Single and Double Pion Photoproduction off the Deuteron

Manuel Dieterle

Munich, June 13\textsuperscript{th} 2011

XIV International Conference on Hadron Spectroscopy
# Outline

1. **Motivation**

2. **Single $\pi^0$ Photoproduction**
   - Status
   - Experiment
   - Results

3. **Double $\pi^0$ Photoproduction**
   - Total Cross Sections
   - Beam-Helicity Asymmetry

4. **Conclusions**
Why Photoproduction of $\pi^0$?

- Test modern hadron models by studying nucleon resonances

- Small coupling of photons to neutral mesons
Why Photoproduction of $\pi^0$?

- Test modern hadron models by studying nucleon resonances

\[ N(J^P_N) \rightarrow N^*(J^P_{N^*}) \rightarrow N(J^P_N) \]

- Small coupling of photons to neutral mesons

\[ \gamma(L^P_\gamma) \rightarrow \pi^0(L^{P}_{\pi^0}) \]
Why on the Neutron?

- Isospin amplitudes of the elementary transitions depend on reactions on proton and neutron

\[
A(\gamma p \rightarrow \pi^+ n) = \sqrt{2} (A^{(0)} + A^{(-)})
\]
\[
A(\gamma n \rightarrow \pi^- p) = \sqrt{2} (A^{(0)} - A^{(-)}) \quad A^{(0)} := \text{isoscalar}
\]
\[
A(\gamma p \rightarrow \pi^0 p) = (A^{(+) + A^{(0)}}) \quad A^{(+)}, A^{(-)} := \text{isovector}
\]
\[
A(\gamma n \rightarrow \pi^0 n) = (A^{(+) - A^{(0)}})
\]

- meson photoproduction from light nuclei, i.e. deuteron
- nuclear effects (rescattering of the mesons, FSI, ...)
World $\pi^0$ Data

SAID Data Base - http://gwdac.phys.gwu.edu/
Former Results - MAMI 1999

\[ \sigma(\pi^0 np)/A \]
\[ \sigma(\pi^0 d)/A \]
\[ \sigma(\pi^0 p) \]
\[ \sigma(\pi^0 p) \text{ folded} \]

- significant reduction in $\sigma/A$ compared to free proton
- can not be explained alone by Fermi motion
- nuclear effect? FSI?

B. Krusche et al., Eur. Phys. J. A 6(1999) 309
Former Results - LNS Sendai 2009

\[ \sigma'(-0.7 < \cos \theta_{\pi^0}^* < 0.6) \]

- \( \sigma(\pi^0 np) \)
- \( \sigma(\pi^0 p) \)
- \( \sigma(\pi^0 n) = \sigma(\pi^0 np) - \sigma(\pi^0 p) \)
- 0.8 * MAID folded

- can not be explained alone by Fermi motion
- nuclear effect? FSI?

H. Shimizu, NNR workshop 2009
Photon beam energies up to $\sim 1.4$ GeV

Target: $\sim 5 \text{ cm} \ LD_2$

Detectors:
- Crystal Ball (CB):
  - surrounding the target
- Two Arm Photon Spectrometer (TAPS):
  - placed as forward wall

$\sim 4\pi$ steradian
Identification of the Reaction Channels

Reaction mechanism for $\pi^0$ photoproduction on deuterium:

$$\gamma + d \to \begin{cases} 
\pi^0 + p(n) & \text{QF on proton} \\
\pi^0 + n(p) & \text{QF on neutron} \\
\pi^0 + d & \text{Coherent ($E_\gamma > 500 \text{ MeV}$)}
\end{cases}$$
Reaction mechanism for $\pi^0$ photoproduction on deuterium:

$$\gamma + d \rightarrow \begin{cases} 
\pi^0 + p(n) & \text{QF on proton} \\
\pi^0 + n(p) & \text{QF on neutron} \\
\pi^0 + d & \text{Coherent ($E_{\gamma} > 500$ MeV)}
\end{cases}$$

Measurements:

- **Exclusive on P:** $\gamma + d \rightarrow \pi^0 + p$
- **Exclusive on N:** $\gamma + d \rightarrow \pi^0 + n$
- **QF-Inclusive:** $\gamma + d \rightarrow \pi^0 + (N)$
π⁰ Total Cross Sections

![Graph showing total cross sections for π⁰ photoproduction on the deuteron. The graph plots σ(π⁰p) and σ(π⁰n) against energy (Eγ [MeV]). The graph includes data points and curves for MAID and SAID folded models.](image)

**Motivation**

- Single π⁰ Photoproduction
- Double π⁰ Photoproduction
- Conclusions

**Outline**

- Single π⁰ Photoproduction
- Double π⁰ Photoproduction
- Conclusions

**π⁰ Total Cross Sections**

**Graph**

- σ(π⁰p)
- σ(π⁰n)
- MAID folded
- SAID folded

**Table**

| Energy (GeV) | σ(π⁰p) [σ] | σ(π⁰n) [σ] |
|-------------|------------|------------|
| 0.5         | 80         | 50         |
| 1.0         | 70         | 40         |
| 1.5         | 60         | 30         |
| 2.0         | 50         | 20         |
| 2.5         | 40         | 10         |

**References**

- Single and Double Pion Photoproduction off the Deuteron
- Manuel Dieterle
\( \pi^0 \) Total Cross Sections

![Graph showing single and double pion photoproduction](image)

**Single \( \pi^0 \) Photoproduction**

- \( \sigma(\pi^0 p) \)
- \( \sigma(\pi^0 n) \)
- MAID folded
- SAID folded

**Double \( \pi^0 \) Photoproduction**

- \( \sigma(\pi^0 np) \)
- \( \sigma(\pi^0 n) + \sigma(\pi^0 p) \)
- \( \sigma(\pi^0 np) \) B. Krusche et al.
- MAID folded
- SAID folded
Comparison to Models

MAID and SAID model scaled down with factor 0.8
Resonance Contributions

![Graph showing single and double pion photoproduction](image)

Contributions
Resonance Contributions

![Graph showing contributions to photoproduction](image)

**Contributions**

$D_{13} : p, n$
Resonance Contributions

\[ \sigma(\pi^0 p) \quad \sigma(\pi^0 n) \]

\[ D_{13} : p, n \quad F_{15} : p \]

Contributions

Full \quad w/o D_{13}

\[ \sigma [\mu b] \]

\[ E_\gamma [\text{MeV}] \]

\[ \sigma [\mu b] \]

\[ E_\gamma [\text{MeV}] \]
Resonance Contributions

Contributions

$D_{13} : p, n$

$F_{15} : p$

$D_{15} : n$
Total Cross Sections (M. Oberle et al.)

Dominated by sequential decay

\[2\pi^0\]
Resonance Contributions

$p(\gamma, 2\pi^0)p$

$n(\gamma, 2\pi^0)n$

- Electromagnetic excitation of the $F_{15}$ stronger on the proton
- Electromagnetic excitation of the $D_{15}$ stronger on the neutron
The Beam-Helicity Asymmetry

Helicity \( h = \vec{S} \hat{P} = -S, \ldots, S \)

\[
I^\odot(\Phi) = \frac{1}{P_\gamma} \frac{d\sigma^+}{d\sigma^+ + d\sigma^-} = \frac{1}{P_\gamma} \frac{N^+ - N^-}{N^+ + N^-}
\]
Former Results (D. Krambrich, F. Zehr et al.)

- Asymmetry indicates strong sensitivity to reaction mechanisms
- Early results contradicted many model predictions

D. Krambrich, F. Zehr et al., Phys. Rev. Lett. 103 (2009) 052002
Helicity Asymmetries for $2\pi^0$ (M. Oberle et al.)

**PRELIMINARY**

$p(\gamma, 2\pi^0)p$

$n(\gamma, 2\pi^0)n$

Fermi defolded compared to free p (F. Zehr et al.)

![Graphs showing helicity asymmetries](image-url)
Conclusions

Single $\pi^0$ Photoproduction:

- Cross Sections for Single $\pi^0$ in good agreement with former results
- MAID/SAID overestimate the cross sections by 25%
- Reduction can not only be explained by Fermi motion

Double $\pi^0$ Photoproduction:

- Same asymmetries for $2\pi^0$ on the proton as on the neutron
- Model predictions not yet in agreement with results, further input needed
- Electromagnetic excitation of the resonances different for proton and neutron. De-excitation of the resonances different for single and double pion production.
Thanks for your attention

This work is supported by:

Swiss National Fund
Deutsche Forschungsgemeinschaft
DXS: QF-Inclusive $E_\gamma = [414, 707]$ MeV
DXS: QF-Inclusive $E_\gamma = [714, 1007]$ MeV
DXS: QF-Inclusive $E_\gamma = [1012, 1306]$ MeV
**DXS: QF-Inclusive** $E_\gamma = [1315, 1397]$ MeV

| Energy (MeV) | $\sigma/d\Omega$ [mb/sr] |
|-------------|--------------------------|
| 1315        |                          |
| 1320        |                          |
| 1333        |                          |
| 1336        |                          |
| 1339        |                          |
| 1345        |                          |
| 1350        |                          |
| 1356        |                          |
| 1362        |                          |
| 1368        |                          |
| 1374        |                          |
| 1380        |                          |
| 1385        |                          |
| 1391        |                          |
| 1397        |                          |

$\cos(\theta_{\text{CM}, \pi^0})$
DXS: Exclusive Proton $E_\gamma = [414, 707]$ MeV
DXS: Exclusive Proton $E_\gamma = [714, 1007]$ MeV
**DXS: Exclusive Proton** \( E_\gamma = [1012, 1306] \text{ MeV} \)
DXS: Exclusive Proton $E_\gamma = [1315, 1397]$ MeV
**DXS: Exclusive Neutron** $E_\gamma = [414, 707]$ MeV

![Graph showing single and double pion photoproduction off the deuteron](image-url)
DXS: Exclusive Neutron $E_\gamma = [714, 1007]$ MeV

$\sigma / d\Omega$ [µb/sr] vs. $\cos(\theta_{CM, \pi^0})$
DXS: Exclusive Neutron $E_\gamma = [1012, 1306]$ MeV
DXS: Exclusive Neutron $E_\gamma = [1315, 1397]$ MeV
Main Contributing Channels

| Initial State | Final State  | Threshold [MeV] |
|---------------|--------------|-----------------|
| $\gamma d \rightarrow$ | $\pi^0 d$ | $\sim 140$ |
|               | $\pi^0 np$ | $\sim 142$ |
## Main Contributing Channels

| Initial State | Final State | Threshold [MeV] |
|---------------|-------------|----------------|
| $\gamma d \rightarrow$ | $\pi^0 d$ | $\sim 140$ |
| | $\pi^0 np$ | $\sim 142$ |
| | $\pi^0 \pi^0 np$ | $\sim 292$ |
| | $\pi^0 \pi^- pp$ | $\sim 297$ |
| | $\pi^0 \pi^+ nn$ | $\sim 297$ |
# Main Contributing Channels

| Initial State | Final State | Threshold [MeV] |
|---------------|-------------|----------------|
| $\gamma d \rightarrow$ | $\pi^0 d$ | $\sim 140$ |
|                 | $\pi^0 np$ | $\sim 142$ |
| $\pi^0 \pi^0 np$ | | $\sim 292$ |
| $\pi^0 \pi^- pp$ | | $\sim 297$ |
| $\pi^0 \pi^+ nn$ | | $\sim 297$ |
| $(\eta \rightarrow 3\pi^0)np$ | | $\sim 630$ |
| $(\eta \rightarrow \pi^0 \pi^+ \pi^-)np$ | | $\sim 630$ |
Identifications of the $\pi^0$-Mesons

$\pi^0 \xrightarrow{99\%} 2\gamma$ ➢ Identify $\pi^0$: $M_{\gamma\gamma} = \sqrt{2E_{\gamma 1} E_{\gamma 2} (1 - \cos(\theta_{\gamma 1\gamma 2}))}$
Identifications of the $\pi^0$-Mesons

$\pi^0 \rightarrow 2\gamma$

$\Rightarrow$ Identify $\pi^0$: $M_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1 - \cos(\theta_{\gamma_1\gamma_2}))}$
Identifications of the $\pi^0$-Mesons

$\pi^0 \rightarrow 2\gamma$  ➢ Identify $\pi^0$: $M_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1 - \cos(\theta_{\gamma_1\gamma_2}))}$

$\pi^0 \rightarrow 2\gamma$  $\eta \rightarrow 2\gamma$

Cut on $M_{\gamma\gamma}$: 110 MeV $< M_{\gamma\gamma} < 160$ MeV
Missing Mass Analysis

Invariant mass spectrum rather clean

➢ Remove remaining background: Competing channels, $\pi^0$ from other channels
Missing Mass Analysis

Invariant mass spectrum rather clean
➢ Remove remaining background: Competing channels, $\pi^0$ from other channels

Missing Mass Analysis: $\gamma + N \rightarrow \pi^0 + X$

$$\Rightarrow M(X) = M(\gamma + N - \pi^0)$$
Missing Mass Analysis

Invariant mass spectrum rather clean

➢ Remove remaining background: Competing channels, $\pi^0$ from other channels

Missing Mass Analysis: $\gamma + N \rightarrow \pi^0 + X$

$\Rightarrow M(X) = M(\gamma + N - \pi^0)$
Missing Mass Analysis

Invariant mass spectrum rather clean
➢ Remove remaining background: Competing channels, $\pi^0$ from other channels

Missing Mass Analysis: $\gamma + N \rightarrow \pi^0 + X$

$$\Rightarrow M(X) = M(\gamma + N - \pi^0)$$
Missing Mass Analysis

Invariant mass spectrum rather clean

- Remove remaining background: Competing channels, $\pi^0$ from other channels

Missing Mass Analysis: $\gamma + N \rightarrow \pi^0 + X$

$\Rightarrow M(X) = M(\gamma + N - \pi^0)$
Missing Mass Analysis

Invariant mass spectrum rather clean
➢ Remove remaining background: Competing channels, $\pi^0$ from other channels

Missing Mass Analysis: $\gamma + N \rightarrow \pi^0 + X$

$\Rightarrow M(X) = M(\gamma + N - \pi^0)$
Missing Mass Analysis

Invariant mass spectrum rather clean

➢ Remove remaining background: Competing channels, $\pi^0$ from other channels

**Missing Mass Analysis:** $\gamma + N \rightarrow \pi^0 + X$

$\Rightarrow M(X) = M(\gamma + N - \pi^0)$
Charged Particle Identification

Crystal Ball: PID

TAPS: $BaF_2$

Single and Double Pion Photoproduction off the Deuteron

Manuel Dieterle
**Missing Energy Analysis**

Coherent Reaction: $d(\gamma, \pi^0)d \leftrightarrow$ two 2-body-decay.

$$\Delta E_i = E^*(i) - E^*_i(E_\gamma), \quad i = d, \pi^0$$
**Coplanarity Cut**

Two final state particles always coplanar: \( \Delta \phi = \phi_1 - \phi_2 \approx 180^\circ \)

Coherent Reaction: \( 175^\circ \leq \Delta \phi \leq 185^\circ \)
Final Invariant Mass Distributions

Exclusive on N:

Exclusive on P:

QF-Inclusive:

Coherent

Single and Double Pion Photoproduction off the Deuteron

Manuel Dieterle
Invariant Mass Cut and Reconstruction

- Cut on invariant mass: $M_{\gamma\gamma}^{\text{second}} \in [110, 160]$ MeV ($M_{\pi^0} \approx 135$ MeV)
- Cut on invariant mass: $M_{\gamma\gamma}^{\text{first}} \in [110, 160]$ or

- $\gamma p \rightarrow \pi^0 \pi^0 p$
- 4 neutral and 1 charged hits
- $\gamma n \rightarrow \pi^0 \pi^0 n$
- 5 neutral hits
- $\gamma D \rightarrow \pi^0 \pi^0 X$
- 4 neutral hits or
- 5 neutral hits or
- 4 neutral and 1 charged hits
(1) Fit signal in side bins (\([85, 110] \& [160, 185] \text{ MeV}\))

(2) Fit background in signal-bins (\([110, 160] \text{ MeV}\))

Calculate ratio (2)/(1)

Correct online for this background

Ratio (2)/(1) as function of \(E_\gamma\)
Missing Mass and Coplanarity Cut

Background mainly from:

$\eta \rightarrow \pi^0\pi^0\pi^0$

$\pi^0$'s and nucleon should be coplanar

$\Phi_{N,2\pi} \in [160^\circ, 200^\circ]$

Fit Peak and plot:

- Peak, Peak $+3\sigma$, Peak $-3\sigma$