A resonance interpretation for the nonmonotonic behavior of the $\phi$ photoproduction cross section near threshold

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Abstract. We study whether the nonmonotonic behavior found in the differential cross section of the $\phi$-meson photoproduction near threshold can be described by a resonance. The resonant contribution is evaluated by using an effective Lagrangian approach. We find that, with the assumption of a $J^P = 3/2^-$ resonance with mass of $2.10 \pm 0.03$ GeV and width of $0.465 \pm 0.141$ GeV, LEPS data can indeed be well described. The ratio of the helicity amplitudes $A_1/A_3$ calculated from the resulting coupling constants differs in sign from that of the known $D_{13}(2080)$. We further find that the addition of this postulated resonance can substantially improve the agreement between the existing theoretical predictions and the recent $\omega$ photoproduction data if a large value of the OZI evading parameter $x_{OZI} = 12$ is assumed for the resonance.

Keywords: Photoproduction, $\phi$ meson, nucleon resonance, Pomeron
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Recently, a local maximum in the differential cross sections (DCS) of $\phi$ photoproduction on protons at forward angles at around $E_\gamma \sim 2.0$ GeV, has been observed by the LEPS collaboration [1]. Models which consist of $t$-channel exchanges Refs. [2]-[7] have not been able to account for such a nonmonotonic behavior.

Here, we study whether the nonmonotonic behavior found in Ref. [1] can be described by a resonance. Namely, we will add a resonance to a model consisting of Pomeron and ($\pi, \eta$) exchange [8, 9] by fiat and see if, with a suitable assignment of spin and parity, mass and width, as well as the coupling constants, one would be able to obtain a good description of all the data reported by the LEPS collaboration. Since the local maximum appears quite close to the threshold, we will investigate, as a first step, the possibility of the spin of the resonance being either $1/2$ or $3/2$. Similar analysis was carried out in a coupled-channel model [10]. However, the analysis was marred by a confusion in the phase of the Pomeron-exchange amplitude [11].

In tree-level approximation, only the mass, width, and the products of coupling constants enter in the invariant amplitudes. The details of the amplitudes can be found in Ref. [12]. They are determined with the use of MINUIT, by fitting to the LEPS experimental data [1].

We found that it is not possible to describe the nonmonotonic behavior of the DCS at forward direction as a function of photon energy with only the nonresonant contribution. Furthermore, with an addition of a $J^P = 1/2^\pm$ resonance also cannot produce a nonmonotonic behavior near threshold, in contrast to the finding of Refs. [10, 11].
FIGURE 1. Our results for the DCS of $\gamma p \to \phi p$ at forward direction as a function of photon energy $E_\gamma$ (left) and as a function of $t$ at eight different photon LAB energies (right). Data are from Refs. [1, 13]. The dotted, dashed, and solid lines denote contributions from nonresonant, resonance with $J^P = 3/2^-$, and their sum, respectively.

We found that both $J^P = 3/2^\pm$ resonances can describe the data reasonably well. However, the extracted properties of the $J^P = 3/2^-$ resonance are more stable against changes in Pomeron parameters compared to that of $J^P = 3/2^+$, hence our preference of $J^P = 3/2^-$ with mass and width of $2.10 \pm 0.03$ and $0.465 \pm 0.141$, respectively. The resulting coupling constants are $e_g^{(1)}(\gamma NN^*)g_{\phi NN^*}^{(1)} = -0.186 \pm 0.079$, $e_g^{(1)}(\gamma NN^*)g_{\phi NN^*}^{(2)} = -0.015 \pm 0.030$, $e_g^{(1)}(\gamma NN^*)g_{\phi NN^*}^{(3)} = -0.02 \pm 0.032$, $e_g^{(2)}(\gamma NN^*)g_{\phi NN^*}^{(1)} = -0.212 \pm 0.076$, $e_g^{(2)}(\gamma NN^*)g_{\phi NN^*}^{(2)} = -0.017 \pm 0.035$, and $e_g^{(2)}(\gamma NN^*)g_{\phi NN^*}^{(3)} = -0.025 \pm 0.037$ [12].

Our best fits with $J^P = 3/2^-$ to the experimental energy dependence of the DCS at forward angle and angular dependence of the DCS [1, 13] are shown in Fig. 1. One sees from Fig. 1 that the resonance improves the agreement with the data.

FIGURE 2. Our results obtained with $J^P = 3/2^-$ resonance: (a) decay angular distributions $W(\cos \theta)$, (b) $W(\Phi - \Psi)$, and (c) $W(\Phi)$, $W(\Phi + \Psi)$, and $W(\Psi)$. All the decay angular distributions are given in two photon LAB energies, 1.97 – 2.17 GeV (upper panel) and 2.17 – 2.37 GeV (lower panel). Data is taken from Ref. [1]. The notation is the same as in Fig. 1.

Our results for the decay angular distributions of the $\phi$-meson in the Gottfried-Jackson system (hereafter, called GJ-frame) [6, 14], are shown in Fig. 2. Here, the inclusion of
resonant contribution does help the agreement with the data, especially for \( W(\Phi - \Psi) \) at \( 2.17 - 2.37 \) GeV and \( W(\Phi) \) at \( 1.97 - 2.17 \) GeV. For both \( W(\Phi + \Psi) \) and \( W(\Psi) \), our model still fail to give adequate agreement with the data which are of rather poor quality with large error bars.

One might be tempted to identify the \( 3/2^- \) as the \( D_{13}(2080) \) as listed in PDG [15]. However, with the coupling constants given above, we obtain a value of \( A_2 / A_2 = 1.16 \) which differ from \(-1.18\) for \( D_{13}(2080) \) [15] in relative sign.

In general, we find that the effects of the resonance are substantial in many of the polarization observables [3]. Results for single and double polarization observables \( \Sigma_x \), \( T_y \), \( C_{BT}^{xy} \), and \( C_{BT}^{yz} \) are shown in left panel of Fig. 3. In the same figure, the results using a \( 3/2^- \) resonance are also shown by dash-dotted curve. We see that measurements of these polarization observables would help to resolve the question of the parity of the resonance.

![Figure 3](image.png)

**FIGURE 3.** Left: Single and double polarization observables \( \Sigma_x \), \( T_y \), \( C_{BT}^{xy} \), and \( C_{BT}^{yz} \) taken at photon laboratory energy \( E_\gamma = 2 \) GeV. The solid and dash-dotted lines correspond to our results with the choices of \( J^P = 3/2^- \) and \( J^P = 3/2^+ \), respectively, while the dotted lines denote the nonresonant contribution. Right: DCS of \( \omega \) photoproduction as a function of \( |t| \) at \( W = 2.105 \) GeV. Solid and dashed lines represent the model predictions of Ref. [16] without and with the addition of our resonance with \( x_{OZI} = 12 \). Data are from Ref. [17].

From the \( \phi - \omega \) mixing, one would expect that a resonance in \( \phi N \) channel would also appear in \( \omega N \) channel. The conventional "minimal" parametrization relating \( \phi NN^* \) and \( \omega NN^* \) is \( g_{\phi NN^*} = -\tan \Delta \theta_V x_{OZI} g_{\omega NN^*} \), with \( \Delta \theta_V \approx 3.7^\circ \) corresponds to the deviation from the ideal \( \phi - \omega \) mixing angle. The larger value of the OZI-evading parameter \( x_{OZI} \) would indicate larger strangeness content of the resonance.

By adding the resonance postulated here to the model of Ref. [16] with \( x_{OZI} = 12 \), whose prediction is given in the dashed line in right panel of Fig. 3, we see that the DCS at \( W = 2.105 \) GeV can be reproduced with roughly the correct strength. The large value of \( x_{OZI} = 12 \) would imply that the resonance we propose here contains a considerable amount of strangeness content.

In summary, we study the possibility of accounting for the nonmonotonic behavior as observed by the LEPS collaboration at energies close to threshold as a possible
manifestation of a resonance. We confirm that nonresonant contribution alone cannot describe the LEPS data, as well as the addition of a resonance with $J = 1/2$. However, with an assignment of $J = 3/2^-$, a nice agreement with most of the LEPS data can be achieved, with a greater stability with respect to changes in the low-energy Pomeron parameters, compared to $J = 3/2^+$. The obtained resonance mass and width are $2.10 \pm 0.03$ and $0.465 \pm 0.141$ GeV, respectively. The resulting coupling constants give rise to a ratio of the helicity amplitudes that differs from that of the known $D_{13}(2080)$ in sign. Furthermore, we find that the postulated resonance gives substantial contribution to the polarization observables, which can also be used to determine the parity of the resonance if it indeed exists. The addition of a $J = 3/2^-$ resonance to the model of Ref. [16] with a choice of a large value of OZI-evading parameter $x_{OZI} = 12$ could indeed considerably improve the agreement of the model prediction with the most recent data. That would imply the resonance postulated here does contain considerable amount of strangeness content.

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REFERENCES

1. T. Mibe et al. (LEPS Collaboration), Phys. Rev. Lett. 95, 182201 (2005) and references therein.
2. A. I. Titov, Y. S. Oh and S. N. Yang, Phys. Rev. Lett. 79, 1634 (1997); A. I. Titov, Y. Oh, S. N. Yang, and T. Morii, Nucl. Phys. A 684, 354 (2001).
3. A. I. Titov, Y. Oh, S. N. Yang, and T. Morii, Phys. Rev. C 58, 2429 (1998).
4. R. A. Williams, Phys. Rev. C 57, 223 (1998).
5. A. I. Titov, T.-S. H. Lee, H. Toki, and O. Streltsova, Phys. Rev. C 60, 035205 (1999).
6. A. I. Titov, T.-S. H. Lee, Phys. Rev. C 67, 065205 (2003).
7. A. I. Titov and B. Kämpfer, Phys. Rev. C 76, 035202 (2007).
8. T. H. Bauer, R. D. Spital, D. R. Yennie and F. M. Pipkin, Rev. Mod. Phys. 50, 261 (1978).
9. A. Donnachie and P. V. Landshoff, Phys. Lett. B 185, 403 (1987); Nucl. Phys. B 244, 322 (1984); Nucl. Phys. B 267, 690 (1986); Nucl. Phys. B 311, 509 (1989).
10. S. Ozaki, A. Hosaka, H. Nagahiro, and O. Scholten, Phys. Rev. C 80, 035201 (2009).
11. A. Hosaka, private communication.
12. A. Kiswandhi, J.-J. Xie, S.N. Yang, Phys. Lett. B 691, 214-218 (2010) and references therein.
13. Durham HEP database (http://www.slac.stanford.edu/spires/hepdata).
14. K. Schilling, K. Seyboth, and G. Wolf, Nucl. Phys. B 15, 397 (1970).
15. Particle Data Group, K. Hagiwara et al., Phys. Rev. D 66, 010001 (2002).
16. Y. Oh, A. I. Titov, and T.-S.H. Lee, Phys. Rev. C 63, 025201 (2001).
17. M. Williams et.al., Phys. Rev. C 80, 065208 (2009).