Development of an accurate DWIA model of coherent $\pi^0$ photoproduction to study neutron skins in medium heavy nuclei

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Neutron stars and nuclei

After zooming in $\times 10^{18}$ (!)

- neutron-rich nuclei
- neutron stars

\{ described by the same eq. of state (EOS) \}
The symmetry energy and the neutron skin

In EOS, symmetry energy: \( S(\rho) = J + L \left( \frac{\rho - \rho_0}{3\rho_0} \right) + \frac{1}{2} K_{\text{sym}} \left( \frac{\rho - \rho_0}{3\rho_0} \right)^2 + \ldots \)

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

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

\( \Rightarrow \) formation of a neutron skin \( \Delta r_{np} \), larger as \( A \) increases

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\( L \) strongly correlated to \( \Delta r_{np} \)

\( \rightarrow \) need to measure accurately

How can we measure it?
The coherent $\pi^0$ photoproduction

In Mainz, at MaMi (A2): coherent $\pi^0$ photoproduction (on $^{116, 120, 124}$Sn)

180-240 MeV $\gamma \rightarrow A \rightarrow A^* \rightarrow \pi^0 \rightarrow \gamma \gamma$

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

- Influence of the 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):

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

- 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 $^{116}$Sn

$\rho(r)$

$\rho_{N}^{116\text{Sn}}$

$\rho_{Z}^{116\text{Sn}}$

Sao Paulo

FSU 00

FSU 40

$\neq$ skins

- Sao Paulo (Phenomenological)
  $\Delta r_{np} = -0.12$ fm

- FSU model (courtesy of J. Piekarewicz)
  $\Delta r_{np}^{FSU00} = 0.17$ fm
  $\Delta r_{np}^{FSU40} = 0.10$ fm

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

For these densities, photo-production in PWIA ($^{116}$Sn, 180-190 MeV):

\[
\frac{d\sigma}{d\Omega}_{\text{PWIA}}
\]

\[
\theta \ [\text{deg}]
\]

\[
0 \quad 50 \quad 100 \quad 150
\]

\[
\frac{d\sigma}{d\Omega}_{\text{PWIA}}
\]

\[
0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7
\]

SP
FSU040
FSU000

\[
\sim 10\%
\]

\[
\Delta r_{np} = -0.12 \text{ fm}
\]

\[
\Delta r_{\text{FSU40}}^{np} = 0.10 \text{ fm}
\]

\[
\Delta r_{\text{FSU00}}^{np} = 0.17 \text{ fm}
\]

How does that compare with experimental data?
Comparison with experiment at $T_\gamma = 180-190$ MeV

Data courtesy of M. Ferretti (PRELIMINARY)

$\theta$ precision $\sim 1^\circ$

Fair agreement

Second peak not reproduced @ PWIA

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

$\theta$ precision $\sim 1^\circ$

Less good agreement

Second peak not reproduced @ PWIA

Data courtesy of M. Ferretti (PRELIMINARY)
Distorted wave impulse approximation (DWIA)

Cross section of photoproduction in DWIA

→ Final state interactions taken into account

\[
\frac{d\sigma_{DWIA}^{\gamma\rightarrow\pi}}{d\Omega_{CM}} \text{ loses its proportionality to } |\rho_A|^2
\]

\[4\text{He}(\gamma,\pi^0)^4\text{He}\]

\[T_\gamma \text{ at MaMi: } 180 - 240 \text{ MeV}\]

- PWIA
- DWIA
- DWIA with DREN

NPA 660, 423
Comparison with experiment at $T_\gamma = 180-190$ MeV

Good agreement
2$^{\text{nd}}$ peak well reproduced
Distortion cancels $\rho_A$ dependence

Data courtesy of M. Ferretti (PRELIMINARY)
Comparison with experiment at $T_\gamma = 200-210$ MeV

Less good agreement than at 180-190 MeV

DWIA reduces $1^{st}$ peak ⇒ better agreement with data

$2^{nd}$ peak not well reproduced even @DWIA

Curves in reversed order ⇒ potential needs to be adjusted

Data courtesy of M. Ferretti (PRELIMINARY)
Conclusion, prospects and thanks

Study of the evolution of neutron skin in nuclei ⇒ information about EoS ⇒ constrains the structure of neutron stars

Coherent $\pi^0$-photoproduction provides a way to infer $n$-skin thickness

- New reaction model implemented
  - PWIA has dependence when differences of skins $\sim 0.10$ fm (small)
  - DWIA $\pi - A$ potential reduces dependence on skin

- What remains to be done
  - Can we infer information about skin from comparing different isotopes?
  - Constraints on $\pi - A$ (at energies of experiment)
  - (Bayesian) analysis of the dependence to $\pi - A$ potential (DWIA)

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