Quantum Information Review
An International Journal

http://dx.doi.org/10.12785/qir/030101

Influence of Double Scattering Effects on the $\gamma d \to \pi^0 d$ Reaction Near the η-Threshold

Eed M. Darwish[1,2,*] *and Ahmed S. Aldobuani*[3]

[1] Physics Department, Faculty of Science, Sohag University, Sohag 82524, Egypt
[2] Physics Department, Faculty of Science, Taibah University, Al-Madinah Al-Munawarah, B.O. Box 30002, Saudi Arabia
[3] Physics Department, Faculty of Science, King Abdulaziz University, P.O. Box 80203, Jeddah 21589, Saudi Arabia

Received: 8 Jul. 2014, Revised: 6 Sep. 2014, Accepted: 8 Sep. 2014
Published online: 1 Jan. 2015

Abstract: The influence of double scattering effects on coherent π^0-photoproduction on the deuteron is studied in the energy region near the η-production threshold at backward center-of-mass angles of the outgoing pion. The model is based on the impulse approximation and double scattering diagrams with intermediate production of both π- and η-mesons. Numerical results for the differential cross section and tensor target asymmetries are predicted and compared with available experimental data and other theoretical models. The effects of double scattering are found to be much larger in the tensor target asymmetries than in the differential cross section. Compared to the experimental data from CLAS Collaboration, sizeable discrepancies are found.

Keywords: Meson production, Photoproduction reactions, Few-body systems, Polarization phenomena in reactions, Spin observables

1 Introduction

The study of meson photo- and electroproduction processes on the deuteron is of fundamental interest in nuclear physics. The photoproduction of mesons is an excellent tool for the study of nucleon resonances [1] and in consequence of the structure of the nucleon. In this context, meson production on the deuteron is of specific importance due to the lack of free neutron targets. Coherent pion photoproduction on the deuteron may be used as an isospin filter and is especially sensitive to the coherent sum of the $\gamma p \to \pi^0 p$ and $\gamma n \to \pi^0 n$ amplitudes. Due to its relative simplicity, the deuteron is the ideal target for such studies.

Coherent π^0-photoproduction on the deuteron has been studied as a source of information on the elementary π^0-photoproduction off the neutron. This reaction has been first studied by Koch and Woloshyn [2] by including the contribution from pion rescattering with charge-exchange contributions. This effect was then verified by Bosted and Laget [3] in studies of coherent π^0-photoproduction on the deuteron in the π-threshold region. In Ref. [4] an approach of $NN-N\Delta$ coupled channels was used. In another approach, developed in Ref. [5], relativistic Feynman diagrams have been evaluated. Blaazer *et al.* [6] studied rescattering corrections to all orders by solving Faddeev equations of the πNN-system. Using a microscopic approach based on the Kerman-McManus-Thaler (KMT) multiple scattering theory [7] in momentum space, Kamalov *et al.* [8] have studied coherent π^0-photoproduction on the deuteron in a coupled channel approach. The energy dependence of the differential cross section was explained in Ref. [9] in the photon lab-energies between 600 and 800 MeV. The main conclusion of Ref. [9] was reproduced in another paper [10], where it was shown that in addition to the two-step process, the full dynamics in the intermediate ηNN system could be important as well.

Unfortunately, none of these theoretical studies considers polarization observables for the reaction $\gamma d \to \pi^0 d$ near the threshold of η-production. Therefore, in Refs. [11,12,13,14,15,16] we have considered the reaction $\gamma d \to \pi^0 d$ with special emphasize on polarization observables.

Our purpose in the present paper is to report on theoretical predictions for the differential cross section and tensor target asymmetries for the reaction $\gamma d \to \pi^0 d$. This work is motivated by the measurements of the CLAS Collaboration [17,18], where a cusp-like structure in the

* Corresponding author e-mail: eeddarwish@yahoo.com

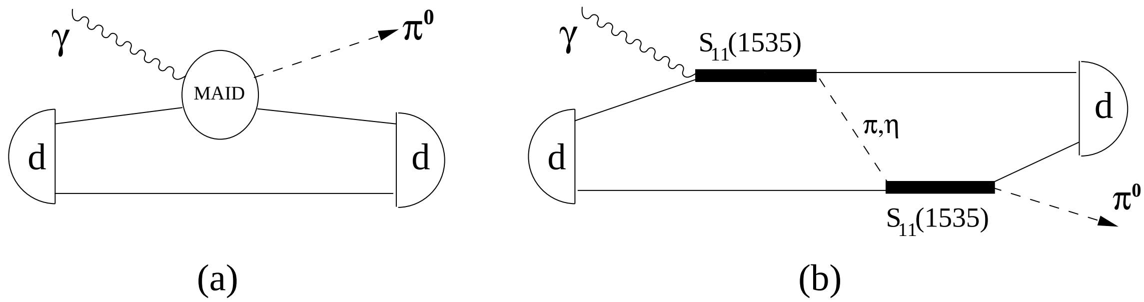

Fig. 1: The considered diagrams in coherent π^0-photoproduction on the deuteron, (a) impulse approximation (IA) and (b) double scattering contribution with intermediate production of both π- and η-mesons (FSI).

energy dependence of the differential cross section has been observed at extremely backward pion angles. The calculation presented in this work is of theoretical interest because, on the one hand, it provides an important test of our understanding of the elementary neutron amplitude in the absence of a free neutron target. On the other hand, we would like to see whether the cusp structure observed in the differential cross section at backward direction can be explored via polarization observables.

This paper is organized as follows. In section 2, a brief description of the formalism ingredients for the reaction $\gamma d \to \pi^0 d$ is given. Numerical results for the differential cross section and tensor target asymmetries are presented and discussed in section 3. Finally, we provide conclusion in section 4.

2 Formalism

As a starting point, we will first consider the formalism of the coherent π^0-photoproduction reaction on the deuteron

$$\gamma(k,\varepsilon_\lambda) + d(d) \to \pi^0(q) + d(d'), \qquad (1)$$

where $k = (E_\gamma, \mathbf{k})$, $q = (E_\pi, \mathbf{q})$, $d = (E_d, \mathbf{d})$, and $d' = (E'_d, \mathbf{d}')$ denote the four-momenta of the incident photon, outgoing pion, initial and final deuteron, respectively. The circular polarization vector of the photon is defined by ε_λ with $\lambda = \pm 1$. We will consider this reaction in the photon-deuteron (γd) center-of-mass (c.m.) frame. There we choose the z-axis along the photon momentum ($\mathbf{e}_z = \hat{k} = \mathbf{k}/|\mathbf{k}|$), the y-axis parallel to $\mathbf{k}\times\mathbf{q}$ and the x-axis such as to form a right-handed system. Thus the outgoing pion is described by the spherical angles $\phi_\pi = 0$ and θ_π with $\cos\theta_\pi = \hat{q}\cdot\hat{k}$.

In the γd c.m. system the differential cross section for coherent π^0-photoproduction on the deuteron is given by [16]

$$\frac{d\sigma}{d\Omega_\pi} = \frac{1}{16\pi^2}\,\frac{|\mathbf{q}|}{|\mathbf{k}|}\,\frac{E_d E'_d}{W^2_{\gamma d}}\,\frac{1}{6}\sum_{m_d m'_d \lambda}\left|T_{m_d m'_d \lambda}(\mathbf{k},\mathbf{q})\right|^2, \qquad (2)$$

with initial (final) deuteron energy $E_d = \sqrt{\mathbf{k}^2 + M_d^2}$ ($E'_d = \sqrt{\mathbf{q}^2 + M_d^2}$). The c.m. momenta of the pion and photon are denoted, respectively, by $\mathbf{q}$ and $\mathbf{k}$. Moreover, the invariant energy of the γd system is given as

$$\begin{aligned} W_{\gamma d} &= E_\gamma + E_d = |\mathbf{k}| + \sqrt{\mathbf{k}^2 + M_d^2}, \\ &= E_\pi + E'_d = \sqrt{\mathbf{q}^2 + m_\pi^2} + \sqrt{\mathbf{q}^2 + M_d^2}, \end{aligned} \qquad (3)$$

where M_d and m_π are the deuteron and neutral-pion masses, respectively. $T_{m_d m'_d \lambda}(\mathbf{k},\mathbf{q})$ denotes the reaction matrix, where the initial and final deuteron spin projections are given by m_d and m'_d, respectively.

For the calculation of the T matrix we include in addition to the pure impulse approximation (IA), i.e., the one-body contribution, the double scattering diagrams with intermediate production of both π- and η-mesons (FSI). A diagrammatical overview of these contributions is given in Fig. 1. The first diagram describes the pure IA and the second one comprises the contribution from FSI. In this approximation, the total transition matrix elements read

$$T_{m_d m'_d \lambda}(\mathbf{k},\mathbf{q}) = T^{\mathrm{IA}}_{m_d m'_d \lambda}(\mathbf{k},\mathbf{q}) + T^{\mathrm{FSI}}_{m_d m'_d \lambda}(\mathbf{k},\mathbf{q}). \qquad (4)$$

The explicit expressions for the two terms in the right-hand side are given in Ref. [16] and we refer the reader to this paper for the details.

3 Results and discussion

We start the discussion with the results for differential cross section as plotted in Figs. 2 as functions of the photon energy. The dotted and solid curves correspond, respectively, to the results of the IA alone and with inclusion of double scattering effects. We see that the double scattering contribution is tiny at forward direction. With increasing pion angles, a noticeable contribution from double scattering is obtained in the photon energy range from $E_\gamma \simeq 700$ to 800 MeV. The double scattering effects become maximum at extremely backward angles.

For photon lab-energies near the threshold of η-production, the double scattering effects lead to increase the cross section at all angles. Furthermore, Fig.

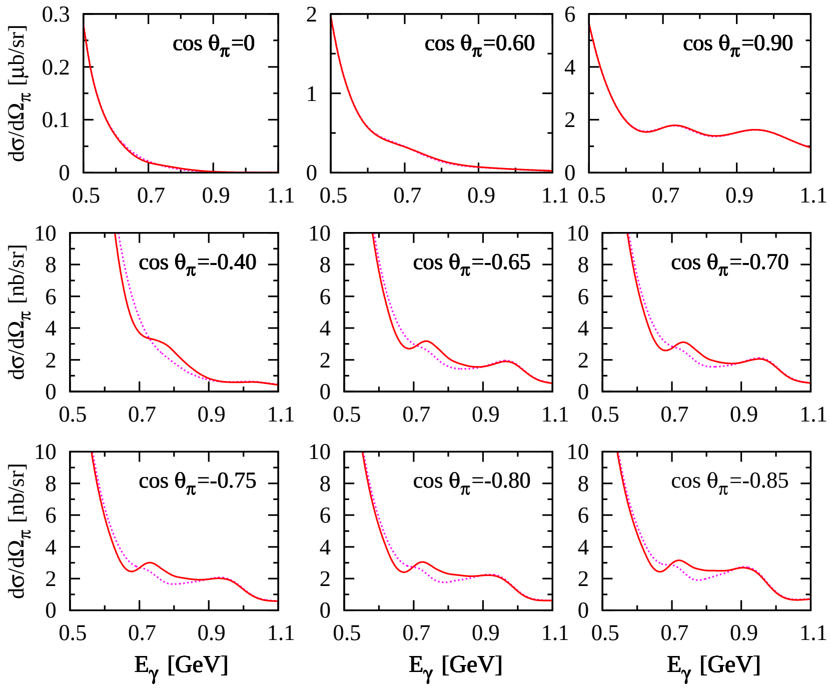

Fig. 2: (Color online) The π^0-angular distribution of $\gamma d \to \pi^0 d$ versus laboratory photon energy at different $\cos\theta_\pi$ in the γd c.m. frame. Shown are the prediction of the IA alone (magenta dotted) and with inclusion of rescattering effect (red solid).

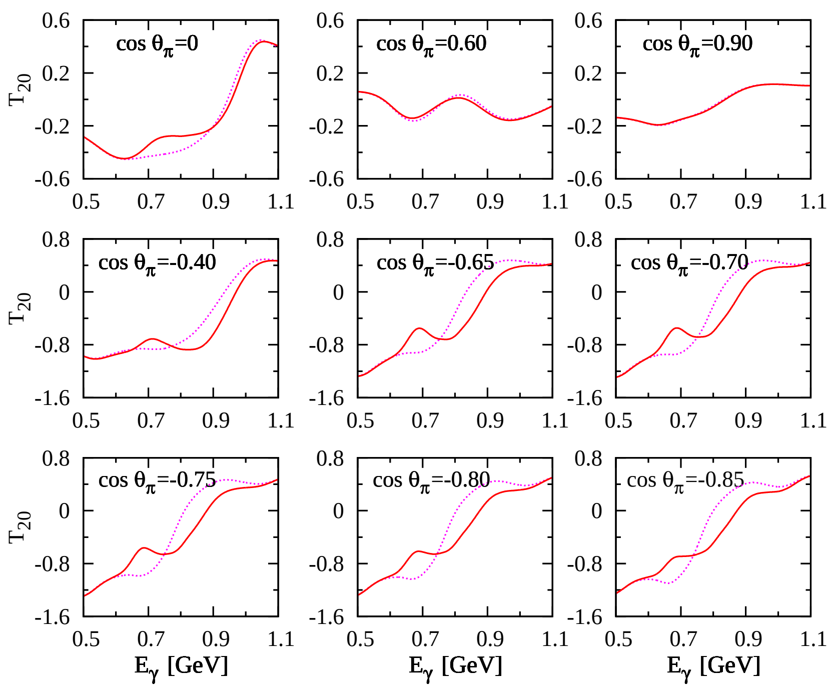

Fig. 3: (Color online) The tensor target asymmetry T_{20} of $\gamma\mathbf{d} \to \pi^0 d$ versus laboratory photon energy at different $\cos\theta_\pi$ in the γd c.m. frame. Notation of the curves as in Fig. 2.

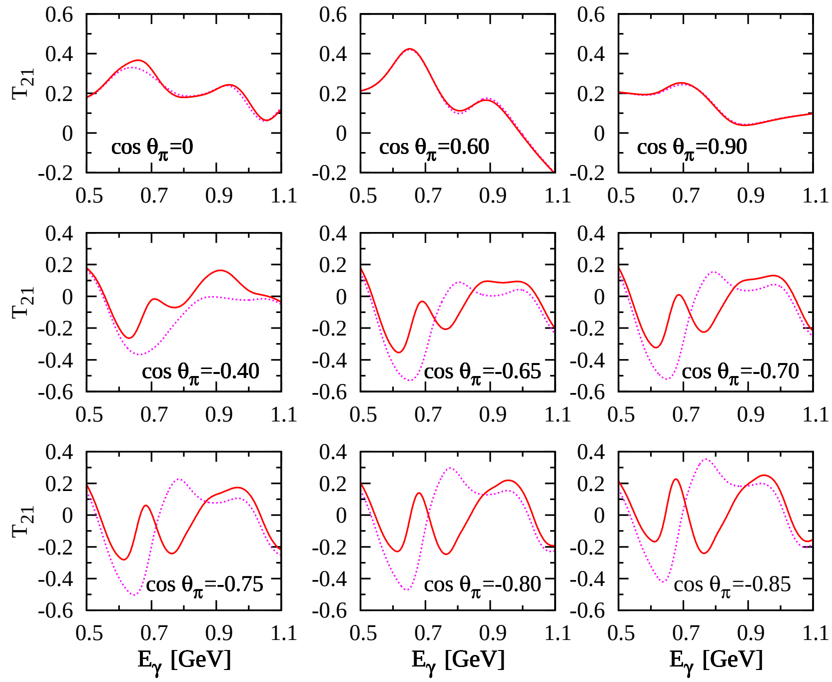

Fig. 4: (Color online) The tensor target asymmetry T_{21} of $\gamma\mathbf{d} \to \pi^0 d$ versus laboratory photon energy at different $\cos\theta_\pi$ in the γd c.m. frame. Notation of the curves as in Fig. 2.

2 demonstrates the peak observed in the energy dependence of the differential cross section at extremely backward pion angles and photon lab-energy slightly above 700 MeV [17,18]. The origin of this effect is the presence of the $S_{11}(1535)$-resonance in the diagram with η-rescattering. In comparison with the calculation of Ref. [10], we can only compare with results for the differential cross section at $\cos\theta_\pi$=0 and -0.85, where differences are found. These differences may be due to the full dynamics in the intermediate ηNN system which was considered in [10], but not included in the present calculations. Another reason lies in the fact that the author of Ref. [10] used the MAID-2003 model [19] for the elementary amplitude and the Bonn potential model (OBEPQ version) [20] for the deuteron wave function, while in the present work we used the extended version MAID-2007 model [21] for the former and the Bonn potential (full model) [22] for the latter. It was found in [12,13,15] that the computations with different elementary amplitudes and various potential models for the deuteron wave function are quite different.

Next, we turn to discuss the results of tensor target asymmetries as displayed in Figs. 3, 4, and 5. The tensor asymmetries are much more sensitive to the rescattering effects. This is particularly apparent in the target asymmetry T_{20} for tensor polarized deuterons and unpolarized photons which is displayed in Fig. 3 as a function of photon lab-energy at fixed values of $\cos\theta_\pi$ in the γd c.m. frame. For the reaction $\gamma\mathbf{d} \to \pi^0 d$ at forward and backward pion angles, the asymmetry T_{20} allows one to draw specific conclusions about details of the reaction mechanism. At extremely backward direction, the asymmetry T_{20} exhibits a minimum value at $E_\gamma \simeq 700$ MeV when only the IA prediction is considered. When the double scattering effects are switched on, one sees a peak at $E_\gamma \simeq 700$ MeV. Also, the T_{20}-asymmetry shows a drastic influence from FSI effect.

The influence of double scattering effects on the target asymmetry T_{21} is clearly addressed in Fig. 4, where the calculation of the pure IA is compared to the one with inclusion of rescattering diagrams. We found that the results of the T_{21}-asymmetry are sensitive to the double scattering effects at backward direction. We would like to emphasize that the T_{21}-asymmetry shows a considerable double scattering effects. The difference between the dotted and the solid curves is noticeable when E_γ changes from 600 to 900 MeV. It emphasizes the importance of double scattering effects in this energy region at backward direction. However, this difference is tiny at forward direction. The tensor asymmetry T_{21} is sizable in the near η-threshold region, exhibiting a sharp peak in absolute values and a drastic influence from the double scattering effects. The T_{21}-asymmetry reaches a second, quite broad maximum above the η-threshold. Moreover, the peak observed in the angular distribution of the differential cross section near the η-production threshold at backward angles is also seen here when double scattering diagrams are considered.

Results for the tensor target asymmetry T_{22} are depicted in Fig. 5. As for the T_{21}-asymmetry, one notes

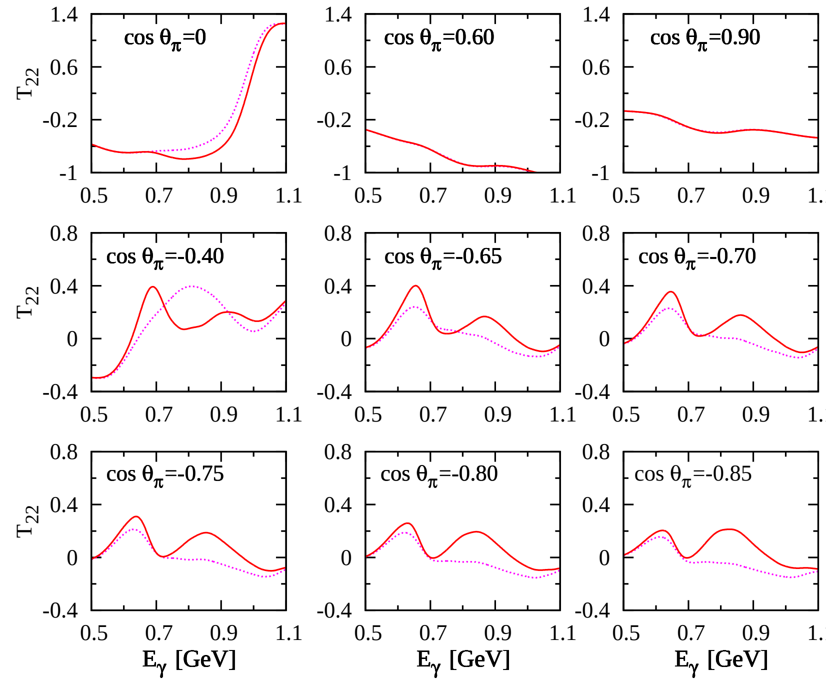

Fig. 5: (Color online) The tensor target asymmetry T_{22} of $\gamma \mathbf{d} \to \pi^0 d$ versus laboratory photon energy at different $\cos\theta_\pi$ in the γd c.m. frame. Notation of the curves as in Fig. 2.

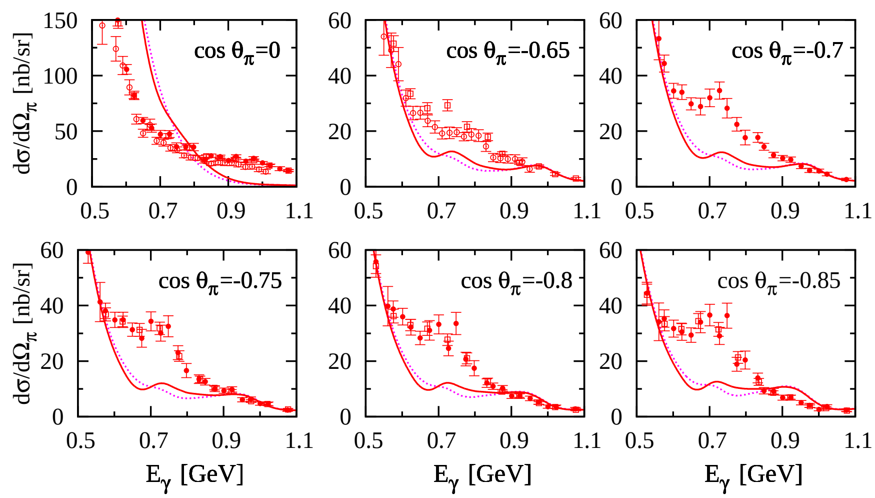

Fig. 6: (Color online) The differential $\gamma d \to \pi^0 d$ cross section calculated in the γd c.m. frame versus laboratory photon energy at different $\cos\theta_\pi$. Notation of the curves as in Fig. 2, but the curves of this figure are multiplied by a factor 4 to clear the peak observed in our predictions. Experimental data are from [23] (open circles), CLAS Collaboration [17] (open squares), and CLAS Collaboration [18] (solid circles).

for the T_{22}-asymmetry a noticeable contribution from double scattering effects at backward pion angles. It shows an oscillatory behavior. We found also that, the asymmetry T_{22} exhibits a peak at $E_\gamma \simeq 600$ MeV and a second, quite broad maximum above the η-threshold. This maximum disappears when only the pure IA is considered.

Last, but not least, we would like to point out that the cusp caused by the opening of the ηN channel is strongly smeared by the Fermi motion effect and can hardly be visible in the reaction on a deuteron. The structure which we really see at backward angles in Figs. 2 to 5 is nothing but a consequence of interference between the IA and FSI terms. It is also clear that in forward and backward pion emission, the spin asymmetry T_{21} vanish at θ_π=0 or π, because of the helicity conservation, i.e., in this case the differential cross section should not depend on ϕ_π, because at θ_π=0 or π the azimuthal angle ϕ_π is undefined or arbitrary.

We now turn to a comparison of our results with experimental data, where available. Figure 6 shows a comparison of the results for the differential cross section calculated in the γd c.m. frame versus laboratory photon energy at different $\cos\theta_\pi$ with the experimental data from [23] and CLAS Collaboration [17,18]. In agreement with data from [23], one can see that our predictions in the pure IA and with inclusion of double scattering contribution cannot describe the experimental data since major discrepancies are evident. Compared to the experimental data from CLAS Collaboration [17,18], we also found that the theory underestimates the data for differential cross section by about one order of magnitude. The same conclusions were drawn by the authors in Refs. [6,10].

One possible source for the existing difference between our predictions and the experimental data could be the neglected three-body treatment of the ηNN interaction. In fact, a noticeable contribution from such an interaction was found in Ref. [10]. A further source could be the neglected two-nucleon mechanisms. For example, meson-exchange currents were found to be quite significant for π^+-photoproduction on ^{3}He in Ref. [24].

4 Conclusion

In this work we have explored the role of differential cross section and tensor target asymmetries in coherent π^0-photoproduction on the deuteron near the η-production threshold at backward pion angles on the influence of double scattering effects. We consider the pure IA and the double scattering diagrams with intermediate production of both π- and η-mesons.

Results for the differential cross section and tensor target asymmetries are presented and compared with the available experimental data and other theoretical models. Within our model, we have found that the differential cross section as well as tensor target asymmetries are influenced by the inclusion of double scattering of the produced π- and η-mesons. A peak structure evolves due to the presence of the $S_{11}(1535)$ resonance in the diagram with η-rescattering. In many cases, the deviation among results obtained using the IA alone and with inclusion of double scattering is large. Although this effect is about a few percent in differential cross section at backward direction, it has a noticeable contribution to tensor target asymmetries. In comparison with the experimental data from [23,17,18] for the differential cross section, major discrepancies are found.

Finally, we would like to point out that not all of the possible rescattering diagrams are considered in this work. Our calculations do not include vector-meson exchange terms in the rescattering amplitude or any other resonance amplitudes besides the $S_{11}(1535)$ contribution. In addition, the three-body problem of the ηNN system is of special importance for understanding the reaction dynamics. Thus there is a way for further improvements of the present model.

References

[1] B. Krusche and S. Schadmand, Prog. Part. Nucl. Phys. **51** (2003) 399; V. Burkert and T.-S.H. Lee, Int. J. Mod. Phys. E **13** (2004) 1035.
[2] J.H. Koch and R.M. Woloshyn, Phys. Rev. C **16** (1977) 1968.
[3] P. Bosted and J.M. Laget, Nucl. Phys. A **296** (1978) 413; J.M. Laget, Phys. Rep. **69** (1981) 1.
[4] P. Wilhelm and H. Arenhövel, Few-Body Syst. Suppl. **7** (1994) 235; P. Wilhelm and H. Arenhövel, Nucl. Phys. A **593** (1995) 435; P. Wilhelm and H. Arenhövel, Nucl. Phys. A **609** (1996) 469.
[5] H. Garcilazo and E.M. de Guerra, Phys. Rev. C **52** (1995) 49.
[6] F. Blaazer, B.L.G. Bakker, and H.J. Boersma, Nucl. Phys. A **590** (1995) 750; F. Blaazer, PhD dissertation (Free University of Amsterdam, 1995).
[7] A.K. Kerman, H. McManus, and R.M. Thaler, Ann. Phys. (N.Y.) **8** (1959) 551.
[8] S.S. Kamalov, L. Tiator, and C. Bennhold, Nucl. Phys. A **547** (1992) 599; S.S. Kamalov, L. Tiator, and C. Bennhold, Few-Body Syst. **10** (1991) 143; S.S. Kamalov, L. Tiator, and C. Bennhold, Phys. Rev. C **55** (1997) 98.
[9] A.E. Kudryavtsev *et al.*, Phys. Rev. C **71** (2005) 035202.
[10] A. Fix, Eur. Phys. J. A **26** (2005) 293.
[11] E.M. Darwish, N. Akopov, and M. El-Zohry, Proceedings of Science (PoS) for the 35th Int. Conf. on High Energy Physics (ICHEP2010), 185 (2011).
[12] E.M. Darwish, N. Akopov, and M. El-Zohry, AIP Conf. Proc. **1370** (2011) 242.
[13] E.M. Darwish, N. Akopov, and M. El-Zohry, J. At. Mol. Sci. **2** (2011) 187.
[14] E.M. Darwish, J. Phys. Soc. Jpn. **83** (2014) 084201.
[15] E.M. Darwish, Quant. Inf. Rev. **2** (2014) 27.
[16] E.M. Darwish and S.S. Al-Thoyaib, Ann. Phys. (N.Y.) (2014), DOI: 10.1016/j.aop.2014.08.008 (in press).
[17] Y. Ilieva (for the CLAS Collaboration), presented at 17th Int. IUPAP Conf. on Few-Body Problems in Physics (FB17), arXiv:nucl-ex/0309017, JLAB-PHY-03-47.
[18] Y. Ilieva *et al.*, Eur. Phys. J. A **43** (2010) 261, arXiv:nucl-ex/0703006.
[19] O. Hanstein, D. Drechsel and L. Tiator, Nucl. Phys. A **632** (1998) 561; D. Drechsel, O. Hanstein, S. Kamalov and L. Tiator, Nucl. Phys. A **645** (1999) 145; wwwkph.kph.uni-mainz.de/MAID/maid2003/.
[20] R. Machleidt, Adv. Nucl. Phys. **19** (1989) 189.
[21] D. Drechsel, S. Kamalov and L. Tiator, Eur. Phys. J. A **34** (2007) 69, wwwkph.kph.uni-mainz.de/MAID/maid2007/.
[22] R. Machleidt, K. Holinde, and Ch. Elster, Phys. Rep. **149** (1987) 1.

[23] A. Imanishi *et al.*, Phys. Rev. Lett. **54** (1985) 2497.
[24] J.A. Gomez Tejeda, S.S. Kamalov and E. Oset, Phys. Rev. C **54** (1996) 31607.

Eed M. Darwish is an Associate Professor of Physics at Sohag University, Egypt. He received his PhD degree in Theoretical Nuclear Physics from the Johannes-Gutenberg University, Mainz, Germany as a DAAD scholarship. Then he became a Faculty Member at Sohag University for six years. He became Assistant Professor of Physics at Sohag University in 2002 and Associate Professor in 2013. He joined Taibah University, Saudi Arabia as an Associate Professor (on leave) in 2008. He has served as Head of Applied Physics Department at Taibah University in 2009-2011. His research includes work on the study of sub-nuclear degrees of freedom in electromagnetic reactions in few-body systems, mainly the deuteron, e.g. photo- and electro-production of pseudo-scalar mesons on the deuteron including polarization observables. He has published more than 60 research papers in reputed international journals of physics. He is referee of several international physics journals in the frame of theoretical physics, nuclear physics, and applied mathematics.

Ahmed S. Aldobuani is an Assistant Lecturer of Theoretical Physics at King Abdulaziz University, Jeddah, Saudi Arabia. He received his B.Sc. in Physics from King Abdulaziz University in 1998. In 2005 he completed his M.Sc. in the field of Theoretical Physics at the Newcastle University, Newcastle Upon Type, United Kingdom.