Development of an accurate DWIA model of coherent π^0-photoproduction to study neutron skins in medium heavy nuclei

Frederic Colomer

Université libre de Bruxelles
Johannes Gutenberg Universität Mainz

January the 23rd, 2019

The symmetry energy

- neutron-rich nuclei
- neutron stars

} properties strongly dependent on symmetry energy

Equation of state (EOS) of asymmetric matter

$$\mathcal{E}(\rho,\alpha) = \mathcal{E}(\rho,\alpha=0) + S(\rho)\,\alpha^2 + \dots \qquad \alpha = \frac{N-Z}{A}$$

where α is the neutron-proton asymmetry.

The symmetry energy

- neutron-rich nuclei
- neutron stars

} properties strongly dependent on symmetry energy

Equation of state (EOS) of asymmetric matter

$$\mathcal{E}(\rho,\alpha) = \mathcal{E}(\rho,\alpha=0) + S(\rho)\,\alpha^2 + \ldots \qquad \alpha = \frac{N-Z}{A}$$

where α is the neutron-proton asymmetry.

Taylor expansion around nuclear saturation density ρ_0 ($\simeq 0.15$ fm^{-1}):

$$S(\rho) = J + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{1}{2}K_{\text{sym}}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \ldots$$

We can constrain L with the neutron skin.

What is the neutron skin?

The symmetry energy

Where go the extra neutrons in n-rich systems (^{208}Pb: N=126, Z=82)?

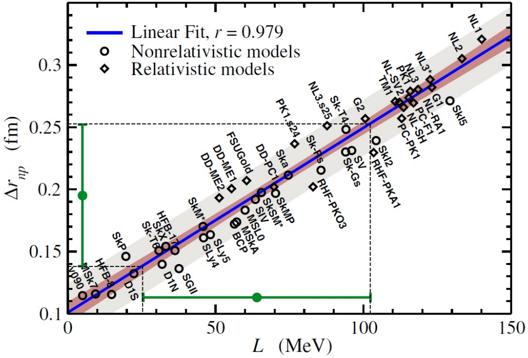
- Symmetry energy favors to move them to the surface
- Surface tension favors spherical drop of *uniform* equilibrium density

$\Rightarrow$ formation of a neutron skin Δr_{np}, larger as A increases

Where go the extra neutrons in n-rich systems (^{208}Pb: N=126, Z=82)?

- Symmetry energy favors to move them to the surface
- Surface tension favors spherical drop of *uniform* equilibrium density

$\Rightarrow$ formation of a neutron skin Δr_{np}, larger as A increases



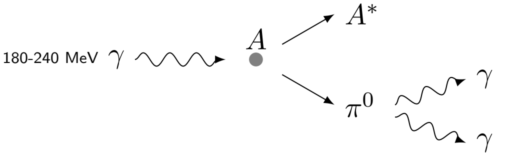
PRL 106, (2011) 252501

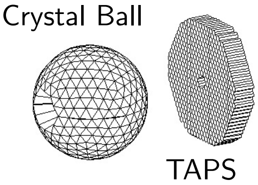
L strongly correlated to Δr_{np}
$\rightarrow$ need to measure accurately

How can we measure it?

The coherent π^0 photoproduction

In Mainz, at MaMi: π^0-photoproduction (on ^{116,120,124}Sn)





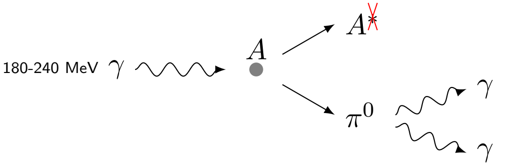
Advantages:

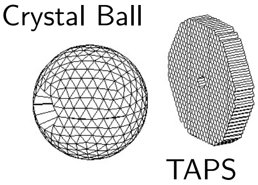
- Same amplitude for n and p
  - $\rightarrow$ Sensitivity to nucleon dist.
- Photon is neutral
  - $\rightarrow$ Whole volume is probed

Drawbacks:

- Final state interactions
  - $\rightarrow$ Model dependence
- Delta resonance region
  - $\rightarrow$ Model dependence

In Mainz, at MaMi: coherent π^0-photoproduction (on ^{116,120,124}Sn)





Advantages:

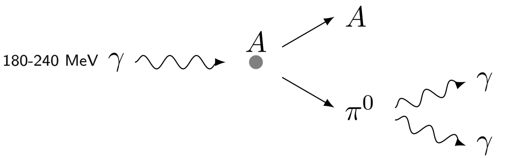
- Same amplitude for n and p
  - $\rightarrow$ Sensitivity to nucleon dist.
- Photon is neutral
  - $\rightarrow$ Whole volume is probed

Drawbacks:

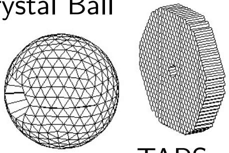
- Final state interactions
  - $\rightarrow$ Model dependence
- Delta resonance region
  - $\rightarrow$ Model dependence

The coherent π^0 photoproduction

In Mainz, at MaMi: coherent π^0-photoproduction (on ^{116,120,124}Sn)



Crystal Ball



TAPS

Advantages:

- Same amplitude for n and p
  - $\rightarrow$ Sensitivity to nucleon dist.
- Photon is neutral
  - $\rightarrow$ Whole volume is probed

Drawbacks:

- Final state interactions
  - $\rightarrow$ Model dependence
- Delta resonance region
  - $\rightarrow$ Model dependence

PRL 112, 242502 (2014): skin of 0.15 $\pm$ 0.05 fm on ^{208}Pb

- ◇ Choice of density
- ◇ Errors due to model dependencies

Plane wave impulse approximation (PWIA)

- Plane wave: no final state interactions of the pion with nucleus.
- Impulse approximation: only one nucleon interacts with the photon.

Cross section (Drechsel, Tiator, Kamalov and Yang in NPA 660, 423):

$$\frac{d\sigma^{\gamma\to\pi}_{\mathrm{PWIA}}}{d\Omega_{\mathrm{CM}}} \propto |f_2(\vec{k}_\pi, \vec{k}_\gamma)\rho_A(q)|^2$$

photo-production elementary amplitude (on one nucleon) → f_2

Nucleon density → ρ_A

Plane wave impulse approximation (PWIA)

- Plane wave: no final state interactions of the pion with nucleus.
- Impulse approximation: only one nucleon interacts with the photon.

Cross section (Drechsel, Tiator, Kamalov and Yang in NPA 660, 423):

$$\frac{d\sigma^{\gamma\to\pi}_{\text{PWIA}}}{d\Omega_{\text{CM}}} \propto |f_2(\vec{k}_\pi, \vec{k}_\gamma)\rho_A(q)|^2$$

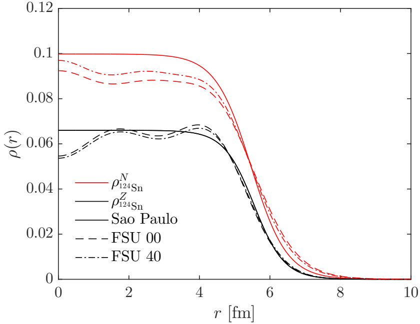
photo-production elementary amplitude (on one nucleon)

Nucleon density

CGLN amplitudes taken from MAID (https://maid.kph.uni-mainz.de/maid2007/helic.html)

Densities used for the calculations

Densities of ^{124}Sn

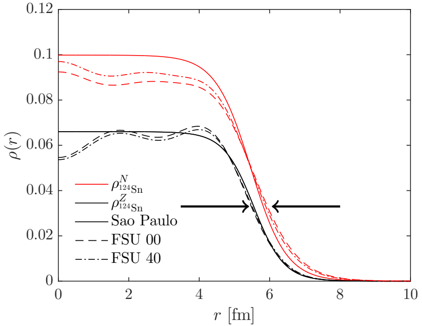


- Sao Paulo (Phenomenological)
  → Fermi-Dirac
- FSU model (courtesy of J. Piekarewicz)
  → Microscopic MF model

Can we differentiate them on a photo-production cross section?

Densities used for the calculations

Densities of ^{124}Sn



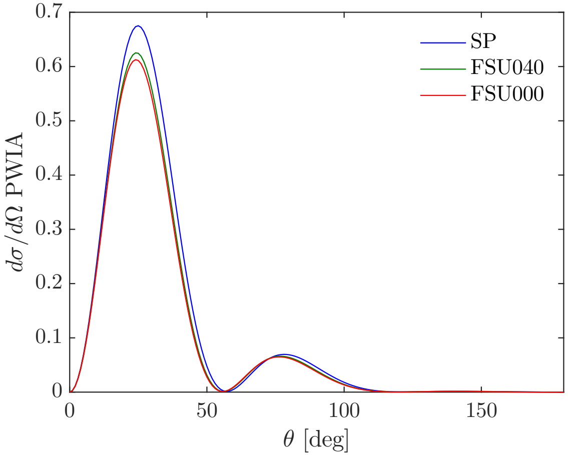
$\neq$ skins

- Sao Paulo (Phenomenological)
  - $\rightarrow$ Fermi-Dirac
    Δr_{np}=0.05 fm
- FSU model (courtesy of J. Piekarewicz)
  - $\rightarrow$ Microscopic MF model
    $\Delta r_{np}^{\mathrm{FSU00}}$=0.28 fm
    $\Delta r_{np}^{\mathrm{FSU40}}$=0.19 fm

Can we differentiate them on a photo-production cross section?

Photo-production cross section in PWIA

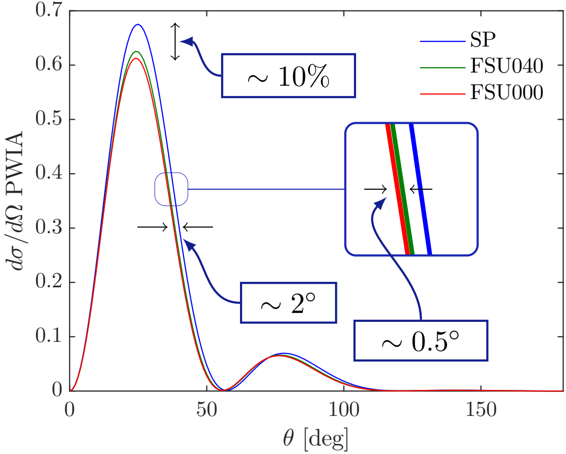
For these densities, photo-production in PWIA (^{124}Sn, 180-190 MeV):



Δr_{np}=0.05 fm
$\Delta r_{np}^{\mathrm{FSU40}}$=0.19 fm
$\Delta r_{np}^{\mathrm{FSU00}}$=0.28 fm

Photo-production cross section in PWIA

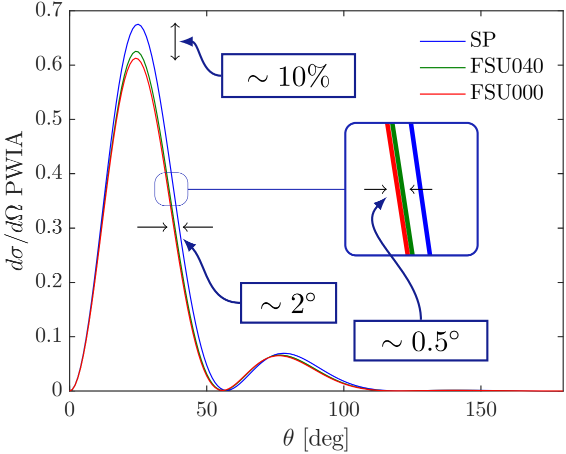
For these densities, photo-production in PWIA (^{124}Sn, 180-190 MeV):



Δr_{np}=0.05 fm
$\Delta r_{np}^{\mathrm{FSU40}}$=0.19 fm
$\Delta r_{np}^{\mathrm{FSU00}}$=0.28 fm

Photo-production cross section in PWIA

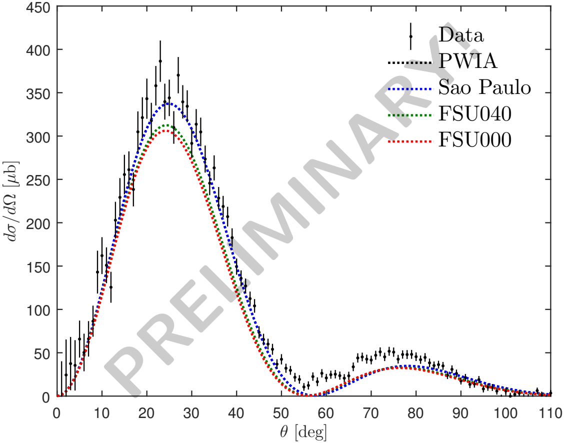
For these densities, photo-production in PWIA (^{124}Sn, 180-190 MeV):



Δr_{np}=0.05 fm
$\Delta r_{np}^{\text{FSU40}}$=0.19 fm
$\Delta r_{np}^{\text{FSU00}}$=0.28 fm

How does that compare with experimental data?

Comparison with experiment at T_γ = 180-190 MeV



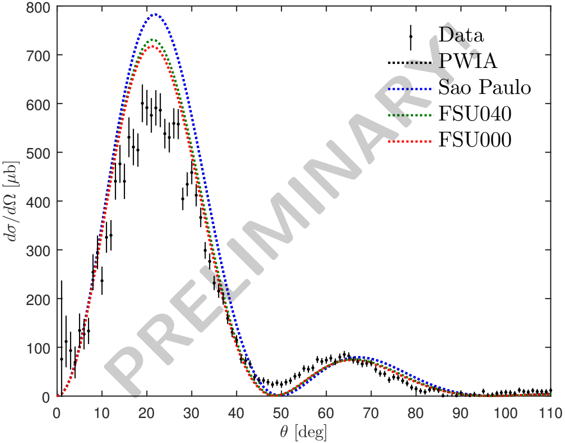
Data courtesy of M. Ferretti (PRELIMINARY)

θ precision $\sim 1^\circ$

Fair agreement

Shift of second peak

Comparison with experiment at $T_\gamma = $ 200-210 MeV



Data courtesy of M. Ferretti (PRELIMINARY)

θ precision $\sim 1^\circ$

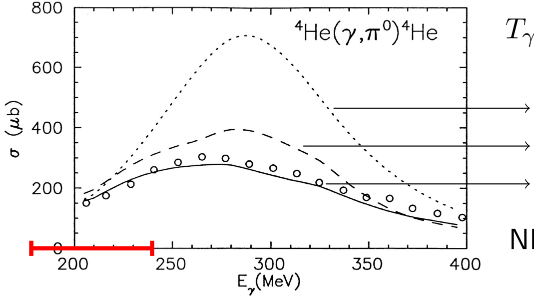
Less good agreement

Shift of second peak

Cross section of photoproduction in DWIA

→ Final state interactions taken into account

$$\frac{d\sigma^{\gamma\to\pi}_{\text{DWIA}}}{d\Omega_{\text{CM}}} \text{ loses its proportionality to } \rho(q)$$



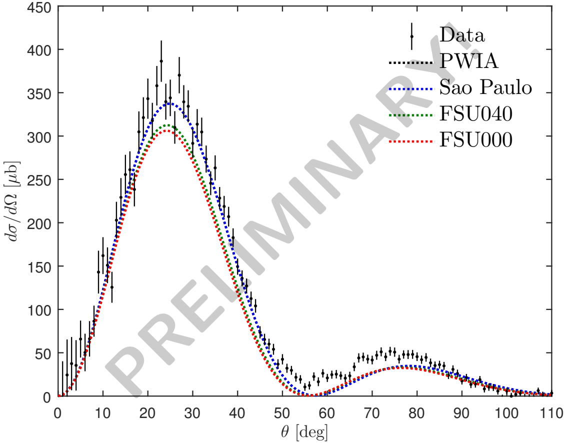
T_γ at MaMi: 180 - 240 MeV

PWIA

DWIA

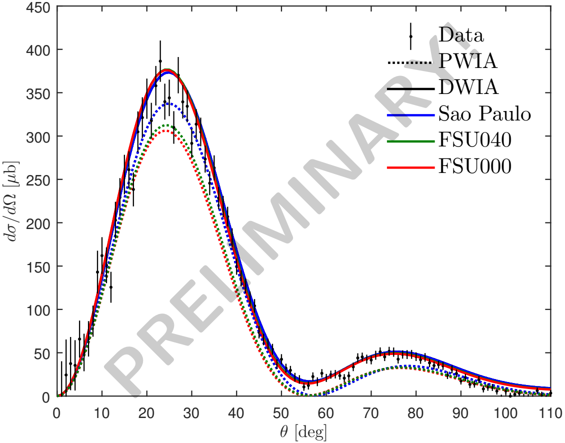
DWIA with DREN

NPA 660, 423



Data courtesy of M. Ferretti (PRELIMINARY)

Comparison with experiment at T_γ = 180-190 MeV



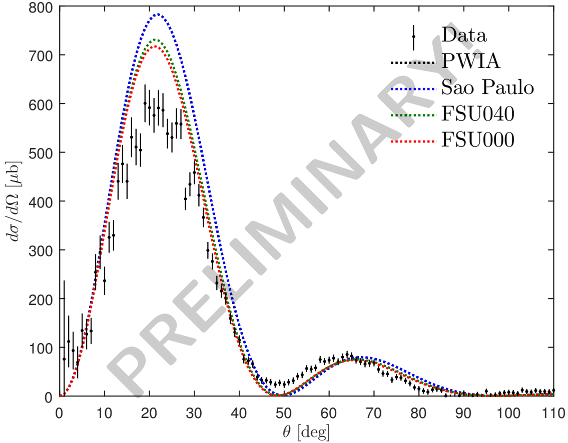
Data courtesy of M. Ferretti (PRELIMINARY)

Good agreement

2^{nd} peak reproduced

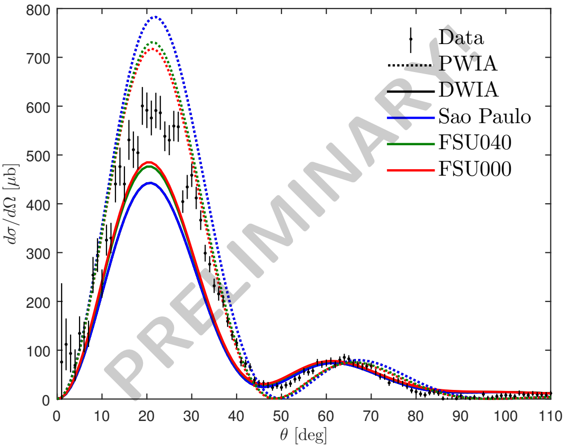
No $\rho(q)$ dependence

Comparison with experiment at T_γ = 200-210 MeV



Data courtesy of M. Ferretti (PRELIMINARY)

Comparison with experiment at $T_\gamma = $ 200-210 MeV



Data courtesy of M. Ferretti (PRELIMINARY)

Less good agreement

1^{st} peak suppressed

2^{nd} peak reproduced

$\rho(q)$ dependence

potential needs to be adjusted

Conclusion, prospects and thanks

- New reaction model implemented
  - ◇ PWIA has dependence when differences of skins $\sim$ 0.10 fm (but little)
  - ◇ DWIA $\pi - A$ potential needs adjustments in range of energies
- What remains to be done
  - ◇ Can we infer information about skin from comparing different isotopes?
  - ◇ Constraints on DWIA $\pi - A$ potential
  - ◇ Analysis of the dependence to $\pi - A$ potential (DWIA)
  - ◇ DREN (Δ resonance) to be studied and adjusted

Conclusion, prospects and thanks

- New reaction model implemented
  - ◇ PWIA has dependence when differences of skins $\sim$ 0.10 fm (but little)
  - ◇ DWIA $\pi - A$ potential needs adjustments in range of energies
- What remains to be done
  - ◇ Can we infer information about skin from comparing different isotopes?
  - ◇ Constraints on DWIA $\pi - A$ potential
  - ◇ Analysis of the dependence to $\pi - A$ potential (DWIA)
  - ◇ DREN (Δ resonance) to be studied and adjusted

Thank you for your attention

Many thanks to my collaborators
(P. Capel, C. Sfienti, M. Vanderhaeghen
M. Thiel, M. Ferretti, V. Tsaran)

Backup

The symmetry energy

Bethe-Weizsäcker: incompressible quantum liquid-drop binding energy

$$B(Z,N) = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \dots$$

In the limit where volume V and $A \to \infty$ but $A/V = \rho_0$ constant

$$\epsilon(\alpha) \equiv -\frac{B(Z,N)}{A} = -a_V + J\alpha^2, \qquad \alpha = \frac{N-Z}{A}$$

α neutron-proton asymmetry.

Incompressible $\rightarrow$ fails to reproduce response to density fluctuations
$\Rightarrow$ Equation of state (EOS) of asymmetric matter

$$\mathcal{E}(\rho,\alpha) = \mathcal{E}(\rho,\alpha=0) + S(\rho)\,\alpha^2 + \dots \qquad \alpha = \frac{N-Z}{A}$$

$\pi - A$ potential used

We currently use the potential (Phys. Rev. C25, 952 (1982))

$$U(\vec{k}', \vec{k}) \propto \left[(\hat{b}_0 + \hat{c}_0 q^2)\rho_A(q) + (\hat{B}_0 + \hat{C}_0 q^2)\rho_{A,2}(q) + (\vec{k} \cdot \vec{k}')\mathcal{L}(q)\right]$$

$$\begin{cases} \mathcal{L}(q) = FT(\mathcal{L}(r)) = FT\left(\dfrac{L(r)}{1 + (4\pi/3)\lambda L(r)}\right) \\ L(r) = \hat{c}_0 \rho_A(r) + \hat{C}_0 \rho_{A,2}(r) \end{cases}$$

Derived from most general $\pi - N$ potential (for spin 0 nucleus!) $+$ Abs.

$$f^{\pi N}(\vec{k}'_\pi, \vec{k}_\pi) = b_0 + b_1 \hat{\boldsymbol{t}}_{\boldsymbol{\pi}} \cdot \hat{\boldsymbol{\tau}}_{\boldsymbol{N}} + (c_0 + c_1 \hat{\boldsymbol{t}}_{\boldsymbol{\pi}} \cdot \hat{\boldsymbol{\tau}}_{\boldsymbol{N}})\vec{k}_\pi \cdot \vec{k}'_\pi$$

$\hat{b}_0, \ldots$ fitted on C, O, Ca, Zr, Pb ($T_\pi^{\rm lab} = 50$ MeV $\rightarrow T_\gamma^{\rm lab} \sim 180$ MeV)

E dep. shaped like $b_0, \ldots$ from SAID (http://gwdac.phys.gwu.edu/analysis/pin_analysis.html)
Derivation of new potential ongoing (with V. Tsaran, M. Vanderhaeghen)

$\pi - A$ potential used

We currently use the potential (Phys. Rev. C25, 952 (1982))

$$U(\vec{k}', \vec{k}) \propto \left[(\hat{b}_0 + \hat{c}_0 q^2)\rho_A(q) + (\hat{B}_0 + \hat{C}_0 q^2)\rho_{A,2}(q) + (\vec{k} \cdot \vec{k}')\mathcal{L}(q) \right]$$

$$\begin{cases} \mathcal{L}(q) = FT(\mathcal{L}(r)) = FT\left(\dfrac{L(r)}{1 + (4\pi/3)\lambda L(r)} \right) \\ L(r) = \hat{c}_0 \rho_A(r) + \hat{C}_0 \rho_{A,2}(r) \end{cases}$$

$\leftarrow$ FT($\rho^2(r)$)

Derived from most general $\pi - N$ potential (for spin 0 nucleus!) + Abs.

$$f^{\pi N}(\vec{k}'_\pi, \vec{k}_\pi) = b_0 + b_1 \hat{\boldsymbol{t}}_{\boldsymbol{\pi}} \cdot \hat{\boldsymbol{\tau}}_{\boldsymbol{N}} + (c_0 + c_1 \hat{\boldsymbol{t}}_{\boldsymbol{\pi}} \cdot \hat{\boldsymbol{\tau}}_{\boldsymbol{N}})\vec{k}_\pi \cdot \vec{k}'_\pi$$

$\hat{b}_0, \ldots$ fitted on C, O, Ca, Zr, Pb ($T_\pi^{\text{lab}} = 50$ MeV $\rightarrow T_\gamma^{\text{lab}} \sim 180$ MeV)

E dep. shaped like $b_0, \ldots$ from SAID (http://gwdac.phys.gwu.edu/analysis/pin_analysis.html)

Derivation of new potential ongoing (with V. Tsaran, M. Vanderhaeghen)

$\pi - A$ potential in development

Derived from most general $\pi - N$ potential (for spin 0 nucleus!)

$$f^{\pi N}(\vec{k}'_\pi, \vec{k}_\pi) = b_0 + b_1 \hat{\boldsymbol{t}}_{\boldsymbol{\pi}} \cdot \hat{\boldsymbol{\tau}}_{\boldsymbol{N}} + (c_0 + c_1 \hat{\boldsymbol{t}}_{\boldsymbol{\pi}} \cdot \hat{\boldsymbol{\tau}}_{\boldsymbol{N}}) \vec{k}_\pi \cdot \vec{k}'_\pi$$

b_0, b_1, c_0 and c_1 taken from SAID (http://gwdac.phys.gwu.edu/analysis/pin_analysis.html)

- + Impulse approximation (other nucleons of nucleus are spectators)
- + Folding with density of nucleus
- + Kinematic corrections ($\pi - N$ to $\pi - A$ cm. frame)
- + Adding absorption (B_0 and C_0 parameters from NPA329, 429 (1979))

Derivation has been done for ^{12}C (V. Tsaran):

$$\begin{aligned} U(\vec{k}', \vec{k}) &\propto U^{\text{1st}} + U^{\text{2nd}} + U^{\text{abs}} \\ &= \left\{ [b_0 + c_0(\vec{k} \cdot \vec{k}' + q^2)] \rho_A(q) + c_0 K(q) \right\} \\ &\quad + \left\{ \tilde{b}_0^2 Z_{ss}(\vec{k}', \vec{k}) + \tilde{bc} Z_{sp}(\vec{k}', \vec{k}) + \tilde{c}_0 Z_{pp}(\vec{k}', \vec{k}) \right\} \\ &\quad + \left\{ B_0 + C_0[\vec{k} \cdot \vec{k}' + q^2] \right\} \rho_{A,2}(q) \end{aligned}$$

Derived from most general $\pi - N$ potential (for spin 0 nucleus!)

$$f^{\pi N}(\vec{k}'_\pi, \vec{k}_\pi) = b_0 + b_1 \hat{\boldsymbol{t}}_{\boldsymbol{\pi}} \cdot \hat{\boldsymbol{\tau}}_{\boldsymbol{N}} + (c_0 + c_1 \hat{\boldsymbol{t}}_{\boldsymbol{\pi}} \cdot \hat{\boldsymbol{\tau}}_{\boldsymbol{N}}) \vec{k}_\pi \cdot \vec{k}'_\pi$$

b_0, b_1, c_0 and c_1 taken from SAID (http://gwdac.phys.gwu.edu/analysis/pin_analysis.html)

- + Impulse approximation (other nucleons of nucleus are spectators)
- + Folding with density of nucleus
- + Kinematic corrections ($\pi - N$ to $\pi - A$ cm. frame)
- + Adding absorption (B_0 and C_0 parameters from NPA329, 429 (1979))

Derivation has been done for ^{12}C with HO (V. Tsaran):

Need w.-funct.

$$U(\vec{k}', \vec{k}) \propto U^{\text{1st}} + U^{\text{2nd}} + U^{\text{abs}}$$
$$= \left\{ [b_0 + c_0(\vec{k} \cdot \vec{k}' + q^2)] \rho_A(q) + c_0 K(q) \right\}$$

Need w.-funct.

$$+ \left\{ \tilde{b}_0^2 Z_{ss}(\vec{k}', \vec{k}) + \tilde{b}\tilde{c} Z_{sp}(\vec{k}', \vec{k}) + \tilde{c}_0 Z_{pp}(\vec{k}', \vec{k}) \right\}$$
$$+ \left\{ B_0 + C_0[\vec{k} \cdot \vec{k}' + q^2] \right\} \rho_{A,2}(q)$$

Derived from most general $\pi - N$ potential (for spin 0 nucleus!)

$$f^{\pi N}(\vec{k}'_\pi, \vec{k}_\pi) = b_0 + b_1 \hat{\boldsymbol{t}}_{\boldsymbol{\pi}} \cdot \hat{\boldsymbol{\tau}}_{\boldsymbol{N}} + (c_0 + c_1 \hat{\boldsymbol{t}}_{\boldsymbol{\pi}} \cdot \hat{\boldsymbol{\tau}}_{\boldsymbol{N}}) \vec{k}_\pi \cdot \vec{k}'_\pi$$

b_0, b_1, c_0 and c_1 taken from SAID (http://gwdac.phys.gwu.edu/analysis/pin_analysis.html)

+ Impulse approximation (other nucleons of nucleus are spectators)
+ Folding with density of nucleus
+ Kinematic corrections ($\pi - N$ to $\pi - A$ cm. frame)
+ Adding absorption (B_0 and C_0 parameters from NPA329, 429 (1979))

Derivation has been done for ^{12}C with HO (V. Tsaran):

$$U(\vec{k}', \vec{k}) \propto U^{\rm 1st} + U^{\rm 2nd} + U^{\rm abs}$$

$$= \left\{ [b_0 + c_0(\vec{k} \cdot \vec{k}' + q^2)] \rho_A(q) + c_0 K(q) \right\}$$

$$+ \left\{ \tilde{b}_0^2 Z_{ss}(\vec{k}', \vec{k}) + \tilde{bc} Z_{sp}(\vec{k}', \vec{k}) + \tilde{c}_0 Z_{pp}(\vec{k}', \vec{k}) \right\}$$

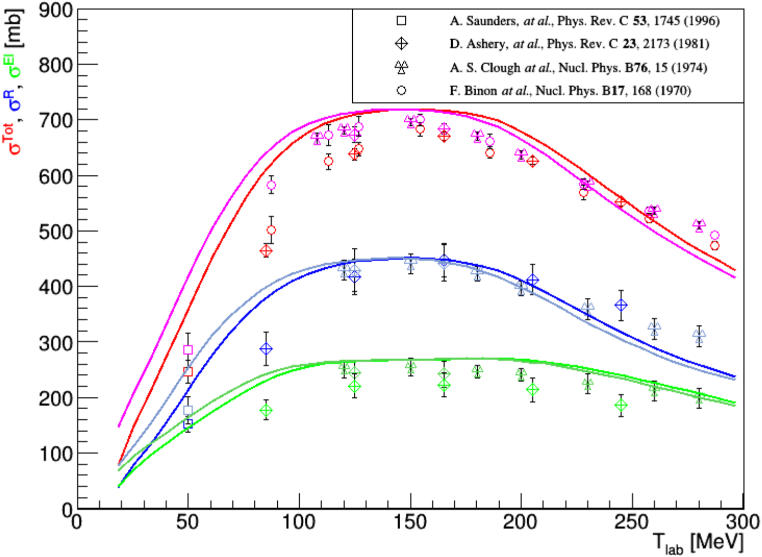
$$+ \left\{ B_0 + C_0[\vec{k} \cdot \vec{k}' + q^2] \right\} \rho_{A,2}(q)$$

Need w.-funct. (→ $K(q)$)

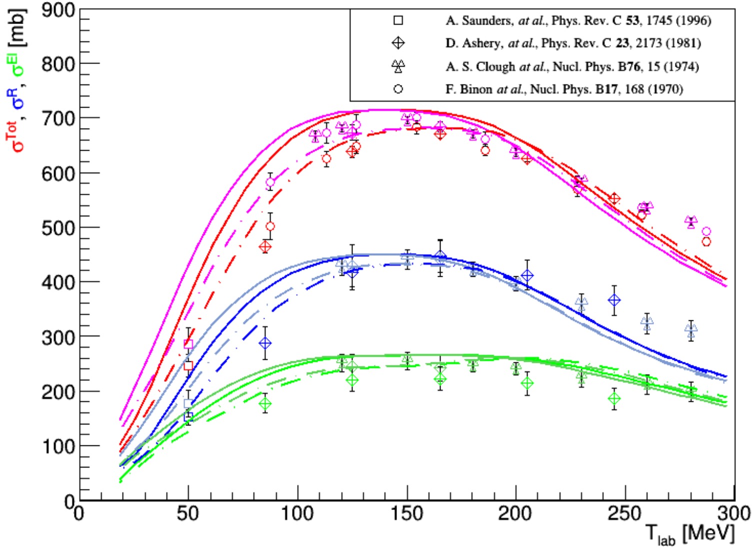
Need w.-funct. (→ second-order term)

FT($\rho^2(r)$) (→ $\rho_{A,2}(q)$)

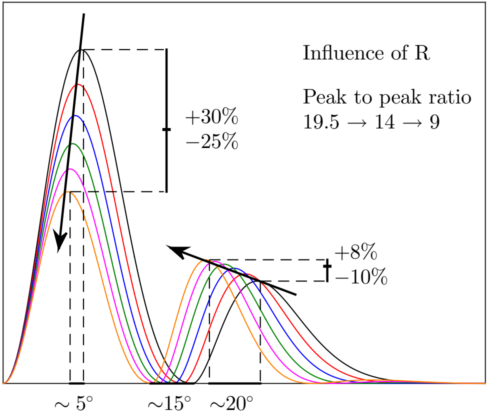
How close to data are we with the potential (on ^{12}C)?



How close to data are we with the potential (on ^{12}C)?



Influence of radius R on the photo-production cross section

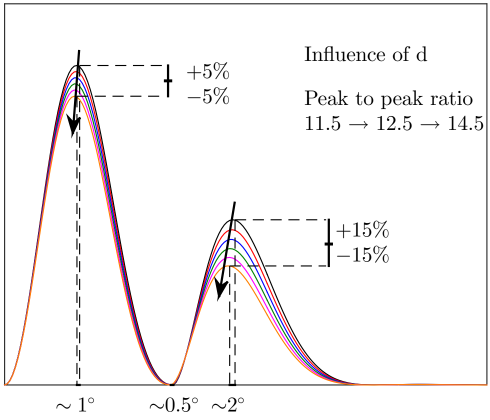


As R increases ($\pm 10\%$),

- First peak $\downarrow$
- Second peak $\uparrow$
- Large shift to small ang.

Peak to peak ratio exhibits large variations

Influence of diffuseness d on the photo-production cross section

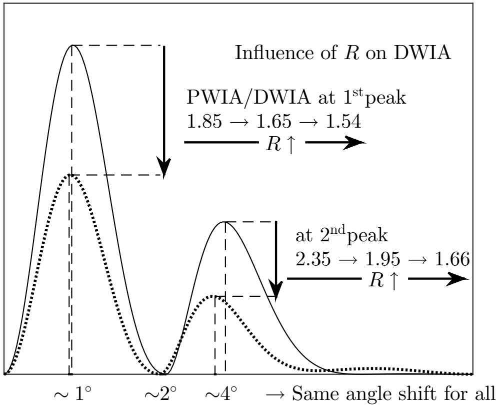


As d increases ($\pm 10\%$),

- First peak ↓ (like R)
- Second peak ↓ ($>< R$)
- Small shift to small ang. ($>< R$)

Peak to peak ratio exhibits small variations

Influence of radius R on the photo-production cross section with distortion



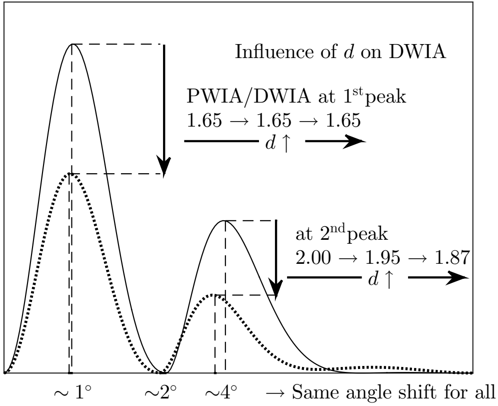
As R increases ($\pm 10\%$), impact of DWIA is

- smaller on first peak
- smaller on second peak
- the same at all angles

Peak to peak ratio exhibits small variations

Influence of the diffuseness d on DWIA

Influence of diffuseness d on the photo-production cross section with distortion



As d increases ($\pm 10\%$), impact of DWIA is

- nil on first peak
- smaller on second peak
- the same at all angles

Peak to peak ratio exhibits small variations