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A new $N^*(1675)$ resonance in the $\gamma N \to \eta N$ reaction

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Abstract

We study the η-photoproduction focusing on the new nucleon resonance which was observed at $\sqrt{s} = 1675$ MeV with a narrow decay width (~ 10 MeV) in the recent GRAAL experiment. Using an effective Lagrangian approach, we compute differential cross sections for the η-photoproduction. In addition to $N^*(1675)$, we employ three other nucleon resonances, i.e., $N^*(1535)$, $N^*(1650)$ and $N^*(1710)$, and vector meson exchanges which are the most relevant ones to this reaction process. As a result, we can reproduce the GRAAL data qualitatively well and observe obvious isospin asymmetry between the transition magnetic moments of $N^*(1675)$: $\mu_{\gamma n n^*} \gg \mu_{\gamma p p^*}$.

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Keywords: η-photoproduction; GRAAL experiment; Pentaquark

1. Introduction

After the first experimental observation of a signal of the pentaquark baryon Θ^+ by the LEPS Collaboration at SPring-8 which was motivated by the theoretical predictions from the chiral soliton model (χSM) [1], we have experienced abundant research activities in hadron physics. However, we still have many unknowns about the Θ^+ baryon, and there have been strong criticisms against it. The negative results of the recent CLAS experiment deepened the question on its existence [2].

In this recent unsettled situation for Θ^+, it is very natural that there have been new theoretical and experimental efforts for Θ^+. Theoretically, for instance, higher spin states of Θ^+ were suggested in the constituent quark model, lattice QCD and reaction studies [3–6]. Experimentally, the LEPS Collaboration reported a new signal for Θ^+ [7]. $I = 1$ Θ^{++} and the charmed pentaquark were also reported by the STAR Collaboration [8]. In addition to them, a recent GRAAL experiment announced a new nucleon resonance with a seemingly narrow decay width ~ 10 MeV and a mass ~ 1675 MeV in the η-photoproduction. This new nucleon-like resonance, $N^*(1675)$, may be regarded as a nonstrange pentaquark because of its narrow decay width, which is assumed to be one of the significant features of typical pentaquark baryons, though one should not exclude a possibility that it might be a known one among existing resonances. Furthermore, the value of its mass, 1675 MeV, is close to that obtained by the χSM (1710 MeV).

Among these new experimental results, we focus on the GRAAL experiment of the η-photoproduction in the present work. We note that the reaction process $\gamma N \to \eta N$ has been explored already experimentally as well as theoretically [9–12]. It has been known from these previous studies that the nucleon-resonance pole (N^*) and vector meson-exchange contributions prevail over those of the background. Especially, the contribution from the $N^*(1535)$ is the most dominant one near the threshold ($\sqrt{s} \sim 1490$ MeV) region. However, we have still many theoretical ambiguities to be solved concerning this reaction process. For instance, the value of the coupling constant $g_{\eta NN}$ lies in a wide range (0–7), depending on either theo-

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retical models or on experiments to estimate the strength (see Refs. [13–18]).

In addition to the known facts of the η-photoproduction mentioned above, a new interesting feature was observed in the GRAAL experiment: the $N^*(1675)$ is preferably excited on the neutron target by photons. It implies that large isospin asymmetry may exist in the electromagnetic transitions for $N^*(1675) \to N\gamma$, since the strong coupling constants $g_{\eta NN^*}$ are independent of the nucleon isospin. It would be difficult to explain the two experimental observations, the narrow peak and its strong isospin dependence, in terms of the conventional knowledge of meson–baryon interactions.

Recently, the values of the magnetic transitions, $\mu_{\gamma NN^*}$, were estimated within the framework of the chiral quark-soliton model (χQSM) [19] in which the $N^*(1675)$ was assumed to be a member of the baryon antidecuplet. Interestingly enough, the results showed obvious isospin asymmetry between $\mu_{\gamma nn^*}$ and $\mu_{\gamma pp^*}$ in their magnitudes, though they depended on the nucleon Σ-term rather sensitively. In fact, the magnetic transition $\mu_{\gamma pp^*}$ vanishes completely as a consequence of SU(3) flavor symmetry when $N^*(1675)$ is assumed to belong to the antidecuplet, while the $\mu_{\gamma nn^*}$ remains finite. The result of the χQSM is thus understood as a general consequence of flavor SU(3) symmetry and its breaking.

In the present work, we investigate the η-photoproduction via the $\gamma N \to \eta N$ reaction process theoretically, including the $N^*(1675)$ in the framework of the effective Lagrangian method at the tree-level calculation with gauge-invariant form factors [20,21] employed. For the numerical calculations, various unknown parameters are determined by existing experimental data. We consider both positive and negative parities of $N^*(1675)$, since we have no experimental information of its parity. Furthermore, we consider both positive and negative anomalous magnetic transition moments $\mu_{\gamma NN^*}$, since the sign of the coupling constant is unknown to date.

We will show in the present work that strong isospin asymmetry, i.e., $\mu_{\gamma nn^*} \gg \mu_{\gamma pp^*}$, does really exist in reproducing the GRAAL data. The estimated values are consistent with those from the χQSM [19] and the phenomenological estimation [22]. As a result, we will see that it is reasonable to regard the newly observed narrow resonance peak by the GRAAL experiment as a member of pentaquark baryon antidecuplet.

This Letter is organized as follows: in Section 2 we will define the effective Lagrangians and construct the invariant amplitudes. We will also discuss various ways of determining parameters. Section 3 will be devoted to the numerical results for the possible parameter combinations. In the final section, we will summarize our work.

2. Formalism

We start with the effective Lagrangians for the interaction vertices as depicted in Fig. 1, where we also define the four-momenta of scattering particles. The effective Lagrangians are given as

$$\begin{aligned}
\mathcal{L}_{\gamma NN} &= -e\bar{N}\not{A}N - i\frac{e\kappa_N}{2M_N}\bar{N}\sigma_{\mu\nu}q^\nu A^\mu N + \text{h.c.},\\
\mathcal{L}_{\eta NN} &= -ig_{\eta NN}\bar{N}\gamma_5\eta N + \text{h.c.},\\
\mathcal{L}_{VNN} &= -g^v_{VNN}\bar{N}\not{V}N - i\frac{g^t_{VNN}}{2M_N}\bar{N}\sigma_{\mu\nu}q^\nu V^\mu N + \text{h.c.},\\
\mathcal{L}_{\gamma NN^*} &= \frac{e\mu_{\gamma NN^*}}{2(M_N+M_{N^*})}\bar{N}^*\Gamma_{\mu\nu}F^{\mu\nu}N + \text{h.c.},\\
\mathcal{L}_{\eta NN^*} &= -ig_{\eta NN^*}\bar{N}\Gamma\gamma_5\eta N^* + \text{h.c.},\\
\mathcal{L}_{\gamma\eta V} &= \frac{eg_{\gamma\eta V}}{4M_\eta}\epsilon_{\mu\nu\sigma\rho}F^{\mu\nu}V^{\sigma\rho}\eta + \text{h.c.},
\end{aligned} \tag{1}$$

where N, N^*, η and V stand for the fields corresponding to the nucleon, nucleon resonance, pseudoscalar meson η, and vector mesons (ρ and ω), respectively. With the parity of the nucleon resonance N^* distinguished, Γ and $\Gamma_{\mu\nu}$ are defined as follows:

$$\begin{aligned}
&\text{Positive parity:} \quad \Gamma^{\mu\nu} = \sigma^{\mu\nu} \text{ and } \Gamma = \mathbf{1}_{4\times4},\\
&\text{Negative parity:} \quad \Gamma^{\mu\nu} = \gamma_5\sigma^{\mu\nu} \text{ and } \Gamma = \gamma_5.
\end{aligned} \tag{2}$$

Although there are about twenty nucleon resonances experimentally known for the energy regions below $\sqrt{s} = 2.0$ GeV, we only consider four nucleon resonances: $N^*(1535, J^P =$

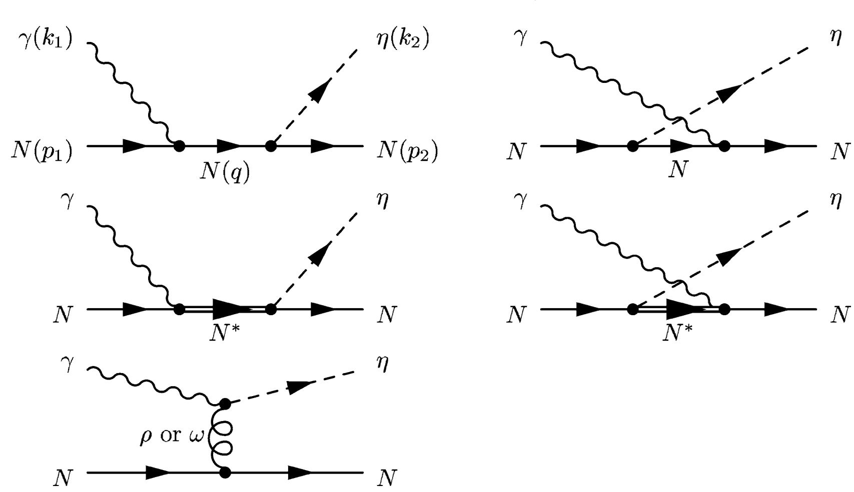

Fig. 1. Born diagrams calculated in the effective Lagrangian method. Top: nucleon pole contributions (left: s-channel and right: u-channel), middle: nucleon-resonance pole contributions (left: s-channel and right: u-channel) and bottom: the vector meson-exchange contributions (t-channel).

$1/2^-$), $N^*(1650, J^P = 1/2^-)$, $N^*(1675, J^P = \text{unknown})$, and $N^*(1710, J^P = 1/2^+)$, which turn out to make major contributions to the η-photoproduction. We verified that other resonances gave negligibly small contributions to the total amplitudes, especially from the threshold to $E_{\rm CM} \leqslant 1.7$ GeV, which is the region we are interested in.

For the coupling constants of the nucleon, i.e., $g_{\eta NN}$, $g^{v,t}_{\rho NN}$ and $g^{v,t}_{\omega NN}$, we adopt the values from the Nijmegen potential [18], while the photon couplings $g_{\rho\eta\gamma}$ and $g_{\omega\eta\gamma}$ are determined by the radiative decays of ρ and ω mesons [23]. Their values are listed in Table 1.

In order to calculate the contributions of the nucleon-resonances, we need to determine the resonance parameters $\kappa_{\gamma NN^*}$ and $g_{\eta NN^*}$. For the known resonances $N^*(1535)$, $N^*(1650)$ and $N^*(1710)$, we utilize the experimental data of the partial decay width and electromagnetic helicity amplitudes [24] via the following relations:

$$g_{\eta NN^*} = \sqrt{\frac{4\pi M_{N^*}\Gamma_{N*\to\eta N}}{|\vec{P}_f|M_N\left(\sqrt{1+\frac{|\vec{P}_f|^2}{M_N^2}}\pm 1\right)}},$$
$$|A_{\frac{1}{2}}|^2 = \left(\frac{e|\kappa_{\gamma NN^*}|}{M_{N^*}+M_N}\right)^2\frac{M_{N^*}^2-M_N^2}{2M_N}. \tag{3}$$

In Eq. (3), the $\pm$ sign corresponds to negative and positive parity resonances. For the new resonance $N^*(1675)$, the value of the total decay width, $\Gamma_{N^*(1675)\to\text{all}}$, was estimated to be ~ 10 MeV in the GRAAL experiment [25,26]. We assume in the present calculation that the decay process of $N^* \to \eta N$ is solely explained by the total decay width from which the coupling constant $g_{\eta NN^*(1675)}$ is determined. We find $g_{\eta NN^*(1675)} = 2.8$ for the positive parity $N^*(1675)$, whereas 0.54 for the negative parity one. Furthermore, in order to make a better comparison with the experimental data which include the effect of the Fermi motion of the neutron in the deuteron, we use an effective width of $N^*(1675)$ $\Gamma_{\rm eff} = 40$ MeV in the Breit–Wigner form. The unknown is the electromagnetic coupling of $\mu_{\gamma NN^*}$, which is the only parameter in our calculation. We vary the value of $\mu_{\gamma NN^*}$: $|\mu_{\gamma NN^*}| \leqslant 0.3\mu_N$ [19]. The resulting coupling constants are listed in Table 2.

Table 1
The relevant coupling constants used in the present work. The meson–nucleon couplings are taken from the Nijmegen potential [18] and the meson–meson–photon ones from Ref. [23]

$g_{\eta NN}$	$g^v_{\rho NN}$	$g^t_{\rho NN}$	$g^v_{\omega NN}$	$g^t_{\omega NN}$	$g_{\rho\eta\gamma}$	$g_{\omega\eta\gamma}$
0.47	2.97	12.52	10.36	4.20	0.89	0.192

The invariant amplitudes are now given as follows:

$$\begin{aligned}
i\mathcal{M}_s &= \frac{eg_{\eta NN}}{\{(k_1+p_1)^2-M_N^2\}}\bar{u}(p_2)\\
&\quad\times\left[\gamma_5\{F_s^N \not{k}_1 + F_c(\not{p}_1+M_N)\}\not{\epsilon}\right.\\
&\quad\left.-\frac{\kappa_N F_s^N}{2M_N}\gamma_5(\not{k}_1+\not{p}_1+M_N)\not{\epsilon}\not{k}_1\right]u(p_1),\\
i\mathcal{M}_u &= \frac{eg_{\eta NN}}{\{(k_2-p_1)^2-M_N^2\}}\bar{u}(p_2)\\
&\quad\times\left[\not{\epsilon}\{F_c(\not{p}_2+M_N)-F_s^N\not{k}_1\}\gamma_5\right.\\
&\quad\left.+\frac{\kappa_N F_u^N}{2M_N}\not{k}_1\not{\epsilon}(\not{p}_2-\not{k}_1+M_N)\gamma_5\right]u(p_1),\\
i\mathcal{M}_t &= \frac{-ieg_{\gamma\eta V}F_t^V}{M_\eta\{(k_1-k_2)^2-M_V^2\}}\bar{u}(p_2)\\
&\quad\times\left[g^v_{VNN}\epsilon_{\mu\nu\sigma\rho}k_1^\mu\epsilon^\nu(k_1-k_2)^\sigma\gamma^\rho\right.\\
&\quad+\frac{g^t_{VNN}}{4M_N}\{\not{q}\epsilon_{\mu\nu\sigma\rho}k_1^\mu\epsilon^\nu(k_1-k_2)^\sigma\gamma^\rho\\
&\quad\left.-\epsilon_{\mu\nu\sigma\rho}k_1^\mu\epsilon^\nu(k_1-k_2)^\sigma\gamma^\rho(\not{k}_1-\not{p}_1)\}\right]u(p_1),\\
i\mathcal{M}_{s^*} &= \frac{e\kappa_{\gamma NN^*}g_{\eta NN^*}}{(M_N+M_{N^*})\{(k_1+p_1)^2-M_{N^*}^2-iM_{N^*}\Gamma_{\eta NN^*}\}}\\
&\quad\times\bar{u}(p_2)\gamma_5\Gamma(\not{k}_1+\not{p}_1+M_{N^*})\Gamma\not{\epsilon}\not{k}_1u(p_1),\\
i\mathcal{M}_{u^*} &= \frac{e\kappa_{\gamma NN^*}g_{\eta NN^*}}{(M_N+M_{N^*})\{(k_2-p_1)^2-M_{N^*}^2-iM_{N^*}\Gamma_{\eta NN^*}\}}\\
&\quad\times\bar{u}(p_2)\Gamma\not{\epsilon}\not{k}_1(\not{k}_2-\not{p}_1+M_{N^*})\gamma_5\Gamma u(p_1).
\end{aligned}\tag{4}$$

The subscripts s^* and u^* denote the nucleon resonance pole terms in the s- and u-channels, respectively, while the usual Born terms of the nucleon are indicated by s, u and t. We note that the nucleon resonance and vector meson pole terms are gauge-invariant. We verified that the invariant amplitudes of Eq. (4) satisfied the Ward–Takahashi identity. In order to take into account extended structures of hadrons, we employ hadronic form factors which preserve the Ward–Takahashi identity in terms of the prescription proposed in Refs. [20,21]. They are parameterized as

$$F_x^i = \frac{\Lambda^4}{\Lambda^4+(x-M_i^2)^2}, \tag{5}$$

where x is the subscript indicating the Madelstam variables, s, t, and u, while i stands for the virtual particle in the channel x. We also employ one common form factor F_c^N to make the s-

Table 2
The parameters of the nucleon resonances: full decay widths, branching ratios and helicity amplitudes for the neutron and proton

	Γ_{N^*} [MeV]	$\Gamma_{N^*\to\eta N}/\Gamma_{N^*}$ [%]	$A^n_{1/2}$ [GeV$^{-1/2}$]	$A^p_{1/2}$ [GeV$^{-1/2}$]
$N^*(1535)$	180 (150–200)	50 (30–55)	−0.065 (−0.046 ± 0.027)	0.087 (0.090 ± 0.030)
$N^*(1650)$	150 (145–190)	7 (3–10)	−0.015 (−0.015 ± 0.021)	0.053 (0.053 ± 0.016)
$N^*(1710)$	100 (50–250)	6 (6 ± 1)	−0.002 (−0.002 ± 0.014)	0.009 (0.009 ± 0.022)

and u-channels satisfy the Ward–Takahashi identity

$$F_c = F_s^N + F_u^N - F_s^N F_u^N. \tag{6}$$

This prescription of F_c is determined by the normalization condition of the form factor, when exchange particles are on mass-shell. The cutoff parameter for the nucleon pole terms is set to be $\Lambda \simeq 0.85$ GeV [27]. For the resonance terms, we do not introduce the form factor as in resonance dominant models [11]. For the ρ-meson exchange diagram, we, however, use a larger value of the cut-off mass for the ρNN vertex [11,28]; $\Lambda \simeq 1.3$ GeV.

3. Numerical results

As explained in the previous section, we consider several Born terms including different nucleon resonances and vector meson exchanges. Theoretically, the relative signs of these terms are important as they are added coherently in the amplitude. We can determine the signs of the resonance contributions of $N^*(1650)$ and $N^*(1710)$ relative to the nucleon pole term through the signs of the helicity amplitudes [24]. We do not know yet the relative sign of the ρ- and ω-exchange terms and the new resonance term of $N^*(1675)$. The relative sign of the vector-meson terms is chosen in such a way that the total amplitude produces the observed energy dependence of the η-photoproduction. Note that due to the isospin structure ρ-meson exchange changes the sign of the proton and neutron targets, while ω-meson exchange leaves it unchanged. We also considered the contribution of $N^*(1675)$ by changing the sign of the electromagnetic coupling $\mu_{\gamma NN^*}$.

Figs. 2 and 3 draw our main results of the present investigation, showing the energy dependence of the differential cross sections at $\theta = 145$ degree. These four panels in each figure correspond to the cases of different isospin states (p or n) of $N^*(1675)$ targets with positive and negative parities. The cross section are computed by using different $\mu_{\gamma NN^*}$ and then are compared with the data of the GRAAL experiment. In all cases, the solid lines represent the result without the $N^*(1675)$ contribution, where $\mu_{\gamma NN^*} = 0$. In fact, the differential cross sections were taken at several angles, $\theta = 120$–155 degrees, within which the results are qualitatively similar.

Before discussing the role of the $N^*(1675)$, we make general remarks. First, the largest peak around $E_{\rm CM} \sim 1530$ MeV is nicely reproduced by choosing reasonable parameters for the $N(1535)$. Furthermore, the results are in a good agreement with experimental data up to $E_{\rm CM} \lesssim 1.9$ GeV for the proton target. In the higher energy region, $E_{\rm CM} \gtrsim 1.7$ GeV, note that ρ-meson exchange interferes with various term. As compared to the proton case, the cross sections for the neutron target is underestimated in the region of $E_{\rm CM} \gtrsim 1.7$ GeV. We have tried to calculate the differential cross sections with parameters varied in the experimentally allowed region and found that it was possible to obtain better results, compared to the GRAAL data. However, it was not easy at all to reproduce both the proton

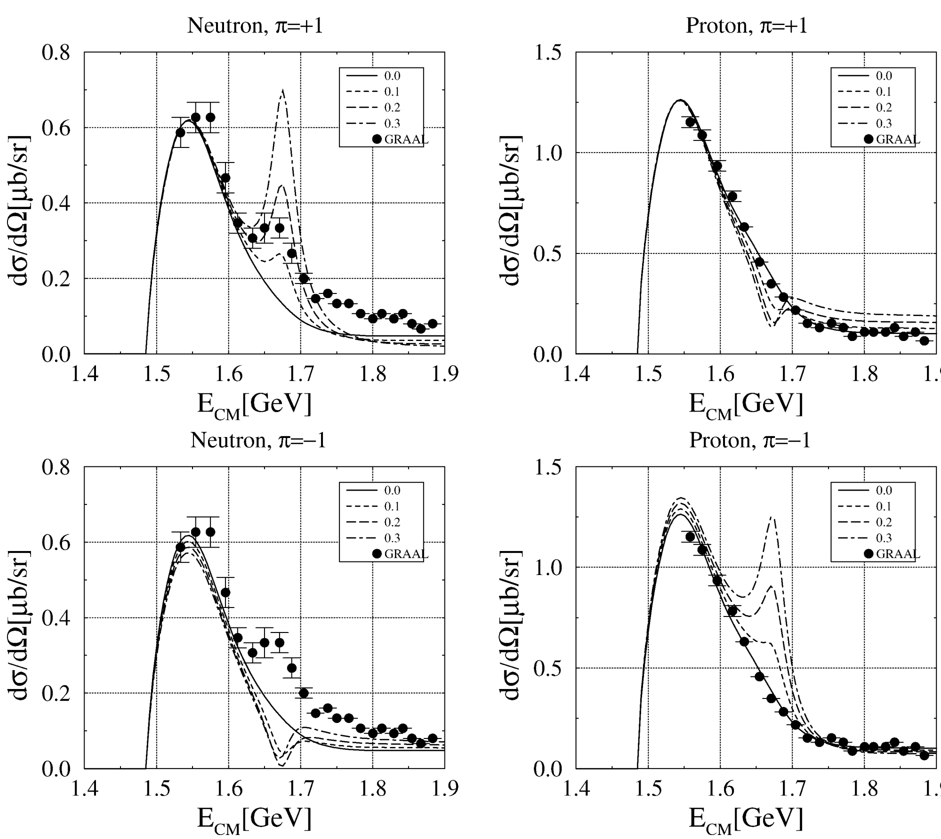

Fig. 2. The differential cross sections as functions of the total energy in the center of mass (CM) energy frame. We depict them in different targets (neutron at left column and proton at right one), parities of $N^*(1675)$ (positive at upper two panels and negative at lower two ones). The four curves in each panel indicate $\mu_{\gamma NN^*} = 0.0, 0.1, 0.2, 0.3\mu_N$. The experimental data are taken from Ref. [25].

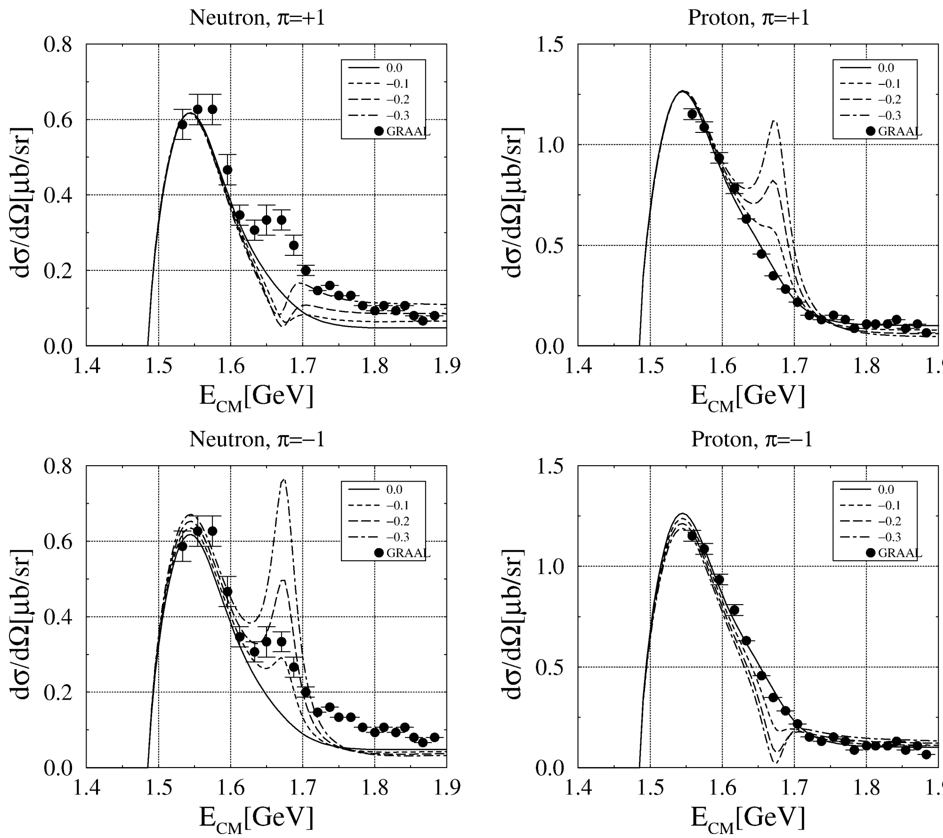

Fig. 3. The differential cross sections as functions of the total energy in the center of mass (CM) energy frame. We depict them in different targets (neutron at left column and proton at left one), parities of $N^*(1675)$ (positive at upper two panels and negative at lower two ones). The four curves in each panel indicate $\mu_{\gamma NN^*(1675)} = 0.0, -0.1, -0.2, -0.3\mu_N$. The experimental data are taken from Ref. [25].

and neutron cases simultaneously in this higher energy region. We expect that introducing other background terms may help improve the results. However, since we are interested in understanding the newly found resonance N^*, not in describing the data quantitatively well, we will not go further on to consider more resonances than here. In the following, let us discuss exclusively the properties of the peak structure at around $E_{\rm CM} \sim 1675$ MeV.

In Fig. 2, we show the results with the positive $\mu_{\gamma NN^*}$. With $\mu_{\gamma NN^*}$ turned on, the differential cross section starts to get changed around $E_{\rm CM} \sim 1675$ MeV, showing various patterns of interference depending on the parity of the N^*. As $\mu_{\gamma NN^*}$ is increased, two different patterns appear: while the differential cross sections of the n (p) with positive (negative) parity show the clearer peaks in the vicinity of 1675 MeV, those of the n (p) with the negative (positive) parity are getting suppressed around that energy. These two different behaviors according to the parity of the N^* stem from either constructive or destructive interference among the $N^*(1675)$ and other contributions. In order to explain the GRAAL data quantitatively with a positive $\mu_{\gamma NN^*}$, we need to assume that the new nucleon-like resonance should have positive parity. Moreover, $\mu_{\gamma pp^*}$ must be much smaller than $\mu_{\gamma nn^*}$, which is consistent with SU(3) flavor symmetry and the recent results of the χQSM. When $\mu_{\gamma nn^*} \simeq 0.2\mu_N$, the resonance structure is well described in the neutron channel.

Fig. 3 shows the results with negative values of $\mu_{\gamma NN^*}$. The tendency is similar to Fig. 2 when the parity is interchanged. The peak structure of the neutron is well reproduced when $\mu_{\gamma NN^*} \sim -0.2\mu_N$ as in Fig. 3. However, in this case, the n^* should have the negative parity. Thus, we conclude that the resonance structure of the neutron may be explained by introducing the resonance $N^*(1675)$ with a finite magnetic transition couplings; $|\mu_{\gamma NN^*}| \sim 0.2\mu_N$. This value is consistent with those investigated in the χQSM and the phenomenological study [22].

4. Summary and conclusion

In the present work, we have investigated the η-photoproduction via the reaction $\gamma N \to \eta N$, based on the effective Lagrangians and the Born approximation. Our focus was on the new nucleon-like resonance $N^*(1675)$ observed in the recent GRAAL experiment [25,26]. We assumed that $N^*(1675)$ was a pentaquark baryon identified as a member of the baryon antidecuplet. In order to make our study rather quantitative, we included several nucleon resonances in addition to the nucleon pole and vector meson exchanges. Moreover, we included the new resonance of $N^*(1675)$ with finite strengths of the electromagnetic coupling constants $\mu_{\gamma NN^*}$.

Since we do not know yet the parity of the resonance, we have considered both positive and negative parities for the $N^*(1675)$. The electromagnetic coupling is then the magnetic type for the positive parity case and electric type for the negative parity one. In both cases, we were able to describe the GRAAL data well, using the transition magnetic moments $|\mu_{\gamma nn^*(1675)}| \sim 0.2\mu_N$ and $|\mu_{\gamma pp^*(1675)}| \sim 0$. It implies that it is quite reasonable to regard the new nucleon-like resonance in the GRAAL data as a nucleon partner of the pentaquark baryon belonging to the SU(3) antidecuplet.

Acknowledgements

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