SOVIET PHYSICS JETP VOLUME 19, NUMBER 1 JULY, 1964

PHOTOPRODUCTION OF STRANGE PARTICLES AT HIGH ENERGIES

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Submitted to JETP editor June 21, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **46**, 293-299 (January, 1964)

Photoproduction of strange particles at high energies and at K-meson production angles $\sim 180°$ in the c.m.s. is considered. Both possible values of the intrinsic parity of the KNY system are discussed. Expressions for asymptotic cross sections and various polarization effects are obtained on the basis of the hypothesis of moving Regge poles in the scattering amplitude.

1. A recent study of the analytic properties of the scattering amplitude as a function of the orbital angular momentum j, has yielded many interesting results in the theory of strong interactions[1]. In particular, it was found that the scattering amplitude is an analytic function of the angular momentum j and can have moving poles in the right half-plane of the complex variable j. The pole farthest to the right determines the asymptotic value of the scattering amplitude A(s, u) at large energies $\sqrt{s}$ and at finite momentum transfers $\sqrt{-u}$ (finite values of u and large s correspond to scattering at angles of the order of 180°).

Gribov[2] has shown that in this region of energies and angles, the asymptotic behavior of processes of the type $\pi + N \to \pi + N$, $\gamma + N \to \gamma + N$, $\gamma + N \to \Sigma + K$, and other analogous processes is determined by the fermion poles, i.e., poles which describe different fermion families. These poles have the property that in the physical region of the scattering channel ($u < 0$) they occur in pairs at complex-conjugate points in the partial helicity amplitudes.

In the present paper we consider the production of strange particles following interaction between high-energy photons and nucleons, i.e., the reactions $\gamma + N \to \Lambda + K$ and $\gamma + N \to \Sigma + K$. The asymptotic behavior of these processes at K-meson emission angles of the order of 180° relative to the photon momentum is determined by a fermion pole that possesses strangeness. Therefore a study of the photoproduction of strange particles in the indicated energy and angle region enables us to check, in principle, the correctness of the hypothesis that the Λ and Σ hyperons are not elementary particles but a bound system of other strongly interacting particles.

2. The amplitude for the photoproduction of K mesons by nucleons is written in the s channel in the form[3]

$$A = \bar{u}(p_2)\{\Gamma\hat{\varepsilon}\hat{k}A_1(s,u) + \Gamma[(\varepsilon p_1)(kp_2) - (\varepsilon p_2)(kp_1)]A_2(s,u) - i\Gamma[\hat{\varepsilon}(kp_1) - \hat{k}(\varepsilon p_1)]A_3(s,u) - i\Gamma[\hat{\varepsilon}(kp_2) - \hat{k}(\varepsilon p_2)]A_4(s,u)\}u(p_1), \quad (1)$$

where $s = -(k + p_1)^2$, $u = -(k - p_2)^2$, k is the photon momentum, p_1 is the momentum of the initial nucleon, p_2 is the momentum of the final hyperon, and ε is the photon polarization vector; $\Gamma = +1$ if the intrinsic parity of the KNY system is positive, $\Gamma = i\gamma_5$ if the intrinsic parity of the KNY system is negative. Inasmuch as this parity has not been established reliably at present, we shall consider both possibilities.

3. We first consider the case of positive intrinsic parity of the KNY system. We change over to the u channel, for which we substitute $-k$ for k in (1). Using the explicit form of the spinors $u(p_2)$ and $u(p_1)$, we proceed in (1) to two-component spinors. The four-component spinors $u(p_1)$ and $u(p_2)$ are of the form

$$u(p_1) = \sqrt{E_1 + M}\begin{pmatrix}\chi_1 \\ \dfrac{\sigma\mathbf{q}}{E_1+M}\chi_1\end{pmatrix},$$

$$u(p_2) = \sqrt{E_2 + M_Y}\begin{pmatrix}\chi_2 \\ \dfrac{\sigma\mathbf{k}}{E_2+M_Y}\chi_2\end{pmatrix}, \quad (2)$$

where σ—Pauli matrices, E_1, M—energy and mass of the nucleon, E_2, M_Y—energy and mass of the final hyperon, **q**—nucleon momentum and **k**—hyperon momentum in the c.m.s. of the u-channel.

We introduce in the u-channel c.m.s. an amplitude F such that the differential cross section of the process $\overline{K} + N \to \gamma + Y$ is expressed in terms of this cross section with the aid of the formula

$$d\sigma / d\Omega = (q/k) |\chi_2^* F \chi_1|^2.$$

The amplitude F can be represented by the expansion

$$F = (\sigma\varepsilon)(\sigma\hat{q}) F_1 + (\sigma\varepsilon)(\sigma\hat{k}) F_2 + (\sigma\hat{k})(\sigma\hat{q})(\hat{q}\varepsilon) F_3 + (\varepsilon\hat{q}) F_4. \quad (3)$$

The amplitudes F_i are related with the invariant amplitudes A_i as follows:

$$F_1(w, \cos\theta) = \frac{k}{4\pi}\sqrt{\frac{E_1 - M}{2w}}\left[A_1 + \frac{w + M_Y}{2}A_4 - \frac{(kp_1)}{w - M_Y}A_3\right],$$

$$F_2(w, \cos\theta) = \frac{k}{4\pi}\sqrt{\frac{E_1 + M}{2w}}\left[A_1 - \frac{w - M_Y}{2}A_4 + \frac{(kp_1)}{w + M_Y}A_3\right],$$

$$F_3(w, \cos\theta) = \frac{kq}{4\pi}\sqrt{\frac{E_1 - M}{2w}}\left[-A_3 - \frac{w - M_Y}{2}A_2\right],$$

$$F_4(w, \cos\theta) = \frac{kq}{4\pi}\sqrt{\frac{E_1 + M}{2w}}\left[-A_3 + \frac{w - M_Y}{2}A_2\right], \quad (4)$$

where w is the total energy in the u channel ($w = \sqrt{u}$).

Recognizing that A_i depends only on s and u, we can readily see from (4) that the following symmetry properties are satisfied for the amplitudes F_i:

$$F_1(w) = -F_2(-w), \qquad F_3(w) = F_4(-w). \quad (5)$$

These properties will be essentially used in what follows.

We introduce the helicity amplitudes in the u channel [4]:

$$f_1 \equiv \left(\tfrac{1}{2}, 1 | F | \tfrac{1}{2}, 0\right) = -2\sin\frac{\theta}{2}\sum_j f_1^j(w)\,[P'_{j+1/2}(z) + P'_{j-1/2}(z)],$$

$$f_2 \equiv \left(-\tfrac{1}{2}, -1 | F | \tfrac{1}{2}, 0\right) = 2\cos\frac{\theta}{2}\sum_j f_2^j(w)\,[P'_{j+1/2}(z) - P'_{j-1/2}(z)],$$

$$f_3 \equiv \left(\tfrac{1}{2}, -1 | F | \tfrac{1}{2}, 0\right) = 2\sin\frac{\theta}{2}\sum_j f_3^j(w)\left[\sqrt{\frac{2j-1}{2j+3}}P'_{j+1/2} + \sqrt{\frac{2j+3}{2j-1}}P'_{j-1/2}\right],$$

$$f_4 \equiv \left(-\tfrac{1}{2}, 1 | F | \tfrac{1}{2}, 0\right) = -2\cos\frac{\theta}{2}\sum_j f_4^j(w)\left[\sqrt{\frac{2j-1}{2j+3}}P'_{j+1/2} - \sqrt{\frac{2j+3}{2j-1}}P'_{j-1/2}\right], \quad (6)$$

where $z = \cos\theta$ and θ is the angle of emission of the quantum in the u channel. These helicity amplitudes are expressed in terms of the amplitudes F_i which we introduced above:

$$f_1 = -2^{-1/2}\sin(\theta/2)\,[(1 + \cos\theta)(F_3 + F_4) - 2(F_1 - F_2)],$$
$$f_2 = 2^{-1/2}\cos(\theta/2)\,[(1 - \cos\theta)(F_3 - F_4) - 2(F_1 + F_2)],$$
$$f_3 = 2^{-1/2}\sin(\theta/2)\,(1 + \cos\theta)(F_3 + F_4),$$
$$f_4 = -2^{-1/2}\cos(\theta/2)\,(1 - \cos\theta)(F_3 - F_4). \quad (7)$$

The partial helicity amplitudes f_α^j can be related with the partial amplitudes with definite parity:

$$f_1^j = {}^1/_2(h_1^j + h_2^j), \quad f_2^j = {}^1/_2(h_1^j - h_2^j),$$
$$f_3^j = {}^1/_2(h_3^j + h_4^j), \quad f_4^j = {}^1/_2(h_3^j - h_4^j), \quad (8)$$

where the partial amplitudes h_1^j and h_3^j have the same parity, opposite that of amplitudes h_2^j and h_4^j.

Starting with the symmetry relations (5), the connection (6) between the helicity and partial amplitudes f_i and f_α^j, and the relations (7) between the helicity amplitudes and the F_i amplitudes, and the definition (8) of the partial amplitudes with definite parity, we can readily verify that a connection exists between the amplitudes with the opposite parity:

$$h_1^j(w) = h_2^j(-w), \qquad h_3^j(w) = h_4^j(-w). \quad (9)$$

In order to obtain (9), it is sufficient to consider (6) and (7) for large $\cos\theta$.

If the $h_\alpha^j(w)$ as functions of j have moving singularities, then at $u = 0$ these singularities for h_1^j and h_2^j should coincide, by virtue of (9); for the same reason, the singularities at $u = 0$ coincide also for the amplitudes h_3^j and h_4^j. In the physical region of the s channel ($u < 0$) the quantity w is pure imaginary, so that conditions (9) require complex conjugate positions of the singularities at $u < 0$ of the amplitudes h_1^j and h_2^j, and also of h_3^j and h_4^j. Therefore, if we assume that the amplitudes h_1^j and h_3^j have a pole, then the amplitudes h_2^j and h_4^j will also have a pole in the physical region of the s channel at a point conjugate to the position of the pole of the amplitudes of h_1^j and h_3^j, with the residues at the poles of the amplitudes h_1^j and h_2^j, h_3^j and h_4^j being pairwise complex conjugate.

Let us consider the asymptotic behavior at $s \to \infty$ and $u = \text{const} < 0$. To this end we transform (6) into an integral by the well known procedure (the Sommerfeld-Watson transformation), and deform the integration contour in suitable fashion; then the main contribution to the asymptotic value will be made by the pole farthest to the right (we assume that the $h_\alpha^j(w)$ as functions of j have singularities in the right half-plane of j only in the form of moving poles). Recognizing that in the helicity partial amplitudes the poles are present in pairs at conjugate points, with conjugate residues, we get

$$\frac{f_1}{2\sin(\theta/2)}+\frac{f_2}{2\cos(\theta/2)}=-\frac{\alpha^*}{\cos\pi j^*}[s^{j^*-1/2}\mp(-s)^{j^*-1/2}],$$
$$\frac{f_1}{2\sin(\theta/2)}-\frac{f_2}{2\cos(\theta/2)}=-\frac{\alpha}{\cos\pi j}[s^{j-1/2}\mp(-s)^{j-1/2}],$$
$$\frac{f_3}{2\sin(\theta/2)}+\frac{f_4}{2\cos(\theta/2)}=\frac{\beta^*}{\cos\pi j^*}[s^{j^*-1/2}\mp(-s)^{j^*-1/2}],$$
$$\frac{f_3}{2\sin(\theta/2)}-\frac{f_4}{2\cos(\theta/2)}=\frac{\beta}{\cos\pi j}[s^{j-1/2}\mp(-s)^{j-1/2}], \quad (10)$$

where α is the residue of h_1^j and β is the residue of h_3^j; both residues are multiplied by some known function which arises when asymptotic values are taken for the Legendre polynomials in (6) and when the sums in (6) are transformed into integrals: the $\mp$ signs correspond to different signatures.

Using the asymptotic expressions (10), we can obtain with the aid of (7) asymptotic formulas for the amplitudes F_i, after which we can get from (4) the asymptotic values of the invariant amplitudes A_i in the physical region of the photoproduction channel ($s\to\infty$, $u<0$).

To calculate the differential cross sections, the polarizations, and the polarization correlations it is convenient to have asymptotic expressions for the helicity amplitudes in the s channel, since all the foregoing quantities are expressed simply in terms of the helicity amplitudes. Leaving out the intermediate calculations, we present the final formulas for the helicity amplitudes in the s channel:

$$F_{1s}\equiv(0,{}^1/_2\,|F_s|\,{}^1/_2,1)=f_+^{(1)}-f_-^{(1)},$$
$$F_{2s}\equiv(0,{}^1/_2\,|F_s|-{}^1/_2,-1)=i(f_+^{(2)}+f_-^{(2)}),$$
$$F_{3s}\equiv(0,{}^1/_2\,|F_s|-{}^1/_2,1)=i(f_+^{(1)}+f_-^{(1)}),$$
$$F_{4s}\equiv(0,{}^1/_2\,|F_s|\,{}^1/_2,-1)=f_+^{(2)}-f_-^{(2)}, \quad (11)$$

where F_s is the amplitude in the c.m.s. of the s channel, analogous to the F-amplitude introduced above in the c.m.s. of the u channel. The quantities $f_\pm^{(1)}$ and $f_\pm^{(2)}$ are connected with the residues α and β:

$$f_+^{(1)}=-\frac{\alpha\sqrt{u}-\beta M_Y}{16\pi}\,\frac{s^{j-1/2}\mp(-s)^{j-1/2}}{\cos\pi j},$$
$$f_-^{(1)}=-\frac{(\alpha\sqrt{u}-\beta M_Y)^*}{16\pi}\,\frac{s^{j^*-1/2}\mp(-s)^{j^*-1/2}}{\cos\pi j^*},$$
$$f_+^{(2)}=-\frac{\alpha M_Y-\beta\sqrt{u}}{16\pi}\,\frac{s^{j-1/2}\mp(-s)^{j-1/2}}{\cos\pi j},$$
$$f_-^{(2)}=-\frac{(\alpha M_Y-\beta\sqrt{u})^*}{16\pi}\,\frac{s^{j^*-1/2}\mp(-s)^{j^*-1/2}}{\cos\pi j^*}. \quad (12)$$

Let us calculate the real and imaginary parts of the asymptotic helicity amplitudes:

$$\mathrm{Re}\,F_{1s}=\pm\rho_1\sin(j''\zeta+\varphi_1)\,s^{j'-1/2},$$
$$\mathrm{Im}\,F_{1s}=-\alpha_\pm\rho_1\sin(j''\zeta+\varphi_1\mp\beta)\,s^{j'-1/2},$$
$$\mathrm{Re}\,F_{2s}=\mp\rho_2\cos(j''\zeta+\varphi_2)\,s^{j'-1/2},$$
$$\mathrm{Im}\,F_{2s}=\alpha_\pm\rho_2\cos(j''\zeta+\varphi_2\mp\beta)\,s^{j'-1/2},$$
$$\mathrm{Re}\,F_{3s}=\mp\rho_1\cos(j''\zeta+\varphi_1)\,s^{j'-1/2},$$
$$\mathrm{Im}\,F_{3s}=\alpha_\pm\rho_1\cos(j''\zeta+\varphi_1\mp\beta)\,s^{j'-1/2},$$
$$\mathrm{Re}\,F_{4s}=\pm\rho_2\sin(j''\zeta+\varphi_2)\,s^{j'-1/2},$$
$$\mathrm{Im}\,F_{4s}=-\alpha_\pm\rho_2\sin(j''\zeta+\varphi_2\mp\beta)\,s^{j'-1/2};$$
$$\alpha_\pm^2=\frac{\mathrm{ch}\,\pi j''\mp\sin\pi j'}{\mathrm{ch}\,\pi j''\pm\sin\pi j'},\quad \mathrm{tg}\,\beta=\frac{\mathrm{sh}\,\pi j''}{\cos\pi j'},\quad \zeta=\ln s, \quad (13)^*$$

where j′ is the real part of the function $j=j(u)$, which describes the position of the pole, and j″ is the imaginary part of this function,

$$\rho_1e^{i\varphi_1}=-(\alpha\sqrt{u}-\beta M_Y)/16\pi,$$
$$\rho_2e^{i\varphi_2}=-(\alpha M_Y-\beta\sqrt{u})/16\pi. \quad (14)$$

With the aid of (11)–(14) we can obtain the differential scattering cross section, averaged over the polarizations of all the particles:

$$d\sigma/d\Omega=2\,[|F_{1s}|^2+|F_{2s}|^2+|F_{3s}|^2+|F_{4s}|^2]$$
$$=2(1+\alpha_\pm^2)(\rho_1^2+\rho_2^2)\,s^{2j'-1}, \quad (15)$$

The polarization of the recoil hyperons for unpolarized target and γ quanta is:

$$P\,d\sigma/d\Omega=2\,\mathrm{Im}\,(F_{1s}^*F_{2s}+F_{3s}F_{4s}^*)$$
$$=4\alpha_\pm\sin\beta\rho_1\rho_2\cos(\varphi_1-\varphi_2)\,s^{2j'-1}. \quad (16)$$

We note that these quantities do not oscillate, in spite of the oscillating character of the helicity amplitudes. If we use high-energy linearly polarized photons, then the differential cross section averaged over the baryon polarizations also oscillates, and the components of the hyperon polarization vector will be non-oscillating functions of the energy and of the angle. The only oscillating quantities are the baryon polarization correlations for polarized and unpolarized photons.

4. We now consider a case when the KNY system has an intrinsic parity equal to −1. As in the preceding case, we introduce in the u-channel c.m.s. an amplitude F, which can be represented in the form

$$F=i(\boldsymbol{\sigma}\boldsymbol{\varepsilon})F_1+i(\boldsymbol{\sigma}\hat{\mathbf{k}})(\boldsymbol{\sigma}\boldsymbol{\varepsilon})(\boldsymbol{\sigma}\hat{\mathbf{q}})F_2$$
$$+i(\boldsymbol{\sigma}\hat{\mathbf{k}})(\hat{\mathbf{q}}\boldsymbol{\varepsilon})F_3+i(\boldsymbol{\sigma}\hat{\mathbf{q}})(\hat{\mathbf{q}}\boldsymbol{\varepsilon})F_4. \quad (17)$$

*ch = cosh, sh = sinh, tg = tan.

Using the explicit form of the spinors, we obtain a connection between the invariant amplitudes A_i and the amplitudes F_i:

$$F_1(w, \cos\theta) = \frac{k}{4\pi}\sqrt{\frac{E_1+M}{2w}}\left[-A_1 - \frac{w+M_Y}{2}A_4 + \frac{(kp_1)}{w-M_Y}A_3\right],$$

$$F_2(w, \cos\theta) = \frac{k}{4\pi}\sqrt{\frac{E_1-M}{2w}}\left[A_1 - \frac{w-M_Y}{2}A_4 + \frac{(kp_1)}{w+M_Y}A_3\right],$$

$$F_3(w, \cos\theta) = \frac{kq}{4\pi}\sqrt{\frac{E_1+M}{2w}}\left[A_3 + \frac{w-M_Y}{2}A_2\right],$$

$$F_4(w, \cos\theta) = \frac{kq}{4\pi}\sqrt{\frac{E_1-M}{2w}}\left[A_3 - \frac{w+M_Y}{2}A_2\right]. \qquad (18)$$

We see from (18) that the amplitudes F_i have the following symmetry properties:

$$F_1(w) = F_2(-w), \qquad F_3(w) = F_4(-w). \qquad (19)$$

We introduce in the u channel helicity amplitudes, the same as in (6), having the same expansions in the helicity partial amplitudes. These helicity amplitudes are connected with the amplitudes F_i by the relations

$$f_1 = 2^{-1/2}\sin(\theta/2)\,[-2(F_1+F_2) - (1+\cos\theta)(F_3+F_4)],$$
$$f_2 = 2^{-1/2}\cos(\theta/2)[-2(F_1-F_2) + (1-\cos\theta)(F_3-F_4)],$$
$$f_3 = 2^{-1/2}\sin(\theta/2)\,(1+\cos\theta)(F_3+F_4),$$
$$f_4 = -2^{-1/2}\cos(\theta/2)\,(1-\cos\theta)(F_3-F_4). \qquad (20)$$

The partial amplitudes with definite parity $h^j_\alpha(w)$ are connected with the helicity partial amplitudes by relations (8). Using the symmetry property (19) in conjunction with Eqs. (20), and repeating the arguments of the preceding section, we obtain

$$h_1^j(w) = h_2^j(-w), \qquad h_3^j(w) = h_4^j(-w). \qquad (21)$$

Therefore the poles of the amplitudes with opposite parity are situated at complex-conjugate points if $u < 0$. Assuming that the partial-amplitude singularity farthest to the right is a pole, we obtain asymptotic expressions similar to (10) for f_i.

We shall write out only the asymptotic formulas for the helicity amplitudes in the s channel

$$F'_{1s} \equiv (1/2, 0\,|F_s|\,1/2, 1) = f_+^{(1)} - f_-^{(1)},$$
$$F'_{2s} \equiv (1/2, 0\,|F_s|-1/2, -1) = -i\,(f_+^{(2)} + f_-^{(2)}),$$
$$F'_{3s} \equiv (1/2, 0\,|F_s|-1/2, 1) = -i\,(f_+^{(1)} + f_-^{(1)}),$$
$$F'_{4s} \equiv (1/2, 0\,|F_s|\,1/2, -1) = f_+^{(2)} - f_-^{(2)}, \qquad (22)$$

where $f_\pm^{(1)}$ and $f_\pm^{(2)}$ are connected with the residues α' and β' of the amplitudes h_1^j and h_3^j:

$$f_+^{(1)} = -\frac{\alpha'\sqrt{u} + \beta' M_Y}{16\pi}\,\frac{s^{j-1/2} \mp (-s)^{j-1/2}}{\cos\pi j},$$

$$f_-^{(1)} = -\frac{(\alpha'\sqrt{u} + \beta' M_Y)^*}{16\pi}\,\frac{s^{j^*-1/2} \mp (-s)^{j^*-1/2}}{\cos\pi j},$$

$$f_+^{(2)} = -\frac{\alpha' M_Y + \beta'\sqrt{u}}{16\pi}\,\frac{s^{j-1/2} \mp (-s)^{j-1/2}}{\cos\pi j},$$

$$f_-^{(2)} = -\frac{(\alpha' M_Y + \beta'\sqrt{u})^*}{16\pi}\,\frac{s^{j^*-1/2} \mp (-s)^{j^*-1/2}}{\cos\pi j^*}. \qquad (23)$$

With the aid of (22) and (23) we can calculate the differential cross section for photoproduction, averaged over the polarizations or the particles:

$$d\sigma/d\Omega = 2\,(1+\alpha_\pm^2)\,(\rho_1'^2 + \rho_2'^2)\,s^{2j'-1},$$
$$\rho_1' e^{i\varphi_1'} = -(\alpha'\sqrt{u} + \beta' M_Y)/16\pi,$$
$$\rho_2' e^{i\varphi_2'} = -(\alpha' M_Y + \beta'\sqrt{u})/16\pi. \qquad (24)$$

The polarization of the recoil hyperons is determined by the formula

$$P\,d\sigma/d\Omega = 4\alpha_\pm \sin\beta\,\rho_1'\rho_2' \cos(\varphi_1' - \varphi_2')\,s^{2j'-1}. \qquad (25)$$

As in the intrinsic-parity variant considered above for the KNY system, the differential cross section and the polarization of the recoil hyperons do not oscillate. Only the various correlation quantities will oscillate. For example, the polarization of the recoil hyperons in a direction perpendicular to the scattering plane, in the case when the nucleons are polarized in the x direction (the x axis is in the scattering plane), is determined by the following expression:

$$P' d\sigma/d\Omega = \rho_1'\rho_2' \sin 2\gamma\,[\sin(j''\zeta + \varphi_1')\sin(j''\zeta + \varphi_2') + \alpha_\pm^2 \sin(j''\zeta + \varphi_1' \mp \beta)\sin(j''\zeta + \varphi_2' \mp \beta)]\,s^{2j'-1}, \qquad (26)$$

where φ is the azimuth of the emission of the K meson. This quantity oscillates with energy and with angle, and the frequency of the angle oscillation increases logarithmically with increasing energy. The remaining correlation quantities can be easily calculated by using the formulas given above for the helicity amplitudes.

In conclusion I am grateful to A. I. Akhiezer for continuous interest in the work and for numerous discussions.

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Translated by J. G. Adashko
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