Final remarks to our study of \( \eta \)-photoproduction on protons in the resonance region

V.A. Tryasuchev*

Tomsk Polytechnic University, Tomsk, Russia

Abstract

The properties of previously discovered nucleon resonances are amended basing on the recent and more detailed experimental data about photoproduction of \( \eta \)-mesons on protons.

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As the experimental data on \( \eta \)-photoproduction on nucleons have been accumulated [1–5]

\[
\gamma + p \to \eta + p, \tag{1}
\]

they were gradually analyzed within dynamical models developed in refs. [6–10]. After the GRAAL measurements of beam asymmetry and differential cross sections in the energy region 1100–1500 MeV were reported, necessity of essential revision of the resonance properties collected in [7,10] has become evident.

In order to explain all the available data for the reaction (1), new \( S_{11} \) resonance with quite definite position on the complex energy plane was required in addition to the already known baryons \( S_{11}(1535) \) and \( S_{11}(1650) \). Information on three \( S_{11} \)-resonances obtained in our works is presented in Table 1. Here, \( \beta \) stands for the sign of the ratio of \( \eta NR \) and \( \pi NR \) couplings. The properties of all resonances, needed to describe the measured observables of the process (1), are listed in Table 2. There, the absolute values \( \xi_{\lambda} \) [11] are proportional to the contributions of the corresponding resonances to the reaction (1).

As one can see, the contribution of \( P_{13}(1720) \) appears to be very important. This resonance strongly influences the shape of angular distributions as well as beam asymmetry in a wide energy region up to 1.9 GeV. By now, opinions differ widely on the role of the baryon \( P_{13}(1720) \) in \( \eta \)-photoproduction. For example, in refs. [12–13] this resonance is shown to be insignificant, whereas in more recent works of [14–16] quite essential contribution of \( P_{13}(1720) \) has been reported. Here we would like to mention that important role of this resonance in the reaction (1) has also been pointed out in our previous works (see, e.g., [7]). The three resonances

\[
P_{11}(1710), D_{15}(1675), F_{15}(1680) \tag{2}
\]

are shown to be less significant, but their inclusion results in better description of the structural details of the observed cross section.

As for the heavier resonances

\[
F_{17}(1990), G_{17}(2190), G_{19}(2250), H_{19}(2220), \tag{3}
\]

among which the last three are marked with four stars in the PDG compilation [17], we found that \( G_{19}(2250) \) provides only small fraction of the resulting cross section. The other resonances, being much more important, govern the shape of \( \eta \) angular distributions at photon energies \( K_0 > 1.5 \) GeV. At the same time, the masses and widths of these states are not uniquely determined. Polarization measurements in the appropriate energy region are necessary for a more precise determination of these parameters.

Several results coming out from our analysis seem to be unrealistic and need further clarification. Firstly, the \( S_{11}(1650) \) photoexcitation amplitude has too large magnitude which appears to be comparable to that of \( S_{11}(1535) \) (see Table 1). Secondly, our model favors equal values of the electromagnetic amplitudes for \( F_{15}(1680) \)

\[
A_{1/2} = A_{3/2}.
\]

This paper is in contradiction with the average PDG results [17], where \( A_{1/2} << A_{3/2} \). We did not show our calculation for photon energies below 930 MeV, since in this region, where the reaction is dominated by \( S_{11}(1535) \), the theoretical description of the data is always good. Furthermore, not presented are the results for beam asymmetry from ref. [4], being in well agreement with the GRAAL data [5], with the exception of \( K_0 = 1050 \) MeV.

The region close to \( K_0 = 1050 \) MeV is just the energy at which the measured asymmetry \( \Sigma \) from ref. [4] along with the experimental results from ref. [5] are depicted in Fig.1.

The energy dependence of the observed total cross section for the reaction (1) is compared with all available data in Fig.2. One sees well agreement which however is not the governing factor for extracting the resonance parameters. The reason is presumable model dependence of the experimental results caused by the limited range of polar angles of particles detected in the GRAAL measurements.

We think the conclusion about total agreement between the calculation and the data would be premature, even if only the limited region of the photon energy (< 1.5 GeV) is considered. In Fig.3 we present beam asymmetry of the reaction (1) as function of the photon energy at different angles of \( \eta \)-mesons.

As is pointed out in [5] and may also be seen in Fig.3, in the region 1.05–1.2 GeV the data exhibit anomalous behavior, in particular, at \( \theta = 90^\circ \) and 142.5°. Here one also notes the maximum deviation between the final GRAAL data [5] and their preliminary results [18], as well as with the results of ref. [4]. This feature was also noticed by the authors of ref. [19] who were searching for signatures of a narrow (\( \Gamma < 25 \) MeV) resonance \( P_{11} \) in meson photoproduction in the second resonance region. Since this resonance is assumed to be the member of the \( SU(3) \) flavor antidecuplet (\( J = 1/2 \)), one can easily show...
that due to conservation of the $U$-spin this state is photoproduced mostly on neutrons, rather than on protons. As is also noticed in refs. [19,20] its existence should result in an anomalous behavior of the beam asymmetry of the process (1) around the invariant energy $W = 1680$ MeV.

Our description of the data at these energies is also inadequate. Direct calculation shows that in the region discussed, the most important contribution comes from $D_{15}(1675)$, $F_{15}(1680)$, whose properties are not well known so far. This however may be direct consequence of the above mentioned narrow resonance, which is seen in the reaction $\gamma p \rightarrow \eta p$. In this connection, further measurements of the $\Sigma$ asymmetry around 1.05–1.2 GeV with a better energy and angular resolution are of special interest, as a tool to study these resonances on a higher quantitative level.

Above 2.2 GeV, experimental uncertainty of photon energy becomes large, so that it is reasonable to analyze only the gross structure of the cross section without trying to reproduce the details. At the same time, in this case the observed angular dependence for $\theta < 30^\circ$ may deserve attention as a way to identify the energy region where the diffraction mechanism of $\eta$-production starts to come into play. The case in point is apparent shifting of the angular distribution to the forward hemisphere (see Fig.4) which might bear witness to significance of the $t$-channel. In most of the isobar models, the $t$-channel mechanisms are suppressed by small coupling constants and/or sharp formfactors. Similar to the present theoretical base, in these models the VNN vertices and cut-offs are usually fitted to the data for the reaction (1) at lower energies ($K_0 < 1.5$ GeV). At the same time, inclusion of only the resonances (3) turns out to be insufficient to account for the peak in the cross-section at forward angles (see Fig.4). Additional resonances are required to reproduce this characteristic shape.

It is worth to note a successful attempt in refs. [15,16,21] to achieve global description of $\eta$-photoproduction on protons. Here rather well agreement with the data is obtained primarily due to additional inclusion of new resonance states (more than three resonances in [15,16]). Or, straight conversely, the number of resonances was artificially reduced in order to make the $\chi^2$-method [21] more effective, so that fitted parameters may further be used in other reactions with $\eta$-mesons.

In conclusion, we presented our analysis of the final experimental results obtained at GRAAL. Special emphasis is put on those aspects of the process (1) which require additional experimental and theoretical investigations. New data are of special interest for further improvements of our knowledge about the known resonances as well as those, whose existence is still under debate.

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Table 1: Parameters of $S_{11}$-resonances, extracted from our analyses of $\gamma p \rightarrow \eta p$. The parameter $\xi_\lambda$ is determined as $\xi_\lambda = \sqrt{\frac{1}{2}G_\lambda^2 \sqrt{\frac{W}{p_\eta^2}}}$, $A_\lambda$. 

| $N^*$ | $W, \text{MeV}$ | $\Gamma, \text{MeV}$ | $\gamma^E, \text{MeV}$ | $\gamma^M, \text{MeV}$ | $\xi^{1/2}, 10^{-1} \text{GeV}^{-1}$ | $\xi^{3/2}, 10^{-1} \text{GeV}^{-1}$ |
|------|----------------|----------------|----------------|----------------|----------------|----------------|
| $S_{11}(1535)$ | 1535 | 156 | 2.15 | - | 2.476 | - |
| $S_{11}(1650)$ | 1642 | 140 | -0.652 | - | - | 0.837 |
| $S_{11}(1830)$ | 1828 | 150 | 0.180 | - | 0.216 | - |
| $P_{11}(1440)$ | 1440 | 350 | - | 0.250 | - | - |
| $P_{11}(1710)$ | 1710 | 100 | - | 0.020 | 0.022 | - |
| $P_{13}(1720)$ | 1730 | 185 | -0.085 | 0.560 | 0.245 | 0.630 |
| $D_{13}(1520)$ | 1520 | 120 | 0.300 | 0.300 | -0.017 | 0.145 |
| $D_{15}(1675)$ | 1675 | 110 | 0.085 | -0.002 | 0.100 | 0.053 |
| $F_{15}(1680)$ | 1685 | 130 | 0.195 | 0.075 | 0.146 | 0.131 |
| $F_{17}(1990)$ | 1980 | 290 | 0.010 | 0.255 | 0.107 | 0.128 |
| $G_{17}(2190)$ | 2240 | 425 | -0.480 | -0.001 | -0.148 | -0.192 |
| $H_{19}(2220)$ | 2240 | 425 | -0.730 | -0.001 | -0.155 | -0.191 |
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Figure 1: Beam asymmetry $\Sigma$ and differential cross section $d\sigma/d\Omega$ for $\gamma p \rightarrow np$. The solid and the dotted curves are obtained in the present analyses and in ref. [9] respectively. The data are taken from the following references: □, ref. [2]; ○, ref. [4]; ●, ref. [5]. The data of ref. [4] are shown with total error.
Figure 2: Total cross section for the reaction $\gamma p \rightarrow \eta p$ as function of the photon lab energy $K_0$. Notation of the curves as in Fig.1. The data are from: [1], ○; [5], ●; [2], □; [3], ▼.

Figure 3: Beam asymmetry for $\gamma p \rightarrow \eta p$ as function of photon energy shown for two $\eta$ c.m. angles: 90°, ▲− data [5] (solid curve is our calculation); 142.5°, •− data [5] (our result is shown by the dashed curve). For $\theta = 90^\circ$ the data are shown by: ○, from ref. [4] and ■, from ref. [18].
Figure 4: Angular distribution of $\eta$-mesons calculated at a photon energy above 1.5 GeV. The meaning of the curves as in Figs. 1 and 2. Experimental data: □, from ref. [2]; ▼, from ref. [3].