\langle\hat{\tau}_{01}\rangle \equiv \langle\mathbf{k}'|\langle\phi_A|\hat{\tau}_{01}(\mathcal{E})|\phi_A\rangle\mathbf{k}\rangle$$

Proton scattering: $$U_{el}(\mathbf{k}',\mathbf{k}) = Z\langle\hat{\tau}_{01}^{pp}\rangle + N\langle\hat{\tau}_{01}^{np}\rangle$$

More precisely:

(A+1) state: $|\phi_n(A)\varphi_k\rangle = |\omega_n(A-1)\chi_n\varphi_k\rangle$

$$\begin{aligned}\langle\varphi_{k'}\phi_n(A)|t|\phi_n(A)\varphi_k\rangle &= \langle\varphi_{k'}\chi_n(p')\omega_n(A-1)|t|\omega_n(A-1)\chi_n(p)\varphi_k\rangle \\ &+ \langle\varphi_{k'}\chi_n(p')|t|\chi_n(p)\varphi_k\rangle\,\langle\omega_n(A-1)|\omega_n(A-1)\rangle\end{aligned}$$

e.g. L·S term
=Wolfenstein C : $i\,[(\boldsymbol{\sigma}(1)+\boldsymbol{\sigma}(2)]\cdot\hat{n}\;C(\mathbf{q},\mathbf{Q})]$ $\hat{n} = \dfrac{\mathbf{q}\times\mathbf{Q}}{|\mathbf{q}\times\mathbf{Q}|}$

$$iC(\mathbf{q},\mathbf{Q})\langle\varphi_{k'}\chi_n(p')|\,[(\boldsymbol{\sigma}(1)+\boldsymbol{\sigma}(2))\cdot\hat{n}]\,|\varphi_k\chi_n(p)\rangle =$$

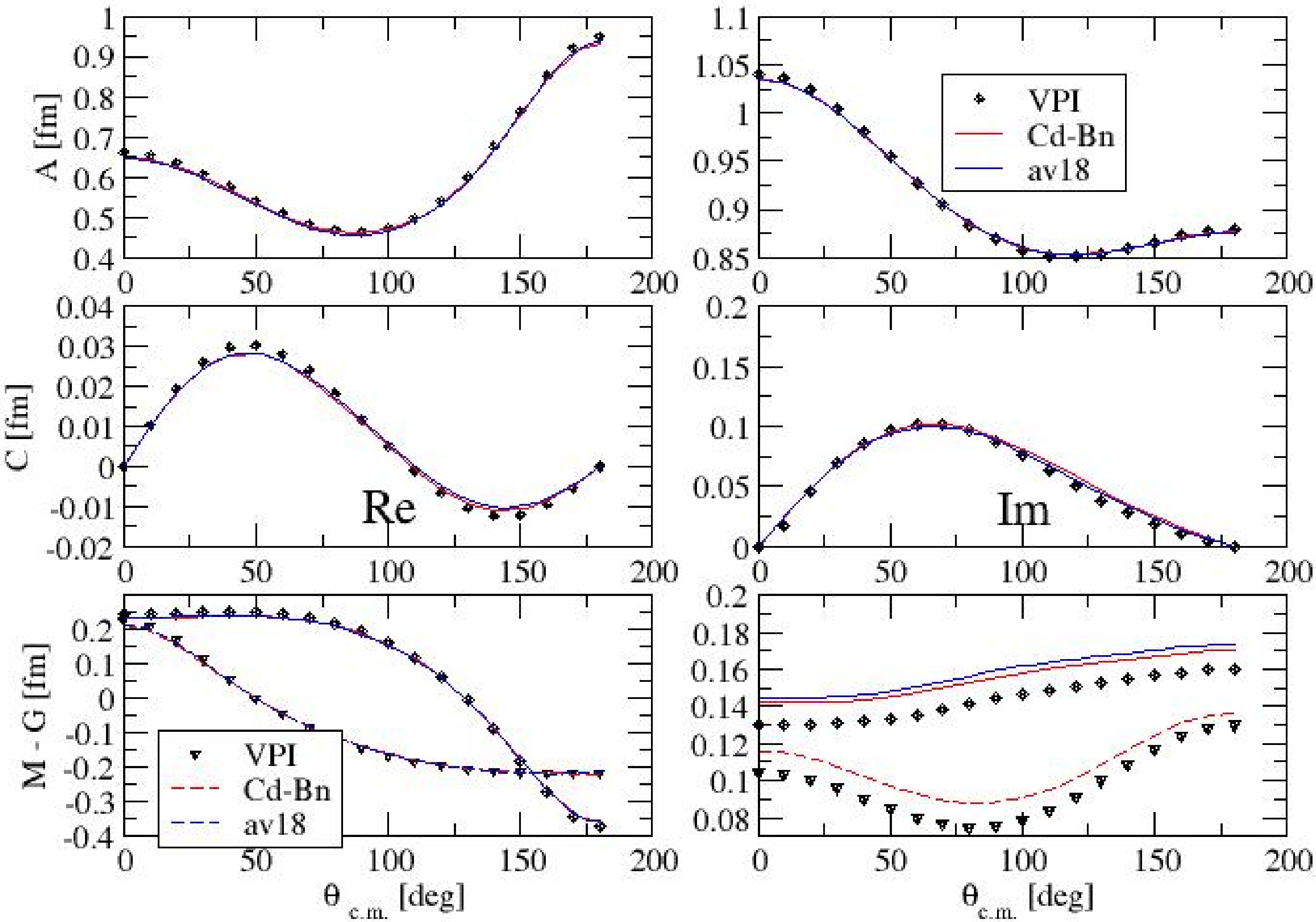
$$\begin{aligned} &= iC(\mathbf{q},\mathbf{Q})\langle\varphi_{k'}\chi_n(p')|\boldsymbol{\sigma}(1)\cdot\hat{n}|\varphi_k\chi_n(p)\rangle + iC(\mathbf{q},\mathbf{Q})\langle\varphi_{k'}\chi_n(p')|\boldsymbol{\sigma}(2)\cdot\hat{n}|\varphi_k\chi_n(p)\rangle \\ &= iC(\mathbf{q},\mathbf{Q})\;\langle\varphi_{k'}|\boldsymbol{\sigma}(1)\cdot\hat{n}|\varphi_k\rangle\langle\chi_n(p')|\chi_n(p)\rangle + iC(\mathbf{q},\mathbf{Q})\;\langle\varphi_{k'}|\varphi_k\rangle\langle\chi_n(p')|\boldsymbol{\sigma}(2)\cdot\hat{n}|\chi_n(p)\rangle \\ &= \underbrace{iC(\mathbf{q},\mathbf{Q})\;\boldsymbol{\sigma}\cdot\hat{n}\;\rho(\mathbf{q},\mathbf{Q})}_{\text{Regular spin-orbit}} + iC(\mathbf{q},\mathbf{Q})\;\underbrace{\langle\chi_n(p')|\boldsymbol{\sigma}(2)\cdot\hat{n}|\chi_n(p)\rangle}_{\text{Only zero for closed shell nuclei}} \end{aligned} \quad (5)$$

NN amplitude $f_{NN}(k'k;E) \approx \langle k' | t_{NN}(E) | k \rangle$

6 invariant amplitudes off-shell (5 on-shell)

	Invariant $\mathcal{I}_\alpha$	Amplitude A_α		
	$\mathbb{1}$	$A\,(q, \mathcal{K}, \vec{q}\cdot\vec{\mathcal{K}})$		
	$(\vec{\sigma}_1 + \vec{\sigma}_2)\cdot\vec{w}$	$C\,(q, \mathcal{K}, \vec{q}\cdot\vec{\mathcal{K}})$		
Contribute to spin-orbit	$\vec{\sigma}_1\cdot\vec{w}\ \ \vec{\sigma}_2\cdot\vec{w}$	$B\,(q, \mathcal{K}, \vec{q}\cdot\vec{\mathcal{K}})$		$M\,(\ldots)$
	$\vec{\sigma}_1\cdot\hat{q}\ \ \sigma_2\cdot\hat{q}$	$E\,(q, \mathcal{K}, \vec{q}\cdot\vec{\mathcal{K}})$	or	$G\,(\ldots)$
	$\vec{\sigma}_1\cdot\hat{\mathcal{K}}\ \ \vec{\sigma}\cdot\hat{\mathcal{K}}$	$F\,(q, \mathcal{K}, \vec{q}\cdot\vec{\mathcal{K}})$ (Wolfenstein)		$H\,(\ldots)$ (Hoshizaki)
	$(\vec{\sigma}_1\cdot\hat{q}\,\vec{\sigma}_2\cdot\hat{\mathcal{K}} + \vec{\sigma}_1\cdot\hat{\mathcal{K}}\,\vec{\sigma}_2\cdot\hat{q})\ \vec{q}\cdot\vec{\mathcal{K}}$	$D\,(q, \mathcal{K}, \vec{q}\cdot\vec{\mathcal{K}}) = 0$ on-shell		

Wolfenstein Amplitudes np $E_{lab} = 50$ MeV



Status

- Cluster ansatz implemented into Watson optical potential for ^{6}He
  - Correlation visible in $d\sigma/d\Omega$ at forward angles
  - Good description of ^{4}He important
  - Cluster ansatz can be implemented for ^{8}He in similar fashion
- Good global phenomenological optical potential fit to ^{4}He, ^{6}Li and ^{6}He with non-standard surface term
  - Guidance from microscopic calculations needed
- For non-closed shell nuclei all NN Wolfenstein amplitudes contribute to the optical potential
  - Calculations with COSMA p-shell neutrons under way
- On CE wishlist: $d\sigma/d\Omega$ and A_y at another energy (150 or 200 MeV/nucleon)