A CASE FOR NARROW NUCLEON EXCITATION $N^*(1685)$*

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An evidence for a narrow nucleon resonance with the mass of $M \sim 1.685$ GeV in the Compton scattering on the neutron is presented. The resonance possesses unusual properties: the narrow width $\Gamma \leq 30$ MeV, and the much stronger photocoupling to the neutron than to the proton. We also added some remarks and simple estimates on putative narrow nucleon $N^*(1685)$ in the η photoproduction on the nucleon.

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1. Introduction

Prediction of light and narrow anti-decuplet of baryons in the framework of the chiral quark soliton model (χQSM) [1] has a direct implication for the classical field of nucleon resonances spectroscopy: one should expect an existence of the nucleon state which is much narrower than the usual nucleon excitations with analogous mass and quantum numbers [1–3]. Additionally, in Ref. [4] it was demonstrated that the nucleon resonance from the anti-decuplet has a clear imprint of its exotic nature: the anti-decuplet nucleon is excited by the photon predominantly from the neutron, its photoexcitation from the proton target must be strongly suppressed.

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Recently, four groups — GRAAL [5, 6], CBELSA/TAPS [7], LNS [8], and Crystal Ball/TAPS [9] — reported evidence for a narrow structure at $W \sim 1.68$ GeV in the η photoproduction on the neutron. The structure was observed as a bump in the quasi-free cross-section and as a peak in the invariant-mass spectrum of the final-state η and the neutron $M(\eta n)$ [6,7,9]. The width of the bump in the quasi-free cross-section is close to that expected due to the smearing of the target neutron bound in a deuteron target by Fermi motion. The width of the peaks observed in the $M(\eta n)$ spectra is close to the instrumental resolution of the corresponding experiments [6,7,9].

Furthermore, a sharp resonant structure at $W \sim 1.685$ GeV was found in the GRAAL data on the beam asymmetry for the η photoproduction on the free proton [10, 11]. Such structure is not (or poorly) seen in the $\gamma p \to \eta p$ cross-section [12]. Any resonance whose photoexcitation on the proton is suppressed may manifest itself in polarization observables due to interference effects.

In Refs. [6,10,11,13,14], the combination of the experimental findings was interpreted as a signal of a nucleon resonance with the mass near ~ 1.68 GeV and unusual properties: the narrow width and the stronger photoexcitation on the neutron comparing to that on the proton. Alternatively, the authors of Refs. [15–17] explained the bump in the quasi-free $\gamma n \to \eta n$ in terms of the interference of well-known resonances.

If narrow $N^*(1685)$ does really exist, it can be seen not only in the η photoproduction on the neutron, but also in various other reactions, *e.g.* Compton scattering on the neutron. On the contrary, the narrow bump in the Compton scattering cannot be generated by the interference of wide resonances, as this process receives contributions of different (from η photoproduction) resonances. We present below the first study of quasi-free Compton scattering on the neutron in the energy range of $E_\gamma = 0.75$–1.5 GeV. Details of the analysis can be found in Ref. [18].

2. Compton scattering off quasi-free neutron and proton

The data were collected at the GRAAL facility. The GRAAL polarized and tagged photon beam is produced by backscattering of laser light on 6.04 GeV electrons circulating in the storage ring of the ESRF (Grenoble, France). The 4π detector (Fig. 1) is designed for the detection of neutral and charged particles.

Both $d(\gamma, \gamma' n)p$ and $d(\gamma, \gamma' p)n$ processes were measured simultaneously in the kinematics that emphasize the quasi-free reaction. Scattered photons were detected in the BGO crystal ball. Recoil neutrons and protons emitted at $\Theta_{\rm lab} = 3$–23° were detected in the assembly of the forward detectors (see Fig. 1).

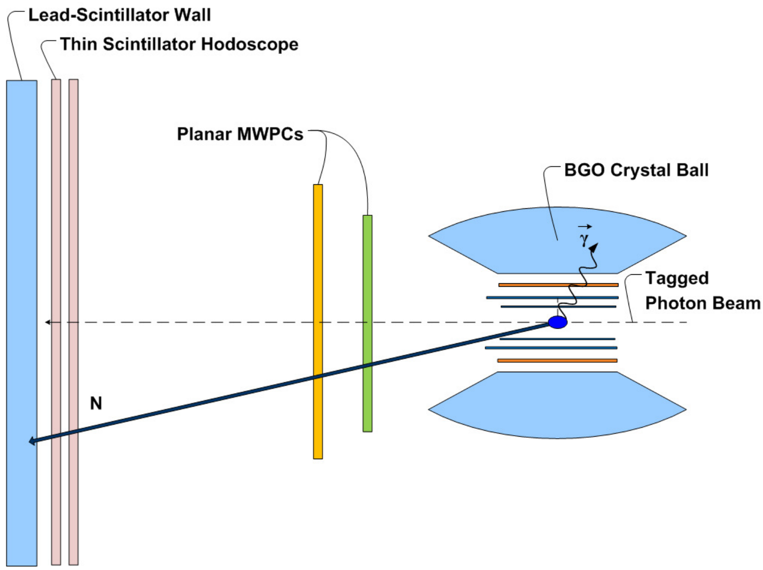

Fig. 1. Schematic view of the GRAAL detector.

As the first step of our analysis, the identification of γN state was achieved by the coplanarity criterion, by the cuts on the neutron (proton) and photon missing masses, as well as by the kinematical fits. The sample of the events selected is still contaminated by the events from the π^0 photoproduction. The π^0 cross-section is about two orders of magnitude larger than that of Compton scattering.

As the second step of the analysis, two types of the π^0 background which mimic Compton events, were taken into consideration:

(i) Symmetric $\pi^0 \to 2\gamma$ decays. The pion decays in two photons of nearly equal energies. Being emitted in a narrow cone along the pion trajectory, such photons imitate a single-photon hit in the BGO ball;

(ii) Asymmetric $\pi^0 \to 2\gamma$ decays. One of the photons takes the main part of the pion energy. It is emitted nearly along the pion trajectory. The second photon is soft and is emitted into a backward hemisphere relative to the pion track. Its energy depends on the pion energy and may be as low as 6–10 MeV.

The symmetric events can be efficiently rejected by analysing the distribution of energies deposited in crystals attributed to the corresponding cluster in the BGO ball. The efficiency of this rejection was verified in simulations and found to be 99%.

The asymmetric $\pi^0 \rightarrow 2\gamma$ decays present the major problem. The GRAAL detector provides the low-threshold (5 MeV) detection of photons in the nearly 4π solid angle. If one (high-energy) photon is emitted at backward angles of $\Theta_{\rm lab} = 130$–150°, the second (low-energy) photon is detected in the BGO ball or in the forward lead-scintillator wall (Fig. 1). This feature makes it possible to suppress the π^0 photoproduction at backward angles of $\theta_{\rm c.m.} = 150$–165°. At more forward angles one of the photons may escape from the detector through the backward hole. Consequently, the background rejection deteriorates dramatically. Therefore, we are able to identify the Compton scattering events only at backward scattering angles of $\theta_{\rm c.m.} = 150$–165°.

For the further selection of the Compton scattering events the missing energy $E_{\rm mis}$ was employed

$$E_{\rm mis} = E_\gamma - E_{\gamma'} - T_N(\theta_N)\,, \tag{1}$$

where E_γ denotes the energy of the incoming photon, $E_{\gamma'}$ is the energy of the scattered photon, and $T_N(\theta_N)$ is the kinetic energy of the recoil neutron or proton.

The right column of Fig. 2 shows the missing energy spectra corresponding to reactions on the free proton, (the first row), the quasi-free proton (the second row), and the quasi-free neutron (the third row). The peaks obtained on the quasi-free nucleons are smeared by Fermi motion.

The left and central columns show the distributions of events which correspond to the cuts on the missing energy -0.05 GeV $\leq E_{\rm mis} \leq 0.04$ GeV and 0.07 GeV $\leq E_{\rm mis} \leq 0.15$ GeV, respectively. The first cut selects events around the Compton peak. These events mostly correspond to Compton scattering with some contamination of π^0 events. The second cut selects only π^0 events.

The distribution of Compton events on the neutron (lower row, left column of Fig. 2) reveals a narrow peak at $W \sim 1.685$ GeV. The peak is very similar to that observed in the η photoproduction on the neutron. In Fig. 3 the 3rd-order-polynomial (the background hypothesis) fit for Compton events on the neutron in the interval $W = 1.53$–1.85 GeV is shown by the dashed line. The background plus Gauss function fit is shown by the solid line in Fig. 3. The log likelihood ratio of these two hypotheses ($\sqrt{2\ln L_{\rm B+S}/L_{\rm B}}$) corresponds to 5.4σ The extracted peak position is $M = 1686 \pm 5_{\rm stat.} \pm 5_{\rm syst.}$ MeV and the Gauss width is $\sigma \sim 15$ MeV (FWHM $\Gamma \sim 35$ MeV). The systematic uncertainty in the mass position is due to the uncertainties in the calibration of the GRAAL tagger. The width of the peak is equal to the smearing of the quasi-free cross-section due to Fermi motion of the target neutron.

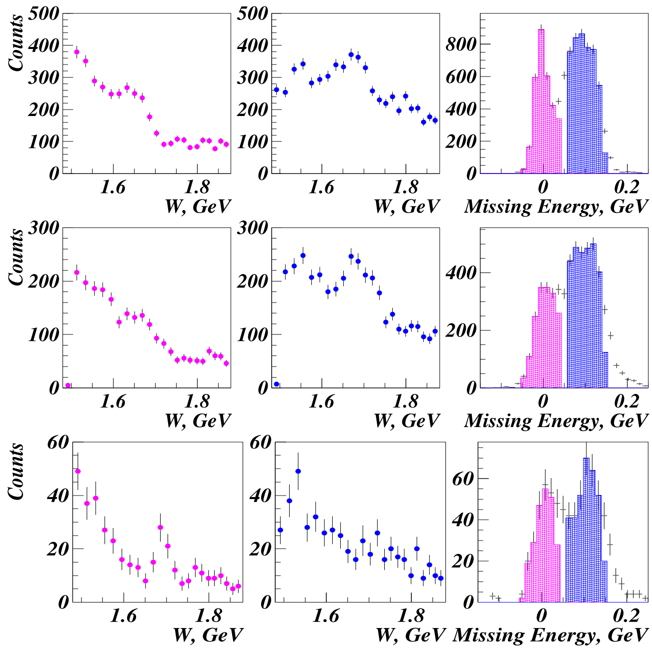

Fig. 2. Experimental data obtained on the free proton (upper row), quasi-free proton (middle row), and quasi-free neutron (lower row). Right column: spectra of missing energy. Light-grey (magenta) and dark-grey (blue) areas indicate cuts used for the selectino of Compton and π^0 events respectively. Middle column: distributions of the events corresponding to dark-grey (blue) areas in the missing-energy spectra (π^0 events). Left column: distribution of the events corresponding to light-grey (magenta) areas in the missing-energy spectra (dominance of Compton events).

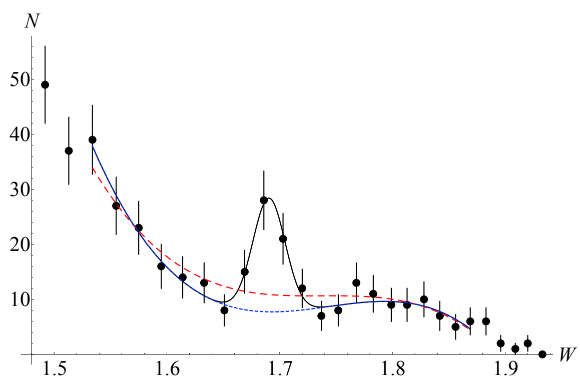

Fig. 3. Gaussian-plus-polynomial fit of the distribution of Compton events on the quasi-free neutron.

3. Conclusions

In summary, we report the evidence for a narrow resonance structure in the Compton scattering on the neutron. This structure is similar to that observed in η photoproduction on the neutron. The combination of the experimental observations suggests the existence of a narrow nucleon resonance with the mass $M \sim 1.685$ GeV and unusual properties: the narrow width $\Gamma \leq 30$ MeV, the much stronger photoexcitation on the neutron than on the proton, and the suppressed branching ratio to πN final states.

We also found that the putative $N^*(1685)$ resonance must have a small branching ratio to πN. That observation confirms the analysis of the πN elastic scattering of Ref. [3]. In the framework of χQSM, the corresponding suppression naturally occurs due to the mixing between N^* from the antidecuplet and nucleon from ordinary octet. Detailed discussion of that mechanism and influence of the excited octets on it is available in the paper of Michał Praszałowicz at this workshop [19].

4. Some remarks on putative narrow $N^*(1685)$

In this section we collect some remarks and simple estimates about narrow $N^*(1685)$.

1. Recently the data of CBELSA/TAPS [7] on η photoproduction off the neutron have been reanalysed by the same collaboration. Namely, the de-folding of the Fermi motion has been performed. The corresponding preliminary results were presented by Krusche at MESON10 workshop in Kraków [20]. One can use the results of this new analysis in order to extract the photocoupling of neutral component of $N^*(1685)$. The method is described in Ref. [13], simple calculations give

$$\sqrt{\mathrm{Br}_{\eta N}} A^n_{1/2} \sim 15 \times 10^{-3}\ \mathrm{GeV}^{-1/2} \quad \text{(CBELSA/TAPS data)}\,. \tag{2}$$

The obtained value of the photocoupling is in a striking agreement with the value obtained in Ref. [13] from the analysis of the GRAAL data of Ref. [6].

2. In Refs. [10, 11] a sharp resonant structure at $W \sim 1.685$ GeV was found in the beam asymmetry data for the η photoproduction on the free proton. Fits to the data provided an estimate of the photocoupling for the charge component of $N^*(1685)$

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

One sees that the photocoupling of $N^*(1685)$ to the proton is much smaller than to the neutron. That is what one expects for the non-strange member of the anti-decuplet [4].

Photocouplings (2) and (3) correspond to the following resonance cross-sections at maximum[1] (at $W = M_{\rm R}$):

$$\sigma_{\rm res}(\gamma n \to \eta n)|_{W=M_{\rm R}} \sim 8.5 \left(\frac{10\ {\rm MeV}}{\Gamma_{\rm tot}}\right)\ \mu{\rm b}\,, \tag{4}$$
$$\sigma_{\rm res}(\gamma p \to \eta p)|_{W=M_{\rm R}} \sim 0.038 \left(\frac{10\ {\rm MeV}}{\Gamma_{\rm tot}}\right)\ \mu{\rm b}\,.$$

Typical values of the non-resonant cross-section at $W \sim 1680$ MeV is $\sigma_n \sim$ 5–6 μb for the neutron and $\sigma_p \sim 3$ μb for the proton. One sees from that rough estimate that the resonance cross-section on the proton is very small and even in a measurement with an ideal resolution it is almost impossible to see the corresponding resonance signal. The signal of weak resonance can be revealed through its quantum interference with the strong but smooth background amplitude, see *e.g.* [21, 22]. The interference enhancement of a weak signal was used in Refs. [10,11] to reveal the signal of narrow $N^*(1685)$ in polarization observables. Note that in the case of interference a weak signal can appear not necessarily as a resonance bump but as a dip, or oscillating with energy structure.

To reveal a weak signal of $N^*(1685)$ in the cross-section of $\gamma p \to \eta p$ processes one needs to perform detailed PWA. Here we just make a "back of an envelop" estimate. As we mentioned already a weak resonance should appear as a bump, dip or oscillating structure in the cross-section. The *maximally possible* magnitude of such structure we can very roughly estimate as

$$2\sqrt{\sigma_p\ \sigma_{\rm res}(\gamma p \to \eta p)|_{W=M_{\rm R}}} \sim 0.6\ \mu{\rm b}\,. \tag{5}$$

(That number corresponds to ~ 0.05 μb/sr in the differential cross-section.) Note that the actual magnitude of the interference structure must be much smaller than the above value, as the estimate (5) assumes that only one partial wave with quantum numbers of the putative resonance contributes to the cross-section. Also note that the interference structure should appear wider than the resonance width. We stress that we did here very rough, order of magnitude estimates. The search for a very weak signal of $N^*(1685)$ in $\gamma p \to \eta p$ process requires detailed PWA.

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[1] We emphasize that the theoretical uncertainties in the estimates of the photocouplings (2) and (3) are rather large $\pm 30\%$. That can lead to $\pm 60\%$ uncertainties in the estimates of the resonance cross-sections.

3. Turning to the $\gamma n \to \eta n$ process, the main difficulties in the interpretation of the experimental observations of the neutron anomaly[2] arise from the fact that the quasi-free cross-section is smeared by the Fermi motion of the target neutron and can be affected by the re-scattering effects. Also this cross-section depends on the way it is extracted from the data, *e.g.* on the type of the cut imposed on the missing mass $\mathrm{MM}(\gamma, \eta)$. One of major tools for the selection of the quasi-free events is the cut on the neutron missing mass MM. From simple kinematical relations[3] one can derive that the corrected for the Fermi motion γn invariant mass (W^*) is related to corresponding invariant mass (W), computed under the assumption that the neutron is at rest, as follows

$$W^* = W - p_z \, \frac{E_\gamma}{W} \, . \tag{6}$$

The neutron missing mass (MM) has the following form

$$\mathrm{MM} \; = \; m_n + p_z \alpha \left(W, \cos\theta_{\mathrm{c.m.}}\right) + \frac{|\vec{p}_\perp||p^*_\eta|}{m_n} \sin\theta_{\mathrm{c.m.}} \cos\Phi \, . \tag{7}$$

Here the function

$$\alpha\left(W, \cos\theta_{\mathrm{c.m.}}\right) \equiv \frac{E_\gamma}{m_n} \left[1 - \frac{E^*_\eta}{W} - \frac{W^2 + m_n^2}{W^2 - m_n^2} \frac{|p^*_\eta|}{W} \cos\theta_{\mathrm{c.m.}} \right] \tag{8}$$

is defined in terms of c.m. momentum of η

$$|p^*_\eta| \equiv \frac{\sqrt{(W^2 - (m_n + m_\eta)^2)(W^2 - (m_n - m_\eta)^2)}}{2W}$$

and the corresponding c.m. energy

$$E^*_\eta = \sqrt{|p^*_\eta|^2 + m_\eta^2} \, .$$

One can easily check the crucial positivity property of function (8): $\alpha\left(W, \cos\theta_{\mathrm{c.m.}}\right) \geq 0$ for any value of the invariant mass W and c.m. scattering angle $\theta_{\mathrm{c.m.}}$.

From Eq. (7) we see that a strong correlation appears between p_z component of the Fermi momentum and MM. For $\mathrm{MM} \leq m_n$, the dominant p_z is negative due to the positive definiteness of the function α. The dominance

[2] The name "neutron anomaly" was introduced in Ref. [11] to denote the bump in the quasi-free $\gamma n \to \eta n$ cross-section around $W \sim 1680$ MeV.

[3] To avoid busy formulae we present here the relations derived in the linear order in the Fermi momentum $(p_z, \vec{p}_\perp)$.

of the negative p_z implies that the real invariant γn mass W^* (see Eq. (6)) is predominantly higher than the invariant mass W computed assuming the neutron at rest. That simple observation implies that if in an analysis of data an asymmetric cut on neutron missing mass is used, the visible position of the resonance bump is shifted in respect to the real resonance mass. For example, if an asymmetric cut $\mathrm{MM} \leq m_n$ is used, the bump in the quasi-free cross-section (as the function of W) should be below the mass of possible resonance. In addition, we note that due to non-trivial dependence of the "correlations coefficient" $\alpha\,(W, \cos\theta_{\mathrm{c.m.}})$ (8) on the c.m. scattering angle the size of the shift of the visible peak in the cross-section from the resonance mass should depend on the scattering angle.

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