THEORETICAL MODEL OF THE ϕ MESON PHOTOPRODUCTION AMPLITUDES

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Dedicated to Jan Kwieciński in honour of his 65th birthday

P-wave amplitudes for elastic K^+K^- photoproduction on hydrogen near the $\phi(1020)$ resonance have been derived in an analytical form and a partial wave decomposition of the amplitudes has been performed. We discuss the high energy limit of the resulting amplitudes and compare two types of pomeron coupling to nucleons.

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1. Introduction

Studies of photoproduction processes are very useful in application to meson spectroscopy. The cross sections for vector meson photo- or electro-production are relatively high since these processes are diffractive at medium and high photon energies. Many aspects of photoproduction reactions of the ρ, ω, ϕ, J/Ψ and other vector mesons have been studied over a few decades [1] and these reactions continue attracting significant attention [2]. After construction of the HERA collider, energies and momentum transfers accessible for photoproduction have been substantially increased [3,4]. Here one should underline many important contributions of Jan Kwieciński in the field of high energy electron and photon interactions (see, for example his contributions in [2] and [5]).

Most of the known mesons are successfully classified as nonets of the $q\overline{q}$ quark model. The scalar mesons, however, escape such a simple classification and are usually referred to as "unusual" mesons. Their properties are lively discussed in theoretical and experimental papers (see, for example, a note on scalar mesons by Spanier and Törnqvist in [6]). There is also a new proposed, GlueX/Hall D experiment at the energy upgraded Jefferson Laboratory in the US, to study production and decay characteristics of gluonic excitations and unusual mesons [7].

Production of scalar mesons by photon beams is suppressed in comparison with production of vector mesons. In particular, these are the cases of the $f_0(980)$ or the $a_0(980)$ meson photoproduction. Nevertheless, even if the cross section for the $f_0(980)$ photoproduction was too small to be directly measurable, it is possible to see effects of the $f_0(980)$ through interferences in the K^+K^- decay channel of the $\phi(1020)$ meson. Experiments exploring such effects have been done at DESY [8, 9] and at the Daresbury Laboratory [10]. In the first experiment, performed in the photon energy range from 4.6 to 6.7 GeV and at low momentum transfers squared $|t| < 0.2$ GeV$/c^2$, the interference of $f_0(980)$ with $\phi(1020)$ has been observed as a forward–backward asymmetry in the K^+ angular distribution. This enabled to set the upper limit for the total $f_0(980)$ photoproduction. In the Daresbury experiment, performed at slightly lower energies, between 2.8 and 4.8 GeV and at much wider momentum transfers, $|t|$ up to 1.5 (GeV/c)^2, the interference between the dominant P-wave, corresponding to the $\phi(1020)$ production, and the S-wave has also been clearly seen. The interpretation of the data, however was not unique. The authors of Ref. [10] obtained values of the total $f_0(980)$ photoproduction cross section between 10 and 100 nb, where the first value was obtained under the assumption of a nonresonant S-wave and the second, for a resonating $f_0(980)$ contribution to the S-wave.

In 1998 the theoretical results of the coupled channel analysis of the S-wave $\pi\pi$ and $K\overline{K}$ photoproduction at a few GeV laboratory photon momentum have been published [11]. The final state interactions in two channels for the effective two-pion or two-kaon masses below and above the $K\overline{K}$ threshold have been included. The momentum transfer distributions and the effective mass distributions as well as the total S-wave cross sections have been calculated. The results indicate that the $\pi\pi$ and $K\overline{K}$ photoproduction processes should be experimentally accessible and could provide valuable information on the structure of the underlying scalar resonances. Recently the experimental results on large momentum transfer photoproduction of $\phi(1020)$ mesons using the CLAS detector at Jefferson Laboratory have been published [13] and low-momentum transfer data for $\pi^0\pi^0$ production are expected from the Hall B Radphi [14] experiment.

The component of the P-wave ($\phi(1020)$) amplitude which can interfere with the S-wave amplitude is different from the dominant P-wave amplitude. In most phenomenological models of ϕ photoproduction only amplitudes corresponding to the ϕ spin projection equal to the photon spin projection,

$+1$ (or -1) were considered. This is a consequence of the s-channel helicity conservation in peripheral production. The S-wave of the produced pair of kaons, however, can interfere only with the non-dominant P-wave helicity amplitude which corresponds to the final $K\overline{K}$ pair angular momentum projection on the quantisation axis equal to zero. Therefore, to treat the S–P interference phenomena of the K^+K^- production in vicinity of the $\phi(1020)$ mass one has to make a model of all P-wave photoproduction amplitudes and not only of the dominant helicity component. The principal aim of this paper is to formulate a relevant model of these amplitudes (for other models of the ϕ meson photoproduction, see for example [15–20], [23] and [24].

In Sec. 2 we present a model of the elastic K^+K^- photoproduction on proton suitable for the photon energies well above the $\phi(1020)$ production threshold. In Sec. 3 we write explicit expressions for twelve independent spin amplitudes. Sec. 4 is devoted to a discussion of the high energy limit. In Sec. 5 alternative pomeron exchange amplitudes are compared to the amplitudes derived in Sec. 3. Concluding remarks are given in Sec. 6.

2. Model of the P-wave photoproduction of the K^+K^- pairs

Let us consider the elastic photoproduction of K^+K^- pairs on the proton from the $K\overline{K}$ threshold to the $K\overline{K}$ effective mass range including the $\phi(1020)$ resonance. We know from [11] that 8 amplitudes are needed to describe the S-wave of the K^+K^- system. In addition to the S-wave amplitudes we have to construct 24 P-wave amplitudes in the above effective mass range. They depend on two spin projections of the photon ($\lambda = \pm 1$), three spin projections of the ϕ ($M = 1, 0, -1$), two incoming proton spin projections ($s_1 = \pm 1/2$) and two final proton spin projections ($s_2 = \pm 1/2$). Parity conservation places further restrictions on the amplitudes and these will be discussed later. If we include only S and P partial waves so that the maximum value of the K^+K^- angular momentum J equals to one then the reaction

$$\gamma + p \to K^+ + K^- + p \tag{1}$$

is described by 36 amplitudes $T^J_M(\lambda, s_1, s_2)$. We denote the photon four-momentum by q, the initial and final proton four-momenta by p_1 and p_2 and the produced kaon K^+ and K^- four-momenta by k_1 and k_2, respectively. The amplitudes $T^J_M(\lambda, s_1, s_2)$ depend on five independent kinematical variables s, t, M_{KK} and Ω_K, where s and t are the Mandelstam variables equal to square of the total energy in the center of mass system and the four-momentum transfer squared, respectively. M_{KK} is the K^+K^- effective mass and Ω_K denotes the K^+ solid angle. The $K\overline{K}$ center of mass system, in which $\boldsymbol{k}_1 + \boldsymbol{k}_2 = 0$, is a convenient frame of reference to discuss kaon angular distributions. One can choose the z-axis antiparallel to the direction of the recoiling proton and the y-axis parallel to $\boldsymbol{p}_1 \times \boldsymbol{p}_2$, where $\boldsymbol{p}_1$ is the initial proton momentum and $\boldsymbol{p}_2$ is the final proton momentum. Thus the photon momentum $\boldsymbol{q}$ lies in the x–z plane being the ϕ-proton production plane. We choose the x-axis in such a way that the x-component of $\boldsymbol{p}_1$ is positive and consequently the projection of $\boldsymbol{q}$ on the x-axis is negative. This frame, called the s-channel helicity frame, is convenient to study the wave interference.

Let us assume that the main production mechanism of two kaons has a diffractive character and proceeds in two steps. In the first step the $\phi(1020)$ meson is produced on a proton and in the second step it decays into two kaons. One can assume that the $\phi(1020)$ is produced via soft pomeron exchange which leads to almost purely imaginary amplitude at small momentum transfers [21]. The $K\overline{K}$ effective mass distribution of the ϕ decay can be simply related to the relativistic Breit–Wigner propagator

$$\mathrm{BW}(M_{KK}) = \frac{1}{(M_\phi^2 - M_{KK}^2 - iM_\phi \Gamma_\phi)}\,, \tag{2}$$

where M_ϕ and Γ_ϕ are the $\phi(1020)$ meson mass and total width. We consider the following P-wave amplitude

$$T^P(\lambda, s_1, s_2) = F(s,t)\,\mathrm{BW}(M_{KK})\overline{u}(p_2,s_2)\gamma_\alpha u(p_1,s_1) w_\alpha^\lambda\,, \tag{3}$$

where

$$w_\alpha^\lambda = q_\alpha \varepsilon^\lambda \cdot (k_1 - k_2) - q \cdot (k_1 - k_2)\varepsilon_\alpha^\lambda\,. \tag{4}$$

In (3) $F(s,t)$ is a phenomenological function which should be suitably parameterised to reproduce the energy, s and t-dependence of the experimental cross section for the $\phi(1020)$ photoproduction. Its analytical form can depend on the t-range covered in a given experiment. The four-component Dirac spinors of incoming and outgoing protons are denoted by $u(p_1,s_1)$ and $u(p_2,s_2)$, respectively; γ_α, $\alpha = 0,1,2,3$, are the Dirac matrices and $\varepsilon_\alpha^\lambda$, $\lambda = \pm 1$, are the photon polarisation four-vectors.

Using the Dirac equations for proton spinors in the initial and final states one can rewrite the P-wave amplitude in an equivalent form

$$T^P(\lambda, s_1, s_2) = F(s,t)\,\mathrm{BW}(M_{KK})\overline{u}(p_2,s_2)\gamma_\alpha u(p_1,s_1) v_\alpha^\lambda\,, \tag{5}$$

where

$$v_\alpha^\lambda = k_\alpha \varepsilon^\lambda \cdot (k_1 - k_2) - q \cdot (k_1 - k_2)\varepsilon_\alpha^\lambda \tag{6}$$

and $k = k_1 + k_2$ is the ϕ meson four-momentum. The P-wave amplitude, introduced above, is gauge invariant. It can be expressed as a sum of three partial waves $T^1_M(\lambda, s_1, s_2)$ corresponding to three different ϕ spin projections M

$$T^P(\lambda, s_1, s_2) = \sum_{M=1,0,-1} T^1_M(\lambda, s_1, s_2) Y^1_M(\Omega_K)\,, \tag{7}$$

where $Y^1_M(\Omega_K)$ are the spherical harmonics.

The resulting amplitudes are invariant under parity transformation. This property can be used to eliminate 12 of the 24 helicity amplitudes since they satisfy the following symmetry relations (valid also for the S-wave, $J = 0$) [22]

$$T^J_{-M}(-\lambda, -s_1, -s_2) = (-1)^{M-s_2-\lambda+s_1} \;\; T^J_M(\lambda, s_1, s_2)\,. \tag{8}$$

Using this symmetry one can consider only amplitudes with $\lambda = +1$ and then one can refer to $T^1_1(1, s_1, s_2)$ as the non-flip amplitude, $T^1_0(1, s_1, s_2)$ as the single-flip amplitude and $T^1_{-1}(1, s_1, s_2)$ as the double-flip amplitude. The first amplitude is dominant and the second one is responsible for the S–P interference.

The four-fold differential cross section can be expressed in terms of the helicity amplitudes $T^J_M(\lambda, s_1, s_2)$ in the following way

$$\frac{d\sigma}{d\Omega dM_{KK}dt} = \frac{1}{4} \sum_{J,M,\lambda,s_1,s_2} \left| T^J_M(\lambda, s_1, s_2) Y^J_M(\Omega_K)\right|^2 . \tag{9}$$

3. Explicit form of the *P*-wave amplitudes

Let us proceed to a derivation of the P-wave amplitudes. In the first step one can evaluate the matrix element consisting of the Dirac matrices $\gamma_\alpha \equiv (\gamma_0, \boldsymbol{\gamma})$

$$\overline{u}(p_2, s_2)\gamma_\alpha u(p_1, s_1) v_\alpha = \overline{u}(p_2, s_2)(v_0\gamma_0 - \boldsymbol{v}\cdot\boldsymbol{\gamma}) u(p_1, s_1)\,. \tag{10}$$

We get

$$\begin{aligned}
\overline{u}(p_2, s_2)\gamma_0 u(p_1, s_1) &= f u^\dagger_{s_2}(A - i\boldsymbol{B}\cdot\boldsymbol{\sigma}) u_{s_1}\,, &(11)\\
A &= 1 + \boldsymbol{r}_1\cdot\boldsymbol{r}_2\,, &(12)\\
\boldsymbol{B} &= \boldsymbol{r}_1 \times \boldsymbol{r}_2\,, &(13)\\
f &= [(E_1 + m)(E_2 + m)]^{1/2} &(14)
\end{aligned}$$

and

$$\begin{aligned}
\overline{u}(p_2, s_2)\boldsymbol{v}^\lambda\cdot\boldsymbol{\gamma} u(p_1, s_1) &= f\, u^\dagger_{s_2}(C^\lambda + \boldsymbol{D}^\lambda\cdot\boldsymbol{\sigma}) u_{s_1}\,, &(15)\\
C^\lambda &= \boldsymbol{v}^\lambda\cdot(\boldsymbol{r}_1 + \boldsymbol{r}_2)\,, &(16)\\
\boldsymbol{D}^\lambda &= i\cdot[\boldsymbol{v}^\lambda \times (\boldsymbol{r}_1 - \boldsymbol{r}_2)]\,. &(17)
\end{aligned}$$

In (11) and (15) u_{s_1} and u_{s_2} are two-component Pauli spinors for the incoming and outgoing protons, and the Dirac spinors are normalised to $2m$, m being the proton mass; E_1 and E_2 are the energies of the incoming and outgoing proton, respectively. The vectors $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are defined as

$$\boldsymbol{r}_1 = \frac{\boldsymbol{p}_1}{E_1 + m}, \qquad \boldsymbol{r}_2 = \frac{\boldsymbol{p}_2}{E_2 + m} . \tag{18}$$

The three Pauli matrices are denoted by $\boldsymbol{\sigma}$. The formulae (11) till (18) are valid in any reference frame.

In the following evaluation of the transition amplitudes we use the transverse gauge so the fourth component of the photon polarisation $\varepsilon_0^\lambda = 0$. In the ϕ center of mass frame one can express the four vector $v_\alpha^\lambda = (v_0^\lambda, \boldsymbol{v}^\lambda)$ as follows

$$v_0^\lambda = -2M_{KK}\, \boldsymbol{\varepsilon}^\lambda \cdot \boldsymbol{k}_1 , \tag{19}$$

$$\boldsymbol{v}^\lambda = 2\boldsymbol{q} \cdot \boldsymbol{k}_1\, \boldsymbol{\varepsilon}^\lambda . \tag{20}$$

Let us denote the polar angle of the K^+ meson by θ and the azimuthal angle by ϕ. The polar angle of the photon momentum $\boldsymbol{q}$ is called θ_q, so the components of $\boldsymbol{q}$ are

$$\boldsymbol{q} = |\boldsymbol{q}|(-\sin\theta_q, 0, \cos\theta_q) . \tag{21}$$

The photon polarisation vectors are perpendicular to $\boldsymbol{q}$ and are equal to

$$\boldsymbol{\varepsilon}^\lambda = -\frac{\lambda}{\sqrt{2}}(\cos\theta_q, i\lambda, \sin\theta_q) . \tag{22}$$

Using the energy and momentum conservation one can calculate the kinematical variables expressed in the ϕ center of mass frame in terms of the invariants s, t and M_{KK}

$$E_1 = \frac{s - m^2 + t}{2M_{KK}}, \quad E_2 = \frac{s - m^2 - M_{KK}^2}{2M_{KK}} , \tag{23}$$

$$|\boldsymbol{q}| = \frac{M_{KK}}{2} - \frac{t}{2M_{KK}} , \tag{24}$$

and

$$\cos\theta_q = \frac{E_1^2 - E_2^2 - |\boldsymbol{q}|^2}{2|\boldsymbol{q}||\boldsymbol{p}_2|} . \tag{25}$$

The partial wave decomposition of the P-wave amplitude (3) is performed by taking into account two identities valid for the scalar products present in (19) and in (20)

$$\boldsymbol{\varepsilon}^\lambda \cdot \boldsymbol{k}_1 = \kappa \left(\frac{4\pi}{3}\right)^{1/2} \sum_{M=\pm1,0} b_M^\lambda\, Y_M^1(\Omega_K) , \tag{26}$$

$$b_M^\lambda = \delta_M^\lambda + \frac{\cos\theta_q - 1}{2}(-1)^{\frac{\lambda-M}{2}} \qquad \text{for } M = \pm 1\,, \tag{27}$$

$$b_0^\lambda = \frac{-\lambda\sin\theta_q}{\sqrt{2}}\,, \tag{28}$$

and

$$\boldsymbol{q}\cdot\boldsymbol{k}_1 = |\boldsymbol{q}|\;\kappa\left(\frac{4\pi}{3}\right)^{1/2}\sum_{M=\pm1,0}\rho_M\;Y_M^1(\Omega_K)\,, \tag{29}$$

$$\rho_1 = \frac{\sin\theta_q}{\sqrt{2}}\,, \qquad \rho_0 = \cos\theta_q\,, \qquad \rho_{-1} = \frac{-\sin\theta_q}{\sqrt{2}}\,. \tag{30}$$

The quantity κ in (26) and (29) is the magnitude of the relative kaon momentum in the ϕ c.m. frame. This momentum is related to the effective $K\overline{K}$ mass

$$\kappa = \left(\frac{M_{KK}^2}{4} - m_K^2\right)^{1/2}\,, \tag{31}$$

where m_K is the kaon mass. The matrix elements (11) and (15) depend on the proton helicities s_1 and s_2, so they form 2×2 matrices, in which the first index $s_1 = \pm 1/2$ labels columns and the second one $s_1 = \pm 1/2$ labels rows. Below we define four spin matrices and write their matrix elements

$$N_{s_1s_2} \equiv u_{s_2}^\dagger u_{s_1} = \begin{pmatrix} \tilde{s} & \tilde{c} \\ -\tilde{c} & \tilde{s} \end{pmatrix}, \tag{32}$$

$$N_{s_1s_2}^x \equiv u_{s_2}^\dagger \sigma_x u_{s_1} = \begin{pmatrix} \tilde{c} & -\tilde{s} \\ -\tilde{s} & -\tilde{c} \end{pmatrix}, \tag{33}$$

$$N_{s_1s_2}^y \equiv u_{s_2}^\dagger \sigma_y u_{s_1} = \begin{pmatrix} i\tilde{c} & -i\tilde{s} \\ i\tilde{s} & i\tilde{c} \end{pmatrix}, \tag{34}$$

$$N_{s_1s_2}^z \equiv u_{s_2}^\dagger \sigma_z u_{s_1} = \begin{pmatrix} -\tilde{s} & -\tilde{c} \\ -\tilde{c} & \tilde{s} \end{pmatrix}. \tag{35}$$

We have introduced the following abbreviations in the matrices written above

$$\tilde{c} = \cos\left(\frac{\theta_1}{2}\right)\,, \qquad \tilde{s} = \sin\left(\frac{\theta_1}{2}\right)\,, \tag{36}$$

where θ_1 denotes the polar angle of the initial proton in the s-channel helicity frame. The following kinematical relation together with formulae (23) can be useful in computations of partial wave amplitudes

$$\cos\theta_1 = \frac{m^2 - E_1\ E_2 - \frac{t}{2}}{|\boldsymbol{p}_1||\boldsymbol{p}_2|}\,. \tag{37}$$

The angle θ_1 of the initial proton tends to 180° in the limit of high photon energy and at small momentum transfers. Let us remark here that the polar angle of the final proton is always equal to 180° in our reference frame.

Finally, putting together the expressions given by (5)–(7), (10)–(20), (26)–(30) and (32)–(35) one obtains the P-wave partial wave amplitudes

$$\begin{aligned} T^1_M(\lambda, s_1, s_2) \ = \ & R\,[N_{s_1 s_2}(M_{KK} b^\lambda_M A + |\boldsymbol{q}|\rho_M G^\lambda) + N^x_{s_1 s_2}|\boldsymbol{q}|\rho_M \boldsymbol{H}^\lambda_x \\ & + N^y_{s_1 s_2}(-iM_{KK} b^\lambda_M |\boldsymbol{B}| + |\boldsymbol{q}|\rho_M \boldsymbol{H}^\lambda_y) + N^z_{s_1 s_2}|\boldsymbol{q}|\rho_M \boldsymbol{H}^\lambda_z]\,, \end{aligned} \tag{38}$$

where

$$G^\lambda = \boldsymbol{\varepsilon}^\lambda \cdot (\boldsymbol{r}_1 + \boldsymbol{r}_2), \tag{39}$$

$H^\lambda_x, H^\lambda_y, H^\lambda_z$ are the components of the vector

$$\boldsymbol{H}^\lambda = i\boldsymbol{\varepsilon}^\lambda \times (\boldsymbol{r}_1 - \boldsymbol{r}_2) \tag{40}$$

and the common factors are included in the R function defined as

$$R = -2\left(\frac{4\pi}{3}\right)^{1/2} \kappa f F(s,t)\, \mathrm{BW}(M_{KK})\,. \tag{41}$$

4. High energy limit

It is instructive to calculate the photoproduction amplitudes in the limit of high photon energy. This is a limit in which the invariant s is much larger that the momentum transfer squared and it is also larger than the square of the effective mass M_{KK}. Let us notice that in this limit the energies or the momenta of the incoming and the outgoing protons in the ϕ c.m. frame are of the same order. Using the formulae (38)–(40) and (13) one can notice that terms proportional to $\boldsymbol{B}$, D^λ_x, D^λ_y and D^λ_z vanish as $1/s$ in the limit $s \to \infty$. It is sufficient to discuss only one case of the photon polarisation $\lambda = 1$. Due to the symmetry property (8) the amplitudes with $\lambda = -1$ are related to the previous case of $\lambda = 1$. Next one can verify that the coefficients b^1_λ behave as follows

$$b^1_1 \approx 1\,, \qquad b^1_0 \approx \frac{-\sqrt{-2t}}{M_{KK}}\,, \qquad b^1_{-1} \approx \frac{-t}{M^2_{KK}}\,, \tag{42}$$

since

$$\cos\theta_q \approx \frac{1+\frac{t}{M_{KK}^2}}{1-\frac{t}{M_{KK}^2}}\,. \tag{43}$$

The presence of the symbol δ_M^λ in (27) means that the ϕ amplitude, which conserves the helicity of the photon, dominates at high energy and the low momentum transfers (the so-called s-channel helicity conservation). Next we see that in the same limit

$$T_1^1(1,s_1,s_2) = 2RN_{s_1s_2}M_{KK}\,, \tag{44}$$

$$T_0^1(1,s_1,s_2) = -RN_{s_1s_2}\sqrt{-2t} \tag{45}$$

and

$$T_{-1}^1(1,s_1,s_2) \approx 0(1/s)\,. \tag{46}$$

From (44) and (45) one notices that the ϕ production with helicity 0 is reduced if $-t$ is much smaller than the square of the effective mass M_{KK}. The amplitude T_{-1}^1 is of the order of $1/s$ and is negligible at high energies.

Let us make a comment on the behaviour of production amplitudes as functions of the proton helicities. In the high energy limit one has

$$\tilde{s} \approx 1\,, \qquad \tilde{c} \approx M_{KK}\frac{\sqrt{-t}}{s}\,. \tag{47}$$

Inspecting the expression in (32) for $N_{s_1s_2}$ we immediately notice dominance of the proton helicity non-flip amplitudes in the $K\overline{K}$ photoproduction over proton helicity flip amplitudes if $s \gg M_{KK}\sqrt{-t}$.

5. "Scalar" pomeron versus "vector" pomeron

In Söding's paper [15] one can find an expression for the diffractive ρ photoproduction amplitude on a nucleon which is different from the P-wave amplitude written in (3) or in (5). While the later amplitude has a typical "vector" or photon-like coupling of the exchanged pomeron to the nucleon the former amplitude is typical for the "scalar" pomeron coupling. Such "scalar" type amplitudes have been used in description of the ϕ photoproduction in [18] and in [20]. The Söding type amplitude adapted for the ϕ photoproduction is proportional to

$$U(\lambda,s_1,s_2) = V_\lambda\, \overline{u}(p_2,s_2)u(p_1,s_1)\,, \tag{48}$$

where

$$V_\lambda = q\cdot k\,\varepsilon^\lambda\cdot(k_1-k_2) - q\cdot(k_1-k_2)\,\varepsilon^\lambda\cdot k\,. \tag{49}$$

This amplitude has a factorised form. The factor V_λ in the ϕ c.m. frame is given by

$$V_\lambda = -2M_{KK}\ |\boldsymbol{q}|\ \boldsymbol{\varepsilon^\lambda}\cdot\boldsymbol{k}_1\,. \tag{50}$$

The nucleon part which depends only on the proton spin projections reads

$$\overline{u}(p_2,s_2)u(p_1,s_1) = f[(2-A)N_{s_1s_2} + i|\boldsymbol{B}|N^y_{s_1s_2}]\,. \tag{51}$$

We make the partial wave decomposition of $U(\lambda,s_1,s_2)$ as follows

$$U(\lambda,s_1,s_2) = \sum_{M=1,0,-1} U^1_M(\lambda,s_1,s_2)Y^1_M(\Omega_K)\,. \tag{52}$$

Then the partial wave amplitudes in the "scalar" pomeron model read

$$U^1_M(\lambda,s_1,s_2) = Z\ b^\lambda_M[(2-A)N_{s_1s_2} + i|\boldsymbol{B}|N^y_{s_1s_2}]\,, \tag{53}$$

where

$$Z = -2\left(\frac{4\pi}{3}\right)^{1/2}\kappa f M_{KK}\ |\boldsymbol{q}|\,. \tag{54}$$

The calculation of the high energy limit specified in the previous chapter can be done using the explicit form of the functions A and $\boldsymbol{B}$ defined in (12), (13), (18) and (42). One obtains

$$U^1_M(\lambda,s_1,s_2) = Z\ b^\lambda_M\frac{4mM_{KK}}{s}\left[N_{s_1s_2} + i\frac{\sqrt{-t}}{2m}N^y_{s_1s_2}\right]\,. \tag{55}$$

We notice that the amplitudes corresponding to the "scalar" pomeron exchange are suppressed as $1/s$ at high energies. There is also another difference between (55) and (45–46), namely the proton helicity flip contributions coming from the second part of (55) proportional to $N^y_{s_1s_2}$, can be important at $-t$ comparable to m^2.

6. Concluding remarks

Photoproduction of kaon pairs with invariant mass near 1 GeV is dominated by the $\phi(1020)$ resonance. This is close to the $K\bar{K}$ threshold and through S- and P- wave interference can give important insight into the soft meson-meson interactions and a possibility of formation of mesonic bound states. The entangled P-wave $K\bar{K}$ state from the $\phi(1020)$ decay has been recognised as a tool for studies of CP and possible CPT violations [25], and the possibility of using both S- and P- wave combinations opens up more possibilities for such studies [26].

As the first step we have derived analytical expressions for the elastic amplitudes for ϕ photoproduction. The main result is given by Eq. (38). From the above formula one can calculate 24 P-wave amplitudes depending on the helicities of the photon, the $K\overline{K}$ pair, and the incoming and outgoing protons. These amplitudes can be used in the partial wave analysis of the K^+K^- photoproduction for the K^+K^- effective masses varying from the $K\overline{K}$ threshold to the range covering the $\phi(1020)$ resonance. In particular one can study the S–P interference effects if the S-wave amplitudes from Ref. [11] are included. This will be a subject of the subsequent investigations.

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