Observation of Narrow $N^{+}(1685)$ and $N^{0}(1685)$ Resonances in $\gamma N \rightarrow \pi \eta N$ Reactions

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Observation of a narrow structure at $W \sim 1.68$ GeV in the excitation functions of some photon- and pion-induced reactions may signal a new narrow isospin-1/2 $N(1685)$ resonance. New data on the $\gamma N \rightarrow \pi \eta N$ reactions from GRAAL seems to reveal the signals of both $N^{+}(1685)$ and $N^{0}(1685)$ resonances.

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Understanding the internal structure of the nucleon is a key task in the domain of hadronic physics. Suggested in the 60th the approximate flavor SU(3) symmetry of QCD led to a remarkably successful classification of low-lying mesons and baryons. Many properties of baryons known at that time were transparently explained by the Constituent Quark Model (CQM) that treats baryons as bound systems of three effective (constituent) quarks.

CQM-based calculations predicted a rich spectrum of baryon resonances with widths varying from $\sim$ 80 to $\sim$ 400 MeV. Nevertheless, in spite of significant efforts, many of the predicted resonances still escape from reliable experimental identification (the so-called “missing resonances”).

The Chiral Soliton Model ($\chi SM$) is an alternative picture of baryons. It treats them as space/flavor rotational excitations of a classical object - a soliton of the chiral field. The model predicts the lowest-mass baryon multiplets to be the $(8, 1/2^+)$ octet and the $(10, 3/2^+)$ decuplet - exactly as CQM does. $\chi SM$ also predicts the existence of long-lived exotic particles [2].

Therefore the search for light-quark exotic states may provide critical benchmarks to examine two different approaches and to establish the connection between them. In this context the observation of a narrow enhancement at $W \sim 1.68$ GeV in the $\gamma n \rightarrow \eta n$ excitation function (the so-called “neutron anomaly”) at GRAAL, CBELSA/TAPS, LNS and A2@MAMI C [3-7] might be quite important. Narrow structures at the same energy were also observed in Compton scattering on the neutron $\gamma n \rightarrow \gamma n$ and in the beam asymmetry for the $\eta$ photoproduction of the proton $\gamma p \rightarrow \eta p$ [9] (see aslocteann). The recent data on the beam asymmetry for Compton scattering on the proton $\gamma p \rightarrow \gamma p$ [11], the precise data for the $\gamma n \rightarrow \eta n$ [12] and $\pi^{+}p \rightarrow \pi^{+}p$ [13] reactions revealed two narrow structures at $W \sim 1.68$ and $W \sim 1.72$ GeV.

The whole complex of experimental observations may signal the existence of one ($N(1685)$) or two ($N(1685)$ and $N(1726)$) narrow nucleon resonances. The properties of $N(1685)$ (if it does exist), namely the isospin 1/2, strangeness $S = 0$, narrow ($\Gamma \lesssim 25$ MeV) width, strong photoexcitation on the neutron and suppressed decay to $\pi N$ final state, do coincide well with those predicted by $\chi SM$ for the second member of the anti-decuplet of exotic particles [14].

On the other hand there are alternative interpretations of the "neutron anomaly" in terms of of the specific interference of known wide resonances [15] or as the sub-threshold meson-nucleon production (cusp) [16]. Although being questionable [17], the first assumption is widely discussed in literature.

The decisive identification of these experimental findings is a challenge for both theory and experiment. In the previous experiments the possible signal of $N(1685)$ was observed in so-called "formation" reactions in which the incoming particle interacts with the target nucleon and excites resonances. If $N(1685)$ does really exist, its signal should also be seen in multi-particle "production" reactions in which it would manifest itself as a peak in the invariant mass spectra of the final-state products.

Possible reactions could be $\gamma N \rightarrow \pi n N$.

The photoproduction of $\pi \eta$ pairs on the proton was previously studied at GRAAL [18], CBELSA/TAPS [19] and A2@MAMI C [20] facilities. The goals were to investigate the spectrum of baryon resonances and to constrain theoretical models. The works [18, 19] were restricted to only the $\gamma p \rightarrow \pi^0 n p$ reaction. The data from Ref. [20] were obtained at photon energies below 1.4 GeV.

In this Letter, we report on the study of the $\gamma p \rightarrow \pi^0 \eta p, \gamma p \rightarrow \pi^+ \eta n, \gamma n \rightarrow \pi^0 \eta n$, and $\gamma n \rightarrow \pi^- \eta p$ reactions. Our ultimate goal is to search for a possible signal of $N(1685)$.

The data were collected at the GRAAL facility [21]. The GRAAL highly-polarized beam was produced by means of the back-scattering of laser light on 6.04 GeV electrons circulating the storage ring of the European Synchrotron Radiation Facility (Grenoble, France). The GRAAL tagging system provided the measurement of photon energies in the range 0.55 - 1.5 GeV. The maximum beam intensity and polarization were in the energy range 1.4 - 1.5 GeV.

Photons from $\eta \rightarrow 2\gamma$ and $\pi^0 \rightarrow 2\gamma$ decays were de-
The angular resolution of photon detection was 6° - 8°. The recoil protons and neutrons emitted at forward angles $\theta_{lab} \leq 25^\circ$ were detected in the assembly of forward detectors. It consisted of two planar wire chambers, a thin scintillator hodoscope and a lead-scintillator wall [23]. Two latter detectors were located at 3 m far from the target. They allowed a measurement of time-of-flights of recoiled nucleons with resolution $\Delta t \sim 1$ psec. Then this quantity was used to retrieve the energy of the incoming photon and the final-state $\pi$ was compared with the invariant mass of the final-state $\eta$ and $N$. To eliminate the contamination of $\gamma N \rightarrow \eta N$ events, the missing mass $M = M(\eta N)$ was shown as a function of the energy of the incoming photon $W = 1.2 - 1.45$ GeV (the average center-of-mass energy $W \sim 1.834$ GeV).

Given the goal of this work, only the events in the range of the energy of the incoming photon $E_\gamma = 1.4 - 1.5$ GeV were selected for further analysis. The lower limit of 1.4 GeV is close to the $\gamma N \rightarrow \pi N(1685)$ threshold. The upper value 1.5 GeV is the limit of the GRAAL beam and it also allows to avoid the contribution from higher-lying resonances.

The left panel of Fig.2 shows the Dalitz plot of the invariant mass $IM(\eta N)$ versus the invariant mass $IM(\pi N)$ (the sum of all reactions under study). The events corresponding to $IM(\pi N) \sim 1.2 - 1.35$ GeV are major contributors. One may assume that they originate from the $\gamma N \rightarrow \eta \Delta$ production. There is a small narrow enhancement at $IM(\eta N) \sim 1.68$ GeV. This enhancement may signal $N(1685)$. The correspondindf spectrum of the extracted invariant mass $M(\eta N)$ is shown on the right panel of Fig.2.

To eliminate the contamination of $\gamma N \rightarrow \eta \Delta$ events, further the cuts on the invariant mass $1.12 \leq IM(\gamma N) \leq 1.22$ GeV and the missing mass $MM(\gamma, \eta) \leq 1.22$ GeV were applied to compromise between the overall statistics of selected events and the rejection of the background.

The spectra of the extracted masses $M(\eta N)$ for each reaction are shown in Fig.3. For the reaction $\gamma p \rightarrow \pi^0 np$ on the free-proton target $M(\eta p)$ was taken as $(MM(\gamma, \pi^0) + IM(\eta p))/2$. This made possible the most proper usage of the information read out from the

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**Fig. 1:** Beam asymmetry $\Sigma_{\phi}$ obtained assuming the $\gamma p \rightarrow \pi^0 R(\pi p)$ reaction. Black circles are the results of this work. Open circles are the results of the CBELSA/TAPS Collaboration [10].

**Fig. 2:** On the left: Bi-dimensional plot of $\eta N$ invariant mass $IM(\eta N)$ versus $\pi N$ invariant mass $IM(\pi N)$ in the energy range 1.4 - 1.5 GeV (sum of all reactions under study). On the right: the corresponding spectrum of the extracted $M(\eta N)$ mass. Neither of cut on the $IM(\pi N)$ was applied.
GRAAL detector and consequently to improve the resolution. In the case of the reaction $\gamma p \rightarrow \pi^+ \eta n$ on the free proton the energy of the $\pi^+$ is retrieved from the momentum conservation. That is why in addition a kinematic fit was employed to achieve the best resolution in the $M(\eta n)$ spectrum. For the reactions on the proton and the neutron bound in a deuteron target, the missing masses $MM(\gamma, \pi)$ are distorted due to Fermi motion of the target nucleon while the invariant masses $IM(\eta N)$ remain almost unaffected. For these reactions the extracted masses $M(\eta N)$ shown in Fig.3 were set equal to the corresponding invariant masses $IM(\eta N)$.

All the spectra exhibit enhancements at $M(\eta N) \sim 1.68$ GeV. It is better pronounced and more narrow for the reactions on the free proton (two upper panels). The statistics for these reactions is better because of the available data. In the case of the reactions of the proton and neutron bound in the deuteron the peaks are wider.

A signal of $N(1685)$ resonance should be seen in both missing mass $MM(\gamma, \pi)$ and invariant mass $IM(\eta N)$. The left panel of Fig.4 shows a bi-dimensional plot of these quantities (the sum of all the reactions under study). There is a clear enhancement at $\sim 1.68$ GeV at both axis. The corresponding spectrum of the $\eta N$ mass reveals a peak-like structure at $W \sim 1.68$ GeV. Being considered in conjunction with high-statistics results on the $\gamma n \rightarrow \eta m$ and other reactions cited, this structure signals the existence of the $N^1(1685)$ resonance.

The positions of the peaks in both missing masses $MM(\gamma, \pi)$ and invariant masses $IM(\eta N)$ for each reaction depend on the quality of the calibration of the GRAAL sub-detectors and tagging system. This in particular concerns the forward time-of-flight detectors. An error in the determination of the time-of-flight of the recoil nucleon of $\sim 20$ psec results in a shift of the peak position $\sim 10$ MeV. These errors might be different for recoil protons and recoil neutrons. Other errors originate from the calibration of the tagging system $\Delta E_\pi = 10$ MeV, from the threshold effects in the BGO Ball, and from the energy losses of the protons during their passes from the target to the detectors. That is why all the spectra were corrected such that the peaks were located at the same average value $M(\eta N) \sim 1.68$ GeV. The deviation of the initial peak positions from this average value did not exceed 10 MeV.

The sum of the corrected $M(\eta N)$ spectra is shown in Fig.5. There is a well pronounced peak at $\sim 1.68$ GeV. The Gaussian+3-order polynomial (signal-plus-background) fit results in the $\chi^2$-square of 23.9/23. The fit by 3-order polynomial (background) gives the $\chi^2$-square of 42.6/26. The log likelihood ratio of these two hypotheses ($\sqrt{2 \ln(L_B+S/L_B)}$) corresponds to the confidence level of $4.6\sigma$.

The extracted peak position is $M = 1678 \pm 0.8_{\text{stat}} \pm 10_{\text{syst}}$ MeV. The systematic uncertainty in the mass position originates from the uncertainties in the calibration of the GRAAL detector and tagger. The width $\Gamma \sim 10$ MeV may be affected by the mentioned above corrections.

Fig. 6 presents the simulated yields of $\gamma p \rightarrow \pi^0 \eta p$ and $\gamma p \rightarrow \pi^+ \eta n$ events obtained by using the same software and cuts as those for real data shown in the Fig.3. The event generator used in $MC$ included flat cross sec-

![Fig. 3: Spectra of extracted masses $M(\eta N)$](image)

![Fig. 4: On the left: Bi-dimensional plot of missing masses $MM(\gamma, \pi)$ vs invariant masses $IM(\eta N)$ (Sum of all channels) with the cut on $IM(\pi N)$. On the right: the corresponding spectrum of the extracted $M(\eta N)$.](image)

![Fig. 5: Spectrum of extracted $M(\eta N)$ mass (sum of all channels) with corrections (see text for detail).](image)
graphs and configurations without any narrow resonances. Neither of peaks appeared in the $M(\eta N)$ spectra.

Our results support the existence of two narrow resonances, $N^+(1685)$ decaying, in particular, into $\eta p$ final state, and $N^0(1685)$ with one possible decay into $\eta n$ (i.e. the isospin-1/2 $N(1685)$ resonance). Although the properties of this resonance (if it does exist) do coincide well to those expected for the second member of the exotic anticuadruplet, [2], its decisive accusation requires in particular the identification of the second structure at $W \sim 1.726$ GeV.

It is unclear if the interference of known wide resonances [15] or the cusp effect [16] - two other hypotheses under discussion - could explain these results.

Our observation requires a confirmation from other groups. It would be interesting to revisit the analysis of the $\gamma p \rightarrow \pi^0 np$ reaction by the CBELSA/TAPS Collaboration [19]. If the similar energy binning ($\Delta E_c = 1.2 - 1.45$ GeV) as in Ref. [15] is used in our analysis and neither cut on $IM(\pi^0 p)$ is imposed, no signal of $N(1685)$ is visible. New dedicated experiments at other facilities could provide data at a higher level of quality.

In summary, we report on the observation of narrow peak-like structure in the $M(\eta p)$ and $M(\eta n)$ spectra in the $\gamma N \rightarrow \pi \eta N$ reactions. Quite likely these structures witnesses the existence of a new narrow isospin-1/2 resonance $N(1685)$.

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