Photoproduction of K Mesons and the Intrinsic Parities of the Strange Particles*,†

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We examine the general properties near threshold of the reactions γ+nucleon→hyperon+K meson, especially from the point of view of using these reactions to determine the intrinsic $Y-K$ parity relative to that of the nucleon from which they are produced. We base our computations on the possibility that, unlike the pion case, there may be no enhancement of the interaction in some special state. Alternatively, departure of the observations from the predictions of such considerations will point out the importance of enhanced states. The approach is through a perturbation computation in which we use, however, a simple model of the Yukawa interaction in order to exhibit in explicit form the dependence of the reaction properties on the hyperon and K-meson moments and on the nature of their interaction. In general, it is pointed out how observations on angular distributions must be combined with relative cross sections and their energy dependence in order to draw unambiguous conclusions.

INTRODUCTION

THE determination of the intrinsic parities of the K meson and hyperons is one of the outstanding current problems in the physics of "strange" particles. This problem is rendered more difficult by the nonconservation of parity in the (weak) interactions responsible for the decay processes. Accordingly, it is necessary to confine our attention to the strong interactions involving the production or absorption of strange particles, such as the associated production on nucleons of a K meson with a Λ or Σ hyperon, or the capture of K mesons by nucleons, leading to Λ- or Σ-hyperon production.

Such processes are, at least according to our present concepts, governed by a Yukawa interaction between nucleons (N=proton, p, or neutron, n), hyperons ($Y=\Lambda^0$ or $\Sigma^{+,0,-}$) and the $K^{+,0}$-meson field,

$$N\rightleftarrows Y+K. \tag{1}$$

The nature of the interaction (1) is determined by the intrinsic parity of the hyperons as well as that of the K meson. Assuming spin $\frac{1}{2}$ for hyperons and spin 0 for the K meson, the $Y-K$ system in (1) is in either an $s_{\frac{1}{2}}$ or a $p_{\frac{1}{2}}$ state, depending upon whether the intrinsic parity of the $Y-K$ system is positive or negative with respect to that of the nucleons. For convenience of notation, we refer to the former as a scalar K meson (interaction) and to the latter as a pseudoscalar.

It should be noted that, in principle, the K meson in (1) might behave as a scalar with Λ hyperons and as a pseudoscalar with Σ hyperons, or vice versa, if the Λ and Σ have opposite intrinsic parities. Since the relative parity of the Λ and Σ hyperons can in principle be determined, by virtue of the strong interactions

$$\Sigma+N\rightarrow\Lambda+N', \tag{2}$$

this possibility is subject to experimental investigation. Alternatively the same information would be provided by independent determinations of the K-meson parity, in the sense defined above, in strong interactions governed by reaction (1) for processes involving the associated production of K mesons with Λ or Σ hyperons.

In a previous communication[1] we have discussed the possibility of determining the hyperon-K-meson parity by observations on the reactions.

$$N+N\rightarrow N'+Y+K. \tag{3}$$

This possibility arises as a result of the Pauli principle, which permits only singlet even-parity and triplet odd-parity initial states for identical nucleons, thus providing a connection between the spin and parity of the possible final states. On the other hand, if we consider the most extensively investigated associated-production reaction,

$$\pi+N\rightarrow Y+K, \tag{4}$$

we have, in the absence of some special properties of this reaction, no means of distinguishing the parity of any state: a state of given angular momentum, j, can be produced by incident pions of orbital angular momenta $l=j\pm\frac{1}{2}$. Furthermore, the pion energies required for reaction (4) are sufficiently far above the angular momentum barriers so that the dependence of cross section on pion energy cannot be used to determine the pion angular momentum corresponding to an observed angular distribution.

However, the preceding arguments notwithstanding, it is possible to conceive of situations in which reaction (4) could be used to distinguish between a scalar and pseudoscalar K. What is required is that there should be some independent means of determining the angular momentum of the pions responsible for the reaction. Thus, for example, given a resonance in the total $\pi-N$ cross section[2] it may be possible to ascertain, from

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[1] G. Costa and B. T. Feld, Phys. Rev. **109**, 606 (1958).

[2] Such as the $t=\frac{3}{2}$ resonance at ~1.3 Bev; Cool, Piccioni, and Clark, Phys. Rev. **103**, 1082 (1956).

observations on the pion scattering, the angular momentum and parity of the resonant state; the angular distribution of the resonant part of reaction (4) would then be determined by the K-meson parity.

Most of the above considerations concerning reaction (4) apply also to the photoproduction reaction

$$\gamma+N\rightarrow Y+K, \tag{5}$$

with, however, the important difference that it may be possible to take advantage of the special and relatively well-understood features of the electromagnetic field in order to obtain information concerning the parities of the states involved. In particular, electric and magnetic radiations carrying the same angular momentum have opposite parities and interact, in general, in relatively distinctive manners.

A number of authors[3–5] have recently presented theoretical considerations on the photoproduction of K mesons from protons near threshold which indicate the possibility, as a result of such observations, of determining the parity of the K meson. Since experimental information is now becoming available[6] on this subject, it is important to examine the physical bases of such theoretical considerations and to attempt to determine, in particular, which features of the photoproduction process will be most susceptible to relatively unambiguous interpretation.

A. PHENOMENOLOGICAL APPROACH

We consider reactions (5) at photon energies sufficiently close to threshold so as to preclude appreciably K-meson production in states of angular momentum $l>1$. Then, in a manner completely analogous to that previously employed to describe the photoproduction of pions,[7] we may write the cross section in terms of the amplitudes for electric and magnetic multipole absorption in the states whose angular momentum and parity permit the emission of an s- or p-wave K meson. The pertinent states and their properties are summarized in Table I, in which we also show the dependence near threshold of the cross sections (amplitudes squared) on the K-meson momentum.

For a scalar K meson, the differential photoproduction cross section, corresponding to s- and p-wave production, is

$$d\sigma/d\Omega=|M_1+(E_1-E_3+M_3')\cos\theta|^2 +\tfrac{1}{2}\{|E_1+2E_3|^2+|E_1-E_3-M_3'|^2\}\sin^2\theta. \tag{6}$$

[3] M. Kawaguchi and M. J. Moravcsik, Phys. Rev. **107**, 563 (1957).
[4] A. Fujii and R. E. Marshak, Phys. Rev. **107**, 570 (1957).
[5] D. Amati and B. Vitale, Nuovo cimento **6**, 394 (1957).
[6] P. L. Donoho and R. L. Walker, Phys. Rev. **107**, 1198 (1957); Clegg, Ernstene, and Tollestrup, Phys. Rev. **107**, 1200 (1957); Silverman, Wilson, and Woodward, Phys. Rev. **108**, 501 (1957); McDaniel, Cortellessa, Silverman, and Wilson, Bull. Am. Phys. Soc. Ser. II, **3**, 24 (1958).
[7] B. T. Feld, Phys. Rev. **89**, 330 (1953); J. J. Sakurai, Phys. Rev. **108**, 491 (1957).

TABLE I. Processes leading to s- and p-wave K mesons in the reaction $\gamma+N\rightarrow Y+K$.

Photon absorbed	Amplitude	State	Scalar K meson l_K	Scalar K meson K-momentum dependence[a]	Pseudoscalar K meson l_K	Pseudoscalar K meson K-momentum dependence
Electric dipole	E_1	$\frac{1}{2}-$	1	η^3	0	η
	E_3	$\frac{3}{2}-$	1	η^3	2	η^5
Magnetic dipole	M_1	$\frac{1}{2}+$	0	η	1	η^3
	M_3	$\frac{3}{2}+$	2	η^5	1	η^3
Electric quadrupole	E_3'	$\frac{3}{2}+$	2	η^5	1	η^3
Magnetic quadrupole	M_3'	$\frac{3}{2}-$	1	η^3	2	η^5

[a] We define $\eta\equiv p_K/mc$, where m is the K-meson mass. We also adopt, in the following, the notation $M\equiv$nucleon mass, $\mathfrak{M}\equiv$hyperon mass.

The cross section for pseudoscalar K-meson photoproduction is obtained from (6) by the substitution $E\leftrightarrow M$, everywhere; the resulting expression is identical with the one which describes the photoproduction of pions, a fact which can be both suggestive and misleading. In this section we examine some of the properties of Eq. (6) on the basis of our experience with pions and with electromagnetic interactions in general.

(1) Low-energy pion interactions are dominated by the strong enhancement in the $j=\frac{3}{2}^+$, $t=\frac{3}{2}$ state. The situation with regard to the possible enhancement of the $K-Y$ interaction in some special state is, to the authors' knowledge, a matter of pure conjecture at the present stage of our knowledge of these fields and their interactions. Accordingly, we must be prepared for a behavior of Eq. (6), or its counterpart for pseudoscalar K mesons, which is essentially dominated by a single amplitude. On the other hand, observations on the photoproduction of pions also indicate that processes involving the other, nonenhanced states behave in a "normal" fashion—i.e., that they may be understood by adopting a perturbation approach to a nonrelativistic field-theoretic description of the pion-nucleon field.[8] In the absence of an *a priori* reason for favoring any state we can, if we wish to proceed at all, proceed only on the assumption that the interaction follows "normal" lines. Nevertheless, it cannot be overemphasized that *the results of the considerations which follow are based on a perturbation approach which, according to previous experience with meson field theories, we have every reason to regard with strong suspicion.*

Proceeding on the naive assumption of "normalcy" we may, assuming a Yukawa interaction of form (1) and without the necessity of detailed computation, draw certain general conclusions concerning the amplitudes in Table I.

(2) The magnitudes of the electric and magnetic dipole amplitudes may be obtained from essentially dimensional arguments. The coefficients of the energy-dependent factors given in columns 5 and 7 of Table I, neglecting numerical factors (to be estimated in a

[8] Watson, Keck, Tollestrup, and Walker, Phys. Rev. **101**, 1159 (1956).

following section), are

$$|E|^2=G^2\left(\frac{e^2}{\hbar c}\right)\left(\frac{\hbar}{mc}\right)^2 p^2, \tag{7}$$

$$|M|^2=G^2\left(\frac{e^2}{\hbar c}\right)\left(\frac{\hbar}{2Mc}\right)^2 g^2, \tag{8}$$

where G is a "coupling constant" characterizing the strength of the Yukawa interaction (1), p is the electric dipole moment of the $Y-K$ system in units of e times the K-meson Compton wavelength, and g is the gyromagnetic ratio governing the magnetic dipole transitions, in nucleon magneton units. We shall return to the problem of estimating p and g; for the moment, it is sufficient to note that if the anomalous hyperon magnetic moments are comparable to those of the nucleons ($|g|\sim 4\sim 2M/m$) we have, at least for charged K-meson production ($p\sim 1$), $|E|\approx|M|$.

As to the electric and magnetic quadrupole amplitudes, we shall disregard these in the general qualitative discussions of this section, although we shall attempt to estimate them later.

In considering the properties of Eq. (6) it is necessary to have information concerning the phases of the amplitudes as well as their magnitudes. Our approach assumes that the amplitudes are all real, an assumption which is justified in a perturbation approximation. Here again it is necessary to emphasize that this situation would not hold for a strongly enhanced state. Furthermore, unlike the case of photopion production,[9] we do not have the possibility of deducing the phases from the $K-Y$ scattering phase shifts, even assuming we knew how to determine these, since there are a number of other absorption channels of comparable or greater importance (absorption with single or multiple pion production) available to the $K-Y$ system.[10]

(3) In the case of the electric dipole matrix elements we may, again on the basis of a simple perturbation approach, note a number of important general properties. First, we expect the Hamiltonian describing the electric dipole absorption process to be essentially spin-independent. This has the consequence, for scalar K mesons, that $E_1=E_3$ in Eq. (6). Hence, insofar as it is justifiable to neglect magnetic quadrupole absorption (M_3'), the interference term vanishes in Eq. (6) and the scalar K-meson photoproduction cross section may be written

$$d\sigma_+/d\Omega\cong\alpha M^2\eta+\gamma E^2\eta^3\sin^2\theta, \tag{9}$$

where E^2 and M^2 are given by Eqs. (7) and (8) and α and γ are numerical factors.

(4) Magnetic dipole absorption, on the other hand, is inherently spin dependent. Accordingly, without invoking any specific model or theory, we expect, barring accidental cancellations, that $|M_1-M_3|\sim M$ for pseudoscalar K mesons, with a resulting cross section of the form

$$d\sigma_-/d\Omega\cong\alpha' E^2\eta+\beta' EM\eta^2\cos\theta+M^2\eta^3(\gamma'\sin^2\theta+\delta'). \tag{10}$$

Equations (9) and (10) are sufficiently different, provided β' is appreciable, so as to indicate a relatively straightforward means of distinguishing between a scalar and pseudoscalar K meson as a result of observations on their photoproduction. Indeed, it is precisely the features discussed above, exhibited quantitatively as a result of perturbation field-theoretic calculations, which have been emphasized in previous publications on this subject.[3,4] However, aside from the ever-present possibility of enhancement of some state, there remains the possibility that, fortuitously or otherwise, $M_1\approx M_3$, in which case $\beta'\approx\delta'\approx 0$ in Eq. (10) and the cross sections for scalar and pseudoscalar K-meson photoproduction would have identical forms. In this connection, it is of interest to recall that early computations by Kaplon[11] on the photoproduction of pions, utilizing a perturbation field-theoretic approach which included effects of the anomalous nucleon moments, yielded just such a cancellation in the case of charged-pion production. Of course, such a fortuitous cancellation in the photoproduction of mesons of one charge would not be expected to apply for the other charge. Indeed, Kaplon's computations gave no such cancellation for π^0 production. Accordingly, we may conclude that while observation of a relatively large interference ($\cos\theta$) term in one process, say

$$\gamma+p\rightarrow\Lambda^0+K^+, \tag{11}$$

would represent evidence for a pseudoscalar K meson, its absence should not be construed as strong evidence for a scalar K meson without the observation of its absence, also, in a process involving other charges, say

$$\gamma+n\rightarrow\Lambda^0+K^0. \tag{12}$$

(5) The possibility of effects such as those discussed in (4) above arises for a pseudoscalar $Y-K$ interaction, as a result of the complex magnetic structure of the virtual $Y-K$ state of the nucleon. Depending on the details of this structure, other simplifications might occur in Eq. (10). Thus, it might be possible, in some reactions, to have $\gamma'\approx 0$. This possibility (still neglecting E_3') requires either $M_3\approx 0$ or $M_3\approx -2M_1$ [see Eq. (6)]. Since the latter situation appears to be a general feature of some reactions according to the simplest kind of models, such as that discussed in the following section, the experimental observations of the presence of an appreciable $\cos\theta$ term in the angular distribution, especially if coupled, in the appropriate reactions, with the relative absence of a $\sin^2\theta$ term,

[9] K. M. Watson, Phys. Rev. **95**, 228 (1954).

[10] This consideration, as well as the arguments concerning the electric dipole amplitudes developed in Sec. (6) below, must be borne in mind in considering the suggestions of Amati and Vitale[5] for determining the K-meson parity.

[11] M. F. Kaplon, Phys. Rev. **83**, 712 (1951).

may be construed as relatively strong evidence for a pseudoscalar $Y-K$ interaction.

(6) There is another means, based on the perturbation approach, for distinguishing between scalar and pseudoscalar K mesons. This involves the observation that the electric dipole matrix element is determined by the charge of the K meson produced.[5] Thus, in this approximation we would expect, for reactions (11) and (12),

$$p(\Lambda^0K^+)\cong 1,$$
$$p(\Lambda^0K^0)\cong 0,$$

and the vanishing of either the η or the η^3 term in reaction (12) would represent a stronger argument for a pseudoscalar or scalar K meson.

The situation is somewhat more complex for $K-\Sigma$ production; we consider the four possible reactions

$$\gamma+p\rightarrow\Sigma^0+K^+, \tag{13a}$$
$$\gamma+p\rightarrow\Sigma^++K^0, \tag{13b}$$
$$\gamma+n\rightarrow\Sigma^-+K^+, \tag{14a}$$
$$\gamma+n\rightarrow\Sigma^0+K^0. \tag{14b}$$

The electric dipole moments are influenced by the charge of the Σ and also by the amplitude of the final state in the Yukawa interaction (1). Assuming charge independence, with isotopic spins 1 and $\frac{1}{2}$ for the Σ and K, respectively, reaction (1) becomes

$$p\rightleftarrows-(\tfrac{1}{3})^{\frac{1}{2}}\Sigma^0K^++(\tfrac{2}{3})^{\frac{1}{2}}\Sigma^+K^0, \tag{15}$$
$$n\rightleftarrows-(\tfrac{2}{3})^{\frac{1}{2}}\Sigma^-K^++(\tfrac{1}{3})^{\frac{1}{2}}\Sigma^0K^0, \tag{16}$$

and we obtain, taking into account the hyperon recoil effects in a classical approximation,

$$p^2(\Sigma^0K^+)\cong\tfrac{1}{3},$$
$$p^2(\Sigma^+K^0)\cong\tfrac{2}{3}(m/\mathfrak{M})^2=0.115,$$
$$p^2(\Sigma^-K^+)\cong\tfrac{2}{3}(1+m/\mathfrak{M})^2=1.33,$$
$$p^2(\Sigma^0K^0)\cong 0,$$

where $\mathfrak{M}$ is the hyperon mass. In particular, we note that owing to the relatively large K-meson mass as well as to the weighting factor in (15), reaction (13b) as compared to (13a) should be reduced only by a factor 3 in electric dipole absorption.

For magnetic dipole absorption, on the other hand, at least insofar as effects of the anomalous hyperon moments are concerned, we would expect all the photoproduction matrix elements [reactions (11), (12), (13), and (14)] to be of comparable magnitude. Accordingly, studies of the relative magnitudes of the η and η^3 terms in the various photoproduction reactions may provide the least ambiguous evidence concerning the K-meson parity.

(7) Finally, it is important to note that even in the (likely) event that the photoproduction reactions are dominated by an enhanced state, considerations of the type outlined above will be important in interpreting the observed cross sections. The angular momentum of the enhanced state can be obtained directly from the angular distributions and energy dependence of the cross sections: see Table I and Eq. (6); its isotopic spin follows from equally simple observations: e.g., a resonance in reactions (11) and (12) must be in a $T=\frac{1}{2}$ state, etc. However, as pointed out in the introduction, the parity of the enhanced state does not follow from such considerations. The parity can, nevertheless, be determined as a result of the effects on the cross sections of the other, unenhanced states which, even if relatively small, produce relatively important interference phenomena. The above considerations can then be applied to the interference effects.

This point is perhaps best illustrated by reference to photopion production, whose energy and angular distributions indicate the importance of the $j=t=\frac{3}{2}$ state. The fact that this state has positive parity (i.e., is produced by $M1$ and $E2$ absorption) may be deduced from the observation that unenhanced s-wave production is important for charged pions and negligible for neutral pions. From this, it may be concluded that s-wave pions result from electric dipole absorption and, consequently, that the pion is pseudoscalar.

B. PERTURBATION ESTIMATES OF THE AMPLITUDES

The qualitative statements of the preceding section may be put into more quantitative form by deriving expressions for the amplitudes in Eq. (6). One method is by use of conventional meson field theory in a perturbation approximation; this is the basis of the computations already reported.[3,4] However, this method has the disadvantage, from our point of view, that the resulting expressions for the cross sections do not permit easy separation into the component processes which are the bases of a phenomenological analysis. Consequently, it is difficult to observe directly the consequences of simple changes in the assumptions, such as those concerning the values of the anomalous magnetic moments of the hyperons. Furthermore, it is difficult to use the field-theoretic results to investigate the consequences of possible final-state enhancements.

We have, instead, derived the amplitudes in Eqs. (6) by use of an approximation to meson field theory in which the virtual Yukawa interactions [e.g., Eqs. (15) and (16)] are replaced by a description of the nucleons in terms of wave functions in which the $Y-K$ state is regarded as a real bound state (the atomic model).[12] Starting with such definite wave functions, the reaction matrix elements are computed by the conventional techniques of nonrelativistic quantum mechanics. Since we are interested in the reactions only near threshold, we have estimated the electric and magnetic transition

[12] E. Fermi, Suppl. Nuovo cimento **2**, 17 (1955); B. T. Feld, Ann. Phys. **1**, 58 (1957) and to be published.

TABLE II. Amplitudes for scalar K-meson photoproduction.[a]

Element	Value	Value of $\langle\ \rangle$: Λ^0K^+	Λ^0K^0	Σ^0K^+	Σ^+K^0	Σ^-K^+	Σ^0K^0
M_1	$(m/2M)\langle g_Y\rangle$	g_{Λ^0}	g_{Λ^0}	$(\frac{1}{3})^{\frac{1}{2}}g_{\Sigma^0}$	$(\frac{2}{3})^{\frac{1}{2}}g_{\Sigma^+}$	$(\frac{2}{3})^{\frac{1}{2}}g_{\Sigma^-}$	$(\frac{1}{3})^{\frac{1}{2}}g_{\Sigma^0}$
E_1-E_3	0	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
E_1+2E_3	$4\eta\rho^2\langle p_1\rangle$	1	0	$(\frac{1}{3})^{\frac{1}{2}}$	$(\frac{2}{3})^{\frac{1}{2}}m/\mathfrak{M}$	$(\frac{2}{3})^{\frac{1}{2}}(1+m/\mathfrak{M})$	0
M_3'	$\eta\rho^2M_1$	g_{Λ^0}	g_{Λ^0}	$(\frac{1}{3})^{\frac{1}{2}}g_{\Sigma^0}$	$(\frac{2}{3})^{\frac{1}{2}}g_{\Sigma^+}$	$(\frac{2}{3})^{\frac{1}{2}}g_{\Sigma^-}$	$(\frac{1}{3})^{\frac{1}{2}}g_{\Sigma^0}$

[a] In units of $\sigma_+^{\frac{1}{2}}=\{\rho^3G^2(e^2/\hbar c)(\hbar/mc)^2\eta\}^{\frac{1}{2}}\simeq\{12\rho^3G^2\eta\ \mu\text{b/sterad}\}^{\frac{1}{2}}$.

TABLE III. Amplitudes for pseudoscalar K-meson photoproduction.[a]

Element	Value	Value of $\langle\ \rangle$: Λ^0K^+	Λ^0K^0	Σ^0K^+	Σ^+K^0	Σ^-K^+	Σ^0K^0
E_1	$2\langle p_1\rangle$	1	0	$(\frac{1}{3})^{\frac{1}{2}}$	$(\frac{2}{3})^{\frac{1}{2}}m/\mathfrak{M}$	$(\frac{2}{3})^{\frac{1}{2}}[1+(m/\mathfrak{M})]$	0
M_1-M_3	$(m/2M)\langle 2g_K-g_Y\rangle$	$[2(M/m)-g_{\Lambda^0}]$	$-g_{\Lambda^0}$	$(\frac{1}{3})^{\frac{1}{2}}[(2M/m)-g_{\Sigma^0}]$	$-(\frac{2}{3})^{\frac{1}{2}}g_{\Sigma^+}$	$(\frac{2}{3})^{\frac{1}{2}}[(2M/m)-g_{\Sigma^-}]$	$-(\frac{1}{3})^{\frac{1}{2}}g_{\Sigma^0}$
M_1+2M_3	$\eta(m/2M)\langle g_Y\rangle$	g_{Λ^0}	g_{Λ^0}	$(\frac{1}{3})^{\frac{1}{2}}g_{\Sigma^0}$	$(\frac{2}{3})^{\frac{1}{2}}g_{\Sigma^+}$	$(\frac{2}{3})^{\frac{1}{2}}g_{\Sigma^-}$	$(\frac{1}{3})^{\frac{1}{2}}g_{\Sigma^0}$
E_3'	$(12/5)\eta\rho^2\langle p_2\rangle$	1	0	$(\frac{1}{3})^{\frac{1}{2}}$	0	$(\frac{2}{3})^{\frac{1}{2}}$	0

[a] In units of $\sigma_-^{\frac{1}{2}}=\{(4/9)\rho^5G^2(e^2/\hbar c)(\hbar/mc)^2\eta\}^{\frac{1}{2}}\simeq\{5.2\rho^5G^2\eta\ \mu\text{b/sterad}\}^{\frac{1}{2}}$.

matrix elements in the approximation of long wavelength,[13] and suppressed such slowly varying factors as (E_γ/mc^2) and $(1+\eta^2)$ which, near threshold, are approximately 1. The results of these computations are exhibited in Tables II and III. In these tables, G^2 is a (dimensionless) coupling constant representing the strength of the appropriate Yukawa interaction and ρ^2 is a parameter which is a measure of the extension of the K-meson cloud, in units of $\hbar/mc$; the rest of the parameters are as previously defined.

Substitution of the elements of Tables II and III into Eq. (6) and its counterpart for pseudoscalar K mesons gives results which reflect the qualitative features described in the previous section. For the pseudoscalar case (Table III), we observe that the magnitude of the interference term, $E_1(M_1-M_3+E_3')\cos\theta$, depends in a critical fashion on the values of the intrinsic hyperon magnetic moments. These can, at best, be only guessed in the present state of our knowledge. However, since $2g_{K^+}=2M/m\simeq4$, it is seen that a $Y-K^+$ photoproduction process in which the hyperon happened to have a g factor$\simeq4$ would have $M_1-M_3\approx0$, a situation whose possibility was envisaged in Sec. A(4). Furthermore, from Table III we observe that, at least on the basis of the model used in these computations, the $\sin^2\theta$ term should be absent [$\gamma'=0$ in Eq. (10)] in all pseudoscalar $Y-K^0$ photoproduction reactions, as anticipated in Sec. A(5). This result, as well as the predictions of this model for the relative values of the electric matrix elements, provides the means for a set of unambiguous tests of the relevance of the model to the photoproduction reactions (5).

In order to use Tables II and III to provide numerical estimates of the cross sections, it is necessary to adopt values of the hyperon magnetic moments. Marshak and co-workers[14] have attempted to compute these moments by deriving field-theoretic connections between the anomalous magnetic moments of the hyperons and their mass differences, assumed electromagnetic in origin. Their results are not unambiguous, but their values fall into two groups, of which we quote representative samples in Table IV. Also included in Table IV are the predictions of the model of Goldhaber,[15] in which the hyperons are assumed to be bound states of a nucleon and an anti-K meson.

The estimates contained in Table IV indicate a wide range of possibilities for the K-meson photoproduction cross sections. It would not seem fruitful, in the present state of our understanding, to attempt a definite choice between such possibilities. It is of some interest, however, to notice how these choices affect the cross sections for the processes which are most likely to be investigated in the near future. Table V presents a summary of the estimated coefficients in the angular distribution, written

$$\frac{1}{\sigma_\pm}\frac{d\sigma_\pm}{d\Omega}=A_s+A_p\eta^2+B\eta\cos\theta+C\eta^2\sin^2\theta \qquad (17)$$

for associated photoproduction of Λ^0K^+, Σ^0K^+, Σ^+K^0 on protons, according to the different moment assumptions contained in Table IV. Some entries in Table V contain two values; the main values correspond to

TABLE IV. Estimates of hyperon magnetic g factors.[a]

Hyperon	Marshak *et al.*[b] Set 1	Set 2	Goldhaber model Scalar K	Pseudoscalar K
Λ^0	2.42	-2.42	0.88	-1.56
Σ^+	2.10	-16.28	5.59	-1.86
Σ^0	2.27	-2.27	0.88	-1.56
Σ^-	2.44	11.74	-3.83	-1.26

[a] All values assume spin $\frac{1}{2}$ and are in units of nucleon magneton $\mu_0=e\hbar/2Mc$.
[b] See reference 14.

[13] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), Chap. 12.
[14] Marshak, Okubo, and Sudarshan, Phys. Rev. **106**, 599 (1957).
[15] M. Goldhaber, Phys. Rev. **92**, 1279 (1953); **101**, 433 (1956).

TABLE V. Some estimated values of the coefficients[a] in the angular distributions for $\gamma+p\rightarrow Y+K$.

Process	Scalar K A_s	Scalar K A_p	Scalar K B	Scalar K C	Pseudoscalar K A_s	Pseudoscalar K A_p	Pseudoscalar K B	Pseudoscalar K C	Assumed moments[b]
$\gamma+p\rightarrow\Lambda^0+K^+$	0.40[c]	0.40(0.10)	0.82(0.41)	7.80(1.95)	4.00	7.60(2.44)	11.0(3.74)	−5.32(−1.89)	Marshak *et al.* (set 1)
Σ^0+K^+	0.12	0.12(0.030)	0.24(0.12)	2.63(0.66)	1.33	2.62(0.84)	3.76(1.27)	−1.89(−0.68)	
Σ^++K^0	0.20	0.20(0.050)	0.40(0.20)	0.82(0.20)	0.46	0.20	−0.61	0	
$\gamma+p\rightarrow\Lambda^0+K^+$	0.40	0.40(0.10)	0.82(0.41)	7.80(1.95)	4.00	16.2(8.05)	16.1(6.80)	−15.7(−7.75)	Marshak *et al.* (set 2)
Σ^0+K^+	0.12	0.12(0.030)	0.24(0.12)	2.63(0.66)	1.33	5.38(2.62)	5.30(2.24)	−5.22(−2.53)	
Σ^++K^0	12.2	12.2(3.05)	24.4(12.2)	−5.18(−1.30)	0.46	12.2	4.75	0	
$\gamma+p\rightarrow\Lambda^0+K^+$	0.054	0.054(0.013)	0.11(0.053)	7.97(2.00)	4.00	14.6(6.85)	15.3(6.30)	−14.0(−6.74)	Goldhaber model
Σ^0+K^+	0.018	0.018(0.004)	0.036(0.018)	2.68(0.67)	1.33	4.86(2.28)	4.90(2.08)	−4.67(−2.24)	
Σ^++K^0	1.44	1.44(0.36)	2.88(1.44)	0.20(0.050)	0.46	0.16	0.54	0	

[a] Values in parentheses correspond to $\rho^2=\frac{1}{2}$; other values correspond to $\rho^2=1$.
[b] See Table IV.
[c] Where no value is given in parentheses, the amplitude in question is independent of ρ; see Tables II and III.

$\rho^2=1$, while those in parentheses assume $\rho^2=\frac{1}{2}$. The latter assumption is intended, in an extremely crude fashion, to reflect the observation[12] that, at least in the case of the Yukawa reaction for pions, the meson cloud appears to be concentrated in a region considerably smaller than $\hbar/\mu c$.

Figure 1 shows a comparison between the available experimental observations[6] on the reaction $\gamma+p\rightarrow\Lambda^0+K^+$ and our computations. We have, for this comparison, arbitrarily chosen the anomalous moments of Marshak, set 1, and $\rho^2=\frac{1}{2}$. No attempt has been made to adjust the parameters for a "best fit"; instead, we have arbitrarily normalized the 1-Bev cross sections to the value 0.22 μb/sterad at 90°. It is clear that these data do not yet provide means for distinguishing between the scalar and pseudoscalar K-meson interactions, at least not on the basis of the considerations of this paper.

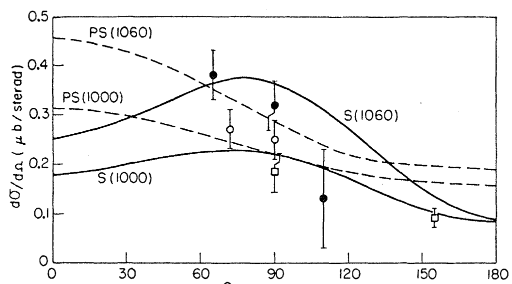

FIG. 1. Comparison of experiments on $\gamma+p\rightarrow\Lambda^0+K^+$ and predictions of Table V, row 1, assuming $\rho^2=\frac{1}{2}$. The data are for photon energies of 1000 Mev (open circles, Cal. Tech.; open squares, Cornell) and 1060 Mev (solid circles, Cal. Tech.), of momenta $\eta=0.385$ and 0.499, respectively. The curves are arbitrarily normalized to $d\sigma/d\Omega(90°)=0.22$ μb/sterad for $E_\gamma=1000$ Mev; this choice corresponds to $G_+{}^2=0.19$, $G_-{}^2=0.15$.

DISCUSSION

The computations of the previous section and the numerical estimates, Table V, are intended only to illustrate the type of behavior to be expected of the K-meson photoproduction cross sections. Clearly, they depend critically on the specific assumptions, of which the most crucial is the use of the perturbation approximation. However, the main features follow from the much more general arguments developed in Sec. A.

With regard to our approximation to meson theory, it should be remarked that the results, although they may appear quite different from those of conventional meson theory,[3,4] essentially reduce to the latter for small η (near threshold). There is, however, one important exception to the foregoing statement, and that is in the appearance of the factor $g_K=M/m$ in the matrix elements for magnetic dipole production of charged pseudoscalar K mesons (Table III). This factor leads to a reversal of the sign of the interference term for charged K-meson production, but does not appear in K^0 production. We may regard this as indicating, for our model, an enhancement of magnetic dipole photoproduction for charged K mesons. Alternatively, this may simply indicate a difference in the anomalous moments of the hyperons associated with charged and neutral K mesons. There is no way, at this stage, of distinguishing between these alternatives. The effect is, however, to facilitate agreement between our model and the observations (Fig. 1) for either parity K meson.

We must re-emphasize that computations based on a perturbation approach cannot provide for the possibility that the $Y-K$ interaction may be enhanced in some special state. The experimental results will, as they are extended, undoubtedly shed light on this question. The main purpose of our examination of the qualitative features of the reactions, and the reason for the adoption of our particular mode of expression of the results, is to provide a physical basis for determining whether such an enhancement is, indeed, a feature of the $Y-K$ interactions. The elucidation of the properties of these interactions should help to provide a firm foundation on which to base a field-theoretic description of the Yukawa reactions involving the strange particles.