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Photoproduction of K Mesons at Low Energy*

FAYYAZUDDIN
Atomic Energy Centre, Lahore, Pakistan

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Photoproduction of K mesons is considered at low energy so that only s and p waves are important. The contribution of Born terms, K^* meson, and N^* resonance is calculated to the reaction $\gamma+N \to K+Y$. The values of unknown parameters such as hyperon magnetic moments and relative strengths and signs of $g_{KN\Lambda}$, $g_{KN\Sigma}$, $g_{K^*N\Lambda}$, and $g_{K^*N\Sigma}$ coupling constants as given by the octet model of unitary symmetry, are used. A reasonable fit to the experimental data on angular distributions for the reactions $\gamma+p \to K^+ + \Lambda^0$ and $\gamma+p \to K^+ + \Sigma^0$ is obtained in this model. In our model odd $K\Lambda$ and even $\Lambda\Sigma$ parities are implied. Thus the difference in the angular distribution of $K^+\Lambda^0$ and $K^+\Sigma^0$ production can be explained for even $\Lambda\Sigma$ parity. Certain predictions for other reactions have been obtained which can be tested experimentally when the data on these reactions will be available.

1. INTRODUCTION

IN the case of photoproduction of the pion at low energies, unitarity gives a simple relation between the phase of pion photoproduction matrix elements and pion nucleon-scattering phase shifts. In the case of K-meson photoproduction we have a multichannel system. The additional complication arises from the fact that more than two particle channels are open, i.e., multipion production is always possible at this energy. One does not know at present how to deal properly with multiparticle states. Therefore, the Mandelstam representation will not be of much use for such problems until the necessary machinery for dealing with multiparticle states has been developed.

We may hope to extract some information about K-meson photoproduction by using single dimensional dispersion relations.[1] We consider K-meson photoproduction at low energies where only s and p waves are important. We also employ the "threshold approximation.[2]" Using this approximation, we write the dispersion relations for the multipoles E_{0+}, E_{1+}, M_{1-}, and M_{1+}. We approximate the t channel $(\gamma+\bar{K} \to \bar{N}+Y)$ by the K^* meson pole. The dispersion integrals for the u channel $(\gamma+Y \to \bar{K}+N)$ can be calculated by inserting the two pion-hyperon resonance Y_1^* and Y_0^*. However, we have no reliable method of estimating the γYY^* couplings. We assume their contribution to be small and neglect them. This is justified by our results. Thus in writing the dispersion relations for the multipoles E_{0+}, E_{1+}, M_{1-}, and M_{1+}, the dispersion integrals for the u channel have been completely neglected.

The three pion-nucleon resonances are in p, d, and f waves, respectively. We, therefore, neglect the contributions of N^{**} and N^{***}. The N^* contributes to $K\Sigma$ production only because the $I=\frac{3}{2}$ channel is absent for $K\Lambda$. The contribution of N^* is essential in our model in order to explain the angular distribution of $K^+\Sigma^0$ production. We assume that the contribution of the rest of the dispersion integrals is small and hence neglect them.[3] In our calculation we have assumed $K\Lambda$ and $K\Sigma$ parities to be odd for which assumption there is now convincing evidence.[4]

Recently Kuo[5] has made calculations for $K^+\Lambda^0$ and $K^+\Sigma^0$ production. He has completely neglected the u channel and thus has included only the nucleon pole in the s channel and K meson and K^* meson poles in the t channel (a p-wave resonance in the s channel has also been included for $K\Lambda$ production). In these reactions the contributions of the nucleon pole and the K-meson pole combine to give gauge-invariant combination. But this is not the case for the processes such as $K^0\Sigma^+$ or $K^+\Sigma^-$ production. Here the contribution of the hyperon pole is necessary in order to get the gauge-invariant combination.

We have many unknown parameters in our calculation such as coupling constants and hyperon magnetic moments. We have taken some of these parameters as given by the octet model of unitary symmetry. We have also used unitary symmetry for fixing the relative signs of $g_{KN\Lambda}$, $g_{KN\Sigma}$, $g_{K^*N\Lambda}$, and $g_{K^*N\Sigma}$ coupling constants. We know that unitary symmetry is badly broken by the large value of the mass ratio $m_K/m_\pi \sim 3.5$. But we believe that it will not affect the relative signs of the coupling constants. The breakdown of this symmetry in a sense has been taken into account in our calculation by taking $g_{KN\Sigma}^2$ to be of the order of $(m_\pi/m_K)^2 g_{\pi NN}^2$.

* Part of this work was done when the author was at Imperial College, London. He is indebted to the British Department of Technical Cooperation for the award of a Fellowship under the Colombo Plan during his stay at Imperial College.

[1] G. F. Chew, M. L. Goldberger, F. E. Low, and Y. Nambu, Phys. Rev. **106**, 1345 (1957).

[2] R. H. Capps, Phys. Rev. **114**, 920 (1959).

[3] There is an indication of a $p_{1/2}$ resonance in $K\Lambda$ system [see Ref. 5 and G. T. Hoff, Phys. Rev. **131**, 1302 (1963)]. We have not included this in our calculation but its contribution can be easily calculated by using Eqs. (3.3) and (3.4). The inclusion of this resonance may improve the agreement between the experimental data and our model.

[4] R. H. Dalitz, in *Proceedings of the Aix-en-Provence Conference on Elementary Particle Physics, 1961* (Centre d'Etudes Nucléaires de Saclay, Seine-et-Oise, 1961). R. D. Tripp, M. B. Watson, and M. Ferro-Luzzi, Phys. Rev. Letters **8**, 28 (1962); **8**, 175 (1962). R. H. Capps, in *Proceedings of the 1962 Annual International Conference on High-Energy Physics at CERN*, edited by J. Prentki (CERN, Geneva, 1962). H. Courant, H. Filthuth, P. Franzini, *et al.*, Phys. Rev. Letters **10**, 409 (1963).

[5] T. K. Kuo, Phys. Rev. **129**, 2264 (1963); **130**, 1537 (1963).

TABLE I. Residues Γ_i and $\bar{\Gamma}_i$ of nucleon and hyperon poles for different isotopic spin invariants. g_Σ and g_Λ are $KN\Sigma$ and $KN\Lambda$ coupling constants, respectively. M, m and K are hyperon, nucleon and K-meson masses, respectively. $\mu_{V,0}=(\mu_+\mp\mu_-)/2$.

	V_+	V_-	V_0	S_+	S_0
Γ_1	$g_\Sigma e/2$	$g_\Sigma e/2$	$g_\Sigma e/2$	$g_\Lambda e/2$	$g_\Lambda e/2$
Γ_2	$g_\Sigma e/(t-K^2)$	$g_\Sigma e/(t-K^2)$	$g_\Sigma e/(t-K^2)$	$g_\Lambda e/(t-K^2)$	$g_\Lambda e/(t-K^2)$
Γ_3	$g_\Sigma(\mu_p-\mu_n)/2$	$g_\Sigma(\mu_p-\mu_n)/2$	$g_\Sigma(\mu_p+\mu_n)/2$	$g_\Lambda(\mu_p-\mu_n)/2$	$g_\Lambda(\mu_p+\mu_n)/2$
Γ_4	$-g_\Sigma(\mu_p-\mu_n)/2$	$-g_\Sigma(\mu_p-\mu_n)/2$	$-g_\Sigma(\mu_p+\mu_n)/2$	$-g_\Lambda(\mu_p-\mu_n)/2$	$-g_\Lambda(\mu_p+\mu_n)/2$
$\bar{\Gamma}_1$	$2(M-m)g_\Sigma(g_\Lambda/g_\Sigma)\mu_T$	$eg_\Sigma+2(M-m)g_\Sigma\mu_V$	$2(M-m)g_\Sigma\mu_0$	$2(M-m)g_\Lambda(g_\Sigma/g_\Lambda)\mu_T$	$2(M-m)g_\Lambda\mu_\Lambda$
$\bar{\Gamma}_2$	0	$2g_\Sigma e/(t-K^2)$	0	0	0
$\bar{\Gamma}_3$	$-g_\Sigma(g_\Lambda/g_\Sigma)\mu_T$	$-g_\Sigma\mu_V$	$-g_\Sigma\mu_0$	$-g_\Lambda(g_\Sigma/g_\Lambda)\mu_T$	$-g_\Lambda\mu_\Lambda$
$\bar{\Gamma}_4$	$-g_\Sigma(g_\Lambda/g_\Sigma)\mu_T$	$-g_\Sigma\mu_V$	$-g_\Sigma\mu_0$	$-g_\Lambda(g_\Sigma/g_\Lambda)\mu_T$	$-g_\Lambda\mu_\Lambda$

We have found that a mixture of D and F couplings[6] gives a reasonable fit to the experimental data for $K^+\Lambda^0$ and $K^+\Sigma^0$ reactions. It must be emphasized that the contribution of N^* is also necessary for $K^+\Sigma^0$ production in order to explain its angular distribution. The difference in the angular distribution of $K^+\Lambda^0$ and $K^+\Sigma^0$ was used to be thought of as qualitative evidence for odd $\Lambda\Sigma$ parity. But in our model even $\Lambda\Sigma$ parity is necessary. We have made certain other predictions for other possible reactions on this model which can be experimentally tested.

2. DISPERSION RELATIONS

The kinematics have been discussed by the author.[7] We shall follow the notation of I.

We assume the following dispersion relation for fixed t for the gauge invariant amplitudes A_i's:

$$A_i(s,u,t)=\frac{\Gamma_i}{m^2-s}+\frac{\bar{\Gamma}_i}{M^2-u}+B_i+\frac{1}{\pi}\int_{(\mu+m)^2}^{\infty}ds'\frac{\operatorname{Im}A_i^1(s',u,t)}{s'-s}+\frac{1}{\pi}\int_{(\mu+M)^2}^{\infty}du'\frac{\operatorname{Im}A_i^2(s,u',t)}{u'-u},$$

where Γ_i and $\bar{\Gamma}_i$ for different isotopic spin invariants $V_{\pm,0}$ and $S_{+,0}$ are given[8] in Table I.

The B_i's denote the contribution of K^* meson pole as given below provided the spin of K^* is unity.[9]

$$B_1^{V\pm,0}=-\begin{Bmatrix}\lambda_V\\-\lambda_V\\\lambda_S\end{Bmatrix}\frac{g_{K^*N\Sigma}(M-m)+tG_{K^*N\Sigma}}{t-m_{K^*}^2},$$

$$B_2^{V\pm,0}=-\begin{Bmatrix}\lambda_V\\-\lambda_V\\\lambda_S\end{Bmatrix}\frac{G_{K^*N\Sigma}}{t-m_{K^*}^2},$$

$$B_3^{V\pm,0}=\begin{Bmatrix}\lambda_V\\-\lambda_V\\\lambda_S\end{Bmatrix}\frac{(M-m)G_{K^*N\Sigma}}{t-m_{K^*}^2},$$

$$B_4^{V\pm,0}=\begin{Bmatrix}\lambda_V\\-\lambda_V\\\lambda_S\end{Bmatrix}\frac{g_{K^*N\Sigma}}{t-m_{K^*}^2},$$

and similar expressions for $K\Lambda$ production where the square bracket is replaced by $\begin{bmatrix}\lambda_V\\\lambda_S\end{bmatrix}$ and $g_{K^*N\Sigma}$ and $G_{K^*N\Sigma}$ are replaced by $g_{K^*N\Lambda}$ and $G_{K^*N\Lambda}$, respectively. We have used $(\lambda_S+\tau_3\lambda_V)$ coupling constant for the γKK^* vertex. It can be shown[10] that $g_{K^*NY}/G_{K^*NY}=g_V/d(0)$ where g_V and $d(0)$ are vector and induced vector coupling constants for the leptonic decay of the hyperon. $d(0)$ is usually neglected in comparison with g_V and hence we shall also neglect G_{K^*NY} in comparison with g_{K^*NY}.

3. DISPERSION RELATIONS FOR MULTIPOLES

Introducing the variable $\epsilon=W-(M+K)$, neglecting the terms of the order ϵ/m, we have the following

[6] J. J. Sakurai, in Proceedings of International Summer School at Varenna, 1962 (to be published).

[7] Fayyazuddin, Phys. Rev. **123**, 1882 (1961). Hereafter this will be referred to as I.

[8] In I, it was assumed that only the isovector part of the electromagnetic current due to Σ hyperon contributes, so that $\mu_0=(\mu_++\mu_-)/2$ was taken to be zero. Here this assumption is discarded. The author is indebted to Dr. G. Halliday and Dr. N. A. Beauchamp for correspondence in this respect. See also, S. Hatsukade and H. J. Schintzer, Phys. Rev. **128**, 462 (1962).

[9] W. Chinowsky, G. Goldhaber, S. Goldhaber *et al.*, Phys. Rev. Letters **9**, 330 (1962); C. H. Chan, *ibid.* **6**, 383 (1961); M. A. Beg and P. C. Decelles, *ibid.* **6**, 145, 428 (E) (1961).

[10] Fayyazuddin and Riazuddin, Nucl. Phys. **31**, 649 (1962); R. E. Norton, Phys. Rev. **126**, 1216 (1962).

TABLE II. Contributions of Born terms (excluding K-meson exchange contribution which is separately given as R_3 and R_4) and K^* exchange to multipoles E_{0+}, E_{1+}, M_{1-}, and M_{1+} for $K\Lambda$ production.[a]

	Contribution of Born terms	Contribution of K^*
$E_{0+}{}^{S+,0}$	$\frac{-D}{2}\left[1-\frac{M+K-m}{m}\mu_1{}^{+,0}\right]$	$-\frac{Q^{S+,0}k}{(\Delta^2+2k\omega)}\left[\frac{K(M+K-m)}{2(M+K)}\right]$
$\frac{E_{1+}{}^{S+,0}}{kq}$	$\frac{D}{12Mk}\left(\frac{M+K-m}{m}\right)\left(\frac{(g_\Sigma/g_\Lambda)\mu_T}{\mu_\Lambda}\right)$	$\frac{Q^{S+,0}}{12(\Delta^2+2k\omega)}\left[\frac{M+K-m}{M+K}\right]$
$\frac{M_{1-}{}^{S+,0}+2M_{1+}{}^{S+,0}}{kq}$	$\frac{D}{4Mk}\left[1+\frac{M+K+m}{m}\mu_1{}^{+,0}-4\frac{M+K}{m}\left(\frac{(g_\Sigma/g_\Lambda)\mu_T}{\mu_\Lambda}\right)\right]$	$-\frac{Q^{S+,0}}{(\Delta^2+2k\omega)4M}\left[4M-K+\frac{mK}{M+K}\right]$
$\frac{M_{1-}{}^{S+,0}-M_{1+}{}^{S+,0}}{kq}$	$\frac{D}{4Mk}\left[1+\frac{M+K+m}{m}\mu_1{}^{+,0}-\frac{M+K-m}{m}\left(\frac{(g_\Sigma/g_\Lambda)\mu_T}{\mu_\Lambda}\right)\right]$	$-\frac{Q^{S+,0}}{(\Delta^2+2k\omega)}\left[\frac{(M-K)(M+K-m)}{4M(M+K)}\right]$
$R_3{}^{S+,0}$	$\frac{D_3}{1-V_K\cos\theta}$	
$R_4{}^{S+,0}$	$\frac{D_4}{1-V_K\cos\theta}$	

[a] Here

$$D=\left(\frac{g_\Lambda e}{4\pi}\right)\left(\frac{M}{M+K}\right)^{1/2}\frac{k}{[(M+K)^2-m^2]},\qquad V_K=\frac{q}{\omega},$$

$$D_3=-\left(\frac{g_\Lambda e}{4\pi}\right)\left(\frac{M}{M+K}\right)^{1/2}\frac{V_K}{2[M+K+m]},\qquad \mu_1{}^{+,0}=\frac{(\mu_p\mp\mu_n)}{2}+\left(\frac{g_\Sigma/g_\Lambda\mu_T}{\mu_\Lambda}\right),$$

$$D_4=\left(\frac{g_\Lambda e}{4\pi}\right)\frac{[M(M+K)]^{-1/2}}{4[M+K-m]}qV_K,\qquad Q^{S+,0}=\begin{bmatrix}\lambda_V\\ \lambda_S\end{bmatrix}\left(\frac{g_{K^*N\Lambda}}{4\pi}\right)\left(\frac{M}{M+K}\right)^{1/2},$$

$$\Delta^2=m_{K^*}{}^2-K^2.$$

In the above expressions we have expressed the magnetic moments in terms of the Bohr magneton.

dispersion relations for the multipoles E_{0+}, E_{1+}, M_{1+}, and M_{1-}:

$$\mathrm{Re}E_{0+}(\epsilon)=E_{0+}{}^B+E_{0+}{}^{K^*}+\frac{k}{\pi}\int_a^\infty\frac{\mathrm{Im}E_{0+}(\epsilon')}{k'(\epsilon'-\epsilon)}d\epsilon', \quad (3.1)$$

$$\mathrm{Re}\frac{E_{1+}(\epsilon)}{kq}=\frac{E_{1+}{}^B+E_{1+}{}^{K^*}}{kq}+\frac{1}{\pi}\int_a^\infty\frac{\mathrm{Im}E_{1+}(\epsilon')}{k'q'(\epsilon'-\epsilon)}d\epsilon', \quad (3.2)$$

$$\mathrm{Re}\frac{M_{1-}(\epsilon)+2M_{1+}(\epsilon)}{kq}=\frac{M_{1-}{}^B+2M_{1+}{}^B+M_{1-}{}^{K^*}+2M_{1+}{}^{K^*}}{kq}+\frac{1}{\pi}\int_a^\infty\mathrm{Im}\frac{M_{1-}(\epsilon')+2M_{1+}(\epsilon')}{k'q'(\epsilon'-\epsilon)}d\epsilon', \quad (3.3)$$

$$\mathrm{Re}\frac{M_{1-}(\epsilon)-M_{1+}(\epsilon)}{kq}=\frac{M_{1-}{}^B-M_{1+}{}^B+M_{1-}{}^{K^*}-M_{1+}{}^{K^*}}{kq}+\frac{1}{\pi}\int_a^\infty\mathrm{Im}\frac{M_{1-}(\epsilon')-M_{1+}(\epsilon')}{k'q'(\epsilon'-\epsilon)}d\epsilon', \quad (3.4)$$

where $a=(\mu+m)-(M+K)$.

In deriving the above expressions, we have completely neglected the dispersion integrals for the u channel. $E_{0+}{}^B$, $E_{0+}{}^{K^*}$, etc., for $K\Lambda$ and $K\Sigma$ production are given in Tables II and III, respectively. $E_{0+}{}^B$, etc., do not contain the contribution of the K-meson pole which is separately given in Tables II and III as R_3 and R_4. In this way we are including to some extent the contribution of higher partial waves.

Taking into consideration the πN and KY intermediate states only, the unitarity gives for $\mathrm{Im}M_{1+}$

$$\mathrm{Im}M_{1+}\sim f_{1+}M_{1+}{}^{*\pi}+g_{1+}M_{1+}{}^*, \quad (3.5)$$

where f_{1+} and g_{1+} are $p_{3/2}$ scattering amplitudes for the processes $\pi+N\to K+Y$ and $K+Y\to K+Y$, respectively. $M_{1+}{}^\pi$ is the magnetic dipole transition for the process $\gamma+N\to\pi+N$. Similar equations can be written for other multipoles. Equation (3.5) is only true for $\epsilon>0$, for $\epsilon<0$ only the first term contributes.

Since we are taking the K couplings to be small as compared with π couplings, we neglect the second term in Eq. (3.5). This is the only justification for neglecting the physical singularity. We shall thus evaluate the integrals (3.1 to 3.4) by taking into consideration the πN intermediate state only. We replace the πN intermediate state by the N^* resonance, so that we have

TABLE III. Contributions of Born terms (excluding contribution of K-meson exchange which is separately given as R_3 and R_4) and K^* exchange to the multipoles E_{0+}, E_{1+}, M_{1-}, and M_{1+} for $K\Sigma$ production.[a]

	Contribution of Born terms	Contribution of K^*
$E_{0+}{}^{V\pm,0}$	$\frac{-D}{2}\left[\begin{pmatrix}1\\-M+2K/M\\1\end{pmatrix}-\frac{M+K-m}{m}\begin{pmatrix}\mu_1{}^{V+}\\\mu_1{}^{V-}\\\mu_1{}^{V_0}\end{pmatrix}\right]$	$-\frac{Q^{V\pm,0}k}{(\Delta^2+2k\omega)}\left[\frac{K(M+K-m)}{2(M+K)}\right]$
$\frac{E_{1+}{}^{V\pm,0}}{kq}$	$\frac{D}{12Mk}\left[\frac{2(M+K)}{m}\begin{pmatrix}0\\2m/(M+K+m)\\0\end{pmatrix}+\frac{M+K-m}{m}\begin{pmatrix}(g_\Lambda/g_\Sigma)\mu_T\\\mu_V\\\mu_0\end{pmatrix}\right]$	$\frac{Q^{V\pm,0}}{12(\Delta^2+2k\omega)}\left[\frac{M+K-m}{M+K}\right]$
$\frac{M_{1-}{}^{V\pm,0}+2M_{1+}{}^{V\pm,0}}{kq}$	$\frac{D}{4Mk}\left[\begin{pmatrix}1\\-M+2K/M\\1\end{pmatrix}+\frac{M+K+m}{m}\begin{pmatrix}\mu_1{}^{V+}\\\mu_1{}^{V-}\\\mu_1{}^{V_0}\end{pmatrix}-4\frac{M+K}{m}\begin{pmatrix}(g_\Lambda/g_\Sigma)\mu_T\\\mu_V\\\mu_0\end{pmatrix}\right]$	$-\frac{Q^{V\pm,0}}{(\Delta^2+2k\omega)4M}\left[4M-K+\frac{mK}{M+K}\right]$
$\frac{M_{1-}{}^{V\pm,0}-M_{1+}{}^{V\pm,0}}{kq}$	$\frac{D}{4Mk}\left[\begin{pmatrix}1\\H\\1\end{pmatrix}+\frac{M+K+m}{m}\begin{pmatrix}\mu_1{}^{V+}\\\mu_1{}^{V-}\\\mu_1{}^{V_0}\end{pmatrix}-\frac{M+K-m}{m}\begin{pmatrix}(g_\Lambda/g_\Sigma)\mu_T\\\mu_V\\\mu_0\end{pmatrix}\right]$	$-\frac{Q^{V\pm,0}}{(\Delta^2+2k\omega)}\left[\frac{(M-K)(M+K-m)}{4M(M+K)}\right]$
$R_3{}^{V\pm,0}$	$\begin{pmatrix}1\\-1\\1\end{pmatrix}\frac{D_3}{1-V_K\cos\theta}$	
$R_4{}^{V\pm,0}$	$\begin{pmatrix}1\\-1\\1\end{pmatrix}\frac{D_4}{1-V_K\cos\theta}$	

[a] D, D_3, and D_4 are the same as in Table II except that g_Λ is replaced by g_Σ.

$$\mu_1{}^{V\pm,0}=\frac{(\mu_p\mp\mu_n)}{2}+\begin{pmatrix}(g_\Lambda/g_\Sigma)\mu_T\\\mu_V\\\mu_0\end{pmatrix},\qquad Q^{V\pm,0}=\begin{bmatrix}\lambda_V\\-\lambda_V\\\lambda_S\end{bmatrix}\left(\frac{g_{K^*N\Sigma}}{4\pi}\right)\left(\frac{M}{M+K}\right)^{1/2}.$$

$$H=\frac{(M+K)(3M-2K-m)-mK}{M(M+K)},$$

Here, also, magnetic moments have been expressed in Bohr magneton.

from Eq. (3.5)

$$\mathrm{Im}E_{0+}(\epsilon')=\mathrm{Im}M_{1-}(\epsilon')=0\,,$$
$$\mathrm{Im}M_{1+}{}^{3/2}(\epsilon')/k'q'=\pi g_{33}\delta(\epsilon'+M+K-M^*)\,,$$
$$\mathrm{Im}E_{1+}{}^{3/2}(\epsilon')/k'q'=\pi f_{33}\delta(\epsilon'+M+K-M^*)\,.$$

Substituting these in Eqs. (3.1) to (3.4), we have

$$E_{0+}{}^{N^*}=0\,,$$
$$E_{1+}{}^{N^*}/kq=f_{33}/(M^*-W)\,,$$
$$(M_{1-}{}^{N^*}+2M_{1+}{}^{N^*})/kq=2g_{33}/(M^*-W)\,,$$
$$(M_{1-}{}^{N^*}-M_{1+}{}^{N^*})/kq=-g_{33}/(M^*-W)\,.$$

M^* is the mass of the N^* resonance. g_{33} and f_{33} are constants.

4. CHOICE OF PARAMETERS

The magnetic moments of the hyperon are unknown. The only guides for fixing their values are the symmetry theories. We shall use the values predicted by the octet model of unitary symmetry[11] of Gell-Mann and Neeman.

Even in the octet model, we have three possible couplings of pseudoscalar meson and baryon, i.e., pure F type, pure D type, and a mixture of D and F. Pure F type coupling is not consistent with experiment as it predicts $g_{\pi\Lambda\Sigma}=0$ which is against experimental evidence provided by Λ-nucleon interaction. The most favored coupling is the mixture of D and F. We have also used the mixture of D and F couplings.[12] We have selected the couplings in such a way that[13]

$$g_{\pi\Lambda\Sigma}{}^2=\tfrac{3}{4}g_{\pi NN}{}^2\,,$$
$$g_{\pi\Sigma\Sigma}{}^2=\tfrac{1}{4}g_{\pi NN}{}^2\,.$$

According to this choice $g_\Lambda/g_\Sigma=-\sqrt{3}$ with g_Λ negative. We have taken $g_\Sigma{}^2/4\pi\sim(m_\pi/m_K)^2 g_{\pi NN}{}^2/4\pi\sim1.2$. The same type of coupling as that for the pseudoscalar meson with the baryon is used for K^* so that

$$g_{K^*N\Lambda}/g_{K^*N\Sigma}=-\sqrt{3}\,,\ \text{with } g_{K^*N\Lambda}\text{ negative}.$$

We write $\lambda_{V,S}$ as

$$\lambda_{V,S}{}^2/4\pi=e^2F_{V,S}{}^2/4\pi m_{K^*}{}^2\,,$$

[11] S. Coleman and S. L. Glashow, Phys. Rev. Letters **6**, 423 (1961); N. Cabibbo and Gatto, Nuovo Cimento **21**, 972 (1961).

[12] This has been suggested to the author by Professor R. H. Capps (private communication).

[13] A. W. Martin and K. C. Wali, Phys. Rev. **130**, 2455 (1963); R. H. Capps, Nuovo Cimento **27**, 128 (1963); S. L. Glashow and A. H. Rosenfeld, Phys. Rev. Letters **10**, 192 (1963). The D, F mixing ratio used in this paper corresponds to $\alpha=\frac{3}{4}$ in Gell-Mann's notation.

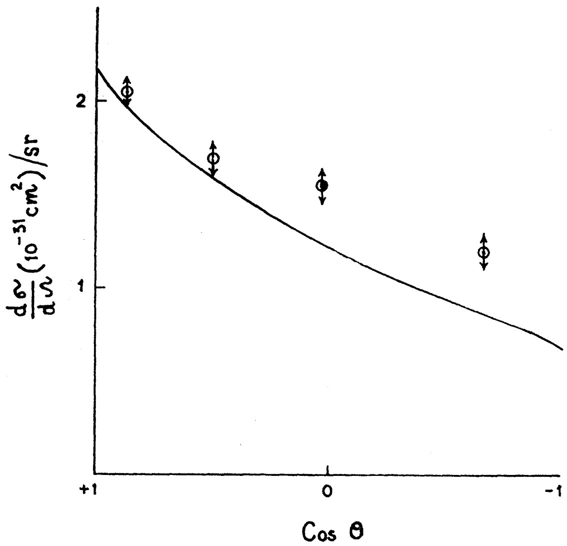

FIG. 1. Differential cross section for $\gamma+p\rightarrow K^{+}+\Lambda^{0}$. The experimental points are those of Ref. 16.

where $F_{V,S}$ is dimensionless. We can write

$$F_{K^{*+}}=F_V+F_S\,,$$
$$F_{K^{*0}}=-F_V+F_S\,,$$

where F_V and F_S are isovector and isoscalar form factors connected with the reaction $K^*\rightarrow K+\gamma$. We take $F_S=0$ and select F_V in such a way that

$$\lambda_V g_{K^*N\Sigma}/4\pi=eF_V g_{K^*N\Sigma}/4\pi m_{K^*}\sim 2.81\times 10^{-2}\,,$$

which gives

$$F_V{}^2 g_{K^*N\Sigma}{}^2/4\pi\approx 4.3\,,$$

where $e^2/4\pi=1/137$ has been used.

TABLE IV. Numerical estimates of E_{0+}, E_{1+}, M_{1-}, M_{1+}, R_3, and R_4 for $K\Lambda$ production using the coupling constants given in Sec. IV. These estimates are in units in which m_π is unity.

	Born terms contribution $\times 10^{-4}$	K^* contribution $\times 10^{-4}$
$E_{0+}{}^{S+,0}$	−31.03	20.84
	54.45	0
$\dfrac{E_{1+}{}^{S+,0}}{kq}$	−0.11	−0.23
	+0.11	0
$\dfrac{M_{1-}{}^{S+,0}+2M_{1+}{}^{S+,0}}{kq}$	−1.01	6.65
	−2.34	0
$\dfrac{M_{1-}{}^{S+,0}-M_{1+}{}^{S+,0}}{kq}$	−3.87	0.41
	+0.52	0
D_3	11.82	...
D_4	−3.85	...

TABLE V. Numerical estimates of E_{0+}, E_{1+}, M_{1-}, M_{1+}, R_3, and R_4 for $K\Sigma$ production using the coupling constants given in Sec. IV. These estimates are in units in which m_π is unity.

	Born terms contribution $\times 10^{-4}$	K^* contribution $\times 10^{-4}$	N^* contribution $\times 10^{-4}$
$E_{0+}{}^{V\pm,0}$	47.51	−13.13	
	68.31	13.13	0
	−5.24	0	
$\dfrac{E_{1+}{}^{V\pm,0}}{kq}$	0.18	0.14	−0.24
	0.25	−0.14	+0.24
	0.06	0	0
$\dfrac{M_{1-}{}^{V\pm,0}+2M_{1+}{}^{V\pm,0}}{kq}$	−1.57	−3.64	9.56
	−0.06	3.64	−9.56
	−0.78	0	0
$\dfrac{M_{1-}{}^{V\pm,0}-M_{1+}{}^{V\pm,0}}{kq}$	2.68	−0.25	−4.78
	1.75	0.25	+4.78
	0.64	0	0
D_3	−8.21	...	...
D_4	2.62	...	...

We estimate g_{33} as follows: $N^*N\gamma$ coupling is given by Chew-Low theory[14] so that

$$g_{33}=(\mu_p{}'-\mu_n{}')/2f(\lambda_{33}\lambda_K)^{1/2}\,,$$

where $(\mu_p{}'-\mu_n{}')=4.69e'/2m$, $\lambda_{33}=\frac{4}{3}f^2$, $e'^2=1/137$, and $f^2=0.08$. λ_K corresponds to $KN^*\Sigma$ coupling. λ_K has been selected in such a way that

$$g_{33}\approx -17.69\times 10^{-4}\,,$$

which gives

$$\lambda_K\sim 1.7(m_\pi/m_K)^2\lambda_{33}\sim 0.01\,.$$

Gourdin and Dufour[15] have shown that E_{1+}/M_{1+}

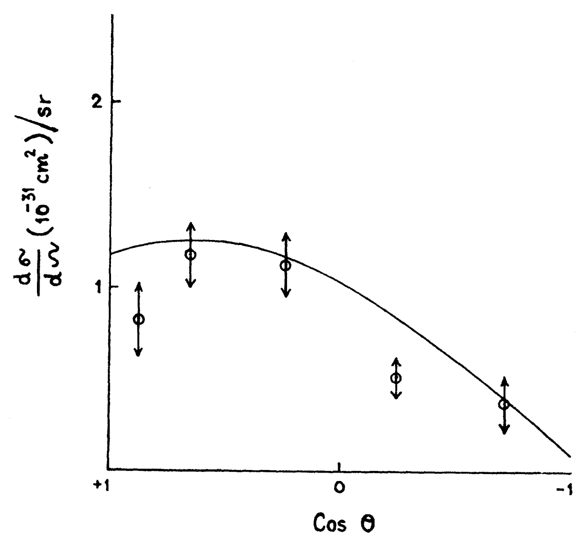

FIG. 2. Differential cross section for $\gamma+p\rightarrow K^{+}+\Sigma^{0}$. The experimental points are those of Ref. 16.

[14] G. F. Chew and F. E. Low, Phys. Rev. **101**, 1579 (1956).
[15] M. Gourdin and J. Dufour, Nuovo Cimento **27**, 1410 (1963).

TABLE VI. Values of the coefficients A, B, C, P, and Q for different reactions.

	$A\times10^{-31}$ cm^2	$B\times10^{-31}$ cm^2	$C\times10^{-31}$ cm^2	$P\times10^{-31}$ cm^2	$Q\times10^{-31}$ cm^2
$\gamma+p\rightarrow K^++\Lambda^0$	1.46	0.75	-0.04	-0.1	-0.13
$\gamma+n\rightarrow K^0+\Lambda^0$	3.77	-1.27	-0.60	...	...
$\gamma+p\rightarrow K^++\Sigma^0$	0.67	0.55	-0.04	-0.40	-0.05
$\gamma+p\rightarrow K^0+\Sigma^+$	12.17	-8.46	-1.56	...	...
$\gamma+n\rightarrow K^++\Sigma^-$	12.87	-8.18	-0.85	-0.50	-0.1
$\gamma+n\rightarrow K^0+\Sigma^0$	1.59	0.98	-0.24	...	...

$=-0.045$ for the photoproduction of the pion. This shows that

$$f_{33}/g_{33}\approx-0.05.$$

5. COMPARISON WITH EXPERIMENTS

In all our analysis we have taken m_π to be unity. The experimental data is available in the form of angular distribution for $K^+\Lambda^0$ production at lab. energies $E_\gamma=975$ MeV, 1003 MeV, 1018 MeV, and 1054 MeV, and for $K^+\Sigma^0$ production at $E_\gamma=1157$ MeV.[16] We, therefore, give in Tables IV and V the numerical estimates of multipoles for $K\Lambda$ and $K\Sigma$ production at $E_\gamma=1003$ and 1157 MeV, respectively, using the Tables II and III and the coupling constants given above.

We write the differential cross section as

$$\frac{d\sigma}{d\Omega}=A+B\cos\theta+C\cos^2\theta+\frac{P\sin^2\theta}{(1-V_K\cos\theta)}+\frac{Q\sin^2\theta}{(1-V_K\cos\theta)^2},$$

where

$$A=(q/k)\,\mathrm{Re}\{|E_{0+}|^2+\tfrac{5}{2}|M_{1+}|^2+\tfrac{9}{2}|E_{1+}|^2+|M_{1-}|^2+M_{1+}^*M_{1-}+3E_{1+}^*(M_{1-}-M_{1+})-12D_4^*E_{1+}/V_K\},$$

$$B=2(q/k)\,\mathrm{Re}\{E_{0+}^*[3E_{1+}-(M_{1-}-M_{1+})]\},$$

$$C=(q/k)\,\mathrm{Re}\{-\tfrac{3}{2}|M_{1+}|^2+\tfrac{9}{2}|E_{1+}|^2-3M_{1+}^*M_{1-}-9E_{1+}^*(M_{1-}-M_{1+})+12D_4^*E_{1+}/V_K\},$$

$$P=2(q/k)\,\mathrm{Re}\{D_3^*[3E_{1+}+(M_{1-}-M_{1+})]+D_4^*E_{0+}+6D_4^*E_{1+}/V_K-2D_3^*D_4/V_K\},$$

$$Q=2(q/k)\,\mathrm{Re}\{|D_3|^2+|D_4|^2+2D_3^*D_4/V_K\}.$$

Using the isotopic spin Table of I and Tables IV and V, we can calculate the coefficients A, B, etc., for any reaction. They are given in Table VI.

Using Table VI we can plot the angular distribution of the K meson for any particular reactions. Such plots for the reactions $\gamma+p\rightarrow K^++\Lambda^0$ at $E_\gamma=1003$ MeV and $\gamma+p\rightarrow K^++\Sigma^0$ at $E_\gamma=1157$ MeV are shown in Figs. 1 and 2. The agreement with the experimental data is reasonable. We have been thus able to explain the difference between the angular distributions for $K^+\Lambda^0$ and $K^+\Sigma^0$ on our model in which odd $K\Lambda$ and even $\Lambda\Sigma$ parity is implied.

We now make the predictions for other reactions for which experimental data are not available but the comparison will be possible in the near future.

A glance at Table VI shows that the cross section for the reaction $\gamma+n\rightarrow K^0+\Lambda^0$ at $E_\gamma=1003$ MeV is higher than that of the reaction $\gamma+p\rightarrow K^++\Lambda^0$ and angular distribution is peaked in the backward direction. For the reactions $\gamma+p\rightarrow K^0+\Sigma^+$ and $\gamma+n\rightarrow K^++\Sigma^-$ at $E_\gamma=1157$, the angular distribution is peaked in the backward direction and the cross section is much higher as can be seen from Table VI. For example, the ratio $(d\sigma/d\Omega)(\gamma+n\rightarrow K^++\Sigma^-)/(d\sigma/d\Omega)(\gamma+p\rightarrow K^++\Sigma^0)$ at 90° is about 12, which seems to be in disagreement with the preliminary experimental results.[17] For the reaction $\gamma+n\rightarrow K^0+\Sigma^0$ at $E_\gamma=1157$ MeV the angular distribution is peaked in the forward direction but the cross section is somewhat higher than that of reaction $\gamma+p\rightarrow K^++\Sigma^0$.

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[16] R. L. Anderson, E. Gahathuler, D. Jones *et al.*, Phys. Rev. Letters **9**, 131 (1962).

[17] T. Tarkot, in *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester* (Interscience Publishers, Inc., New York, 1960).