Incoherent η photoproduction from the deuteron near threshold

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Very recent data for the reaction $\gamma d \to \eta np$, namely, total cross sections, angular and momentum spectra, are analyzed within a model that includes contributions from the impulse approximation and next-order corrections due to the np and ηN interactions in the final state. Comparison between the calculations and the new data indicate sizable contributions from the np and ηN final-state interactions. Some systematic discrepancies between the calculations and the data are also found.

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The reaction $\gamma d \to \eta np$ close to the meson production threshold offers an opportunity to investigate the final-state interactions (FSIs) between the outgoing particles: proton, neutron, and η meson. Provided the FSI between the nucleons is understood, the reaction allows us to draw conclusions about the ηN interaction at low energies. In Refs. [1,2] we investigated incoherent η photoproduction from the deuteron close to threshold taking into account that the reaction amplitude is given by the sum of the first-order term, the impulse approximation (IA), and the terms of next higher order due to the final-state interactions in the neutron-proton (np) the η-nucleon (ηN) system.

When comparing our calculations to the data [3] available at that time we found that the few experimental points for the cross section of the reaction $\gamma d \to \eta np$ close to the reaction threshold require for an adequate description the additional contribution from the η-nucleon final-state interaction.

In Fig. 1 these old data points are indicated by open squares. It seemed clear that more precise measurements are necessary to further understand the interplay between the final-state interactions of the two subsystems. Moreover, in Ref. [1] we concluded that due to the strong np final-state interaction the momentum spectra of the η meson should be enhanced at high momenta if the reaction is considered close to threshold.

Very recently the TAPS Collaboration reported new data [4] for the incoherent photoproduction of η mesons from the deuteron near threshold. These new data not only contain the total $\gamma d \to \eta np$ reaction cross section but also angular and momentum spectra of the η meson. In this brief communication we study whether those new data [4] can shed some light on issues raised in our previous work [1,2].

For the sake of completeness we briefly summarize the main ingredients of our previous calculations [2] on incoherent photoproduction of η-mesons from the deuteron. Let us recall that for a given spin S and isospin T of the final nucleons the amplitude $\mathcal{M}_{IA}$ for the impulse approximation is written as

$$\mathcal{M}_{IA} = A^T(s_1)\,\phi(p_2) - (-1)^{S+T} A^T(s_2)\,\phi(p_1), \qquad (1)$$

where $\phi(p_i)$ is the deuteron wave function [5], p_i $(i=1,2)$ is the momentum of the proton or neutron in the deuteron rest frame, and A^T is the isoscalar or isovector η-meson photoproduction amplitude on a nucleon at the squared invariant collision energy s_N,

$$s_N = s - m_N^2 - 2(E_\gamma + m_d)E_N + 2\vec{k}_\gamma \cdot \vec{p}_i\,. \qquad (2)$$

The photon momentum is given by k_γ, and the invariant mass by $s = m_d^2 + 2m_d E_\gamma$, E_N is the total nucleon energy and m_N and m_d are the nucleon and deuteron mass, respectively.

Now the amplitude $\mathcal{M}_{NN}$ for the NN final-state interaction is given by

$$\mathcal{M}_{NN} = m_N \int dk\, k^2 \frac{t_{NN}(q,k) A^T(s'_N)\,\phi(p'_N)}{q^2 - k^2 + i\epsilon}, \qquad (3)$$

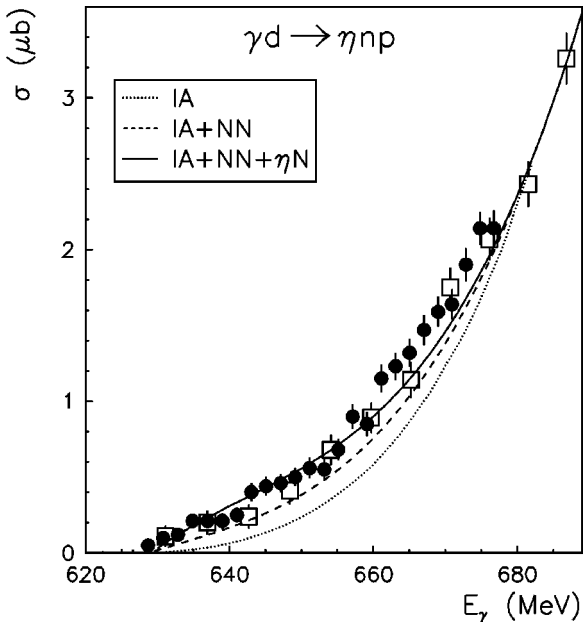

FIG. 1. The total cross section for inclusive photoproduction of η mesons off deuterium as function of the photon energy E_γ. The open squares are old data [3], while the circles indicate new results [4]. The dotted line represents the IA calculation, while the dashed line is the result with the np final-state interaction. The solid line shows the full calculation, including the ηN final-state interaction from the Jülich meson-baryon model [2].

where q is the nucleon momentum in the final np system and

$$\vec{p}\,'_N = \vec{k} + \frac{\vec{k}_\gamma - \vec{p}_\eta}{2}, \tag{4}$$

p_η is the η-meson momentum and $p'_N = |\vec{p}\,'_N|$. The half-shell np scattering matrix $t_{NN}(q,k)$ in the $^1S_0$ and $^3S_1$ partial waves was obtained at corresponding off-shell momenta k from the CD-Bonn potential [5].

Finally, the amplitude $\mathcal{M}_{\eta N}$ for the ηN final-state interaction is given as

$$\mathcal{M}_{\eta N} = \frac{m_N m_\eta}{m_N + m_\eta} \int dk\, k^2 \frac{t_{\eta N}(q,k) A^T(s''_N)\, \phi(p''_N)}{q^2 - k^2 + i\epsilon}, \tag{5}$$

where the η-meson momenta in the final and intermediate state of the ηN system are indicated by q and k, $t_{\eta N}(q,k)$ is the half-shell ηN scattering matrix in the S_{11} partial wave and

$$\vec{p}\,''_N = \vec{k} + \frac{m_N(\vec{k}_\gamma - \vec{p}_N)}{m_N + m_\eta}, \tag{6}$$

where $\vec{p}_N$ is the momentum of final proton or neutron in the deuteron rest frame and m_η is η-meson mass.

Furthermore, within the effective range approximation, the ηN on-shell scattering matrix is related to the scattering length $a_{\eta N}$ as

$$\left[iq - \frac{1}{a_{\eta N}} \right]^{-1} = \pi \frac{\sqrt{q^2 + m_N^2}\sqrt{q^2 + m_\eta^2}}{\sqrt{q^2 + m_N^2} + \sqrt{q^2 + m_\eta^2}} t_{\eta N}(q,q). \tag{7}$$

In our previous work [1,2] we showed that within our approach the uncertainty of the calculations is dominated by the insufficient knowledge of the strength of the ηN interaction at low energies, here represented by $a_{\eta N}$. Moreover, possible effects due to higher-order corrections from the multiple scattering expansion [6,7] might be overshadowed by the sizeable variation of $a_{\eta N}$, which as a result of different model calculations or extractions can range from $0.25 + i0.16$ to $1.05 + i0.27$ fm. In our calculations we adopt $t_{\eta N}(q,k)$ from the Jülich meson-baryon model [8], which gives a scattering length $a_{\eta N} = 0.42 + i0.32$ fm. When comparing our calculations [1] with the old cross-section data for the reaction $\gamma d \to \eta np$ [3], we concluded that the value of $a_{\eta N}$ given by this model was consistent with the data.

A comparison between our full calculation, including NN and ηN FSIs, with the recent experimental information [4] for the total cross section of the reaction $\gamma d \to \eta np$ is shown in Fig. 1. Here the new data are indicated by filled circles. We can well describe the data close to the reaction threshold, while there is systematic underprediction of $\simeq$10% of the experimental results between 660 and 680 MeV photon energy. We should not attribute this discrepancy to $a_{\eta N}$, since we found in Ref. [2] that the ηN interaction acts predominantly very close to threshold. We also want to point out that our calculation matches up with the older data (open squares) at energies larger than 680 MeV.

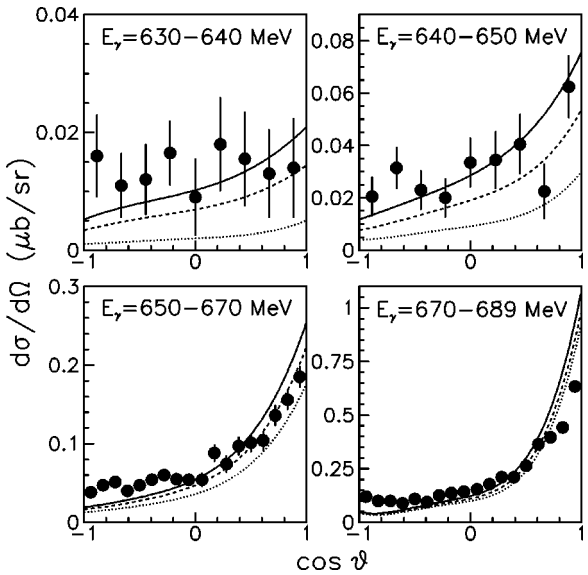

FIG. 2. The angular spectra of η mesons in the photon-deuteron c.m. system at different photon energies E_γ. The data are from Ref. [4]. The dotted lines show IA calculations, while the dashed lines represent the results using only the np final-state interaction. The solid lines show the full calculation, including the ηN final-state interaction from the Jülich meson-baryon model.

The recent data of Ref. [4] are more complete and contain not only total cross sections but also angular distributions of η mesons in the photon-deuteron center-of-mass (c.m.) system at different photon energies. They are shown in Fig. 2 together with our calculations. The angular spectra at the lower energies, $630 \leqslant E_\gamma \leqslant 650$ MeV, are quite sensitive to both final-state interactions. Especially, the ηN FSI is necessary to describe the data.

At photon energies $650 \leqslant E_\gamma \leqslant 689$ MeV our predictions show a stronger peaking at forward angles compared to the data, and a slight but systematic underestimation of the data at backward angles. The latter might be attributed to an additional contribution from rescattering mechanism with intermediate π-meson and $\pi N \to \eta N$ transition. However, we are aware that we cannot make any final assessment about the discrepancies at the present stage.

The momentum spectra of the η mesons in the $(\gamma - d)$ cm frame are shown in Fig. 3 and compared with our calculations. We would like to emphasize that the theoretical results displayed represent an average over a finite energy interval. This is done in order to make the predictions comparable to the experiment, where likewise an averaging over energy bins is made [4]. Specifically for the momentum distribution of the η meson this averaging has a significant influence on the result as shown in Ref. [1]. The vertical arrows in Fig. 3 indicate the maximally allowed η momentum, which is given by

$$p_\eta = \frac{[\{s - (m_n + m_p)^2 - m_\eta^2\}^2 - 4(m_n + m_p)^2 m_\eta^2]^{1/2}}{2\sqrt{s}}, \tag{8}$$

and calculated for the maximal photon energy E_γ indicated in the figure.

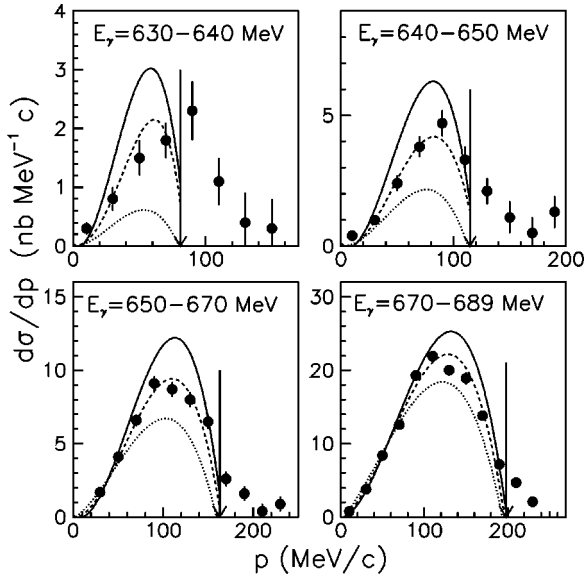

FIG. 3. The momentum spectra of η mesons in the photon-deuteron c.m. system at different photon energies E_γ. The data are from Ref. [4]. The lines show our calculations with notations similar to Fig. 2. The arrows indicates the kinematical limit for η-meson momenta calculated by Eq. (8).

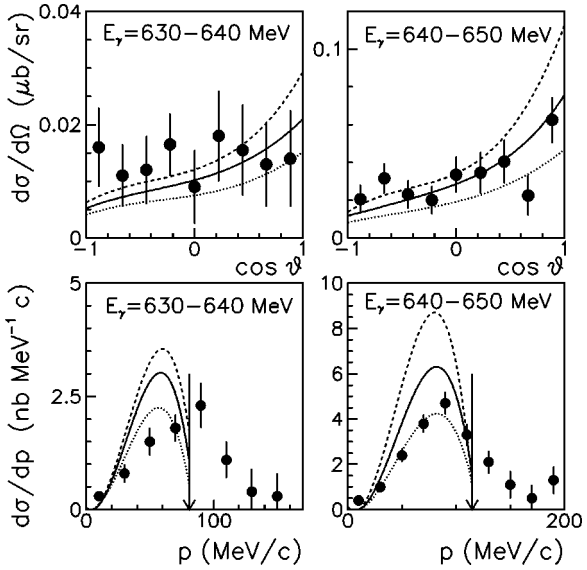

FIG. 4. The angular (upper part) and momentum (lower part) spectra of η mesons in the photon-deuteron c.m. system at photon energies $E_\gamma = 630-640$ and $640-650$ MeV. The data are from Ref. [4]. The lines show our calculations with different ηN scattering lengths, namely, $a_{\eta N} = 0.42 + i0.32$ (solid), $0.74 + i0.27$ (dashed), and $0.25 + i0.16$ fm (dotted). The arrows indicate the kinematical limit for η-meson momenta calculated by Eq. (8).

As Fig. 3 clearly indicates, for the lowest energy interval a substantial part of experimental points is located beyond the kinematical limit. This might [9] stem from a larger experimental uncertainty in determining the η-meson momentum. These errors are not indicated in Fig. 3 by horizontal error bars. Unfortunately, due to this a clean comparison between our calculations and the data cannot be made. As an aside, when shifting all data points by the same percentage inside the kinematically allowed region, the cross section points fall closer toward our calculation. However, this can only serve as a guide to the eye and does not allow any further speculations.

In order to investigate the sensitivity of the η momentum distribution to the ηN scattering length we calculate η-meson angular and momentum spectra at $E_\gamma = 630-640$ and $640-650$ MeV with different values for $a_{\eta N}$ and compare our results with the data [4] in Fig. 4. Here the solid lines show our calculations with $a_{\eta N} = 0.42 + i0.32$ fm, the dashed lines the ones with $a_{\eta N} = 0.74 + i0.27$ fm, and the dotted line the calculations with $a_{\eta N} = 0.25 + i0.16$ fm. As it turns out, both observables are quite sensitive to the size of $a_{\eta N}$.

It can be instructive to consider different possibilities of analyzing the data to find a representation that may shed a different light on the reaction $\gamma d \to \eta np$. For this reason we consider the Dalitz plot representation, which is given as

$$\frac{d\sigma}{ds_{\eta p} ds_{np}} = \frac{|\mathcal{M}_{IA} + \mathcal{M}_{NN} + \mathcal{M}_{\eta N}|^2}{256\pi^3 s(s - m_d^2)}. \tag{9}$$

Here $s_{\eta p}$ and s_{np} denote the squared invariant mass of the ηp and np subsystems.

This representation may be an additional tool to isolate the different FSIs. In Fig. 5 we display the Dalitz plot projections calculated at photon energies $E_\gamma = 643$ and 681 MeV. For this calculation we employ the ηN FSI given by the Jülich model with $a_{\eta N} = 0.42 + i0.32$ fm. The hatched ar-

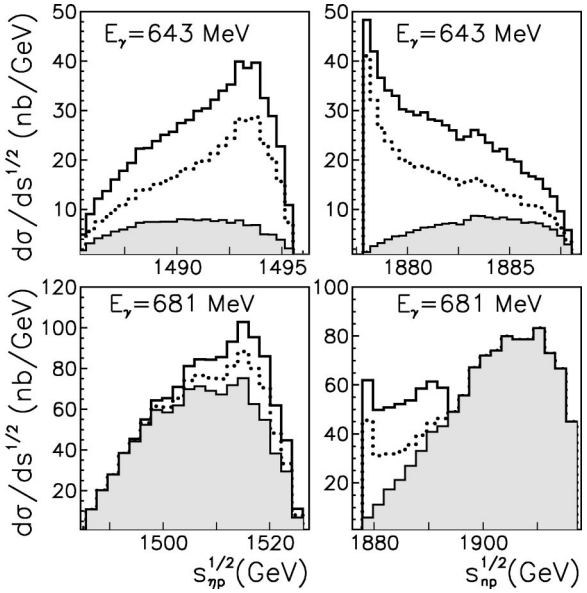

FIG. 5. The invariant mass spectra of the ηp (left) and np (right) subsystem produced in $\gamma d \to \eta np$ reaction at photon energies $E_\gamma = 643$ and 681 MeV. The hatched areas show calculations based on the IA, the dashed lines stand for the calculation including the np FSI only, while the solid lines represent the full calculations including both np and ηN FSIs.

eas indicate the contributions from the impulse approximation, the dotted lines stand for the calculations with np FSI alone, while the solid lines represent the full calculations. The difference between the impulse approximation and full calculation is not only a result of the absolute sizes, but essentially the different shapes of the invariant mass spectra. At $E_\gamma = 643$ MeV the low-mass part of np spectrum is substantially enhanced by the np FSI. Thus the ηp spectrum is shifted to higher masses. The difference between the calculations with ηN and np FSIs and that with np alone can be considered as an overall rescaling of the model results. This can be well understood through our findings in Ref. [2], namely that a quite weak ηN interaction can manifest itself through the interference with the substantially stronger np FSI.

The results become more exciting at $E_\gamma = 681$ MeV. While the shape of the ηp distribution is almost similar to that obtained at $E_\gamma = 643$ MeV, the np spectrum clearly shows a low mass structure due to the np and ηN FSIs, and the size of this enhancement is given by the coherent sum of the np and ηN interactions. The production mechanism alone, or the contribution of the impulse approximation may well be isolated by imposing np invariant mass cuts.

We believe that an experimental observation of such double-peak structure might serve as direct evidence of FSI effects. Finally, we notice that the Dalitz plot analysis of the reaction $pp \to pp\eta$ measured at COSY [10] indicates quite a similar structure in the pp invariant mass distribution. This finding may encourage further analysis of the new $\gamma d \to \eta np$ data [4].

In conclusion, we presented a detailed comparison between our model for the reaction $\gamma d \to \eta np$ developed in Refs. [1,2] and recently published experimental information [4] on total cross sections as well as angular and momentum η-meson spectra for this reaction. For our calculations we employ the ηN FSI obtained from the Jülich meson-baryon model.

The comparison between the data [4] and our calculations shows reasonable agreement. The $\gamma d \to \eta np$ data close to the reaction threshold require additional contributions from the ηN FSI and are consistent with the size of $a_{\eta N} = 0.42 + i0.32$ fm given by the Jülich model. The angular and momentum η-meson spectra at $E_\gamma \leqslant 650$ MeV are very sensitive to the size of $a_{\eta N}$.

However, we found some $\simeq 10\%$ disagreement between our calculations and the new data [4] for the total cross section for the reaction $\gamma d \to \eta np$ at photon energies $650 \leqslant E_\gamma \leqslant 689$ MeV. Furthermore, at these energies the model predicts a stronger peaking of the angular distribution at forward angles and a slight but systematic underestimation of the data at backward angles. Further investigations are necessary in order to clarify whether this discrepancy stems from rescattering mechanisms.

In addition, we found that the Dalitz plot analysis of the reaction $\gamma d \to \eta np$ may serve as a very helpful tool for isolating FSI effects. The Dalitz plot projection on np invariant mass may show a clean double-peak structure at $E_\gamma = 681$ MeV, while at low photon energy $E_\gamma = 643$ MeV the np invariant mass spectrum is substantially enhanced at low masses.

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