Vol. 39 (2008) ACTA PHYSICA POLONICA B No 8

EVIDENCE FOR A NARROW $N^*(1685)$ RESONANCE IN η PHOTOPRODUCTION OFF THE NUCLEON

V. Kuznetsov[a,b], M.V. Polyakov[c,d], T. Boiko[e], J. Jang[a], A. Kim[a] W. Kim[a,f], H.S. Lee[a], A. Ni[a], G.-S. Yang[c]

[a] Kyungpook National University, 702-701, Daegu, Republic of Korea
[b]Institute for Nuclear Research, 117312, Moscow, Russia
[c]Institute für Theoretische Physik II, Ruhr-Universität Bochum 44780 Bochum, Germany
[d]Petersburg Institute for Nuclear Physics Gatchina, 188300, St. Petersburg, Russia
[e]Belarussian State University, 220030, Minsk, Republic of Belarus
[f]Daegu Center, Korea Basic Science Institute, Daegu, 702-701 Republic of Korea

(Received June 23, 2008)

Revised analysis of Σ beam asymmetry for η photoproduction off the free proton from GRAAL is presented. New analysis reveals a narrow structure near $W \sim 1.685$ GeV. We describe this structure by the contribution of a narrow resonance with quantum numbers P_{11}, or P_{13}, or D_{13}. Being considered together with the recent observations of a bump-like structure at $W \sim 1.68$ GeV in the quasi-free η photoproduction off the neutron, this result provides an evidence for a narrow ($\Gamma \leq 25$ MeV) $N^*(1685)$ resonance. Properties of this possible new nucleon state, namely the mass, the narrow width, and the much stronger photocoupling to the neutron, are similar to those predicted for the non-strange member of anti-decuplet of exotic baryons.

PACS numbers: 13.60.Le, 14.20.Gk

1. Introduction

η photoproduction off the nucleon is a unique tool to explore nucleon states with isospin 1/2. Experimental studies of η photoproduction off the proton [1–4] resulted in rich information about low-lying nucleon excitations. Experiments on η photoproduction off the quasi-free neutron (bound in ^{2}H, ^{3}He, and ^{4}He) until recently were limited to low photon energies $E_\gamma \leq$ 820 MeV [5–9]. They made it possible to determine the isospin structure of the $S_{11}(1535)$ resonance [10]. At higher energies the rapid rise of the neutron to proton cross section ratio near $E_\gamma \approx 1$ GeV was observed at GRAAL [11].

Further measurements at this facility [12, 13] revealed an interesting phenomenon, a bump-like structure in the neutron cross section (Fig. 1) near $E_\gamma \sim 1.03$ GeV (the invariant energy $W \sim 1.68$ GeV). This observation has been recently confirmed by two other groups: CBELSA/TAPS [14] and

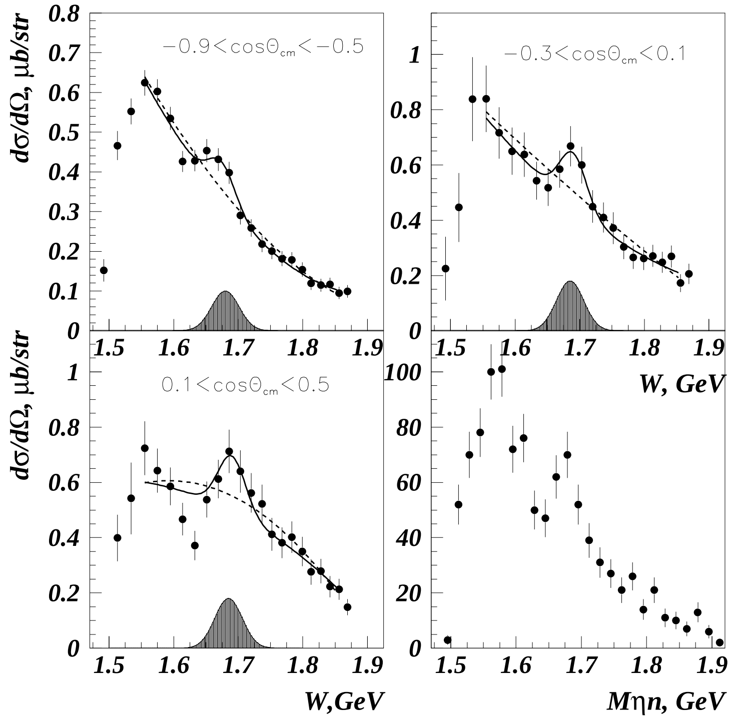

Fig. 1. Quasi-free cross sections and ηn invariant mass spectrum (low right panel) for the $\gamma n \to \eta n$ reaction (data from [13]). Solid lines are the fit by the sum of 3-order polynomial and narrow state. Dashed lines are the fit by 3-order polynomial only. Dark areas show the simulated signal of a narrow state.

LNS-Sendai [15]. All three experiments found a bump in the quasi-free cross section off the neutron[1]. The width of the bump is close to that expected for a signal of a narrow resonance smeared by Fermi motion of the target neutron. In addition, the GRAAL and CBELSA/TAPS groups observed a narrow peak in the ηn invariant mass spectrum at 1680–1685 MeV. The positions of the peaks are $\sim$ 1680 MeV at GRAAL data (low right panel of Fig. 1) and $\sim$ 1683 MeV at CBELSA/TAPS (Fig. 2). The widths of the

[1] Let us call it as the "neutron anomaly" because the quasi-free cross section is affected strongly by the Fermi motion and by rescattering/final-state interaction. This observable is more difficult for a theoretical analysis than the cross section off the free nucleon.

peaks (40 MeV in the GRAAL data and 60 ± 20 MeV in the CBELSA/TAPS data) are close to the instrumental resolutions. Such strong peak structure was not observed in the η photoproduction off the proton [1].

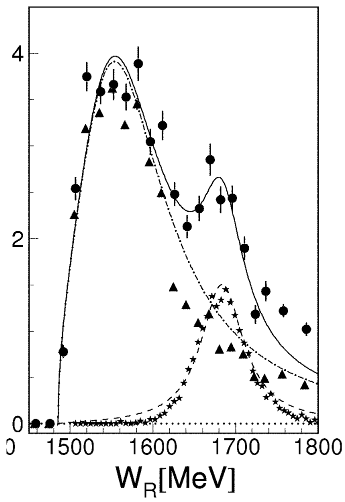

Fig. 2. $M(\eta n)$ spectrum from CBELSA/TAPS [14] (filled circle) in comparison with $M(\eta p)$ spectrum (filled triangles). Stars show the simulated signal of a narrow state with zero width.

The anomalous behaviour of the quasi-free neutron cross section and the narrow peak the ηn invariant mass spectrum calls for a theoretical explanation. A partial-wave analysis of the quasi-free neutron cross section is rather complicated because the target neutron is bound in the deuteron. That is why the search for this narrow structure (possibly strongly suppressed) in the η photoproduction off the free proton is important. In the present paper we revise the GRAAL data on Σ beam asymmetry for η photoproduction off the free proton. Our goal is to look for peculiarities near $W \sim 1.68$ GeV in the dependence of the beam asymmetry on the photon energy.

A simple and concise explanation of the "neutron anomaly" and the peak in the ηn invariant mass is the existence of a narrow nucleon resonance with much stronger photocoupling to the neutron than to the proton. Actually, such option was suggested prior the observation of the "neutron anomaly" [23, 26, 27]. Therefore, before the discussion of experimental data, in Section 2 we provide details on logic and history of this prediction. Then, in Section 3, we discuss the current state-of-art in η photoproduction off neutron. In Section 4 we present the revised analysis of the free-proton Σ beam asymmetry for the η photoproduction from GRAAL. In Section 5 our main results and concluisons are summarized.

2. On predictions of non-strange pentaquark

If the exotic $S = +1$ pentaquark Θ^+ would exist, this would imply the existence of a new-type (beyond octet, decuplet and singlet) flavour multiplet of baryons. The simplest possibility that is realized in the Chiral Quark Soliton model (χQSM) [16], is the anti-decuplet of baryons. The anti-decuplet contains ten baryons. Three of them are explicitly exotic (*i.e.* their quantum numbers can not be build out of three quarks only). The other seven baryons have non-exotic quantum numbers. The non-strange members of the anti-decuplet are two nucleon states (two isospin partners): the neutral state (n^*) and the positively charge one (p^*). In the χQSM the spin-parity quantum numbers of the anti-decuplet members are unambiguously predicted to be $J^P = \frac{1}{2}^+$ [16], so that the N^* from the anti-decuplet was predicted to be a P_{11} nucleon resonance. The idea of the authors of Ref. [16] was to identify the N^* from anti-decuplet with the known $P_{11}(1710)$ resonance. The choice has been made because of the following reasons:

- Dynamical calculations in the χQSM gave the mass of N^* in the range of $1650 \div 1750$ MeV.
- At the time Particle Data Group [17] reported the partial decay branchings of $P_{11}(1710)$ consistent with the pattern predicted for the decays of anti-decuplet: strong coupling to $\eta N, K\Lambda$ and $\pi\Delta$ channels with suppression of πN decay mode.
- In 1997 the total width of P_{11} was very uncertain and could accommodate the narrow width of ≤ 40 MeV predicted by Ref. [16] for the N^* from anti-decuplet.

The last point concerns the total width. It was not easy for the authors of Ref. [16] to adopt that so small width of ≤ 40 MeV was barely compatible with the data. The authors thought about existence of a new nucleon resonance in this mass region, therefore they quoted the result of the Zagreb group:

> However, it should be mentioned that a recent analysis [18] suggests that there might be two nucleon resonances in the region of ~ 1700 MeV: one coupled stronger to pions and another to the η meson.

On other hand, at that time it was hard to believe that intensive studies of baryon spectroscopy for many years could miss a relatively light and narrow $\Gamma \leq 40$ MeV nucleon resonance.

First reports [20, 21] on the observation of the exotic Θ^+ pentaquark (begining of 2003) with the mass close to predicted in χQSM [16, 22] posed new questions about the non-strange member of the anti-decuplet. It was suggested in Ref. [23] that photoproduction of mesons off the neutron can be used as a benchmark to reveal the anti-decuplet nature of a nucleon resonance. The transition $\gamma p \to p^*$ of the N^* from the anti-decuplet should be strongly suppressed relatively the to the $\gamma n \to n^*$. This suppression is proportional to $\mathrm{SU_{fl}}(3)$ symmetry breaking and can be as large as 1/10 in scattering amplitudes. The same paper [23] suggested to probe the anti-decuplet nature of a nucleon resonance by using $\gamma n \to \eta n$ and $\gamma n \to K\Lambda$ reactions. Predictions of Ref. [23] stimulated one of us (V. K.) to push forward the study the η photoproduction off the neutron at GRAAL. In 2004 these efforts had led to the observation of the "neutron anomaly" [12]. This finding was firstly taken skeptically by a part of the (former) GRAAL Collaboration (see, for example, [24]). Nevertheless, after numerous checks, the result has been published [13]. Now it is confirmed by the CBELSA/TAPS [14] and LNS-Sendai [15] collaborations. The discussion on the "neutron anomaly" is given in the next section.

By autumn of 2003 reports on the observation of the exotic Θ^+ baryon were piling up. At that time it had became clear that if Θ^+ exists, it is very narrow. Most of these evaluations were obtained from the re-analysis of KN scattering data [25]. Here we skip the discussion of details. An important point is that the tentative Θ^+ should be very narrow, having the width in the (sub)MeV range. Obviously, so small Γ_{Θ^+} is in contrast with the width $\sim$ 100 MeV ascribed [19] to the $P_{11}(1710)$ resonance. Consequently the existence of a new nucleon resonance with the mass near $\sim$ 1700 MeV was suggested in Refs. [26, 27]. The authors of Ref. [26] used the Gell-Mann–Okubo mass relations in the presence of mixing, in order to predict the mass of this new nucleon resonance. As an input for the Gell-Mann–Okubo mass formula the authors of Ref. [26] used the mass of the reported by the NA49 collaboration [28] Ξ^{--} baryon. In Ref. [27], in order to constrain the mass of this possible new narrow N^*, the modified PWA of πN scattering data was employed. It was found that the easiest way to accommodate a narrow N^* is to set its mass around 1680 MeV and quantum numbers to P_{11} ($J^P = \frac{1}{2}^+$). In the same paper the width of the possible N^* was analysed in the framework of χQSM. It was found that the width of new N^* is in range of tens of MeV[2] (most probably below 30 MeV if one combines the model analysis with modified PWA). Extensive studies of the decay widths of anti-decuplet baryons in the framework of χQSM were performed in Refs. [29–31]. It was shown that the $\mathrm{SU_{fl}}(3)$ symmetry breaking effects contribute considerably to the partial widths of the non-strange member of the anti-decuplet. In particular, they suppress the partial decay $N^* \to \pi N$

[2] The analysis is rather uncertain due to large uncertainty in the mixing angle of N^* with ground state nucleon.

whereas provide a small contribution to the ηN and $K\Lambda$ decay modes. The phenomenological analysis of baryon spectrum in the framework of broken flavour $\mathrm{SU_{fl}}(3)$ of Refs. [32] suggests that the width of non-strange member of the anti-decuplet is below of 50 MeV.

Recent different χQCM calculations [33–35] of the anti-decuplet widths have shown that the width of Θ^+ is in (sub)MeV region and the width of the non-strange partner N^* is in the range 15–20 MeV. Detailed discussion of the narrow widths of pentaquarks in the χQSM is available in Ref. [36].

3. η Photoproduction off the neutron

The study of the quasi-free $\gamma n \to \eta n$ reaction at GRAAL [12,13] (Fig. 1), CBELSA/TAPS [14] (Fig. 2), and LNS-Tohoku [15] facilities provided an evidence for a relatively narrow structure at invariant energy $W \sim 1.68$ GeV. The structure has been observed as a bump in the quasi-free cross section and in the ηn invariant mass spectrum. The width of the bump in the quasi-free cross section was found to be close to that expected due to smearing by Fermi motion of the target neutron bound in the deuteron. A narrow resonance, which would manifest as a peak in the cross section off the free neutron, would appear in the quasi-free cross section as a bump of about 50 MeV width [13] (Fig. 1). The simulated signal of such resonance (folded with momentum distribution of bound neutron) with the mass $M \sim 1.68$ GeV and the width $\Gamma = 10$ MeV is shown in Fig. 1. The cross section is well fitted by the sum of a background and the contribution of this resonance.

The ηn invariant mass is almost unaffected by Fermi motion. The narrow peak in the ηn invariant spectrum mass cannot originate from rescattering effects. The widths of the peaks in the $M(\eta n)$ spectra (40 MeV at GRAAL [13] and 60 MeV at CBELSA/TAPS [14]) are nearly equal to the instrumental resolutions.

Such bump is not seen in η photoproduction off the proton. The cross section off the proton exhibits only a minor peculiarity in this mass region [1]. Therefore the bump in η photoproduction off the neutron may signal a nucleon resonance with unusual properties: the mass $M \sim 1.68$ GeV, the narrow width, and the much stronger photocoupling to the neutron than to the proton.

On the base of the data from Refs. [12,13], the photocoupling of the tentative N^* was estimated in Ref. [50] as $\sqrt{\mathrm{Br}_{\eta N}}A^n_{1/2} \sim 15\times10^{-3}\ 1/\sqrt{\mathrm{GeV}}$ [3]. This value is in good agreement with χQCM calculations [49]. The influence of a narrow resonance on various observables was investigated in Ref. [37]. It was shown that the inclusion of a narrow resonance could describe the

[3] Possible theoretical errors of this analysis are up to a factor of two.

experimental data. However, important effects of Fermi motion of the target neutron were ignored in this publication. The inclusion of such resonance into the Reggeized version of an isobar model for η photoproduction η-MAID [38] generates a narrow peak in the cross section off the free neutron. This peak is transformed into a wider bump similar to experimental observation, if the Fermi motion is taken into account [39].

The standard η-Maid isobar model [42] provides an enhancement in the neutron cross section over the proton one for $E_\gamma \geq 1$ GeV due to the contribution of $D_{15}(1675)$ resonance. This resonance has stronger coupling to the neutron than to proton. However it is ~ 150 MeV wide. The contribution of the $D_{15}(1675)$ cannot explain the narrow bump in the ηn invariant mass spectrum. Moreover, the standard η-Maid [42] isobar model uses the branching ratio for the decay $D_{15}(1675) \to \eta N$ of 0.17. This value is in the sharp contrast with the PDG value of $\mathrm{Br}_{\eta N} = 0.00 \pm 0.01$. Also so large branching ratio contradicts the $\mathrm{SU_{fl}}(3)$ analysis of the baryon decays in Ref. [32] which limits this branching to the range 0.02–0.03.

Alternative explanations of the "neutron anomaly" was suggested in Ref. [40,41]. The authors demonstrated that the bump in the $\gamma n \to \eta n$ cross section could be explained in terms of photoexcitation and interference of the known $S_{11}(1650)$ and $P_{11}(1710)$ (or $S_{11}(1535)$ and $S_{11}(1650)$) resonances. However, the authors did not discuss how to explain the narrow bump in ηn mass spectrum in the GRAAL [13] and the CBELSA/TAPS [14] data. Anyway, the generation of a narrow bump in the $\gamma n \to \eta n$ cross section due to the interference of known resonances requires a fine tuning of the neutron photocouplings of these resonances, without changing the proton ones. This implies that the models [40, 41] predict no narrow structure in observables in the proton channel. On contrary, the narrow N^* would produce a narrow structure in observables off the proton, even if its photoexcitation off the proton is suppressed due to the $\mathrm{SU_{fl}}(3)$ symmetry breaking effects. This is a benchmark test for these models.

Any decisive conclusion about the nature of the anomalous behavior of the neutron cross section requires a complete partial-wave analysis. This procedure is sophisticated: model calculations are usually performed for the free neutron while measured quasi-free observables are smeared by Fermi motion. The significant influence of Fermi motion on differential cross sections is shown in Ref. [39]. Moreover, the quasi-free cross section is distorted by re-scattering and final-state interaction (FSI). Those events which originate from re-scattering and FSI, are in part eliminated in data analysis. Accordingly the measured quasi-free cross section might be smaller than the calculated cross section off the free neutron smeared by Fermi motion.

In this sense free-proton data are much more attractive. If photoexcitation of a nucleon resonance occurs on the neutron its isospin partner should be produced in the proton channel as well. However a strong suppression in the proton channel is possible. For example, the exact $\mathrm{SU_{fl}}(3)$ would forbid the photoexcitation of the non-strange pentaquark from the anti-decuplet off the proton. Accounting for the $\mathrm{SU_{fl}}(3)$ violation leads to the cross section of its photoproduction off the proton 10–50 times smaller (but not 0) than that off the neutron [23, 49].

4. η Photoproduction off free proton

η photoproduction off the proton below $W \sim 1.7$ GeV is dominated by photoexcitation of the $S_{11}(1535)$ resonance. This resonance contributes to the E_0^+ multipole only. $|E_0^+|^2$ is the major component of the cross section

$$\sigma \sim |E_0^+|^2 + \text{interference terms} \tag{1}$$

while other multipoles contribute through the interference with E_0^+ or between themselves. A narrow weakly-photoexcited state with the mass below 1.7 GeV would appear in the cross section as a small peak/dip structure on the slope of the dominating $S_{11}(1535)$ resonance. In experiment this structure would be in addition smeared by the resolution of a tagging system (for example, the resolution of the tagging system at GRAAL is 16 MeV FWHM), and might be masked due to inappropriate binning.

Polarization observable — the polarized photon beam asymmetry Σ is much less affected by the $S_{11}(1535)$ resonance. This observable is the measure of azimuthal anisotropy of a reaction yield relatively the linear polarization of the incoming photon. In terms of $L \leq 1$ multipoles the expression for the beam asymmetry does not include the multipole E_0^+:

$$\begin{aligned}\Sigma(\theta) \;\sim\; & \frac{3\sin^2\theta}{2}\mathrm{Re}\,(-3|E_1^+|^2 + |M_1^+|^2 \\ & -2M_1^{-*}(E_1^+ - M_1^+) + 2E_1^{+*}M_1^+)\,. \end{aligned} \tag{2}$$

This observable is mostly governed by the multipoles others than E_0^+ and therefore is much more sensitive to signals of non-dominant resonances than the cross section. The possible weak signal of N^* could be amplified in beam-asymmetry data due to the interference between multipoles.

For η photoproduction off the proton the beam asymmetry Σ was measured at the GRAAL facility[4]. First results [2] covered the energy range from threshold to 1.05 GeV. Two statistically-independent and consistent sets of data points were reported (Fig. 3). These data sets were produced using two different samples of events:

[4] General description of the GRAAL facility is available in [43].

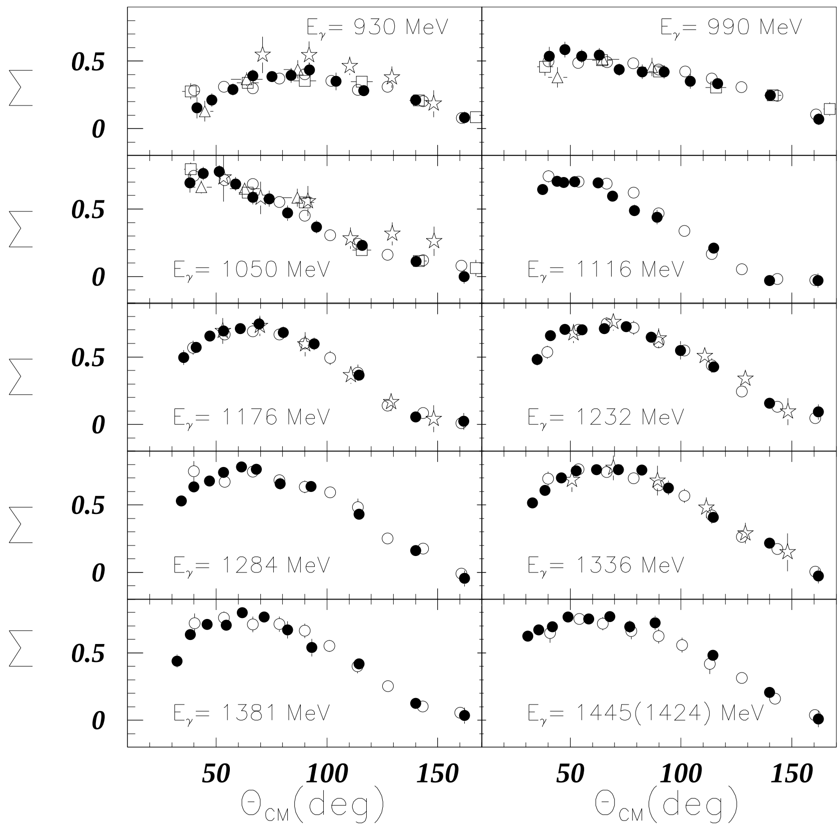

Fig. 3. Published data for Σ beam asymmetry for η photoproduction off the free proton. Open triangles and squares are from [2]: squares correspond to the detection of two photons from $\eta \to 2\gamma$ decays in the BGO ball; triangles are obtained detecting one photon in the forward shower wall and the second in the BGO ball. Black circles are the data from [3]. Open circles are from [48]. Stars are the results from [4].

(i) Events in which two photons from $\eta \to 2\gamma$ decays were detected in the BGO Ball [44].

(ii) Events in which one of the photons emitted at the angles $\theta_{\rm lab} \leq 25^\circ$ was detected in the forward shower wall [45], and the other in the BGO ball.

Second type of events was found to be particularly efficient at forward angles and energies above 0.9 GeV. The contamination of such events at the angles below 50° reaches 80%. The results shown a marked peaking at forward angles and $E_\gamma \sim 1.05$ GeV (see Fig. 3).

An extension to higher energies up to 1.5 GeV was reported in [3]. Two samples of events were merged and analyzed together. This made it possible to reduce significantly error bars at forward angles and to retrieve a maximum in the angular dependence at 50° and $E_\gamma \sim 1.05$ GeV (Fig. 3)

A new measurement was done at CBELSA/TAPS [4] using the different technique of the photon-beam polarization, the coherent bremsstrahlung from a diamond radiator. The results are in a good agreement with [2, 3] but exhibit slightly larger error bars (see Fig. 3).

Very recently a new data obtained at the GRAAL facility, was published in Ref. [48]. The data set is based on the full statistics collected at GRAAL. The results are quite similar to those presented in Ref. [3] (Fig. 3), but, despite the triple increase of statistics, are less accurate at forward angles. The reason is that the described above second type of events was excluded from the data analysis without any explanation of the motivation.

In the previous publications [2–4] the main focus was done on the angular dependencies of the beam asymmetry. Data points were produced using relatively narrow angular bins but nearly 60 MeV wide energy bins. Such wide energy bins do not allow to reveal any narrow peculiarities in the energy dependence of the beam asymmetry.

An ultimate goal of this work is to produce beam asymmetry data using narrow bins in energy, in order to reveal in detail the dependence of the beam asymmetry on the photon energy in the region of $E_\gamma = 0.85$–1.15 GeV (or $W = 1.55$–1.75 GeV) and to search for a signal of a narrow resonance.

In this paper we present the revised analysis of data collected at the GRAAL facility in 1998–1999. Only two experimental runs are used in the analysis, in order to avoid additional (up to ± 8 MeV) uncertainties in the determination of the photon energy due to the different adjustments and calibrations of the GRAAL tagging system in the different run periods.

The data collection was carried out as a sequence of alternate measurements with two orthogonal linear polarization states of a photon beam produced through the backscattering of laser light off 6.04 GeV electrons circulating in the storage ring of European Synchrotron Radiation Facility. The degree of polarization was dependent on photon energy and varied from 0.5 to 0.85 in the energy range of $E_\gamma = 0.85$–1.15 GeV.

The procedure of selection of events is similar to that used in [2, 3]. Two types of events described above are considered. The first type of events is identified by means of the invariant mass of two photons from $\eta \to 2\gamma$ detected in the BGO ball. The momentum of the η meson is reconstructed from photon energies and angles. The measured parameters of the recoil proton are compared with ones calculated using kinematics constrains. Those events in which one of the photons is detected in the forward shower wall [45], are analyzed in a different way: the initial selection is done using the missing mass calculated from the energy of the incoming photon and the measured momentum of the recoil proton.

After that a kinematical fit is applied for both types of events. The center-of-mass angles of η and the ϕ-angles of the reaction plane are determined by a χ^2 minimization procedure comparing the calculated energies and angles in the laboratory system with the measured ones and their estimated errors. This procedure provides the most accurate determination the reaction θ and ϕ angles and allows to reduce the influence of the detector granularity. For the second type of events, it also allows the determination the energy of the photon detected in the forward wall. After that the events are selected using kinematics constraints and the value of χ^2. At the final stage both samples of events are merged and used together to extract beam asymmetries.

The results are shown in Fig. 4 by filled circles. They are consistent with the previous data from Ref. [3]. New data points are obtained using narrow energy bins $\Delta E_\gamma \sim 16$ MeV. Angular bins are chosen to be rather

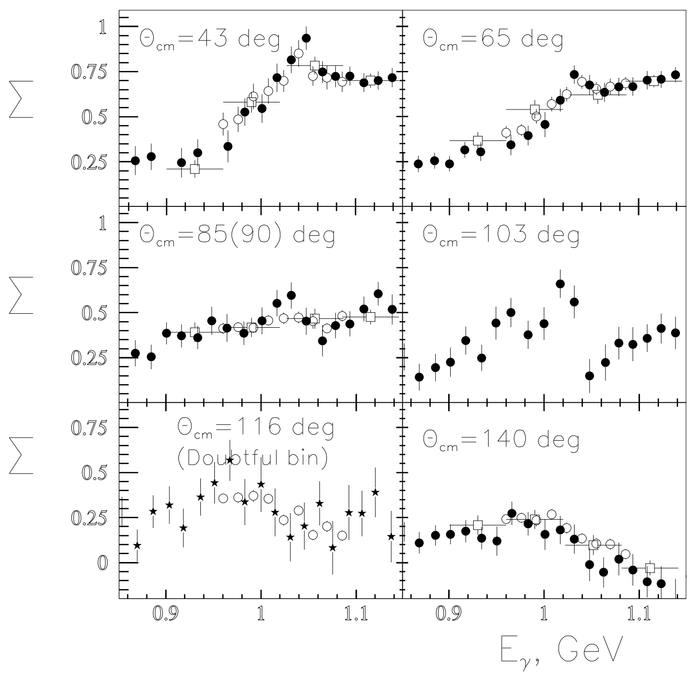

Fig. 4. Beam asymmetry Σ for the η photoproduction off the free proton obtained here with narrow energy bins (black circles). Open squares are previous data from Ref. [3]. Open circles are the data from Ref. [48]. Stars are our results at 116° obtained using the same angular binning as in Ref. [48].

wide, about 20°–40°, to gain statistics and hence reduce error bars. At forward angles $\theta_{cm} = 43°$ and $E_\gamma = 1.04$ GeV data points form a sharp peak with the asymmetry in its maximum reaching values as large as 0.94. The peak becomes less pronounced but clear at 65°. It is replaced by an oscillating structure at 85° and at 105°. At more backward angles the values of asymmetry above 1.05 GeV drop down almost to 0 (Fig. 3) while statistical errors grow up. The peak at forward angles and the oscillating structure at central angles altogether form an interference pattern which may signal a narrow nucleon resonance.

It is worth to noting that the authors of Ref. [48] found "...no evidence for a narrow $P_{11}(1670)$ state ..." in the beam asymmetry data. In Fig. 4 our data and the data from Ref. [48] are plotted together. Both data sets are consistent. Furthermore, at forward angles (43°) the data sets are nearly statistically independent. As it was explained above, our results at forward angles are dominated by the events in which one of the photons from the $\eta \to 2\gamma$ decay is detected in the forward wall. Such events are not used in Ref. [48]. Their results are based on only events in which both photons are detected in the BGO ball. Nevertheless both data sets exhibit a sharp peak-like structure. The major difference is that we observe the oscillating structure at 103°. The authors of Ref. [48] show the data at 116° where they do not observe any structure. However no reliable data can be produced in this (116°) angular bin. At the photon energy 1.05 GeV recoil protons are emitted into a gap between the forward and the central part of the GRAAL detector where they cannot be properly detected. The statistics for this particular angular bin drops considerably due to the low acceptance of the detector. This drop of statistics is clearly reflected in our large error bars for the 116° angular bin (see low left panel of Fig. 4). It is surprising that the authors of Ref. [48] have been able to obtain so small errors in this bin. It would be helpful if the authors of Ref. [48] would present their results at the angles near 100° as well.

To examine the assumption of a narrow resonance, we employ the multipoles of the recent E429 solution of the SAID partial-wave analysis [46] for η photoproduction as the model for the smooth part of the observables. In general, the SAID solution provides good description of the data. However in the narrow photon-energy interval $E_\gamma = 1.015$–1.095 it considerably deviates from the new data (Fig. 5. The χ^2 value for 24 points in this energy interval at 43°, 65°, 85°, and 103° for the SAID solution is $\chi^2/\mathrm{dof} = 74/24$.

To model this deviation, we add a narrow resonance (either S_{11}, or P_{11}, or P_{13}, or D_{13}) in the Breit–Wigner form (see *e.g.* [42]) to the SAID multipoles. The contribution of this resonance is parametrized by the mass, width, photocouplings (multiplied by square of ηN branching), and the phase. These parameters are varied, in order to achieve the best reproduction of experimental data, whereas the SAID multipoles are kept fixed. We consider the SAID multipoles as a good approximation for the non-resonant and/or wide resonances contributions. The narrow S_{11}, P_{11}, P_{13}, and D_{13} resonances are tried one by one. The difference between calculated and experimental values of the asymmetry Σ in the region of the peak/dip structure (6 points in the energy interval $E_\gamma = 1.015$–1.095 in the angular bins of 43°, 65°, 85°, and 103°) is used as a criterion for the minimization.

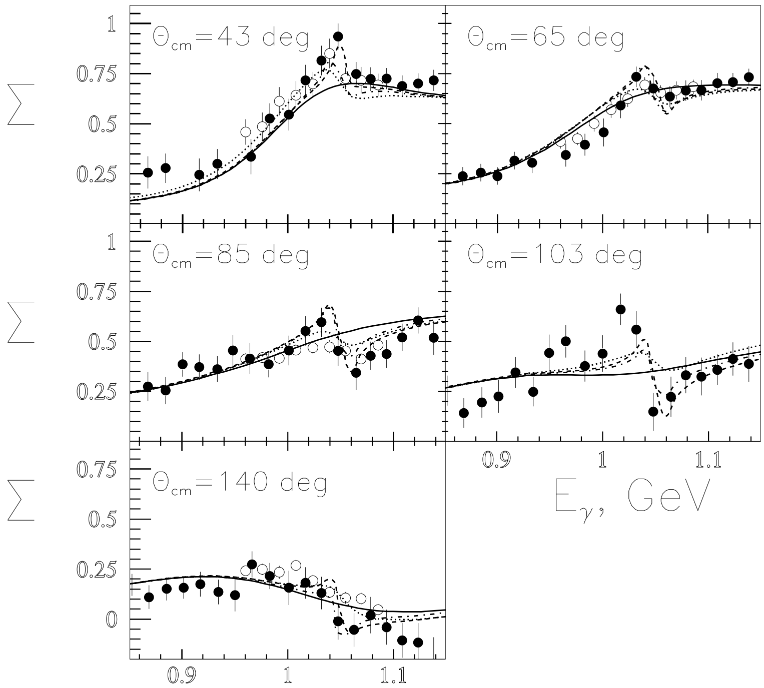

Fig. 5. Fit of experimental data (filled circles data obtained in present analysis, open squares results of Ref. [3]). Solid lines show our calculations based on the SAID multipoles only, dotted lines include the P_{11} resonance with the width $\Gamma =$ 19 MeV; dashed lines are calculations with the P_{13} ($\Gamma = 8$ MeV), while the dash-dotted lines use the resonance D_{13}, also with $\Gamma = 8$ MeV. Open circles are the data from Ref. [48].

The curves corresponding to the SAID multipoles only are smooth and do not exhibit any structure (Fig. 5). The inclusion of either P_{11} or P_{13} or D_{13} resonances improves the agreement between the data and the calculations and allows to reproduce the peak/dip structure. The corresponding values of χ^2 is changed from $\chi^2/\mathrm{dof} = 74/24$ for the original SAID multipoles to $\chi^2/\mathrm{dof} = 56/22$ for the SAID and P_{11}, $\chi^2/\mathrm{dof} = 25/20$ for the SAID and P_{13}, and $\chi^2/\mathrm{dof} = 39/20$ for the SAID and D_{13} resonances.

The mass of the included resonance is strongly constrained by the data points. Its values belong to the range of $M_{\rm R} = 1.685$–1.690 GeV. The best fit is obtained with the mass $M_{\rm R} = 1.688$ GeV. However, the extracted mass value includes the uncertainty of ± 5 MeV which originates from the quality of the calibration of the GRAAL tagging system, and the uncertainy of about ± 4 MeV due to the energy binning. Also it may depend on the basic multipoles used in the fit (in our case SAID multipoles). That is why at present we quote only the approximate mass value $M \sim 1.685$ GeV. The best fit is obtained with the width of $\Gamma \sim 8$ MeV for P_{13} and D_{13}, and $\Gamma \sim 19$ MeV for P_{11}. However, the reasonable reproduction of the data is achieved up to $\Gamma \leq 25$ MeV.

The S_{11} resonance generates a dip at 43° in the entire range of variation of its photocoupling and phase. Its inclusion does not lead to the improvement of the χ^2. This indicates that the observed structure most probably cannot be attributed to S_{11}.

The curves shown in Fig. 5, corresponds to

$$\sqrt{\mathrm{Br}_{\eta N}} A^p_{1/2} \sim 1 \times 10^{-3} \sqrt{\mathrm{GeV}}\,, \tag{3}$$

for the P_{11} resonance.

$$\sqrt{\mathrm{Br}_{\eta N}} A^p_{1/2} \sim -0.3 \times 10^{-3} \sqrt{\mathrm{GeV}}\,, \tag{4}$$

$$\sqrt{\mathrm{Br}_{\eta N}} A^p_{3/2} \sim 1.7 \times 10^{-3} \sqrt{\mathrm{GeV}}\,, \tag{5}$$

for the P_{13} quantum numbers of the resonance. Eventually we obtain

$$\sqrt{\mathrm{Br}_{\eta N}} A^p_{1/2} \sim -0.1 \times 10^{-3} \sqrt{\mathrm{GeV}}\,, \tag{6}$$

$$\sqrt{\mathrm{Br}_{\eta N}} A^p_{3/2} \sim 0.9 \times 10^{-3} \sqrt{\mathrm{GeV}}\,, \tag{7}$$

for the D_{13} resonance.

The obtained value of $\sqrt{\mathrm{Br}_{\eta N}} A^p_{1/2}$ for the narrow P_{11} resonance is in good agreement with estimates for the non-strange pentaquark from the antidecuplet performed in Chiral Quark–Soliton Model [23, 49]. Comparing the value with the analogous quantity for the neutron extracted in the phenomenological analysis of the GRAAL and CBELSA/TAPS data [39,50], we obtain the ratio

$$A^n_{1/2}/A^p_{1/2} \sim 10\text{–}20\,.$$

This ratio is close to that expected for the non-strange pentaquark in the Chiral Quark–Soliton model [23, 49]. Such large ratio of photoproduction amplitudes indicates the strong suppression of photoexcitation of this resonance off the proton. The calculated differential cross section is shown in

Fig. 6 together with the data from Ref. [48]. The included narrow P_{13} and D_{13} resonances generate only minor 10-MeV wide structures. The P_{11} generate a 20-MeV wide small bump. In our opinion, the quality of the data from Ref. [48] is not enough to reveal such fine peculiarities. The cross section data shown in Fig. 6 are smeared due the resolution of the GRAAL tagging system ($\sigma(E_\gamma) = 16$ MeV(FWHM)), and by the 16-MeV wide binning. Furthermore, this data is the compilation from many experimental runs collected at the GRAAL@ESRF facility during 1998–2003. The determination of the photon energy in each runs includes a systematic shift up to ± 8 MeV which originates from the adjustment and calibration of the GRAAL tagging system, and from different operating conditions of the ESRF. Neither of effort was done in Ref. [48] to reduce this uncertainty. These factors altogether smooth the data and may hide small peculiarities in the experimental cross section.

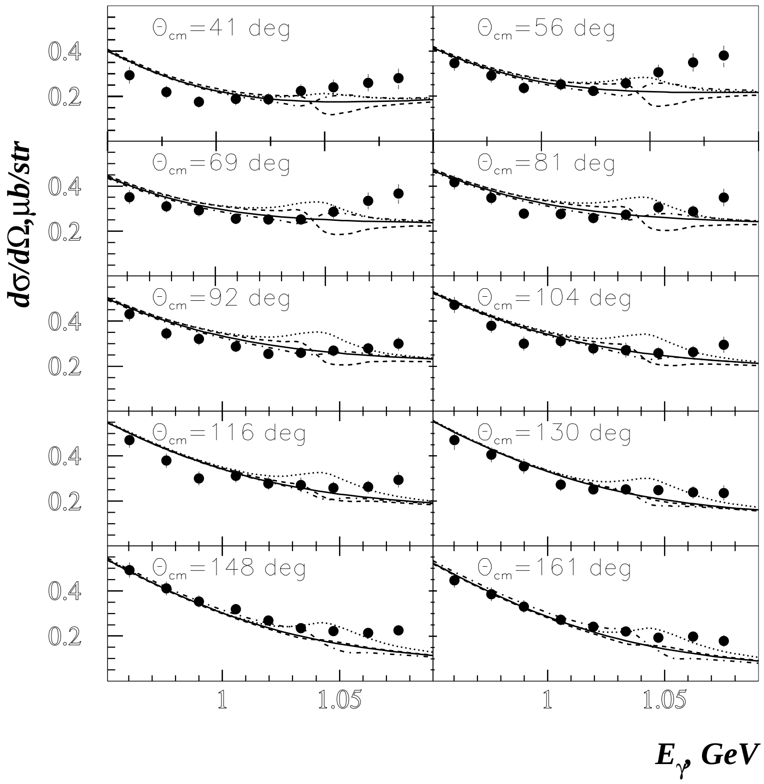

Fig. 6. Differential cross section for η photoproduction off the free proton. Black circles are the data from Ref. [48]. The legend for curves is the same as in Fig. 5.

New high-resolution data would be crucial to confirm/close the existence of this resonance. Recently the CLAS collaboration reported a relatively narrow structure at $W \sim 1.7$ GeV in η electroproduction off the proton [52]. This structure was tentatively explained as a signal of the $P_{11}(1710)$ (or $P_{13}(1720)$) resonance. To reproduce the data, the width of $P_{11}(1710)$ was set to $\Gamma = 100$ MeV. It would be interesting to fit together new η photo- and electroproduction data in the region $W = 1.62$–1.72 GeV.

5. Summary and discussion

In summary we report the evidence for a narrow structure in the Σ beam-asymmetry data for η photoproduction off the free proton. This structure is described by the contribution of a narrow resonance with the mass $M \sim 1.685$ GeV and the width $\Gamma \leq 25$ MeV. Candidates are either the P_{11} or P_{13} or D_{13} resonances. The mass and width of the suggested nucleon resonance are consistent with the parameters of the peak observed in quasi-free cross section η photoproduction off the neutron [13–15].

The explanation of the bump in the quasi-free neutron cross sections by the interference effects of known resonances [40, 41] predicts no any narrow structure in the proton channel. Our new Σ beam asymmetry data for η photoproduction off the free proton does not support this assumption.

If to follow the Occam's razor principle the most simple and concise explanation of the observations of Refs. [13–15] and results of the present paper (see also [51]) is the existence of a narrow nucleon resonance $N^*(1685)$ with much stronger photocoupling to the neutron than to the proton. Being a candidate for the non-strange member of the exotic anti-decuplet, such resonance supports the existence of the exotic Θ^+ pentaquark. Presently the majority of the community jumped to the conclusion that Θ^+ does not exist (see *e.g.* Ref. [53]). The evidences for a new narrow nucleon resonance — good candidate for the non-strange pentaquark — presented here, encourages the further search for the Θ^+ baryon. A new approach for this search is suggested in Ref. [54]. On the other hand, the exact determination of the quantum numbers of the reported $N^*(1685)$ state is crucial for the decisive conclusion about its nature. New dedicated high-resolution experiments are certainly needed for that.

It is a pleasure to thank the staff of the European Synchrotron Radiation Facility (Grenoble, France) for stable beam operation during the experimental run. We are thankful to Y. Azimov, A. Fix, K. Goeke, I. Strakovsky, and L. Tiator for many valuable discussions. P. Druck is thanked for support in data processing. The authors appreciate very much voluntary help with the analysis and continuous interest, and support to this work of K. Hildermann, D. Ivanov, I. Jermakowa, M. Oleinik, and N. Sverdlova. This work has been supported in part by the Sofja Kowalewskaja Programme of Alexander von Humboldt Foundation, by DFG (TR16), and in part by the Korean Research Foundation.

REFERENCES

[1] B. Krusche *et al.*, *Phys. Rev. Lett.* **74**, 3736 (1995); A. Bock *et al.*, *Phys. Rev. Lett.* **81**, 534 (1998); F. Renard *et al.* [GRAAL Collaboration], *Phys. Lett.* **B528**, 215 (2002) [`arXiv:hep-ex/0011098`]; M. Dugger *et al.* [CLAS Collaboration], *Phys. Rev. Lett.* **89**, 222002 (2002), Erratum, *Phys. Rev. Lett.* **89**, 249904 (2002); V. Crede *et al.* [CB-ELSA Collaboration], *Phys. Rev. Lett.* **94**, 012004 (2005) [`arXiv:hep-ex/0311045`]; O. Bartholomy *et al.* [CB-ELSA Collaboration], *Eur. Phys. J.* **A33**, 133 (2007).

[2] J. Ajaka *et al.*, *Phys. Rev. Lett.* **81**, 1797 (1998).

[3] V. Kuznetsov *et al.*, πN *NewsLetters* **16**, 160 (2002), data are available in the SAID data base at `http://gwdac.phys.gwu.edu`

[4] D. Elsner *et al.* [CBELSA Collaboration], *Eur. Phys. J.* **A33**, 147 (2007) [`arXiv:nucl-ex/0702032`].

[5] B. Krusche *et al.*, *Phys. Lett.* **B358**, 40 (1995).

[6] P. Hoffmann-Rothe *et al.*, *Phys. Rev. Lett.* **78**, 4697 (1997).

[7] V. Hejny *et al.*, *Eur. Phys. J.* **A6**, 83 (1999).

[8] J. Weiss *et al.*, *Eur. Phys. J.* **A11**, 371 (2001) [`arXiv:nucl-ex/0304009`].

[9] J. Weiss *et al.*, *Eur. Phys. J.* **A16**, 275 (2003) [`arXiv:nucl-ex/0210003`].

[10] B. Krusche, S. Schadmand, *Prog. Part. Nucl. Phys.* **51**, 399 (2003) [`arXiv:nucl-ex/0306023`].

[11] V. Kuznetsov *et al.* [GRAAL Collaboration], Proceedings of Int.Workshop on the Physics of Excited Nucleons NSTAR2002, Pittsburgh, USA, Oct. 2002, Ed. E. Swanson, World Scientific, p. 267.

[12] V. Kuznetsov *et al.* [GRAAL Collaboration], Proceedings of Workshop on the Physics of Excited Nucleons NSTAR2004, March, 2004, Grenoble, France, Eds. J.-P. Bocquet, V. Kuznetsov, D. Rebreyend, World Scientific, p. 197, [`arXiv:hep-ex/0409032`].

[13] V. Kuznetsov *et al.*, *Phys. Lett.* **B647**, 23 (2007); `hep-ex/0606065`.

[14] I. Jaegle *et al.*, `arXiv:0804.4841 [nucl-ex]`.

[15] F. Miyahara *et al.*, *Prog. Theor. Phys. Suppl.* **168**, 90 (2007).

[16] D. Diakonov, V. Petrov, M. V. Polyakov, *Z. Phys.* **A359**, 305 (1997) [`arXiv:hep-ph/9703373`].

[17] R.M. Barnett *et al.* [Particle Data Group], *Phys. Rev.* **D54**, 1 (1996).

[18] M. Batinic, I. Slaus, A. Svarc, B.M.K. Nefkens, *Phys. Rev.* **C51**, 2310 (1995), Erratum, *Phys. Rev.* **C57**, 1004 (1998) [arXiv:nucl-th/9501011].

[19] W.M. Yao *et al.* [Particle Data Group], *J. Phys. G* **33**, 1 (2006).

[20] T. Nakano *et al.* [LEPS Collaboration], *Phys. Rev. Lett.* **91**, 012002 (2003) [arXiv:hep-ex/0301020].

[21] V.V. Barmin *et al.* [DIANA Collaboration], *Phys. Atom. Nucl.* **66**, 1715 (2003) [*Yad. Fiz.* **66**, 1763 (2003)] [arXiv:hep-ex/0304040].

[22] M. Praszalowicz, *Phys. Lett.* **B575**, 234 (2003) [arXiv:hep-ph/0308114].

[23] M.V. Polyakov, A. Rathke, *Eur. Phys. J.* **A18**, 691 (2003) [arXiv:hep-ph/0303138].

[24] D. Rebreyend, Talk given at the 10th International Symposium on Meson–Nucleon Physics and the Structure of the Nucleon MENU2004, Beijing, August 29–Sep. 04 2004, China, http://www.ihep.ac.cn/menu03/index.html (→ First Circular → Scientific program).

[25] S. Nussinov, arXiv:hep-ph/0307357; J. Haidenbauer, G. Krein, *Phys. Rev.* **C68**, 052201 (2003) [arXiv:hep-ph/0309243]; R.N. Cahn, G.H. Trilling, *Phys. Rev.* **D69**, 011501 (2004) [arXiv:hep-ph/0311245]; R.A. Arndt, I.I. Strakovsky, R.L. Workman, *Nucl. Phys.* **A754**, 261 (2005) [arXiv:nucl-th/0311030]; W. R. Gibbs, *Phys. Rev.* **C70**, 045208 (2004) [arXiv:nucl-th/0405024].

[26] D. Diakonov, V. Petrov, *Phys. Rev.* **D69**, 094011 (2004) [arXiv:hep-ph/0310212].

[27] R.A. Arndt, Y.I. Azimov, M.V. Polyakov, I.I. Strakovsky, R.L. Workman, *Phys. Rev.* **C69**, 035208 (2004) [arXiv:nucl-th/0312126].

[28] C. Alt *et al.* [NA49 Collaboration], *Phys. Rev. Lett.* **92**, 042003 (2004) [arXiv:hep-ex/0310014].

[29] J.R. Ellis, M. Karliner, M. Praszalowicz, *J. High Energy Phys.* **0405**, 002 (2004) [arXiv:hep-ph/0401127].

[30] M. Praszalowicz, *Acta Phys. Pol. B* **35**, 1625 (2004) [arXiv:hep-ph/0402038].

[31] M. Praszalowicz, *Annalen Phys.* **13**, 709 (2004) [arXiv:hep-ph/0410086].

[32] V. Guzey, M.V. Polyakov, arXiv:hep-ph/0501010; *Annalen Phys.* **13**, 673 (2004); arXiv:hep-ph/0512355.

[33] D. Diakonov, V. Petrov, *Phys. Rev.* **D72**, 074009 (2005) [arXiv:hep-ph/0505201].

[34] C. Lorce, *Phys. Rev.* **D74**, 054019 (2006) [arXiv:hep-ph/0603231].

[35] T. Ledwig, H.C. Kim, K. Goeke, arXiv:0805.4063 [hep-ph].

[36] D. Diakonov, *AIP Conf. Proc.* **892**, 258 (2007) [arXiv:hep-ph/0610166].

[37] K.S. Choi, S.i. Nam, A. Hosaka, H.C. Kim, *Phys. Lett.* **B636**, 253 (2006) [arXiv:hep-ph/0512136]; S.i. Nam, K.S. Choi, A. Hosaka, H.C. Kim, *Prog. Theor. Phys. Suppl.* **168**, 97 (2007) [arXiv:0704.3101 [hep-ph]]; K.S. Choi, S.i. Nam, A. Hosaka, H.C. Kim, arXiv:0710.2185 [hep-ph]; arXiv:0707.3854 [hep-ph].

[38] W.T. Chiang, S.N. Yang, L. Tiator, M. Vanderhaeghen, D. Drechsel, *Phys. Rev.* **C68**, 045202 (2003) [arXiv:nucl-th/0212106].

[39] A. Fix, L. Tiator, M.V. Polyakov, *Eur. Phys. J.* **A32**, 311 (2007) [arXiv:nucl-th/0702034].

[40] V. Shklyar, H. Lenske, U. Mosel, *Phys. Lett.* **B650**, 172 (2007) [arXiv:nucl-th/0611036].

[41] A.V. Anisovich, talk at the NSTAR07, Bonn, September, 2007, http://nstar2007.uni-bonn.de/talks

[42] W.T. Chiang, S.N. Yang, L. Tiator, D. Drechsel, *Nucl. Phys.* **A700**, 429 (2002) [arXiv:nucl-th/0110034].

[43] V. Bellini *et al.*, *Eur. J. A.* **26**, 299 (2006).

[44] F. Ghio *et al.*, *Nucl. Inst. Meth. A* **404**, 71 (1998).

[45] V. Kouznetsov *et al.*, *Nucl. Inst. Meth. A* **487**, 128 (2002).

[46] R.A. Arndt, W.J. Briscoe, I.I. Strakovsky, R.L. Workman, in progress, http://gwdac.phys.gwu.edu.

[47] SAID multipoles can be obtained via ssh said@gwdac.phys.gwu.edu

[48] O. Bartalini *et al.*, *Eur. Phys. J.* **A33**, 169 (2007), [nucl-ex:0707.1385].

[49] H.C. Kim, M. Polyakov, M. Praszalowicz, G.S. Yang, K. Goeke, *Phys. Rev.* **D71**, 094023 (2005) [arXiv:hep-ph/0503237].

[50] Y. Azimov, V. Kuznetsov, M.V. Polyakov, I. Strakovsky, *Eur. Phys. J.* **A25**, 325 (2005) [arXiv:hep-ph/0506236].

[51] V. Kuznetsov *et al.*, arXiv:0801.0778 [hep-ex];
V. Kuznetsov, M. Polyakov, T. Boiko, J. Jang, A. Kim, W. Kim, A. Ni, arXiv:hep-ex/0703003.

[52] H. Densili *et al.* [CLAS Collaboration], *Phys. Rev.* **C76**, 025211 (2007).

[53] F. Close, *Nature* **435**, 287 (2005); R.L. Jaffe, *AIP Conf. Proc.* **792**, 97 (2005).

[54] M. Amarian, D. Diakonov, M.V. Polyakov, arXiv:hep-ph/0612150.