\( \eta \) Photoproduction off the nucleon revisited: Evidence for a narrow \( N(1688) \) resonance?

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Abstract. Revised analysis of \( \Sigma \) beam asymmetry for the \( \eta \) photoproduction on the free proton reveals a structure at \( W \sim 1.69 \) GeV. Fit of the experimental data based on the E429 solution of the SAID partial wave analysis suggests a narrow \( (\Gamma < 25 \text{ MeV}) \) resonance. Possible candidates are \( P_{11}, P_{13}, \) or \( D_{13} \) resonances. The result is considered in conjunction with the recent evidence for a bump-like structure at \( W \sim 1.67 - 1.68 \) GeV in the quasi-free \( \eta \) photoproduction on the neutron.

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The evidence for a narrow resonant structure at \( W \sim 1.67 - 1.68 \) in the quasi-free \( \eta n \) photoproduction at GRAAL \(^{1,2}\), CB/TAPS@ELSA \(^3\), and LNS-Tohoku \(^4\) facilities is one of the most important recent findings in the domain of the physics of nucleon resonances. The structure has been observed as a relatively narrow bump in the quasi-free cross section and in the \( \eta n \) invariant mass spectrum.

\( M(\eta, n) \) (Fig. 1). Such bump is not (or poorly) seen in the cross-section data for \( \eta \) photoproduction on the free proton \(^5\).

The width of the bump in the \( \gamma n \to \eta n \) cross section is close to that expected due to Fermi motion of the target neutron bound in the deuteron. A narrow resonance which would manifest itself as a peak in the free neutron cross section, would appear in the quasi-free cross section as a bump of \( \sim 50 \text{ MeV (FWHM)} \) width \(^1\) (Fig. 1). The \( M(\eta, n) \) spectrum is much less affected by Fermi motion but includes larger uncertainties due to detector response. The observed width, of \( \sim 50 \text{ MeV (FWHM)} \), is close to the instrumental resolution \(^1\).

Several attempts to explain the observed bump have been recently done. The authors of \(^6,7,8\) suggested a narrow \( P_{11}(1675) \) resonance. Alternatively, the authors of \(^9,10\) explained the observed bump in terms of photoexcitation and interference of the \( S_{11}(1650) \) and \( P_{11}(1710) \) or \( S_{11}(1535) \) and \( S_{11}(1650) \) resonances.

The quasi-free cross section is smeared by Fermi motion of the target neutron and is affected by re-scattering and final-state interaction (FSI). Those events whose kinematics is relatively stronger distorted by Fermi motion or those which originate from the re-scattering and FSI, are in part eliminated in the data analysis. This procedure necessarily depends on experimental setup and on cuts used in data analysis. Therefore the quasi-free cross section measured in experiment may deviate from the cross section calculated for the free neutron and then smeared by Fermi motion. \( M(\eta, n) \) is almost unaffected by Fermi motion. Its spectrum exhibits a narrow peak at \( M(\eta, n) = \)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig_1}
\caption{Quasi-free cross sections and \( \eta n \) invariant mass spectrum for the \( \gamma n \to \eta n \) reaction obtained at GRAAL (data from Ref.\(^1\)). Solid lines fit the data by the sum of a 3-order polynomial and a narrow state. Dashed lines are 3-order polynomials only. Dark areas show the simulated signals of a narrow \( (\Gamma = 10 \text{ MeV}) \) resonance.}
\end{figure}
1.678 GeV. This peak seems not to be reproduced by calculations [9,10].

Thus the bump in the \( \eta \) photoproduction on the neutron may signal a nucleon resonance with unusual properties: a possibly narrow width and a much stronger photo-coupling to the neutron than to the proton. Its identification is now a challenge for both theory and experiment.

If photoexcitation of any resonance occurs on the neutron it should generally occur also on the proton, even being suppressed by any reason. The \( \eta \) photoproduction on the proton below \( W \sim 1.7 \) GeV is dominated by excitation of the \( S_{11}(1535) \) resonance. 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 dominant \( S_{11}(1535) \) resonance. This structure would be smeared in experiment by resolution of a tagging system (for example, the resolution of the GRAAL tagging system is 16 MeV FWHM [11]), and might be hidden due to inappropriate binning.

Polarization observable - the polarized photon beam asymmetry \( \Sigma \), is much less affected by the \( S_{11}(1535) \) resonance. This observable is the measure of azimuthal anisotropy of the reaction yield when the incoming photon is linearly polarized. \( \Sigma \) beam asymmetry is much more sensitive to signals of non-dominant resonances than the cross section.

For the \( \eta \) photoproduction on the proton, the beam asymmetry \( \Sigma \) has been twice measured at GRAAL. The first results[12] covered the energy range from threshold to 1.05 GeV. Two statistically-independent but consistent data sets have been reported. The data sets were based on two different samples of events: i) Events with both photons from \( \eta \rightarrow 2\gamma \) decays detected in the BGO Ball; ii) Events in which one of the photons, being emitted at the angles \( \theta_{lab} \leq 25^\circ \), was detected in the forward shower wall, and the other was detected in the BGO ball. The second type of events was found to be particularly efficient at forward angles and energies above 0.9 GeV. The results have shown a marked peaking at forward (\( \sim 40-50^\circ \)) angles and \( E_\gamma \sim 1.05 \) GeV. An extension to higher energies up to 1.5 GeV has been reported in Ref. [13]. Two samples of events were merged and analyzed together. This made it possible to significantly reduce error bars at forward angles and to retrieve a maximum in the angular dependence at \( 50^\circ \) and \( E_\gamma \sim 1.05 \) GeV. A new measurement has been done by the CB/TAPS Collaboration using a different technique of the photon-beam polarization, the coherent bremsstrahlung from diamond radiator [14]. Results are in good agreement with Refs. [12,13].

Very recently a new data attributed to the GRAAL facility, has been published in Ref. [13]. This data is quite similar that presented in Ref. [13] but, despite the triple increase of statistics, is less accurate at forward angles. The reason is that the second type of events described above, has not been used in the data analysis.

In Refs. [12,13,14] the main focus has been done on the angular dependencies of \( \Sigma \). Data points have been produced using relatively narrow angular bins, but nearly 60 MeV wide energy bins. Such wide bins do not allow to reveal narrow peculiarities in the energy dependence of \( \Sigma \). An ultimate goal of this work is to produce beam asymmetries using narrow bins in energy, in order to retrieve in detail the photon energy dependence of \( \Sigma \) for \( E_\gamma = 0.85 - 1.15 \) GeV (or \( W = 1.55 - 1.75 \) GeV) and to search for a signal of a narrow resonance.

In this contribution we present the revised analysis of data collected at the GRAAL facility in 1998 - 1999. In general, the data analysis is the same as in Ref. [13]. Two types of events, as described above, are merged and used together to extract beam asymmetries.

The results are shown in Fig. 2. Data points are obtained using narrow energy bins \( \Delta E_\gamma \sim 16 \) MeV. Angular bins are chosen to be rather wide, about \( (20 - 40)^\circ \), to gain statistics and hence to reduce error bars.

At forward angles (\( \theta_{cm} = 43^\circ \)) and \( E_\gamma = 1.04 \) GeV the data points form a sharp peak with \( \Sigma \) in its maximum as large as 0.94. The peak becomes less pronounced at \( 65^\circ \). It is replaced by an oscillating structure at \( 85^\circ \) and \( 106^\circ \). At more backward angles, the asymmetry above 1.05 GeV drops down almost to 0 (Fig. 2) while its statistical errors grow up.

The peak at forward angles and the oscillating structure at central angles together exhibit an interference pattern which may signal a narrow nucleon resonance. To examine such assumption, we employ the multipoles of the recent E429 solution of the SAID partial-wave analy-
sion (PWA) \cite{17} for \( \eta \) photoproduction, adding to them a narrow Breit-Wigner resonance (as in Ref.\cite{7}). The narrow \( S_{11}, P_{11}, P_{13}, \) and \( D_{13} \) resonances are tried one by one. Each resonance contribution is parameterized by the mass, width, photocouplings (multiplied by the square root of the \( \eta N \) branching), and the phase. These parameters are varied to achieve the best agreement with experimental data. The curves with the original SAID multipoles are smooth and do not exhibit any structure \cite[(Fig. 2)]. The inclusion of either \( P_{11} \), or \( P_{13} \), or \( D_{13} \) allows to improve agreement between the data and calculations and to reproduce the peak/dip structure. The mass of the included resonance is strongly constrained by experimental data. Its value belongs to the range of \( M_R = 1.682 - 1.690 \) GeV. The best agreement with data corresponds to the width \( \Gamma \sim 8 \) MeV. However, reasonable curves may be obtained with \( \Gamma \) up to 25 MeV.

The \( S_{11} \) resonance generates a dip at 43° in the entire range of variation of its photocoupling and phase. This indicates that the observed structures, most probably, can not be attributed to a narrow \( S_{11} \) resonance.

The calculated cross section is weakly affected by the added resonances: the \( P_{11} \) generates a small peak/dip structure near \( W \sim 1.69 \) GeV while the \( P_{13} \) and the \( D_{13} \) resonances produce almost no effect. This explains while the possible underlying resonance is not (or poorly) seen in the free-proton cross section data.

The mass estimate for the underlying resonance is about 5-10 MeV higher than the value obtained in \( \eta \) photoproduction on the free proton. This structure may allow no underlying resonance is not (or poorly) seen in the forward and the central part of the GRAAL detector where they cannot be properly detected. A question to be addressed to the authors of Ref.\cite{15}: whether do they observe a dip structure near 100°?\footnote{Some consideration of this issue is given in the slide 19 of Ref.\cite{16}.}

In summary, we report an evidence for a narrow resonance structure in the \( \Sigma \) beam asymmetry data for the \( \eta \) photoproduction on the free proton. This structure may manifest a narrow resonance with the mass \( M \sim 1.688 \) GeV and the width \( \Gamma \leq 25 \) MeV. As candidates, narrow \( S_{11}, P_{11}, P_{13}, \) and \( D_{13} \) resonances are tried. Among them, either the \( P_{11} \), or \( P_{13} \), or \( D_{13} \) resonance improves the description of the data. Most probably, the same resonance is observed in the cross section of the \( \eta \) photoproduction on the neutron, where its photocoupling is much stronger.

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