Asymmetry in $\tilde{\omega}$ meson photoproduction and the phase of $\omega\pi\gamma$ coupling

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Abstract

We analyze the double polarization asymmetry of the $\omega$-meson photoproduction in the vector-meson–dominance model of diffractive production and the one-pion exchange model. We find that the longitudinal beam-target asymmetry is very sensitive to the real part of the diffractive photoproduction amplitude and to the sign of the $\omega\pi\gamma$ coupling because of the different spin structures of the amplitudes associated with the different mechanisms.

Key words: $\omega$ photoproduction; Polarization observables; Vector-meson dominance model; One-pion exchange model

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Most phenomenological models to the pion photoproduction include hadron resonances as explicit degrees of freedom in addition to the low energy theorem contributions [1–3] in order to explain the experimental data including resonance region. This inevitably leads us to the inclusion of the vector-meson degrees of freedom as well as the nucleon resonances. In some literature [2–4], it has been claimed that some physical quantities of the \( \pi^0 \) photoproduction depend on the phases of \( V_{\pi\gamma} \) coupling constants, where \( V \) stands for a vector-meson, and that it requires a special choice on the phases of \( g_{V\pi\gamma} \)'s to reproduce the experimental observation. This problem has been also raised from the meson exchange current contribution in the deuteron form factors [5] and proton-nucleon bremsstrahlung [6]. Actually, in this case one deals with the relative phase of the vector-meson exchanged amplitudes and the Born terms which is chosen often by the Gari and Hyuga convention [5]. However, these contributions are combined with other mechanisms and the present level of experimental accuracy does not allow us to fix the signs uniquely and the conclusion is still controversial. Thus an independent process that is directly proportional to the phase of the couplings will be useful to resolve this problem.

Another motivation of our study concerns with the real part of the vector-meson–dominance model (VDM) amplitude, which is related to the study of the strangeness content of the nucleon through the \( \phi \)-meson photoproduction from proton [7]. In Ref. [8] it is pointed out that the double polarization observables in \( \phi \) photoproduction may be used as a good probe for hidden strangeness in the proton. Although its effect is expected to be small, however, the interference between the real part of the VDM amplitude and the one-pion exchange model (OPE) amplitude may give some contribution to the asymmetries. Therefore, independent analyses on the real part of the VDM amplitude are highly desirable.

In this paper we propose to use the double polarization asymmetry of \( \omega \) photoproduction as a tool to resolve the above two issues. We will show that the beam–target double polarization asymmetry of \( \omega \) photoproduction is proportional to the product of \( g_{\omega\pi\gamma} \) and the real part of VDM amplitude and that the measurements of the asymmetry can give an information about the two quantities directly, because the real part of the VDM amplitude is strictly related to its imaginary part by the dispersion relation while the phase of the imaginary part is fixed by the unitarity condition. Throughout this paper, we restrict our consideration to the \( \omega\pi\gamma \) coupling because the asymmetries in the \( \rho \) photoproduction are expected much smaller because of the relatively small value of the \( \rho\pi\gamma \) coupling constant.

Following Ref. [9], we assume that, for the initial photon energy in a few GeV region, the total amplitude of vector-meson photoproduction process comes mainly from two sources: the vector-meson dominance model of diffractive production and the one-pion exchange model as depicted in Fig. 1. We define the kinematical variables as follows. The four-momenta of the incoming photon, outgoing \( \omega \), initial proton and final proton are \( k, q, p \) and \( p' \), respectively. In laboratory frame, we define \( k = (E_{kL}, \vec{k}_L), q = (E_{\omega L}, \vec{q}_L), p = (E_p^L, \vec{p}_L) \) and \( p' = (E_{p'}^L, \vec{p}'_L) \). The corresponding variables in CM system are defined as \( k = (\nu, \vec{k}), q = (E_{\omega}, \vec{q}), p = (E_p, -\vec{k}) \) and \( p' = (E_{p'}, -\vec{q}) \). We also use \( t = (p - p')^2 \) and \( s = (p + k)^2 \) with the nucleon mass \( M_N \), the \( \omega \)-meson mass \( M_\omega \) and the pion mass \( M_\pi \).

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Fig. 1. (a) Diffractive $\omega$-meson photoproduction within the vector-meson-dominance model by means of a Pomeron ($P$) exchange. (b) One pion exchange process in the $\omega$ photoproduction. The blob includes the direct $\omega\pi\gamma$ coupling and the $\omega\pi\rho$ coupling with $\rho\gamma$ vertex.

The diffractive $\omega$ photoproduction mechanism of VDM assumes that the incoming photon mixes into the $\omega$-meson and then scatters diffractively with the proton through an exchange of a Pomeron ($P$) [10]. Experimental observations for the vector-meson production, small-\(|t|\) elastic scattering and diffractive dissociation indicate that the Pomeron behaves rather like an isoscalar photon-like particle [11]. Although it is widely accepted that the Pomeron can be described in terms of non-perturbative two gluon exchange [12–15], in this paper we make use of the Pomeron–photon analogy, which is expected to be valid at low energy. Using the spin structure of the standard $VV\gamma$ coupling [16] for the $VV_P$ vertex, the invariant amplitude of the diffractive production process reads

$$T^{VDM}_{m_f,\lambda; m_i, \lambda\gamma} = i T_0 \bar{u}(p', m_f) \gamma_\alpha u(p, m_i) \varepsilon_{\mu}^{\lambda\omega}(\omega) \Gamma^{\alpha, \mu\nu} \varepsilon^{\lambda\gamma}(\gamma),$$

$$\Gamma^{\alpha, \mu\nu} = (k + q)^\alpha g_{\mu\nu} - k^\mu g_{\alpha\nu} - q^\mu g_{\alpha\nu},$$

(1)

where $m_i(f)$ is the spin projection of the initial (final) proton and $\lambda(\omega)$ is the helicity of the photon ($\omega$-meson). Here $T_0$ includes the dynamics of Pomeron-hadron interaction, $\varepsilon_{\mu}(\omega)$ and $\varepsilon_{\mu}(\gamma)$ are the polarization vectors of the $\omega$ and the photon, respectively, and $u(p)$ is the proton Dirac spinor. We use the form and parameters of $T_0$ determined from the parameterization [9],

$$\left(\frac{d\sigma}{dt}\right)_{VDM} = c \left(1 + \frac{d}{E_\gamma}\right) \exp(b_\omega t),$$

(2)

with $b_\omega = 6.7 \ GeV^{-2}$, $c = 9.3 \ \mu b/GeV^2$ and $d = 1.4 \ GeV$ which are determined from the experimental data at $\sqrt{s} = 2.8 \sim 9.7 \ GeV$ as in Ref. [9]. The phase of $T^{VDM}$ is assumed to be fixed by the optical theorem.

The relevant amplitude of the OPE diagram reads [17]
\[ T^{\text{OPE}}_{m_f,\omega;i,m_i,\lambda} = \frac{1}{t-M^2_\pi} g_{NN\pi} \tilde{g}_{\omega\pi\gamma} W^F_{m_f,m_i} W^B_{\lambda,\lambda}, \]

where

\[ W^F_{m_f,m_i} = \bar{u}(p', m_f) \gamma_5 u(p, m_i), \quad W^B_{\lambda,\lambda} = i\epsilon^{\mu\nu\alpha\beta} q_\mu k_\alpha \varepsilon^{\lambda_\omega}_\nu(\omega) \varepsilon^{\lambda_\gamma}_\beta(\gamma), \]

from the interaction Lagrangian,

\[ \mathcal{L}_{\omega\gamma\pi} = \tilde{g}_{\omega\pi\gamma} \epsilon^{\mu\nu\alpha\beta} \partial_\mu \omega_\nu \partial_\alpha A_\beta \pi^0, \]

with the photon field \( A_\alpha \). Direct calculation of \( W^F \) and \( W^B \) gives

\[ W^F_{m_f,m_i} = C \left\{ 2m_f (\alpha' \cos \theta - \alpha) \delta_{m_f,m_i} - \alpha' \sin \theta \delta_{m_f,-m_i} \right\}, \]

\[ W^B_{\lambda,\lambda} = -\nu \left\{ \lambda_\gamma (E_\omega - q \cos \theta) \tilde{\varepsilon}(\omega) \cdot \tilde{\varepsilon}(\gamma) + \frac{q \sin \theta}{\sqrt{2} M_\omega} (q - E_\omega \cos \theta) \delta_{\lambda,0} \right. \\
- \left. \frac{1}{2} \lambda_{\omega} q \sin^2 \theta \right\}, \]

where

\[ \tilde{\varepsilon}(\omega) \cdot \tilde{\varepsilon}(\gamma) = \left[ 1 + \left( \frac{E_\omega}{M_\omega} - 1 \right) \delta_{\lambda,0} \right] d^4_{\lambda',\lambda}(\theta), \]

with \( \theta \) the scattering angle in CM frame, \( q \equiv |q| \) and \( C = \sqrt{(\gamma_p + 1)(\gamma'_p + 1)/2} \). We use \( \gamma_p = E_p/M_N \) and \( \alpha = \sqrt{\gamma_p - 1}/(\gamma_p + 1) \) for the initial proton while \( \gamma'_p \) and \( \alpha' \) are defined in the same way for the final proton. Note that the OPE amplitude is pure real. We use \( g^2_{NN\pi}/4\pi = 12.562 \) and the effective coupling constant \( \tilde{g}_{\omega\pi\gamma} \) is determined from the decay of \( \omega \to (\rho\pi) \to \gamma\pi \) so that \( \tilde{g}^2_{\omega\pi\gamma} = 0.498 \text{ GeV}^{-2} \). Each vertex contains the Benecke-Dürr form factors as given in Refs. [17,18].

In the literature, the Pomeron exchange amplitude is mostly assumed to be pure imaginary [19]. In this approximation, OPE amplitude does not interfere with the VDM one in the cross section. However, if we assume the real part of the VDM amplitude, then it may interfere with the OPE amplitude. The real part of the VDM amplitude may be estimated using the subtracted dispersion relation for the amplitude \( f(s,t) \) normalized so that \( s\sigma_T = \text{Im} f(s,|t|_{\text{min}}) \) as in Ref. [20],

\[ \text{Ref}(s,t) = \frac{2g^2}{\pi} \text{P} \int_{s_{\text{min}}}^\infty \frac{ds'}{s'(s'^2 - s^2)} \text{Im} f(s',t), \]
which can be evaluated analytically to give a derivative relation in the limit of high energy. However, at finite energy region of our interest, we need to evaluate (9) in a numerical way. Since the parameterization of (2) is valid only in the limited region of energy and we have to integrate (9) over the whole region of $s$, we assume the standard $s$-dependence of the imaginary part as $f \sim s^{\alpha_P}$ with $\alpha_P \approx 1$ instead of using Eq. (2). This gives us the ratio $\mathcal{R} \equiv \text{Re} f(s,t)/\text{Im} f(s,t) = 0.12 \sim 0.087$ at $E_\gamma = 2 \sim 3$ GeV. The idea of this paper is to extract the value of $\mathcal{R}$ from the measurement of the polarization observables. So in our qualitative estimation we take $\mathcal{R} = 0.1$ and we write the real part of the VDM amplitude as

$$\text{Re} T_{f,i}^{\text{VDM}} = \mathcal{R} \text{Im} T_{f,i}^{\text{VDM}}.$$  
(10)

The VDM amplitude will be renormalized by multiplying $1/\sqrt{1 + \mathcal{R}^2}$. Since $\mathcal{R}$ is around 0.1, the contribution from the real part of VDM amplitude to the differential cross section is only about 1% of that of the imaginary VDM amplitude, which makes it hard to disentangle the real part of VDM amplitude from the cross section measurements. It should be kept in mind that this relation is valid only at $|t| \rightarrow |t|_{\text{min}}$ (or $\theta \rightarrow 0$) that is the most interesting region where the cross section is at maximum. However, for our qualitative analysis we will assume this relation for the whole region of $t$ [21]. We also assume the constant value of $\mathcal{R}$ at low energy although it is a function of $s$ in general.

It is, then, straightforward to obtain the corresponding amplitudes in helicity basis with the relation [22,23],

$$H_{\lambda_f,\lambda_\omega;\lambda_i,\lambda_\gamma} = (-1)^{1-\lambda_i-\lambda_f} \sum_{m_i,m_f} d_{m_i,-\lambda_i}^{1/2}(0) \ d_{m_f,-\lambda_f}^{1/2}(\theta) \ T_{m_f,\lambda_\omega;m_i,\lambda_\gamma};  \hspace{1cm} (11)$$

where $\lambda_{i,f}$ are the helicity of the target and recoil proton, respectively. Analyses of the amplitudes show that at small $|t|$ their dominant parts have the spin/helicity conserving form as

$$\text{Im} H_{\lambda_\omega,\lambda_f;\lambda_i,\lambda_\gamma}^{\text{VDM}} = M_0^{\text{VDM}} \delta_{\lambda_\omega,\lambda_i} \delta_{\lambda_f,\lambda_\gamma};  \hspace{1cm} (12)$$
$$H_{\lambda_\omega,\lambda_f;\lambda_i,\lambda_\gamma}^{\text{OPE}} = 2\lambda_i\lambda_\gamma M_0^{\text{OPE}} \delta_{\lambda_\omega,\lambda_\gamma} \delta_{\lambda_i,\lambda_f};  \hspace{1cm} (13)$$

where

$$M_0^{\text{VDM}} \simeq -2\bar{q}CT_0(1 + \alpha\alpha'),$$
$$M_0^{\text{OPE}} \simeq -\frac{\nu(E_\omega - |\bar{q}|)}{t - M_{\pi}^2} g_{NN\pi} \tilde{g}_{\omega\pi\gamma}. \hspace{1cm} (14)$$

The qualitative difference between (12) and (13) lies on the existence of the additional phase factor $2\lambda_i\lambda_\gamma$ in (13) that comes from the $NN\pi$ coupling and the magnetic structure of the $\omega\pi\gamma$ interaction. This factor plays an important role in the longitudinal double polarization asymmetry $L_{BT}$ for the circularly polarized photon beam defined as
Fig. 2. Unpolarized $\omega$ photoproduction cross sections at two photon energies, (a) $E^L_\gamma = 2.8$ GeV and (b) 4.7 GeV. The dotted and dot-dashed lines correspond to the OPE and VDM contributions, respectively, and the solid lines are the total differential cross section. The experimental data are taken from [9].

$$L_{BT} = \frac{d\sigma_{\mp} - d\sigma_{\mp}}{d\sigma_{\mp} + d\sigma_{\mp}},$$  \hspace{1cm} (15)$$

where $d\sigma_{\mp}$ ($d\sigma_{\mp}$) represents $d\sigma/dt$ for the parallel (anti-parallel) helicity states of the target and the photon beam. Near the forward scattering region, therefore, we have

$$L_{BT} \simeq \frac{|iM_0^{VDM} + RM_0^{VDM} - M_0^{OPE}|^2 - |iM_0^{VDM} + RM_0^{VDM} + M_0^{OPE}|^2}{|iM_0^{VDM} + RM_0^{VDM} - M_0^{OPE}|^2 + |iM_0^{VDM} + RM_0^{VDM} + M_0^{OPE}|^2} \simeq -2 \mathcal{R} \eta_\omega \sqrt{\frac{d\sigma^{OPE} d\sigma^{VDM}}{d\sigma^{tot}}},$$  \hspace{1cm} (16)$$

for small value of $\mathcal{R}$, where $\eta_\omega$ is the sign of $\tilde{g}_{\omega\pi\gamma}$ and $d\sigma^{OPE}$ denotes the differential cross section $d\sigma/dt$ of OPE, etc. This shows that $L_{BT}(\theta = 0)$ vanishes when $\mathcal{R} = 0$ and its sign is directly related to the phase $\eta_\omega$. 

Results of our calculation are shown in Figs. 2 and 3. Shown in Fig. 2 are the unpolarized cross sections at two initial photon energies, 2.8 and 4.7 GeV, with the experimental data from Ref. [9]. One can find that the VDM and OPE channels have the same order of magnitude at smaller $E^L_\gamma$ and similar $t$-dependence so that they cannot be distinguished easily from the comparison with the data. Furthermore, the dependence of the cross section on the phase $\eta_\omega$ is negligible because of small value of $\mathcal{R}$. Predictions for the double polarization asymmetry $L_{BT}$ in the model of VDM and OPE are shown in Fig. 3. Its $t$-dependence is given in Fig. 3(a) with the initial photon energy $E^L_\gamma = 2.8$ GeV, where the solid line shows the prediction with the pure imaginary VDM amplitude (and with OPE) and the dotted (dot-dashed) line corresponds to $\eta_\omega = +1 \ (-1)$ including the real part of the VDM amplitude with $\mathcal{R} = 0.1$. It shows the non-monotonic behavior and some enhancement at small $|t|$. In
Fig. 3. Double polarization asymmetry $L_{BT}$: (a) $t$-dependence at fixed energy $E^L_\gamma = 2.8$ GeV. The solid line is the result without Re $T^{VDM}$ and the dotted (dot-dashed) line is for $\eta_\omega = +1 (-1)$ with Re $T^{VDM}$ when $R = 0.1$. (b) $E^L_\gamma$-dependence at $|t| = |t|_{\min}$ (i.e., $\theta = 0$) with various $R$ for $\eta_\omega = -1$. The results for $\eta_\omega = +1$ can be obtained by changing the sign of $L_{BT}(\theta = 0)$. The OPE amplitude is included in all graphs.

In summary, we find that the double polarization asymmetry $L_{BT}$, especially at forward scattering region, is very sensitive to the real part of the VDM diffractive photoproduction amplitude and the phase of the $\omega\pi\gamma$ coupling constant. This indicates that the both ($R$ and $\eta_\omega$) can be directly extracted from the double polarization measurements. Since the asymmetry decreases with increasing photon energy, the optimal initial photon laboratory energy would be less than 5 GeV. The currently available experimental data [9] are not sufficient for their estimates and new experiments are strongly favored in the new facilities at the photon energy region of $2 \sim 4$ GeV (see, e.g., Ref. [24]). At theoretical side, further refinement of the photoproduction mechanisms is also required. For example, we need more precise information of the VDM amplitude to determine the sign and magnitude of $R$ in a more realistic way, because it depends on the energies and the parameterization of the imaginary VDM amplitude [25]. It would be also interesting to study the final state interactions, which can contribute to the polarization observables at this energy region. Finally, the phase fixing of OPE amplitude in this manner can give a clue to the phase problem of pion photoproduction [2–4].

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References

[1] M.G. Olsson and E.T. Osypowski, Nucl. Phys. B 87 (1975) 399; Phys. Rev. D 17 (1978) 174.
[2] H. Garcilazo and E. Moya de Guerra, Nucl. Phys. A 562 (1993) 521.
[3] T. Feuster and U. Mosel, Nucl. Phys. A 612 (1997) 375.
[4] I.-T. Cheon, in: Proc. of the Circum-Pan-Pacific Workshop on High Energy Spin Physics ’96, (Kobe, Oct. 1996), eds. T. Morii and S. N. Mukherjee (Kobe Univ., Kobe, 1997) p. 69.
[5] M. Gari and H. Hyuga, Nucl. Phys. A 264 (1976) 409; P. Sarriguren, J. Martorell and D.W.L. Sprung, Phys. Lett. B 228 (1989) 285.
[6] J.A. Eden and M.F. Gari, Phys. Lett. B 347 (1995) 187; M. Jetter and H.W. Fearing, Phys. Rev. C 51 (1995) 1666.
[7] A.I. Titov, S.N. Yang and Y. Oh, Nucl. Phys. A 618 (1997) 259.
[8] A.I. Titov, Y. Oh and S.N. Yang, Phys. Rev. Lett. 79 (1997) 1634; A.I. Titov, Y. Oh, S.N. Yang and T. Morii, (in preparation).
[9] J. Ballam et al., Phys. Rev. D 7 (1973) 3150.
[10] T.H. Bauer, R.D. Spital, D.R. Yennie and F.M. Pipkin, Rev. Mod. Phys. 50 (1978) 261, (E) 51 (1979) 407; D.G. Cassel et al., Phys. Rev. D 24 (1981) 2787.
[11] A. Donnachie and P.V. Landshoff, Nucl. Phys. B 244 (1984) 322.
[12] A. Donnachie and P.V. Landshoff, Phys. Lett. B 185 (1987) 403; Nucl. Phys. B 311 (1988/89) 509.
[13] J.R. Cudel, Nucl. Phys. B 336 (1990) 1.
[14] S.V. Goloskokov, Phys. Lett. B 315 (1993) 459.
[15] J.-M. Laget and R. Mendez-Galain, Nucl. Phys. A 581 (1995) 397.
[16] J.D. Bjorken and S.D. Drell, Relativistic quantum mechanics, Vol. I (McGraw-Hill, New York, 1964).
[17] P. Joos et al., Nucl. Phys. B 122 (1977) 365.
[18] J. Benecke and H.P. Dürr, Nuovo Cim. 56A (1968) 269.
[19] G.L. Kane and A. Seidl, Rev. Mod. Phys. 48 (1976) 309.
[20] J.B. Bronzan, G.L. Kane and U.P. Sukhatme, Phys. Lett. B 49 (1974) 272.
[21] See also J. Dias de Deus, Nuovo Cim. 28A (1975) 114.
[22] M. Jacob and G.C. Wick, Ann. Phys. (N.Y.) 7 (1959) 404.
[23] C. Bourrely, E. Leader and J. Soffer, Phys. Rep. 59 (1980) 95; M. Pichowsky, Ç. Savkli and F. Tabakin, Phys. Rev. C 53 (1996) 593.
[24] M. Fujiwara, in Proposal of “Laser-Electron $\gamma$-ray Facility in SPring-8”, RCNP (1996), unpublished.

[25] D.P. Sidhu and U.P. Sukhatme, Phys. Rev. D 11 (1975) 1351.