Abstract

We present a unitary and gauge-invariant model with coupled channels, which provides a consistent description of pion photoproduction off nucleons in the $E_{0+}$ channel and $\eta$-meson photoproduction off protons and deuterons. An effective field theory with hadrons and photons is constructed, which includes non-resonant Born terms as well as the $S_{11}(1535)$ and $S_{11}(1650)$ baryon resonances. Due to the coupling between the channels, the production of $\eta$-mesons is strongly affected by the $S_{11}(1650)$ although its direct coupling to the $\eta N$ channel is negligible. The rho- and omega-meson exchange terms are important for achieving a consistent description of both pion- and photon-induced reactions.

1 Introduction and summary

In recent years the physics of the $\eta$-meson has been studied intensively. New measurements of $\eta$-production in hadronic and heavy-ion collisions have been performed at SATURNE [1], Los Alamos [2], Brookhaven [3] and GSI [4]. The availability of high-duty-factor electron accelerators, MAMI in Mainz and ELSA in Bonn, has opened the possibility to perform precise experiments with electromagnetic probes, e.g. photon- and electron-induced $\eta$-meson production off nucleons [5–7] and nuclei [8,9]. The accurate measurements of electromagnetic processes provide strong constraints on models for the elementary $\eta$-meson–hadron and photon–hadron interactions, which are the basis for a theoretical description of $\eta$-meson propagation in hadronic matter and production in heavy-ion collisions. The theoretical interpretation of the data has
lead to the development of new models for photon-induced $\eta$-meson production [10–12].

In this letter, we present a model for $\eta$-meson photoproduction off nucleons and deuterons through the dominant $E_{0+}$ channel. An effective field theory with hadrons and photons is constructed, using a coupled-channels model [13] for $\pi N$ scattering and pion-induced $\eta$-production in the $S_{11}$ channel as a starting point and coupling the electromagnetic field to the hadrons in a gauge-invariant way. As compared to existing models the following substantially new features are:

- Resonance and background contributions are taken into account in a strictly unitary way. The consistent inclusion of final-state interactions between the hadrons is important.
- In addition to the dominant $S_{11}(1535)$ resonance, which couples strongly to the $\eta N$ channel, we also take the second resonance $S_{11}(1650)$ in the $\pi N$ $S_{11}$ channel into account. We find that the upper resonance is essential, although its small direct coupling to the $\eta N$ channel can be neglected. This is due to the coupling of the $S_{11}(1650)$ to the $\eta N$ channel through intermediate $\pi N$ states. Because of the modifications due to the second resonance, agreement with experimental data can be obtained only when the $\rho$- and $\omega$-meson exchange terms are included. These terms are not needed in [10] because there the $S_{11}(1650)$ resonance is neglected. The hadronic and electromagnetic coupling constants of the $S_{11}(1535)$ are, due to large interference effects, different from those obtained in one-resonance models.
- The hadronic part of the model, which describes the final-state interactions between the hadrons, is determined exclusively by fitting elastic $\pi N$ scattering data. The consistency is checked by comparing the cross section for the inelastic channel $\pi N \rightarrow \eta N$ with experiment. Since the hadronic parameters are fixed, the electromagnetic coupling constants are uniquely determined by the photoproduction data. Thus we obtain values for the helicity amplitudes of the resonances. These are of great interest as a test for the quark model. Within our model we achieve a consistent description of the pion photoproduction off nucleons in the $E_{0+}$ channel and of the $\eta$-meson photoproduction off nucleons and deuterons.

2 The model

Let us briefly summarize the hadronic part of our model (for details see [13]). As already mentioned there are two $N^*$ resonances in pion-nucleon scattering in the $S_{11}$ channel at center-of-mass energies below $\sqrt{s} = 1.8$ GeV [14]. The lower one at 1535 MeV ($S_{11}(1535)$) decays into $\pi N$, $\eta N$ and $\pi \pi N$ with the branching ratios 35–55%, 30–50% and 5–20%, respectively. The upper one
at 1650 MeV ($S_{11}(1650)$) couples strongly to the $\pi N$ and $\pi\pi N$ channels with branching ratios of 60–80% and 5–20%, respectively, but only weakly to the $\eta N$ channel with a decay probability of approximately 1%.

In order to describe these experimental facts, we include the following interaction terms in the lagrangian,

\[
\mathcal{L}_I = -i g_{\pi NN} \bar{\Psi}_N \gamma_5 \overline{\pi} \Psi - g_{\sigma NN} \bar{\Psi}_N \psi - g_{\sigma \pi} \overline{\pi} \psi \\
- g_{\pi NN_1} \bar{\Psi}_{N_1} \pi \overline{\pi} + \text{h.c.} - g_{\pi NN_2} \bar{\Psi}_{N_2} \overline{\pi} \psi + \text{h.c.} \\
- g_{\eta NN_1} \bar{\Psi}_N \eta + \text{h.c.} \\
- i g_{\zeta NN_1} \bar{\Psi}_{N_1} \sigma_5 \zeta + \text{h.c.} - i g_{\zeta NN_2} \bar{\Psi}_{N_2} \sigma_5 \zeta + \text{h.c.}.
\]  

The first line contains the interaction terms of the linear sigma-model which incorporates chiral symmetry and describes low-energy $\pi N$ scattering. In the second line the $\pi NN^*$ interaction terms for the two $N^*$ resonances ($N_{1*}^* \equiv S_{11}(1535)$, $N_{2*}^* \equiv S_{11}(1650)$) are given, whereas that in the third line is the $\eta NN_1^*$ coupling. We neglect the weak $\eta NN$ and $\eta NN_2^*$ couplings. The effect of the physical two-pion continuum is parametrized by means of an effective scalar field $\zeta$ of positive parity, mass $m_\zeta = 400$ MeV and zero width. The field $\zeta$ interacts through the $\zeta NN^*$ couplings, given in the last line of (1). The question why the $\sigma$- and the $\zeta$-fields are not identical is discussed in [13].

The Bethe-Salpeter equation, which couples the three open channels $\pi N$, $\eta N$ and $\zeta N$, is solved by using a $K$-matrix approach, which guarantees a unitary $S$-matrix. We identify the $K$-matrix elements with the diagrams shown in Fig. 1.

![Fig. 1: Matrix elements $K_{ji}$: The first diagram shows the contributions from the resonances, which contribute in all three channels (i, j=\pi, \eta, \zeta; except $\eta NN_1^*$). The last three diagrams correspond to the $\pi N$ Born terms which are included in the tree approximation to the linear sigma-model.](image)

In this approximation the $K$-matrix, and consequently also the $T$-matrix, is free of divergences. After introducing form factors at the non-resonant Born terms, the coupling constants and resonance masses are determined by fitting elastic $\pi N$ scattering data, employing the KA84 partial-wave analysis [14]. The data are well reproduced up to and including the energy region of the
second resonance [13]. A test of the consistency of the model is provided by the cross section for the process $\pi^- + p \rightarrow \eta + n$. The data for this process are well described by the model without further adjustment of the parameters. It is important to note the essential role played by the $S_{11}(1650)$ resonance not only in the elastic but also in the inelastic channel. In previous calculations [10,16] this resonance has not been included.

In this paper we extend the model by introducing electromagnetic interactions. We stress that the hadronic part of the model is not modified in any way. To lowest order in the electromagnetic interaction the $T$-matrix for the process $\gamma p \rightarrow \eta p$ is related to the $K$-matrix by

\[ T_{\eta\gamma} = K_{\eta\gamma} - i\pi \sum_i T_{\eta i}\delta(E - H_i)K_{i\gamma}, \]  

(2)

where the sum is over all open channels, $i = \pi, \eta, \zeta$. The final-state interactions, described by $T_{\eta i}$, is entirely due to strong interactions. In accordance with experiment [5] we assume that the total cross section for photoproduction of $\eta$-mesons is dominated by the $S_{11}$ channel and use our model for $\pi N$ scattering and pion-induced $\eta$-meson production in this channel to describe the final-state interactions.

The resonance contributions to the $K$-matrix elements $K_{i\gamma}$ are identified with the first diagram shown in Fig. 2. The $\gamma NN^*$ coupling is given by the lagrangian

\[ \mathcal{L}_{\gamma NN^*} = \frac{-ie}{2(m_{N^*} + m_N)} \bar{\Psi}_{N^*} \left( k_{N^*}^S + k_{N^*}^V \tau_3 \right) \gamma^5 \sigma^\mu\nu \Psi_N F_{\mu\nu} + \text{h.c.}, \]  

(3)

where $m_{N^*}$ and $m_N$ are the resonance and nucleon masses. This interaction is obviously gauge invariant, because it involves only the electromagnetic field-strength tensor $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$. Since the interaction has an isoscalar and an isovector part, there are two new unknown coupling constants per resonance. They are proportional to the isoscalar and isovector helicity amplitudes of the resonances.
Fig. 2: Matrix elements $K_{i\gamma}$: The first diagram represents the resonance processes which, except for the process $\gamma N \rightarrow N^*_2 \rightarrow \eta N$, are non-zero ($i=\pi, \eta, \zeta$). The following diagram, showing $\rho$- and $\omega$-meson exchange, contributes to $K_{\pi\gamma}$ as well as to $K_{\eta\gamma}$, whereas the remaining ones correspond to $\pi N$ Born terms.

Furthermore, the $\rho$- and $\omega$-meson exchange processes, represented by the second diagram in Fig. 2, give important contributions to $K_{\pi\gamma}$ as well as to $K_{\eta\gamma}$.

The corresponding lagrangian reads

$$
\mathcal{L}_V = -f_{\omega NN} \overline{\Psi}_N \gamma^\mu \Psi_N \omega_\mu - f_{\rho NN} \overline{\Psi}_N \gamma^\mu \overline{r} \Psi_N \rho_\mu + \frac{f_{\rho NN}}{2M} \kappa_\rho \overline{\Psi}_N \sigma^{\mu\nu} \overline{r} \Psi_N \partial_\nu \rho_\mu
+n \frac{\lambda_{\omega\gamma}}{4m_\eta} \epsilon_{\alpha\beta\gamma\delta} F^{\alpha\beta} \omega^{\gamma\delta} \eta + \frac{\lambda_{\rho\gamma}}{4m_\eta} \epsilon_{\alpha\beta\gamma\delta} F^{\alpha\beta} \rho^{\gamma\delta}
+n \frac{\lambda_{\rho\pi}}{4m_\pi} \epsilon_{\alpha\beta\gamma\delta} F^{\alpha\beta} \rho^{\gamma\delta} \pi + \frac{\lambda_{\omega\pi}}{4m_\pi} \epsilon_{\alpha\beta\gamma\delta} F^{\alpha\beta} \omega^{\gamma\delta} \pi.
$$

Here, $\omega^{\gamma\delta}$ and $\rho^{\gamma\delta}$ are the field strength tensors of $\omega$- and $\rho$-meson, respectively. The first line contains the interaction of $\omega$- and $\rho$-meson with the nucleon, where the corresponding coupling constants are well known [15]: $f_{\rho NN} = 2.52, f_{\omega NN} = 3f_{\rho NN}$ and $\kappa_\rho = 6.6$. We neglect the small coupling of the $\omega$-meson to the nucleon anomalous magnetic moment. The interactions which are responsible for the decays of $\omega$ and $\rho$ mesons into a photon and an $\eta$- or $\pi$-meson are given in the two bottom lines. The constants $\lambda_{\omega\eta} = 0.329$, $\lambda_{\rho\eta} = 1.02$ and $\lambda_{\omega\pi} = 0.32$ are determined by the experimentally well known decay widths. The uncertainty in the branching ratio for the decay of a neutral $\rho$-meson into $\pi^0\gamma$ is rather large, while the corresponding decay for the $\omega$-meson is quite well known. We therefore use the SU(2) relation $\lambda_{\rho\pi\gamma} = \lambda_{\omega\pi\gamma}/3$ to determine the $\rho\pi\gamma$ coupling constant. The resulting value is compatible with the measured branching ratio.

We also include non-resonant Born terms in $K_{\pi\gamma}$ in order to be consistent with the interaction terms of the linear sigma-model and to fulfil the low-energy...
theorems of pion photoproduction. The corresponding interaction terms are obtained by minimal coupling of the photon to the lagrangian of the linear sigma-model. This generates a coupling of the photon to the electromagnetic currents of the nucleon and the pion, and consequently in tree approximation the diagrams in the second row of Fig. 2. We obtain the lagrangian

$$L_{\gamma NN} + L_{\gamma \pi \pi} = -e \frac{1 + \frac{1}{2}}{2} \gamma^\mu A_\mu \Psi_N + \frac{1}{2} \partial_\mu \overline{\pi} i e A_\mu T_3 \pi + \frac{1}{2} i e A_\mu T_3 \pi \overline{\pi} \partial_\mu \pi$$

where we have added the coupling to the anomalous magnetic moment. Here $k^S$ and $k^V$ are the isoscalar and isovector part of the anomalous magnetic moment of the nucleon, $k^S = -0.06$ and $k^V = 1.85$.

Since the linear sigma-model is chirally invariant, PCAC and consequently the low-energy theorems of pion photoproduction are satisfied. However, as shown in [17], the low-energy theorems are not satisfied on the tree level but only once one-loop diagrams are included. In order to satisfy the low-energy theorems in the absence of loop diagrams an additional contact interaction of the form

$$L^c = \frac{i e g_{\pi NN}}{8m_N^2} \overline{\Psi}_N \gamma^5 \{ \tau, k^S + k^V T_3 \} \sigma^{\mu \nu} \Psi_N F_{\mu \nu}$$

has to be added, which contains an anticommutator of nucleon isospin matrices. One can construct this form by starting from a lagrangian with pseudovector $\pi NN$ interaction, coupling the photon in a minimal way, adding a coupling to the anomalous magnetic moment of the nucleon and then performing a chiral rotation of the baryon fields [18,19]. Neglecting higher-order interaction terms, one ends up with a model with pseudoscalar $\pi NN$ interaction plus the additional interaction term (6), which satisfies the low-energy theorems. We note that this contact term, shown in Fig. 2, should be distinguished from the Kroll-Ruderman term, which is obtained by coupling the photon in a minimal way to a pseudovector $\pi NN$-interaction.

Now the essential contributions are accounted for. The contributions of other resonance or meson exchange terms are expected to be small either due to small decay widths into the relevant channels or because of large masses in intermediate states.

We introduce form factors for the contact term and the vector-meson exchange contributions. Gauge invariance implies large cancellations between the form factor at the $\pi NN$-vertex and additional terms generated by coupling the electromagnetic field to the form factor in a minimal way. The net effect is
that for the current coupling, the diagrams in the bottom row of Fig. 2 should be computed without form factors because the form factor corrections to these diagrams are cancelled by other contributions [20–22].

3 Results

The model is now defined and the electromagnetic parameters, namely the isoscalar and isovector couplings of the photon to the two resonances as well as the cutoffs, should be determined. The ideal way to proceed would be to fit the parameters to the E_{0+}-amplitude of pion photoproduction and then predict the total cross section for photoinduced η-production. However, in view of the fact that there are substantial deviations between different existing partial-wave analyses for pion photoproduction this is not a useful way to proceed. Therefore we choose a more pragmatic approach and search for an optimal description of both π- and η-photoproduction. Considering the uncertainty in the analyses, we obtain reasonable agreement with the data on the E_{0+}-amplitude of pion photoproduction in all isospin channels [23] for a parameter set which also describes the total cross section of η-production off protons and deuterons [24]. We find the following helicity amplitudes (in units of 10^{-3} GeV^{-1/2}): A_{1/2}^p = 102, A_{1/2}^n = -82 for the S_{11}(1535) and A_{1/2}^p = 83 and A_{1/2}^n = -24 for the S_{11}(1650), which correspond to k^{S}_{N^*(1535)} = 0.09, k^{V}_{N^*(1535)} = 0.84, k^{S}_{N^*(1650)} = 0.25 and k^{V}_{N^*(1650)} = 0.45. The resulting total cross section of the process $\gamma+p \rightarrow \eta+p$ is shown by the solid line in Fig. 3, together with data from [5,6].

![Fig. 3: Total cross sections for the photoproduction of η-mesons off protons (solid line). The data are taken from [5,6]. See text for further details.](image-url)
It is instructive to examine the contributions of the different processes to the cross section. The short-dashed line shows the cross section when all processes except those involving the $S_{11}(1535)$ are neglected. Accidentally this is relatively close to the data. The dot-dashed line is obtained by including also the non-resonant pion-nucleon Born terms, while the long-dashed line is found by adding also the second resonance. Thus, in the calculation corresponding to the long-dashed line only the vector-meson exchange terms are neglected. Obviously the presence of the second resonance leads to destructive interference and a shift of the peak towards higher energies compared to a model which includes only one resonance. This shift is compensated by the vector meson exchange contributions. Hence, when the second resonance is included one cannot describe simultaneously both the $\pi N \rightarrow \eta N$ and $\gamma N \rightarrow \eta N$ data without vector-meson exchange contributions. In other models, where the second resonance is ignored, the vector-meson exchange contributions are not needed [10]. Although the direct coupling of the $S_{11}(1650)$ to the $\eta N$ channel is very weak and consequently neglected in our model, this resonance plays an important role in the photoproduction of $\eta$-mesons, due to the coupling to the $\eta N$-channel via intermediate $\pi N$ states. This effect can never be described in tree level calculations [11].

The total cross section for $\eta$-meson photoproduction off deuterons is computed in the impulse approximation, i.e., we assume that the elementary meson-production amplitudes from the two nucleons in their bound state can be added to form the production amplitude from the deuteron. The corrections due to final-state interactions between the nucleons as well as between the produced meson and the spectator nucleon are expected to be small\(^2\), because of the large distance between the two nucleons in the deuteron [25]. Since the nucleon which is hit by the photon is not on its mass shell in the deuteron, we must use half-off-shell elementary amplitudes here. In the impulse approximation the other nucleon is a spectator, which must be on its mass shell. Thus, the energy $E_N$ of the off-shell nucleon is, for a given value of its momentum $\vec{p}_N$, determined by energy and momentum conservation. The initial $K$-matrix element $K_{i\gamma}$ is computed with an off-shell nucleon with energy $E_N$ and momentum $\vec{p}_N$ and an on-shell photon with energy $E_\gamma$ in the initial state and on-shell particles in the final state. The subsequent interactions are treated in the $K$-matrix approximation, with on-shell propagation at an invariant mass squared $s = (E_N + E_\gamma)^2 - (\vec{p}_N + \vec{p}_\gamma)^2$.

The $T$-matrix for photoproduction off the deuteron is obtained by multiplying with the deuteron wave function $\Psi_D(p_N)$ of the Paris potential [27]. The resulting cross section is in good agreement with data (cf. Fig. 4). Note that the momentum distribution of the nucleons in the deuteron has an important effect on the cross section. At small photon energies one observes the

\(^2\) except near threshold where the NN cross section is large (see below)
so-called subthreshold production. At the peak, the deuteron cross section is much smaller than twice the proton cross section, whereas at $E_\gamma \approx 850$ MeV their ratio is about two, in agreement with experiment [8,26]. This has been interpreted in terms of different energy dependencies of the neutron and proton cross sections: At low energies $\sigma_n/\sigma_p \approx 2/3$, while at energies above $E_\gamma \approx 850$ MeV a ratio exceeding unity was found, implicitly assuming that the nucleons in the deuteron are at rest. In our model, which is consistent with the data, the ratio $\sigma_n/\sigma_p$ is almost constant for $E_\gamma \leq 900$ MeV and increases for larger energies, reaching unity at $E_\gamma \approx 950$ MeV. Thus, the smearing in energy due to the momentum distribution plays a crucial role here, and invalidates the naive interpretation of the deuteron cross section.

![Figure 4: Total cross section for the photoproduction of $\eta$-mesons off the deuteron. Data are taken from [8].](image)

In order to explore the sensitivity of the cross section to uncertainties in the deuteron wave function we repeated the calculation with the wave function of the Bonn potential [28]. The results are indistinguishable, since the wave functions differ significantly only at relative nucleon momenta higher than 400 MeV, which play a negligible role here.

Due to the dominant isovector character of the $S_{11}(1535)$ helicity amplitudes one might expect strong destructive interference between the two elementary $\gamma N \rightarrow \eta N$ amplitudes, where in the one case the photon hits the proton and in the other the neutron. However, the interference term is negligible because of the following reason. The participating nucleon in one of the two interfering matrix elements is a spectator in the other one. Since the final states of both matrix elements have to be identical, this means that, due to the large momentum transfer to the participating nucleon, the interference term probes
Finally, we note that near threshold the model underestimates the data by \(\sim 50\%\). The discrepancy may be due to proton–neutron final-state interactions [25]. A calculation including this effect is in progress.

### 4 Conclusion

The \(\eta\)-meson photoproduction off nucleons is described within a unitary and gauge-invariant model. Elastic \(\pi N\) scattering data are used to determine the hadronic parameters of the model. The predicted cross section for pion-induced \(\eta\)-production agrees well with the data. We obtain a consistent description of the photoproduction of \(\eta\)-mesons and pions which satisfies the low-energy theorems for the latter reaction. In all these processes not only the \(S_{11}(1535)\)-resonance but also the \(S_{11}(1650)\)-resonance plays an important role. We also find that the \(\rho\)- and \(\omega\)-exchange processes play a crucial role in the photoproduction of \(\eta\)-mesons.

Estimates of the \(\eta N N\) coupling constant in the framework of a nonlinear \(SU(3) \times SU(3)\) sigma-model with mesons and baryons imply that the contribution of the \(\eta\)-nucleon pole terms to the photoproduction of \(\eta\)-mesons is small and can be neglected [29]. Thus, our model provides a consistent description of \(\eta\)-meson production, with all essential contributions included.

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