Eta Photoproduction as a Test of the Extended Chiral Symmetry

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Abstract

We analyze the $\gamma p \to \eta p$ process from threshold up to 1.2 GeV, employing an effective Lagrangian approach that allows for a mixing of eta couplings of pseudoscalar and pseudovector nature. The mixing ratio of the couplings may serve as a quantitative estimation of the $SU_L(3) \times SU_R(3)$ extended chiral symmetry violation in this energy regime. The data analyzed (differential cross sections and asymmetries) show a preference for the pseudoscalar coupling — 91% of pseudoscalar coupling component for the best fit. We stress that a more conclusive answer to this question requires a more complete electromagnetic multipole database than the presently available one.

Our knowledge on effective field theories (EFTs) based upon Quantum Chromodynamics (QCD) has been enlarged thanks to the development and success of chiral perturbation theory (χPT) [1]. The starting point for χPT is QCD reduced to massless quarks u and d. Under these assumptions the chiral $SU_L(2) \times SU_R(2)$ symmetry holds and is spontaneously broken into $SU_I(2)$ symmetry, emerging the nucleon as the ground state of the EFT and the pion as the Goldstone boson that mediates the strong interaction in the EFT.

Even if the quarks u and d masses are strictly nonzero, they are small and relatively close, so that chiral symmetry is a well-established approximate symmetry of the strong interaction. Indeed, chiral symmetry requires a vanishing

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πNN coupling for vanishing pion momentum. The simplest way to achieve this is by means of a pseudovector coupling to the pion [2]. The extension of χPT to strange particles has been investigated in the last years [3,4,5,6,7,8,9] with the extended chiral symmetry (EχS) $SU_L(3) \times SU_R(3)$ whose validity is more debatable. This symmetry is spontaneously broken into $SU_V(3)$ symmetry and eight Goldstone bosons emerge: four non-strange pseudoscalar mesons ($\pi^{\pm}$, π^0, and η) and four strange pseudoscalar mesons ($K^{\pm}$, K^0, and $\bar{K}^0$). One can appreciate that the EχS is not restored as a good symmetry at the same level as standard chiral symmetry looking at the differencies among the masses of the meson octect [10]. The question arises about how important this breakdown of EχS arises already at the level of EFT or whether any restoration effect might happen in reactions, beyond the mass differences of hadrons or mesons belonging to EχS multiplets.

This Letter is devoted to the $\gamma p \to \eta p$ process and the nature of the coupling of the η particle, as a possible indication of violation of the EχS. The study of the eta photoproduction process is well motivated from both theoretical and experimental points of view. This is due to the relation of the eta to the EχS and the study of the electromagnetic properties of the nucleon excitations as well as to the experimental programs on eta photoproduction developed in several worldwide facilities over the last years [11,12,13,14]. We focus on the nature of the coupling of the eta to the nucleon and its excitations, mainly the N(1535) which presents a large ηN branching ratio and dominates the threshold behavior of the eta photoproduction reaction. Whereas the pion coupling is usually chosen pseudovector because of the chiral symmetry, there is no compelling *ab initio* reason to decide that the η meson has to be either pseudoscalar (PS) or pseudovector (PV). However, if the EχS were exactly fulfilled, the eta would couple to the nucleon and its excitations through purely PV couplings with no PS admixture, as in the case of pions. Hence, if the PS-PV mixing ratio ε of the coupling could be reliably derived from experimental data, it might provide a quantitative indication of EχS breakdown in the nucleon mass energy regime. With this aim, we explore whether the ηNN and ηNN^* vertices are either of PS, PV, or PS-PV mixing nature by fitting an effective Lagrangian model to data.

One must be well aware that in meson-baryon to meson-baryon processes PS and PV couplings are indistinguishable, because they provide the same amplitude [15,16,17]. Thus, meson photoproduction emerges as the ideal way to distinguish between both couplings. The contribution of the anomalous magnetic moment of the proton makes a difference in the amplitudes [15] originating from PV or PS couplings. We study whether, within the presently available experimental information, it is feasible to extract the possible PS contribution to the amplitude and test the EχS in the meson sector.

EχS is at the basis of an extensive study of the nucleon and its excitations

by means of eta photoproduction [5,9] and meson scattering [7] using chiral unitary approaches. Coupled-channel chiral unitary models have been succesful in describing certain resonances as dynamically generated states, for instance, N(1535) [4,7,8], N(1520) [6] and N(1650) [8]. However, the nature of the N(1535), N(1520) and N(1650) is debatable. Standard quark models [18], for instance, provide the right quantum numbers and mass predictions [9] for these baryon states. Despite of the success of these models, one must be aware of the fact that meson-baryon scattering cannot be used to test EχS. The possible PS-PV mixing cannot be unveiled by these processes due to the fact that, on-shell, both the PV and the PS couplings yield the same amplitudes for meson-baryon scattering. As already mentioned, to study the possible PS-PV mixing one has to explore photoproduction reactions. The eta photoproduction process has been described within the chiral unitary approach with different results. In Ref. [5], the authors succeeded in reproducing the total cross section within a computation which allows for terms in the Lagrangian that explicitly break the EχS, while the computation of the total cross section in [9] needs further improvements to achieve results in as good agreement with the data as the ones presented in [5] and in this Letter.

In this Letter we present a realistic model of the $\gamma p \rightarrow \eta p$ reaction based upon the effective Lagrangian approach (ELA), that from the theoretical point of view is a very suitable and appealing method to study meson photoproduction and nucleon excitations. Recently, we presented a model for pion photoproduction on free nucleons based on ELA [19]. In this Letter, we extend this model to the eta photoproduction process. The model includes Born terms and ω and ρ vector mesons as well as nucleon resonances up to 1.8 GeV mass and up to spin-3/2, covering the energy region from threshold up to 1.2 GeV of photon energy in the laboratory frame. The model is fully relativistic and displays gauge invariance and crossing symmetry among other relevant features that will be pointed out throughout this Letter.

We choose the ηNN interaction to be

$$\mathcal{L}_{\eta NN}^{\text{PS-PV}} = g_{\eta NN} \left[\frac{(1-\varepsilon)}{2M} \bar{N}\gamma_\alpha\gamma_5 N \partial^\alpha \eta - i\varepsilon \bar{N}\gamma_5 N \eta \right], \qquad (1)$$

where M is the mass of the nucleon, $g_{\eta NN}$ is the ηNN coupling constant, and ε is the mixing parameter which runs from 0 to 1. Both $g_{\eta NN}$ and ε will be fitted to data within their physical ranges. The pure PS ($\varepsilon = 1$) and PV ($\varepsilon = 0$) choices for the ηNN coupling have been explored in Ref. [15]. In this Letter we go further, not only because we allow for a mixing of PS and PV couplings through the parameter ε but also because we apply the mixing to both Born terms and nucleon resonance contributions.

The mixing idea has been previously used in studies of the effect of meson-exchange currents in muon capture by ^{3}He [20] and to pion scattering [16].
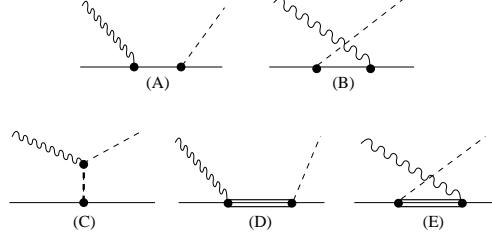
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Fig. 1. Feynman diagrams for Born terms: (A) s channel, (B) u channel; (C) vector-meson exchange terms; and nucleonic excitations: (D) s channel and (E) u channel.

The latter obviously provides the same result for both couplings because in the absence of the contribution from the anomalous magnetic moment of the nucleon, PS and PV couplings yield the same amplitudes [17].

The electromagnetic coupling to the nucleon (γNN Lagrangian) is given by

$$
\begin{aligned}
\mathcal{L}_{\gamma NN} = & - e \hat{A}^\alpha \bar{N} \gamma_\alpha \frac{1}{2} \left(1 + \tau_3\right) N \\
& - \frac{ie}{4M} \bar{N} \frac{1}{2} \left(\kappa^S + \kappa^V \tau_3\right) \gamma_{\alpha\beta} N F^{\alpha\beta},
\end{aligned}
\tag{2}
$$

where e is the absolute value of the electron charge, $F^{\alpha\beta} = \partial^\alpha \hat{A}^\beta - \partial^\alpha \hat{A}^\beta$ is the electromagnetic field, $\hat{A}^\alpha$ is the photon field, and $\kappa^S = \kappa^p + \kappa^n = -0.12$ and $\kappa^V = \kappa^p - \kappa^n = 3.70$ are respectively the isoscalar and the isovector anomalous magnetic moments of the nucleon.

Vector mesons are included through the standard Lagrangians ($V = \omega, \rho$) [19]

$$
\begin{aligned}
\mathcal{L}_V = & - F_{VNN} \bar{N} \left[\gamma_\alpha - i \frac{K_V}{2M} \gamma_{\alpha\beta} \partial^\beta \right] V^\alpha N \\
& + \frac{e G_{V\eta\gamma}}{m_\eta} \tilde{F}_{\mu\nu} \left(\partial^\mu \eta\right) V^\nu,
\end{aligned}
\tag{3}
$$

with $\tilde{F}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}$. From Particle Data Group [10] we take the following values: $m_\eta = 547.3$ MeV, $m_{\rho^0} = 768.5$ MeV, $m_\omega = 782.57$ MeV, $G_{\rho^0\eta\gamma} = 1.06$ ($\Gamma_{\rho^0\eta\gamma} = 0.062$ MeV), and $G_{\omega\eta\gamma} = 0.29$ ($\Gamma_{\omega\eta\gamma} = 0.005486$ MeV). From the analysis of the nucleon electromagnetic form factors performed by Mergell, Meißner, and Drechsel [21] we take the values $F_{\rho NN} = 2.6$, $K_\rho = 6.1 \pm 0.2$, $F_{\omega NN} = 20.86 \pm 0.25$, and $K_\omega = -0.16 \pm 0.01$.

Besides Born (diagrams (A) and (B) in Fig. 1) and vector meson exchange terms (ρ and ω, diagram (C) in Fig. 1), the model includes six nucleon resonances: N(1520), N(1535), N(1650), N(1700), N(1710), and N(1720) — diagrams (D) and (E) in Fig. 1. Due to the isoscalar nature of the η meson, all the nucleon resonances involved are isospin-1/2. An important virtue of the model employed here which overtakes former approaches lies in the treatment

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of the resonances. We avoid well-known pathologies in the Lagrangians of the spin-3/2 resonances (such as N(1520)) of previous models, thanks to a modern approach due to Pascalutsa [22]. This coupling scheme has been applied succesfully to pion photoproduction from the nucleon and provides a better overall description of the behavior of the resonances [19] than other spin-3/2 coupling schemes [23,24]. Under this approach the (spin-3/2 resonance)-nucleon-eta and the (spin-3/2 resonance)-nucleon-photon vertices have to fulfill the condition $q_\alpha \mathcal{G}^{\alpha\cdots} = 0$ where q is the four-momentum of the spin-3/2 particle, $\mathcal{G}^{\alpha\cdots}$ stands for the vertex, α the vertex index which couples to the spin-3/2 field, and the dots stand for other possible indices. Within this prescription, the PS coupling to the eta yields a zero amplitude contribution [22] and, thus, there is no PS-PV mixing for (spin-3/2 resonances)-nucleon-eta Lagrangians. The D_{13} Lagrangian, N(1520) and N(1700) resonances, can be written

$$
\begin{aligned}
\mathcal{L}_{D_{13}} = & -\frac{H_{\eta NN^*}}{m_\eta M^*} \bar{N} \epsilon_{\mu\nu\lambda\beta} \gamma^\beta \left(\partial^\mu N^{*\nu}\right) \left(\partial^\lambda \eta\right) \\
& + \frac{3e}{4M(M+M^*)} \bar{N} \left[i \left(g_1^S + g_1^V \tau_3\right) \tilde{F}_{\mu\nu} \gamma_5 \right. \\
& \left. + \left(g_2^S + g_2^V \tau_3\right) F_{\mu\nu} \right] \partial^\mu N^{*\nu} + \text{H.c.},
\end{aligned}
\tag{4}
$$

where M^* is the mass of the resonance, H.c. stands for Hermitian conjugate, $g_{1,2}^S$ and $g_{1,2}^V$ stand for the isoscalar and isovector electromagnetic coupling constants respectively, and $H_{\eta NN^*}$ is the strong coupling constant. The P_{13} Lagrangian, N(1720) resonance, is obtained placing an overall γ_5 in (4).

For S_{11} resonances, N(1535) and N(1650), we build the PS-PV Lagrangian

$$
\begin{aligned}
\mathcal{L}_{S_{11}}^{\text{PS-PV}} = & \varepsilon i G_{\eta NN^*} \bar{N} N^* \eta - (1-\varepsilon) \frac{H_{\eta NN^*}}{m_\eta} \bar{N} \gamma_\alpha N^* \partial^\alpha \eta \\
& - \frac{ie}{4M} \bar{N} \gamma_{\alpha\beta} \gamma_5 \left(g_S + g_V \tau_3\right) N^* F^{\alpha\beta} + \text{H.c.}
\end{aligned}
\tag{5}
$$

Despite the fact that we name two strong coupling constants $H_{\eta NN^*}$ and $G_{\eta NN^*}$, they only represent one parameter in the model because they are both related to the same experimental quantity, the partial decay width of the resonance into the ηN state, Γ_η. The P_{11} Lagrangian, N(1710) resonance is obtained placing an overall γ_5 in (5).

Dressing of the resonances is considered by means of a phenomenological width which takes into account decays into one pion, one eta and two pions [19]. The phenomenological width employed is an improvement of those used by Manley et al. [25] (inspired by Blatt and Weisskopf factors [26]) and Garcilazo and Moya de Guerra [23]. This width is energy dependent and is built so that it fulfills crossing symmetry and contributes to both direct and crossed channels of the resonances. It also accounts for the right angular barrier of the resonance at threshold. Consistency requires to incorporate the energy dependence of the

Table 1
Comparison among the PS, PV, and PS-PV prescriptions. The subindex '3' stands for the fits where the constrain $g_{\eta NN}^2/4\pi = 1.7$ has been imposed and the subindex '0' stands for the fits where $g_{\eta NN}$ has been fitted to data. dof stands for degrees of freedom and ε for the mixing ratio.

	ε	$g_{\eta NN}^2/4\pi$	dof	χ^2/dof
PS$_3$	1	1.7	633	15.37
PV$_3$	0	1.7	633	18.19
PS-PV$_3$	0.99	1.7	632	15.36
PS$_0$	1	1.08	632	13.91
PV$_0$	0	0.054	632	15.95
PS-PV$_0$	0.91	0.52	631	13.80

width in the strong coupling constants. In order to regularize the high energy behavior of the model we include a crossing symmetric and gauge invariant form factor for Born and vector meson exchange terms, which contains the only free parameter in the model (the cutoff Λ) together with the mixing parameter ε. The form factor for Born terms is [27]

$$\hat{F}_B(s,u,t) = F(s) + F(u) + G(t) - F(s)F(u) \\ -F(s)G(t) - F(u)G(t) + F(s)F(u)G(t), \tag{6}$$

where,

$$F(l) = \left[1 + \left(l - M^2\right)^2/\Lambda^4\right]^{-1}, \; l = s, u; \tag{7}$$

$$G(t) = \left[1 + \left(t - m_\eta^2\right)^2/\Lambda^4\right]^{-1}; \tag{8}$$

and for vector mesons we adopt $\hat{F}_V(t) = G(t)$ with the change $m_\eta \to m_V$.

In order to assess the parameters of the model we minimize the function

$$\chi^2 = \sum_{j=1}^n \left[\frac{\mathcal{O}_j^{\text{experiment}} - \mathcal{O}_j^{\text{model}}\left(\varepsilon, \Lambda, g_{\eta NN}, \dots\right)}{\Delta\mathcal{O}_j^{\text{experiment}}}\right]^2, \tag{9}$$

where $\mathcal{O}$ stands for the observables — namely differential cross sections and asymmetries (recoil nucleon polarization, polarized target, and polarized beam). We use all the available experimental database up to 1.2 GeV photon energy, a total amount of $n = 665$ data points [28]. To perform the minimization we have used a genetic algorithm combined with the E04FCF routine (gradient-based routine) from NAG libraries [29]. For each prescription of the model we have allowed the parameters (masses, widths, and electromagnetic coupling
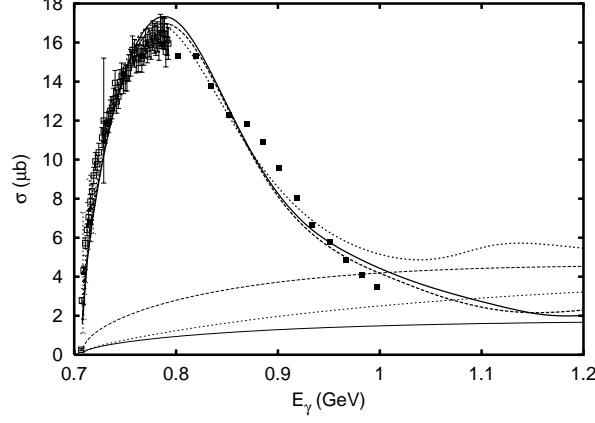
Fig. 2. Total cross section for the $\gamma p \rightarrow \eta p$ reaction. Thick lines: Full calculations; Thin lines: B+VM contribution. Solid, PS-PV$_0$ fit; Dashed, PS$_0$ fit; Dotted, PV$_0$ fit. Data are from ELSA (solid triangles) [12], MAMI (open squares) [13], and GRAAL (solid squares) [14].
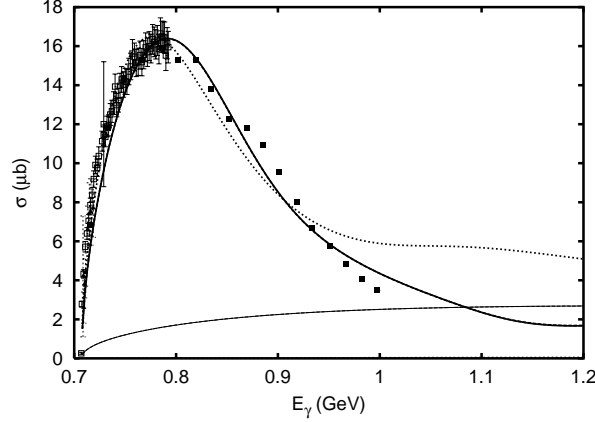

Fig. 3. Total cross section for the $\gamma p \rightarrow \eta p$ reaction with $g_{\eta NN}^2/4\pi = 1.7$. Thick lines: Full calculations; Thin lines: B+VM contribution. Solid, PS-PV$_3$ fit; Dashed, PS$_3$ fit; Dotted, PV$_3$ fit. Data as in Fig. 2. PS$_3$ and PS-PV$_3$ curves overlap. The B+VM contribution to PV$_3$ curve is almost negligible.

constants) to vary within the ranges given by the PDG independently. Details on the optimization procedure applied can be found in [30].

In order to explore the reliability of the EχS we have performed six fits using three different prescriptions: PS ($\varepsilon = 1$), PV ($\varepsilon = 0$), and PS-PV where ε has been fitted to data. Exact EχS predicts $g_{\eta NN}^2/4\pi = 1.7$ [15] so for each kind of fit we have performed fits with and without this constrain. The fits where this condition is imposed are named PS$_3$, PV$_3$, and PS-PV$_3$ and the fits where we let $g_{\eta NN}$ run freely within a sensible range are named PS$_0$, PV$_0$, and PS-PV$_0$. In Table 1 we provide a summary of our results. We will report more extensive results obtained with our eta photoproduction model in a forthcoming publication [31]. In advance, we provide in Figs. 2 and 3 the results for the total cross section.

In the energy region near threshold, the contribution of Born terms and vector mesons (B+VM in what follows) to the cross section is small compared to the N(1535) resonance contribution, but as energy increases the importance of B+VM contribution to the cross section increases and eventually becomes the most important contribution. Therefore, the relevance of the mixing parameter ε stands out mainly through the η-N(1535) vertex in the low-energy region and through the ηN vertex in the high-energy region. We find that the B+VM background to the cross section is important – at variance with Ref. [32] – and highly dependent on the coupling prescription. In our model we do not account for final state interactions which might be important [19] in a reliable calculation/fit of the electromagnetic multipoles.

The PS and the PV prescriptions provide equally good agreement in the near-threshold region, but as the energy increases and the Born terms become more important, the PV prescription deviates from data (see Figs. 2 and 3). This fact together with the worse χ^2/dof supports PS coupling as a better option for the phenomenological Lagrangian. Hence, the EχS seems not to be an adequate underlying symmetry, at least for effective Lagrangians. Differences between PS and PV coupling are visible in the low energy region, not so much in the total cross section as in other observables that are used to fit the parameters of the model, such as single polarization asymmetries and differential cross sections.

High-lying resonances contribute more in the high-energy region than in the low-energy one, but they are not the main source of differences between results with PS and PV coupling for the total cross section. These resonances determine the shape of the differential cross section and the asymmetries. Their contribution to the total cross section in the high energy region, though sizeable, is small compared to the one of the tail of the N(1535) resonance plus Born terms and vector mesons contributions.

The assumption of one single mixing parameter ε is not the most general choice. In order to test this assumption we have repeated the fits to data with two ε's, one related to Born terms and another to the resonances. We have performed the fits varying these parameters independently and no improvement in the χ^2/dof was found. The PS component remains dominant at the level of 90% in both the resonances and the Born terms.

In summary, we have shown that eta photoproduction is sensitive to the nature of the coupling and, thus, it is able to disentangle PS or PV couplings. More high-quality experimental data, to allow electromagnetic multipole separation, are needed in order to constrain the parameters of the model. This will also allow to study final state interaction effects, which becomes mandatory in order to attain further progress in this topic. Meanwhile, the presented result for the dominance of the PS coupling should be taken with caution. Further

research on the nature of the eta-nucleon-baryon coupling becomes mandatory. Kaon photoproduction is another interesting process where the EχS can be tested following the lines presented in this Letter.

Acknowledgements

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