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Incoherent photoproduction of ϕ-meson from deuteron at low energies

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Abstract. The LEPS and CLAS data of the incoherent photoproduction of ϕ meson from deuteron at low energies are studied with a model for ϕ meson photoproduction from nucleon consisting of Pomeron, π, and η meson exchanges in the t-channel, and a postulated resonance, with parameters fitted to recent LEPS data on ϕ production from proton near threshold. The resonance was introduced to explain an observed bump in the forward differential cross section. Within impulse approximation, we find that the Fermi motion, final state interaction, and the resonance excitation all give important contributions to improve the agreement with data. However, discrepancies remain. Contributions from ϕ production via spectator nucleon by other mesons like π, ρ, and ϕ produced from the first nucleon need to be calculated in order to gain insight on the medium effects as well as the existence of the postulated nucleon resonance.

The ϕ-meson photoproduction reaction has long been extensively studied as it involves many interesting physics issues like, Pomeron (P) exchange, nondiffractive processes of the pseudoscalar (π, η)-meson exchanges, nucleon exchange, nucleon resonances excitation, second Pomeron exchange, t-channel scalar meson and glueball exchanges, and $s\bar{s}$-cluster knockout. Recently, another intriguing data of this reaction has appeared. Namely, LEPS collaboration observed a near-threshold bump structure in the forward differential cross sections of ϕ photoproduction on protons. It has not been possible to explain it by the processes mentioned above.

We found in [1] that, with an addition of a resonance of $(3/2)^-$, with mass $M = 2.10 \pm 0.03$ GeV and width $\Gamma = 0.465 \pm 0.141$ GeV to the background mechanism which consists of Pomeron and (π, η)-meson exchanges in t-channel, not only the peak in the forward differential cross section but also the t-dependence of differential cross section (DCS), ϕ meson decay angular distribution, and the spin density matrix elements can be well described.

We have set about to extend the above model further to study the incoherent photoproduction of ϕ-meson from deuteron at low energies, where data have recently become available from LEPS [2, 3] and CLAS [4]. Our purposes are three-fold. First is to see whether the resonance postulated in our model for ϕ photoproduction would manifest itself in someway in the case of deuteron target. Next is to learn

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some information on the ϕ production from neutron. Lastly, we are interested in the possible medium effects like Fermi motion, final-state interaction (FSI), and meson rescatterings on the vector meson propagation in the simplest nuclear target, the deuteron.

In this contribution, we will present our first results within the impulse approximation with the FSI effects fully taken into account.

Within the impulse approximation (IA) without final state interaction, the T-matrix of $\gamma d \to \phi pn$ is a sum of $T = T^{(p)} + T^{(n)}$, where the superscript p and n denotes whether the struck nucleon is a proton or neutron. Symbolically, e.g., one can write

$$T^{(p)} = T_{\gamma p \to \phi p} \Psi(\vec{p}_n - \vec{P}_d/2), \tag{1}$$

where Ψ denotes the deuteron wavefunction; while $\vec{p}_n$ and $\vec{P}_d$ are the three-momentum of the neutron and deuteron, respectively. In our calculation, all the spin dependences of the $\gamma p \to \phi p$ amplitude $T_{\gamma p \to \phi p}$, are taken into account and the explicit form of $T^{(p)}$ would then read like,

$$\begin{aligned} T^{(p)}\left(m_\gamma, m_d; m_\phi, m_p, m_n\right) \sim T_{\gamma p \to \phi p}\left(m_\gamma, m_d - m - m_n; m_\phi, m_p\right) C(1, m_d; l, m, 1, m_d - m) \\ \times\, C(1, m_d - m; 1/2, m_d - m - m_n, 1/2, m_n)\psi_l(|\mathbf{p}_n|) Y_{lm}(\Omega_{\mathbf{p}_n}), \end{aligned} \tag{2}$$

where $m's$ stand for the spin projections of the particles and $C's$ the CG coefficients, $Y_{lm}(\Omega_{\mathbf{p}})$ the spherical harmonics. The wave function $\psi_l(|\mathbf{p}|)$, describing the momentum-space radial distribution of the proton is taken from Bonn potential.

For the case when the struck nucleon is a neutron, we first assume that $T^{(n)}(P) = T^{(p)}(P)$ because Pomeron behaves like an isoscalar. For the excitation of the postulated $N^*(3/2^-)$ from neutron, we take the relativistic quark model of [5] as a guide. We assume that the photocoupling of the resonance is similar to that of $N^*_{3/2^-}(2095)$ predicted in that model and use its predicted helicity amplitudes to determine $g_{\gamma N N^*}$. We then use the fitted value of $g_{\gamma p N^*} g_{\phi p N^*}$ determined in [1] and assume $g_{\phi n N^*} = g_{\phi p N^*}$ to obatain $g_{\gamma n N^*} g_{\phi n N^*}$.

The IA amplitude with FSI included, i.e., where the struck nucleon which produces the ϕ proceeds to interact with the spectator nucleon, can be written as

$$\begin{aligned} &\langle \vec{q}, \vec{p}_1', \vec{p}_2' \mid T \mid k, \vec{p}_1, \vec{p}_2 \rangle \\ &= \int d\vec{p}_1'' \langle \vec{q}, \vec{p}_1', \vec{p}_2' \mid t_{NN}(E + i\epsilon) \mid \vec{q}, \vec{p}_1'', \vec{p}_2 \rangle \frac{1}{E_i - H_0 + i\epsilon} \langle \vec{q}, \vec{p}_1'', \vec{p}_2 \mid t_{\gamma\phi} \mid k, \vec{p}_1, \vec{p}_2 \rangle \\ &= \int d\vec{p}_1'' \langle \vec{p}_1', \vec{p}_2' \mid t_{NN}(E + i\epsilon) \mid \vec{p}_1'', \vec{p}_2 \rangle \frac{1}{E_i - H_0 + i\epsilon} \langle \vec{q}, \vec{p}_1'', \mid t_{\gamma\phi} \mid k, \vec{p}_1 \rangle, \end{aligned} \tag{3}$$

where t_{NN} and the $t_{\gamma\phi}$ denote the two-body amplitudes of NN scattering and ϕ production from a single nucleon, respectively. H_0 and E_i refer to the free Hamiltonian of the intermediate states and the initial energy of the γd system, respectively, and E denotes the energy available to the intermediate NN pair before they rescatter.

Now note that the propagator of the intermediate states in Eq. (3) can be decomposed as,

$$\frac{1}{E_i - H_0 + i\epsilon} = \frac{\mathbf{P}}{E_i - H_0} - i\pi\delta(E_i - H_0). \tag{4}$$

The amplitude T in Eq. (3) obtained with the use of the first and the second terms in Eq. (4) as propagator would give the FSI effects in which the NN pair in the final state scatter either off-energy-shell or on-shell.

The calculations with Eqs. (2) and (3) are tedious, time consuming, but manageable. We can now compare our results with the data of [2, 3] and [4]. However, a word of caution is in order concerning the DCS presented in [3]. The DCS data shown in Fig. 2 of [3] are actually the $d\sigma/dt$ of $\gamma N \to \phi N$ extracted from $\gamma d \to \phi pn$, namely, $(d\sigma_p/dt)\mid_p + (d\sigma_n/dt)\mid_n$, with struck nucleon at rest,

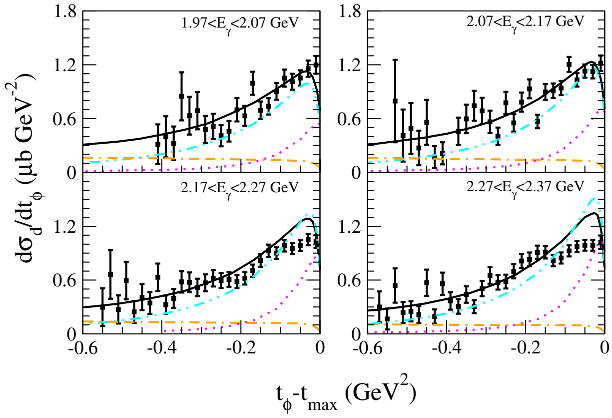

Figure 1. Comparison of our model predictions for the DCS of $\gamma d \to \phi pn$ as a function of momentum transfer t_ϕ at four energy bins for four energy bins between 1.97–2.37 GeV with data of [3, 6]. See text for notations.

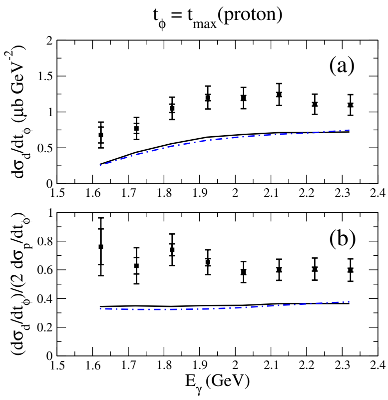

Figure 2. (a) The DCS of $\gamma d \to \phi pn$ and (b) the ratio of the DCS of $\gamma d \to \phi pn$ to twice the DCS of $\gamma p \to \phi p$, both at forward angle as a function of E_γ.

by the experimentalists. The extraction was done with the help of GEANT3 which took into account experimental parameters, Fermi motion, and the off-shell effects of the target nucleons inside deuteron. With a prescription provided by Chang [6], we have reconstructed the raw data of $d\sigma/dt(\gamma d \to \phi pn)$ for comparison with the results of our calculations.

Our model predictions for the DCS of $\gamma d \to \phi pn$ as a function of momentum transfer $t_\phi = (q_\phi - k)^2$, where q_ϕ and k are the momentum of ϕ and photon, respectively, at four energy bins between 1.97–2.37 GeV are shown in Fig. 1 and compared with the data of [3, 6]. The solid lines are the full results of including nonresonant (NR), i.e, Pomeron and (π, η) exchanges, and resonance (R) contributions, with pn FSI taken into account. The dash-dotted, and dash-dot-dotted lines are the results R and NR contributions without the pn FSI included, respectively, i.e., within the impulse approximation. The dotted lines denote the results of FSI effects of Eq. (3) only, namely, the contribution with rescattering between pn after ϕ is produced. The squares with error bars are the experimental data of Refs. [3, 6]. One sees that 1). the resonance contribution is nonnegligible; 2). FSI effect is large at forward angles, i.e., $t_\phi - t_{max} \sim 0$. The agreement of the full results are in general satisfactory but discrepancies are considerable at forward angles.

In Fig. 2, our predictions for (a) the DCS of $\gamma d \to \phi pn$, and (b) the ratio of the DCS of $\gamma d \to \phi pn$ to twice the DCS of $\gamma p \to \phi p$, both at forward angle as a function of E_γ, are compared with the LEPS data [3, 6]. The solid and dash-dotted lines denote the results of the full calculations and those without the inclusion of FSI. It appears that the FSI effects are small. However, it arises from an unexpected almost complete cancelation between the on-shell and off-shell rescatterings effects as given in Eq. (4). The substantial discrepancies between our results and the data reflect the considerable difference between

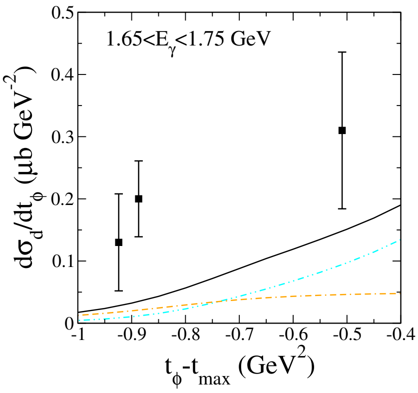

Figure 3. Comparison of our results with the CLAS data for $1.65 \leq E_\gamma \leq 1.75$ GeV as function of $t_\phi - t_{max}$. Notation same as Fig. 1.

our prediction and the data already seen in Fig. 1. In our opinion, the recipe employed by LEPS to extrapolate their data [3, 6] to the forward angles might be questionable as the DCS should show a sharp drop near forward direction [7] which is not seen in the LEPS data.

Lastly, we compare our results with the CLAS DCS data [4] for $1.65 \leq E_\gamma \leq 1.75$ GeV as function of $t_\phi - t_{max}$ in Fig. 3. The notations are the same as in Fig. 1. Note that the CLAS data are taken in the much larger momentum transfer region as compared with the LEPS data. The difference between our results and the data is substantial.

We have also calculated the spin density matrix elements and compared them with the LEPS data [2]. The agreement is in general reasonable and will be shown elsewhere because of the space limit here.

In summary, we have presented the results of a calculation, within impulse approximation with final state interaction between outgoing proton and neutron taken into account, for the incoherent photoproduction of ϕ from deuteron at low energies and compared them with the data from LEPS and CLAS. The Fermi motion, resonance, and the FSI effects are found important in certain kinematics. The overall agreement between our predictions and the data ranges from poor to reasonable. Further improvements are needed, e.g., the production of ϕ from the spectator nucleon by intermediate mesons, like π, ρ, ϕ, produced from the first nucleon struck by the photon, and medium effects of the propagation of the intermediate mesons, should be investigated. The last would be to tune the strength of the photon and ϕ meson to excite a neutron to produce the postulated resonance and see the possible effect induced.

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