

Evidence for a parity doublet $\Delta(1920)P_{33}$ and $\Delta(1940)D_{33}$ from $\gamma p \rightarrow p\pi^0\eta$

I. Horn¹, A.V. Anisovich^{1,2}, G. Anton³, R. Bantes⁴, O. Bartholomy¹, R. Beck¹, Yu. Beloglazov², R. Castelijns⁵, V. Crede⁶, A. Ehmans¹, J. Ernst¹, I. Fabry¹, H. Flemming⁷, A. Fösel³, M. Fuchs¹, Chr. Funke¹, R. Gothe⁴, A. Gridnev², E. Gutz¹, St. Höffgen⁴, J. Hößl³, J. Junkersfeld¹, H. Kalinowsky¹, F. Klein⁴, E. Klempt¹, H. Koch⁷, M. Konrad⁴, B. Kopf⁷, B. Krusche⁸, J. Langheinrich⁴, H. Löhner⁵, I. Lopatin², J. Lotz¹, H. Matthäy⁷, D. Menze⁴, J. Messchendorp⁹, V. Metag⁹, V.A. Nikonov^{1,2}, D. Novinski², M. Ostrick⁴, H. van Pee¹, A.V. Sarantsev^{1,2}, C. Schmidt¹, H. Schmieden⁴, B. Schoch⁴, G. Suft³, V. Sumachev², T. Szczepanek¹, U. Thoma¹, D. Walther¹, and Chr. Weinheimer¹

(The CB-ELSA Collaboration)

¹ *Helmholtz-Institut für Strahlen- und Kernphysik der Universität Bonn, Germany*

² *Petersburg Nuclear Physics Institute, Gatchina, Russia*

³ *Physikalisches Institut, Universität Erlangen, Germany*

⁴ *Physikalisches Institut, Universität Bonn, Germany*

⁵ *KVI, Groningen, Netherlands*

⁶ *Department of Physics, Florida State University, USA*

⁷ *Physikalisches Institut, Universität Bochum, Germany*

⁸ *Physikalisches Institut, Universität Basel, Switzerland and*

⁹ *Physikalisches Institut, Universität Giessen*

(Dated: June 26, 2008)

Evidence is reported for the existence of a parity doublet of Δ resonances with total angular momentum $J = 3/2$ from photoproduction of the $p\pi^0\eta$ final state. The two parity partners $\Delta(1920)P_{33}$ and $\Delta(1940)D_{33}$ make significant contributions to the reaction. Cascades of resonances into $\Delta(1232)\eta$, $N(1535)\pi$, and $N\alpha_0(980)$ are clearly observed.

PACS numbers: 13.60.Le, 12.40.Nn, 13.40.Gp

Chiral symmetry and chiral symmetry breaking play key roles for understanding strong interactions. Chiral symmetry implies that chiral partners having the same angular momentum J but opposite parity should be degenerate in mass. The spin-parity partner of the nucleon with $J^P = 1/2^-$, $N(1535)$, is found 600 MeV above the nucleon; the mass splitting between the chiral partners $N(1520)$ with $J^P = 3/2^-$ and $\Delta(1232)$ with $J^P = 3/2^+$ is 288 MeV. The large mass gaps are indications that chiral symmetry is broken spontaneously.

Surprisingly, the high-mass light baryon spectrum exhibits a new phenomenon, the occurrence of parity doublets where pairs of N^* or Δ resonances with the same J but opposite parities form (nearly) mass-degenerate doublets. In 1999, Glozman suggested to explain the mass degeneracy by assuming that chiral symmetry is restored in highly excited hadronic states [1]. The concept of chiral symmetry breaking and its restoration was extended to postulate chiral multiplets [2] in which all four nucleon and Δ resonances with the same J are degenerate in mass. A new and expanding field - reviewed in [3, 4] - was created. In a recent paper, Shifman and Vainshtein pointed out [5] that in highly excited mesons, chiral symmetry seems not to be restored since some mass gaps in would-be chiral multiplets are of the same order of magnitude as mass gaps on Regge trajectories per unit of angular momentum.

The high theoretical interest in chiral multiplets is,

however, not balanced by reliable experimental information. In [4], seven chiral multiplets (with $J = 1/2$ to $J = 15/2$) are listed but none of them comprises four established states (with 3-star or 4-star rating in the Review of Particle Properties (RPP) [6]). From the 14 parity doublets only two consist of a pair of established resonances, one of them being questioned in [7]. Obviously, new studies are needed to explore the high-mass region of nucleon and Δ resonances.

This letter reports evidence for a parity doublet of Δ states with $J^P = 3/2^\pm$ at a mass of ≈ 1980 MeV from a study of the reaction

$$\gamma p \rightarrow p\pi^0\eta \quad (1)$$

for photon energies from the $p\pi^0\eta$ production threshold up to 3 GeV. RPP lists two $J = 3/2$ states in this mass range, the positive-parity $\Delta(1920)$ with 3 stars and the negative-parity $\Delta(1940)$. Neither of them was seen in [7].

Reaction (1) is very well suited to study decays of Δ resonances into $\Delta(1232)\eta$. The η acts as an isospin filter: resonances decaying into $\Delta(1232)\eta$ must have isospin $I = 3/2$ and belong to the Δ states. For low photon energies phase space is limited, and $\Delta(1232)$ and η should be in a relative S-wave. We thus may expect a high sensitivity for baryon resonances with isospin $I = 3/2$, spin $J = 3/2$ and negative parity. If such resonances decay into $N\pi$, they need $L = 2$ between N and π ; resonances with these quantum numbers are characterized by $L_{2I,2J} = D_{33}$.

$\Delta(1232)$ and η in a relative P-wave can be produced from the $L_{2I,2J} = P_{33}$ wave with isospin $I = 3/2$, spin $J = 3/2$ and positive parity.

The experiment was carried out at the tagged photon beam of the **EL**ectron **ST**retcher **AC**celerator **ELSA** at Bonn [8], using the Crystal Barrel detector [9]. A description of the experiment and data reconstruction can be found elsewhere [10, 11], a more detailed documentation of this analysis in [12]. The data cover photon energies from the $p\pi^0\eta$ production threshold to $3.0 \text{ GeV}/c^2$.

Events due to reaction (1) were selected by the following cuts: five clusters of energy deposits were required in the Crystal Barrel calorimeter, one proton and four photons. The proton was identified by matching one cluster to the charged particle emerging from the liquid H_2 target and hitting a three-layer scintillation fiber detector [13] surrounding the liquid H_2 target (length 5 cm, diameter 3 cm). The fast coincidence between a tagged photon and a hit in the scintillation fiber detector was used as first level trigger. A second level trigger required at least three clusters of energy deposits in the Crystal Barrel. This decision needed about $5 \mu\text{s}$.

These events were subjected to a kinematic fit imposing energy and momentum conservation. Proton and the four photons were assumed to be produced in the target center. In a first step, the $\gamma p \rightarrow p\pi^0\gamma\gamma$ hypothesis was tested and events with a probability (c.l.) exceeding 10% were retained. In a next step, events compatible, at a c.l. $>1\%$, with the $\gamma p \rightarrow p2\pi^0$ hypothesis were rejected. The resulting $\gamma\gamma$ invariant mass of the photon-pair is shown in Fig. 1. These events passed a final kinematic fit to the $\gamma p \rightarrow p\pi^0\eta$ hypothesis requiring a probability exceeding 1%. This sample contains 17469 events due to reaction (1) and 910 background events (shaded area in Fig. 1). The 910 events closest in phase space to the events falling into the η side bins ($380\text{--}440 \text{ MeV}/c^2$; $640\text{--}700 \text{ MeV}/c^2$) were subtracted to obtain the final event sample.

In Fig. 2a and b the total cross section is displayed. The errors include the statistical error and the system-

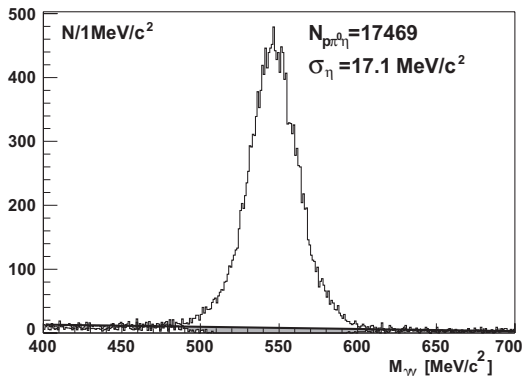


FIG. 1: The $\gamma\gamma$ invariant mass distribution after a kinematic fit to $\gamma p \rightarrow p\pi^0\gamma\gamma$ (with c.l. $> 10\%$) and a cut rejecting $\gamma p \rightarrow p\pi^0\pi^0$ events (with c.l. $> 1\%$).

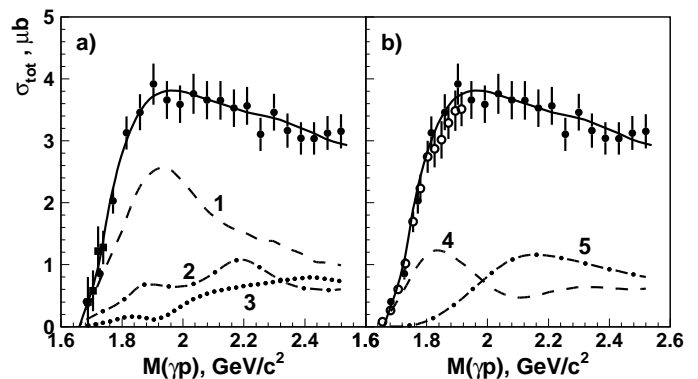


FIG. 2: Total cross sections for $\gamma p \rightarrow p\pi^0\eta$. \bullet this work; (left) black squares [14], (right) open circles [15]. The solid curve represents a PWA fit. (a): Excitation functions. (1) shows the contribution from the $\Delta(1232)\eta$ intermediate state, (2) the $N(1535)\pi$, and (3) the $N a_0(980)$ contribution. (b): Contributions of the D_{33} (4) and P_{33} (5) partial waves.

atic errors due to event reconstruction ($\approx 6\%$) and due to the acceptance correction ($\approx 5\%$) deduced from different solutions of the partial wave analysis (PWA) described below. A $\pm 15\%$ systematic error (not shown) is assigned to the uncertainty in the photon flux normalization. The solid curve shows the PWA result. The total cross section reaches a maximum of almost $4 \mu\text{b}$ in the $2 \text{ GeV}/c^2$ region and then decreases slowly to $3 \mu\text{b}$. Our cross section is compatible with results obtained at Sendai [14] (see Fig. 2a) and GRAAL [15] (see Fig. 2b).

A few leading contributions for the low- and high-mass range are visible in the Dalitz plots (Fig. 3). The low-mass data are dominated by the $\Delta(1232)\eta$ intermediate state and there is, in agreement with GRAAL, no visible $N(1535)\pi$ contribution. At large masses, $N(1535)$ can be seen in its $p\eta$ decay. The mass projection and the partial wave analysis reveal the existence of $p a_0(980)$ as third contribution.

Fig. 4 shows the $p\eta$ (a,d), $p\pi^0$ (b,e), and $\pi^0\eta$ (c,f) mass distributions for $W < 1.9 \text{ GeV}/c^2$ and $W > 2.1 \text{ GeV}/c^2$, respectively. In Figs. 4b,e large $\Delta(1232)$ contributions are observed. Fig. 4d reveals $N(1535)\pi$ with $N(1535)$ decaying into $N\eta$; in Fig. 4f, $p a_0(980)$ - with $a_0(980) \rightarrow \pi^0\eta$ - becomes visible. In the 1.9 to $2.1 \text{ GeV}/c^2$ mass region (not shown), $\Delta(1232)\eta$ is still significant, and a small $p\eta$ threshold enhancement due to $N(1535)\pi$ appears.

These findings are confirmed in a partial wave analysis (PWA). The P_{33} and D_{33} partial waves discussed here (and three further important partial waves S_{11} , P_{11} , and P_{13}) are described by K-matrices [16]. The corresponding elastic πN scattering amplitudes from [7] were added to the combined analysis for invariant masses up to $2.4 \text{ GeV}/c^2$ ($2.25 \text{ GeV}/c^2$ for P_{33}). Thus our results contain the full information leading to the results presented in [7]. The fit to the elastic amplitudes can be viewed in [12] (Fig. 8). However, our analysis is constrained by photo-production data.

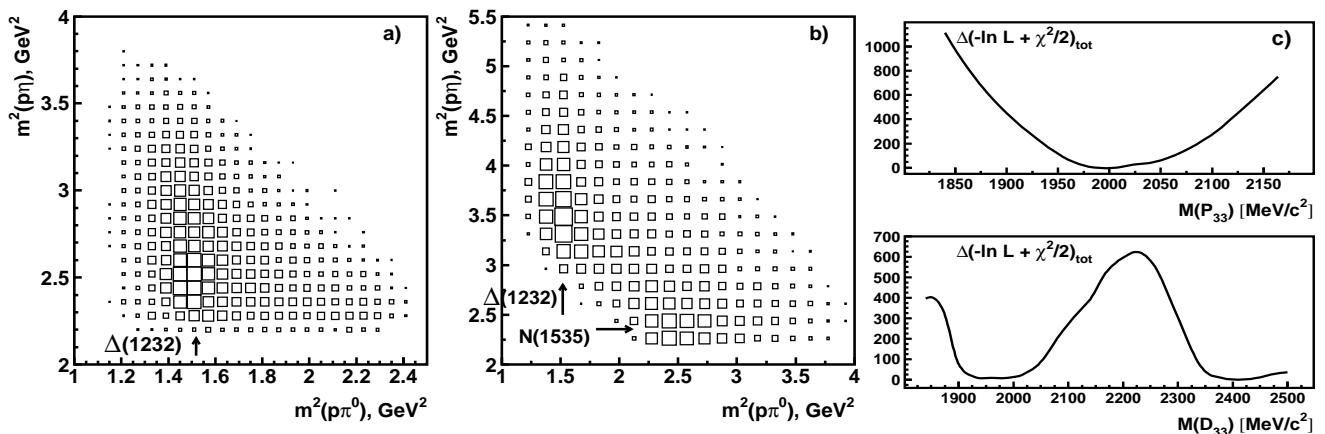


FIG. 3: Dalitz plot for the reaction $\gamma p \rightarrow p\pi^0\eta$ for $E_\gamma < 1.9$ GeV (a) and $E_\gamma > 1.9$ GeV (b). $\Delta(1232)$ is seen in both Dalitz plots; $N(1535)$ is visible only for high photon energies even though the $N(1535)\pi$ production threshold (~ 1.0 GeV) is lower than the $\Delta(1232)\eta$ production threshold (~ 1.2 GeV). c) Total likelihood as a function of the mass of a ΔP_{33} (top) or ΔD_{33} (bottom) resonance. The width is fixed to 350 MeV/ c^2 .

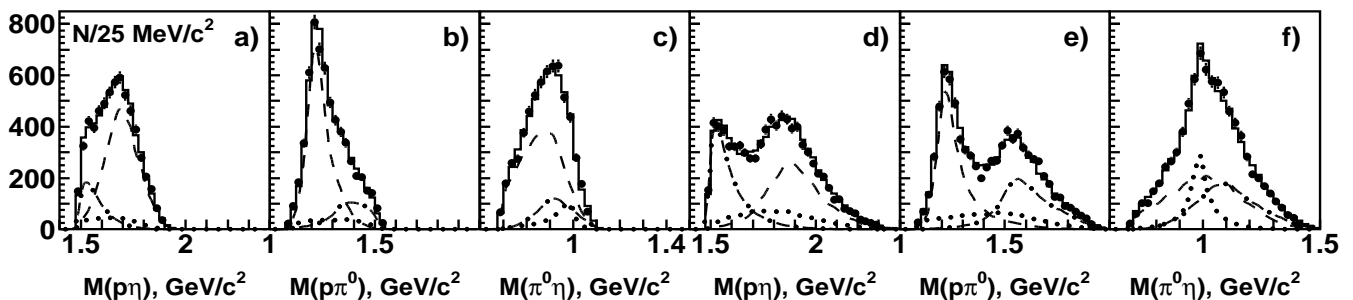


FIG. 4: Mass distributions for $E_\gamma < 1.9$ GeV (a-c) and $E_\gamma > 2.1$ GeV (d-f). The distributions are not corrected for the detector acceptance or undetected decay modes. The solid curves show the result of the partial wave analysis. The dashed lines represent the $\Delta(1232)\eta$ intermediate state, the dashed-dotted lines $N(1535)\pi$, the dotted lines $pa_0(980)$.

In addition to the data on $\gamma p \rightarrow p\pi^0\eta$ presented here, data on photoproduction of single pions, $2\pi^0$, η , and of Λ and Σ hyperons are included. References to the data, an outline of the PWA method and the definition of likelihood contributions can be found in [16]. Included here are new data on the beam asymmetry for $\gamma p \rightarrow p\pi^0\eta$ [17]. The different data enter with weights w_i . The weights range from $w = 1$ for high-statistics data which we want to be described approximately to $w = 30$ for low-statistics data which we insist to be described well by the fit. The mean weight is $\bar{w} = 4.2$. For this data and those from [17], $w_{\gamma p \rightarrow p\pi^0\eta} = 10$ is chosen. Too small a weight leads to a bad description of this data, a very large weight deteriorates the description of other data.

The data on reaction (1) presented here, and those on $\gamma p \rightarrow p\pi^0\pi^0$, are fit using an event-based maximum likelihood method taking into account all correlations between variables in the 5-dimensional phase space. Minimized is the weighted sum of the (negative) logarithmic likelihood from 3-body final states and the $\chi^2/2$ contribution from other data.

The excitation functions for $\Delta(1232)\eta$, $N(1535)\pi$, and $pa_0(980)$ deduced from the PWA, are shown in Fig. 2a.

$\Delta(1232)\eta$ makes the most significant contribution; close to the threshold, it dominates the reaction. It reaches a maximum just below 2 GeV/ c^2 . $N(1535)\pi$ exhibits a structure at 1.9 GeV/ c^2 due to the $N(1880)$ (with P_{11} quantum numbers, formerly called $N(1840)$ [18]) and $\Delta(1940)D_{33}$, and a second bump at 2.2 GeV/ c^2 which we interpret as nucleon resonance with P_{13} quantum numbers. With increasing mass, $pa_0(980)$ gains a notable intensity. In Fig. 2b, contributions of individual partial waves are shown. The D_{33} wave rises quickly above the threshold, mostly due to $\Delta(1940)D_{33}$. The P_{33} partial wave shows no significant features.

The fit requires contributions from eight resonances; two of them do not couple to $\Delta(1232)\eta$ and are assigned to nucleon excitations. Most pole positions agree with previously reported values. The $N(1880)$ is observed at $M - \frac{i}{2}\Gamma = 1880 - i110$ MeV/ c^2 . It decays to $N(1535)\pi$ and contributes $\sim 12\%$ to reaction (1). $N(2200)P_{13}$ decays mainly into $Na_0(980)$. These two resonances were already required in an analysis of $\gamma p \rightarrow N\pi$, ΛK^+ and ΣK^+ [18]. Here, they are found to contribute to $p\pi^0\eta$. However, due to limited statistics and without measurements of polarization variables covering the region above

TABLE I: Properties of the $\Delta(1920)P_{33}$ and $\Delta(1940)D_{33}$ resonances. Masses and widths are given in MeV/c^2 , branching ratios in %. The branching ratios are corrected using Clebsch-Gordan coefficients and for unseen decay modes of final-state mesons (π^0 and η). The helicity couplings are in $\text{GeV}^{-1/2}$.

	M_{pole}	Γ_{pole}	M_{BW}	Γ_{tot}^{BW}	$\text{Br}_{N\pi}$	$\text{Br}_{\Delta(1232)\eta}$	$\text{Br}_{N(1535)\pi}$	$\text{Br}_{N\alpha_0(980)}$	$A_{1/2}$	$A_{3/2}$
$\Delta(1920)P_{33}$	1980_{-45}^{+25}	350_{-55}^{+35}	1990 ± 35	375 ± 50	15 ± 8	10 ± 5	6 ± 4	4 ± 2	22 ± 8	42 ± 12
$\Delta(1940)D_{33}$	1985 ± 30	390 ± 50	1990 ± 40	410 ± 70	9 ± 4	5 ± 2	2 ± 1	2 ± 1	160 ± 40	110 ± 30

2 GeV/c^2 , quantum number assignments above 2 GeV/c^2 have to be taken with some precaution. $\Delta(1905)F_{35}$ contributes a small but significant fraction. It is observed with a pole at $1920 - i145 \text{ MeV}/c^2$. The other states belong to the P_{33} and D_{33} wave which are discussed next.

The P_{33} and D_{33} are described by K-matrices with 3-pole 6-channel (πN , $\Delta(1232)\pi$ (P, F -waves), $\Delta(1232)\eta$, $N(1535)\pi$, $N\rho$) K-matrix in the P_{33} wave and 2-pole 6-channel (πN , $\Delta(1232)\pi$ (S, D -waves), $\Delta(1232)\eta$, $N(1535)\pi$, $N\rho$) K-matrix in the D_{33} wave. The statistical evidence for the two suggested states (see Table I) was estimated by removing them individually from the fit. The masses, widths and branching ratios of the Breit-Wigner states given in Table I are calculated from the residues of the K-matrix poles (see [11] for details). They are determined from the range of values obtained in a large number of fits. The pole position of the second P_{33} state (above $\Delta(1232)$) is found at $1510_{-50}^{+20} - i115 \pm 20 \text{ MeV}/c^2$. $\Delta(1700)D_{33}$ is observed in decays to $\Delta(1232)\eta$ and $N(1535)\pi$ with a pole at $1650 - i160 \text{ MeV}/c^2$.

To this solution we added, one by one, Breit-Wigner amplitudes in different partial waves. The fit improves notably by adding a third D_{33} state; the statistical significance is 4 standard deviations for this data and more than 10σ for the overall fit. Its mass optimizes at about 2.36 GeV/c^2 and at a width in the 400-600 MeV/c^2 range. However, its mass is close to the end of the available phase space. An upper bound for its mass is not well defined and we do not claim that this state exists. With this state included, the D_{33} elastic scattering amplitude can be fitted up to 2.4 GeV/c^2 invariant mass. By adding resonances with other quantum numbers we did not find a significant improvement. In all waves the fit produced a resonance with mass at the end of phase space and a very broad width. The only exception was the D_{35} wave which optimized with $M \approx 2150 \text{ MeV}/c^2$, $\Gamma \approx 160 \text{ MeV}/c^2$, and a 1% fractional contribution. However the statistical evidence for this state was marginal, $\approx 2\sigma$. No evidence was found for $\gamma p \rightarrow N(1520)\eta$ or $\gamma p \rightarrow \Delta(1600)\eta$.

Finally, we performed mass scans for the P_{33} and D_{33} waves by replacing the highest-mass K-matrix pole in the solution above by a relativistic Breit-Wigner amplitude. Then the masses of the Breit-Wigner amplitudes were scanned in the region 1.85-2.4 GeV . The result of the mass scan is shown in Fig. 3c. In the P_{33} scan, the likelihood has a clear minimum around 1980-1990 MeV/c^2 ,

while the D_{33} scan reveals two minima at 1940-2000 and 2400 MeV/c^2 . The clear minima support our claim that both, $\Delta(1920)P_{33}$ and $\Delta(1940)D_{33}$, are observed in the reaction $\gamma p \rightarrow p\pi^0\eta$. Further details of the analysis can be found elsewhere [12].

Summarizing, we have reported evidence for a $J = 3/2$ parity doublet of Δ resonances at $\approx 1980 \text{ MeV}/c^2$ from $\gamma p \rightarrow p\pi^0\eta$. The parity doublet is compatible with the conjectured restoration of chiral symmetry at high baryon excitation energies. Parity doublets are not expected in quark models even though our findings are - within experimental errors - not incompatible with quark model predictions and certainly compatible with predictions based on QCD/AdS [22].

We would like to thank the technical staff of ELSA and of the participating institutions for their invaluable contributions to the success of the experiment. We acknowledge financial support from the Deutsche Forschungsgemeinschaft (DFG-TR16) and the Schweizerische Nationalfond. The collaboration with St. Petersburg received funds from DFG and RFBR.

-
- [1] L.Y. Glozman, Phys. Lett. B **475** (2000) 329.
 - [2] T.D. Cohen and L.Y. Glozman, PR D **65** (2002) 016006.
 - [3] R.L. Jaffe *et al.*, Phys. Rept. **435** (2006) 157.
 - [4] L.Y. Glozman, Phys. Rept. **444** (2007) 1.
 - [5] M. Shifman and A. Vainshtein, PR D **77** (2008) 034002.
 - [6] W.M. Yao *et al.*, J. Phys. G **33** (2006) 1.
 - [7] R.A. Arndt *et al.*, PR C **74** (2006) 045205.
 - [8] W. Hillert, Eur. Phys. J. A **28S1** (2006) 139.
 - [9] E. Aker *et al.*, Nucl. Instrum. Meth. A **321** (1992) 69.
 - [10] H. van Pee *et al.*, Eur. Phys. J. A **31** (2007) 61.
 - [11] U. Thoma *et al.*, Phys. Lett. B **659** (2008) 87.
 - [12] I. Horn *et al.*, "Study of the reaction $\gamma p \rightarrow p\pi^0\eta$ ", in preparation".
 - [13] G. Suft *et al.*, Nucl. Instrum. Meth. A **538** (2005) 416.
 - [14] T. Nakabayashi *et al.*, PR C **74** (2006) 035202.
 - [15] J. Ajaka *et al.*, PRL **100** (2008) 052003.
 - [16] A. V. Anisovich *et al.*, Eur. Phys. J. A **34** (2007) 243.
 - [17] E. Gutz *et al.*, Eur. Phys. J. A **35**, 291 (2008).
 - [18] A.V. Sarantsev *et al.*, Eur. Phys. J. A **25** (2005) 441.
 - [19] R.E. Cutkosky *et al.*, "Pion - Nucleon Partial Wave Analysis," 4th Int. Conf. on Baryon Resonances, Toronto, Canada, July 14-16, 1980. QCD161:C45:1980.
 - [20] D.M. Chew, in: [19].
 - [21] D.M. Manley, E.M. Saleski, PR D **45** (1992) 4002.
 - [22] E. Klempt, " Δ resonances, quark models, chiral symmetry and AdS/QCD", in preparation.