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Evidence for a narrow $N^*(1685)$ resonance in quasifree Compton scattering on the neutron

V. Kuznetsov,[1,2] M. V. Polyakov,[3,4] V. Bellini,[5,6] T. Boiko,[7] S. Chebotaryov,[1] H.-S. Dho,[1] G. Gervino,[8,9] F. Ghio,[10,11] A. Giusa,[5,6] A. Kim,[1,12] W. Kim,[1] F. Mammoliti,[5,6] E. Milman,[1] A. Ni,[1] I. A. Perevalova,[13] C. Randieri,[5,6] G. Russo,[5,6] M. L. Sperduto,[5,6] C. M. Sutera,[5] and A. N. Vall[13]

[1] *Kyungpook National University, 702-701 Daegu, Republic of Korea*
[2] *Institute for Nuclear Research, 117312 Moscow, Russia*
[3] *Institute für Theoretische Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany*
[4] *Petersburg Nuclear Physics Institute, Gatchina, 188300, St. Petersburg, Russia*
[5] *INFN—Sezione di Catania, via Santa Sofia 64, I-95123 Catania, Italy*
[6] *Dipartimento di Fisica ed Astronomia, Universitá di Catania, via Santa Sofia 64, I-95123 Catania, Italy*
[7] *Belarussian State University, 220030 Minsk, Republic of Belarus*
[8] *Dipartamento di Fisica Sperimentale, Universitá di Torino, via P. Giuria, I-00125 Torino, Italy*
[9] *INFN—Sezione di Torino, I-10125 Torino, Italy*
[10] *INFN—Sezione di Roma, piazzale Aldo Moro 2, I-00185 Roma, Italy*
[11] *Instituto Superiore di Sanitá, viale Regina Elena 299, I-00161 Roma, Italy*
[12] *Thomas Jefferson National Accelerator Facility, Jefferson Avenue, 23606 Virginia, USA*
[13] *Physics Department, Irkutsk State University, Karl Marx str. 1, 664003 Irkutsk, Russia*

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The study of quasifree Compton scattering on the neutron in the energy range of $E_\gamma = 0.75$–1.5 GeV is presented. The data reveal a narrow peak at $W \sim 1.685$ GeV. This result, being considered in conjunction with the recent evidence for a narrow structure at $W \sim 1.68$ GeV in η photoproduction on the neutron, suggests the existence of a nucleon resonance with unusual properties: a mass $M \sim 1.685$ GeV, a narrow width $\Gamma \leqslant 30$ MeV, and the much stronger photoexcitation on the neutron than on the proton.

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Many properties of known baryons were transparently explained by the constituent quark model (CQM) [1] that treats baryons as bound system of three valence quarks in the ground or excited state. Some baryon properties remain a mystery: Almost half of the CQM-predicted nucleon and Δ resonances [2] still escape the reliable experimental identification [3] (so-called missing resonances).

The chiral quark soliton model (χQSM) is an alternative view of baryons in which they are treated as space-flavor rotational excitations of a classical object—a chiral mean field. χQSM predicts the lowest-mass multiplets of baryons to be the $1/2^+$ octet and $3/2^+$ decuplet—exactly as CQM does. The χQSM predictions for higher multiplets are different from CQM [4].

Thus, the experimental study of baryon resonances provides benchmark information for the development of theoretical models and for finding relations between them.

In this context the possible observation of a new narrow resonance $N^*(1685)$ is of potential importance. Recently, four groups—GRAAL [5], CBELSA/TAPS [6], LNS [7], and Crystal Ball/TAPS [8]—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 quasifree cross section and as a peak in the invariant-mass spectrum of the final-state η and the neutron $M(\eta n)$ [5,6,8]. The width of the bump in the quasifree cross section is close to the smearing caused by Fermi motion of the target neutron bound in a deuteron target [5]. The width of the peaks observed in the $M(\eta, n)$ spectra is close the instrumental resolution of the corresponding experiments [5,6,8].

Furthermore, a sharp resonant structure at $W \sim 1.685$ GeV was found in the GRAAL beam asymmetry data for the η photoproduction on the free proton [9,10] (see also [11]). Such a structure is not (or poorly) seen in the $\gamma p \rightarrow \eta p$ cross section [13]. Any resonance whose photoexcitation on the proton is suppressed by any reason may manifest itself in polarization observables due to interference effects.

In Refs. [5,9,10,14–16], the combination of the experimental findings was interpreted as a possible signal of a nucleon resonance with unusual properties: a mass near $M \sim 1.68$ GeV, a narrow width, and strong photoexcitation on the neutron. Alternatively, the authors of Refs. [17,18] explained the bump in the quasifree $\gamma n \rightarrow \eta n$ cross section in terms of the interference of well-known resonances or as the virtual subthreshold $K\Lambda$ and $K\Sigma$ photoproduction [19].

If the narrow $N^*(1685)$ does really exist, it can be seen not only in the η photoproduction but also in other reactions on the neutron, e.g., in Compton scattering or in π^0 photoproduction. In contrast, the narrow bump cannot be generated by the interference of wide resonances in these reactions, as they receive contributions of different (from the η photoproduction) resonances.

In this Rapid Communication, we present the measurement of Compton scattering on the neutron at photon energies of $E_\gamma = 0.75$–1.5 GeV ($W \sim 1.5$–1.9 GeV). focusing on the search for the signal of $N^*(1685)$. Simultaneously, we

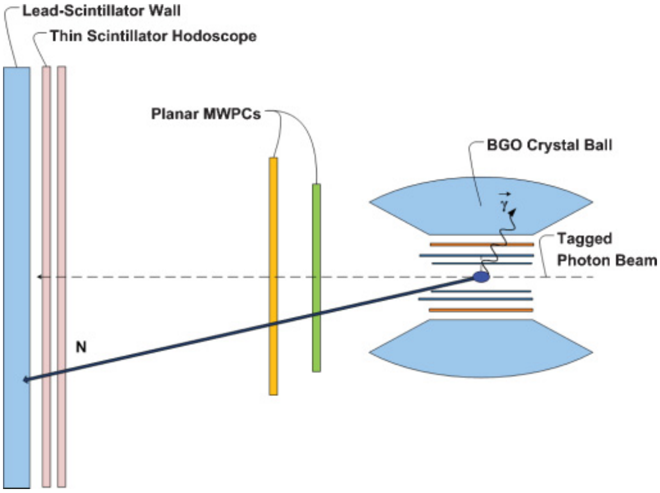

FIG. 1. (Color online) Schematic view of the GRAAL detector.

investigate the photoproduction of neutral pions on the neutron and the isospin-mirrored reactions $\gamma p \to \gamma p$ and $\gamma p \to \pi^0 p$.

The existing data for Compton scattering and π^0 production on the neutron are scarce. The available data for Compton scattering is limited to lower energies $E_\gamma \leqslant 400$ MeV [20–22]. There are no published data for the $\gamma n \to \pi^0 n$ cross section in the domain of $W \sim 1.6$–1.7 GeV. New preliminary data on the $\gamma n \to \pi^0 n$ cross section were presented in [23,24].

The data were collected at the GRAAL facility [25]. 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 European Synchrotron Radiation Facility (Grenoble, France). The 4π detector (Fig. 1) is designed for the detection of neutral and charged particles. It is composed of a cylindrically symmetrical central part, for the detection of the particles emitted at $\theta_{\text{lab}} = 25^\circ$–$155^\circ$ with respect to a beam axis, and of a forward part for the detection of the particles emitted at $\theta_{\text{lab}} \leqslant 25^\circ$.

The central part consists of two coaxial cylindrical wire chambers, a 5-mm-thick plastic scintillator barrel, which provides ΔE information for particle identification, and a BGO ball made of 480 crystals each of 21 radiation lengths. The energy resolution for the detection of photons at 1 GeV is 3% (FWHM).

The forward part consists of two planar multiwire chambers, which provide tracking angular resolution of $\sim 0.5^\circ$ for charged particles, and a double hodoscope wall made of two layers of 3-cm-thick plastic scintillator bars covering an area of 3×3 m^2 and located 3 m away from the target. The hodoscope wall is followed by the time-of-flight (TOF) lead-scintillator wall, which is an assembly of 16 modules covering the same area as the hodoscope wall [27]. Each module is composed of four $300 \times 19 \times 4$ cm^3 scintillator bars separated by three layers of 3-mm-thick lead converter. The wall provides the detection of photons, neutrons, and charged particles with an angular resolution of 3° and ΔE information. The TOF resolution is 600 ps (FWHM) for charged particles and 700–800 ps for neutrons. The estimated efficiency of the detection of photons and neutrons is about 95% and 22%, respectively. The particle identification (photons, neutrons, protons, or charged pions) in the forward assembly is achieved by means of coincidence (anticoincidence) of the corresponding signals in the lead-scintillator wall and the preceding planar chambers and the hodoscope wall, and by using ΔE-TOF relations. Momenta of the charged particles and neutrons can be reconstructed from the measured TOF and angular quantities.

Both $d(\gamma, \gamma' n)p$ and $d(\gamma, \gamma' p)n$ reactions were measured simultaneously in the kinematics that emphasize the quasifree reaction. Scattered photons were detected in the BGO crystal ball [26]. Recoil neutrons and protons emitted at $\Theta_{\text{lab}} = 3^\circ$–$23^\circ$ were detected in the assembly of the forward detectors (Fig. 1).

As the first step, the identification of γN final states was achieved using the criterion of coplanarity, along with cuts on the neutron (proton) and photon missing masses, and comparing the measured TOF and the angle of the recoil nucleon with the same quantities calculated by assuming a $\gamma N \to \gamma N$ reaction. The sample of the selected events was still contaminated by the events from π^0 photoproduction. The π^0 cross section is about two orders of magnitude larger than that of Compton scattering.

At the second step, two types of the π^0 background were taken into consideration:

(i) Symmetric $\pi^0 \to 2\gamma$ decays: The pion decays into 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 were efficiently rejected by analyzing 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 was found to be 99%.

The asymmetric $\pi^0 \to 2\gamma$ 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 $\Theta_{\text{lab}} = 130^\circ$–$150^\circ$, 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 $\theta_{\text{c.m.}} = 150^\circ$–$165^\circ$. At more forward angles one of the photons may escape from the detector through the backward hole. Consequently, the background rejection deteriorates dramatically.

For the further selection of events the missing energy E_{mis} was employed:

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

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(proton).

The simulated spectrum of the missing energy for the free proton is shown in the left panel of Fig. 2. π^0 events form

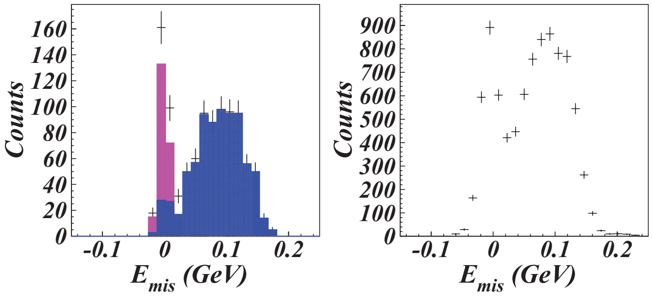

FIG. 2. (Color) Left: Simulated spectrum of missing energy for a free-proton target. The area colored in magenta shows Compton events. The blue area corresponds to the photoproduction of π^0s. Right: Spectrum of missing energy measured in the experiment with a free-proton target.

a wide distribution. Compton events generate a narrow peak centered at $E_{\rm mis} = 0$. The events in the region of this peak mainly belong to Compton scattering. In contrast, the cut $E_{\rm mis} \geqslant 0.05$ GeV selects only π^0 events. The right panel of Fig. 2 shows the same spectrum measured with the free-proton target. This spectrum is similar to the simulated one.

The right column of Fig. 3 shows the missing-energy spectra corresponding to reactions on the free proton (the first row), the quasifree proton (the second row), and the quasifree neutron (the third row). The data obtained on the quasifree nucleons are smeared by Fermi motion.

The left and central columns show the distributions of events which correspond to the cuts $-0.05 \leqslant E_{\rm mis} \leqslant 0.04$ GeV and $0.07 \leqslant E_{\rm mis} \leqslant 0.15$ 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 mostly π^0 events.

The distributions of π^0 events obtained on the free and quasifree proton are similar and exhibit a wide bump near $W \sim 1.65$ GeV. This bump is well seen in the published data for this reaction [25]. The Compton events on the proton indicate a similar structure. This structure was also seen in the previous measurements [28]. In contrast, the distribution of π^0 events on the neutron is flat. This observation is in agreement with the preliminary results from Crystal Ball/TAPS [23] and LNS Collaborations [24].

The distribution of Compton events on the neutron (lower row, left column of Fig. 3) reveals a narrow peak at $W \sim 1.685$ GeV. The peak is similar to that observed in the η photoproduction on the neutron.

In left panel of Fig. 4 the second-order-polynomial (the background hypothesis) fit for Compton events on the neutron in the interval $W = 1.585$–1.888 GeV is shown by the dashed line. The solid line in the same figure shows the background-plus-Gaussian fit. The χ^2 of both fits are 3.7/6 and 18.5/9, respectively. The log-likelihood ratio of these two hypotheses $[\sqrt{2\ln(L_{B+S}/L_B)}]$ corresponds to the confidence level of $\sim 4.6\sigma$ The extracted peak position is $M = 1686 \pm 7_{\rm stat} \pm 5_{\rm syst}$ MeV. and the rms is $\sigma \sim 12 \pm 5$ MeV ($\Gamma \approx 28 \pm 12$ MeV). The systematic uncertainty in the mass position is due to the uncertainties in the calibration of the GRAAL tagger.

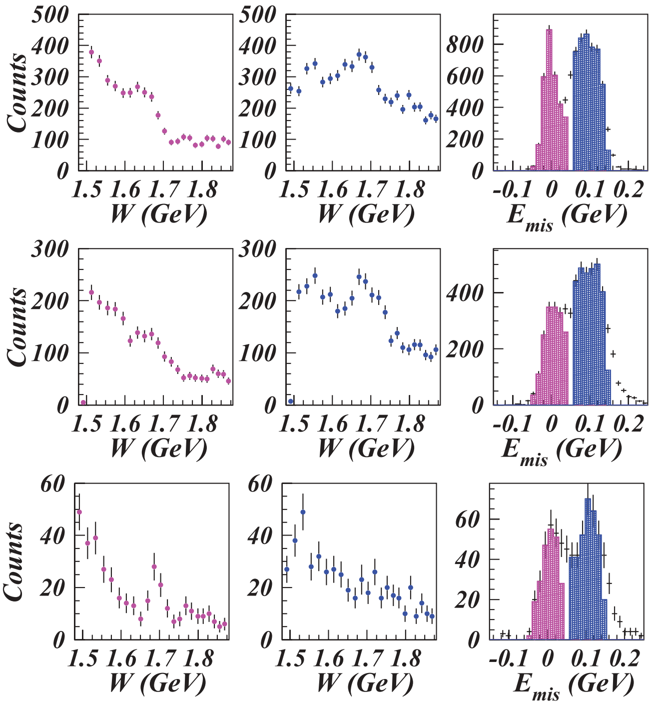

FIG. 3. (Color) Experimental data obtained on the free proton (upper row), quasifree proton (middle row), and quasifree neutron (lower row). Right column: Spectra of missing energy. Magenta and blue areas indicate cuts used for the selection of Compton and π^0 events, respectively. Middle column: W distributions of events corresponding to blue areas in the missing-energy spectra (π^0 events). Left column: Distribution of events corresponding to magenta areas in the missing-energy spectra (dominance of Compton events).

The middle panel of the Fig. 4 shows the similar distribution obtained with the wider cut on the missing energy $-0.1 \leqslant E_{\rm mis} \leqslant 0.075$ GeV. The contamination of the π^0 background is increased (especially at the higher energies) while the peak at $W \sim 1.685$ GeV remains almost unaffected.

The right panel of Fig. 4 presents the simulated yield of events obtained with the same cuts as in the left panel of the same figure. The event generator used in simulations included a flat Compton cross section. Neither peak appeared in the W spectrum of events.

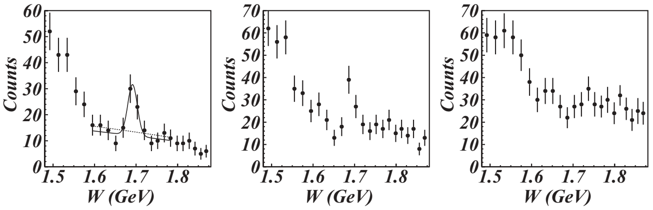

FIG. 4. Left: The W spectrum of events obtained with the cut on the missing energy $-0.05 \leqslant E_{\rm mis} \leqslant 0.04$ GeV. The solid line indicates the Gaussian-plus-second-order-polynomial fit. The dashed line corresponds to the second-order-polynomial fit only. Middle panel: The W spectrum of events obtained with the cut $-0.1 \leqslant E_{\rm mis} \leqslant 0.075$ GeV. Right panel: The simulated W spectrum obtained with the same cuts as in the left panel.

The observation of the narrow peak, along with its position and width, being considered together with the high-statistics results on the η photoproduction on the neutron [5–8] and the beam asymmetry data on the free proton [9,10], supports the existence of a narrow nucleon $N^*(1685)$ resonance and challenges the explanations [17,18] of the bump structure in the quasifree $\gamma n \to \eta n$ cross section in terms of the interference of well-known resonances.

The assumption on the virtual subthreshold $K\Lambda$ and $K\Sigma$ photoproduction [19] cannot be excluded. However, it requires an explanation for why this effect occurs in the $\gamma n \to \eta n$ and $\gamma n \to \gamma n$ reactions and is not seen in $\gamma n \to \pi^0 n$.

The putative $N^*(1685)$ resonance is dominantly photoexcited on the neutron whereas its photoexcitation on the proton is suppressed. Such a feature was suggested in Ref. [29] as the benchmark signature of a resonance belonging to the flavor SU(3) antidecuplet of exotic baryons predicted by χQSM [4]. Interestingly, the mass, the narrow width, and the isospin of $N^*(1685)$ are also in agreement with the predictions for this member of the antidecuplet [30–32].

The decisive identification of $N^*(1685)$, in particular its definite association with the second member of the exotic antidecuplet, requires further efforts and more experimental data. A critical point is to determine the spin and the parity of this state. It is worthwhile to note that the fit of the beam asymmetry data for the η on the proton resulted in three possible quantum numbers, namely P_{11}, P_{13}, or D_{13} [9,10].

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

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