Coherent $\phi$ and $\omega$ meson photoproduction from deuteron and non-diffractive channels

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The prime interest in the $\phi$ and $\omega$ meson photoproduction at a few GeV is related to the possible manifestation of non-diffractive "exotic" channels. In $\phi$ photoproduction, the amplitude of the unnatural parity-exchange processes is responsible for such exotic mechanisms as the direct knockout of $s\bar{s}$ component of the strangeness sea in a nucleon (cf. [1, 2, 3] for references) and the anomaly Regge trajectories associated with the non-perturbative gluon-exchange processes [4]. In the $\omega$ photoproduction it is the baryon resonance excitation [4, 5, 6], which is closely related to several aspects of intermediate and high energy physics, ranging from resolving the so-called "missing" resonance problem [7] to estimating in-medium modifications on the vector meson properties [8].

The contribution of the exotic non-diffractive channels to the total unpolarized cross section is rather small compared to the dominant diffractive Pomeron exchange in $\phi$ photoproduction and the $\pi$-meson exchange in $\omega$ photoproduction. Therefore, we are pinning our hopes on the measurement of spin observables. These could select the amplitudes with different parity-exchange symmetries, like the decay asymmetry $\Sigma_V$, $(V = \omega, \phi)$ [14, 15], or to find such observables which are proportional to the interference terms of the amplitudes with different parity properties, like beam-target asymmetry in reactions with circular polarized beam and a polarized target [3, 10].

The central problem when studying spin observables is the relatively strong influence of the unnatural parity $\pi$-exchange amplitude (PEA). In $\omega$ photoproduction, PEA dominates more than 90% of the resonance excitation. In the $\phi$ photoproduction at forward angles, the PEA contribution is comparable to those expected from exotic non-diffractive channels. This situation causes considerable difficulties in extracting the true exotic-channel contributions from the forthcoming experimental results from LEPS at SPring-8, Thomas Jefferson National Accelerator Facility, ELSA-SAPHIR at Bonn, and GRAAL at Grenoble.

One of the possible solutions to eliminate the contribution of the isovector $\pi$-meson exchange process is to use an isoscalar target. The simplest case is coherent photoproduction from the deuteron. The deuteron, with spin 1, has an advantage compared to spinless isoscalar targets. It gives the opportunity to examine the various beam-target asymmetries, which are sensitive to the non-diffractive channels.

In the present Rapid Communication, we wish to report this particular important and interesting aspect of the coherent $\phi$ and $\omega$ photoproduction from deuteron. The coherent photoproduction from the deuteron at higher energies with different points of view and purpose was analyzed in Ref. [12].

We define the kinematical variables for the $\gamma \to VD$ reaction with usual notations. The four momenta of the incoming photon, outgoing vector meson, initial deuteron, and final deuteron are denoted as $k$, $k_V$, $p$, and $p'$, respectively. The standard Mandelstam variables are defined as $t = (p' - p)^2 = (k - k_V)^2 = -Q^2$, $s = W^2 = (p + k)^2$. The space component of the transferred momentum transfers to deuteron in the laboratory system is $q^2 = q^2 = Q^2(1 + Q^2/4M_D^2)$, where $M_D$ is the deuteron mass.

We consider the case where the initial photon energy is below $2 - 3$ GeV and momentum transfer $Q^2$ is smaller than 0.5 GeV$^2$. Under these conditions, the dominant contribution to the amplitude comes from the single scattering processes, which are depicted in Fig. 1a. The double scattering diagrams shown in Fig. 1b are suppressed at low $Q^2$ [16]. At considered momentum transfers a non-relativistic approach for the deuteron structure is quite reasonable. We use the deuteron wave function with a realistic (Paris) nucleon-nucleon potential [15], which fairly well reproduces the deuteron electromagnetic form factor for $Q^2 \leq 1$ GeV$^2$ [16] and has been used successfully in describing the $\eta$ photoproduction [17].
The total vector meson photoproduction amplitude in the reaction $\gamma D \to V D$ reads

$$T_{M_1}^{D, M_1: \lambda_V \lambda_\gamma} = 2 \sum_{\alpha \beta} \langle M_f \lambda_V, \beta | T^a_{\beta \alpha; \lambda_V \lambda_\gamma} | M_i \lambda_\gamma, \alpha \rangle,$$  \hspace{1cm} (1)

where $M_i, M_f, \lambda_\gamma$, and $\lambda_V$ stand for the deuteron-spin projections of the initial and the final states, and helicities of the incoming photon and the outgoing vector meson, respectively. $T^a$ is the amplitude of the vector meson photoproduction from the isoscalar nucleon

$$T^a = \frac{1}{2} (T^p + T^n).$$  \hspace{1cm} (2)

The indices $\alpha$ and $\beta$ in Eq. (1) refer to all quantum numbers before and after the collision. For the ”elementary” photoproduction amplitudes $T^{p,n}$, we use the Pomeron-exchange contribution, pseudoscalar $\pi$ and $\eta$ exchange and direct and crossed $N$ and $N^*$ exchanged amplitudes shown in Fig. [1] and described in Refs. [7, 11]. Because of Eq. (2) the isovector $\pi$-exchange terms in the total amplitude are cancelled since $T_{\pi} = -T_{\pi}$.

![Fig. 2: Diagrammatic representation of vector meson photoproduction from nucleon: (a) Pomeron exchange contribution, (b) pseudoscalar $\pi$ and $\eta$ exchange and (c) direct and (d) crossed $N$ and $N^*$ exchanged processes.](image)

Using the standard decomposition of the deuteron state in terms of $s$ ($U_0$) and $d$ ($U_2$) wave functions, one can rewrite Eq. (1) in the explicit form

$$T_{M_1}^{D, M_1: \lambda_V \lambda_\gamma} (t) = 2 \sqrt{\pi} \sum L \gamma M_0 (\hat{q})$$

$$C_{M_1}^{L M_2} C_{M_2}^{L' M_L} C_{M_L}^{L' M_L} C_{M_L}^{L' M_L} C_{M_L}^{L' M_L} R_{L L' \lambda} (q^2)$$

$$U_{M_{1'}} U_{M_{1'}} R_{L L' (q^2)} T_{M_{1''} M_{1''}'; \lambda' \lambda_\gamma} (t),$$  \hspace{1cm} (3)

where $\hat{j} = \sqrt{j(j+1)}$, and the radial integral $R_{L L' \lambda}$ reads

$$R_{L L' \lambda} (q^2) = \int dr U_{L}(r) U_{L'}(r) j_{\lambda} (qr/2).$$  \hspace{1cm} (4)

Eq. (3) is simplified if one chooses the quantization axis along the transferred momentum $q$ and only keeps the spin/helicity conserving terms with the natural $T^N$ and unnatural $T^U$ parity exchange in the total amplitude

$$T_{M_1}^{DN, M_1: \lambda_V \lambda_\gamma} (t) = 2M_1 \lambda_\gamma \delta_{M_1} \lambda_\gamma T_{0}^{DN} (t).$$  \hspace{1cm} (5)

Here, $T_{0}^{DN} (t)$ is the scalar, spin-independent part of the amplitudes. Using Eq. (3) with Eq. (5), we get the following result for the natural and unnatural parity-exchange parts of the total amplitude

$$T_{M_1}^{DN, M_1: \lambda_V \lambda_\gamma} = 2 M_1 \lambda_\gamma \delta_{M_1} \lambda_\gamma (\delta_{\pm 1 M_1} S_{1}^{N} + \delta_{0 M_1} S_{0}^{N}) T_{0}^{DN},$$

$$T_{M_1}^{DU, M_1: \lambda_V \lambda_\gamma} = 2 M_1 \lambda_\gamma \delta_{M_1} \lambda_\gamma \delta_{\pm 1 M_1} S_{1}^{U} T_{0}^{DU}.$$  \hspace{1cm} (6)

The form factors $S_{M}^{N,U}$ are similar to the deuteron electromagnetic form factors. The form factors for the natural exchange amplitude $S_{1}^{N}$, correspond to the electric form factors, and are expressed as the combination of charge ($F_C = R_{000} + R_{220}$) and quadrupole ($F_Q = R_{120} - R_{222}/\sqrt{8}$) form factors. The form factor for the unnatural parity exchange amplitude $S_{1}^{U}$ is equal to the magnetic form factor $F_M = R_{000} - R_{220}/2 + \sqrt{2}R_{120} + R_{222}$. We thus write

$$S_{1}^{N} (q^2) = F_C (q^2) - \frac{1}{\sqrt{2}} F_Q (q^2),$$

$$S_{1}^{U} (q^2) = F_M (q^2),$$

$$S_{0}^{N} (q^2) = F_C (q^2) + \sqrt{2} F_Q (q^2).$$  \hspace{1cm} (7)

Note that the presentation of the total amplitude in Eq. (3) is valid at extremely small transferred momentum, when one can neglect spin-flip terms in the elementary amplitudes. Also it assumes the quantization axis is along $(\hat{q})$, for some spin observables it is chosen along the beam velocity in center of mass or in the vector meson rest frame (Gottfried-Jackson system), which in general, is different from the direction of $(\hat{q})$. These conditions are realized at forward $\phi$-photoproduction where the possible spin-flip diagrams in the $N$ and $N^*$ exchange processes are suppressed. In the case of the finite transferred momentum these simplification do not hold and one has to take into account all these effects and have to use the exact form in Eq. (3), which we have done in our numerical calculations.

Let us start from the $\phi$ photoproduction. Inspection of Eqs. (4) and (5) results in the following:

1. $T^D$ decreases with $-t$ much faster then elementary amplitude $T^a$, because the form factors $S_{M}^{N,U}$ decrease rapidly.

2. The elementary spin conserving amplitude $T^s$ generates the spin conserving $T^{U}$-amplitude.

3. Unnatural parity-exchange transitions are suppressed for the deuteron target with spin projection $M_t = 0$.

4. The form factors of the natural parity-exchange (Pomeron) amplitudes with spin polarization $M_{t,f} = \pm 1$ and $M_{t,f} = 0$ are different. Moreover, both of them are different from the unnatural parity-exchange form factor $S_{1}^{U}$. $S_{0}^{N}$ decreases much faster with $q^2$ than the form factors $S_{0}^{N}$. The form factor $S_{1}^{N}$ has a node at $q^2 \approx 0.5$ GeV$^2$. This difference is illustrated in Fig. [3] where we show the $q^2$ - dependence of $|S_{N,U}|^2$.

5. Contribution of the isovector $\pi$-exchange amplitude is strongly suppressed.

Item (1) is illustrated in Fig. 4, where the unpolarized differential cross sections for the $\gamma p \to \phi p$ and $\gamma D \to \phi D$
for $E_\gamma = 2.2$ GeV reactions are presented. One can see that the slope of $d\sigma^{\gamma D}/dt$ is steeper than that of $d\sigma^{\gamma p}/dt$ and the ratio of these cross sections at $|t| \sim 4$ GeV$^2$ is determined by the form factors $|S|^2(100)$ (cf. Fig. 3). The relative contribution of the unnatural-parity exchange (pseudoscalar-exchange) channel in the $\gamma D \to \phi D$ reaction is much smaller than those in the $\gamma p \to \phi p$ reaction, because it comes only from the $\eta$-meson exchange which is much smaller than the contribution of $\pi$-meson exchange in the $\gamma p \to \phi p$ reaction.

The other items 2 to 5 mentioned above, are important for the spin observables. Let us consider the $\phi$-meson decay asymmetry $\Sigma_{\nu = \phi}$, defined through the spin-density matrix $\rho_{\lambda\nu}^\phi$ [1]

$$\Sigma_{\nu} = \frac{\rho_{11}^{\phi} + \rho_{11}^{-1}}{\rho_{11}^{\phi} + \rho_{11}^{-1}}. \quad (8)$$

It has a definite value $\Sigma_{\nu} = +1(-1)$ for the natural (unnatural) parity-exchange amplitude, taken separately. Using this notation and Eq. (8) we can estimate $\Sigma_{\nu}$ and $\Sigma_0^D$ for $\gamma p$ and $\gamma D$ reactions, respectively, and investigate them simultaneously at $t \simeq t_{\text{max}}$

$$\Sigma_{\nu} \simeq 1 - 2|\alpha^\nu + \alpha^s|^2,$$

$$\Sigma_0^D \simeq 1 - 2|\alpha^s|^2 \frac{r_u^2}{2 + r_0^2} \simeq 1 - 0.67|\alpha^s|^2 \quad (9)$$

where $r_u^2 = (S_u^U/S_u^N)^2 \simeq 1.34$ and $r_0^2 = (S_0^U/S_0^N)^2 \simeq 2$; $\alpha^\nu, (\alpha^s)$ is the isovector (isoscalar) part of the unnatural parity-exchange amplitude relative to the dominant isoscalar natural parity-exchange amplitude in the $\gamma p$ reaction

$$\alpha^{(v,s)} = \frac{T_0^U(v,s)}{T_0^N(v,s)} e^{i\delta^{(v,s)}}, \quad (10)$$

and $\delta^{(v,s)}$ is the relative phase. In our case, $\alpha^v$ and $\alpha^s$ are identified with the strength of $\pi$ and $\eta$-exchange amplitudes with $|\alpha^s/\alpha^v| \ll 1$. This qualitative estimation is verified by the numerical calculation shown in Fig. 3. The deviation of $\Sigma_{\nu}$ from 1 for $\gamma D \to \phi D$ is very small as compared to the case of photoproduction from the proton. On the other hand, if there are some non-diffractive exotic channels [3, 4], which could generate an isoscalar unnatural parity-exchange amplitude with

$$|\alpha^s| = |\alpha^\text{exotic}| \sim |\alpha^v|, \quad (11)$$

the difference $\Sigma_{\nu}^0 - 1$ is finite and a combined analysis of $\Sigma_{\nu}^0$ and $\Sigma_0^D$ gives information on the ratio $|\alpha^\text{exotic}|/|\alpha^v|$ and the relative phase of $\alpha^s$ and $\alpha^v$.

Complementary information about $\alpha^s$ may be obtained from the double beam target asymmetries. For the circular polarized photon and polarized deuteron, we have three initial spin states with the total spin projection $J_z$; $\left( \uparrow \uparrow ; J_z = 2 \right)$ when the deuteron is polarized along the beam polarization, $\left( \downarrow \downarrow ; J_z = 0 \right)$ when the deuteron is polarized along the opposite direction to the beam polarization, and $\left( \uparrow \downarrow ; J_z = 1 \right)$ when the deuteron is polarized perpendicular to the beam polarization. In contrast to the $\gamma p$ reaction with only one beam target asymmetry between $J_z = \frac{1}{2}$ and $J_z = \frac{3}{2}$ total spin states, we have three beam-target asymmetries

$$C_{BT}^{21} = \frac{d\sigma(\uparrow \uparrow) - d\sigma(\uparrow \downarrow)}{d\sigma(\uparrow \uparrow) + d\sigma(\uparrow \downarrow)}$$

$$C_{BT}^{20} = \frac{d\sigma(\uparrow \downarrow) - d\sigma(\downarrow \downarrow)}{d\sigma(\uparrow \downarrow) + d\sigma(\downarrow \downarrow)}$$

$$C_{BT}^{10} = \frac{d\sigma(\uparrow \downarrow) - d\sigma(\downarrow \uparrow)}{d\sigma(\uparrow \downarrow) + d\sigma(\downarrow \uparrow)} \quad (12)$$

Since the amplitude of photoproduction from deuteron with a fixed spin state depends on the corresponding form factor $S$, and since these form factors are different for the natural and unnatural parity-exchange amplitudes,
we expect (i) a strong influence of the unnatural parity exotic component and (ii) a difference in behaviour and magnitude of the various beam-target asymmetries. Using Eq. (8) we can estimate the beam target asymmetries at \( t \approx t_{\text{max}} \) as follows

\[
C_{BT}^{21} \simeq \frac{1 - r_0^2}{1 + r_0^2} + 2|\alpha^s| |\xi| \frac{r_0}{1 + r_0^2} \simeq -0.33 + 0.77 |\alpha^s| |\xi|, \\
C_{BT}^{20} \simeq 2|\alpha^s| |\xi|, \\
C_{10}^{BT} = -C_{21}^{BT},
\]

(13)

where \( \xi = \cos \delta^s \). If \( |\alpha^s| = |\alpha^s| \ll |\alpha^s| \) one gets the different threshold behaviour of these two asymmetries

\[
C_{21}^{BT}(t_{\text{max}}) \simeq -0.33, \\
C_{21}^{BT}(t_{\text{max}}) \simeq 0.
\]

(14)

Our estimation agrees with the corresponding numerical calculation of \( C_{BT}^{21} \) and \( C_{BT}^{20} \), shown in Fig. 6, where \( \alpha_s \) is defined by the corresponding pseudoscalar and Pomeron exchange amplitudes described in [5]. This result can be considered as a "non-exotic" background for the \( \gamma D \to \phi D \) reaction. If any deviation from the predicted values are measured, the existence of an exotic isoscalar unnatural parity-exchange component will be confirmed. For the proton target, the corresponding estimation reads

\[
C_{BT}^{20}(t_{\text{max}}) \simeq 2(\alpha^v \cos \delta^v + \alpha^s \cos \delta^s).
\]

(15)

Therefore, the combined study of photoproduction from proton and deuteron can unambiguously fix the amplitudes of the exotic channels and also of the isovector channel.

The total cross section of the \( \gamma D \to \omega D \) reaction is predicted to strongly decrease as compared to the \( \gamma p \to \omega p \) reaction because the \( \pi \)-exchange amplitude, dominant in the nucleon case, is strictly suppressed for the deuteron. At \( E_\gamma \sim 2 \) GeV, the dominant channels would be the Pomeron exchange and the resonance excitations. Therefore, we expect that the cross section of \( \gamma D \to \omega D \) reaction is of the same order of magnitude as of the \( \gamma D \to \phi D \) reaction. In the calculation of the nucleon and the baryon resonances excitation channels, we have to use the isoscalar coupling constants \( g_{sNN} = (g_{pNN} + g_{nNN})/2 \) and \( g_{sNN} = (g_{pNN} + g_{nNN})/2, \) for the \( \gamma NN \) and \( \gamma NN^* \) interactions, respectively. In the present calculation, we include all the low-energy resonances, listed in the Particle Data Group using the effective-Lagrangian approach of Ref. [7].

Fig. 6 shows the result for the \( \gamma p \to \omega p \) and \( \gamma D \to \omega D \) reactions at \( E_\gamma = 1.92 \) GeV. The cross section of the \( \gamma D \to \omega D \) reaction is strongly suppressed and becomes comparable with the cross section of \( \phi \) meson photoproduction. We also see the dominance of the Pomeron exchange and strong suppression of the relative contribution of the unnatural parity-exchange part which stems from the \( \eta \)-exchange diagrams. This modification affects the \( \omega \) decay asymmetry, which is shown in Fig. 7a. The asymmetry changes drastically from a value of \(-0.9\) for the \( \gamma p \) reaction to \(+1\) for the \( \gamma D \) reaction at forward-angle photoproduction. Deviation from \(+1\) for the \( \gamma D \to \omega D \) reactions would be a strong indication for existence of an unnatural parity-exchange exotic non-diffractive channels. Effects of \( N^* \)-excitation are only 2-3% and therefore are not shown in in Fig. 7b.

![FIG. 7: (a): The \( \omega \) decay asymmetry for reactions \( \gamma p \to \omega p \) (dot-dashed line) and \( \gamma D \to \omega D \) (solid line). The results without including \( N^* \) are only 2-3% difference in both cases and therefore are not shown here. (b): Beam-target asymmetries \( C_{BT}^{21} \) and \( C_{BT}^{20} \) for the \( \gamma D \to \omega D \) reaction. \( E_\gamma = 1.92 \) GeV. The open circles show the results of calculation without \( N^* \)-channels.](image)

In summary, we have shown that the coherent \( \phi \) and \( \omega \)-meson photoproduction from the deuteron opens an unique opportunity to study the non-diffractive mechanisms with unnatural parity exchange exchanges, such as the \( s\bar{s} \)-knockout, anomalous Regge trajectories, and the spin-flip excitations of baryon resonances. For future experimental tests, we have presented predictions for various spin observables in Figs. 5 and 7.

Finally, we stress that the present investigation is a very first step. It would be important to study whether the meson-exchange currents and relativistic effects, which are known to be important in the processes...
with high-momentum transfers \([12, 18]\), are significant in the considered kinematical region.

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