Incoherent Photoproduction of $\eta$-mesons from the Deuteron near Threshold

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Abstract

Incoherent photoproduction of the $\eta$-meson on the deuteron is studied for photon energies from threshold to 800 MeV. The dominant contribution, the $\gamma N$-$\eta N$ amplitude, is described within an isobar model. The final state interaction derived from the CD-Bonn potential is included and found to be important for the description of the production cross section close to threshold. Possible effects from the $\eta N$ final state interaction are discussed.

I. INTRODUCTION

Recent measurements by the TAPS collaboration [1-3] at the MAMI accelerator of the $\eta$-meson photoproduction on deuterium and helium indicate an enhancement of the total inclusive cross section at photon energies close to the reaction threshold. The data were specifically collected with high statistical accuracy in order to clarify the first observation [1] of the rather large total cross section in that energy regime. It was suggested [2] that such a threshold enhancement could result either from the formation of the quasi bound $\eta$-nucleus state or from the interaction between the final nucleons.

Indeed, a strong influence of the final state interaction (FSI) on the cross sections of $\pi$, $\eta$, $\eta'$ and $\omega$-meson production in nucleon-nucleon ($NN$) collisions was observed in experiments at the IUCF, COSY and CELSIUS accelerator facilities [4-11]. With the exception of the $\eta$ channel, those experiments producing mesons in $NN$ collisions can be described almost perfectly by theoretical calculations accounting only for the final state interactions between the nucleons [4,11]. In case of $\eta$ production there is evidence that the $\eta N$ FSI could play a role as well [5,6]. Therefore, one might expect that the TAPS data can be understood in terms of the strong neutron-proton ($np$) FSI and possibly an $\eta N$ FSI.

However, recent calculations [12] which include the $np$ as well as the $\eta N$ final state interactions underestimate the cross section for the reaction $\gamma d \rightarrow np\eta$ at photon energies close to the threshold. Within a different approach, three body calculations [13] of the reaction $\gamma d \rightarrow np\eta$ performed by the same authors reproduce the main features of the experimental data, but again do not explain the rather large total cross section near the reaction threshold. On the other hand, an older calculation of the reaction $\gamma d \rightarrow np\eta$ performed by Ueda [14], which considers the formation of a quasi bound $\eta d$ state, leads to a much too strong enhancement of the production cross section close to threshold, and is ruled out by
the TAPS data. Therefore, the explanation of the TAPS data is still open and needs further investigations.

Here we evaluate the reaction $\gamma d \rightarrow np\eta$ within the impulse approximation. In addition we account for the FSI between the neutron and proton by employing the most recent CD-Bonn potential \[13\]. In Sect. 2 we specify the elementary $\gamma N \rightarrow \eta N$ amplitude which serves as input for our calculation of the reaction $\gamma d \rightarrow np\eta$. Specifically, we assume that the elementary $\eta$-production proceeds via the excitation of the $N^* S_{11}(1535)$ resonance. The free parameters of our model are fixed by a fit to available data for the reaction $\gamma p \rightarrow \eta p$. In Sect. 3 we provide some details about the evaluation of the reaction amplitude for $\gamma d \rightarrow np\eta$ and present results for the impulse approximation as well as for the inclusion of the FSI in the $np$ system. Possible effects from the $\eta N$ FSI are discussed in Sect. 4. In addition we provide predictions for the angular spectrum and for the momentum spectrum of the produced $\eta$ meson for selected incident photon energies in the vicinity of the $\eta$-production threshold. The section ends with a brief summary of our results.

II. THE ELEMENTARY $\gamma N \rightarrow \eta N$ AMPLITUDE.

The dominant contribution to $\eta$-meson photoproduction from a nucleon is given by the $N^*$ isobar excitation \[20,21\]. We do not consider the nucleon s-channel pole term nor $t$-channel vector meson exchanges, since their contributions were found to be negligible \[20,21\].

The square of the invariant collision energy of the reaction $\gamma N \rightarrow N\eta$ is defined as

$$s = m_N^2 + 2m_N E_\gamma,$$

where $m_N$ and $E_\gamma$ are the nucleon mass and the photon energy, respectively. The photon momentum $k$ and the $\eta$-meson momentum $q$ in the center of mass system are given by

$$k = \frac{s - m_N^2}{2\sqrt{s}}, \quad q = \frac{\lambda^{1/2}(s, m_N^2, m_\eta^2)}{2\sqrt{s}},$$

where $m_\eta$ stands for the mass of the $\eta$-meson. The Kälen function is defined as

$$\lambda(x, y, z) = (x - y - z)^2 - 4yz.$$  \[(3)\]

The resonant contribution is given by helicity amplitudes in the relevant partial waves \[22,23\], namely

$$A_{l\pm} = \pm F A_{1/2}^N,$$

$$B_{l\pm} = \pm F \left[ \frac{4}{l(l+2)} \right]^{1/2} A_{3/2}^N,$$

$$C_{l\pm} = \pm FC_{1/2}^N,$$

where the factor $F$ accounts for the resonance decay into the $N\eta$ channel. $l$ denotes the orbital angular momentum. Taking into account the phase space factor and the relativistic Breit-Wigner propagator as introduced in Ref. \[24\] one obtains
\[ F = \left[ \frac{\Gamma_\eta}{\pi(2j + 1)} \right]^{1/2} \frac{\sqrt{s}}{M_R^2 - s - i\sqrt{s}\Gamma} \left[ \frac{k}{q \sqrt{s}} \right]^{1/2} m_N \left( 2j + 1 \right) \frac{\sqrt{s}}{M_R^2 - s - i\sqrt{s}\Gamma}. \] (5)

Here \( M_R \) is the resonance mass, and \( \Gamma \) and \( \Gamma_\eta \) are the total and \( R \rightarrow N\eta \) partial resonance widths, respectively, while \( j \) is the spin of the resonance.

The standard relation between the Breit-Wigner helicity amplitudes and electric, magnetic and longitudinal multipoles are given in Refs. [20,21].

Following the analysis of pion photoproduction, we account for the energy dependence of the hadronic widths [25] in order to satisfy the threshold dependence [20,26] of the multipole amplitudes of the outgoing meson momentum \( q_\xi \). The energy dependence of the partial width for each final meson \( \xi \) is given as

\[ \Gamma_\xi = \Gamma_\xi(M_R) \frac{\rho_\xi(\sqrt{s})}{\rho_\xi(M_R)}, \] (6)

where \( \Gamma_\xi(M_R) \) is the \( R \rightarrow N\xi \) partial resonance width at the resonance pole, while \( \rho_\xi \) is given by [25]

\[ \rho_\xi(\sqrt{s}) = \frac{q_\xi}{\sqrt{s}} B_1^2(q_\xi R), \quad q_\xi = \frac{\lambda^{1/2}(s, m_\xi^2, m_\eta^2)}{2\sqrt{s}}. \] (7)

Here \( B_1 \) is the Blatt-Weisskopf function for the orbital angular momentum \( l \). The interaction radius was taken as \( R = 1 \text{ fm} \), and \( m_\xi \) stands for the mass of the meson. The function \( \rho_\xi(M_R) \) in Eq. 6 is evaluated at the resonance pole \( \sqrt{s} = M_R \). In addition, the total energy-dependent resonance width is given by the sum over the partial widths of all available final states.

In principle, one may consider the contributions from the resonances \( P_{11}(1440) \), \( D_{13}(1520) \), \( S_{11}(1535) \), \( S_{11}(1650) \), \( D_{15}(1675) \), and higher mass resonances to the photoproduction of \( \eta \)-mesons [20] and evaluate the resonance parameters from the available differential cross section data and recoil nucleon polarization data [21]. Contributions from \( S \)-wave resonances provide an isotropic angular spectrum \( d\sigma/d\cos\theta \) of \( \eta \)-mesons, with \( \theta \) denoting the \( \eta \)-meson emission angle in the c.m. system. The \( P \)-wave resonances contribute proportionally to \( \cos\theta \), while the \( D \)-wave resonances result in a \( \cos^2 \theta \) dependence. Although contributions from higher partial waves to the total photoproduction cross section of \( \eta \)-mesons can be very small, they can be evaluated from the differential \( d\sigma/d\cos\theta \) cross section with the help of interference terms. However, most recent data [4] for differential cross sections of the reaction \( \gamma p \rightarrow p\eta \) at photon energies from 716 to 788 MeV indicate that, within the experimental errors, the angular spectrum is dominated almost entirely by the \( S \)-wave distribution. Estimated contributions from \( P \) and \( D \)-wave resonances can be given only at very low confidence level [27]. Furthermore, data on the nucleon recoil polarization, which in principle must be sensitive to the resonant contribution [21], have large uncertainties and are thus not significant.

Since there is no strong experimental evidence [27] for contributions to the \( \eta \)-meson photoproduction from resonances other than the \( S_{11}(1535) \) resonance in the near-threshold region, we will consider in the following only this resonance. The partial decay widths, \( S_{11}(1535) \rightarrow N\eta \) and \( S_{11}(1535) \rightarrow N\pi \), are related to the relevant coupling constant \( g_{RN\xi} \), \( \xi = \eta, \pi \), by
\[ \Gamma_\xi = \frac{g_{RN\xi}^2 q_\xi (E_N + m_N)}{4\pi M_R}. \]

Here the momentum \( q_\xi \) and the nucleon energy \( E_N \) are evaluated in the rest frame of the resonance at the pole position of \( S_{11}(1535) \).

Considering only the contribution of the \( S_{11}(1535) \) resonance, the data for \( \eta \)-meson photoproduction off protons can be well fitted with the following resonance parameters at the \( S_{11}(1535) \) pole:

\[ M_R = 1544 \text{ MeV}, \quad \Gamma = 203 \text{ MeV}, \]
\[ \Gamma_\eta/\Gamma = 0.45, \quad \Gamma_\pi/\Gamma = 0.45, \quad \Gamma_{\pi\pi}/\Gamma = 0.1. \]  

(9)

For the electromagnetic helicity amplitudes in Eq. 4 we use the values \( A_{1/2}^p = 0.124 \text{ GeV}^{-1/2} \) and \( A_{1/2}^n = -0.1 \text{ GeV}^{-1/2} \). The result of this fit for the total cross section for the reaction \( \gamma p \to p\eta \) is displayed in Fig. 1.

**III. THE REACTION \( \gamma D \to \eta NP \)**

Using the impulse approximation (IA) the amplitude \( \mathcal{M} \) of the reaction \( \gamma d \to np\eta \) for given spin \( S \) and isospin \( T \) of the final nucleons can be written as

\[ \mathcal{M}_{IA} = A_T(s_1)\phi(\vec{p}_2) - (-1)^{S+T} A_T(s_2)\phi(\vec{p}_1), \]  

(10)

where \( \phi(p_i) \) stands for the deuteron wave function and \( p_i \) \((i = 1, 2)\) is the momentum of the proton or neutron in the deuteron rest frame. The quantity \( A_T \) denotes the isoscalar or isovector photoproduction amplitude at the squared invariant energy \( s_N \) given by

\[ s_N = s - m_N^2 - 2(E_\gamma + m_d)E_N + 2k_\gamma \cdot \vec{p}_N. \]  

(11)

Our calculation within the framework of the IA is shown in Fig. 2 and corresponds to the dashed line. It describes the data [1] at photon energies above \( \approx 680 \text{ MeV} \) reasonably well. Close to the reaction threshold, however, the IA result substantially underestimates the data. We take this as an indication that effects from the \( NN \) and/or \( \eta N \) final state interaction play an important role here. Indeed, as already mentioned in the Introduction, it is well known from meson production in \( NN \) collisions that close to threshold FSI effects lead to a significant modification of the cross section.

In meson production in \( NN \) collisions FSI effects result predominantly from strong \( S \)-wave interactions in the outgoing \( NN \) system. Therefore, we will take into account this contribution for the reaction \( \gamma d \to np\eta \). The corresponding amplitude is given by

\[ \mathcal{M}_{FSI} = m_N \int dk k^2 \frac{T(q, k) A_T(s_N)\phi(p_i)}{q^2 - k^2 + i\epsilon}. \]  

(12)

Here \( q \) is the nucleon momentum in the final \( np \) system and \( T(q, k) \) is the half-shell \( np \) scattering matrix in the \( ^1S_0 \) and \( ^3S_1 \) partial waves. In the calculations presented here, the half-shell t-matrix is obtained at corresponding on-shell momenta \( q \) from the latest CD-Bonn
potential \([\Pi]\), which describes the \(NN\) data base with a \(\chi^2/\text{datum}\) of about 1. In order to find out if a high precision description of the \(NN\) data, in our specific case the \(NN\) s-waves, is crucial, we carried out the calculations with an older one-boson-exchange model, OBEPQ \([16]\), also describing the s-waves reasonably well. We found the difference of those two calculations being negligible.

The total cross section \(\gamma d \rightarrow np\eta\) including the \(np\) FSI in S-waves is displayed in Fig. 2 as solid line. Now the model calculation describes the data \([1]\) reasonably well and lies, in fact, within the experimental uncertainties. As expected, the FSI interaction gives rise to a significant increase of the production cross section close to threshold as is required for getting agreement with the data.

IV. DISCUSSION

In \(\eta\)-production experiments in \(pp\) as well as in \(np\) collisions one has observed that there is an even stronger enhancement of the production cross section close to threshold, which cannot be explained by FSI effects from the \(NN\) interaction alone \([4,4]\). This additional enhancement is, in general, seen as an indication of FSI effects due to the \(\eta N\) interaction \([28,29]\). Thus, it may be suggested that similar effects are seen in the reaction \(\gamma d \rightarrow np\eta\). In order to expose a possible influence from the \(\eta N\) FSI we again show the experimental data in Fig. 3, but now divide them by our model calculation, which includes the enhancement from the FSI between the nucleons. Any effects from the \(\eta N\) FSI present in the data would then reveal themselves as additional enhancement. Indeed, as can be seen in Fig. 3, there is a deviation from our calculation for energies very close to threshold, which may be interpreted as being caused by an \(\eta N\) FSI, though the error bars are large. It is interesting to mention, that the magnitude and also the energy range of this deviation are comparable to the effects seen in \(\eta\)-production via hadronic probes. In the reactions \(pp \rightarrow pp\eta\) as well as in \(pn \rightarrow d\eta\) the observed additional enhancement very close to threshold was a factor of 2 to 3, cf. Ref. \([6]\) and \([5]\), respectively, and the enhancement was limited to excess energies below roughly 15 MeV for the former and roughly 10 MeV for the latter reaction. In any case, it would be very useful to have data with higher statistics available at those energies very close to threshold in order to chart the possible enhancement due to the \(\eta N\) FSI more accurately \([3]\).

Angular spectra of \(\eta\)-mesons in the photon-deuteron rest frame are shown for different photon energies in Fig. 4. The IA calculation underestimates the data at \(E_\gamma = 627-665\) MeV, but already reasonably reproduces experimental results at 665-705 MeV.

Momentum spectra of the \(\eta\)-mesons in the \(\gamma - d\) rest frame at different photon energies are displayed in Fig. 5. At the lower photon energy, 627-665 MeV, the IA calculation differs considerably from the full calculation including FSI. The latter leads to a significant enhancement of the yield for larger \(\eta\) momenta. This is not surprising because in this case the \(\eta\)-meson carries away much of the available kinetic energy and the \(NN\) system emerges with a small relative momentum, and the interaction is particularly strong. This enhancement at large \(\eta\) momentum is clearly seen in the new still preliminary data of the TAPS collaboration \([3]\). As the photon energy increases, the difference between the IA and the calculation including the \(NN\) FSI becomes smaller. At a photon energy of 665-705 MeV,
the effect of the FSI has basically vanished, consistent with the observations in Fig. 2.

We would like to emphasize that the theoretical results displayed in Figs. 4,5 represent an average over a finite energy interval. This is done in order to make the predictions comparable to the experiments where likewise an averaging over energy bins is made [1,3]. Specifically for the momentum distribution of the \( \eta \) meson this averaging has a significant influence on the results. The maximal \( \eta \)-momentum available at a given fixed photon energy for the reaction \( \gamma d \rightarrow np\eta \) is defined by

\[
p_{\eta}^{\text{max}} = \frac{\lambda^{1/2}(s, [m_p + m_n]^2, m_\eta^2)}{2\sqrt{s}}, \tag{13}
\]

where \( s \) is defined in Eq. 1. Averaging over the photon energy leads to a smearing of \( p_{\eta}^{\text{max}} \). Since the \( NN \) FSI is most strongly felt for \( \eta \) momenta close to \( p_{\eta}^{\text{max}} \) its effect is also smeared out by averaging over \( E_\gamma \), as is the case with the results shown in Fig. 5. Predictions for a sharp incident photon energy show a much stronger structure due to FSI as is exemplified in Fig. 6. Clearly, this suggests that a high energy resolution in the experiments is very desirable if one wants to see and study effects from the FSI.

V. SUMMARY

We calculated the reaction \( \gamma d \rightarrow np\eta \) including the dominant \( S_{11}(1535) \) resonance and the neutron-proton final state interaction. We find that the impulse approximation reproduces the cross section for inclusive photoproduction of \( \eta \)-mesons and the \( \eta \)-meson angular spectrum quite well for energies around 680 MeV and higher. At lower energies the consideration of the FSI between the outgoing nucleons is necessary to describe the relative enhancement of the cross-section data with respect to the impulse approximation. Though the \( NN \) FSI accounts for a large part of the observed enhancement, our analysis suggests that there is still a remaining discrepancy with regard to the data for very small excess energies. This discrepancy is of similar size as found in the \( \eta \)-production in \( NN \) collisions and may be taken as signature of the \( \eta N \) final state interaction very close to threshold.

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FIGURES

FIG. 1. Total $\gamma p \rightarrow p\eta$ cross section. Experimental data are from Ref. [1], while the solid line gives our result.

FIG. 2. The cross section for inclusive photoproduction of $\eta$-mesons off deuterium. Experimental data are taken from Ref. [1]. The dashed line shows the IA calculation, while the solid line is the result with $np$ final state interaction.

FIG. 3. The cross section for inclusive photon production of $\eta$-mesons off the deuteron as a function of the excess energy $\varepsilon$. Shown is the experimental cross section divided by the full calculation given in Fig. 2.

FIG. 4. The angular spectra of the $\eta$-meson in the photon-deuteron rest frame at different the photon energies. Experimental data are taken from Ref. [1]. The dashed line shows the IA calculation, while the solid line is the result with $np$ FSI. The theoretical results represent an average over the given finite energy interval.

FIG. 5. The $\eta$-meson momentum spectra in the photon-deuteron rest frame at different ranges of the photon energies. The dashed line shows the IA calculation, while the solid line represents the result with $np$ FSI. The theoretical results represent an average over the given finite energy interval.

FIG. 6. The $\eta$-meson momentum spectrum in the photon-deuteron rest frame at the sharp photon energy of $E_\gamma = 660$ MeV. The dashed line is the result without $NN$ FSI whereas the solid line includes it.
FIG. 3

\[ \gamma d \rightarrow \eta np \]

Ratio = \( \frac{\sigma_{exp}}{\sigma_{th}} \)

\( \varepsilon \) (MeV)

FIG. 4

\( E_\gamma = 665 - 705 \text{ MeV} \)

\( \frac{d\sigma}{d\Omega} \) (\( \mu b/\text{sr} \))

\( E_\gamma = 627 - 665 \text{ MeV} \)

\( \cos \theta \)
FIG. 5

FIG. 6

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