Quantum Information Review
An International Journal

http://dx.doi.org/10.12785/qir/020202

The Double Polarization E-Asymmetry for $\vec{\gamma}\vec{d} \to \pi^0 d$ near the η-Production Threshold

Eed M. Darwish [1,2,*]

[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

Received: 29 Mar. 2014, Revised: 20 Apr. 2014, Accepted: 25 Apr. 2014
Published online: 1 Jul. 2014

Abstract: The double polarization E-asymmetry for the $\vec{\gamma}\vec{d} \to \pi^0 d$ reaction is predicted for incident photon lab-energies near the η-threshold at backward center-of-mass emission pion angles. The influence of first-order rescattering effect with intermediate production of both π- and η-mesons on the E-asymmetry is investigated. A strong effect from first-order rescattering is obtained. It reached on average about 40% at extreme backward direction in the η-threshold region. In addition, the sensitivity of the results to the elementary pion photoproduction operator and deuteron wave function is also investigated. Considerable dependence of the results on the elementary amplitude and deuteron wave function is found.

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

1 Introduction

Few-body systems are ideal to investigate fundamental problems in nuclear physics. They provide a testing ground for models of the NN interaction, reaction mechanisms and for models of nuclei. The last twenty years have witnessed an increasing interest in theoretical research of few-body systems [1,2,3,4,5,6,7,8,9,10,11,12]. This interest was revived by many laboratories which have contributed to this study (in alphabetical order): ALS (Saclay, France), ELSA (Bonn, Germany), GRAAL (Grenoble, France), Jefferson Lab or JLAB (Newport News, VA, USA), LEGS (Brookhaven, USA), MAMI (Mainz, Germany), MAX-LAB (Lund, Sweden), MIT-Bates (Middleton, USA), NIKHEF (Amsterdam, The Netherlands), and SLAC (Stanford, CA, USA) [for an experimental overview see Refs. [13,14,15]]. These new facilities have made coincidence experiments possible that explore new, previously inaccessible kinematical regions with very high statistical precision. We will therefore focus on the study of few-body systems using electromagnetic reactions such as coherent π^0-photoproduction on the deuteron.

In a recent experiment on coherent π^0-photo-production on the deuteron, the differential cross sections exhibit a cusp-like structure at backward pion angles for photon lab-energies around the η-threshold [16]. This nontrivial energy dependence of the differential cross sections was explained in Ref. [3]. The main conclusion of Ref. [3] was reproduced in another paper [4], 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. Subsequently, in Ref. [12] we have studied the reaction $\gamma d \to \pi^0 d$ in the pure impulse approximation (henceforth denoted by IA) with special emphasize on polarization observables and the sensitivity of results to the elementary amplitude.

Most recently, we have investigated in Ref. [1] the influence of first-order rescattering with intermediate production of both π and η-mesons (in what follows denoted by FSI) on unpolarized cross sections and single spin asymmetries of the reaction $\gamma d \to \pi^0 d$ near the η-production threshold at backward pion angles. It was found that FSI effect is much larger in single spin asymmetries than in unpolarized cross sections. Thus, in Ref. [2] we have extended out approach recently presented in [1] to clarify the role of FSI effect on the helicity dependence in the doubly polarized differential and total photo-absorption cross sections with respect to

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

parallel and antiparallel spins of photon and deuteron of the reaction $\vec{\gamma}\vec{d} \to \pi^0 d$ near the η-threshold. In addition, we have also evaluated the contribution of coherent π^0-photoproduction channel to the deuteron Gerasimov-Drell-Hearn (GDH) integral by explicit integration up to a photon lab-energy of 900 MeV. It was found that the FSI effect is negligible in the doubly polarized total photo-absorption cross sections and the deuteron GDH integral. On the contrary, the FSI effect was strong in the doubly polarized differential cross sections at extreme backward direction in the η-threshold region.

The ultimate goal of the present manuscript is, therefore, to study the role of FSI effect on the double polarization E-asymmetry of the reaction $\vec{\gamma}\vec{d} \to \pi^0 d$ near the η-threshold at backward pion angles. This helicity asymmetry provides valuable information on the nucleon spin structure and allow us to extract information on the neutron. It contains very interesting physics with respect to the hadron structure of the system describing its optical activity which reflects an internal screw-like or chiral structure. The knowledge of this asymmetry is also required to test the validity of the GDH sum rule [17] on the deuteron and the neutron as well as to explore which are the dominant contribution to the GDH integral. In addition, the dependence of the results obtained for the helicity E-asymmetry on the input elementary pion photoproduction operator and the potential model used for the deuteron wave function will be investigated.

In section 2 of this manuscript the formalism for coherent π^0-photoproduction on the deuteron is briefly introduced. The separate contributions of the pure IA and the FSI effect in the transition matrix are described [1]. Details of the actual calculation and the results are presented and discussed in section 3. Finally, we conclude our results in section 4. Throughout the paper we use natural units $\hbar = c = 1$.

2 The formalism

The formalism of coherent π^0-photoproduction on the deuteron is presented in detail in our recent work [1]. Here we briefly recall the necessary notation and definitions. The coherent π^0-photoproduction reaction on the deuteron is given by

$$\gamma(E_\gamma, \vec{k}, \lambda) + d(E_d, -\vec{k}) \to \pi^0(E_\pi, \vec{q}) + d(E'_d, -\vec{q}), \quad (1)$$

where energy and momenta of the participating particles are given in the parentheses, and λ stands for the circular photon polarization.

The unpolarized differential cross section of the reaction $\gamma d \to \pi^0 d$ in the γd center-of-mass (c.m.) system is given by

$$\frac{d\sigma}{d\Omega_\pi} = \frac{E_d E'_d}{(4\pi W)^2} \frac{|\vec{q}\,|}{|\vec{k}\,|} \frac{1}{6} \sum_{\lambda} \sum_{m_d m'_d} \left| T_{m_d m'_d \lambda}(\vec{k}, \vec{q}\,) \right|^2, \quad (2)$$

with $T_{m_d m'_d \lambda}$ as reaction amplitude, m'_d (m_d) is the spin projection of the outgoing (incoming) deuteron and $\vec{q}$ and $\vec{k}$ are the c.m. momenta of the pion and photon, respectively. The invariant energy of the γd system is given as

$$\begin{aligned} W &= E_\gamma + \sqrt{\vec{k}^{\,2} + M_d^2}, \qquad E_\gamma = |\vec{k}\,|, \\ &= E_\pi + \sqrt{\vec{q}^{\,2} + M_d^2}, \qquad E_\pi = \sqrt{\vec{q}^{\,2} + m_\pi^2}, \end{aligned} \quad (3)$$

where M_d and m_π are the deuteron and neutral-pion masses, respectively. In the present work, the γd c.m. frame is chosen with the z-axis along the photon momentum $\vec{k}$, the y-axis parallel to $\vec{k} \times \vec{q}$ and the x-axis such as to form a right-handed system. Thus the outgoing pion is described by the spherical angles ϕ_π and θ_π with $\cos\theta_\pi = \hat{q} \cdot \hat{k}$.

For the amplitude of coherent π^0-photoproduction on the deuteron we include in addition to the pure IA, i.e., the one-body contribution, the FSI diagram with intermediate production of both π- and η-mesons. A diagrammatical overview of these contributions which are considered in this work 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

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

As shown in [1], one has for the IA contribution (diagram (a) in Fig. 1) the amplitude $T^{\mathrm{IA}}_{m_d m'_d \lambda}$ for the transition between the deuteron target states with spin projections m_d and m'_d on the z-axis, chosen along the photon momentum,

$$\begin{aligned} T^{\mathrm{IA}}_{m_d m'_d \lambda}(\vec{k}, \vec{q}\,) = 2 \int \frac{d^3p}{(2\pi)^3}\, \phi^\dagger_{m'_d}(\vec{p}\,') \\ \times t^\lambda_{\pi\gamma}(\vec{k}, \vec{p}_i, \vec{q}, \vec{p}_f) \phi_{m_d}(\vec{p}\,) \end{aligned} \quad (5)$$

with $t^\lambda_{\pi\gamma}$ standing for the corresponding elementary amplitude $\gamma N \to \pi^0 N$. Furthermore, the vectors $\vec{p}_i$ and $\vec{p}_f$ denote initial and final momenta of the active nucleon in the deuteron, for which we have $\vec{p}_i = \vec{p} - \vec{k}/2$ and $\vec{p}_f = \vec{p} - \vec{q} + \vec{k}/2$, and $\vec{p}\,' = \vec{p} + (\vec{k} - \vec{q}\,)/2$ denotes the relative momentum in the final deuteron state.

For the deuteron wave function we use the familiar ansatz

$$\phi_{m_d}(\vec{p}\,) = \sum_{L=0,2} \sum_{m_L m_S} (L m_L 1 m_S | 1 m_d) u_L(p) Y_{L m_L}(\hat{p}) \chi_{m_S} \zeta_0, \quad (6)$$

where χ_{m_S} and ζ_0 denote spin and isospin wave functions, respectively. In the present work, we compute the radial deuteron wave function in the initial and final states using the realistic high-precision Bonn potential (full model) form [18].

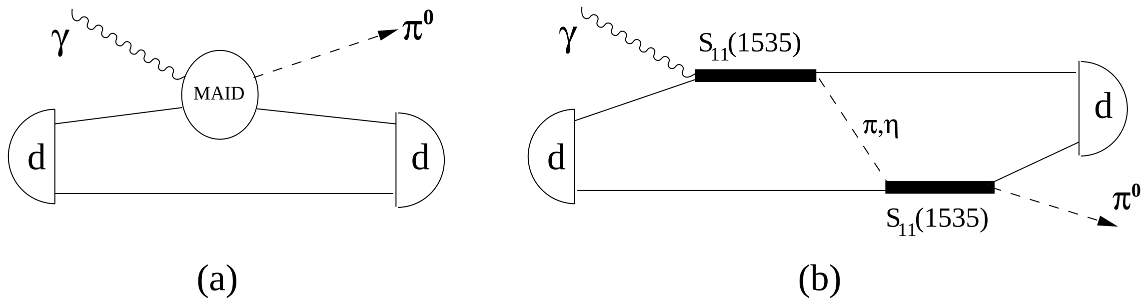

Fig. 1: Feynman diagrams considered in coherent π^0-photoproduction on the deuteron, (a) impulse approximation (IA) and (b) first-order rescattering contribution with intermediate production of both π- and η-mesons (FSI). Diagrams when the elementary operators act on nucleon '2' are not shown in the figure but are included in the calculations. In the calculations, each diagram shown in the figure goes accompanied by the diagram obtained by the exchange $N_1 \leftrightarrow N_2$.

In addition, we use the realistic MAID-2007 model [19] for the elementary pion photoproduction operator on the free nucleon. This model has been developed to analyze the world data for pion production off protons and neutrons. The MAID model is a unitary isobar model for a partial wave analysis, where all parameters are fitted to experimental observables as cross sections and polarization asymmetries from pion photo- and electro-production in the energy range from pion threshold up to $W_{\gamma^* N} = 2$ GeV and photon virtualities $Q^2 < 5$ GeV^2. It is based on a non-resonant background described by Born terms and vector-meson exchange contributions and nucleon resonance excitations. The MAID-2007 model is parameterized in terms of invariant amplitudes and allows for the evaluation in any frame of reference.

The transition matrix elements for the calculation of the additional contribution of FSI (diagram (b) in Fig. 1) read

$$T^{\rm FSI}_{m_d m'_d \lambda}(\vec{k},\vec{q}) = T^{\rm FSI,\pi}_{m_d m'_d \lambda}(\vec{k},\vec{q}) + T^{\rm FSI,\eta}_{m_d m'_d \lambda}(\vec{k},\vec{q}), \quad (7)$$

where the rescattering contributions with intermediate π- and η-mesons are given, respectively, by the first and second terms of the right-hand side. These two terms are govern by various hadronic and electromagnetic two-body reactions included in our treatment of diagram (b) in Fig. 1. Due to the strong coupling between the ηN and πN channels in the $S_{11}(1535)$ resonance region, the transitions $\eta N \leftrightarrow \pi N$ must in general be taken into account. Therefore, in the present work, only the $S_{11}(1535)$ resonance is considered in the calculation of the pion-exchange contribution and all contributions from other resonances are neglected.

For the elementary amplitudes appearing in diagram (b) of Fig. 1, we assume that the pion and eta photoproduction reactions on the nucleon as well as their interactions with nucleons proceed exclusively via the excitation of the $S_{11}(1535)$ resonance. According to this assumption the separable transition matrix $T_{\alpha N}$ with $\alpha \in \{\pi,\eta\}$ is given by the conventional isobar model [20]

$$T_{\alpha N}(\vec{p},\vec{p}\,';W) = \frac{g_\alpha(\vec{p}\,)\,g_\pi(\vec{p}\,')}{W - M_0 - \Sigma_\eta(W) - \Sigma_\pi(W) - \Sigma_{\pi\pi}(W)}, \quad (8)$$

as a function of the invariant energy W, where $\alpha \in \{\pi,\eta\}$ and Σ_π, Σ_η, and $\Sigma_{\pi\pi}$ denote the $S_{11}(1535)$ self energy contributions from the πN, ηN, and $\pi\pi N$ channels, respectively. The $T_{\alpha N}$ matrix is determined by the bare resonance mass $M_0 = 1598$ MeV and the parameters of the vertex functions $g_\alpha(\vec{p}\,)$. For the latter, we take a simple Hulthén form

$$g_\alpha(\vec{p}\,) = g_\alpha\left(1+\frac{p^2}{\Lambda_\alpha^2}\right)^{-1}, \quad (9)$$

containing the strength of the coupling g_α and the range of the Hulthén form factor Λ_α. The scattering parameters $g_\pi = 2.51$, $g_\eta = 2.0$, $\Lambda_\pi = 404.5$ MeV, and $\Lambda_\eta = 694.6$ MeV are used [4].

The contributions to the self energy from the various channels are expressed in terms of $g_\alpha(\vec{p}\,)$ as follows

$$\Sigma_\alpha(W) = \frac{1}{2\pi^2}\int_0^\infty \frac{q^2 dq}{2\omega_\alpha}\,\frac{g_\alpha^2(q)}{W - E_N(q) - \omega_\alpha(q) + i\varepsilon}, \quad (10)$$

with $\alpha \in \{\pi,\eta\}$ and E_N and ω_α denoting the on-shell energies of nucleon and meson, respectively. Since the double pion channel $\pi\pi N$ is not explicitly included in the present calculations, primarily because of its rather weak coupling to the $S_{11}(1535)$ resonance, we parameterize, following to [20], the corresponding self energy in a simplified manner as a pure imaginary contribution proportional to the three-particle phase space

$$\Sigma_{\pi\pi}(W) = -\frac{i}{2}\,\gamma_{\pi\pi}\,\frac{W - M_N - 2m_\pi}{m_\pi}, \quad (11)$$

with $\gamma_{\pi\pi} = 4.3$ MeV.

For the π- and η-photoproduction amplitudes on the nucleon, we take the same ansatz as in (8) where one hadronic vertex function is replaced by the electromagnetic vertex $g_{\gamma N}$ for $\gamma N \to S_{11}(1535)$ which depends only on the invariant energy W and is parameterized in the form

$$g_{\gamma p}(W) = \begin{cases} \dfrac{e}{\sqrt{4\pi}} \displaystyle\sum_{n=0}^{4} a_n \left(\dfrac{q_\pi}{m_\pi}\right)^n , & \text{for } W \geq M_N + m_\pi \,, \\ g_{\gamma p}(M_N + m_\pi)\,, & \text{else}\,, \end{cases} \tag{12}$$

$$g_{\gamma n}(W) = -0.82\, g_{\gamma p}(W)\,,$$

where $a_0 = 0.5502$, $a_1 = -0.01923$, $a_2 = 0.1018$, $a_3 = 0.002255$, and $a_4 = -0.007042$ [4]. The pion c.m. momenta corresponding to the total invariant energy W is given by

$$q_\pi = \frac{1}{2W}\sqrt{(W^2 - (M_N + m_\pi)^2)(W^2 - (M_N - m_\pi)^2)}\,. \tag{13}$$

Following to Ref. [21], the isospin dependence of the $S_{11}(1535)$ photo-excitation amplitude is taken in the present work according to the relation

$$\frac{\sigma(\gamma p \to \eta p)}{\sigma(\gamma n \to \eta n)} \approx 0.67\,. \tag{14}$$

The parameters, appearing in the expressions (8) through (12), are chosen in such a way that, on the one hand, the reactions $\gamma N \to \alpha N$ and $\pi^- p \to \eta n$ are well reproduced in the $S_{11}(1535)$ channel (see also Refs. [22, 23]). On the other hand, the chosen parameter set predicts the value $a_{\eta N} = (0.5 + i0.3)$ fm for the ηN scattering length which has been considered in Ref. [4] as an approximate average of the various values provided by the ηN analyses.

3 Numerical Results

The discussion of our results is divided into two parts. First, we discuss the influence of FSI effect on the beam-target double polarization E-asymmetry. The contribution to the pion photoproduction amplitude is evaluated by taking a realistic potential model for the deuteron wave functions in the initial and final states. In the present work, the wave function of the Bonn potential (full model) [18] was used. For the elementary pion photoproduction operator, the unitary isobar MAID-2007 model [19] was considered. For the various hadronic and electromagnetic two-body reactions included in our treatment of the rescattering diagram, only the $S_{11}(1535)$ resonance was taken into account in the pion-exchange contribution. In addition, the photoproduction of π- and η-mesons on the nucleon as well as their interactions with nucleons were assumed to be proceed exclusively via the extraction of the $S_{11}(1535)$ resonance.

In the second part we explore the dependence of the results for the helicity E-asymmetry in the $\vec{\gamma}\vec{d} \to \pi^0 d$ reaction on the input elementary pion photoproduction operator and the potential model used for the deuteron wave functions in the initial and final states. We show results for the double polarization E-asymmetry in the energy region near the η-threshold, using as elementary reaction amplitudes the ones provided by the ELA model from [24] and those obtained using MAID model [19]. For the deuteron wave function, we use the CD-Bonn [25], Bonn (full model) [18], and Bonn (OBEPQ) [26] potential models.

3.1 The double polarization E-asymmetry

We start the discussion with the results for the double polarization E-asymmetry. This asymmetry is given by

$$E(\theta_\pi) = \frac{d(\sigma^A - \sigma^P)/d\Omega_\pi}{d(\sigma^A + \sigma^P)/d\Omega_\pi} = \frac{d(\sigma^A - \sigma^P)/d\Omega_\pi}{2(d\sigma/d\Omega_\pi)}\,. \tag{15}$$

The helicity dependent photo-absorption cross sections for parallel and antiparallel helicity states of photon and deuteron, $d\sigma^P/d\Omega_\pi$ and $d\sigma^A/d\Omega_\pi$, respectively, are well suited to verify the GDH sum rule [17], to do partial channel analysis, and to give contributions to the double polarization E-asymmetry. This helicity asymmetry appears as an interference between the amplitudes with different parity-exchange properties.

As already mentioned in the introduction, there is a great deal of interest in experiments [13] to determine the beam-target double polarization asymmetries for meson production on light nuclei. In connection with this study, we provide in Figs. 2 and 3 results for the double polarization E-asymmetry of the reaction $\vec{\gamma}\vec{d} \to \pi^0 d$ in the near η-threshold region at extremely backward pion angles.

When only the pure IA is considered (dotted curve in Fig. 2), one notes that the helicity E-asymmetry has qualitatively a similar behavior for all photon energies. The maximum value of the helicity E-asymmetry equals unity at $\theta_\pi = 180^\circ$ for all photon lab-energies. The dotted curve begins with a negative value of $E = -0.1$ at $\theta_\pi = 100^\circ$ and decreases as the pion angle increase until a minimum value is reached at about 110°. Then, it increases again to unity. We would like to emphasize that the negative values in the E-asymmetry come from higher positive contribution in the doubly polarized differential cross section for parallel helicity state $d\sigma^P/d\Omega_\pi$ [2].

The influence of FSI effect on the double polarization E-asymmetry is shown in Fig. 2 – see the difference between the dotted and solid curves. We find that the helicity E-asymmetry exhibits a strong effect of the rescattering contribution. Also, one notes that the FSI effect is sizeable at all photon lab-energies around the η-production threshold. The E-asymmetry is found to be a broad structureless at extremely backward direction. It exhibits a minimum at emission pion angle $\theta_\pi \simeq 110^\circ$ when the IA alone is considered. When the rescattering

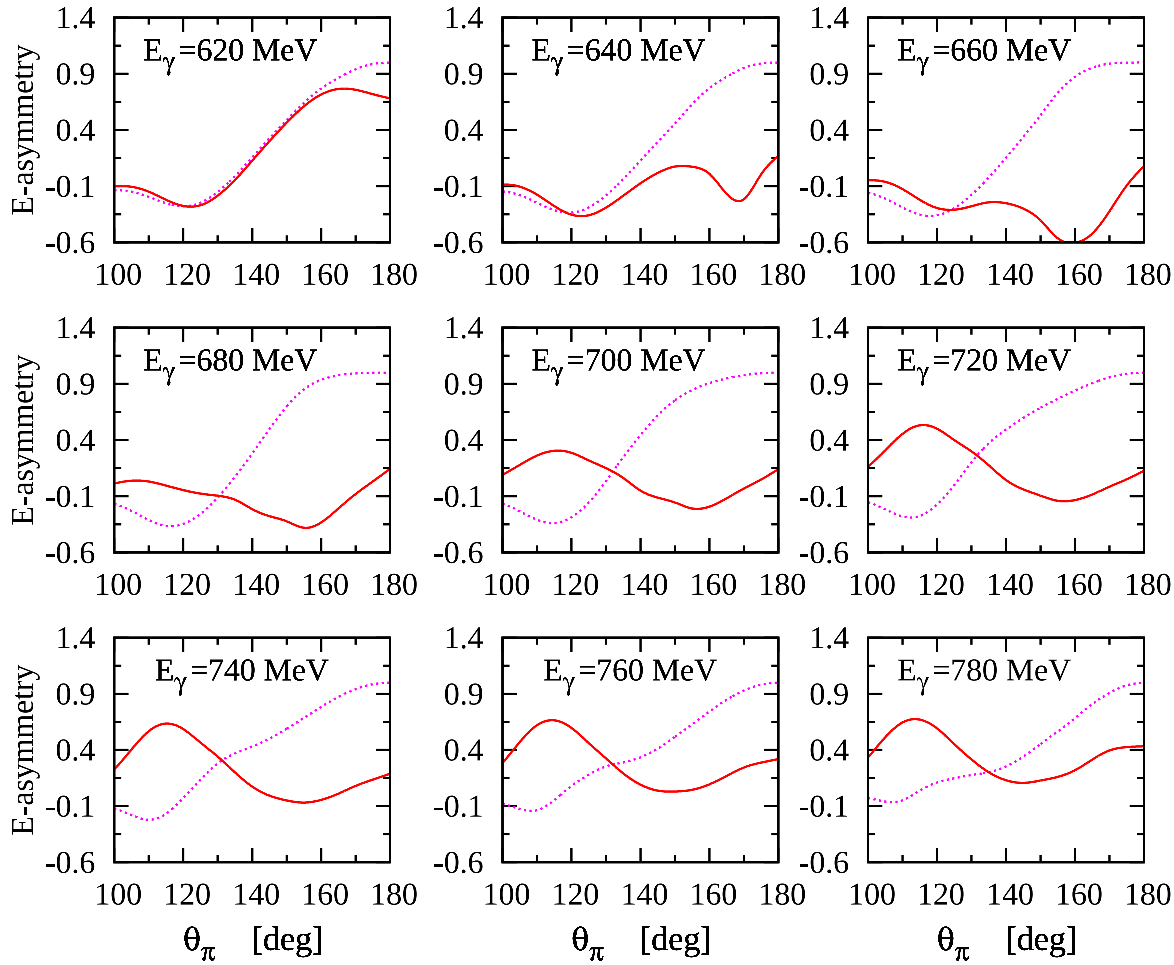

Fig. 2: (Color online) The double polarization E-asymmetry of the reaction $\vec{\gamma}\vec{d} \to \pi^0 d$ versus emission pion angle in the γd c.m. frame at various photon lab-energies. Shown are the prediction of the IA alone (magenta dotted) and with inclusion of FSI effect (red solid).

contribution is taken into account, this minimum changes its shape to a broad peak at the same pion angle and photon lab-energies $E_\gamma \geq 700$ MeV. Then, it decreases with increasing pion angle until a minimum value is reached at about 150° and increases again

The role of FSI effect on the double polarization E-asymmetry as a function of photon lab-energy at fixed values of $\cos\theta_\pi$ in the γd c.m. frame is shown by the difference between the dotted and solid curves in Fig. 3. The E-asymmetry is found to be a broad structureless at extremely backward direction. The sensitivity of rescattering effect is strong. We see that, the E-asymmetry exhibits a peak at $E_\gamma \simeq 700$ MeV when the IA alone is considered. When the FSI effect is taken into account, this peak changes its shape to a deep minimum at extremely backward angles. We would like to emphasize that the contribution from FSI effect reached on average about 40% in the η-threshold region at extremely backward pion angles.

This description is very nicely demonstrated by a three-dimensional plot of the helicity E-asymmetry as a function of photon lab-energy and emission pion angle shown in Fig. 4. The upper and lower panels show the results of the IA alone and with inclusion of FSI effect, respectively. Apparently, our calculation with FSI exhibits a visible broad minimum at extremely backward pion angles which is not the case when only the pure IA is considered. In the latter case, a broad maximum is observed. This reflects again the importance of rescattering effects in spin observables.

3.2 Sensitivity to the elementary amplitude and deuteron wave function

In what follows, we discuss the influence of different choices for the input elementary pion photoproduction operator and the potential model used for the deuteron

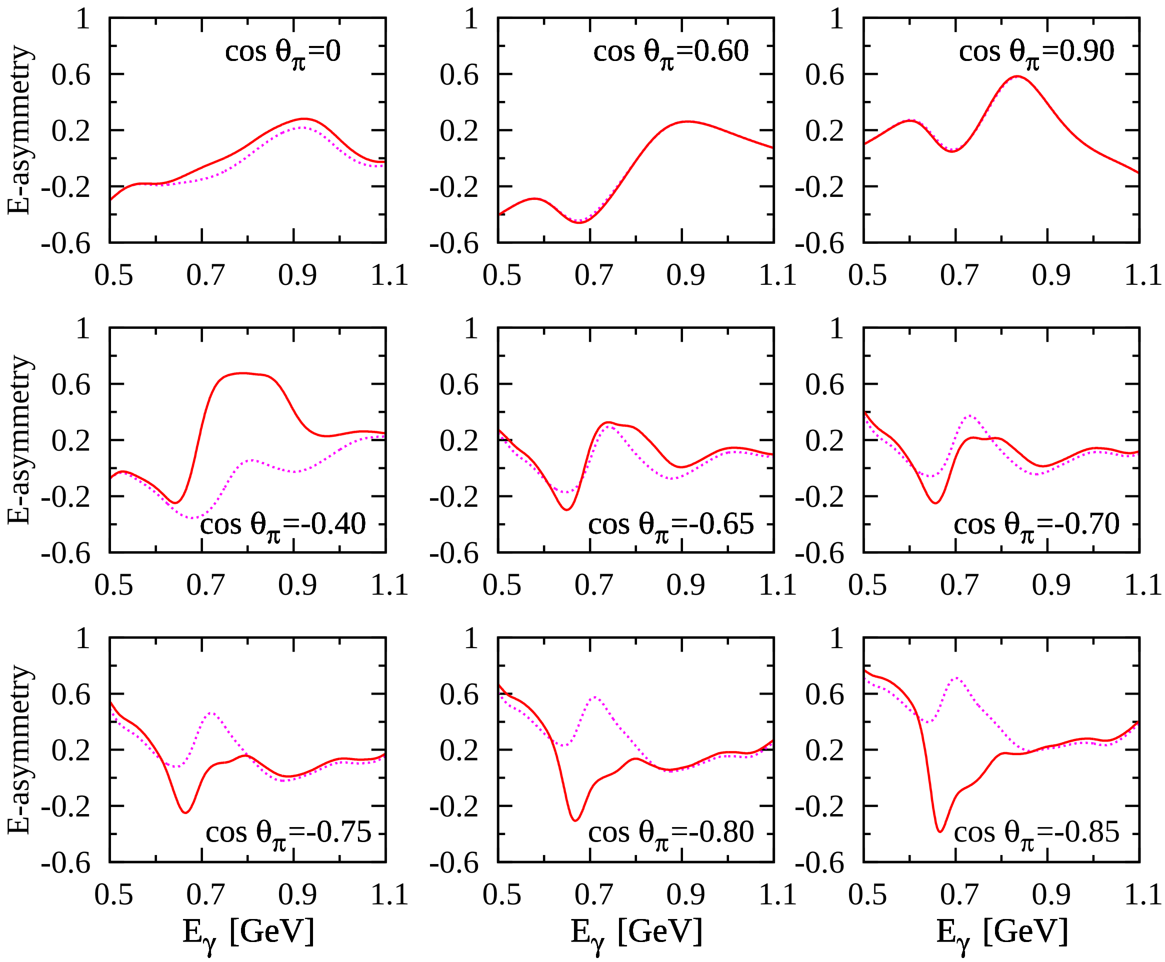

Fig. 3: (Color online) The helicity E asymmetry of $\vec{\gamma}\vec{d} \to \pi^0 d$ versus laboratory photon energy at different $\cos\theta_\pi$ in the γd c.m. frame. Notation of the curves as in Fig. 2.

wave function on the results presented above for the helicity E-asymmetry of the $\vec{\gamma}\vec{d} \to \pi^0 d$ reaction with inclusion of FSI effect. The first comparison (Fig. 5) shows the sensitivity of the results for the double polarization E-asymmetry as a function of photon lab-energy at different $\cos\theta_\pi$ in the γd c.m. frame on the elementary pion photoproduction operator using the Bonn potential (full model) [18] for the deuteron wave function. The solid (dotted) curve in Fig. 5 shows the results of IA+FSI using the MAID-2007 (MAID-2003) model [19], whereas the dashed curve shows the results of IA+FSI using the dressed electromagnetic multipoles of ELA model [24].

We find that the double polarization E-asymmetry presents qualitative similar behaviors for different elementary operators. One sees that the asymmetry E decreases with increasing the photon energy until a minimum at about 660 MeV is reached. Then the E-asymmetry increases with increasing the photon energy until a broad plateau in the energy range 750-850 MeV is reached and decreases again. It is also clear that the computations with different elementary amplitudes are quite different. For example, at the minimum position we obtain smaller, but in absolute value larger, values using MAID than using ELA. In addition, the plateau obtained using MAID appears as a peak at photon energy of about 700 MeV using ELA. This discrepancy shows up the differences among elementary operators. This means that the double polarization E-asymmetry is sensitive to the choice of the elementary amplitude.

Figure 6 shows the dependence of our results for the helicity E-asymmetry of the reaction $\vec{\gamma}\vec{d} \to \pi^0 d$ as a function of photon lab-energy at different $\cos\theta_\pi$ in the γd c.m. frame on the deuteron wave function using the MAID-2007 model [19] for the elementary amplitude. The solid, dashed, and dotted curves in Fig. 6 show the results of IA+FSI using the Bonn (full) [18], Bonn (OBEPQ) [26], and CD-Bonn [25] potential models, respectively. In general, one sees qualitatively similar behaviors for the double polarization E-asymmetry. The

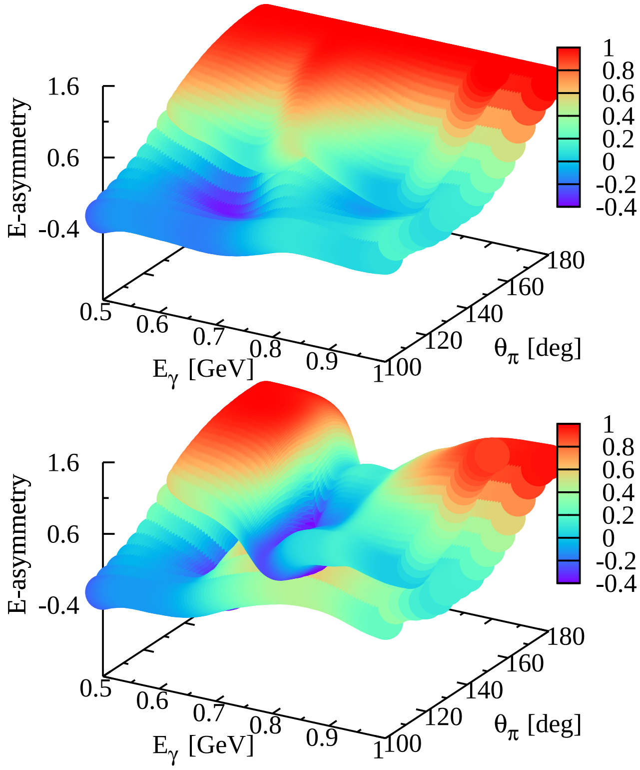

Fig. 4: (Color online) A three-dimensional plot for the helicity E asymmetry of $\vec{\gamma}\vec{d} \to \pi^0 d$. The upper (lower) panel shows the results of the IA alone (with inclusion of FSI effect).

results using various models for the deuteron wave function are different, specially at the plateau region where a sizeable difference is obtained in the energy range 730-930 MeV. We find that the results using the deuteron wave function of the Bonn (OBEPQ) potential is greater than those using CD-Bonn potential and the latter is greater than the ones using Bonn (full) potential. This means that the helicity E-asymmetry is also sensitive to the choice of the potential model used for the deuteron wave function.

From the preceding discussion it is apparent that first-order rescattering and the choices of the elementary operator and deuteron wave function have a visible effect on the helicity E-asymmetry.

4 Conclusions

The main topic of this manuscript was the investigation of the double polarization E-asymmetry for coherent π^0-photoproduction on the deuteron in the energy region near the threshold of η-production at backward pion angles, including first-order rescattering effect with intermediate production of both π- and η-mesons. For the elementary operator, a realistic unitary isobar model from MAID-2007 [19] has been used. The sensitivity to the elementary $\gamma N \to \pi^0 N$ operator and the deuteron wave function of the results has also been investigated.

For the deuteron wave functions in the initial and final states, the realistic high-precision Bonn potential (full model) [18] was used. For the hadronic and electromagnetic two-body amplitudes taken into account in the calculation of the rescattering diagram, only the $S_{11}(1535)$ resonance was considered in the pion-exchange contribution. The π- and η-photoproduction reactions on free nucleons as well as their interactions with nucleons were assumed to be proceeds exclusively via the extraction of the $S_{11}(1535)$ resonance.

Within our model, we have found that the inclusion of FSI effect is important for the double polarization E-asymmetry, especially at extremely backward direction and photon energies near the η-threshold. The influence of FSI effect is found to be strong and in many cases, the deviation among results obtained using the IA alone and with inclusion of FSI effect is large. We find also that the double polarization E-asymmetry is sensitive to the choices of the elementary operator and deuteron wave function. In many cases, the deviation among results obtained using different deuteron wave functions as well as different elementary operators is large. In view of these results, we conclude that the process $\gamma d \to \pi^0 d$ can serve as a filter for different elementary operators and deuteron wave functions since their predictions provide different values for the helicity E-asymmetry.

Finally, we would like to point out that not all of the possible rescattering diagrams are considered in this

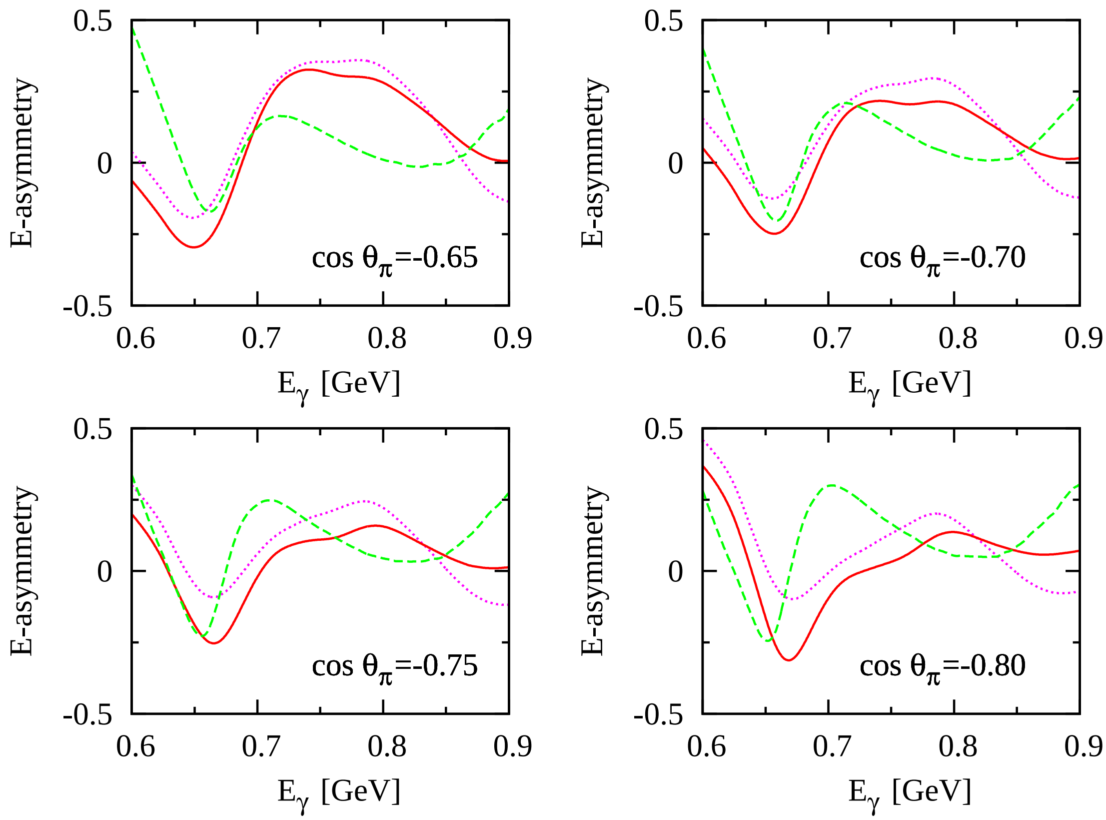

Fig. 5: (Color online) The helicity E-asymmetry for the reaction $\vec{\gamma}\vec{d} \to \pi^0 d$ as a function of photon lab-energy at different $\cos\theta_\pi$ in the γd c.m. frame using different elementary pion photoproduction operators and the deuteron wave functions in the initial and final states from the Bonn (full) model [18]. Curve conventions: green dashed, IA+FSI using dressed ELA [24]; magenta dotted, IA+FSI using MAID-2003 [19]; red solid, IA+FSI using MAID-2007.

work. Our calculations do not include two-nucleon mechanisms in the rescattering amplitude or any other resonance amplitudes besides the $S_{11}(1535)$ contribution. For example, vector-meson exchange currents were found to be quite significant for π^+-photoproduction on ^{3}He in Ref. [27]. In addition, the three-body treatment of the ηNN interaction is of special importance for understanding the reaction dynamics. In fact, a noticeable contribution from such an interaction was found in unpolarized differential cross section [4]. Polarization observables in general constitute more stringent tests for theoretical models due to their sensitivity to small amplitudes. At this point, a much needed measurement on the spin asymmetries will certainly provide us with an important observable to test our knowledge of the pion photoproduction on the neutron process and, hence, to provide us with valuable information on the neutron spin asymmetry in an indirect way. Thus there is a way for further improvements of the present model.

Acknowledgement

This work was supported by the Deanship of Scientific Research of the Taibah University, Saudi Arabia under project No. 433/1653.

References

[1] E.M. Darwish and S.S. Al-Thoyaib, submitted (2014).
[2] E.M. Darwish, submitted (2014).
[3] A.E. Kudryavtsev *et al.*, Phys. Rev. C **71**, 035202 (2005).
[4] A. Fix, Eur. Phys. J. A **26**, 293 (2005).
[5] E.M. Darwish and S.S. Al-Thoyaib, Ann. Phys. **326**, 604 (2011).
[6] E.M. Darwish, C. Fernández-Ramírez, E. Moya de Guerra, and J.M. Udías, Phys. Rev. C **76**, 044005 (2007).
[7] M.I. Levchuk, A.Yu. Loginov, A.A. Sidorov, V.N. Stibunov, and M. Schumacher, Phys. Rev. C **74**, 014004 (2006).
[8] H. Arenhövel and A. Fix, Phys. Rev. C **72**, 064004 (2005); A. Fix and H. Arenhövel, Phys. Rev. C **72**, 064005 (2005).
[9] E.M. Darwish, H. Arenhövel, and M. Schwamb, Eur. Phys. J. A **16**, 111 (2003).

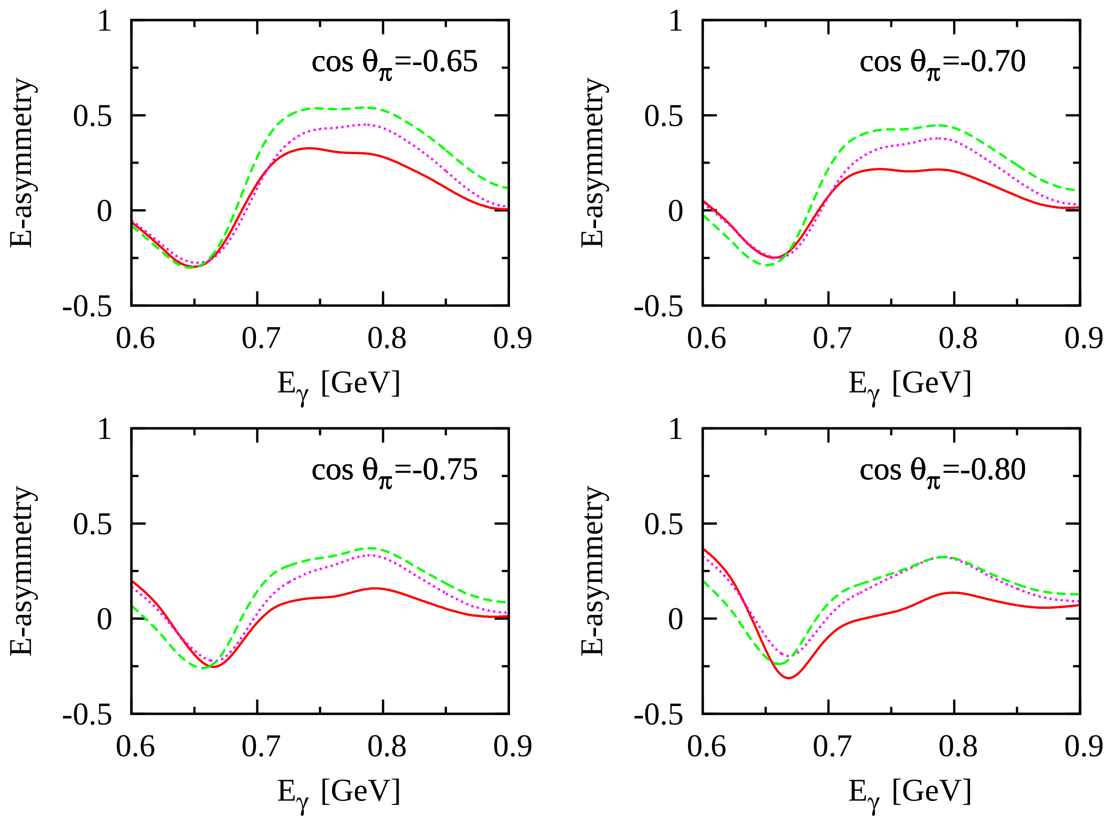

Fig. 6: (Color online) The helicity E-asymmetry for the reaction $\vec{\gamma}\vec{d} \to \pi^0 d$ as a function of photon lab-energy at different $\cos\theta_\pi$ in the γd c.m. frame using different realistic potential models for the deuteron wave functions in the initial and final states and the elementary pion photoproduction operator from the MAID-2007 model [19]. Curve conventions: green dashed, IA+FSI using Bonn (OBEPQ) [26]; magenta dotted, IA+FSI using CD-Bonn [25]; red solid, IA+FSI using Bonn (full) [18].

[10] E.M. Darwish, H. Arenhövel, and M. Schwamb, Eur. Phys. J. A **17**, 513 (2003).

[11] H. Arenhövel, A. Fix, and M. Schwamb, Phys. Rev. Lett. **93**, 202301 (2004); M. Schwamb, Eur. Phys. J. **A28**, Suppl. 1, 39 (2006); M. Schwamb, Phys. Rep. **485**, 109 (2010).

[12] E.M. Darwish, N. Akopov, and M. El-Zohry, AIP Conf. Proc. **1370**, 242 (2011); *ibid*, J. At. Mol. Sci. **2**, 187 (2011); *ibid*, PoS ICHEP2010, 185 (2010).

[13] B. Krusche and S. Schadmand, Prog. Part. Nucl. Phys. **51**, 399 (2003); V. Burkert and T.-S.H. Lee, Int. J. Mod. Phys. E **13**, 1035 (2004); D. Drechsel and L. Tiator, Ann. Rev. Nucl. Part. Sci. **54**, 69 (2004); H. Dutz *et al.*, Phys. Rev. Lett. **93**, 032003 (2004); K. Helbing, Prog. Part. Nucl. Phys. **57**, 405 (2006); A. Thomas, Eur. Phys. J. A **28**, Suppl. 1, 161 (2006); T. Rostomyan, Nucl. Phys. A **755**, 451c (2005); J. Ahrens *et al.*, Phys. Rev. C **74**, 045204 (2006); J. Ahrens *et al.*, Phys. Rev. Lett. **97**, 202303 (2006); J. Ahrens *et al.*, Phys. Rev. Lett. **98**, 039901(E) (2007).

[14] B. Krusche, Eur. Phys. J. Special Topics **198**, 199 (2011).

[15] B. Krusche *et al.*, Eur. Phys. J. A **22**, 277 (2004).

[16] Y. Ilieva *et al.*(for the CLAS Collaboration), Nucl. Phys. A **737**, S158 (2004) (Proceedings of the 17th International IUPAP Conference on Few-Body Problems in Physics, Durham NC (2003)); arXiv:nucl-ex/0309017; Y. Ilieva *et al.*, Eur. Phys. J. A **43**, 261 (2010), arXiv:nucl-ex/0703006.

[17] S.B. Gerasimov, Yad. Fiz. **2**, 598 (1965) (Sov. J. Nucl. Phys. **2**, 430 (1966)); S.D. Drell and A.C. Hearn, Phys. Rev. Lett. **16**, 908 (1966).

[18] R. Machleidt, K. Holinde, and Ch. Elster, Phys. Rep. **149**, 1 (1987).

[19] O. Hanstein, D. Drechsel and L. Tiator, Nucl. Phys. A **632**, 561 (1998); D. Drechsel, O. Hanstein, S. Kamalov and L. Tiator, Nucl. Phys. A **645**, 145 (1999); D. Drechsel, S. Kamalov and L. Tiator, Eur. Phys. J. A **34**, 69 (2007); *MAID Program*, Institut für Kernphysik, Johannes Gutenberg-Universität, Mainz, Germany, http://www.kph.uni-mainz.de/de/MAID/.

[20] C. Bennhold and H. Tanabe, Nucl. Phys. A **530**, 62 (1991).

[21] V. Hejny *et al.*, Eur. Phys. J. A **6**, 83 (1999).

[22] A. Fix and H. Arenhövel, Eur. Phys. J. A **19**, 275 (2004).

[23] A. Fix and H. Arenhövel, Phys. Rev. C **68**, 044002 (2003).

[24] C. Fernández-Ramírez, E. Moya de Guerra, and J.M. Udías, Ann. Phys. (N.Y.) **321**, 1408 (2006); C. Fernández-Ramírez, PhD dissertation, Universidad Complutense de Madrid, Spain (2006); C. Fernández-Ramírez, E. Moya de Guerra, and J.M. Udías, Phys. Lett. B **660**, 188 (2008).

[25] R. Machleidt, F. Sammarruca, and Y. Song, Phys. Rev. C **53**, R1483 (1996); R. Machleidt, Phys. Rev. C **63**, 024001 (2001).

[26] R. Machleidt, Adv. Nucl. Phys. **19**, 189 (1989).
[27] J.A. Gomez Tejeda, S.S. Kamalov and E. Oset, Phys. Rev. C **54**, 31607 (1996).

Eed M. Darwish is Associate Professor of Physics at Sohag University, Egypt. He received the PhD degree in Theoretical Nuclear Physics at the Institute for Nuclear Physics of the Johannes-Gutenberg University, Mainz, Germany as a DAAD scholarship. Since 2008, he joined Taibah University, Saudi Arabia as Associate Professor (on leave). He is the former Head of Applied Physics Department at Taibah University. His main research interests include 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 research articles in reputed international journals of physics. He is referee of several international physics journals.