Evidence for a Narrow $N'(1685)$ Resonance in Quasifree Compton Scattering on the Neutron

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The first study of quasi-free Compton scattering on the neutron in the energy range of $E_\gamma = 0.75 - 1.5$ GeV is presented. The data reveals 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 the $\eta$ photoproduction on the neutron, suggests the existence of a new nucleon resonance with unusual properties: the mass $M \sim 1.685$ GeV, the narrow width $\Gamma \leq 30$ 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)\cite{3} 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 $\Delta$ resonances\cite{2} still escape the reliable experimental identification\cite{2} (so-called “missing resonances”).

The chiral quark soliton model ($\chi$QSM) is an alternative view of baryons which are treated as space/flavor rotational excitations of a classical object - a chiral mean-field. $\chi$QSM predicts the lowest-mass multiplets of baryons to be the $1/2^+$ octet and $3/2^+$ decuplet - exactly as CQM does. The $\chi$QSM predictions for higher multiplets are different from CQM\cite{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\cite{5}, CBELSA/TAPS\cite{6}, LNS\cite{2}, and Crystal Ball/TAPS\cite{8} - reported evidence for a narrow structure at $W \sim 1.68$ GeV in the $\eta$ 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 $\eta$ and the neutron $M(\eta n)$\cite{5,6,8}. The width of the bump in the quasi-free cross section is close to the smearing caused by Fermi motion of the target neutron bound in a deuteron target\cite{8}. The width of the peaks observed in the $M(\eta n)$ spectra is close the instrumental resolution of the corresponding experiments\cite{2,6,8}.

Furthermore, a sharp resonant structure at $W \approx 1.685$ GeV was found in the GRAAL beam asymmetry data for the $\eta$ photoproduction on the free proton\cite{5,10}(see also\cite{11}). Such structure is not (or poorly) seen in the $\gamma p \rightarrow \eta p$ cross section\cite{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.\cite{5,6,10,11,12,13}, the combination of the experimental findings was interpreted as a possible signal of a nucleon resonance with unusual properties: the mass near $M \sim 1.68$ GeV, the narrow width, and the strong photoexcitation on the neutron. Alternatively, the authors of Refs.\cite{17,18} explained the bump in the quasi-free $\gamma n \rightarrow \eta n$ cross section in terms of the interference of well-known resonances or as the virtual sub-threshold $K\Lambda$ and $K\Sigma$ photoproduction\cite{19}.

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

In this paper, we present the first measurement of Compton scattering on the neutron at the 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 $N^*(1685)$.
The forward part is composed of two coaxial cylindrical wire chambers, a 5 mm thick plastic scintillator barrel, which provides $\Delta E$ information for particle identification, and a BGO ball made of 480 crystals each of 21 radiation length. 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 2 layers of 3 cm thick plastic scintillator bars covering an area of 3x3 m$^2$ and located 3 m away from the target. The hodoscope wall is followed by the TOF lead-scintillator wall which is an assembly of 16 modules covering the same area as the hodoscope wall. Each module is a composition of four 300x19x4 cm$^3$ scintillator bars separated by 3 layers of 3 mm thick lead converter. The wall provides the detection of photons, neutrons and charged particles with an angular resolution of $3^\circ$ and $\Delta E$ 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 using $\Delta E$-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 quasi-free reaction. Scattered photons were detected in the BGO crystal ball. Recoil neutrons and protons emitted at $\Theta_{\text{lab}} = 3 - 23^\circ$ were detected in the assembly of the forward detectors (Fig. 1).

As the first step, the identification of $\gamma N$ final states was achieved using the criterion of coplanarity, 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 assuming the $\gamma N \to \gamma N$ reaction. The sample of the selected events was still contaminated by the events from the $\pi^0$ photoproduction. The $\pi^0$ cross section is about two orders of magnitude larger than that of Compton scattering.

At the second step, two types of the $\pi^0$ background 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 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 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 $4\pi$ solid angle. If one (high-energy) photon is emitted at backward angles $\Theta_{\text{lab}} = 130 - 150^\circ$, 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 $\pi^0$ photoproduction at backward angles $\theta_{\text{cm}} = 150 - 165^\circ$. At more forward angles one of the photons may escape out from the detector through the backward hole. Consequently, the background rejection deteriorates dramatically.

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

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

(1)
where $E_\gamma$ denotes the energy of the incoming photon, $E_\pi$ 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. $\pi^0$ events form a wide distribution. Compton events generate a narrow peak centered at $E_{mis} = 0$. The events in the region of this peak mainly belong to Compton scattering. On the contrary, the cut $E_{mis} \geq 0.05$ GeV selects only $\pi^0$ 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 quasi-free proton (the second row), and the quasi-free neutron (the third row). The data 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 $-0.05$ GeV $\leq E_{mis} \leq 0.04$ GeV and $0.07$ GeV $\leq E_{mis} \leq 0.15$ GeV respectively. The first cut selects events around the Compton peak. These events mostly correspond to Compton scattering with some contamination of $\pi^0$ events. The second cut selects mostly $\pi^0$ events.

The distributions of $\pi^0$ events obtained on the free and quasi-free 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 [22]. The Compton events on the proton indicate a similar structure. This structure was also seen in the previous measurements [28]. On the contrary, the distribution of $\pi^0$ 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 $\eta$ photoproduction on the neutron.

In left panel of Fig. 4 the 2nd-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 $\chi^2$ of both fits are 3.7/6 and 18.5/9 respectively. The log likelihood ratio of these two hypotheses ($\chi^2/2 \ln(2B/S)$) corresponds to the confidence level of $\sim 4.6\sigma$ The extracted peak position is $M = 1686 \pm 7_{stat} \pm 5_{syst}$ MeV, and the r.m.s 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.

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

The right panel of the 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 MC included a flat Compton cross section. Neither of any peak appeared in the $W$ spectrum of events.
It is worth noting that the authors of Ref. [12] arrived at a different conclusion. The detailed critique of the results from Ref. [12] is available in Ref. [9]. This critique remains unreplied.

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 \( \eta \) on the proton resulted in three possible quantum numbers, namely \( P_{11} \), or \( P_{13} \), or \( D_{13} \).

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

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