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Photoproduction of the η' mesons as a new tool to probe baryon resonances

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We examine η' photoproduction as a novel tool to study baryon resonances around 2 GeV, of particular interest to the quark shell model, which predicts a number of them. We find important roles of the form factors at the strong vertices, and show that the $N^*(2080)$ can be probed efficiently by this reaction.

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Thanks to the advent of the first continuous wave (cw) electron machine in the 4–6 GeV region of electron energy, now in operation at CEBAF, a powerful tool is at hand to probe the baryon resonances with real and virtual photons. A novel reaction to use in this context, focus of this paper, is

$$\gamma + p \to \eta' + p, \tag{1}$$

where $\eta'(958)$ is the heaviest member of the ground state pseudoscalar meson nonet. Very little is known about this reaction either theoretically or experimentally. Our paper aims at establishing the importance of this reaction in probing the nucleon resonances around 2 GeV, whereabout the quark shell model predicts a rather rich structure [1]. The present experimental picture is very confusing [2], not yet confirming many of these resonances, giving rise to what has been termed a *missing resonances* problem [3]. The threshold for the reaction is $W = 1896$ MeV, corresponding to a lab photon energy of $E_\gamma = 1447$ MeV. At present, the world supply of the photoproduction data comes from the old work of the Aachen-Berlin-Bonn-Hamburg-Heidelberg-München (ABBHHM) group at DESY [4], consisting of just ten points of total cross section over a very broad energy range ($E_\gamma = 1.7$–5.2 GeV), with poor energy resolution and statistics. New experiments, proposed [5] at CEBAF, would change this situation radically in the near future.

The η' meson is interesting in its own right, along with its close relative, the $\eta(547)$, for a variety of reasons. First is the question of the η_1, η_8 mixing angle. There are large discrepancies between values obtained from the linear and quadratic mass formulas of the nonet [6]. There is also the issue of the quark content of the η and η', on which some [7] information are available from the $J/\psi \to$vector+pseudoscalar decays. The question of the relevance of the SU(3)×SU(3) chiral perturbation theory [8] is not clear here; no information is available on its application to the reaction (1). Finally, there is the old issue of the chiral U(1) symmetry breaking and the η mass [9], hence its possible relevance to the η' mass.

Of special interest to the reaction (1) are questions connected with the effective Lagrangian of the $\eta' NN$ interaction. We can write this at the tree level [10,11]

$$\begin{aligned} L_{\eta' NN} = g_{\eta'}[&-i\epsilon \bar{N}\gamma_5 N \eta' \\ &+(1-\epsilon)(1/2M)\bar{N}\gamma_\mu\gamma_5 N \partial^\mu \eta'], \end{aligned} \tag{2}$$

where $0 \le \epsilon \le 1$, the coupling constant $g_{\eta'}$ is essentially unknown. There is no compelling reason, from the heavy mass of the η', to choose either $\epsilon = 1$ [pseudoscalar (PS)] or $\epsilon = 0$ [pseudovector (PV)] limit, or any particular value in between. In this paper, we shall investigate the pseudoscalar coupling case ($\epsilon = 1$).

We can make an estimate of the coupling constant $g_{\eta'}$ by using the quark-model mixing relation, where the singlet to octet mixing angle is θ. We have with singlet and octet coupling taken as g_{η_8} and g_{η_1}, respectively,

$$\begin{pmatrix} g_\eta \\ g_{\eta'} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} g_{\eta_8} \\ g_{\eta_1} \end{pmatrix}. \tag{3}$$

We assume that strange quark content of the nucleons is negligible and take the $g_{\eta_1}/g_{\eta_8} \simeq \sqrt{2}$ [12]. This simply follows from the SU(3)-flavor wave functions of the η_8 and η_1 configurations. From this, we can write

$$g_{\eta'} = \frac{\sqrt{2}\cos\theta - \sin\theta}{\cos\theta + \sqrt{2}\sin\theta} g_\eta. \tag{4}$$

The coupling constant g_η is also poorly known. But the η photoproduction data have yielded [10] a range, $0.6 \le g_\eta^2/4\pi \le 6.4$, for $\epsilon = 1$. This allows us to vary the coupling of the η' meson to the nucleon in the domain

$$1.9 \le g_{\eta'} \le 6.2, \tag{5}$$

assuming $\theta \simeq 20°$ [6], $\epsilon = 1$. This would be the coupling constant range we shall be using in this work. We have found that the process (1) is not very sensitive to this quantity.

The tree-level structure of the photoproduction amplitude can be determined in parallel to that of the η photoproduction [10]. While there are obvious similarities, the differences must be stressed, starting with $g_{\eta'}$ in (2). The t-channel vector meson exchanges [13] involve the ρ and ω mesons, with the product of their relevant strong and electromagnetic coupling constants [10] constrained by the relations

$$\lambda'_\rho g_v^\rho + \lambda'_\omega g_v^\omega \simeq 4.1, \tag{6}$$

$$\lambda'_\rho g_t^\rho + \lambda'_\omega g_t^\omega \simeq 12.1. \tag{7}$$

Relations (6) and (7) are obtained, in parallel to the case of the η meson [10], taking into account the η' structure in the quark model. The experimentally measured ratio of the widths [2] of the radiative processes $\eta' \to \rho^0\gamma$ and $\eta' \to \omega\gamma$ is about 10, while our quark model estimate gives 11.7.

The biggest difference from the η photoproduction comes from the intermediate N^*'s excited in the η' photoproduction. In the η photoproduction $N^*(1535)$ is known to be dominant [10]. In reaction (1) the specific relevance of the N^*'s can be roughly determined from the work of Capstick and Roberts (CR) [1]. Based on the strength of the product

$$\chi_\lambda = \Gamma_{\eta'}^{1/2} A_\lambda / \Gamma_0, \tag{8}$$

where A_λ is the electromagnetic excitation amplitude $N\gamma \to N^*$ for helicity λ, $\Gamma_{\eta'}$ and Γ_0 are the η' nucleon and total decay widths, respectively, for a given N^*. We choose nine resonances in this work as candidates for excitation in reaction (1). These are two S11 resonances [$N^*(2030)$ and $N^*(2090)$], three $D13$'s [$N^*(2055)$, $N^*(2080)$, and $N^*(2095)$], two $D15$'s [$N^*(2080)$ and $N^*(2200)$], one $F15$ [$N^*(2000)$], and one $F17$ [$N^*(1990)$], respectively (here $L2I2J$ is the quantum number of the resonances in the meson-nucleon partial wave channel). From our analysis, we find the contributions [14] of the spin-5/2 and spin-7/2 nucleon resonances to be negligible. Hence we do not discuss these contributions in any detail.

The effective Lagrangians involving the γNR and $\eta' NR$ vertices, where R is a particular nucleon resonance, are needed here [10]. To illustrate this, we take the case of the odd parity, spin-3/2, R. The Lagrangian for the $\eta' NR$ interaction is

$$\mathcal{L}_{\eta' NR} = \frac{f_{\eta' NR}}{\mu} \bar{R}^\mu \theta_{\mu\nu}(Z) \gamma_5 N \partial^\nu \eta' + \text{H.c.}, \tag{9}$$

where R^μ is the vector spinor for R and the tensor $\theta_{\mu\nu}$ is

$$\theta_{\mu\nu}(Z) = g_{\mu\nu} + \left[\tfrac{1}{2}(1+4Z)A + Z\right]\gamma_\mu\gamma_\nu. \tag{10}$$

We choose the point-transformation parameter A to be -1 without any loss of generality, and fit the parameter Z and two other similar ones from the electromagnetic vertices.

An interesting feature of reaction (1) is the role of the s and u dependences of the form factor at the $\eta' NR$ vertex. Not much is known [15] about this form factor either theoretically or experimentally. Figure 1 demonstrates the importance of the use of a form factor, without which the cross section would simply grow unphysically with energy. We discuss below our choice of the form factors.

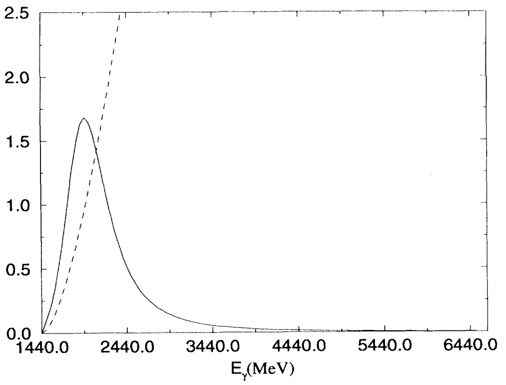

FIG. 1. Calculated total η' photoproduction cross section using the $D13(2080)$ resonance only. The solid line is the $D13(2080)$ contribution with the form factor given by Eq. (15), the dashed line is without the form factor.

The s- and u-channel resonance excitation amplitudes are separately gauge invariant [10]. Therefore, the choice of form factors for these contributions is relatively simple, but theoretically not rigidly fixed. The phenomenological success in reproducing the shape of the experimental cross section is the important guide here. Thus, we utilize a form factor for the s-channel resonance excitation [16]

$$F(s) = 1 \Big/ \left(1 + \frac{(s - M_R^2)^2}{\Lambda^4}\right). \tag{11}$$

Here we use $\Lambda^2 = 1.2$ GeV^2 for the $S11$ resonances and 0.8 GeV^2 for the $D13$ resonances. The values of Λ's are determined from the best fit. A form similar to (11), with u replacing s, would also do for the u channel. For the t-channel vector meson exchange, the form factor that we use is standard [17]:

$$F(t) = \left(\frac{\Lambda^2 - M_V^2}{\Lambda^2 - t}\right)^2, \tag{12}$$

where we take $\Lambda^2 = 1.2$ GeV^2, and M_V is the mass of the vector meson exchanged.

For the nucleon Born terms one should also attach form factors at the strong vertices, since the intermediate nucleon is off shell. This, in general, will not preserve gauge invariance and care is needed to maintain gauge invariance. We use $F(s)$ in form (11), with M replacing M_R, consistent with the requirement of gauge invariance, choosing $\Lambda^2 = 1.2$ GeV.

Figure 2 shows the main result of this paper. The available total cross-section data from the DESY experiment are well described by our effective Lagrangian approach. *The main contribution to the photoproduction amplitude comes from the N^* (2080) alone.* In this sense, the η' photoproduction reaction is helpful to illuminate the property of this resonance. However, the multipoles E_{2-} and M_{2-}, in which this baryon resonance is "resonant," are not the important multipoles contributing to the cross section. It is the E_{0+} multipole, to which $N^*(2080)$ contributes as a "background," providing the bulk of the strength of cross section. The shape of the cross section of Fig. 2 is influenced by the rise of the cross section, as W increases from the η' threshold and the $N^*(2080)$ peak is reached. It then falls, as the strong

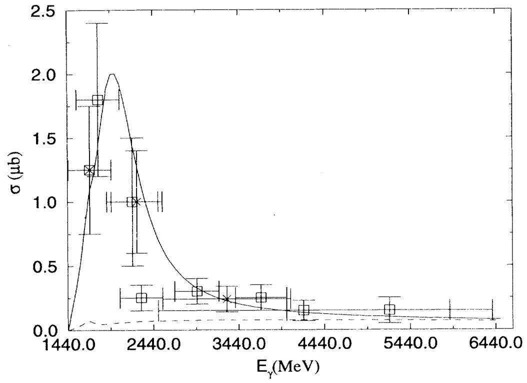

FIG. 2. Calculated total η' photoproduction cross section in our effective Lagrangian approach, compared with the experimental data [4], stars from Erbe *et al.* [4] and squares from Wolf and Söding [4]. The parameter $g_{\eta'}$ is taken as 1.9. The solid line is our full calculation, the dashed line is the total cross section obtained without the $D13(2080)$ contribution.

TABLE I. Contributions to the real part of the E_{0+} multipole, in units of $10^{-3}/m_{\pi^+}$, for the η' photoproduction at the threshold. The resonances that are reported in PDG-94 are indicated by N^*. Additional resonances, predicted in the quark-model calculation [1] and not observed yet, are indicated by R.

Contributions	E_{0+}
Nucleon Born terms	−0.55
$\rho + \omega$	0.89
$R(2030)[S11]$	0.13
$R(2055)[D13]$	0.03
$N^*(2080)[D13]$	1.15
$N^*(2090)[S11]$	−0.09
$R(2095)[D13]$	0.01
Total	1.56

form factors for the $\eta' NR$ and $\eta' NV$ vertices (R, nucleon resonances; V, vector mesons) fall.

Table I shows the contributions [18] to the real part of the dominant amplitudes coming from various exchanges. *Note the effective dominance of the $N^*(2080)$.* Further examination of this reveals the importance of both the s-channel pole and the nonpole contributions involving the $N^*(2080)$. This is due to the fact that the effective parameter $\Gamma_0 \chi_\lambda$ controlling this are predicted [1] to be 95 and −113 for $\lambda = 1/2$ and $3/2$, respectively, for $N^*(2080)$, by far the largest. This parameter is only −42 for $N^*(2090)$, the next important resonance excitation [1,2].

To summarize, we are seeing a promising aspect of the η' photoproduction process (1) in being valuable to explore the property of $N^*(2080)$, one of the many resonances around 2 GeV predicted in the quark shell model [1,3]. Not much is experimentally known about the electromagnetic and strong properties of this resonance. Our work shows that the process (1) would probe these properties. The study of η' photoproduction is a nice prospect for the CEBAF-type facilities. It should allow more precise tests of the quark model at this interesting region of $W \approx 2$ GeV. Strong form factors, about which we know little and want to know more, are important to reproduce the experimental data. We have investigated each multipole contribution and found that the main contribution comes from the E_{0+} multipole. The surprising fact is that it is the "background" contribution of a $D13$ resonance, $N^*(2080)$, that dominates this multipole, and the cross section. This almost mimics a classic resonance behavior, reminding us again of the difficulty of distinguishing between a resonance and a nonresonant background [19]. Due to poor data, we cannot yet give a very precise estimate of the properties of $N^*(2080)$. The next theoretical step is to take into account the unitarity effects in the process, which requires extensive studies of various decay channels involved in the reaction (1). This would come with new experimental initiatives at CEBAF [5].

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