Study of baryon resonances with meson photoproduction

F. Zehr, University of Basel, Department of Physics

Overview Talk Group Professor B. Krusche
Introduction to nucleon resonances and meson photoproduction

The setup at MAMI in Mainz and ELSA in Bonn

Some selected topics:
- Magnetic moment of the $\Delta(1232)$ resonance
- $\eta'$ photoproduction
- $\eta$ photoproduction off light nuclei: $^2$H, $^3$He and $^7$Li
- Isospin structure of excitations
- Coherent $\eta$ production & $\eta$ mesic nuclei

Double pion photoproduction off the proton

Outlook
What do we have in common?

We study meson photoproduction off the nucleon via the excitation of nucleon resonances (or production at threshold)
Nucleon Resonances

What is the structure of the nucleon?

QCD

Valence quarks

Sea quarks

Gluons

Complex structure
Nucleon at Low Energies

→ Constituent Quark Models with effective degrees of freedom

3 equivalent constituent quarks  quark diquark  quark flux tubes

... much more models available (chiral soliton models, coupled channel dynamics) with different number of degrees-of-freedom
Resonances: Excited states of the nucleon

- Related to the number of degrees-of-freedom

Ground State: Nucleon

Spin-Flip →
First Resonance: 'Delta'
Resonances: Excited states of the nucleon

→ Related to the number of degrees-of-freedom

Quark → 1p
S_{11} and D_{13}: Second resonance region

And so on ...
**Resonances**: Comparison between Constituent Quark Model and experiment

S. Capstick and W. Roberts
*Phys. Rev. D* 1994
How do we study resonances?

Resonances decay into \textit{mesons} is dominant → large cross sections

Historically, lots of results on resonances provided by elastic and inelastic scattering of charged pions

\[
\begin{align*}
\pi^+ & \rightarrow \eta \\
\pi^+ & \rightarrow \pi^0, \pi^0 \\
N^* & \rightarrow N + \pi^+ \\
N & \rightarrow N + \pi^+ \\
N^* & \rightarrow N + \pi^+
\end{align*}
\]
How do we study resonances?

Resonances decay into mesons is dominant → large cross sections

Historically, lots of results on resonances provided by elastic and inelastic scattering of charged pions

But not suited for resonances coupling weakly to pions → experimental bias: missing resonances?
**Photoproduction:**

\[ \gamma \rightarrow N^* N N \]

Gives another access to nucleon resonances

**Advantage:**

Gives access to additional information: 
- electromagnetic transition amplitude

**Drawback:**

- Very small cross sections (~ 3 orders of magnitude smaller)
- Lots of background (non resonant terms)
Total photoabsorption cross section:

From left to right: $P_{33} (1232)$, $P_{11} (1440)$, $D_{13} (1520)$, $S_{11} (1535)$, $F_{15} (1680)$

**Difficulty:** Due to short lifetime, resonances are broad and strongly overlapping
What we all have in common:

- Resonance
- or threshold reaction
- High energy photon
- Meson Decay Products (mostly photons)
- Recoil Nucleon, charged pions
What we all have in common: The Setup

We need to...

1: Produce high energy photons
   100MeV to ... (3.2 GeV)

2: Detect decay products
   photons, protons, neutrons, charged pions, electrons, ...
Producing high energy photons:

Bremsstrahlung tagging

Polarized photons are produced on a diamond radiator via coherent bremsstrahlung.

\[ \frac{1}{E} \text{ spectrum} \]

\[ E_\gamma = E_e - E_{e'} \]
Accelerators: MAMI in Mainz

Upgrade:
Mami C → 1.5 GeV
First data taking in progress

Mami B: 883 MeV
Until march 2007

Very High Current: 80 μA
Accelerators: ELSA in Bonn

Electron Stretcher Accelerator (ELSA)

Up to 3.5 GeV

Current: 5 \mu A
Detectors:

In Mainz, Crystal Ball and TAPS
Detectors:
In Mainz, Crystal Ball and TAPS, highly segmented calorimeters

TAPS as forward wall:
• 510 BaF2 Crystals
• Veto wall

Crystal Ball:
• 672 NaI Crystals
• Vetos
• 2 MWPCS
Detectors:

In Bonn, Crystal Barrel and TAPS,
Detection Technique 1/3:

Vetos

- Small energy deposition in the vetos
- Large energy deposition in the Crystal Ball

Ratio is different for each type of charged particle
Detection Technique 2/3:

Time Of Flight

Photon Speed: $c$  
$\rightarrow$ straight line

Nucleon Speed: $v(E_N)$  
$\rightarrow$ 'banana'

Only possible for TAPS
Detection Technique 3/3:

Pulse Shape Analysis (TAPS)

BaF2 has a short (2 us) and a long (some ms) light component.

the ratio is different for each type of particle
What do we want to do: Some selected topics

- $\Delta(1232)$ magnetic moment
- $\eta'$ production
- Isospin structure of resonances
- Coherent $\eta$ production
- $\eta$ mesic nuclei
- Double pion production
We want a precise description of the lowest lying resonances
We want a precise description of the lowest lying resonances

\[ \Delta(1232) \]

- Mass: \( 1232 \pm 2 \text{ MeV} \)
- Width: \( 118 \pm 2 \text{ MeV} \)

Next fundamental quantity:

**Magnetic moment**

Due to quark spins and to the average of quark currents

Very sensitive test of the theoretical hadron description

\[ \gamma p \rightarrow \Delta \rightarrow \gamma' \Delta \rightarrow \gamma' \Delta \pi^0 \]

Benedicte Boillat (11h00)
We want a precise description of the lowest lying resonances

Remark:
Magnetic moment of the $S_{11}(1535)$ is determined in the same way

$\gamma p \rightarrow S_{11} \rightarrow \gamma' S_{11} \rightarrow \gamma' \Delta \eta$

Measurement under way ...
We want to know precisely the isospin structure of the electromagnetic excitations of the resonances

We want to use the *difference between the proton and the neutron* (Isospin) to characterize resonances
Electromagnetic interaction violates isospin

In a meson photoproduction reaction, the transition operator is split into an isoscalar ($A^I_{S}$, $I = 0$) and an isovector part ($A^I_{V}$, $I = 0, \pm 1$).

\[
\sigma(\gamma p \rightarrow \eta p) \sim |A^p|^2 = |A^I_{S} + A^I_{V}|^2
\]

\[
\sigma(\gamma n \rightarrow \eta n) \sim |A^n|^2 = |A^I_{S} - A^I_{V}|^2
\]

Clebsch Gordan, Isospin Composition

Values of $A^I_{S}$ and $A^I_{V}$ different for each resonance
Neutron Target? \rightarrow \text{Deuterium Target}

Nuclear effects have to be taken in account.
Neutron Target? \rightarrow \text{Deuterium Target}

Nuclear effects have to be taken in account

First try on the $S_{11}$ which has a large (50\%) coupling to the eta

$$\frac{\sigma(\gamma n \rightarrow \eta n)}{\sigma(\gamma p \rightarrow \eta p)} = 0.66 \pm 0.08$$

$$\frac{|A^{IS} - A^{IV}|}{|A^{IS} + A^{IV}|} = 0.82 \pm 0.02$$

Close to 1: Either $A^{IS}$ or $A^{IV}$ is dominant
\[
\sigma(\gamma n \to \eta n)/ \sigma(\gamma p \to \eta p) = 0.66 \pm 0.08
\]

\[
|A^{IS} - A^{IV}| / |A^{IS} + A^{IV}| = 0.82 \pm 0.02
\]

Close to 1: Either \(A^{IS}\) or \(A^{IV}\) is dominant

Further analysis

\(A^{IV}\) is dominant:
\(A^{IS}/A^p = 0.09\)

**Isoscalar contribution to \(S_{11}\) cross section is small (9%)**
Beyond the $S_{11}(1535)$

Behaviour of $\sigma_n/\sigma_p$ completely different at higher energies

Signature of higher lying resonances that couple stronger to the neutron than to the proton.

$D_{15}(1675)$ (MAID)

$P_{11}(1710)$ Member of the decuplet predicted by chiral soliton model

Interference between $S_{11}(1535)$ and $S_{11}(1650)$

Due to $\Sigma K$ threshold
Isovector part is dominant in $S_{11}$ (1535) excitation $A^{IS}/A^{P} = 0.09$

Test with coherent eta production on different nuclei $S_{11}$ is dominant

Quantum Numbers

\[ \gamma(E1) + N \rightarrow S_{11} \rightarrow N + \eta \]

\[ J_{z}: \quad -1 \quad +1/2 \quad -1/2 \quad -1/2 \quad 0 \]

Spin Flip
Isovector part is dominant in $S_{11} (1535)$ excitation $A^{IS}/A^P = 0.09$

Quantum Numbers

$$\gamma(E1) + N \rightarrow S_{11} \rightarrow N + \eta$$

$J_z$: $\begin{array}{cccc} -1 & +1/2 & -1/2 & -1/2 & 0 \end{array}$

Test on light nuclei

$^4$He: $I=0$, $J=0$ (Isoscalar, non spin-flip) no coherent production

$^2$H: $I=0$, $J=1$ (Isoscalar, spin-flip) small coherent production

$^3$He: $I=1/2$, $J=1/2$ (Isovector, spin-flip) large coherent production

$^7$Li: $I=1/2$, $J=3/2$ (Isovector, spin-flip) large* coherent production

* Due to nuclear form factor, coherent cross section on $^7$Li smaller by ~ 1 order of magnitude

$^3$He: Francis Pheron (11h40) $^7$Li: Yasser Maghrbi (11h20)
More Exotic: η mesic nuclei on $^3$He

Search of a 3He-η quasi-bound state

Coherent eta production enhanced at threshold

Search for back-to-back pion-proton

More statistics needed → Francis Pheron (11h40)
$\eta'$: same work with a different probe

\[ \frac{\sigma(n\eta')}{\sigma(p\eta')} = 0.68 \pm 0.05 \]

**New experiment in progress**

Dominik Werthmüller (next year)
We want to study resonances with double pion decay

Decay with double pion final states opens new ways to study resonances.

\[ \text{P}_{11} (1440) \rightarrow (\pi^0 \pi^0)_{s\text{-wave}} \]

\[ \text{D}_{13} (1520) \rightarrow \rho n \rightarrow \pi^0 \pi^+ n \]
Double $^0$ photoproduction off deuterium

Precise measurement of the neutron and proton cross sections

Input for complex theoretical models
Double pion off the proton:

The asymmetry: a good tool to disentangle resonances

The asymmetry is defined by the angle between the reaction plane and the plane defined by the two pions

Asymmetry: \[ \gamma p \rightarrow \pi^0 \pi^+ n \]

\[ A = \frac{1}{P_y} \frac{\sigma^+-\sigma^-}{\sigma^++\sigma^-} \]

For circularly polarized photons (left and right handed)

Rich information due to the presence of 3 particles in the final state
The asymmetry: results

The asymmetry is very sensitive to the internal detail of the models.

Suited for an individual study of the resonances

Black: This Work
Purple: A. Fix
Red: L. Roca full model
Blue: L. Roca without $D_{13}(1520)$ contribution
\( \gamma p \rightarrow \pi^0 \pi^0 p \) at threshold: test of Chiral Perturbation Theory

ChPT predicts that cross section at threshold is dominated by 'pion loops' for double \( \pi^0 \) but not for \( \pi^0 \pi^+ \) and \( \pi^- \pi^+ \)

Thus \( \sigma_{\text{thresh}}(\pi^0 \pi^0) > \sigma_{\text{thresh}}(\pi^0 \pi^+) \) but \( \sigma(\pi^0 \pi^0) < \sigma(\pi^0 \pi^+) \)

Black: This work

Red: Previous TAPS measurement
M. Kotulla

Curves: ChPT Average and Upper Limit
V. Bernard
Outlook

Meson photoproduction is a broad and precise tool to study nucleon resonances

In a 35 minutes talk, $P_{11} (1232)$, $S_{11} (1535)$, $P_{11} (1440)$, $D_{13} (1520)$, $S_{11} (1650)$, $D_{15} (1675)$ and $P_{11} (1710)$ and various threshold processes have been mentioned

*Well established & speculative ones*

**Very active field: new double polarization experiments**

*Next year: meson photoproduction on heavy nuclei, in-medium modification of mesons and resonances.*