η photoproduction data on the proton up to $E_{\text{lab}}^\gamma \approx 2$ GeV are interpreted within a chiral constituent quark formalism, which embodies all known three and four star resonances. This study confirms the need for a new $S_{11}$ resonance, with $M=1.780$ GeV and $\Gamma=280$ MeV, already introduced in investigating lower energy data.

1. Introduction

Recent data\cite{1,2,3,4,5} on the electromagnetic production of the $\eta$ meson off the proton constitute an exciting challenge for phenomenologists\cite{6,7,8,9,10,11}. This isospin pure process, dominated at low energies by a single nucleon resonance, offers appealing features not only for pinning down the reaction mechanism and the extraction of the fundamental $\eta N$ coupling constant, but also for search of new nucleon resonances\cite{6,7}. Then, such experimental and theoretical efforts are expected to test various QCD-inspired approaches\cite{12,13} in the hadron spectroscopy realm, allowing strong test of the underlying concepts.

In this note, we investigate the reaction $\gamma p \rightarrow \eta p$, and report on the results of a chiral constituent quark formalism\cite{8,14}, which embodies\cite{7} the configuration mixing phenomenon\cite{15,16}, and the related $SU(6) \otimes O(3)$ symmetry breaking effects\cite{7,8}.

2. Theoretical Frame

The chiral constituent quark approach for meson photoproduction is based on the low energy QCD Lagrangian\cite{17}, with four components for the photoproduction of pseudoscalar mesons. The first one is a seagull term, generated by the gauge transformation of the axial vector $A_\mu$ in the QCD
Lagrangian. The second and the third terms correspond to the $s$- and $u$-channels, respectively. The forth term is the $t$-channel contribution and contains two parts: \( i \) charged meson exchanges which are proportional to the charge of outgoing mesons and thus do not contribute to the process \( \gamma N \to \eta N \); \( ii \) $\rho$ and $\omega$ exchange in the $\eta$ production which are excluded here due to the duality hypothesis\(^7\).

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

\[
M_{N^*} = \frac{2M_{N^*}}{s - M_{N^*} \left[ M_{N^*} - i\Gamma(q) \right]} e^{-\frac{k^2 + q^2}{m^2 h^2}} A_{N^*},
\]

with \( k = |k| \) and \( q = |q| \) the momenta of the incoming photon and the outgoing meson respectively, \( \sqrt{s} \) the total energy of the system, \( e^{-\frac{(k^2+q^2)}{6\alpha h^2}} \) is a form factor in the harmonic oscillator basis with the parameter \( \alpha^2 h^2 \) related to the harmonic oscillator strength in the wave-function, and \( M_{N^*} \) and \( \Gamma(q) \) are the mass and the total width of the resonance, respectively. The amplitudes \( A_{N^*} \) are divided into two parts\(^14\): 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 these resonances.

The contributions from each resonance to $\eta$ photoproduction is determined by introducing\(^8\) a new set of parameters $C_{N^*}$ and the $A_{N^*} \to C_{N^*}, A_{N^*}$ substitution rule for the amplitudes, so that $M_{N^*}^{exp} = C_{N^*}^2 M_{N^*}^{qm}$, where $M_{N^*}^{exp}$ is the experimental value of the observable, and $M_{N^*}^{qm}$ is calculated in the quark model\(^14\). The $SU(6) \otimes O(3)$ symmetry predicts $C_{N^*} = 0$ for $S_{11}(1650)$, $D_{13}(1700)$, and $D_{15}(1675)$ resonances, and $C_{N^*} = 1$ for other relevant resonances: $S_{11}(1535)$, $P_{11}(1440), P_{11}(1710), P_{13}(1720), P_{13}(1900), D_{13}(1520), F_{15}(1680)$, and $F_{15}(2000)$. Thus, the coefficients $C_{N^*}$ give a measure of the discrepancies between the theoretical results and the data and show the extent to which the $SU(6) \otimes O(3)$ symmetry is broken in the process investigated here.

One of the main reasons that the $SU(6) \otimes O(3)$ symmetry is broken is due to the configuration mixings caused by the one gluon exchange\(^15,16\). 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 can be expressed in terms of the mixing angle between the two $SU(6) \otimes O(3)$ states with the total quark spin 1/2 and 3/2.
3. Results and Discussion

Using our approach and the MINUIT minimization code from the CERN Library, we have fitted all \( \approx 650 \) data points from recent measurements for both differential cross-sections \( \sigma_1, \sigma_2, \sigma_5 \) and single polarization asymmetries \( \alpha_4 \). The adjustable parameters of our models are one \( SU(6) \otimes O(3) \) symmetry breaking strength coefficient \( C_N^* \) per resonance, except for the resonances \( S_{11}(1535) \) and \( S_{11}(1650) \) on the one hand, and \( D_{13}(1520) \) \( D_{13}(1700) \) on the other hand, for which we introduce the configuration mixing angles \( \theta_S \) and \( \theta_D \).

The first model includes explicitly all eleven known relevant resonances, mentioned above, with mass below 2 GeV, and the contributions from the known excited resonances above 2 GeV for a given parity, assumed to be degenerate and hence written in a compact form \( 14 \).

In Fig. 1, we compare this model (dashed curves) to the data at nine incident photon energies. As shown in our earlier works \( 7,8 \), such a model reproduces correctly the data at low energies \( E_{\gamma}^{lab} \leq 1 \text{ GeV} \). Above, the model misses the data. A possible reason for these theory/data discrepancies could be that some yet unknown resonances contribute to the reaction mechanism. We have investigated possible rôle played by extra \( S_{11}, P_{11}, \) and \( P_{13} \) resonances, with three free parameters (namely the resonance mass, width, and strength) in each case.

By far, the most significant improvement was obtained by a third \( S_{11} \) resonance, with the extracted values \( M=1.780 \text{ GeV} \) and \( \Gamma=280 \text{ MeV} \). The configuration mixing angles came out to be \( \theta_S=12^\circ \) and \( \theta_D=-35^\circ \), in agreement with the Isgur-Karl model \( 15 \) and by large-\( N_c \) approaches \( 18 \).

The outcome of this latter model is depicted in Fig. 1 (full curve) and shows very reasonable agreement with the data, improving the reduced \( \chi^2 \), on the complete data-base, by more than a factor of 2. The extracted values for the mass and width of a new \( S_{11} \) are close to those predicted by the authors of Ref. \( 19 \) (\( M=1.712 \text{ GeV} \) and \( \Gamma=184 \text{ MeV} \)), and our previous findings \( 7 \). Moreover, for the one star \( S_{11}(2090) \) resonance \( 20 \), the Zagreb group coupled channel analysis \( 21 \) produces the following values \( M = 1.792 \pm 0.023 \text{ GeV} \) and \( \Gamma = 360 \pm 49 \text{ MeV} \). The BES Collaboration reported \( 22 \) on the measurements of the \( J/\psi \rightarrow pp\eta \) decay channel. In the latter work, a partial wave analysis leads to the extraction of the mass and width of the \( S_{11}(1535) \) and \( S_{11}(1650) \) resonances, and the authors find indications for an extra resonance with \( M = 1.800 \pm 0.040 \text{ GeV} \), and \( \Gamma = 165^{+165}_{-85} \text{ MeV} \).

A very recent work \( 13 \) based on the hypercentral constituent quark model,
and presented during this workshop, predicts a missing $S_{11}$ resonance with $M=1.861$ GeV. Finally, a self-consistent analysis of pion scattering and photoproduction within a coupled channel formalism, indicates the existence of a third $S_{11}$ resonance with $M = 1.803 \pm 0.007$ GeV.

The main shortcoming of our model concerns the deviations between theory and very forward data at highest energies (Fig. 1), indicating the need for a more careful treatment of higher mass resonances or, equivalently, the introduction of the t-channel contributions.

Finally, given the quality of the data, coupled-channel effects studied in the associated strangeness photoproduction sector, have to be extended to the $\eta$ photoproduction process.

In summary, results presented in this note and those reported in the quoted works, allow us to confidently conclude that the existence of a

![Figure 1](image-url)

Figure 1. Differential cross section for the process $\gamma p \rightarrow \eta p$: angular distribution at nine incident photon energies ($E_{\text{lab}}$), with the corresponding total center-of-mass energy ($W$) also given; units are in GeV. The dashed curves are from the model embodying all known three and four star resonances. The full curves show the model including, in addition, a new $S_{11}$ resonance, with $M=1.780$ GeV and $\Gamma=280$ MeV. CLAS (circles) and GRAAL (stars) data are from Refs. [1] and [2], respectively.
third $S_{11}$ resonance with $M\approx 1.8$ GeV is being established. Our preliminary results on the double polarization asymmetries show that some of those observables can provide us with strong criteria on the issues of new resonances. Such measurements will, hopefully, be performed in the near future in GRAAL, JLAB, and/or Spring8.

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