Photoproduction of $\eta$, $\eta'$, and double $\pi$-mesons off nucleons

B. Krusche, U. Basel (PhD works of I. Jaegle, F. Zehr), CBELSA, Crystal Ball, TAPS colls.

Introduction

Photoproduction of $\eta$ mesons and $\eta'$ mesons

Double-Pion photoproduction

Conclusions

Structure of the Nucleon

- complex many body system
  - valence quarks
  - sea quarks
  - gluons

- models - effective dof’s:
  - 3 equivalent constituent quarks
  - quark - diquark models (fewer states)
  - quarks - flux tubes etc. (more states)
  - chiral soliton models (anti-decuplet states)
  - coupled channel dynamics (molecule-like states)

- comparison: known excited states - constituent quark model (Capstick & Roberts)

- ordering of (low-lying) states?
- missing resonance problem?

low lying excited states

\[
\begin{array}{c}
\begin{array}{c}
S=3/2, L^\pi=1^-, J^\pi=(1/2,3/2,5/2)^- \\
D_{13}(1700), 3/2^- \\
D_{15}(1675), 5/2^- \\
S_{11}(1650), 1/2^- \\
\end{array} \\
\begin{array}{c}
S=1/2, L^\pi=1^-, J^\pi=(1/2,3/2)^- \\
S_{11}(1535), 1/2^- \\
D_{13}(1520), 3/2^- \\
\end{array} \\
\begin{array}{c}
S=1/2, L^\pi=0^+, J^\pi=1/2^+ \\
P_{11}(939), 1/2^+ \\
\end{array}
\end{array}
\]

\[
\begin{array}{c}
N(I=1/2) \\
D_{13}(1700) \\
D_{15}(1675) \\
S_{11}(1650) \\
S_{11}(1535) \\
D_{13}(1520) \\
P_{11}(1440) \\
\end{array} \\
\Delta(I=3/2) \\
D_{33}(1700) \\
S_{31}(1620) \\
P_{33}(1600) \\
P_{33}(1232) \\
\end{array}
\]

Notation: \( L_{2I2J} : L=0(S), 1(P), 2(D), \ldots \)

Electron Stretcher Accelerator (ELSA)

- Booster synchrotron: 0.5 - 1.6 GeV
- Stretcher ring: 0.5 - 3.5 GeV
- Medium energy physics experiments

- Electron gun
- LINAC 1: 20 MeV
- LINAC 2: 26 MeV
- Electron stretcher accelerator (ELSA)
- Compton polarimeter
- Mott polarimeter
- PETRA cavity
- DORIS cavity
- Tune jump quadrupole
- Superconducting solenoid
- Injection septa
- Skew quadrupoles
- Extraction septa

- FZK laboratory
- DESY cavity
- Electrons bunch stretcher

- Beamlines for SR experiments
- BN0, BN1, BN2, BN3
- Half cell of ELSA
- Electro-magnetic stretcher
- Medium energy physics experiments
- Dipole (horizontal)
- Dipole (vertical)
- Quadrupole
- Skew Quadrupole
- Sextupole
- Combined-Function Magnet
- Radio Frequency
- Solenoid

- LINAC 1: 20 MeV
- LINAC 2: 26 MeV
- Electron source: 50 keV
MAMI accelerator in Mainz

Mainz Microtron (MAMI)
continuous wave electron accelerator, max. beam energy 883

0. Stage: Linac (2.5 GHz, 3.45 MeV)

1.-3. Stage: Racetrack Microtrons:
- microbunches of 0.4ns
- linear accelerator structures
- constant B field ⇒ varying radii (18, 51, 90 return cycles)
- very efficient acceleration and continuous mode
- high current (0.1mA)

4. Stage: Harmonic Double Sided Microtron
maximum energy: 1.5 GeV

**experimental setups - Ball, Barrel and TAPS and ...**

- **Bonn ELSA accelerator:**
  - Crystal Barrel (CsI), TAPS (BaF$_2$) forward wall, inner detectors
  - $E_\gamma \leq 3.5$ GeV, lin. pol.: available, circ. pol.: available

- **Mainz MAMI accelerator:**
  - Crystal Ball (NaJ), TAPS (BaF$_2$) forward wall, inner detectors
  - $E_\gamma \leq 0.8$ (1.5) GeV, lin. pol.: available, circ. pol.: available

Experimental setup: Crystal Barrel and TAPS

$N_\gamma = 10^7$/s

TAPS Crystal Ball - MAMI 2004/2005

$\eta$ photoproduction from the nucleon at threshold:
- dominance of the $S_{11}(1535)$ resonance...

- total cross section

- expected energy dependence for resonances:
  
  $S_{11}(L_{N\eta} = 0) : \sigma \propto (E_\gamma - E_{thres})^{1/2}$
  
  $P_{11}(L_{N\eta} = 1) : \sigma \propto (E_\gamma - E_{thres})^{3/2}$
  
  $D_{13}(L_{N\eta} = 2) : \sigma \propto (E_\gamma - E_{thres})^{5/2}$

- strong dominance of $S_{11}(1535)$, background small
  (vector mesons, Born terms),
  some interference with $S_{11}(1650)$

---

\( \eta \) photoproduction from the nucleon at threshold:

...and a tiny little bit of \( D_{13}(1520) \)

- angular distributions

- fitted with:

\[
\frac{d\sigma}{d\Omega} = \frac{q_\eta^*}{k_\gamma^*} \left[ A + B \cos(\Theta^*) + C \cos^2(\Theta^*) \right]
\]

\( S_{11}, (P_{11}), \text{VM}, \) \( D_{13} \)

\( \Rightarrow b_\eta(D_{13}) = 0.23 \pm 0.04 \% \)

(Tiator et al., Chiang et al.)

CB-ELSA:

\[ \gamma p \rightarrow p \eta : \]
\[ \eta \rightarrow \gamma \gamma \]
\[ \eta \rightarrow 3\pi^0 \]

→ Photons are detected
→ Proton direction measured

CLAS:

→ Proton detected
→ \( \eta \) from missing mass

\[ \eta' \rightarrow \pi^0 \pi^0 \eta \]
resonances coupling to $\eta$ photoproduction

branching ratios and elm. couplings (PDG):

<table>
<thead>
<tr>
<th>state</th>
<th>$b_\eta$ [%]</th>
<th>$A^p_{1/2}$</th>
<th>$A^p_{3/2}$</th>
<th>$A^n_{1/2}$</th>
<th>$A^n_{3/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{13}(1520)$</td>
<td>0.23±0.04</td>
<td>-24</td>
<td>166</td>
<td>59</td>
<td>139</td>
</tr>
<tr>
<td>$S_{11}(1535)$</td>
<td>30 - 55</td>
<td>90</td>
<td>-46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{11}(1650)$</td>
<td>3 - 10</td>
<td>53</td>
<td>-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_{15}(1675)$</td>
<td>0 ± 1</td>
<td>19</td>
<td>15</td>
<td>-43</td>
<td>-58</td>
</tr>
<tr>
<td>$F_{15}(1680)$</td>
<td>0 ± 1</td>
<td>-15</td>
<td>133</td>
<td>29</td>
<td>-33</td>
</tr>
<tr>
<td>$D_{13}(1700)$</td>
<td>0 ± 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{11}(1710)$</td>
<td>6.2±1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{13}(1720)$</td>
<td>4±1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- $D_{15}(1675)$ has stronger electromagnetic coupling to the neutron than to the proton but parameters quite uncertain:
  $A^p_{1/2}=6 - 34, A^p_{3/2}=3-30, A^n_{1/2}=-(21-57), A^n_{3/2}=-(30-77)$
  $b_\eta=0 \sim 1\%$ (PDG), $b_\eta=17\%$ (ETA-MAID, Chiang et al.)

- interference structure in $S_{11}$-sector?

Data:
- TAPS: B. Krusche et al., PRL74 (195) 3736
- GRAAL: F. Renard et al., PLB528 (2002) 215
- CLAS: M. Dugger et al., PRL89 (2002) 222002
- Crystal Barrel: V. Crede et al., PRL94 (2005) 012004

The reaction $n(\gamma, \eta)n$ in the second resonance region

- ratio of $n(\gamma, \eta)n$ and $p(\gamma, \eta)p$
- total cross sections

- ratio of total $n(\gamma, \eta)n$ and $p(\gamma, \eta)p$
- angular distributions

For $S_{11}$: $|A_{1/2}^n/A_{1/2}^p| = 0.82$ \& $A_{1/2}^{IS} << A_{1/2}^{IV}$ \implies $A_{1/2}^{IS}/A_{1/2}^p = 0.09$

resonance contributions to $\gamma N \rightarrow \eta N$ in the MAID model

- dominance of $S_{11}(1535)$
- strong cancelation between $S_{11}(1535)$ and $S_{11}(1650)$
- proton: only small contributions from other resonances
- neutron: strong contribution from $D_{15}(1675)$?
quasifree eta photoproduction from p,n: results from GRAAL

V. Kouznetsov for the GRAAL collaboration, proceedings NSTAR 2004, page 197

- proton cross section in agreement with free proton results
- narrow structure in quasifree neutron cross section at $W=1675$, width $\Gamma \approx 40$ MeV
- predicted properties of nucleon-like pentaquark

$\Theta^+[ud]^2s^-$

$N^+ |[ud]^2\bar{d}\rangle$

$N_s^+ |[ud][su]_+\bar{s}\rangle$

$\Sigma^+ |[ud][su]_+\bar{d}\rangle$

$\Sigma_s^+ |[su]^2\bar{s}\rangle$

$\Sigma_3^{3/2}^+ |[ds]_u^2\rangle$

$\Sigma_3^{3/2}^- |[us]^2\bar{d}\rangle$

Identification of $\eta$-meson production (exclusive)

- decay channel: $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$
- select events with 7 hits
- invariant mass off all photon pairs
- cut on $\pi^0$ invariant mass
- select best combination of $6\gamma$ to $3\pi^0$ by $\chi^2$-test
- use $\pi^0$ mass as constraint, construct $3\pi^0$ invariant mass
- cut on $3\pi^0$ invariant mass
- missing mass analysis to remove $\eta\pi$ final states etc.
- treat recoil nucleon as missing particle: $m^2 = (P_\gamma + P_N - P_\eta)^2$,
Nucleon Identification CB

inner detector:
- 3 layers of scintillating fibers
- cylindrical shape
- proton:
  2 or 3 layers match a hit in the CB
- neutron:
  no layer has fired
Nucleon Identification TAPS

taps veto detector:
- 5 mm plastic scintillator
- individual for each BaF$_2$ crystal

proton:
- veto hit in front of BaF$_2$ crystal
  + E vs TOF

neutron:
- no veto hit in front of BaF$_2$ crystal
  + E vs TOF

quasifree $\eta$-photoproduction off the deuteron

- cross section for $\gamma n \rightarrow \eta n$ from two analyses with very different systematics:
  1. $\eta$ in coincidence with recoil neutrons
  2. difference of inclusive cross section and $\eta$ in coincidence with recoil protons

![Graphs showing cross sections as a function of $E_\gamma$]
angular distributions

\[ \cos(\Theta_{\eta}) \cos(\Theta_{\eta}^*) \]

comparison with models

\[ E_{\gamma} = 800 \text{ MeV}, W = 1542 \text{ MeV} \]

\[ E_{\gamma} = 1000 \text{ MeV}, W = 1660 \text{ MeV} \]

excitation functions in angular bins

\begin{align*}
\text{cos}(\Theta) &= -1.0 - 0.6 \\
\text{cos}(\Theta) &= -0.6 - 0.2 \\
\text{cos}(\Theta) &= -0.2 + 0.2 \\
\text{cos}(\Theta) &= +0.2 + 0.6 \\
\text{cos}(\Theta) &= +0.6 + 1.0 \\
\end{align*}

\begin{align*}
E_\gamma [\text{MeV}] \\
\frac{d\sigma}{d\Omega} [\mu b/\text{sr}] \\
\end{align*}

fit of angular distributions

- fit with:
  \[
  \frac{d\sigma}{d\omega} = \frac{q^*}{k^*} \sum A_i P_i(\cos(\Theta^*))
  \]

- result:
  - all coefficients similar for proton and neutron above 1.25 GeV
  - \(A_0\) coefficient: dominance of \(S_{11}\) resonances, for neutron small shoulder around 1 GeV
  - \(A_1\) coefficient: interference \(S_{11}, P_{11}\)?
  - \(A_2\) coefficient: interference \(S_{11} - D_{13}\) resonance

- quasifree neutron • quasifree proton — free proton (Ff)
- q.f. neutron (Maid) — q.f. neutron (Shklyar et al.)

comparison of free and quasi-free cross sections

- quasi-free total cross sections corrected for Fermi smearing with correction factors calculated by folding known free proton cross section, respectively ETA-MAID prediction with momentum distribution of bound nucleons.

result:
- in $S_{11}(1535)$ peak below 0.9 GeV perfect agreement between free and quasi-free proton data and quasi-free neutron data scaled by 2/3.
- Fit parameters for $S_{11}$ Breit-Wigner:
  - proton: $W=1538$ MeV, $\Gamma=157$ MeV, $A^p_{1/2}=103$
  - neutron: $W=1538$ MeV, $\Gamma=148$ MeV, $A^n_{1/2}=85$
- narrow structure around 1 GeV in neutron/proton ratio, width is only upper bound

Bonn-Gatchina PWA analysis

- basis: coupled channel isobar analysis with background terms

- different scenarios to reproduce 'bump' structure:
  - $S_{11}$ wave proportional to $\gamma p \rightarrow \eta p$, all other resonance couplings free: 'bump' non-reproducible
  - left: introduction of narrow $P_{11}$: possible solution (narrow $S_{11}$ or $D_{13}$ also possible)
  - right: free fit of $S_{11}$ couplings without additional narrow resonance, 'bump' structure from $S_{11}(1535)$ and $S_{11}(1650)$ interference and cusp effect at $K\Sigma$ threshold

de-folding of Fermi smearing

- for events with neutron in TAPS \((\cos(\Theta^*_\eta) < -0.1)\)
- neutron energy from time-of-flight
- comparison: \(W\) from photon energy (Fermi smeared) - \(W\) from nucleon - meson 4-vectors (resolution smeared)
- de-folded proton cross section similar to free proton, de-folded neutron cross section shows structure around 1.7 GeV:
  - position: \(W = 1683\) MeV
  - width: \(\Gamma = 60\pm20\) MeV
  - (resolution dominated)
new experiments: double polarization observables $E$, $G$

- double polarization observable $E$: circularly polarized beam on longitudinally polarized target
  Experiment at MAMI C with Crystal Ball
  expected quality (simulation) of:
  - angular dependence at $W=1675$ MeV
  - energy dependence around $\Theta=60^\circ$

- double polarization observable $G$: linearly polarized beam on longitudinally polarized target
  Experiment at ELSA with Crystal Barrel
  expected quality (simulation) of:
  - angular dependence at $W=1630$ MeV
  - energy dependence around $\Theta=90^\circ$

---

resonances in photoproduction of $\eta'$-messons

- experiments: 'resonance' like structure around 1.8 GeV
- known resonances ($\sqrt{s} \approx 2$ GeV): $P_{13}(1900)$ (*), $F_{17}(1990)$ (**), $F_{15}(2000)$ (**), $D_{13}(2080)$ (**), $S_{11}(2090)$ (*), $P_{11}(2100)$ (*);
  no branching ratios known
- quark model predictions:
  many states, strongest coupling of $\eta'$ to: $S_{11}(2090)$, $D_{13}(2080)$ (*);

analyses of previous photoproduction data:
- Mukhopadhyay et al. (1995):
  effective Lagrangian approach fitted to old data:
  dominance of $D_{13}(2080)$ resonance
- Plötzke et al. (1998):
  BW resonances, SAPHIR 5-track events:
  dominance of $S_{11}$ and $P_{11}$ resonances
  with poles close to 2 GeV
- Link (2000):
  Regge parameterization, SAPHIR 3-track events:
  dominance of Regge exchange, possibly $S_{11}$ state at threshold
- Sibirtsev et al. (2003):
  SAPHIR data (3-track events renormalized)
  dominance of $\rho$, $\omega$ poles in t-channel,
  small contribution from $S_{11}(1535)$ resonance
- Chiang et al. (2003):
  reggeized model, SAPHIR 5-track events:
  strong contribution from Regge exchange, $S_{11}$ with pole around 1950 MeV,
  possibly $P_{11}$ and/or $P_{13}$ (poles close to 1950 MeV)
Interpretation of existing data

- total cross section (Plötzke et al.):
  \[ \sigma(\mu b) \]

- angular distribution:
  \[ \frac{d\sigma}{d\Omega} = \frac{q}{k}(A + B\cos(\Theta) + C\cos^2(\Theta)) \]

fit results:
- \( S_{11} (M = 1897 \pm 50 \text{ MeV}) \)
- \( P_{11} (M = 1986 \pm 26 \text{ MeV}) \)
quasifree $\eta'$-photoproduction off the deuteron

- same game as before...preliminary results

only $\eta' \rightarrow \eta \pi^0 \pi^0 \rightarrow 6\gamma$ data, ($\ldots \rightarrow 10\gamma$ still under analysis) (I. Jaegle)

free proton data CBELSA/TAPS Kotulla et al.

\[ \sigma(\text{NN}\eta'X) \]
\[ \sigma(\text{pm}\eta') \]
\[ \sigma(\eta\pi') \]
\[ \sigma(\eta p\eta') \]
\[ \sigma(\eta p\eta') - \sigma(p\eta') \]
angular distributions

- quasifree and free proton cross sections in good agreement
- quasifree neutron and proton cross sections similar at high energies - different shape around 1700 MeV
double pion photoproduction in the second resonance region

- $\gamma p \rightarrow p\pi^+\pi^-$
- $\gamma p \rightarrow n\pi^0\pi^+$
- $\gamma p \rightarrow p\pi^0\pi^0$

**double $\pi^0$ photoproduction**

**interpretation by Laget model:**

**BoGa analysis of most recent Mainz and Bonn data:**

- P$_{11}$ small, D$_{13}$ strong, D$_{33}$ strong,
- double-bump structure from interference between D$_{11}$(1520) and D$_{33}$(1700)

---

new precise invariant mass distributions for $2\pi^0$ and $\pi^0\pi^+$

- $\pi^0$ - n invariant mass
- $\pi^+$ - n invariant mass

beam-helicity asymmetry (circularly pol. beam)
beam-helicity asymmetries for $2\pi^0$ and $\pi^0\pi^+$

- $\pi^0\pi^0$ - asymmetry
- $\pi^0\pi^+$ - asymmetry

π⁰π⁰ photoproduction off the deuteron

Preliminary

γn→π⁰π⁰n measured in 2 different ways:

- π⁰π⁰ in coincidence with the recoil neutron
- difference of inclusive cross section and in coincidence with the recoil proton
summary

exclusive, quasifree $\eta$-photoproduction off deuteron:
- large difference for resonance contributions to $p(\gamma, \eta)p$ and $n(\gamma, \eta)n$
- narrow structure in excitation function off neutron
- next steps: (double) polarization observables, better neutron ToF resolution

$\eta'$-photoproduction off the deuteron:
- large difference in total cross section and shape of angular distributions around cross section maximum for free proton

double pion photoproduction
- precise invariant mass distributions for $\pi^0\pi^0$ and $\pi^0\pi^+$
- precise beam-helicity asymmetries for $\pi^0\pi^0$ and $\pi^0\pi^+$
- first results for $n(\gamma, \pi^0\pi^0)n$: peak in cross section ratio around 900 MeV