Differential cross section of ϕ-meson photoproduction at threshold

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We show that the differential cross section $d\sigma/dt$ of the $\gamma p \to \phi p$ reaction at threshold is finite and its value is crucial to the mechanism of ϕ-meson photoproduction and for the models of ϕN interaction.

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Now it becomes clear that ϕ-meson photoproduction at low energies, $E_\gamma \simeq$ 2–3 GeV, plays an important role in understanding nonperturbative Pomeron-exchange dynamics and the nature of ϕN interaction. It is expected that in the diffractive region the dominant contribution comes from the Pomeron exchange, because trajectories associated with conventional meson exchanges are suppressed by the OZI rule [1]. The exception is the finite contribution of the pseudoscalar π, η-meson-exchange channel, but its properties are quite well understood [2]. Therefore, low-energy ϕ-meson photoproduction may be used for studying the additional (exotic) processes. Candidates are Regge trajectories associated with scalar and tensor mesons containing a large amount of strangeness [3,4], glueball exchange [1], or other channels with [5–7] or without [8] suggestions of the hidden strangeness in the nucleon.

One possible indication of the manifestation of the exotic channels is nonmonotonic behavior of the differential cross section $d\sigma/dt$ of the $\gamma p \to \phi p$ reaction, reported recently by the LEPS Collaboration [9]. The data show a bump structure around $E_\gamma \simeq 2$ GeV, which disagrees with the monotonic behavior predicted by the conventional (Pomeron exchange) model. Another peculiarity of the LEPS's data is the tendency of $d\sigma/dt$ at forward photoproduction angle ($\theta \simeq 0$) to be finite when the photon energy E_γ approaches the threshold value $E_{\rm thr} \simeq 1.574$ GeV. This is in contradiction with relatively old [1,10] and recent [11] expectations of $d\sigma/dt = 0$ at $\theta = 0$ and $E_\gamma \simeq E_{\rm thr}$, based on a relation that near threshold $d\sigma/dt$ behaves as q_ϕ^2/k_γ^2, where k_γ and q_ϕ are the momenta of the incoming photon and the outgoing ϕ meson in the center of mass, respectively. Thus, the equation for the differential cross section $d\sigma/dt$ in Ref. [11] derived from the base of the conventional vector meson dominance approach, being quite reasonable at finite q_ϕ, can not be applied in the vicinity of $q_\phi \sim 0$, which is just a goal of our present consideration.

The aim of our article is to concentrate on this particular aspect of the experimental data. We intend (i) to show the absence of the so-called "threshold factor" q_ϕ^2/k_γ^2 in the differential cross section and (ii) to stress that $d\sigma/dt$ at $E_\gamma \simeq E_{\rm thr}$ is related to the ϕN scattering length, which can be used as a test for the models of ϕN interactions.

A. Threshold behavior of the differential cross section. Assuming the vector dominance model (VDM) and using the optical theorem, the differential cross section of the $\gamma p \to \phi p$ reaction can be written according to Ref. [11] in the form

$$\frac{d\sigma}{dt}^{\gamma p\to\phi p}(\theta = 0) = \frac{\alpha}{16\gamma_\phi^2}\frac{q_\phi^2}{k_\gamma^2}\,[1 + r^2]\sigma_{\phi p}^{\rm tot\,2}, \qquad (1)$$

where $\sigma_{\phi p}^{\rm tot}$ is the total cross section of the ϕp interaction and r is the ratio of the real to imaginary parts of the elastic ϕp scattering amplitudes $r = {\rm Re}\,T^{\phi p}/{\rm Im}T^{\phi p}$. The coupling $\gamma_\phi \simeq 6.7$ is defined from the $\phi \to e^+e^-$ decay. Here we keep only the diagonal transition $\gamma p \to \phi p \to \phi p$. Taking r to be constant, one gets the threshold factor q_ϕ^2/k_γ^2 in explicit form. Because ${\rm Im}T^{\phi p} \sim q_\phi$ [11] and ${\rm Re}T^{\phi p}$ related to the real part of the scattering length is finite, we have

$$r^2(q_\phi \to 0) \sim \frac{1}{q_\phi^2}. \qquad (2)$$

This leads to the cancellation of q_ϕ^2 dependence and the elimination of the threshold factor q_ϕ^2/k_γ^2 in Eq. (1). The value of r near the threshold is unknown, and therefore one cannot utilize the threshold factor in practice without additional assumptions.

For more consistent analysis of the threshold behavior we express the differential cross section of $\gamma p \to \phi p$ through the differential cross section of $\phi p \to \phi p$ elastic scattering,

$$\frac{d\sigma}{dt}^{\gamma p\to\phi p} = \frac{\alpha\pi^2}{\gamma_\phi^2 k_\gamma^2}\,\frac{d\sigma}{d\Omega}^{\phi p\to\phi p}. \qquad (3)$$

At small q_ϕ, the differential cross section $d\sigma^{\phi p\to\phi p}/d\Omega$ becomes isotropic and it can be expressed through the spin averaged ϕp scattering length $a_{\phi p}$,

$$\frac{d\sigma}{d\Omega}^{\phi p\to\phi p} = a_{\phi p}^2. \qquad (4)$$

This leads to the following estimation,

$$\frac{d\sigma}{dt}^{\gamma p\to\phi p}_{\rm threshold} = \frac{\alpha\pi^2}{\gamma_\phi^2 k_\gamma^2}\,a_{\phi p}^2. \qquad (5)$$

One can see that at threshold the cross section of ϕ-meson photoproduction is finite and its value is defined by the ϕp scattering length.

1. Direct estimations. The direct estimation of the ϕp scattering length on the basis of QCD sum rules was carried out by Koike and Hayashigaki [12]. They got $a_{\phi p} \simeq -0.15$ fm, which results in

$$\left.\frac{d\sigma_{\rm thr}}{dt}^{\gamma p\to\phi p}\right|_1 \simeq 0.63\,\mu\text{b/GeV}^2. \quad (6)$$

This value is in qualitative agreement with the experimental indication [9].

One can estimate $a_{\phi N}$ using the ϕN potential approaches. Thus, for example, Gao, Lee, and Marinov [13] suggested using the QCD van der Waals attractive ϕN potential for analysis of ϕ-nucleus bound states. This potential reads

$$V_{\phi N} = -A\exp(-\mu r)/r, \quad (7)$$

where $A = 1.25$ and $\mu = 0.6$ GeV. The corresponding scattering length, $a_{\phi p} \simeq 2.37$ fm, found by direct solution of the Schrödinger equation, leads to large cross section $d\sigma/dt \simeq 1.6\times 10^2\mu$b/GeV^2. It is more than two orders of magnitude greater than the experimental hint and provides a problem for this potential model. Thus, to get the scattering length $a_{\phi p} \simeq \pm 0.15$ fm (and, correspondingly, the cross section $d\sigma/dt$ close to the experiment), one has to choose $A = 2.56$ or 0.226 for the positive (strong attraction) or negative (weak attraction) $a_{\phi p}$, respectively. At $A \simeq 2.75$, the elastic scattering disappears ($a_{\phi p} = 0$) and we get some kind of Ramsauer effect [14]. In principle, such analysis may be used for other potentials as well.

2. SU(3) symmetry considerations. Estimation of the upper bound of $|a_{\phi p}|$ may be carried out on the assumption that the amplitudes of the ϕp and ωp scattering are dominated by the scalar σ-meson exchange. Then the SU(3) symmetry gives the relation

$$a_{\phi p} = \xi a_{\omega p}, \quad (8)$$

where $\xi \equiv -\text{tg}\Delta\theta_V$ ($\Delta\theta_V \simeq 3.7^\circ$ is the deviation of the ϕ-ω mixing angle from the ideal mixing [15]). More complicated processes such as s-channel exchange with intermediate nucleon or nucleon resonances, or box diagrams with $\omega(\phi)\pi\rho$ vertices, would give terms proportional to ξ^2 and, generally speaking, violate Eq. (8). But for crude estimation of the order of magnitude of $a_{\phi p}$ one can utilize Eq. (8) using $a_{\omega p}$ as an input.

Thus, the QCD sum rule analysis of Koike and Hayashigaki [12] results in $a_{\omega p} = -0.41$ fm. The coupled channel unitary approach of Lutz, Wolf, and Friman [16] leads to $a_{\omega p} = (-0.44 + i0.20)$ fm. An effective Lagrangian approach based on the chiral symmetry developed by Klingl, Waas, and Weise [17] results in $a_{\omega p} = (1.6 + i0.3)$ fm. The corresponding ϕ-meson photoproduction cross sections for these scattering lengths, denoted with subscripts 2, 3, and 4, respectively, read

$$\left.\frac{d\sigma_{\rm thr}^{\gamma p\to\phi p}}{dt}\right|_2 = 2.0\times 10^{-2}\,\mu\text{b/GeV}^2, \quad (9)$$

$$\left.\frac{d\sigma_{\rm thr}^{\gamma p\to\phi p}}{dt}\right|_3 = 2.7\times 10^{-2}\,\mu\text{b/GeV}^2, \quad (10)$$

$$\left.\frac{d\sigma_{\rm thr}^{\gamma p\to\phi p}}{dt}\right|_4 = 3.1\times 10^{-1}\,\mu\text{b/GeV}^2. \quad (11)$$

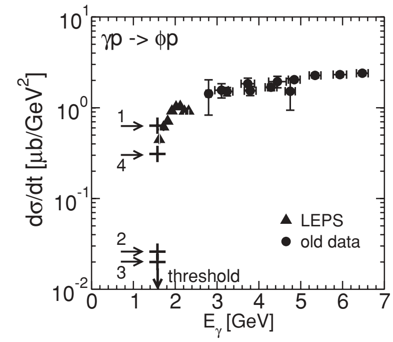

FIG. 1. Differential cross section of the $\gamma p \to \phi p$ reaction at $\theta = 0$ as a function of the photon energy. The enumerated symbols "plus" correspond to the threshold predictions, given in Eq. (6) and Eqs. (9)–(11). Experimental data are taken from Refs. [9,18].

Figure 1 shows predictions of Eq. (6) and Eqs. (9)–(11) by the enumerated symbols "plus." Experimental data at $\theta = 0$ are taken from Refs. [9,18]. The predictions of Eqs. (6) and (11) seem to be preferable. The difference between Eqs. (9) and (10) and data can indicate a small ωp scattering length or the necessity to introduce a large OZI rule evading factor in Eq. (8) that can be related to the finite hidden strangeness in the nucleon. For example, analysis of ϕ-meson photoproduction at large angles in Refs. [2,19] favors the large OZI rule evading factor $x_{\rm OZI} \simeq 3$–4. Such values result in increasing the threshold predictions based on $a_{\omega p}$ by almost an order of magnitude. Employing this evading factor seems to be consistent with predictions in Eqs. (9) and (10) and create a problem for one in Eq. (11).

B. Nondiagonal transitions. The nondiagonal transition $\gamma p \to \rho p \to \phi p$ also contributes near threshold. Such an example is ϕ-meson photoproduction with π- and η-meson exchange, shown in Fig. 2, which is associated with the $\rho \to \phi$ transition.

The corresponding invariant amplitude written in obvious standard notation reads

$$T_m^{\gamma p\to\phi p} = -i\frac{e g_{NNm} g_{\gamma\phi m}}{M_\phi(t - m_m^2)}\epsilon^{\mu\nu\alpha\beta}\varepsilon_\mu(\gamma)\varepsilon_\nu^*(\phi)k_{\gamma\alpha}q_{\phi\beta} \times [\bar{u}_{p'}\gamma_5 u_p]F_m^2(t), \quad (12)$$

where $m = \pi, \eta$, $g_{\gamma\phi m}$ has a sense of $g_{\rho\phi m}/2\gamma_\rho$ coupling and it is taking from $\phi \to \gamma\pi(\eta)$ decay: ($g_{\gamma\phi\pi(\eta)} \simeq 0.14\,(0.71)$ [15]). For the $g_{NN\pi}$ coupling constant we take its standard value $g_{NN\pi} \simeq 13.3$, and following estimates based on QCD sum rule [20] and chiral perturbation theory [21], as well as the phenomenological analysis of η photoproduction [22], we use $g_{NN\eta} \simeq 1.94$. The function $F_m^2(t)$ is a product of the form

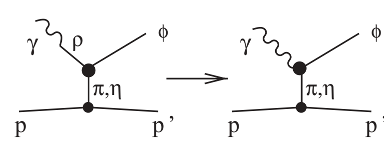

FIG. 2. Diagrammatic presentation of the pseudoscalar π, η exchange processes in the $\gamma p \to \phi p$ reaction.

factors in $\gamma\phi m$ and NNm coupling vertices, taken as

$$F(t) = \frac{\Lambda^2 - m_m^2}{t - m_m^2}. \quad (13)$$

The amplitude of Eq. (12) leads to the estimate

$$\frac{d\sigma}{dt}^{\gamma p\to\phi p\,(\pi,\eta)}_{\text{threshold}} = \frac{\alpha|t_0|\left(M_\phi^2 - t_0\right)^2}{64E_0 M_N^2 M_\phi^2}\left(\frac{g_{NN\pi}g_{\gamma\phi\pi}F_\pi^2(t_0)}{t_0 - m_\pi^2} + \frac{g_{NN\eta}g_{\gamma\phi\eta}F_\eta^2(t_0)}{t_0 - m_\eta^2}\right)^2, \quad (14)$$

where $E_0 = E_{\text{thr}} = (2M_N M_\phi + M_\phi^2)/2M_N \simeq 1.5745$ GeV and $t_0 = t_{\text{thr}} = -M_N M_\phi^2/(M_N + M_\phi) \simeq -0.49\,\text{GeV}^2$. All parameters in Eq. (14) are fixed, except the cutoff parameter Λ in Eq. (13). Actually, this parameter defines the relative contribution of the pseudoscalar exchange channel and can be determined from the spin density matrix element ρ^1_{1-1}, which defines the angular distribution of the $\phi \to K^+K^-$ decay as a function of the angle between the decay plane and the plane of the photon polarization and has a sense of asymmetry between transitions with natural (Pomeron exchange) and unnatural parity (pseudoscalar meson) exchanges [23]. The experimental measurement of this value at $|t| - |t_{\max}| < 0.2\ \text{GeV}^2$ and $E_\gamma = 1.97$–2.17 GeV gives $\rho^1_{1-1} \simeq 0.2$ [9]. Using for the "diagonal" transition the Donnachie-Landshoff Pomeron model [2], one can get $\rho^1_{1-1} \simeq 0.2$ at $\Lambda = 1.05$ GeV. Using this data one can find

$$\frac{d\sigma}{dt}^{\gamma p\to\phi p\,(\pi,\eta)}_{\text{threshold}} \simeq 0.1\mu\text{b/GeV}^2, \quad (15)$$

giving about of 50% of the total cross section at the threshold. So again, $d\sigma^{\gamma p\to\phi p}/dt$ is finite and its magnitude is in the range of the uncertainty of other estimations. This example has a practical significance. As long as only the "diagonal" transition is related to the scattering length, then for its determination, one has to subtract the "nondiagonal" contribution from the total cross section. For this aim, the precise data on ϕ-meson decay distribution in reactions with linearly polarized photon near the threshold are required.

Finally we notice, that the differential $d\sigma^{\gamma p\to\phi p}/d\Omega$ and the total $\sigma^{\gamma p\to\phi p}$ cross sections have the obvious kinematical phase space factor q_ϕ/k_γ. For example, for the diagonal transition we get

$$\frac{d\sigma}{d\Omega}^{\gamma p\to\phi p}_{\text{threshold}} = \frac{q_\phi}{k_\gamma}\frac{\alpha\pi}{\gamma_\phi^2}a_{\phi p}^2, \quad \sigma^{\gamma p\to\phi p}_{\text{threshold}} = \frac{q_\phi}{k_\gamma}\frac{4\alpha\pi^2}{\gamma_\phi^2}a_{\phi p}^2. \quad (16)$$

If one accepts the threshold behavior of $d\sigma/dt$ as in Eq. (1) with a constant r, then the cross sections $d\sigma/d\Omega$ and $\sigma^{\gamma p\to\phi p}$ will decrease near threshold as $(q_\phi/k_\gamma)^3$, which seems to be rather strong.

In summary, we analyzed the differential cross section $d\sigma/dt$ of the $\gamma p \to \phi p$ reaction at threshold and have shown that it is finite. A part of the threshold cross section is directly related to the ϕN scattering length. This offer to put constraints on the ϕN interaction. Non-natural parity exchange (or nondiagonal VDM) transition also gives a finite contribution at threshold. The way to separate diagonal (Pomeron exchange) and nondiagonal (pseudoscalar meson exchange) transitions requires the performance of high statistic experiments with linearly polarized photon beams. The problems discussed above may be studied experimentally at the electron and photon facilities at LEPS of SPring-8, JLab, Crystal-Barrel of ELSA, and GRAAL of ESRF.

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