Associative photoproduction of Roper resonance and ω meson

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Associative photoproduction of ω meson and $N^*(1440)$ on nucleons, $\gamma+N\rightarrow\omega+N^*(1440)$, in the near threshold region is investigated in a framework employing effective Lagrangians. Besides π exchange in the t channel, baryon exchanges, i.e., N and N^* exchanges, in the s and u channels are also taken into account in calculations of differential cross section and beam asymmetry. Important inputs of this model are the vector and tensor coupling constants of $\omega NN^*(1440)$ vertex, which are assumed to be equal to the values of these couplings for ωNN vertex. Using our previous estimation of ωNN coupling constants obtained from a fit to available experimental data on photoproduction of ω meson in the near threshold region, we produce the necessary numerical predictions for different observables in $\gamma+N\rightarrow\omega+N^*(1440)$. Numerical results show that at low $|t|$ dominant contribution comes from t channel π exchange while the effects of nucleon and $N^*(1440)$ pole terms can be seen at large $|t|$. Our predictions for the differential cross section and beam asymmetry for the processes $\gamma+N\rightarrow\omega+N^*(1440)$, where N is proton and neutron, at $E_\gamma=2.5$ GeV are presented with zero width approximation and also with the inclusion of width effects of $N^*(1440)$.

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I. INTRODUCTION

Baryon resonances, in particular the Roper resonance $N^*_{1/2,1/2}(1440)$, have a special interest at the moment from the theoretical and experimental points of view. $N^*(1440)$ is the first excited state of a nucleon with a broad full width of 350 ± 100 MeV, which is twice as compared to those of the neighboring resonances $N^*(1520)$ and $N^*(1535)$ [1]. Although the Roper resonance was discovered first during the phase shift analysis of π-N scattering [2], it has not been observed directly yet. Some quark [3–7] and bag models [8,9] try to explain its nature, but it is still not well known. Photoproduction of vector mesons in a particular channel, where the target nucleon is excited to Roper resonance, $\gamma+N\rightarrow V+N^*(1440)$, might provide supplementary knowledge about this resonance and its couplings to meson-nucleon channels.

In order to extract information on Roper resonance from associative production of vector mesons and $N^*(1440)$, it is essential to understand the production mechanisms. Since Roper resonance has quantum numbers (spin 1/2, isospin 1/2, and positive parity) similar to those of a nucleon, the corresponding dynamics of the associative photoproduction of vector mesons and $N^*(1440)$, $\gamma+N\rightarrow V+N^*(1440)$, can be studied analogously to that of the "elastic" vector meson photoproduction, $\gamma+N\rightarrow V+N$. Theoretical studies on photoproduction of neutral vector mesons [10–19] involve different combinations of the following mechanisms: (i) pseudoscalar (π,η) and scalar (σ) meson exchanges in the t channel; (ii) one-nucleon exchange in the $(s+u)$ channel; (iii) the Pomeron exchange in the t channel.

In Ref. [20], the associative neutral vector meson (ρ and ω) and $N^*(1440)$ production near threshold in γp interaction has been analyzed within an approach based on the tree level diagrams of the t channel π and σ exchanges and effective Lagrangians. For such exchanges, although it is possible to obtain some constraints on $\pi NN^*(1440)$ and $\sigma NN^*(1440)$ couplings, measurement of above reactions with linearly polarized photon will be more decisive. Considering both these mechanisms alone will also result in trivial polarization phenomena that can be predicted without the knowledge of exact values of coupling constants and phenomenological form factors. For example, the beam asymmetry Σ induced by the linear polarization of the photon beam, and all possible T-odd polarization observables as such, for example, target asymmetry or polarization of final proton produced in collisions of unpolarized particles, will be zero identically for any kinematical conditions of the considered reaction. Analogously, it is possible to predict that $\rho_{11}=1$, and all other elements of the ρ-meson density matrix must be zero. Evidently, contributions other than the above mechanisms should be estimated to assess the relevance of the proposed measurement.

In consideration of other mechanisms, one problem that must be stressed is the applicability of Pomeron exchange in the near threshold region. In accordance with resonance-Reggeon duality [21], at low energies sum of the resonance contributions in the s channel can be effectively described by the different t channel Reggeon (but not by the Pomeron). Thus, we face a double counting problem when the s channel resonance contributions and the t channel exchanges are considered simultaneously [22], and therefore division of threshold amplitude into resonance and background cannot be done in a unique way. In this respect, Born contributions to $\gamma+N\rightarrow V+N^*(1440)$ must be considered as background.

Complex spin structure in matrix elements of the reaction $\gamma+N\rightarrow\omega+N^*(1440)$ as compared with the pseudoscalar meson photoproduction on nucleon, has been a barrier to go further to include the resonances. For example, for the spin $J\geqslant3/2$ case, there are six independent multipole amplitudes with six unknown coupling constants different from zero and a large number of nucleon resonances N^* in the considered reaction. Therefore, the effects of each resonance cannot be considered with good accuracy. The determination of $VN^*N^*(1440)$ is also another problem in consideration of resonance mechanisms of these reactions because there is no information directly available from experiments. Without having the polarization data with polarized beam, polarized target, and the measurements on polarization properties of final vector meson for the $\gamma+N\rightarrow\omega+N^*(1440)$ reaction, the inclusion of resonance mechanisms does not seem suitable for the analysis of these reactions.

In the present work, we investigate the role played by the $(s+u)$ channel $[\mathrm{N}+N^*(1440)]$ exchanges, $\gamma+N\rightarrow\omega+N^*(1440)$, in the associative photoproduction of ω meson and Roper resonance in the near threshold region ($E_\gamma<3$ GeV). Our model contains $[\mathrm{N}+N^*(1440)]$ exchange mechanisms together with the π exchange but without Pomeron exchange. The advantage of this model compared to the oversimplified π exchange model is that it allows one to find nonzero values for the polarization observables, which are in T-even character, such as beam asymmetry Σ induced by linear photon polarization, and density matrix elements of the vector meson produced in polarized and unpolarized particles. In the proposed model it is also possible to discriminate the isotopic spin effects in observables on proton and neutron targets due to $\pi\otimes N$ interference and different N contributions.

The paper is organized as follows. In Sec. II we give the model independent formalism for the calculation of differential cross section and beam asymmetry and describe our model in the framework of exchange mechanisms. The results of our calculations for the differential cross section and beam asymmetry are presented and are discussed in Sec. III. In the last section conclusions extracted from the discussion of our results are given with a few remarks.

II. FORMALISM AND MODEL

Calculations of different observables for the associative photoproduction $\gamma+N\rightarrow N^*+\omega$ are performed by using the formalism of so-called transversal amplitudes in the center of mass system (CMS) of the considered reaction. The advantage of this formalism is that it is effective for the analysis of polarization phenomena in photoproduction reactions.

The matrix element of any photoproduction mechanism can be written in terms of 12 independent transversal amplitudes as

$$\mathcal{M}=\varphi_2^\dagger\mathcal{F}\varphi_1,$$

$$\begin{aligned}\mathcal{F}=&\,if_1(\vec{\varepsilon}\cdot\hat{\vec{m}})(\vec{U}\cdot\hat{\vec{m}})+if_2(\vec{\varepsilon}\cdot\hat{\vec{m}})(\vec{U}\cdot\hat{\vec{k}})+if_3(\vec{\varepsilon}\cdot\hat{\vec{n}})(\vec{U}\cdot\hat{\vec{n}})\\&+(\vec{\sigma}\cdot\hat{\vec{n}})[f_4(\vec{\varepsilon}\cdot\hat{\vec{m}})(\vec{U}\cdot\hat{\vec{m}})+f_5(\vec{\varepsilon}\cdot\hat{\vec{m}})(\vec{U}\cdot\hat{\vec{k}})\\&+f_6(\vec{\varepsilon}\cdot\hat{\vec{n}})(\vec{U}\cdot\hat{\vec{n}})]+(\vec{\sigma}\cdot\hat{\vec{m}})[f_7(\vec{\varepsilon}\cdot\hat{\vec{m}})(\vec{U}\cdot\hat{\vec{n}})\\&+f_8(\vec{\varepsilon}\cdot\hat{\vec{n}})(\vec{U}\cdot\hat{\vec{m}})+f_9(\vec{\varepsilon}\cdot\hat{\vec{n}})(\vec{U}\cdot\hat{\vec{k}})]\\&+(\vec{\sigma}\cdot\hat{\vec{k}})[f_{10}(\vec{\varepsilon}\cdot\hat{\vec{m}})(\vec{U}\cdot\hat{\vec{n}})+f_{11}(\vec{\varepsilon}\cdot\hat{\vec{n}})(\vec{U}\cdot\hat{\vec{m}})\\&+f_{12}(\vec{\varepsilon}\cdot\hat{\vec{n}})(\vec{U}\cdot\hat{\vec{k}})],\end{aligned}\qquad(1)$$

where $\hat{\vec{k}}$, $\hat{\vec{n}}$, and $\hat{\vec{m}}$ are defined as $\hat{\vec{k}}=\vec{k}/|\vec{k}|$, $\hat{\vec{n}}=\vec{k}\times\vec{q}/|\vec{k}\times\vec{q}|$, $\hat{\vec{m}}=\hat{\vec{n}}\times\hat{\vec{k}}$, $\vec{k}$ and $\vec{q}$ are the three-momentum of the photon and the vector meson in CMS, respectively, φ_1 (φ_2) is the two-component spinor for initial nucleon (final Roper resonance), and transversal amplitudes f_i, $i=1,\ldots,12$, are complex functions of s and t, $f_i=f_i(s,t)$.

Differential cross section and beam asymmetry are given by

$$\frac{d\sigma}{d\Omega}=\frac{1}{2}\mathcal{N}\overline{\mathcal{F}\mathcal{F}^\dagger}\qquad(2)$$

and

$$\Sigma=\frac{d\sigma_\parallel/d\Omega-d\sigma_\perp/d\Omega}{d\sigma_\parallel/d\Omega+d\sigma_\perp/d\Omega},\qquad(3)$$

where $\mathcal{N}=|\vec{q}|/64\pi^2s|\vec{k}|$ and $d\sigma_\parallel/d\Omega$ ($d\sigma_\perp/d\Omega$) is the differential cross section induced by a photon whose polarization is parallel (perpendicular) to the reaction plane in which all other particles in the initial and final states are unpolarized. The corresponding differential cross section and beam asymmetry, which are obtained by using Eqs. (1), (2), and (3), can be written in terms of transversal amplitudes f_i:

$$\frac{d\sigma}{d\Omega}=\mathcal{N}(h_1+h_2),$$

$$\Sigma=\frac{(h_1-h_2)}{(h_1+h_2)},$$

$$\begin{aligned}h_1=\frac{1}{2}\Bigg\{&[|f_1|^2+|f_2|^2+|f_4|^2+|f_5|^2+|f_7|^2+|f_{10}|^2]\\&+\left[\frac{|\vec{q}|^2\sin^2\theta}{m_v^2}\right][|f_1|^2+|f_4|^2]+\left[\frac{|\vec{q}|^2\cos^2\theta}{m_v^2}\right][|f_2|^2+|f_5|^2]\\&+\left[\frac{|\vec{q}|^2 2\sin\theta\cos\theta}{m_v^2}\right]\mathrm{Re}[(f_1f_2^*)+(f_4f_5^*)]\Bigg\},\end{aligned}$$

$$\begin{aligned}h_2=\frac{1}{2}\Bigg\{&[|f_2|^2+|f_6|^2+|f_8|^2+|f_9|^2+|f_{11}|^2+|f_{12}|^2]\\&+\left[\frac{|\vec{q}|^2\sin^2\theta}{m_v^2}\right][|f_8|^2+|f_{11}|^2]+\left[\frac{|\vec{q}|^2\cos^2\theta}{m_v^2}\right][|f_9|^2\\&+|f_{12}|^2]+\left[\frac{|\vec{q}|^2 2\sin\theta\cos\theta}{m_v^2}\right]\mathrm{Re}[(f_8f_9^*)+(f_{11}f_{12}^*)]\Bigg\},\end{aligned}\qquad(4)$$

where m_v is the mass of the vector meson, θ is the angle between $\vec{k}$ and $\vec{q}$ in CMS, and h_1 and h_2 are the structure functions of the considered reaction.

Due to the large width of Roper resonance, width effects must be included in the calculation of $\gamma p\rightarrow\omega N^*(1440)$ reaction near threshold. We introduce these effects by the Breit-Wigner parametrization as

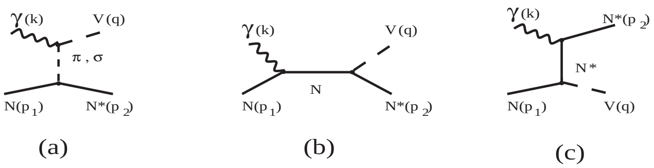

FIG. 1. Mechanisms of the model for associative photoproduction of Roper resonance and ω photoproduction: (a) t channel exchanges, (b) and (c) s and u channel nucleon exchanges.

$$\frac{d\sigma}{d\Omega}[\gamma p \to \omega N^*(1440) \to \omega \pi^0 p] = \int_{m_{\pi^0}+m_p}^{M_{N^*}^{max}(s,t)} \frac{d\sigma}{dt}[\gamma p \to \omega N^*(1440)] B(M_{N^*}) dM_{N^*} \tag{5}$$

in which $M_{N^*}^{max}$ is the maximum mass of the Roper resonance for fixed s and t, and $B(M_{N^*})$ is the Breit-Wigner function in the form

$$B(M_{N^*}) = \frac{2}{\pi} \frac{M_{N^*} M_{N^*}^0 \Gamma_{N^*(1440)\to \pi^0 p}(M_{N^*})}{(M_{N^*}^{02} - M_{N^*}^2)^2 + M_{N^*}^{02} \Gamma_{N^*(1440)}^2 (M_{N^*})}. \tag{6}$$

Energy dependent partial and total widths are given by

$$\Gamma_{N^*(1440)\to\pi^0 p}(M_{N^*}) = \Gamma_{N^*(1440)\to\pi^0 p}(M_{N^*}^0) \times \frac{M_{N^*}^0}{M_{N^*}} \left[\frac{E(M_{N^*}-M_N)}{E(M_{N^*}^0 - M_N)}\right] \frac{p[E(M_{N^*})]}{p[E(M_{N^*}^0)]} \tag{7}$$

and

$$\Gamma_{N^*(1440)}^{tot}(M_{N^*}) = \Gamma_{N^*(1440)}(M_{N^*}^0) \times \frac{M_{N^*}^0}{M_{N^*}} \left[\frac{E(M_{N^*}-M_N)}{E(M_{N^*}^0 - M_N)}\right] \frac{p[E(M_{N^*})]}{p[E(M_{N^*}^0)]}, \tag{8}$$

where $E(M_{N^*})$ and $p[E(M_{N^*})]$ are the energy and three-momentum of M_{N^*} in the rest frame of decay $N^*(1440) \to \pi N$. We use the values for $\Gamma_{N^*(1440)\to\pi^0 p}(M_{N^*}) = 76$ MeV and $\Gamma_{N^*(1440)}^{tot}(M_{N^*}^0) = 350$ MeV [1].

The suggested model for the reaction $\gamma + N \to \omega + N^*(1440)$ contains t, s, and u channel exchange mechanisms, which are shown in Fig. 1. Following the discussion of Ref. [19], we consider only the π exchange mechanism in the t channel. The matrix element for this exchange mechanism can be written as

$$\mathcal{M}_t = e \frac{g_{\omega\pi\gamma}}{m_\omega} \frac{g_{\pi NN^*}}{t - m_\pi^2} F_{\pi NN^*}(t) F_{\omega\pi\gamma}(t) [\overline{u}(p_2)\gamma_5 u(p_1)] \times (\epsilon^{\mu\nu\alpha\beta} \varepsilon_\mu k_\nu U_\alpha q_\beta), \tag{9}$$

where $t = (k-q)^2$, $m_\omega(m_\pi)$ is the mass of the $\omega(\pi)$ meson, $\varepsilon_\mu(U_\mu)$ is the polarization four-vector of photon (vector meson), $u(p_1)[u(p_2)]$ is the Dirac spinor for the initial nucleon (final Roper resonance), and $g_{\pi NN^*}$ and $g_{\omega\pi\gamma}$ are the strong and electromagnetic coupling constants of the $\pi NN^*(1440)$ and $\omega\pi\gamma$ vertices, respectively. Notation of particle four-momenta is given in Fig. 1. Form factors that appear in the above matrix element are of the form

$$F_{\pi NN^*}(t) = \frac{\Lambda_{\pi NN^*}^2 - m_\pi^2}{\Lambda_{\pi NN^*}^2 - t}, \quad F_{\omega\pi\gamma}(t) = \frac{\Lambda_{\omega\pi\gamma}^2 - m_\pi^2}{\Lambda_{\omega\pi\gamma}^2 - t}, \tag{10}$$

where $\Lambda_{\pi NN^*}(\Lambda_{\omega\pi\gamma})$ is the cutoff parameter of the considered vertices in pole diagrams.

The nucleon s channel contribution is described by the following amplitude:

$$\mathcal{M}_s = \frac{e}{s - M^2} \overline{u}(p_2) \left(g_{\omega NN^*}^V \hat{U} + \frac{g_{\omega NN^*}^T}{(M+M^*)} \hat{U}\hat{q} \right) \times (\hat{p}_1 + \hat{k} + M) \left(Q_N \hat{\varepsilon} - \frac{\kappa_N}{2M} \hat{\varepsilon}\hat{k} \right) u(p_1), \tag{11}$$

where $\varepsilon \cdot k = U \cdot q = 0$, $\hat{a} = \gamma^\mu a_\mu$, M (M^*) is the mass of the initial nucleon (final Roper resonance), $Q_N = 1$ (0) is the electric charge for the proton (neutron), $\kappa_N = 1.79$ (-1.91) is the anomalous magnetic moment for the proton (neutron). Different from the nucleon exchange in the s channel amplitude, Roper resonance exchange in the u channel amplitude is considered, which is given by

$$\mathcal{M}_u = \frac{e}{u - M^{*2}} \overline{u}(p_2) \left(Q_N \hat{\varepsilon} - \frac{\kappa_N^*}{2M^*} \hat{\varepsilon}\hat{k} \right) (\hat{p}_2 - \hat{k} + M^*) \times \left(g_{\omega NN^*}^V \hat{U} + \frac{g_{\omega NN^*}^T}{(M+M^*)} \hat{U}\hat{q} \right) u(p_1), \tag{12}$$

where $u = (k - p_2)^2$, κ_N^* is the anomalous magnetic moment of Roper resonance $N^*(1440)$. Neglecting their possible dependence on the virtuality in s and u of the intermediate nucleon and Roper resonance, $g_{\omega NN^*}^V$ and $g_{\omega NN^*}^T$ (vector and tensor coupling constants) are chosen to be the same in both channel matrix elements.

For s and u channel amplitudes it is possible to dress the form factors with s and u dependencies either in the form of $F(s)$ and $F(u)$ or $F(s,u)$. Use of the form factor as in the first case causes the violation of the gauge invariance. Even if the latter form preserves the gauge invariance, this type of phenomenological form factor [23], being the function of both Mandelstam variables, behaves like an amplitude rather than a form factor. Therefore, following the prescription of

Ref. [24], we use the constant form factors $F(s)=F(u)=1$. In this case the effects are absorbed by the coupling constants $g^V_{\omega NN*}$ and $g^T_{\omega NN*}$ of $\omega NN^*(1440)$ vertices.

Let us note that these couplings are free parameters of our model and their values must be different from the values in spacelike region of the vector meson momentum. In literature the values of the $g^V_{\omega NN*}$ and $g^T_{\omega NN*}$ coupling constants are obtained from the reactions $N+N\to N^*+N$ and $N^*+N\to N+N$ [25] following arguments of Ref. [26]. However, the values of such coupling constants obtained from the NN and NN^* potentials will be different from those of the coupling constants used in the associative photoproduction of ω meson and Roper resonance because they are considered in different regimes, spacelike in the first case whereas timelike in the latter case. Another approach in the calculation of transition couplings for a virtual meson is suggested in the framework of constituent quark model [27], but the values obtained are suggestive rather than being definite quantitative predictions. At this stage determining the values of $\omega NN^*(1440)$ coupling constants is also not possible due to the fact that there are no direct experimental data on these coupling strengths. To overcome this problem we assume that the values of $\omega NN^*(1440)$ coupling constants are equal to those of ωNN coupling constants. With this assumption it is possible to determine the values of these constants from the fit to experimental data on the differential cross section for the photoproduction of ω meson [28].

III. RESULTS AND DISCUSSION

In the preceding section, we have defined all the necessary parameters in t, s, and u channel amplitudes of our model for the process $\gamma+N\to\omega+N^*(1440)$. Let us specify here in more detail the coupling strengths and cutoff parameters of the considered model. For the coupling constant $g_{\omega\pi\gamma}$ we take the most commonly used value 1.82 [19] obtained from the experimental partial decay width of $\omega\to\pi\gamma$ decay. The situation is, however, not clear for coupling strength of $\pi NN^*(1440)$ vertex. Because of the large uncertainty in the partial decay width of $N^*(1440)$ into the $N\pi$ channel (228 ± 82) MeV the coupling constant $g_{\pi NN*}$ cannot be determined precisely. Following Ref. [20] we will use the value 3.4 for $g_{\pi NN*}$.

The remaining inputs of our model are the $\omega NN^*(1440)$ coupling constants and cutoff parameters Λ_i. In consideration of the coupling constants not only their absolute values but also their relative signs are important because of the essential interference effects. Cutoff parameters are in any case positive and by convention $g_{\omega\pi\gamma}g_{\pi NN*}$ is chosen as positive. Therefore, the signs of $g^V_{\omega NN*}$ and $g^T_{\omega NN*}$ that appear in our results are their relative signs with respect to the π contribution, and not their absolute signs. Since the applicability of the same form factor for different processes is not proved rigorously we can fix absolute values of cutoff parameters at some plausible values. Consequently, we are left with two fitting parameters $g^V_{\omega NN*}$ and $g^T_{\omega NN*}$.

For our calculations, the following three different sets with almost the same value of χ^2, which are obtained from the fit to the experimental data about $d\sigma[\gamma p\to p\omega]/dt$ in the near threshold region [28], are chosen for the coupling constants $g^{V,T}_{\omega NN*}$:

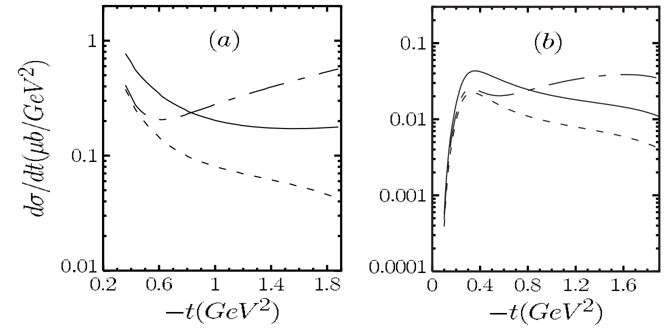

FIG. 2. Differential cross section for the processes, (a) $\gamma p\to\omega N^*(1440)$ in the zero-width approximation, (b) $\gamma p\to\omega N^*(1440)\to\omega\pi^0 p$, at $E_\gamma=2.5$ GeV. Solid, dashed, and dot-dashed lines correspond to $g^V_{\omega NN*}=0.5$ and $g^T_{\omega NN*}=0.1$; $g^V_{\omega NN*}=-0.01$, and $g^T_{\omega NN*}=0.6$; $g^V_{\omega NN*}=-1.4$ and $g^T_{\omega NN*}=0.4$, respectively.

Set 1,

$$g^V_{\omega NN*}=-1.4,\quad g^T_{\omega NN*}=0.4,\quad \chi^2=2.2; \tag{13}$$

Set 2,

$$g^V_{\omega NN*}=0.5,\quad g^T_{\omega NN*}=0.1,\quad \chi^2=1.6; \tag{14}$$

Set 3,

$$g^V_{\omega NN*}=-0.01,\quad g^T_{\omega NN*}=0.6,\quad \chi^2=1.9. \tag{15}$$

To obtain set 1, we use the standard values of cutoff parameters $\Lambda_{\pi NN*}=\Lambda_{\pi NN}=0.7$ GeV and $\Lambda_{\omega\pi\gamma}=0.77$ GeV. In analyzing the sensitivity of the best fit to $\Lambda_{\pi NN*}$ and $\Lambda_{\omega\pi\gamma}$, we discover that the standard values of Λ_i do not give the best solution. If the values of $\Lambda_{\pi NN*}$ and $\Lambda_{\omega\pi\gamma}$ are changed to 0.5 GeV and 1.0 GeV, respectively, we find better sets for the coupling constants $g^{V,T}_{\omega NN*}$, namely, set 2 and set 3. We follow the same minimization procedure as used in Ref. [29] for the determination of vector and tensor coupling constant values.

The values of the above coupling constant obtained from the fit to the data regarding the photoproduction of ω meson should not be considered well determined because of the absence of experimental data for the differential cross section and other single and double spin polarization observables. Therefore, it is very interesting to compare our results with the quark model predictions of Capstick and Roberts [30] and those determined from the vector meson dominance model (VMD) by Post and Mosel [31]. However, comparison cannot be done exactly because these two works use different coupling schemes, so their relation with ours is not obvious. On the other hand, the coupling constant $f_{\omega NN*}$ in Ref. [31] corresponds to our tensor coupling constant $g^T_{\omega NN*}$. Values for coupling constant $f_{\omega NN*}$ extracted from the helicity amplitudes of Refs. [32,33] are determined from VMD as 0.61 ± 0.68 and 0.85 ± 0.48, respectively,

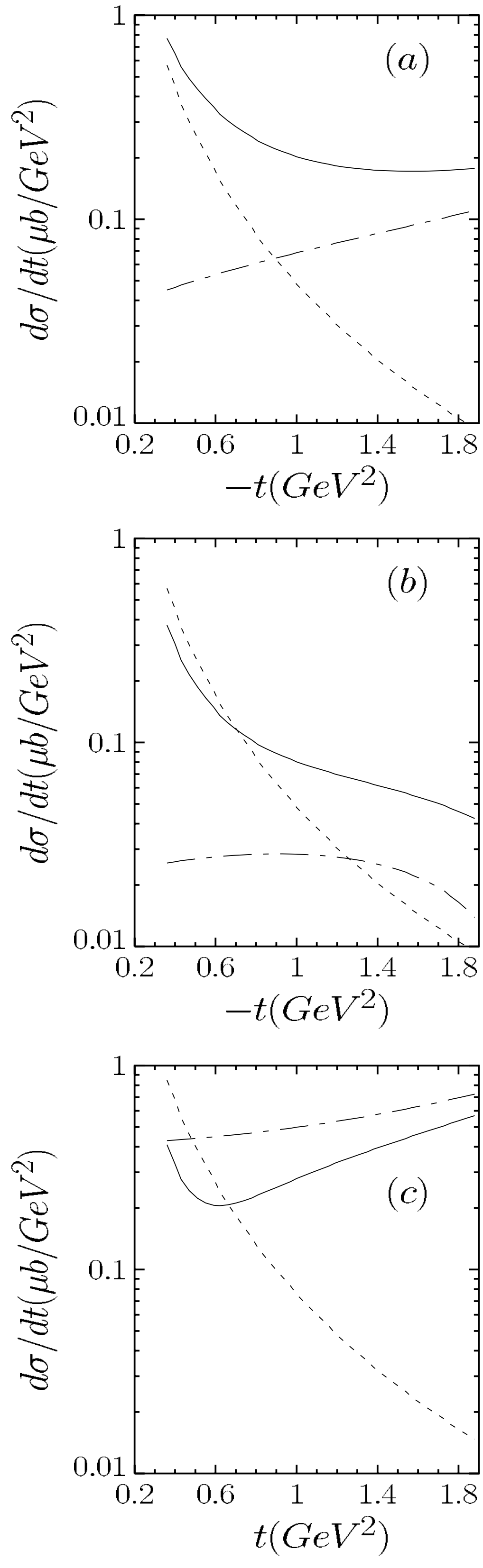

FIG. 3. Different contributions to $d\sigma[\gamma p \rightarrow \omega N^*(1440)]/dt$ at $E_\gamma = 2.5$ GeV for three different fitted parameter values: (a) $g^V_{\omega NN*} = 0.5$, $g^T_{\omega NN*} = 0.1$, (b) $g^V_{\omega NN*} = -0.01$, $g^T_{\omega NN*} = 0.6$, and (c) $g^V_{\omega NN*} = -1.4$, $g^T_{\omega NN*} = 0.4$. Solid, dashed, and dot-dashed lines correspond to total, π, and $(s+u)$ contributions, respectively.

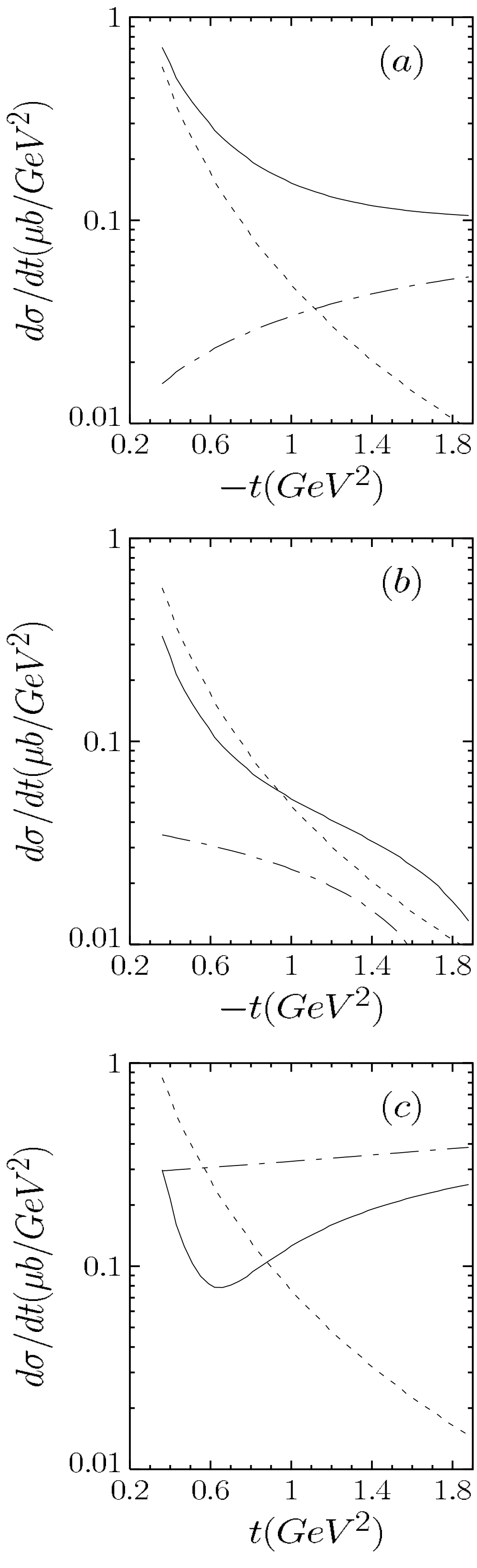

FIG. 4. Different contributions to $d\sigma[\gamma n \rightarrow \omega N^*(1440)]/dt$ at $E_\gamma = 2.5$ GeV for three different fitted parameter values: (a) $g^V_{\omega NN*} = 0.5$, $g^T_{\omega NN*} = 0.1$; (b) $g^V_{\omega NN*} = -0.01$, $g^T_{\omega NN*} = 0.6$; and (c) $g^V_{\omega NN*} = -1.4$, $g^T_{\omega NN*} = 0.4$. Notations are same as in Fig. 3.

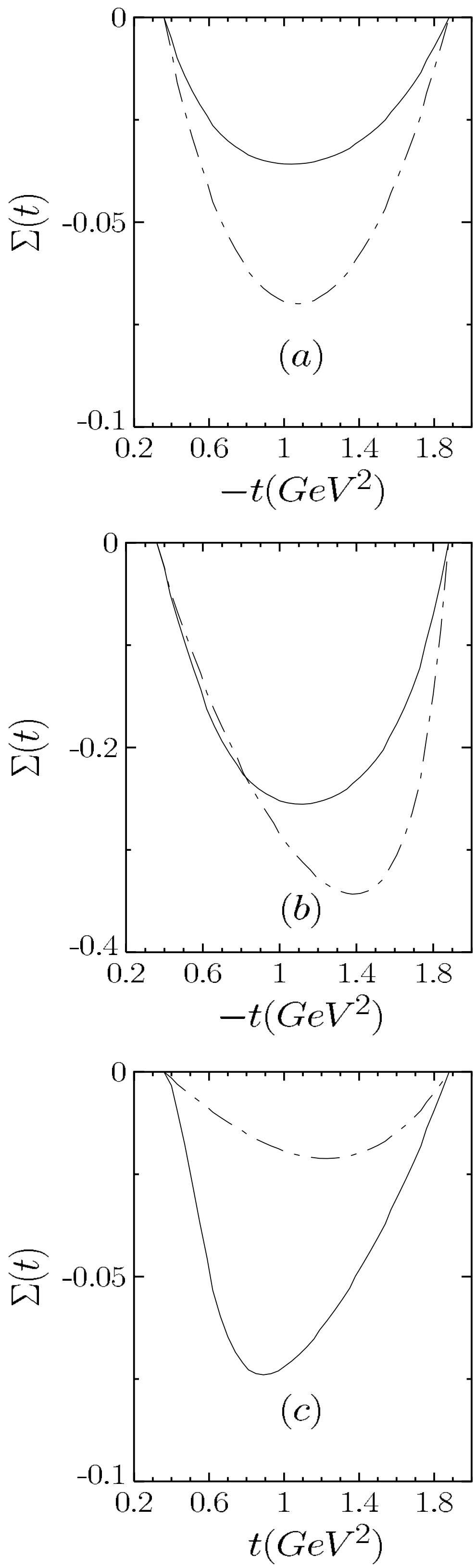

FIG. 5. Different contributions to $\Sigma[\gamma p \rightarrow \omega N^*(1440)]$ at $E_\gamma = 2.5$ GeV for three different fitted parameter values: (a) $g^V_{\omega NN*} = 0.5$, $g^T_{\omega NN*} = 0.1$; (b) $g^V_{\omega NN*} = -0.01$, $g^T_{\omega NN*} = 0.6$; and (c) $g^V_{\omega NN*} = -1.4$, $g^T_{\omega NN*} = 0.4$. Notations are same as in Fig. 3.

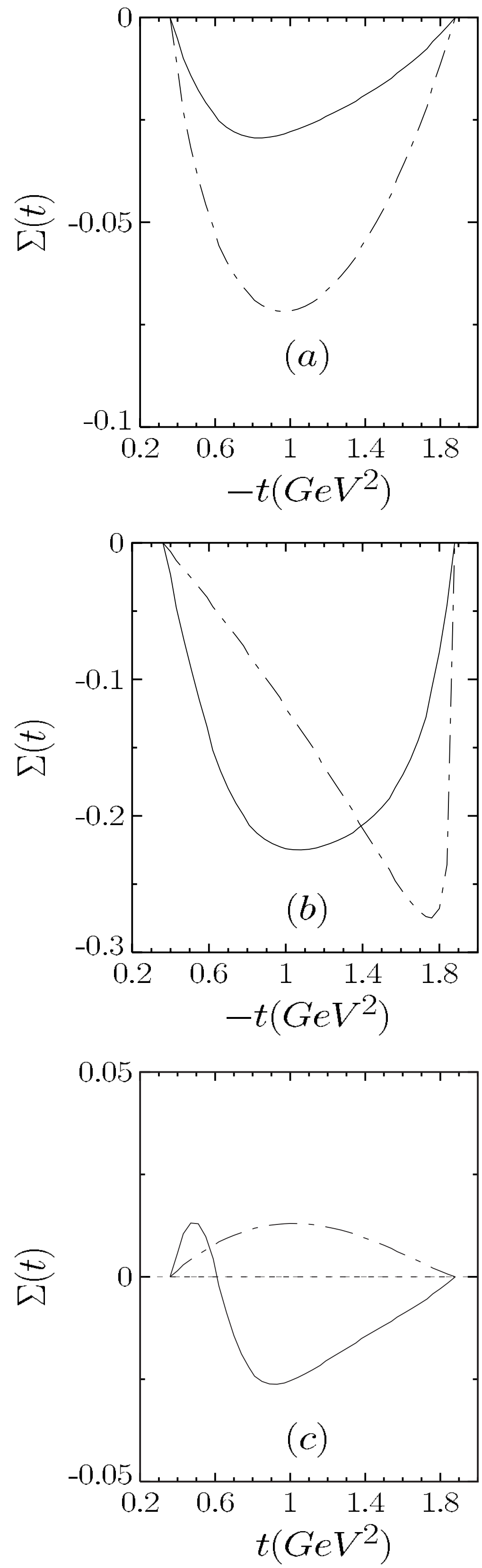

FIG. 6. Different contributions to $\Sigma[\gamma n \rightarrow \omega N^*(1440)]$ at $E_\gamma = 2.5$ GeV for three different fitted parameter values: (a) $g^V_{\omega NN*} = 0.5$, $g^T_{\omega NN*} = 0.1$; (b) $g^V_{\omega NN*} = -0.01$, $g^T_{\omega NN*} = 0.6$; and (c) $g^V_{\omega NN*} = -1.4$, $g^T_{\omega NN*} = 0.4$. Notations are same as in Fig. 3.

which are close to our values of sets 1 and 3, but the value obtained by using the helicity amplitudes of Ref. [34] is very different. This is not surprising at the initial stage of this development. Not only can the situation be improved by the use of experimental data for the spin observables for the reaction considered in this work, but also more experimental data for the spin observables for the ω meson photoproduction are needed.

The differential cross section for $\gamma p \to \omega N^*(1440)$ reaction at $E_\gamma = 2.5$ GeV using the above sets of coupling constants of our model and zero-width approximation is shown in the left panel of Fig. 2. All these sets give different cross sections for $\gamma p \to \omega N^*(1440)$. We also consider the width effects of Roper resonance on differential cross section, assuming that $N^*(1440)$ decays subsequently into the $\pi^0 p$ channel. These effects are presented in the right panel of Fig. 2. At $-t = 0.36$ GeV^2, the differential cross section for the process $\gamma p \to \omega N^*(1440) \to \omega \pi^0 p$ is about 20 times smaller than the differential cross section for $\gamma p \to \omega N^*(1440)$ in the zero-width approximation. This difference comes from the partial decay width of $N^*(1440)$ into the $\pi^0 p$ channel, which is nearly 20%, and the interval of the M_{N^*} appearing in the integral of Eq. (5) reduces the strength of Roper resonance excitation by a factor of about 4 compared to the case where all strength is concentrated at $M^0_{N^*} = 1.44$ GeV. Progress on the width effects is directly linked to the availability of new experimental data providing constraints on the couplings of $N^*(1440)$ to the πN and ωN channels.

The contributions of different amplitudes to $d\sigma[\gamma p \to \omega N^*(1440)]/dt$ and $d\sigma[\gamma n \to \omega N^*(1440)]/dt$ are presented in Figs. 3 and 4. Set 1 and set 3 for the coupling constants produce negative $\pi \otimes [N + N^*(1440)]$ interference, while set 2 has a positive interference in the differential cross section for the associative photoproduction of Roper resonance and ω meson on proton and neutron targets. For all these cases up to $-t = 0.5$ GeV^2, our predictions for differential cross section do not differ significantly from the one-pion exchange results, but beyond this value of t predictions of both models are different. Predicted behavior of differential cross section for $\gamma n \to \omega N^*(1440)$ as compared with $\gamma p \to \omega N^*(1440)$ indicates that differential cross section on proton and neutron targets can have differences by a factor of 2 or more, i.e., we can predict definite isotopic effects.

Another prediction of our model is the t dependence of beam asymmetry $\Sigma[\gamma p \to \omega N^*(1440)]$ and $\Sigma[\gamma n \to \omega N^*(1440)]$ at $E_\gamma = 2.5$ GeV, shown in Fig. 5 and Fig. 6. For the proton target, all three sets of coupling constants produce negative Σ, but although the absolute value of Σ is small for set 1 and set 2, being $|\Sigma| \leqslant 0.1$, it is nearly 0.25 at $|t| = 1.2$ GeV^2. However, in the neutron case, especially for set 1, beam asymmetry shows a different behavior, i.e., positive in sign for $|t| \leqslant 0.6$ GeV^2 and negative in the rest of the interval of $|t|$. Moreover, our model results show that beam asymmetry is sensitive to the sets of coupling constants in our model.

At present time, there is no systematic investigation of the role played by the $(s+u)$ contribution in associative photoproduction of the Roper resonance and ω meson in near threshold region. In fact, the unknown $\omega NN^*(1440)$ couplings have been the barrier to go further to include these contributions. However, our approach to determine these couplings makes detailed analysis possible for the description of differential cross section and beam asymmetry. At this stage, of course, it is very difficult to say that our results are decisive because of the absence of any differential cross section and polarization data about the processes $\gamma + N \to \omega + N^*(1440)$, but we can test our model by comparing it with the proposed one-boson exchange model, which include only the π contribution and is valid in the region $|t| \leqslant 0.5 - 0.6$ GeV^2. In this region our predictions of the differential cross section for $\gamma p \to \omega N^*(1440)$ are consistent with the predictions of Ref. [20] obtained from the π exchange model. This indicates that if the simple π exchange model makes sense, our assumption about the coupling strengths of $\omega NN^*(1440)$ is reasonable. Therefore, this model seems appropriate to perform the calculations on the boundary of the modern approaches to these processes and it should be considered as a first approach.

IV. CONCLUSIONS

The analysis done in the preceding section results in the following conclusions.

The relatively simple model $(\pi + N + N^*)$ is proposed to describe the associative photoproduction of Roper resonance and ω meson on proton and neutron targets near threshold region ($E_\gamma < 3$ GeV) for the whole t region. Comparison of this model with the one-pion calculations demonstrates the definite difference in the behavior of differential cross section.

The different solutions for the coupling constants and the cutoff parameters obtained from the fitting procedure result in the constructive and destructive $\pi \otimes (N + N^*)$ interference contributions to $d\sigma[\gamma p \to \omega N^*(1440)]/dt$.

The Σ asymmetry is different from zero and its t behavior is sensitive to our model parameters, namely, $g^{V,T}_{\omega NN^*}$ coupling constants, which are obtained in the timelike region of vector meson four-momentum.

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