Spin Phenomena in Elastic Scattering of ^{6}He off Protons

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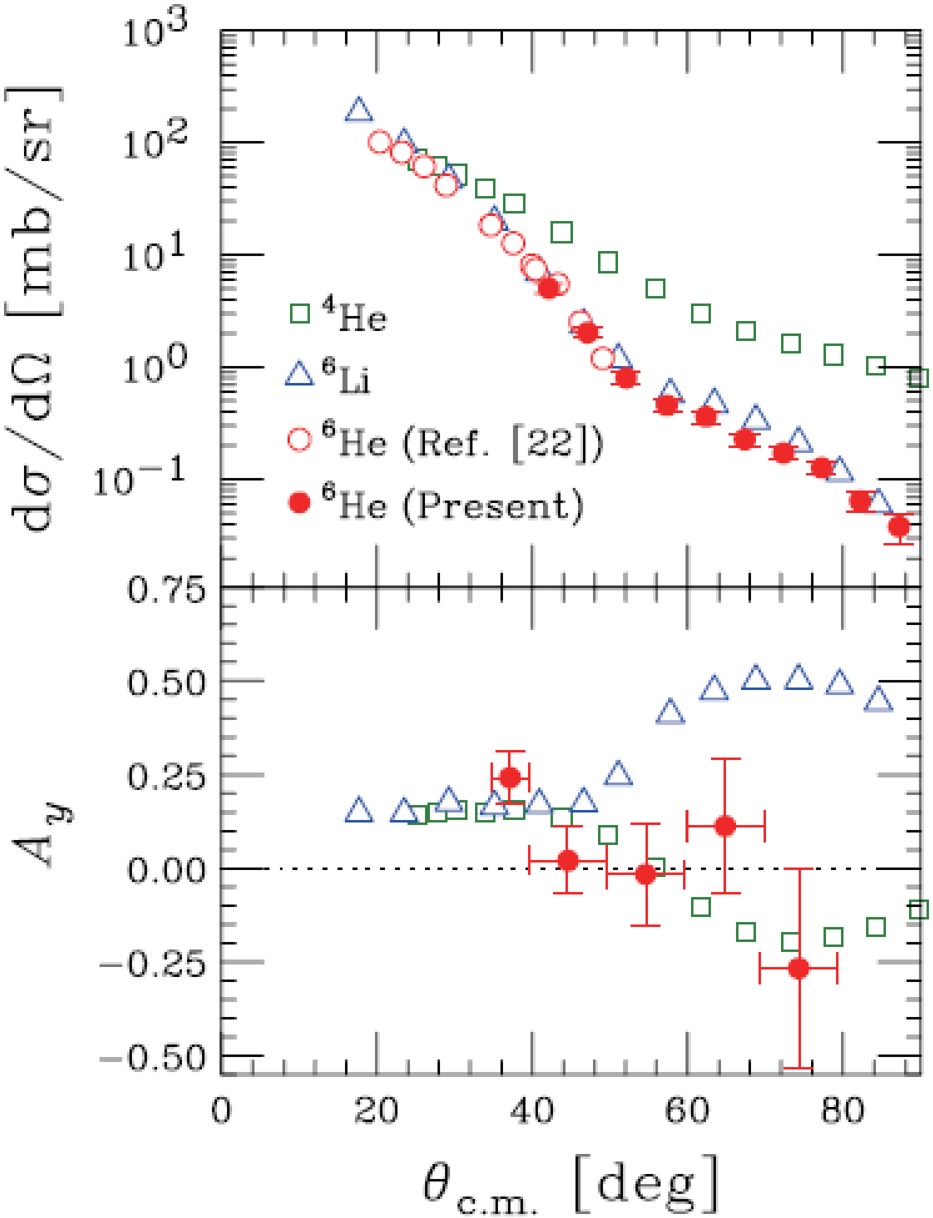
RIKEN:
$^{6}He(p,p)^{6}He$
@ 71 MeV

S. Sakaguchi et al.

Phys.Rev. C84 (2011) 024604

Physics Challenge:
Optical Potential
for Halo Nucleus



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

S. Sakaguchi et al.

Phys.Rev. C84 (2011) 024604

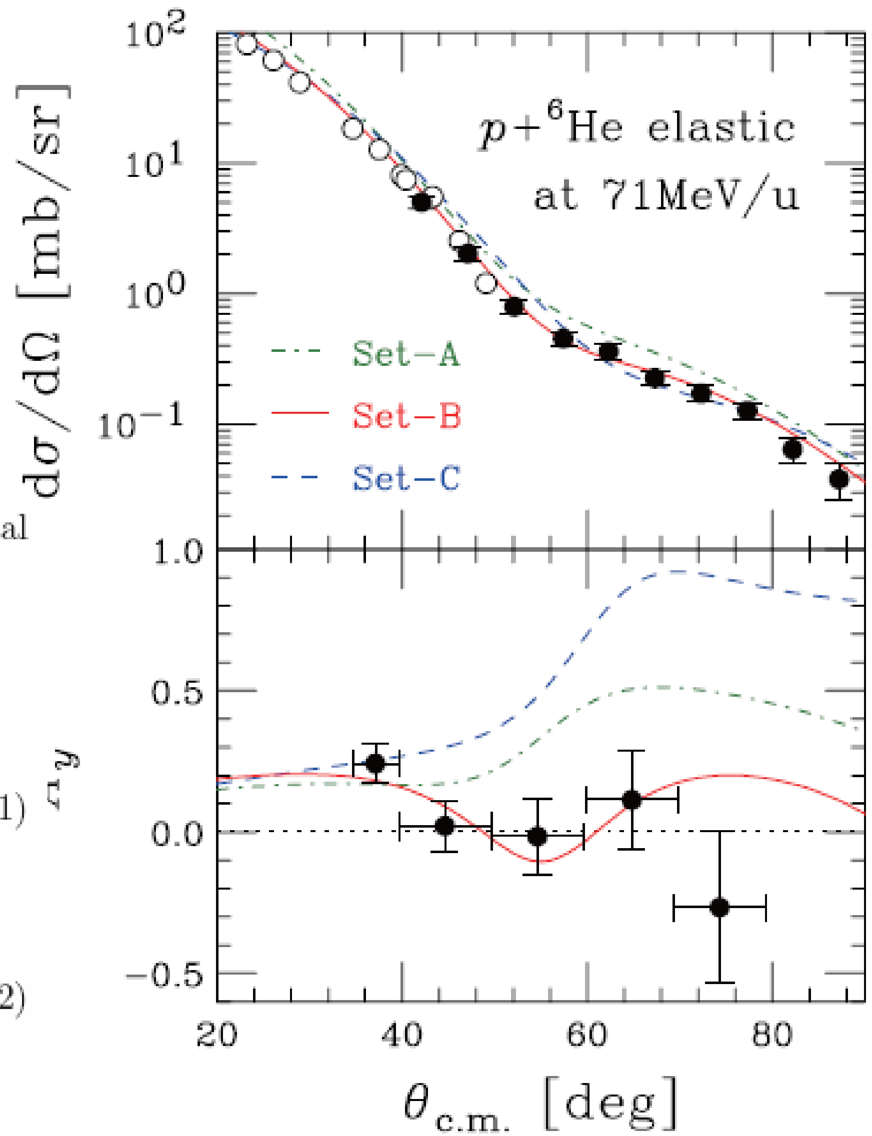
We adopted a standard Woods-Saxon optical potential with a spin-orbit term of the Thomas form:

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

with

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

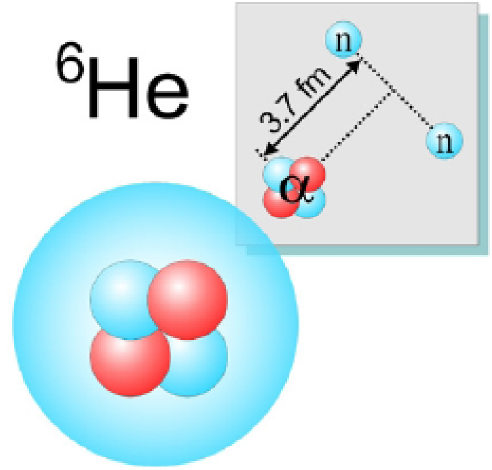
$$(x = r, i, id, \text{ or } s).$$



Challenges for ^{6}He

(and similar exotic nuclei)

- **^{6}He is loosely bound nucleus**
  - **with cluster structure:**
  - **Alpha core + 2 valance neutrons**



- ^{6}He is spin-0 nucleus
  - NOT a closed-shell nucleus

Traditional microscopic optical potentials do NOT consider those properties

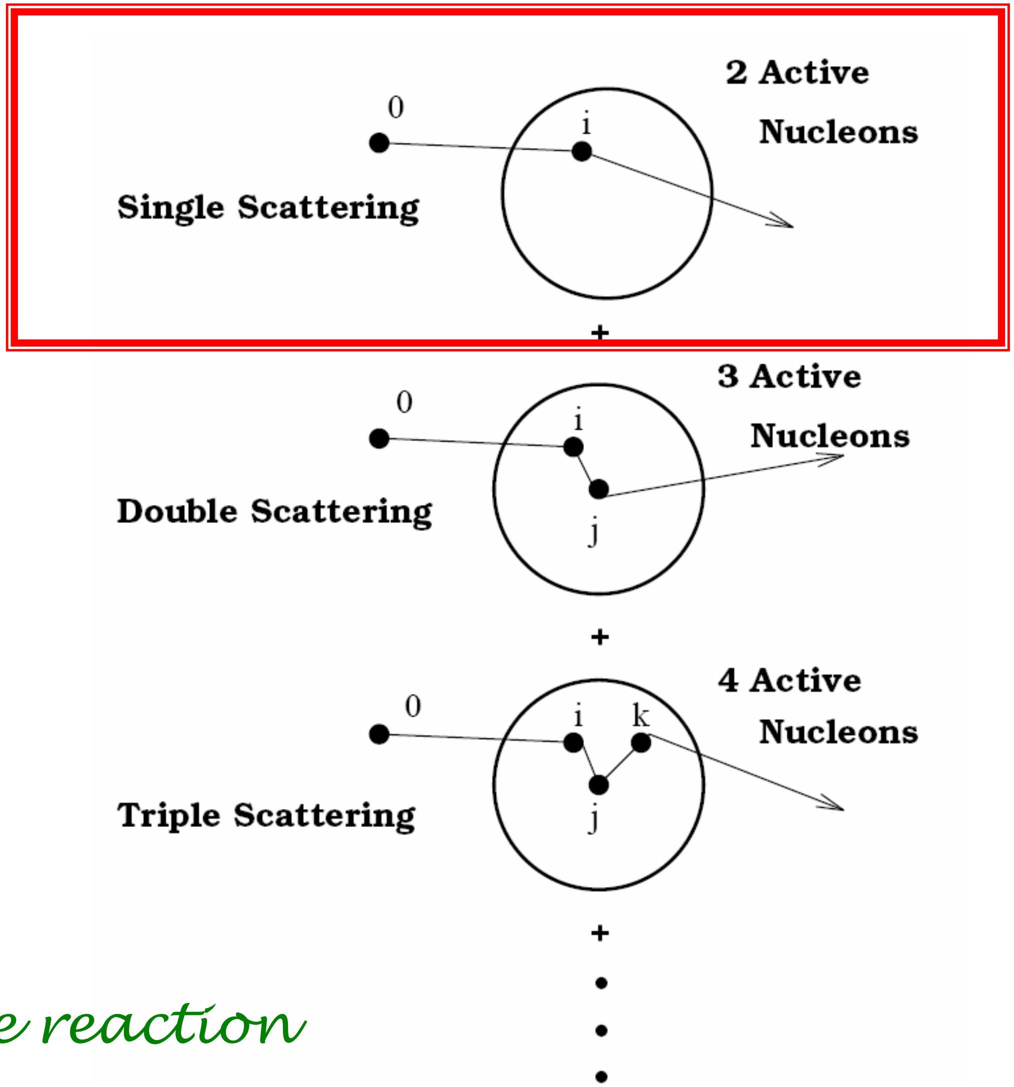
p+A Scattering
as multiple scattering problem

Spectator Expansion:

Written down by

Siciliano, Thaler (1977)

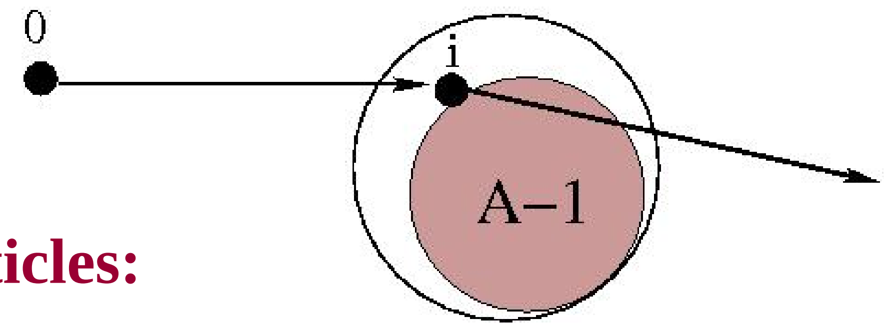
Picklesimer, Thaler (1981)



Expansion in:

- *particles active in the reaction*
- *Antisymmetrized in active particles*

Single Scattering



In principle:

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 a g-matrix folding with local density approximation
  - Picked up by Amos, Karataglidis and extended to exotic nuclei

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
- $P\,T\,P = P\,U\,P + P\,U\,P\,G_0(E)\,P\,T\,P$
- Or
  - **$T = U + U\,G_0(E)\,P\,T$**
  - **$U = V + V\,G_0(E)\,Q\,U$ $\Leftarrow$ "optical potential"**

Single Scattering: $\mathbf{U^{(1)} \approx \Sigma^{A}{}_{i=0}\, \tau_{0i}}$ (1^{st} order)

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

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

- $G_0(E) = (E - h_0 - H_A + i\varepsilon)^{-1}$ == (A+1) body operator
  - Standard **“impulse approximation”:**
  - Average over $H_A \Rightarrow$ c-number
  - $\rightarrow G_0(e)$ ==: two body operator
- Handle operator **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}
  - $\tau_{oi} = t_{0i}^{free} - t_{0i}^{free}\, G_0(e)\, \tau_{oi}$ **[integral equation]**
  - Important for keeping correct iso-spin character of optical potential
  - $U^{(1)} = \Sigma^{A}_{i=1}\, \tau_{oi} =: N\, \tau_n + Z\, \tau_p$

Chinn, Elster, Thaler, PRC47, 2242 (1993)

“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
- 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

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

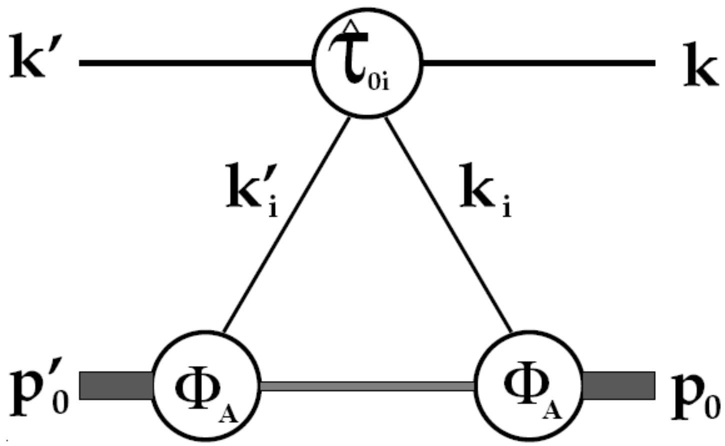
- **This formulation allows a more complicated structure of the optical potential, e.g. a cluster ansatz**

More explicit:

P:= projector on ground state

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

$$\langle \mathbf{k}_1\mathbf{k}_2\mathbf{k}_3\mathbf{k}_4...\mathbf{k}_A|\phi_A\rangle = \delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3+\mathbf{k}_4...+\mathbf{k}_A-\mathbf{p}_0)\langle\boldsymbol{\zeta}_1\boldsymbol{\zeta}_2\boldsymbol{\zeta}_3\boldsymbol{\zeta}_4...\boldsymbol{\zeta}_{\mathbf{A-1}}|\phi_A\rangle.$$

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

With single particle density matrix :

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

$$\langle\hat{\tau}_{01}\rangle = \int d\boldsymbol{\zeta}'_1 \int d\boldsymbol{\zeta}_1\langle\mathbf{k}'\ \boldsymbol{\zeta}'_1+\frac{\mathbf{p}'_0}{A}|\hat{\tau}_{01}(\mathcal{E})|\mathbf{k}\ \boldsymbol{\zeta}_1+\frac{\mathbf{p}_0}{A}\rangle\ \rho(\boldsymbol{\zeta}'_1,\boldsymbol{\zeta}_1)$$
$$\delta(\frac{A-1}{A}\mathbf{p}'_0-\boldsymbol{\zeta}'_1-\frac{A-1}{A}\mathbf{p}_0+\boldsymbol{\zeta}_1).$$

Better Variables:

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

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

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

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

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

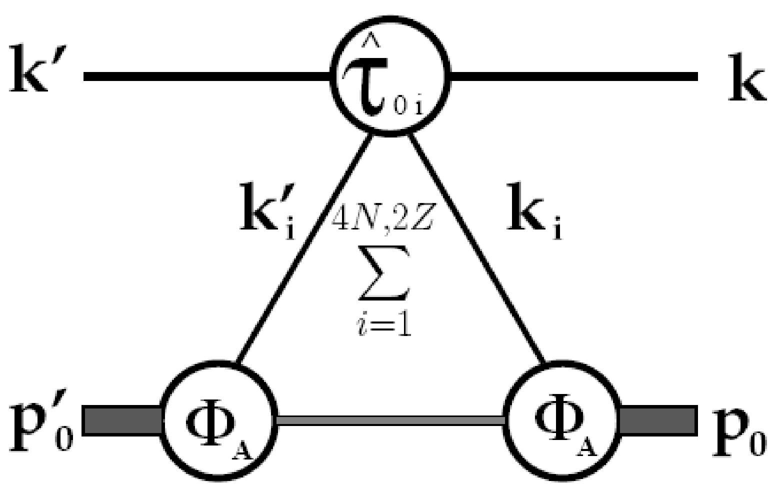
Elster, Weppner, PRC 57. 189 (1998)

Full-Folding Optical Potential

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

NN t-matrix

Single Particle Density Matrix



Elster, Weppner, Chinn, PRC 56, 2080 (1997)

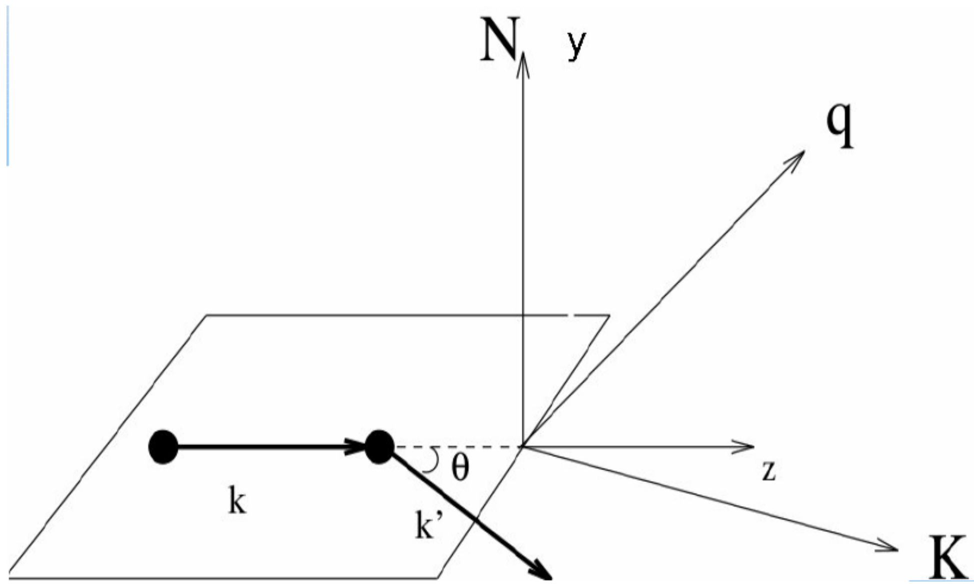
$$U_{el}(\mathbf{q},\mathbf{K}) = \sum_{i=n,p}\int d\mathbf{P}\,\hat{\tau}_{0i}(\mathbf{q},\frac{1}{2}(\frac{A+1}{A}\mathbf{K}-\mathbf{P}),\hat{\mathcal{E}})\;\rho_i(\mathbf{P}-\frac{A-1}{2A}\mathbf{q},\mathbf{P}+\frac{A-1}{2A}\mathbf{q})$$

Depends on |q|, |K|, cos(θ)qK

$$\vec{q} = \vec{k}' - \vec{k}$$

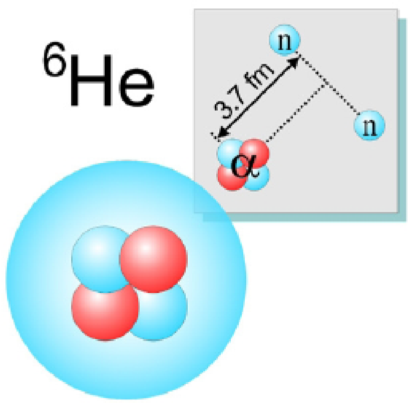
$$\vec{K} = \tfrac{1}{2}\left(\vec{k}' + \vec{k}\right)$$

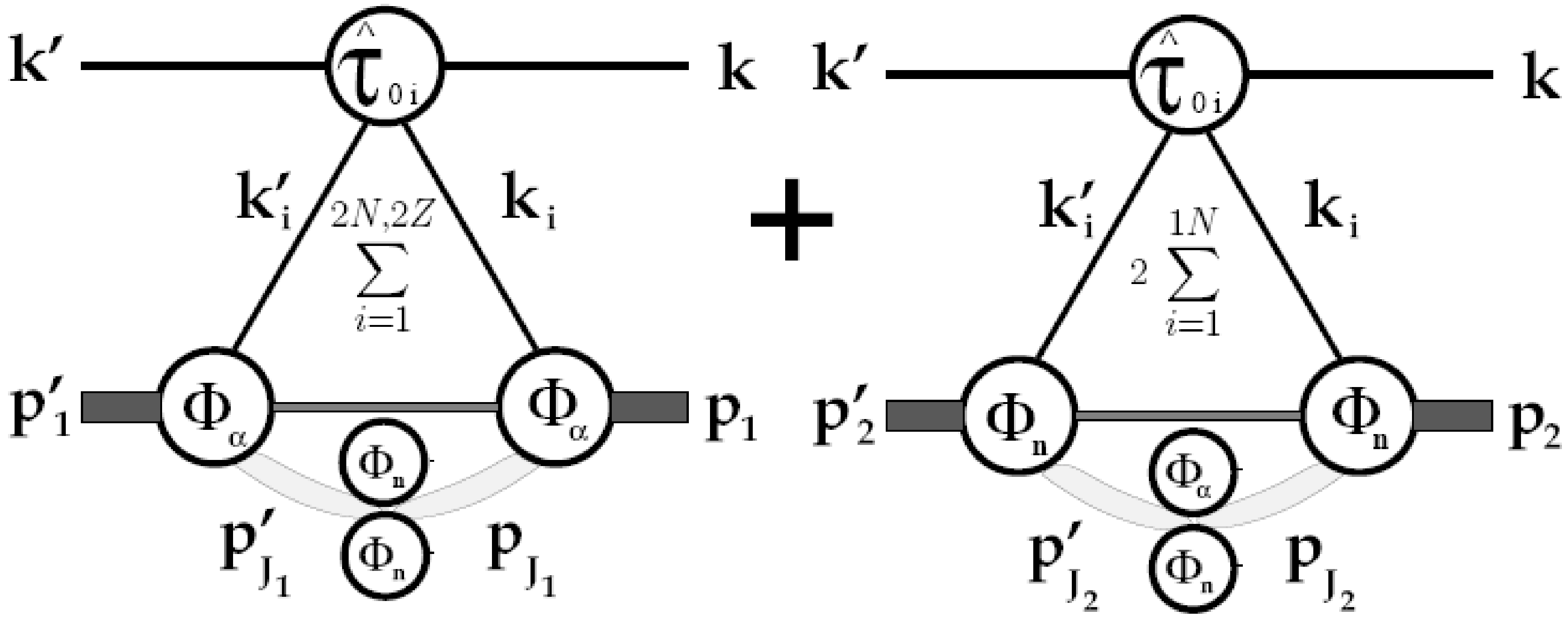
$$\vec{n} = \vec{k} \times \vec{k}'$$



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

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





Weppner, Elster, PRC 85, 044617 (2012)

Cluster Folding Optical Potential (n+n+α)

Jacobi momenta

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

Correlation Density

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

$p_{3/2}$ HO state

Cluster optical potential

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

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

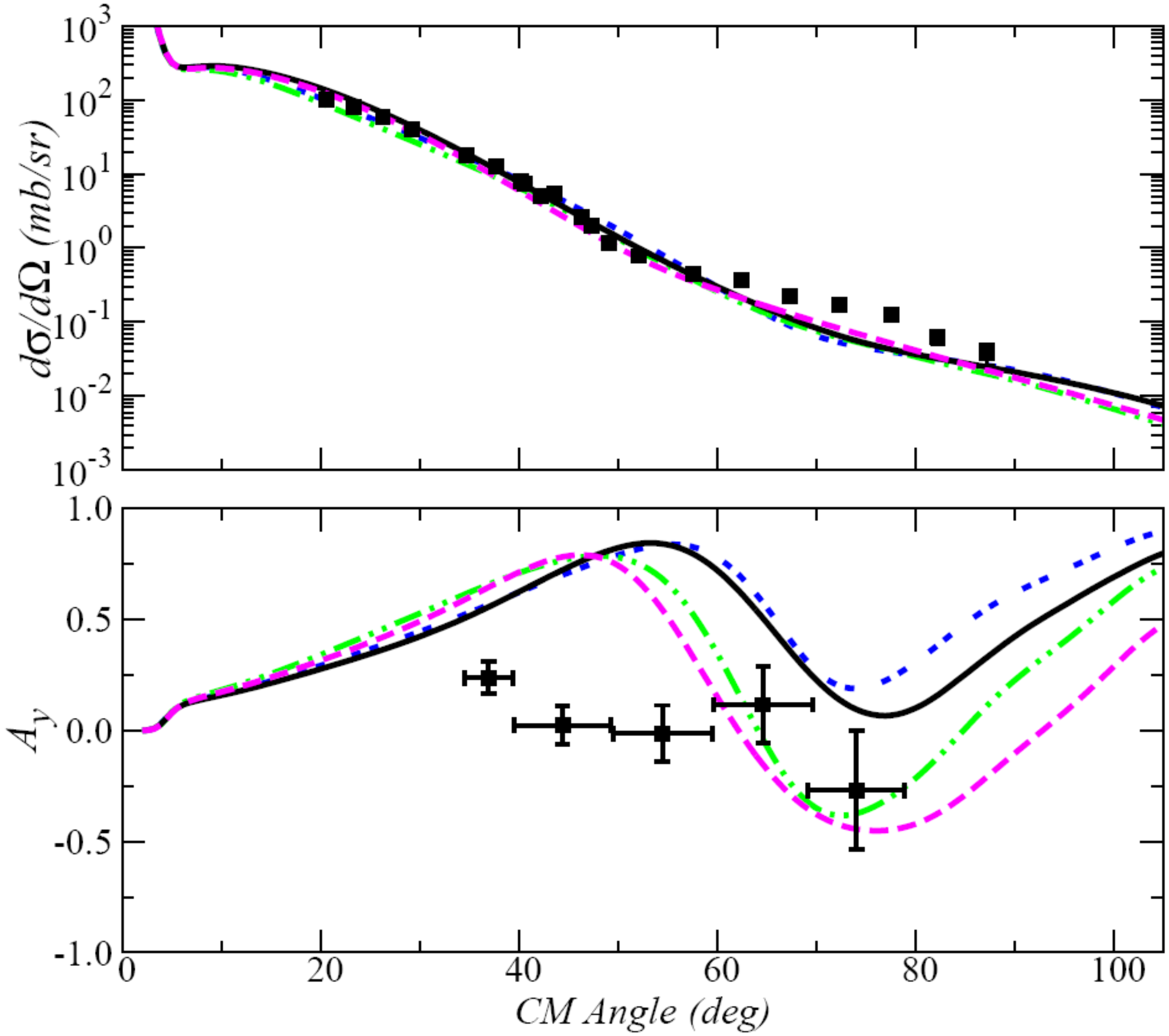
Densities:

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

Fitted to give rms radius of ^{6}He (older value)

and for ^{4}He: Gogny density with coupling to medium

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



COSMA single particle OP

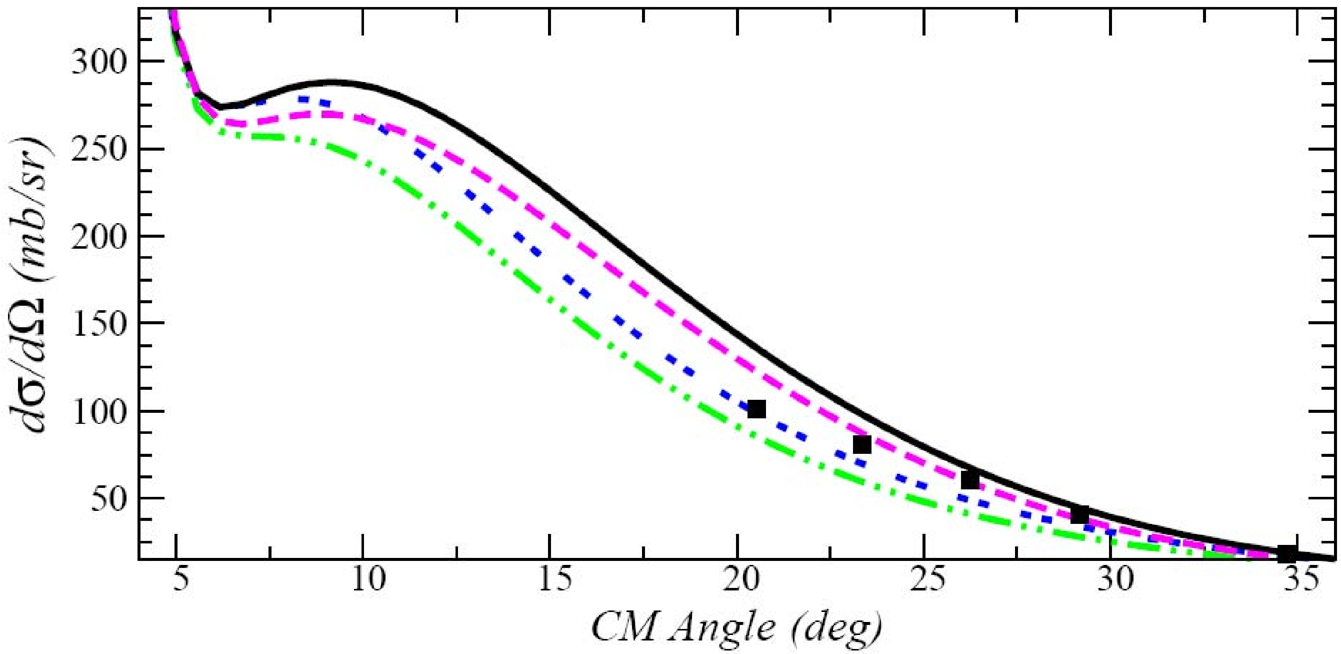
COSMA cluster OP

α- HFB

n - COSMA

α - HFB
n – COSMA
no correlations

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



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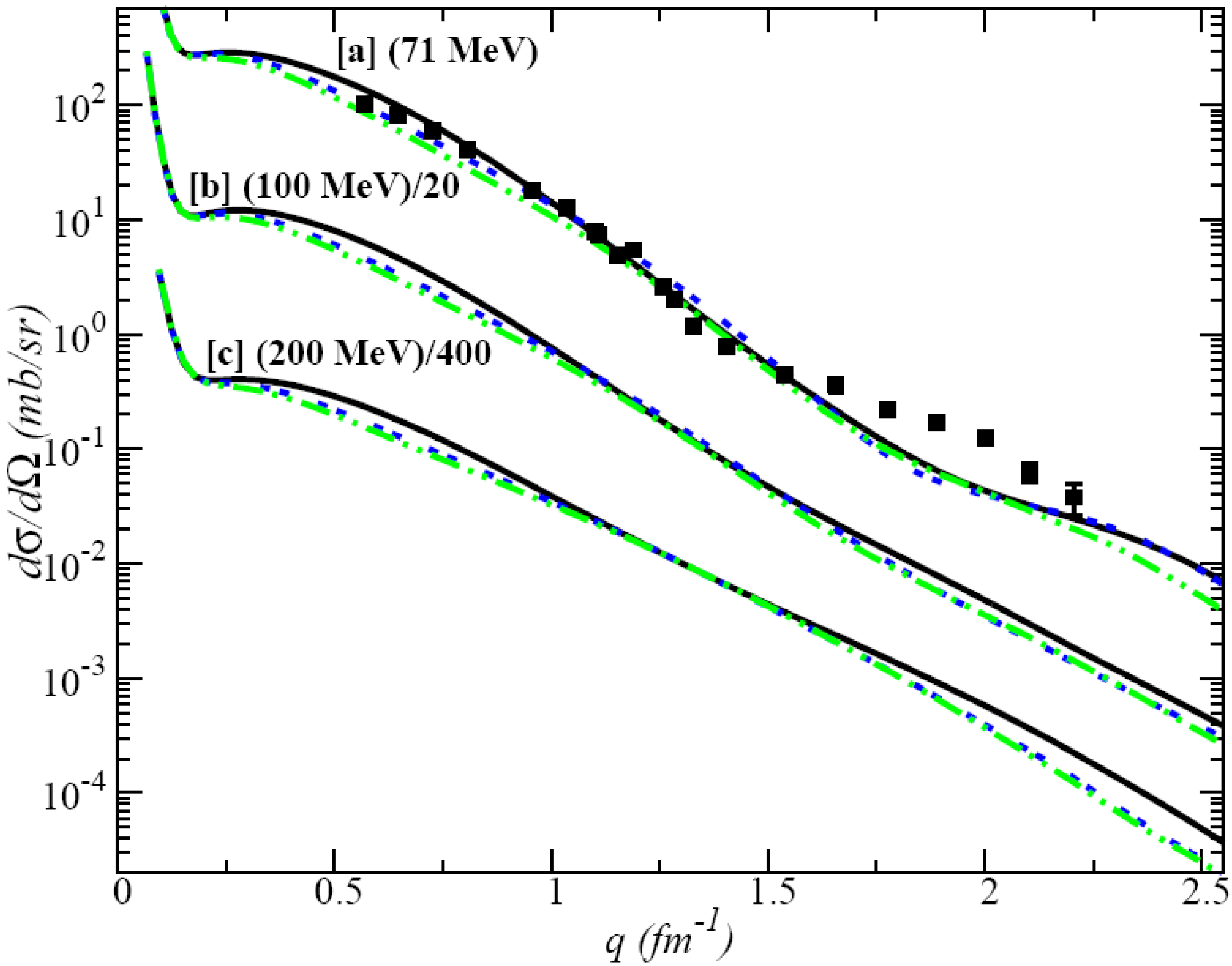
^{6}He (p,p) ^{6}He

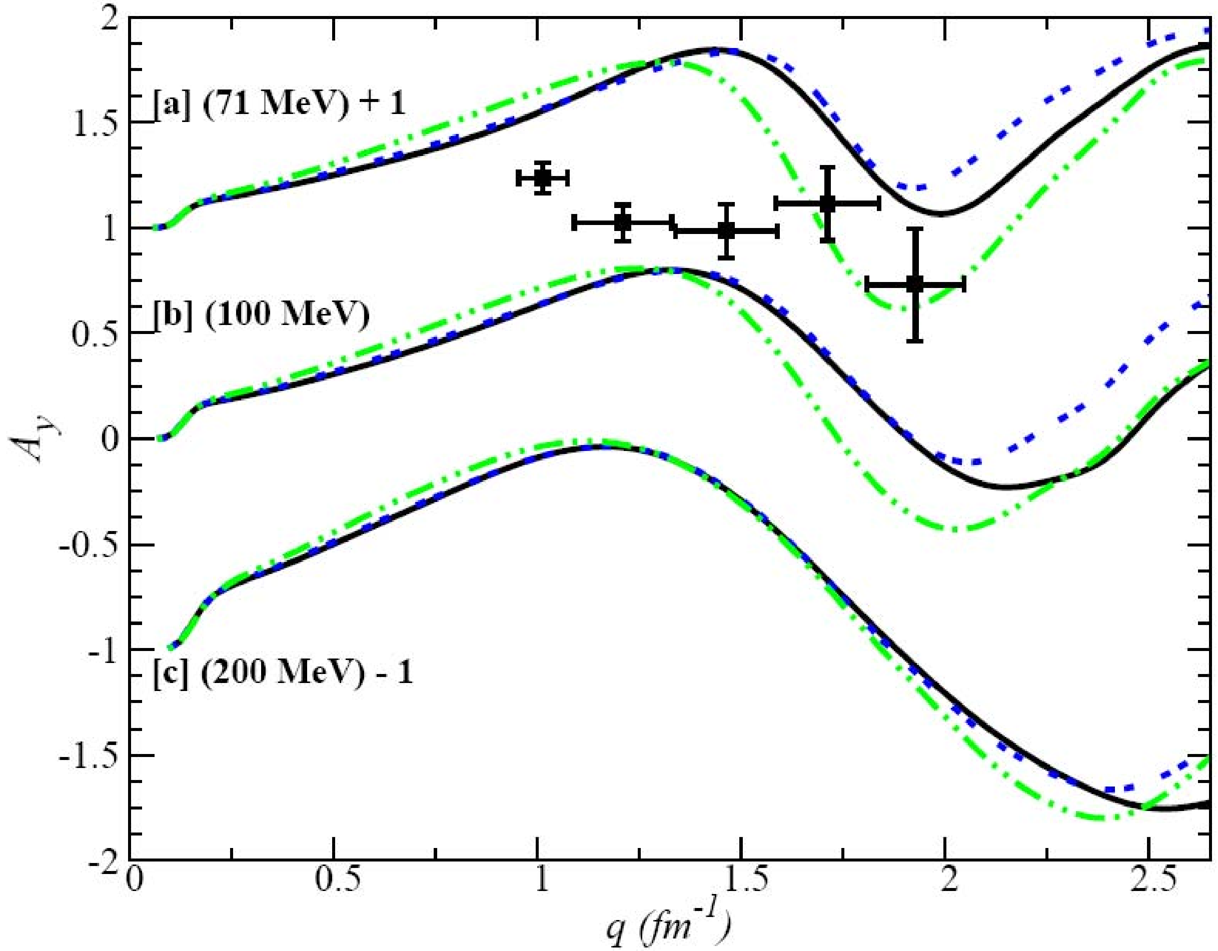


Black: COSMA single particle

Blue: Cosma Cluster

Green: ^{4}He - HFB

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



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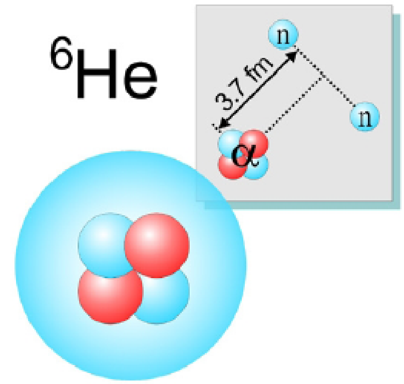
Challenges for ^{6}He

(and similar exotic nuclei)



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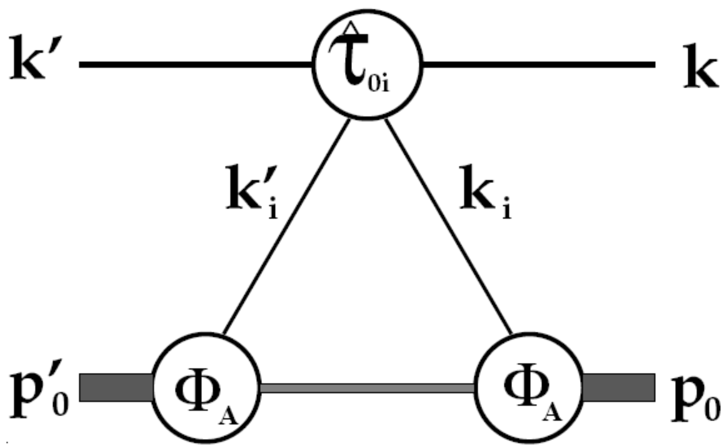
More explicit:

P:= Projector on ground state

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

Ansatz for ^{6}He Density Matrix

HO ansatz for s and p shell

$$\psi_s^m(p) = (2\pi)^{3/2}\left(\frac{4}{\sqrt{\pi}\nu_s^{3/2}}\right)^{1/2}\frac{1}{4\pi}e^{-p^2/2\nu_s}\mathcal{Y}_{0m}^{\frac{1}{2}}(\hat{p})$$

$$\psi_p^m(p) = (2\pi)^{3/2}\left(\frac{4}{\sqrt{\pi}\nu_p^{3/2}}\right)^{1/2}\sqrt{\frac{2}{3}}\frac{p}{\sqrt{\nu_p}}e^{-p^2/2\nu_p}\ \mathcal{Y}_{1m}^{\frac{3}{2}}(\hat{p})$$

With valence neutrons in $p_{3/2}$ shell

$$\psi_{p_{3/2}}(p) := f_{p_{3/2}}(p)\frac{1}{\sqrt{4}}\left(\mathcal{Y}_{1\frac{3}{2}}^{\frac{3}{2}}(\hat{p}) - \mathcal{Y}_{1\frac{1}{2}}^{\frac{3}{2}}(\hat{p}) + \mathcal{Y}_{1-\frac{1}{2}}^{\frac{3}{2}}(\hat{p}) - \mathcal{Y}_{1-\frac{3}{2}}^{\frac{3}{2}}(\hat{p})\right)$$

Ansatz for ^{6}He Density Matrix

Parameters for 1st calculation:

Zhukov, M.V. et al. Phys.Rept. 231 (1993) 151-199

Korsheninnikov, A.A. et al. Phys.Lett. B316 (1993) 38-44

Table 1: Charge Radii and Oscillator Parameters of ^{4}He, ^{6}He and ^{8}He.

Isotope He	Charge radius fm	Matter radius fm	Oscillator parameter ν_s fm^{-2}	Oscillator parameter ν_p fm^{-2}
^{4}He	1.676 [37]	1.676 [37]	0.534	None
^{6}He	2.054 [34]	2.320 [35]	0.355	0.322
^{8}He	1.929 [38]	2.490 [39]	0.403	0.224

NN t-matrix [Wolfenstein Representation]

$$
\begin{aligned}
t_{NN}(\mathbf{q},\mathbf{K},\varepsilon) = & A(\mathbf{q},\mathbf{K},\varepsilon)\mathbf{1} + i\,(\boldsymbol{\sigma}^{(1)}+\boldsymbol{\sigma}^{(2)})\cdot\hat{\mathbf{n}}\,C(\mathbf{q},\mathbf{K},\varepsilon) \\
& +(\boldsymbol{\sigma}^{(1)}\cdot\hat{\mathbf{n}})(\boldsymbol{\sigma}^{(2)}\cdot\hat{\mathbf{n}})M(\mathbf{q},\mathbf{K},\varepsilon) \\
& +(\boldsymbol{\sigma}^{(1)}\cdot\hat{\mathbf{q}})(\boldsymbol{\sigma}^{(2)}\cdot\hat{\mathbf{q}})(G(\mathbf{q},\mathbf{K},\varepsilon)-H(\mathbf{q},\mathbf{K},\varepsilon)) \\
& +(\boldsymbol{\sigma}^{(1)}\cdot\hat{\mathbf{K}})(\boldsymbol{\sigma}^{(2)}\cdot\hat{\mathbf{K}})(G(\mathbf{q},\mathbf{K},\varepsilon)+H(\mathbf{q},\mathbf{K},\varepsilon)) \\
& +\left[(\boldsymbol{\sigma}^{(1)}\cdot\hat{\mathbf{q}})(\boldsymbol{\sigma}^{(2)}\cdot\hat{\mathbf{K}})+(\boldsymbol{\sigma}^{(1)}\cdot\hat{\mathbf{K}})(\boldsymbol{\sigma}^{(2)}\cdot\hat{\mathbf{q}})\right]D(\mathbf{q},\mathbf{K},\varepsilon)
\end{aligned}
$$

only off-shell

Closed Shell Nuclei:

$$
\left\langle \Phi_A \left| \vec{\sigma}\cdot\vec{K} \right| \Phi_A \right\rangle = 0
$$

see e.g. Elster, Cheon, Redish, Tandy PRC 41, 814 (1990)

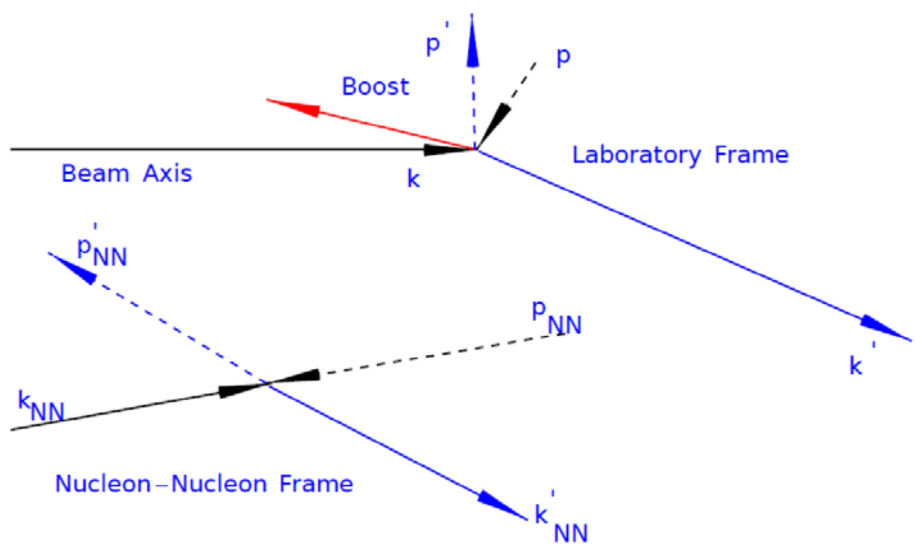
Expectation Values for p-shell

$$\Psi_p(\hat{\mathbf{p}}')\boldsymbol{\sigma}^{(2)} \cdot \hat{\mathbf{n}}\Psi_p(\hat{\mathbf{p}}) = \frac{2}{9\pi^{3/2}\nu_p^{5/2}}\, p\, p'\, exp\left(-\frac{p^2}{2\nu_p} - \frac{p'^2}{2\nu_p}\right) \sin\alpha_{pp'} \;\cos\beta$$

$$\Psi_p(\hat{\mathbf{p}}')\boldsymbol{\sigma}^{(2)} \cdot \hat{\mathbf{q}}\Psi_p(\hat{\mathbf{p}}) = 0$$

$$\Psi_p(\hat{\mathbf{p}}')\boldsymbol{\sigma}^{(2)} \cdot \hat{\mathbf{K}}\Psi_p(\hat{\mathbf{p}}) = \frac{2}{9\pi^{3/2}\nu_p^{5/2}}\, p\, p'\, exp\left(-\frac{p^2}{2\nu_p} - \frac{p'^2}{2\nu_p}\right) \sin\alpha_{pp'} \;\cos\delta$$

Boost from NN frame to N-Nucleus frame



Optical Potential for Valence Neutrons of ^{6}He

± indicate spin-flip amplitudes

$$U_{val}(q, \mathcal{K}) =$$

$$N \int t_{2B}(q, \mathcal{K}, p, p') \, \rho^{neutron}_{j=\frac{3}{2}, l=1}(q, \mathcal{K}, p, p') \, d^3p \, d^3p' =$$

$$N \int \left(f_{j=\frac{3}{2}, l=1}(p) \, f_{j=\frac{3}{2}, l=1}(p') \right)_{neutron} \left((\mathcal{A} \pm \mathcal{C}) \left(\frac{\pi}{2} P_{l=1}(\cos[\gamma]) \right) + \left(\frac{i \pi \sin[\gamma]}{6} \right) \left(\mathcal{C} \cos[\beta] \pm \mathcal{M} \cos[\beta] + \right. \right.$$

$$(\mathcal{G} + \mathcal{H}) \left(\frac{1}{2 |\mathcal{K}_{nn}|} \left(|k_{nn}| + |k'_{nn}| \, e^{(\mp i \gamma_{nn})} \right) \cos[\alpha] \right) +$$

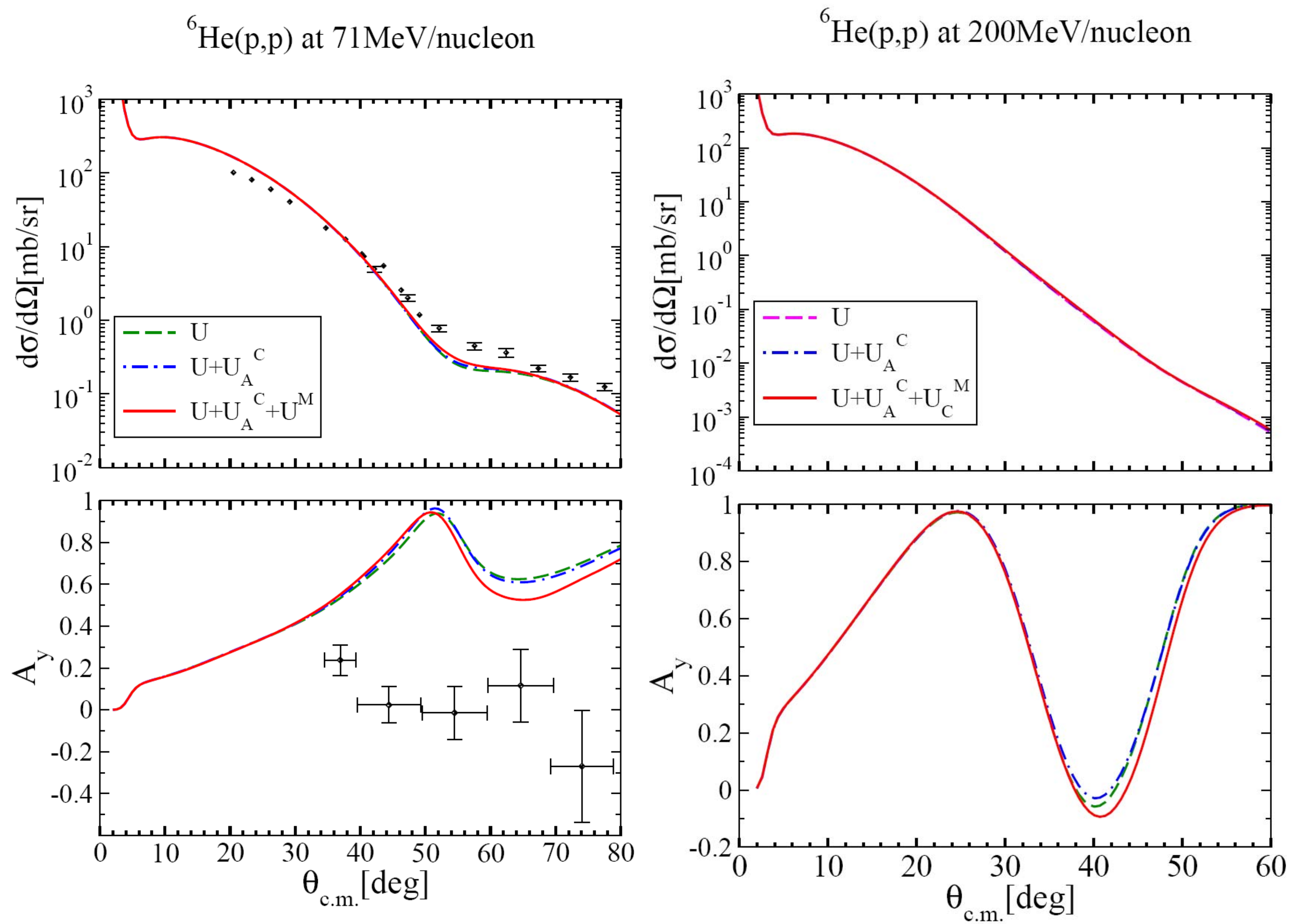
$$\left. \left. \mathcal{D} \left(\frac{1}{|q_{nn}|} \left(-|k_{nn}| + |k'_{nn}| \, e^{(\mp i \gamma_{nn})} \right) \cos[\alpha] \right) \right) \right) d^3p \, d^3p',$$

Give zero contribution integrated with p-3/2 states !

Optical Potential for ^{6}He
with all terms from the valence neutrons

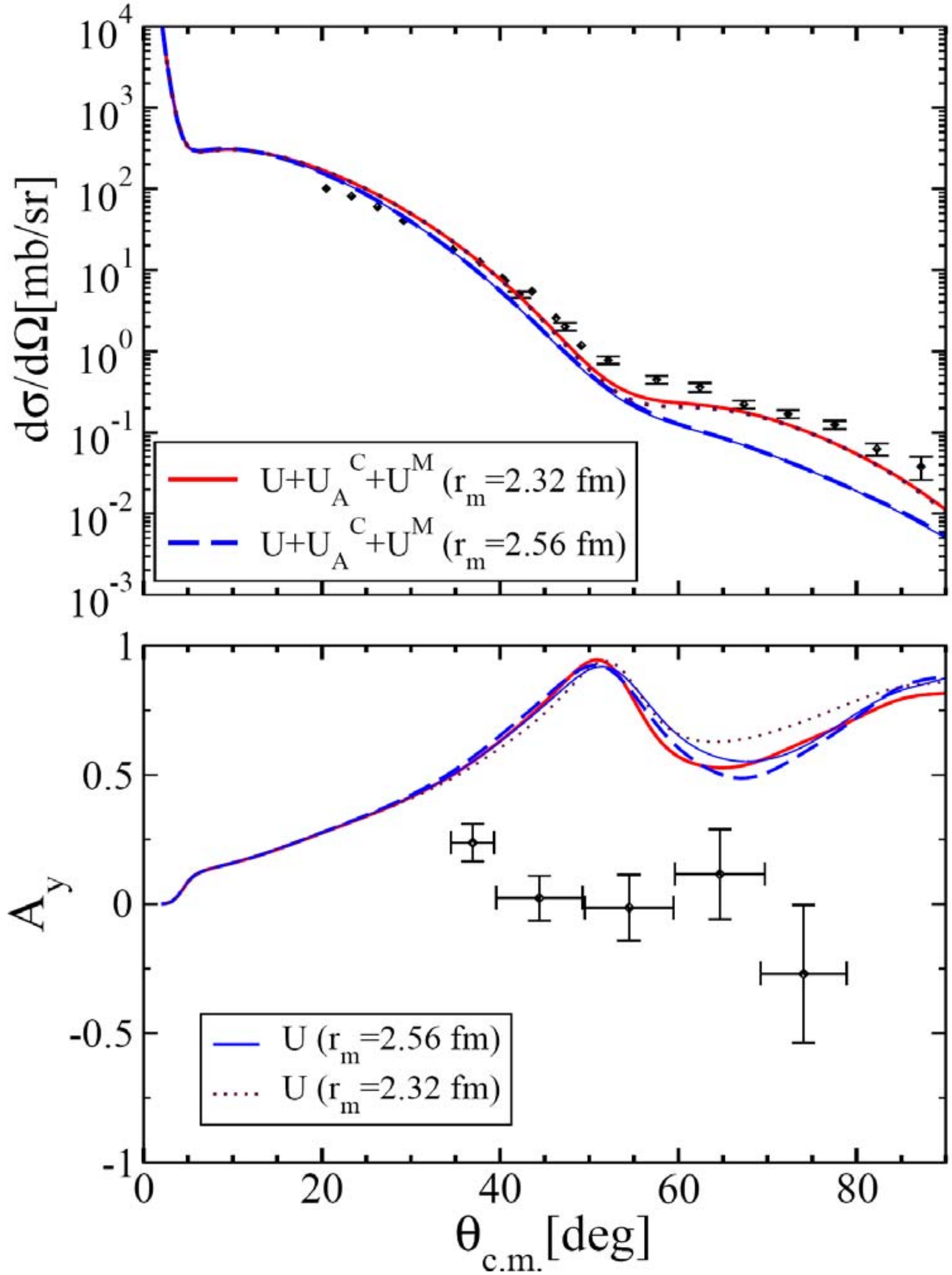
$$U_{^6He}(\mathbf{q},\mathbf{K}) = \sum_{i=N,P} U_{core}(\mathbf{q},\mathbf{K}) + U_{val}(\mathbf{q},\mathbf{K})$$

$$\begin{aligned} U_{val_{central}} &= U_A(\mathbf{q},\mathbf{K}) + U_A^C(\mathbf{q},\mathbf{K}) \\ U_{val_{spin-orbit}} &= U_C(\mathbf{q},\mathbf{K}) + U^M(\mathbf{q},\mathbf{K}) \end{aligned}$$

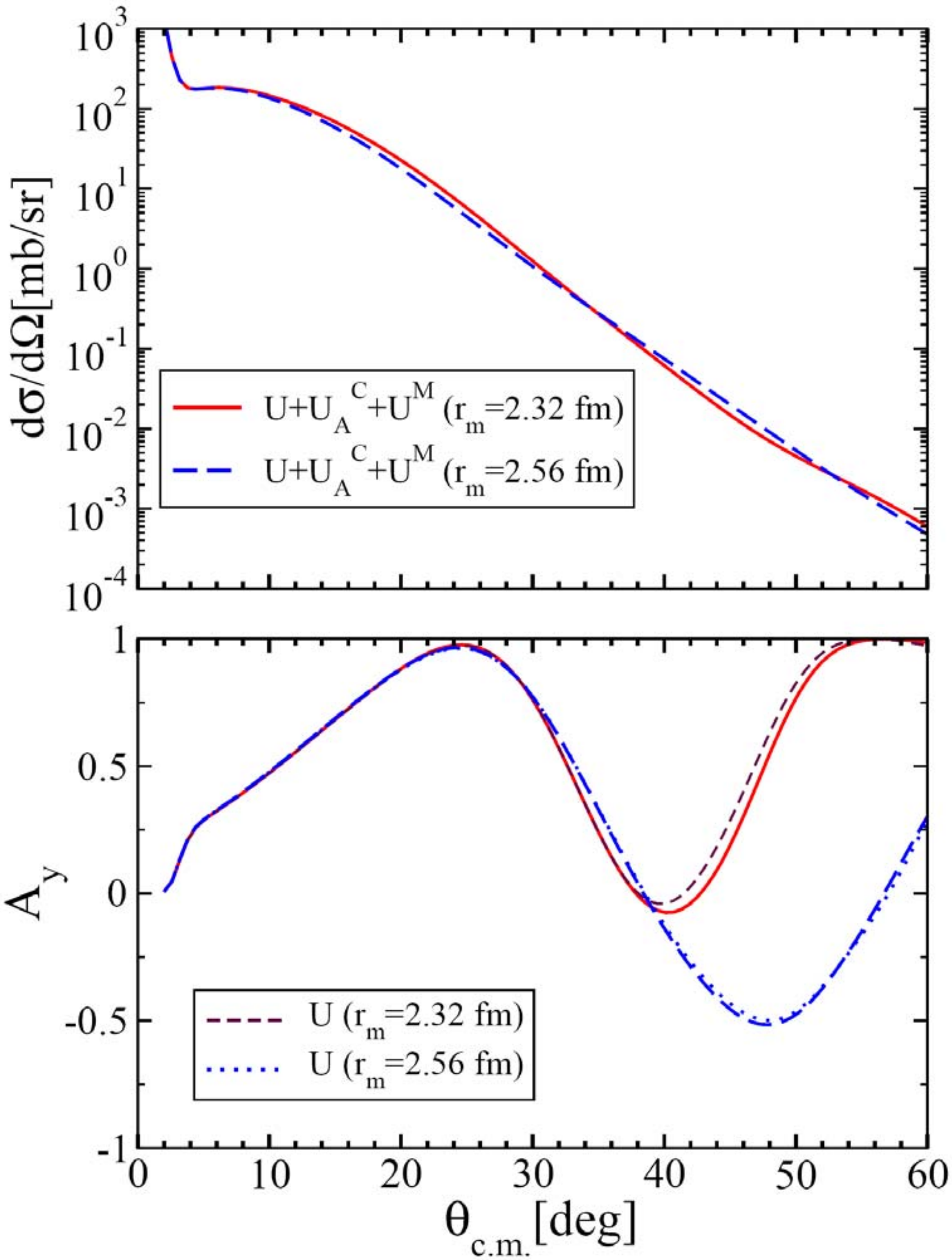


6He(p,p) at 71MeV/nucleon
6He(p,p) at 200MeV/nucleon
dσ/dΩ[mb/sr]
U
U+U_A^C
U+U_A^C+U^M
U+U_A^C+U_C^M
A_y
θ_c.m.[deg]

^{6}He(p,p) at 71MeV/nucleon



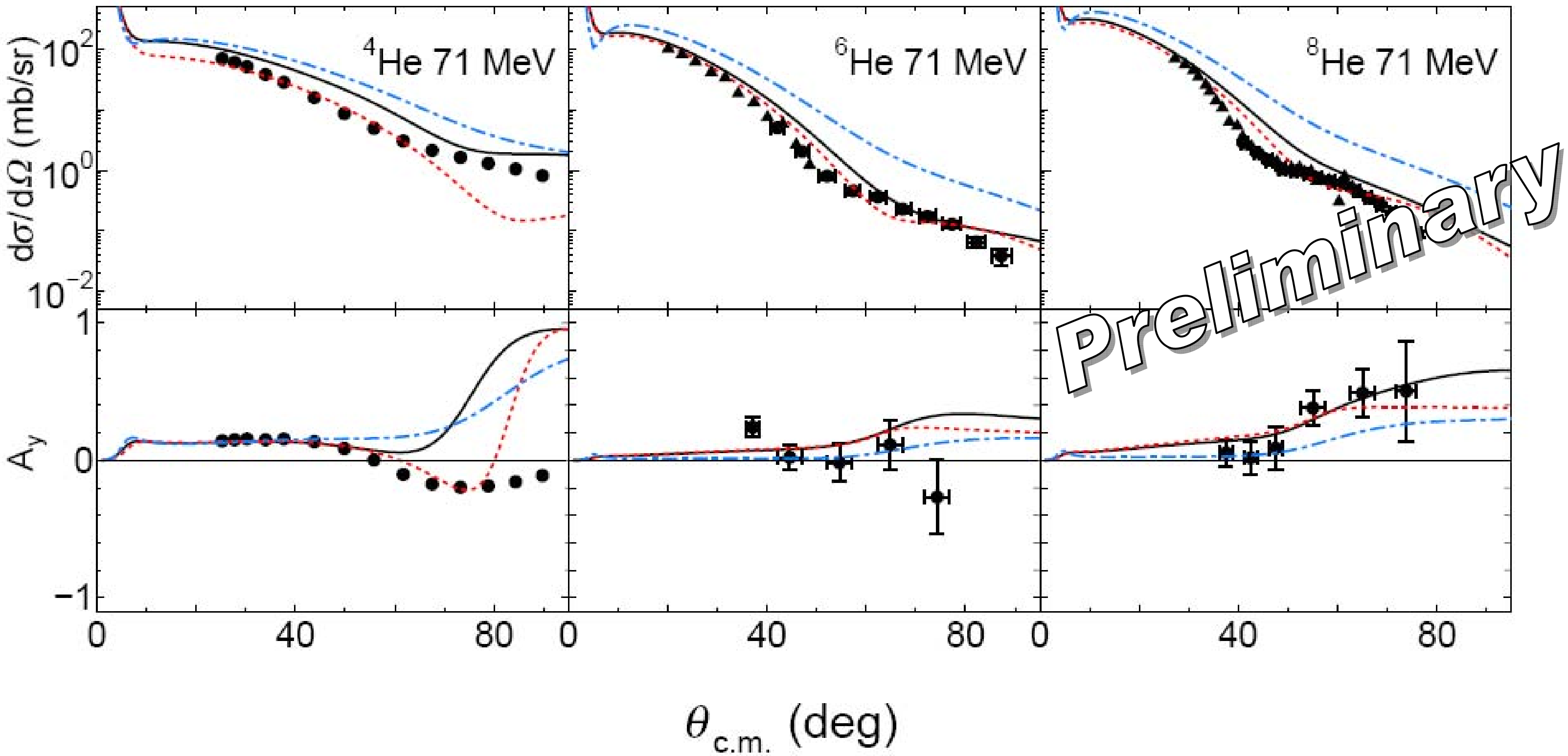
Explore sensitivity to matter radius



^{6}He(p,p) at 200 MeV/nucleon

Explore sensitivity to matter radius

Experiment with ^{8}He available soon (October)



From Kaki, Suzuki, Wiringa: Glauber approach

arXiv:1207.0545

Challenges for ^{6}He

- **^{6}He is a loosely bound nucleus ⇒ Cluster ansatz**
  - Correlation visible in $d\sigma/d\Omega$ at forward angles
  - Only microscopic calculation with a negative A_y at 71 MeV
  - Good description of ^{4}He important
  - Cluster ansatz can be implemented for ^{8}He in similar fashion
- **^{6}He is not a closed shell nucleus (as is ^{8}He)**
  - In microscopic OP in principle all six Wolfenstein amplitudes contribute
  - Projection on ground state p-3/2: G, H, D do not contribute
  - Additional terms to central and spin-orbit potential
- **Finally the additional p-shell terms will also have to be combined with the cluster description**
- Polarization ⇒ Interference can amplify small contributions