

Chiral constituent quark model study of the process $\gamma p \rightarrow \eta p$

Jun He¹, Bijan Saghai¹, Zhenping Li², Qiang Zhao³, Johan Durand¹

¹DAPNIA/SPhN, DSM, CEA/Saclay, 91191 Gif-sur-Yvette, France

²Department of Computer and Information Science, University of Maryland, MD 20783, USA

³Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, 100049, P.R. China

Received: date / Revised version: date

Abstract. A constituent quark model is developed for the reaction, allowing us to investigate all available data for differential cross sections as well as single polarization asymmetries (beam and target) by including *all* of the PDG, one to four star, nucleon resonances (S_{11} , P_{11} , P_{13} , D_{13} , D_{15} , F_{15} , F_{17} , G_{17} , G_{19} , H_{19} , $I_{1,11}$, and $K_{1,13}$). Issues related to the missing resonances are also briefly discussed by examining possible contributions from several new resonances (S_{11} , P_{11} , P_{13} , D_{13} , D_{15} , and $H_{1,11}$).

PACS. 13.60.Le Meson production – 14.20.Gk Baryon resonances with S=0

1 Introduction

Investigation of η -meson production *via* electromagnetic and hadronic probes offers access to fundamental information on hadron spectroscopy, including the search for missing baryon resonances [1]. Extensive recent experimental efforts on η photoproduction are opening a new era in this field. The focus in this contribution is to study recent $\gamma p \rightarrow \eta p$ data [2–8] for $E_\gamma^{lab} \leq 3$ GeV ($W \equiv E_{total}^{cm} \leq 2.6$ GeV) within a chiral constituent quark formalism [9], proven to be appropriate for the study of meson photo- and electro-production [10–13], and meson-nucleon scattering [14] in the resonance region.

2 Theoretical frame

The starting point of the meson photoproduction in the chiral quark model is the low energy QCD Lagrangian [15]

$$\mathcal{L} = \bar{\psi} [\gamma_\mu (i\partial^\mu + V^\mu + \gamma_5 A^\mu) - m] \psi + \dots, \quad (1)$$

where ψ is the quark field in the $SU(3)$ symmetry, $V^\mu = (\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger)/2$ and $A^\mu = i(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger)/2$ are the vector and axial currents, respectively. The chiral transformation is $\xi = e^{i\phi_m/f_m}$, where ϕ_m is the Goldstone boson field and f_m the meson decay constant. Then, the Lagrangian in Eq. (1) is invariant under the chiral transformation. Therefore, there are four components for the photoproduction of pseudoscalar mesons [9] based on the QCD Lagrangian,

$$\mathcal{M}_{fi} = \langle N_f | H_{m,e} | N_i \rangle + \sum_j \left\{ \frac{\langle N_f | H_m | N_j \rangle \langle N_j | H_e | N_i \rangle}{E_i + \omega - E_j} + \frac{\langle N_f | H_e | N_j \rangle \langle N_j | H_m | N_i \rangle}{E_i - \omega_m - E_j} \right\} + \mathcal{M}_T, \quad (2)$$

where $|N_i\rangle$, $|N_j\rangle$, and $|N_f\rangle$ stand for the initial, intermediate, and final state baryons, respectively, $\omega(\omega_m)$ represents the energy of incoming (outgoing) photons (mesons), and H_m and H_e are the pseudovector and electromagnetic couplings at the tree level.

The first term in Eq. (2) is a seagull term. The second and third terms correspond to the s - and u -channels, respectively. The last term is the t -channel contribution.

The contributions from the s -channel resonances to the transition matrix elements can be written as

$$\mathcal{M}_{N^*} = \frac{2M_{N^*}}{W^2 - M_{N^*}(M_{N^*} - i\Gamma(q))} e^{-\frac{k^2+q^2}{6\alpha_{h^0}^2}} \mathcal{A}_{N^*}, \quad (3)$$

with $k = |\mathbf{k}|$ ($q = |\mathbf{q}|$) the momentum of the incoming photon (outgoing meson), W the total energy of the system, $e^{-(k^2+q^2)/6\alpha_{h^0}^2}$ a form factor in the harmonic oscillator basis with the parameter $\alpha_{h^0}^2$ related to the harmonic oscillator strength in the wave-function, and M_{N^*} and $\Gamma(q)$ the mass and the total width of the resonance, respectively. The transition amplitudes \mathcal{A}_{N^*} have been translated into the standard CGLN amplitudes in the harmonic oscillator basis.

The contributions from each resonance is determined by introducing [10] a new set of parameters C_{N^*} , and the substitution

$$\mathcal{A}_{N^*} \rightarrow C_{N^*} \mathcal{A}_{N^*}, \quad (4)$$

so that,

$$\mathcal{M}_{N^*}^{exp} = C_{N^*}^2 \mathcal{M}_{N^*}^{qm}, \quad (5)$$

with $\mathcal{M}_{N^*}^{exp}$ the experimental value of the observable, and $\mathcal{M}_{N^*}^{qm}$ calculated in the quark model [9]. The $SU(6) \otimes O(3)$ symmetry predicts, e.g. $C_{N^*} = 0.0$ for the $S_{11}(1650)$,

$D_{13}(1700)$, and $D_{15}(1675)$ resonances, and $C_{N^*} = 1.0$ for other $n \leq 2$ shell resonances. Thus, the coefficients C_{N^*} measure the discrepancies between the theoretical results and the experimental data and show the extent to which the $SU(6) \otimes O(3)$ symmetry is broken in the relevant process. 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 [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 $|N(^2P_M) \rangle$ and $|N(^4P_M) \rangle$, with the total quark spin 1/2 and 3/2.

In our previous investigations [10], the s -channel resonances with masses above 2 GeV were treated as degenerate. In other words, the transition amplitudes, translated into the standard CGLN amplitudes were restricted to harmonic oscillator shells $n \leq 2$. In the present work we extend that approach and derive explicitly the amplitudes also for $n=3$ to 6 shells [17]. Moreover, we also include t -channel contributions.

3 Results and discussion

Using the formalism sketched above, we have investigated the cross-section and single polarization observables for the process $\gamma p \rightarrow \eta p$. In our model, non-resonant components include nucleon pole term, u -channel contributions (treated as degenerate to the harmonic oscillator shell n), and t -channel contributions due to the ρ - and ω -exchanges [18].

The resonant part embodies the following $n=1$ to 6 shell nucleon resonances:

- $n=1$: $S_{11}(1535)$, $S_{11}(1650)$, $D_{13}(1520)$, $D_{13}(1700)$, and $D_{15}(1675)$;
- $n=2$: $P_{11}(1440)$, $P_{11}(1710)$, $P_{13}(1720)$, $P_{13}(1900)$, $F_{15}(1680)$, $F_{15}(2000)$, and $F_{17}(1990)$;
- $n=3$: **$S_{11}(1730)$** , $S_{11}(2090)$, **$D_{13}(1850)$** , $D_{13}(2080)$, **$D_{15}(1950)$** , $D_{15}(2200)$, $G_{17}(2190)$, , and $G_{19}(2250)$;
- $n=4$: **$P_{11}(1810)$** , $P_{11}(2100)$, **$P_{13}(2170)$** , $H_{19}(2220)$, and **$H_{1,11}(2200)$** ;
- $n=5$: $I_{1,11}(2600)$;
- $n=6$: $K_{1,13}(2700)$.

Resonances considered here embody all of the 21 isospin-1/2 nucleon resonances in the PDG [19], plus 6 new resonances reported in various publications. Those resonances are given in the above list in bold character and refer to the following works: **$S_{11}(1730)$** [1, 10, 13, 20, 21], **$P_{11}(1810)$** [22–24], **$P_{13}(2170)$** [1, 13, 21, 25], **$D_{13}(1850)$** [1, 13, 23, 24, 26], **$D_{15}(1950)$** [23, 24], **$H_{1,11}(2200)$** [27].

The masses attributed to those resonances are determined by the present work and are compatible with other findings.

Because of lack of space, here we show excitation functions at three angles (Fig. 1), polarized beam and target asymmetries at two angles (Fig. 2) for each of the single

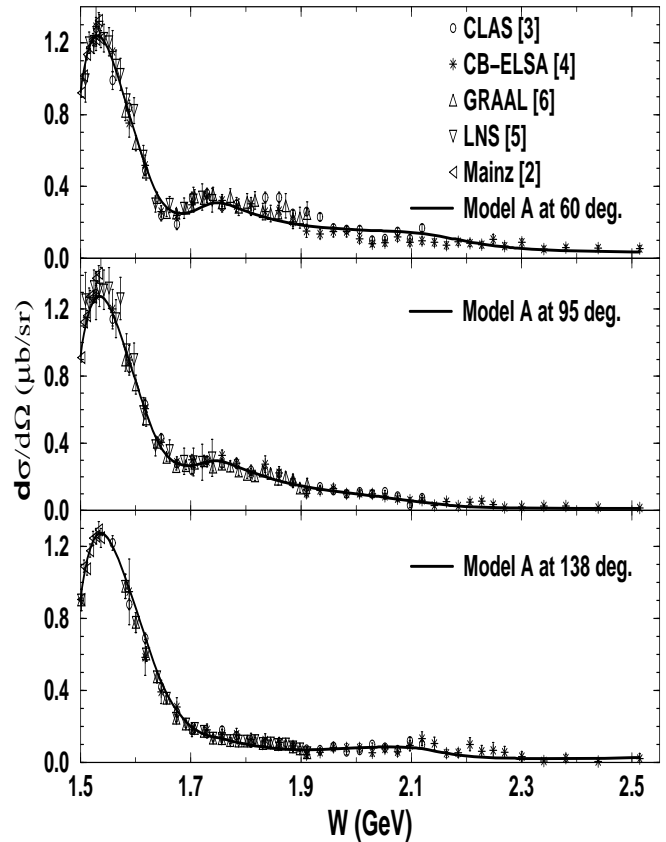


Fig. 1. Excitation functions for the process $\gamma p \rightarrow \eta p$ at $\theta = 60^\circ$, 95° , and 138° . Model A is explained in the text.

polarization observables. (Consistencies among differential cross-section data obtained at five facilities deserves to be underlined.)

Model A has been obtained, using the CERN-MINUIT code, by fitting the data with all $n = 1$ to 6 shell resonances enumerated above. The adjustable parameters are the $SU(6) \otimes O(3)$ symmetry breaking coefficients C_{N^*} (Eq. 4), and mass and width of the six new resonances. The used data base contains 1588 differential cross-sections [2–6], 184 polarized beam asymmetries [6, 8], and 50 polarized target asymmetries [7]. The reduced χ^2 comes out to be 1.8.

The overall agreement between theory and experiment (Fig. 1) is satisfactory. The extracted configuration mixing angles are $\theta_S = -35^\circ$ and $\theta_D = 15^\circ$, close enough to the Karl-Isgur model values [16].

Model A reproduces reasonably well the single polarization observables (Fig. 2). Given the very limited number of data points for the polarized target asymmetry (T), they do not put any significant constraint on the adjustable parameters, hence, the curves can be considered rather as predictions.

Starting from the full model A, we have switched off one resonance at a time and checked the variation of the χ^2 , without further minimizations. In the model A, the

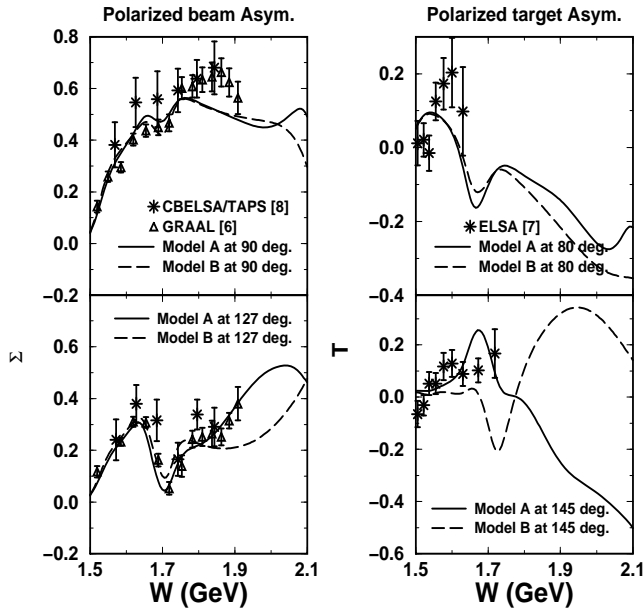


Fig. 2. Polarization observables for the process $\gamma p \rightarrow np$. Left panel: polarized beam asymmetries (Σ) at $\theta = 90^\circ$ and 127° . Right panel: polarized target asymmetries (T) at $\theta = 80^\circ$ and 145° . Models *A* and *B* are explained in the text.

dominant resonances come out to be the following nine resonances: $S_{11}(1535)$, $S_{11}(1650)$, $\mathbf{S}_{11}(1730)$, $S_{11}(2090)$, $P_{13}(1720)$, $P_{13}(1900)$, $D_{13}(1520)$, $D_{13}(1700)$, and $F_{15}(1680)$. The highest χ^2 variations are observed in turning off the $S_{11}(1535)$, and to less extent, the $D_{13}(1520)$. Among the six new resonances, only the $\mathbf{S}_{11}(1730)$ happens to play a significant role.

The model *B* is obtained by fitting the data with merely those nine dominant resonances plus the same non-resonant terms as in the model *A*. The reduced χ^2 goes up from 1.8 (model *A*) to 2.1 (model *B*). For the differential cross-sections depicted in Fig. 1, the difference between the two models *A* and *B* is not large enough to be visible in the figure. However, the single polarization observables show significant sensitivities to the reaction mechanism ingredients in models *A* and *B*. The highest sensitivity is observed in the case of polarized target asymmetry at backward angle and around $W = 1.9$ GeV. Further data for this latter observable are highly desirable for a more comprehensive understanding of the reaction mechanism.

In summary, we have developed a chiral quark model allowing us to include all known and suggested nucleon resonances. The data base, embodying 1822 data points, was fitted successfully for differential cross-section and single polarization observables (beam and target). Out of the 27 nucleon resonances included in the model, nine of them play major roles in the reaction mechanism. One of those resonances is a new one: S_{11} , for which we have extracted mass and width: $M = 1730$ and $\Gamma = 100$ MeV, compatible with other findings [10, 13, 20, 21].

A more scrutiny investigation is in progress with respect to the sensitivity of different data sets and/or energy ranges to the ingredients of our approach. Afterwards, this

elementary operator for the direct channel can be used in a dynamical coupled-channel formalism [28], which embodies πN , $\pi\Delta$, ηN , σN , and ρN intermediate states.

References

1. S. Capstick and W. Roberts, *Prog. Part. Nucl. Phys.* **45**, (2000) 5241; and references therein.
2. B. Krusche *et al.*, *Phys. Rev. Lett.* **74**, (1995) 3736.
3. M. Dugger *et al.* (CLAS Collaboration), *Phys. Rev. Lett.* **89**, (2002) 222002.
4. V. Crede *et al.* (CB-ELSA Collaboration), *Phys. Rev. Lett.* **94**, (2005) 012004.
5. T. Nakabayashi *et al.*, *Phys. Rev. C* **74**, (2006) 035202.
6. O. Bartalini *et al.* (GRAAL Collaboration), *Eur. Phys. J. A* **33**, (2007) 169.
7. A. Bock *et al.*, *Phys. Rev. Lett.* **81**, (1998) 534;
8. D. Elsner *et al.* (CB-ELSA and TAPS Collaborations), *Eur. Phys. J. A* **33**, (2007) 147.
9. Z. Li, H. Ye, M. Lu, *Phys. Rev. C* **56**, (1997) 1099.
10. Z. Li and B. Saghai, *Nucl. Phys. A* **644**, (1998) 345; B. Saghai and Z. Li, *Eur. Phys. J. A* **11**, (2001) 217; B. Saghai and Z. Li, *Proceedings of NSTAR 2002 Workshop on the Physics of Excited Nucleons*, Pittsburgh, PA (USA), 2002; Editors S.A. Dytman and E.S. Swanson (World Scientific, New Jersey, 2003), arXiv: nucl-th/0305004.
11. Q. Zhao, B. Saghai, Z. Li, *J. Phys. G* **28**, (2002) 1293.
12. Q. Zhao, J.S. Al-Khalili, R.L. Workman, *Phys. Rev. C* **65**, (2002) 065204.
13. B. Juliá-Díaz, B. Saghai, T.-S.H. Lee, F. Tabakin, *Phys. Rev. C* **73**, (2006) 055204.
14. Xian-Hui Zhong, Qiang Zhao, Jun He, Bijan Saghai, arXiv: nucl-th/0706.3543; nucl-th/0710.4212.
15. A. Manohar and H. Georgi, *Nucl. Phys. B* **234**, (1984) 189.
16. N. Isgur and G. Karl, *Phys. Lett. B* **72**, (1977) 109; N. Isgur, G. Karl, R. Koniuk, *Phys. Rev. Lett.* **41**, (1978) 1269; J. Chimza and G. Karl, *Phys. Rev. D* **68**, (2003) 054007.
17. Jun He, Bijan Saghai, Zhenping Li, Qiang Zhao, Johan Durand, *manuscript in preparation*.
18. M. Benmerrouche, N.C. Mukhopadhyay, J.F. Zhang, *Phys. Rev. D* **51**, (1995) 3237.
19. W. M. Yao *et al.*, *J. Phys. G* **33**, (2006) 1.
20. Z. Li and R. Workman, *Phys. Rev. C* **53**, (1996) R549; A. Švarc and S. Ceci, arXiv: nucl-th/0009024; G.-Y Chen *et al.*, *Nucl. Phys. A* **723**, (2003) 447; W.-T. Chian *et al.*, *Phys. Rev. C* **68**, (2003) 045202. V. A. Tryasuchev, *Eur. Phys. J. A* **22**, 97 (2004).
21. M.M. Giannini, E. Santopinto, and A. Vassallo, *Eur. Phys. J. A* **12**, (2001) 447.
22. T. Corthals, J. Ryckebusch, and T. Van Cauteren, *Phys. Rev. C* **73**, 045207 (2006).
23. A.V. Anisovich *et al.*, *Eur. Phys. J. A* **25**, (2005) 427.
24. A.V. Sarantsev *et al.*, *Eur. Phys. J. A* **25**, (2005) 441.
25. M. Ablikim *et al.* (BES Collaboration), *Phys. Rev. Lett.* **97**, (2006) 202002. Sh. Fang (BES Collaboration), *Int. J. Mod. Phys. A* **21**, (2006) 839.
26. T. Mart and C. Bennhold, *Phys. Rev. C* **61**, 012201 (2000); N.G. Kelkar, M. Nowakowski, K.P. Khemchandani, S.R. Jain, *Nucl. Phys. A* **730**, (2004) 121.
27. R.A. Arndt, W.J. Brisco, I.I. Strakovsky, and R.L. Workman, *Phys. Rev. C* **74**, 045205 (2006).
28. B. Juliá-Díaz *et al.*, arXiv: nucl-th/0704.1615.