η Photoproduction from Threshold through the $S_{11}(1535)$ Resonance

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(Received 22 April 1991)

We study photoproduction of η mesons off protons in the effective Lagrangian approach. Unlike the π^0 case, the η photoproduction at threshold is strongly dominated by resonance excitation. The quantity $(\chi\Gamma_\eta)^{1/2}A_{1/2}/\Gamma_T$, characteristic of the photoexcitation of the $S_{11}(1535)$ resonance and its decay into the η-nucleon channel, of interest to hadron models, is determined to be $(0.22\pm0.02)\times10^{-3}$ MeV^{-1} from the existing data.

PACS numbers: 13.60.Le, 12.40.Aa, 25.10.+s, 25.20.Lj

There has been a tremendous renewal [1] of interest in the study of photoproduction and electroproduction of pseudoscalar mesons near threshold. In this Letter, we broaden the above discussion by examining the reaction [2,3]

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

near threshold. In contrast to the (γ,π^0) reaction on protons, with threshold at the photon laboratory energy $E_\gamma=144.7$ MeV, the reaction (1) has a threshold at $E_\gamma=709.3$ MeV. Experimental information on (1) is rather old [4], with two exceptions: a study [5] at Tokyo at E_γ between 808 MeV and 1.01 GeV, and another at the Bates Laboratory at $E_\gamma=725$ and 750 MeV, preliminary results of which have been recently reported [6].

The importance of η mesons in the context of the extended chiral symmetry is well known [7], as is the flavor-SU(3) mixing [8] in the quark model for η and η'. The latter, along with the SU(6)$\otimes$O(3) mixing [9], results in the large coupling of the ηN channel to the $S_{11}(1535)$ resonance. These provide the obvious motivation to study the process (1), to which we can add a number of others. First, we wish to treat the process (1) in the framework of the effective Lagrangian theory [10,11]. This reduces drastically the number of free parameters, to be determined from the data, compared with those in other existing analyses [2,5]. Second, we show that the π^0 and η photoproductions near threshold have very significant differences, even as they share common contributions, such as those of the nucleon Born terms [Figs. 1(a) and 1(b)], the basis for the predictions of the low-energy theorems (LET) for the π^0 case. Among these differences, we find the contribution to (1) of the s-channel excitation of the $S_{11}(1535)$ resonance to be the most significant [Fig. 1(d)], along with that of the vector-meson exchange in the t channel [Fig. 1(c)]. Third, the dominance of the former allows us to extract the electromagnetic transition amplitude [8] $A_{1/2}$ for the baryonic transition $\gamma p\to S_{11}(1535)$, of great interest to topical hadron models [9]. Last, but not least, this analysis provides us with a theoretical basis to unravel the nonresonant background contributions to the *electroproduction* of η mesons, to be explored in emerging continuous-wave electron facilities like CEBAF, an essential step in extracting the resonant transition amplitude.

The effective Lagrangian approach (ELA) [10] helps us sort out the tree-level structure of the η photoproduction amplitude. We start with the leading s- and u-channel nucleon Born terms [Figs. 1(a) and 1(b)]; add to that the leading vector mesons (ρ,ω) in the t channel [Fig. 1(c)]; finally, we also consider the s- and u-channel nucleon resonance contributions [Figs. 1(d) and 1(e)]. In the case of pion photoproduction, the πNN coupling is preferred to be pseudovector (PV), in accord with the LET and chiral symmetry. Because of the relative largeness of the η mass and big breaking of the chiral SU(3)$\otimes$SU(3) symmetry, there is no compelling reason to choose the PV form of the ηNN Lagrangian, which is the same as the pseudoscalar (PS) one *plus* equivalence-breaking anomalous magnetic-moment interaction. We thus write the ηNN interaction to be

$$L_{\eta NN}=g_\eta[-i\epsilon\bar{N}\gamma_5N\eta+(1-\epsilon)(1/2M)\bar{N}\gamma_\mu\gamma_5N\partial^\mu\eta]\,, \tag{2}$$

M being the nucleon mass. In this work, we study the two limiting cases $\epsilon=0$ (PV) and 1 (PS). The coupling g_η for the ηNN vertex is not very well known [12], except in the SU(3)-flavor symmetry limit, $g_\eta^2/4\pi\simeq1.7$. The γNN coupling is given by QED:

$$L_{\gamma NN}=-e\bar{N}\gamma_\mu\frac{1+\tau_3}{2}NA^\mu+\frac{e}{4M}\bar{N}(k^s+k^v\tau_3)\sigma_{\mu\nu}NF^{\mu\nu}\,. \tag{3}$$

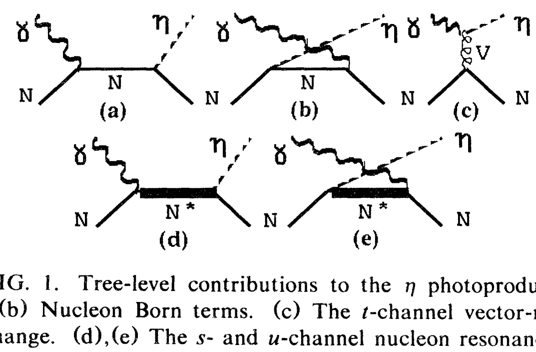

FIG. 1. Tree-level contributions to the η photoproduction. (a),(b) Nucleon Born terms. (c) The t-channel vector-meson exchange. (d),(e) The s- and u-channel nucleon resonance excitations.

Here k^s and k^v are the isoscalar and isovector anomalous magnetic moments. Equations (2) and (3) yield the amplitudes in Figs. 1(a) and 1(b).

The strong and electromagnetic vertices involving the vector meson [Fig. 1(c)] are given by the Lagrangians

$$L_{VNN}=-g_v\bar{N}\gamma_\mu NV^\mu+(g_t/4M)\bar{N}\sigma_{\mu\nu}NV^{\mu\nu}, \quad (4)$$

$$L_{V\eta\gamma}=(e\lambda/4\mu)\epsilon_{\mu\nu\lambda\sigma}F^{\mu\nu}V^{\lambda\sigma}\eta, \quad (5)$$

with the vector-meson field tensor $V_{\mu\nu}=\partial_\nu V_\mu-\partial_\mu V_\nu$, μ being the η mass. We consider the roles of ρ, ω, and ϕ exchanges, and find ϕ to be unimportant. Because of near degeneracy of the ρ and ω masses, we can combine their couplings into a set of two effective ones. We take [12] $\lambda_\rho g_v^\rho+\lambda_\omega g_v^\omega=5.92\pm0.81$ and $\lambda_\rho g_t^\rho+\lambda_\omega g_t^\omega=17.66\pm2.60$. At the VNN vertex, we use a suitable form factor [12] $F(q^2)$.

The s- and u-channel nucleon resonance exchanges [Figs. 1(d) and 1(e)] complete the tree-level amplitude for the process (1). Here we must explore contributions of different $I=\frac{1}{2}$ resonances. In theory this is a complicated task, somewhat simplified in this instance by the dominance of the s-channel $S_{11}(1535)$ excitation. The effective Lagrangians for the $I=J=\frac{1}{2}$ resonances are

$$L_{\eta NR}=-ig_R\bar{N}\Gamma R\eta+\text{H.c.}, \quad (6)$$

$$L_{\gamma NR}=\frac{e}{2(M_R+M)}\bar{R}(k_R^s+k_R^v\tau_3)\Gamma_{\mu\nu}NF^{\mu\nu}+\text{H.c.}, \quad (7)$$

where R is the generic notation for the resonance. Here $\Gamma=1$ and $\Gamma_{\mu\nu}=\gamma_5\sigma_{\mu\nu}$ for the odd-parity resonances, and $\Gamma=\gamma_5$ and $\Gamma_{\mu\nu}=\sigma_{\mu\nu}$ for the even-parity ones.

Finally, interaction Lagrangians for odd parity and isospin-$\frac{1}{2}$, spin-$\frac{3}{2}$ resonances proceed in a fashion parallel to that [10] for $\Delta(1232)$. These are

$$L_{\eta NR}=\frac{g_R}{\mu}\bar{R}^\nu\theta_{\nu\mu}(Z)\gamma_5N\partial^\mu\eta+\text{H.c.}, \quad (8)$$

$$L_{\gamma NR}^1=\frac{ie}{2M}\bar{R}^\mu\theta_{\mu\nu}(Y)\gamma_\lambda(G_s^{(1)}+G_v^{(1)}\tau_3)NF^{\lambda\nu}+\text{H.c.}, \quad (9)$$

$$L_{\gamma NR}^2=-\frac{e}{4M^2}\bar{R}^\mu\theta_{\mu\nu}(X)(G_s^{(2)}+G_v^{(2)}\tau_3)\partial_\lambda NF^{\lambda\nu}+\text{H.c.}, \quad (10)$$

where R is the spin-$\frac{3}{2}$ field operator here, and $G_p^{(i)}=G_s^{(i)}+G_v^{(i)}$ for the proton target, and $\theta_{\mu\nu}(A)=g_{\mu\nu}-[\frac{1}{2}(1+2A)]\gamma_\mu\gamma_\nu$, where A is an off-shell parameter [10]. We explore the possibility of a coupling of resonances to the derivative of the η field and unitarization procedures for the total amplitude in a forthcoming paper [3].

It is straightforward to compute observables for the process (1) in our ELA. In particular, a comparison of (1) with the (γ,π^0) reaction at threshold can be easily made by computing the E_{0+} multipole, experimentally accessible as $(k/q)d\sigma/d\Omega|_{q\to0}=|E_{0+}|^2$, where k and q are the c.m. photon and η momenta, and $d\sigma/d\Omega$ is the c.m. differential cross section. The nucleon Born terms [Figs. 1(a) and 1(b)] give

$$E_{0+}^N=-\frac{eg_\eta}{8\pi M}\frac{\beta}{(1+\beta)^{3/2}}(1+xk_p), \quad (11)$$

where $\beta=\mu/M$, and $x=1$ for the PS and $-\beta/2$ for the PV coupling at the ηNN vertex, demonstrating explicitly the equivalence-breaking effect between them. The t-channel vector-meson exchanges [Fig. 1(c)], essentially ρ and ω, contribute

$$E_{0+}^V=\frac{e\lambda}{16\pi}\frac{\beta(2+\beta)\mu}{(1+\beta)^{3/2}}\frac{g_v+g_t}{\mu^2+M_V^2(1+\beta)}, \quad (12)$$

significantly larger than that in the (γ,π^0) case (Table I). For brevity, we can only show here the dominant contribution out of those from the excitation of various nucleon resonances, that of $S_{11}(1535)$ in the s channel [Fig. 1(d)]. This is

$$E_{0+}^R=-\frac{ek_R^pg_R}{8\pi W(M_R+M)}\frac{ab_\eta(W-M)(W+M_R)}{W^2-M_R^2+iM_R\Gamma_T(W)}, \quad (13)$$

where $a^2=(W+M)^2/2W$, $b_\eta^2(W)=[(W+M)^2-\mu^2]/2W$, and $\Gamma_T(W)$ is the total width of the resonance, the W dependence of which is prescribed in the ELA.

The crucial parameter for the resonance R, to be extracted from the data, is the product $ek_R^pg_R$; the quantities ek_R^p, g_R satisfy the relations

$$ek_R^p=\left[\frac{2M(M_R+M)}{M_R-M}\right]^{1/2}A_{1/2}^p, \quad (14)$$

$$|g_R|=\left[\frac{4\pi M_R}{q_R(b_\eta^R)^2}\Gamma_\eta\right]^{1/2}, \quad (15)$$

where $A_{1/2}^p$ is the familiar helicity amplitude for the electromagnetic transition $\gamma p\leftrightarrow S_{11}(1535)$, as defined [8] by the Particle Data Group (PDG), Γ_η is the partial width of the resonance for the decay into the η-nucleon channel, and b_η^R is the value of b_η evaluated at $W=M_R$.

Previous attempts [2,5] at the analysis of η photoproduction data have not only suffered from the crudeness of

TABLE I. Contributions to the real part of the E_{0+} multipole, in units of $10^{-3}/m_{\pi^+}$, for the η and π^0 photoproduction at their respective thresholds. PS and PV refer to different η-nucleon couplings in the nucleon Born terms.

Contributions	$\gamma+p\to\eta+p$	$\gamma+p\to\pi^0+p$
Nucleon Born terms PS, PV	−6.0, −1.1	−7.9, −2.5
Vector mesons $\rho+\omega$	2.9	0.04
Dominant resonance	12.4	0.4
Other resonances PS, PV	0.2, −4.9	0.1
Total PS, PV	9.5, 9.3	−7.4, −2.0
Experiment	⋯	−2.0 ± 0.2 [a]

[a] Analysis of Bernstein and Holstein [1].

the data, but also from *the lack of enough theoretical constraints* in restricting the number of parameters fitted, 24 or more. The ELA provides us with a tremendous reduction in the number of free parameters, 8 in our case. Of these, g_η, $g_R k_R^p$, and three parameters associated with $D_{13}(1520)$ turn out to be the most crucial. We fix, in our analysis, masses and total widths of all resonance parameters at their nominal values listed by PDG [8], in order to reduce the number of free parameters, which we determine by making use of an improved version of the CERN fitting routine MINUIT. We utilize the existing database for the differential cross section [4,5] for E_γ between 725 and 1200 MeV, and examine if the preliminary data from Bates [6] at 725 and 750 MeV make any difference to our fit. The latter do not appear to influence the nature of our fit very much. We also include in our fit (examples in Fig. 2) the old polarization measurement [4] [seven data points, of which 5 are at 90° and plotted in Fig. 2(b)] for E_γ between 725 and 1100 MeV. Their poor quality invites urgent experimental attention at emerging photon facilities.

Results of our analysis can be divided in three parts: (1) contrast between π^0 and η photoproduction off proton

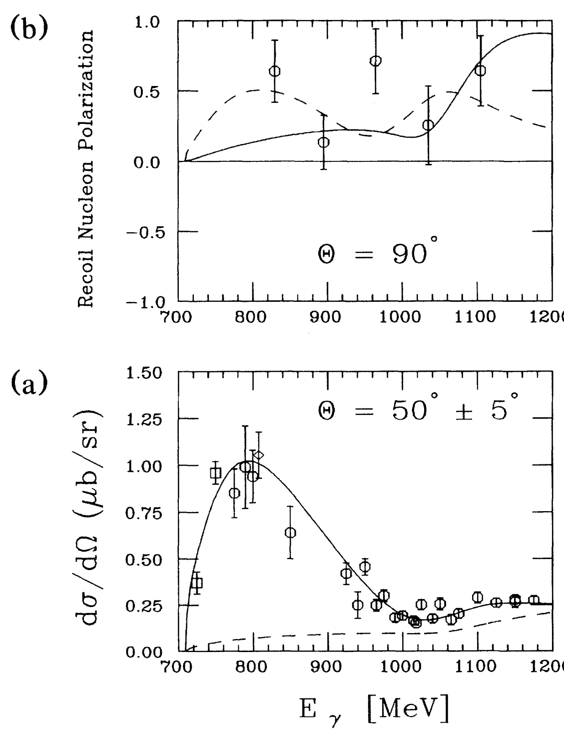

FIG. 2. (a) Differential cross section for the η photoproduction as a function of the laboratory photon energy at c.m. angle 50°. Data: circles, Ref. [4]; diamonds, Homma *et al.* [5]; squares, preliminary data of Dytman *et al.* [6]. (b) Recoil nucleon polarization at the c.m. angle 90°. Data are from Heusch *et al.* quoted in Ref. [4]. The solid line is our full fit; the dashed line omits the contribution of the $S_{11}(1535)$ excitation.

at threshold (Table I), (2) sample fits of available cross-section and polarization data (Fig. 2), and (3) extraction of the helicity amplitude $A_{1/2}$ for the $\gamma p \leftrightarrow S_{11}(1535)$ transition.

Table I demonstrates the real part of the E_{0+} amplitude for the η photoproduction at threshold off proton, contrasted with the same for the π^0. While there is clear preference for the PV coupling at the $\pi^0 NN$ vertex, this is not so for the η meson. Interestingly, the value of the ηNN coupling constant extracted from our fit is *not* sensitive to the choice of the PV or PS coupling at the meson-nucleon vertex: We get $g_\eta^2/4\pi \sim 1.4$, in fair agreement with the SU(3) value [12]. For the η photoproduction, vector-meson contributions are sizable and the $S_{11}(1535)$ excitation amplitude in the *s* channel stands out, in contrast to the π^0 case, where vector-meson and $\Delta(1232)$ contributions are minor.

Figures 2(a) and 2(b) display typical results of our fits. Figure 2(a) demonstrates the dominance of the differential cross section at c.m. angle of 50° by the *s*-channel excitation of the $S_{11}(1535)$ resonance. Figure 2(b) shows the recoil nucleon polarization. Contributions from all the multipoles relevant to the process (1), not just the E_{0+} multipole, are included in computing the observables in Figs. 2(a) and 2(b). At both $E_\gamma = 725$ and 750 MeV, we expect a flat angular distribution, in agreement with the preliminary Bates [6] data at $E_\gamma = 750$ MeV, but *not* with those at 725 MeV, which show a stronger angular dependence. Our prediction for the total cross section nicely agrees with the data [4] for E_γ between 730 MeV and 1.2 GeV.

Our analysis yields the product $\Gamma_\eta^{1/2} A_{1/2} = (26 \pm 3) \times 10^{-3}$. Assuming [8] a partial width Γ_η of 75 MeV, we obtain $A_{1/2} = (95 \pm 11) \times 10^{-3}$ GeV$^{-1/2}$ for the proton, which lies in between the predicted extremes [9] of recent theoretical estimates in the quark model, ranging from 54 to 162, in the same units. The corresponding value, reported by the PDG [8], extracted from the pion photoproduction is 73 ± 14. Finally, we obtain a rather precise determination of the following quantity for the $\gamma p \to S_{11}(1535) \to \eta p$ process:

$$\alpha \equiv (\chi \Gamma_\eta)^{1/2} A_{1/2}/\Gamma_T = (0.22 \pm 0.02) \times 10^{-3}\ \mathrm{MeV}^{-1},$$

where $\chi = Mk/qM_R$, k and q corresponding to $W = M_R$. This should be of fundamental interest to future precision tests of hadron models.

In conclusion, we have studied photoproduction of η mesons, from threshold through the excitation of the $S_{11}(1535)$ resonance, in the effective Lagrangian approach. This has drastically reduced the number of parameters fitted to the data. Evaluation of the tree-level amplitude reveals large differences between the η and π^0 photoproduction at threshold. Among the quantities determined from this study are the ηNN coupling constant and a precise parameter α characteristic of the $S_{11}(1535)$ resonance. The latter, in turn, yields a good estimate of the helicity amplitude $A_{1/2}$. These are relevant to topical hadron models, and hence to the test of QCD in its nonperturbative domain. Much theoretical work remains to be done in that regard as we await precise experiments on the η photoproduction and electroproduction processes in the newer generation photon-electron facilities.

We thank Dr. R. Davidson for many useful theoretical discussions, and Dr. B. Doyle for his help with MINUIT. We are grateful to Professor S. Dytman and Professor W. Daehnick for allowing us a preview of their as-yet unpublished data of the reaction (1), obtained at Bates. This research has been supported by the U.S. Department of Energy, Grant No. DE-FG02-88ER40448.A003.

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