Mesons electromagnetic production study *via* a constituent quark approach

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Abstract

Using a chiral constituent quark approach based on the broken $SU(6) \otimes O(3)$ symmetry, we focus on the spectroscopy of isospin-1/2 nucleonic resonances. A model for the η photoproduction, embodying all known nucleonic resonances, shows clear need for a yet undiscovered S_{11} resonance, for which we determine the mass (1.730 GeV) and the total width (180 MeV).

1. Introduction

The advent of new facilities offering high quality electron and photon beams and sophisticated detectors, has stimulated intensive experimental and theoretical study of the mesons photo- and electro-production.

Among various formalisms [1], the advantage of the quark model in this realm is two fold : i) it allows us to embody, in the reaction mechanism, all known baryonic resonances, ii) the electromagnetic production data can directly be related to the internal structure of those resonances. As a result, such an approach offers a reliable frame in search for new resonances.

Within a constituent quark model based on the $SU(6) \otimes O(3)$ symmetry, we have investigated [1-6] the following reactions:

$$\gamma\, p \quad \rightarrow \quad \eta\, p,\ K^+\Lambda, K^+\Sigma^\circ,\ \Phi\, p \tag{1}$$

$$e\, p \quad \rightarrow \quad e'\, \eta\, p. \tag{2}$$

Here, we focus on the η photoproduction, for which rather copious recent data are available and more is expected in the near future.

2. Theoretical frame

The starting point of the meson electromagnetic production in the chiral quark model is the low energy QCD Lagrangian [7-8]. The baryon resonances in the s- and u-channels are treated as three quark systems. The transition matrix elements based on the low energy QCD Lagrangian include the s-, u-, and t-channel contributions

$$\mathcal{M}_{if} = \mathcal{M}_s + \mathcal{M}_u + \mathcal{M}_t. \tag{3}$$

The contributions from the s-channel resonances can be written as

$$\mathcal{M}_{N^*} = \frac{2M_{N^*}}{s - M_{N^*}(M_{N^*} - i\Gamma(q))} e^{-\frac{k^2+q^2}{6\alpha^2_{ho}}} \mathcal{A}_{N^*}, \tag{4}$$

where k and q represent the momenta of the incoming photon and the outgoing meson respectively, $\sqrt{s} \equiv W$ is the total c.m. energy of the system, $e^{-(k^2+q^2)/6\alpha^2_{ho}}$ is a form factor in the harmonic oscillator basis with the parameter α^2_{ho} related to the harmonic oscillator strength in the wave-function,

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Table 1. Resonances included explicitly in our study with their assignments in $SU(6)\otimes O(3)$ configurations, masses, and widths. The mass and width of the $S_{11}(1535)$ resonance, left as adjustable parameters, are given in Table 2. Higher mass resonances are treated as degenerate.

States	$SU(6)\otimes O(3)$	Mass (GeV)	Width (MeV)
$S_{11}(1535)$	$N(^2P_M)_{\frac{1}{2}^-}$		
$S_{11}(1650)$	$N(^4P_M)_{\frac{1}{2}^-}$	1.650	150
$D_{13}(1520)$	$N(^2P_M)_{\frac{3}{2}^-}$	1.520	130
$D_{13}(1700)$	$N(^4P_M)_{\frac{3}{2}^-}$	1.700	150
$D_{15}(1675)$	$N(^4P_M)_{\frac{5}{2}^-}$	1.675	150
$P_{13}(1720)$	$N(^2D_S)_{\frac{3}{2}^+}$	1.720	150
$F_{15}(1680)$	$N(^2D_S)_{\frac{5}{2}^+}$	1.680	130
$P_{11}(1440)$	$N(^2S'_S)_{\frac{1}{2}^+}$	1.440	150
$P_{11}(1710)$	$N(^2S_M)_{\frac{1}{2}^+}$	1.710	100
$P_{13}(1900)$	$N(^2D_M)_{\frac{3}{2}^+}$	1.900	500
$F_{15}(2000)$	$N(^2D_M)_{\frac{5}{2}^+}$	2.000	490

and M_{N^*} and $\Gamma(q)$ are the mass and the total width of the resonance, respectively. The amplitudes $\mathcal{A}_{N^*}$ are divided into two parts [8]: the contribution from each resonance below 2 GeV, the transition amplitudes of which have been translated into the standard CGLN amplitudes in the harmonic oscillator basis, and the contributions from the resonances above 2 GeV treated as degenerate, since little experimental information is available on those resonances.

The u-channel contributions are divided into the nucleon Born term and the contributions from the excited resonances. The matrix elements for the nucleon Born term is derived explicitly, while the contributions from the excited resonances above 2 GeV for a given parity are assumed to be degenerate so that their contributions could be written in a compact form.

The t-channel contribution contains two parts: *i)* charged meson exchanges which are proportional to the charge of outgoing mesons and thus do not contribute to the process $\gamma N \to \eta N$; *ii)* ρ- and ω-exchange in the η production which are excluded here due to the duality hypotheses.

Within the exact $SU(6)\otimes O(3)$ symmetry the $S_{11}(1650)$ and $D_{13}(1700)$ do not contribute to the investigated reaction mechanism. However, the breaking of this symmetry leads to the configuration mixings.

Here, the most relevant configuration mixings are those of the two S_{11} and the two D_{13} states around 1.5 to 1.7 GeV. The configuration mixings, generated by the gluon exchange interactions in the quark model [9-10], can be expressed in terms of the mixing angle between the two $SU(6)\otimes O(3)$ states $|N(^2P_M)>$ and $|N(^4P_M)>$, with the total quark spin 1/2 and 3/2;

$$\begin{pmatrix} |S_{11}(1535)> \\ |S_{11}(1650)> \end{pmatrix} = \begin{pmatrix} \cos\Theta_S & -\sin\Theta_S \\ \sin\Theta_S & \cos\Theta_S \end{pmatrix} \begin{pmatrix} |N(^2P_M)_{\frac{1}{2}^-}> \\ |N(^4P_M)_{\frac{1}{2}^-}> \end{pmatrix}, \tag{5}$$

and

$$\begin{pmatrix} |D_{13}(1520)> \\ |D_{13}(1700)> \end{pmatrix} = \begin{pmatrix} \cos\Theta_D & -\sin\Theta_D \\ \sin\Theta_D & \cos\Theta_D \end{pmatrix} \begin{pmatrix} |N(^2P_M)_{\frac{3}{2}^-}> \\ |N(^4P_M)_{\frac{3}{2}^-}> \end{pmatrix}, \tag{6}$$

The amplitudes $\mathcal{A}_{N^*}$ in terms of the product of the photo- and meson-transition amplitudes are related to the mixing angles,

$$\mathcal{A}_{N^*} \propto < N|H_m|N^* >< N^*|H_e|N >, \tag{7}$$

where H_m and H_e are the meson and photon transition operators, respectively. Using Eqs. (5) to (7), for the resonance $S_{11}(1535)$ one finds

$$\begin{aligned}\mathcal{A}_{S_{11}} \quad \propto \quad & < N|H_m(\cos\Theta_S|N(^2P_M)_{\frac{1}{2}^-} > -\sin\Theta_S|N(^4P_M)_{\frac{1}{2}^-} >)(\cos\Theta_S < N(^2P_M)_{\frac{1}{2}^-}| - \\ & \sin\Theta_S < N(^4P_M)_{\frac{1}{2}^-}|)H_e|N >,\end{aligned} \tag{8}$$

Due to the Moorhouse selection rule, the photon transition amplitude $< N(^4P_M)_{\frac{1}{2}^-}|H_e|N >$ vanishes in our model. So, Eq. (8) becomes

$$\mathcal{A}_{S_{11}} \quad \propto \quad (\cos^2\Theta_S - \mathcal{R}\sin\Theta_S\cos\Theta_S) < N|H_m|N(^2P_M)_{\frac{1}{2}^-} >< N(^2P_M)_{\frac{1}{2}^-}|H_e|N >, \tag{9}$$

where $< N|H_m|N(^2P_M)_{\frac{1}{2}^-} >< N(^2P_M)_{\frac{1}{2}^-}|H_e|N >$ determines the CGLN amplitude for the $|N(^2P_M)_{\frac{1}{2}^-} >$ state, and the ratio $\mathcal{R} = < N|H_m|N(^4P_M)_{1/2^-} > / < N|H_m|N(^2P_M)_{1/2^-} >$ is a constant determined by the $SU(6) \otimes O(3)$ symmetry. Using the meson transition operator H_m from the Lagrangian used in deriving the CGLN amplitudes in the quark model, we find $\mathcal{R}$ = -1 for the S_{11} and $\sqrt{1/10}$ for the D_{13} resonances.

3. Results

Using the above approach, we have fitted the following sets of the η-photoproduction data: differential cross-sections from MAMI/Mainz [11] and Graal [12], as well as the polarized beam asymmetry from Graal [13]. Then we have predicted [1] the total cross-section and the polarized target asymmetry. This latter observable has been measured at ELSA/Bonn [14].

In Figures 1 and 2, we show comparison for the total and differential cross-sections, respectively, for the two models I and II (Table 2).

Both models include all known resonances, given in Table 1, as well as those with mass higher than 2 GeV. They also satisfy the configuration mixing relations, Eqs. (5) and (6).

For the model I, the extracted mixing angles, Table 2, are in agreement with Isgur-Karl [9] predictions. The mass and the width of the $S_{11}(1535)$ come out in the PDG [15] ranges. This model

Table 2. Results of minimizations.

parameter	Model I	Model II	Isgur-Karl [9]
Θ_S (deg.)	-32 $\pm$ 2	-27 $\pm$ 1	-32
Θ_D (deg.)	5.1 $\pm$ 0.2	5.1 $\pm$ 0.2	6
$M_{S_{11}(1535)}$ (GeV)	1.530	1.542	
$\Gamma_{S_{11}(1535)}$ (MeV)	142	162	
Mass of the third S_{11} (GeV)		1.729 $\pm$ 0.003	
Width of the third S_{11} (MeV)		183 $\pm$ 10	
$\chi^2_{d.o.f}$	3.8	1.6	

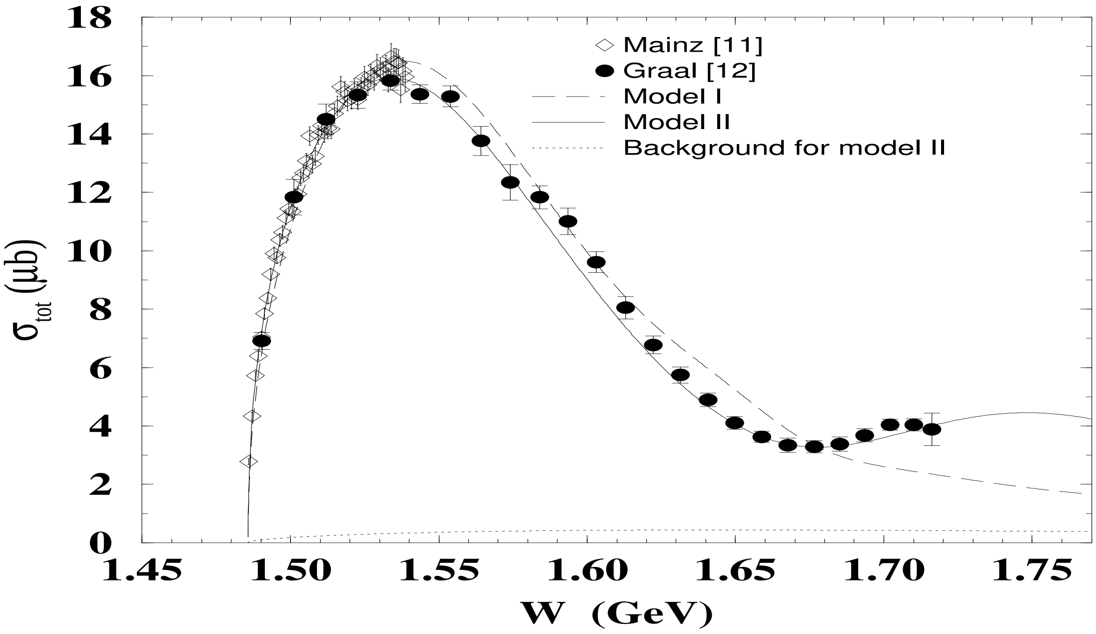

Fig. 1. Total cross section for the reaction $\gamma p \to \eta p$ as a function of total center-of-mass energy. The curves come from the models I (dashed), II (full). The dotted curve shows the background terms contribution in the model II. Data are from Refs. [11] (empty diamonds), and [12] (full circles).

reproduces fairly well the total cross-section data (Fig. 1) up to $W \approx 1.61$ GeV. Between this latter energy and ≈ 1.68 GeV, the model overestimates the data, and above 1.68 GeV, the predictions underestimate the experimental results, missing the total cross-section increase.

In summary, results of the model I show clearly that an approach containing a correct treatment of the Born terms and including *all known resonances* in the s- and u-channels *does not* lead to an acceptable model, even within broken $SU(6) \otimes O(3)$ symmetry scheme.

To go further, one possible scenario is to investigate manifestations of yet undiscovered resonances, because of their weak or null coupling to the πN channel. A rather large number of such resonances has been predicted by several authors [16-18]. To find out which ones could be considered as relevant candidates, we examined the available data.

The excitation functions (Fig. 2), show clearly that this mismatch is due to the forward angle peaking of the differential cross-section for $W \geq$1.68 GeV ($E_\gamma^{lab} \geq 1.$ GeV). Such a behaviour might likely arise from missing strength in the S-waves. This latter conclusion is endorsed by the role played by the E_0^+ in the multipole structure of the differential cross-section and the single polarization observables. If there is indeed an additional S-wave resonance in this mass region, its dependence on incoming photon and outgoing meson momenta would be qualitatively similar to that of the $S_{11}(1535)$, even though the form factor might be very different. Thus, for this new resonance, we use the same CGLN amplitude expressions as for the $S_{11}(1535)$. We have hence introduced [1] a third S_{11} resonance and refitted the same data base as for the model I, leaving it's mass and width as free parameters. The results of this model, depicted in Figs. 1 and 2 (full curves), reproduce nicely the data. This is also the case [1] for the polarized beam and polarized target asymmetries. For this latter observable, our predictions come out in agreement with the data.

The extracted values for different free parameters in the model II are given in Table 2, third

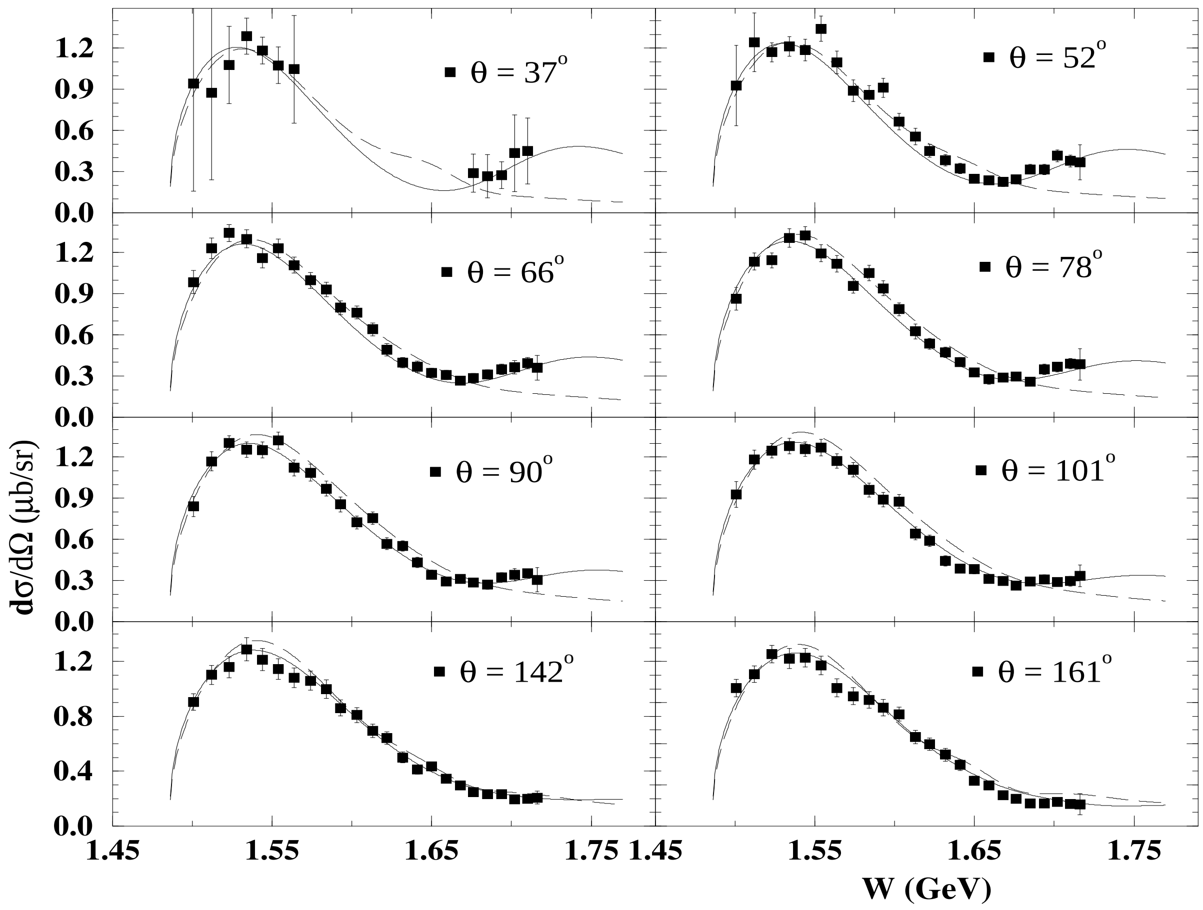

Fig. 2. Excitation function for the reaction $\gamma p \rightarrow \eta p$ as a function of total center-of-mass energy. The curves are as in Fig 1 and have been calculated at the angles given in the figures. Data are from Graal [12] and correspond roughly to the given angle $\pm 2°$.

column (Model II). The mixing angles are still compatible with the quark model predictions [9] and results coming from the large-N_c effective field theory based approaches [19-20]. The mass and the width of the $S_{11}(1535)$ are within the ranges reported in the PDG [15]. For the new S_{11} resonance, we find M=1.729 GeV and Γ=183 MeV. These values are amazingly close to those of a predicted [16] third S_{11} resonance, with M=1.712 GeV and Γ_T=184 MeV. Moreover, for the one star $S_{11}(2090)$ resonance [15], the Zagreb group coupled channel analysis [21-22] produces the following values M = 1.792 $\pm$ 0.023 GeV and Γ_T = 360 $\pm$ 49 MeV.

Introducing this third resonance, hereafter referred to as $S_{11}(1730)$, modifies the extracted values for the parameters of the two other S_{11} resonances [1]. The mass and width of the first S_{11} resonance come out compatible with their recent determination by the CLAS collaboration [23], as well as with those of the Zagreb group coupled channel analysis [21-22].

In summary, a new S-wave nucleonic resonance is needed to interpret the recent η-photoproduction data between threshold and $E_\gamma^{lab} \approx$1.1 GeV. The crucial questions then are: i) what is the nature of this resonance? ii) are there other relevant reactions to be investigated?

With respect to the first question, the authors of Ref. [16] suggest a $K\Sigma$ molecular structure for the third resonance that they predict. We need hence, to find out whether that resonance and the $S_{11}(1730)$ found here, are the same, or this latter resonance has a 3-quark structure. One way is to go from the photoproduction to the electroproduction of η-meson. We are currently extending our electroproduction study [4], limited to the $S_{11}(1535)$ region data [23], to higher W. Actually, the very recent higher energy data [24] from JLab allow us to perform such investigations. The Q^2 dependence of the cross-section is expected to teach us about the nature of this resonance. It is worthwhile underlining that those data, at the lowest measured Q^2, show also a minimum around the same W as in Fig. 1. Moreover, if the $S_{11}(1730)$ has an exotic $K\Sigma$ structure, strangeness production [5] close to threshold would deserve special attention from experimentalists. Vector meson channels [6,25] might also be of interest.

We hope that the investigation of pseudoscalar and vector mesons electromagnetic production within the same chiral constituent quark model, will offer an appropriate means in search for new resonance and will allow us to deepen our understanding of the baryons spectroscopy.

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