Associated Photoproduction of K and Λ Particles and Possible "Up-down" Asymmetry in the Λ Decay*

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The possibility of detecting parity nonconservation in the decay of Λ particles produced by the reaction $\gamma+p\rightarrow\Lambda^0+K^+$ is discussed. The photoproduction matrix is studied from a phenomenological point of view, and the conditions essential for the detection of an "up-down" asymmetry are examined.

THE nonconservation of parity in the weak interactions involving neutrinos has been firmly established by various recent experiments. The question naturally arises as to whether we can possibly detect parity nonconservation in decay interactions where the neutrino plays no role. Following the original suggestion of Lee and Yang,[1] attempts have been made to observe a possible "up-down" asymmetry arising from the parity-nonconserving decay of hyperons produced by

$$\pi+p\rightarrow Y+K, \tag{1}$$

where Y may stand for Λ or Σ. To date no asymmetry has been reported out of a total of several hundred events.[2]

In order to find possible causes for the lack of asymmetry, let us recall that the angular distribution of the decay pion is given by[3]

$$W(\theta,\xi)d\Omega d\xi=\frac{d\sigma}{d\Omega}d\Omega\tfrac{1}{2}[1+\alpha P(\theta)\xi]d\xi. \tag{2}$$

In this formula ξ is defined as the projection of the momentum of the decay pion in the direction normal to the production plane (i.e., along $\mathbf{p}_{\text{in}}\times\mathbf{p}_Y$) in units of its maximum value (≈ 99 Mev/c in the case of $\Lambda^0\rightarrow p+\pi^-$) α is the asymmetry parameter arising from the parity-nonconserving decay interaction of the hyperon, and some field-theoretic speculations are made as to its magnitude in Appendix I. $d\sigma/d\Omega$ stands for the angular distribution of associated photoproduction of K and Λ particles in the center-of-mass system. $P(\theta)$ is the polarization of the hyperon defined in the usual manner.[4] Then the lack of asymmetry can be attributed to either (or possibly both) of the following two reasons:

(A) There is no interference between the s and p states of the pion-nucleon system resulting from the decay of the hyperon, and this fact implies $\alpha=0$. This may be the case if the decay into a p-state is highly suppressed [in which case the relatively frequent mesonic decay of ${}_\Lambda He^4$ (and ${}_\Lambda H^4$) forces us to conclude that the spin of ${}_\Lambda He^4$ (and ${}_\Lambda H^4$) is zero[5]] or if the parity-conserving and parity-nonconserving amplitudes are $\approx 90°$ out of phase. The latter situation is *nearly* accomplished when charge-conjugation invariance is not violated, since the effect of the final-state interaction is negligible, especially in the case of the Λ decay where the pion kinetic energy is only 37 Mev.

(B) The process (1) does not lead to a significant amount of polarization of the hyperon. It is well known that polarization in such processes arises from the interference between the spin-flip and the non-spin-flip amplitudes. The observed angular distribution is strongly peaked in the beam direction[6] (forward or backward depending on the type of hyperon). It is particularly worth noting that the most peaked angular distribution resulting from s and p waves alone is

$$d\sigma/d\Omega\propto(1\pm\cos\theta)^2, \tag{3}$$

which implies no spin-flip, and hence $P(\theta)=0$.

If (B) is the major reason for our failure to detect the nonconservation of parity, we may ask whether or not a photoproduction process such as

$$\gamma+p\rightarrow\Lambda^0+K^+ \tag{4}$$

polarizes the hyperon. To answer this question it is essential that we study the structure of the photoproduction matrix with special attention to possible polarization of the hyperon. In the following we restrict ourselves to associated photoproduction of K and Λ particles, but the method is readily applicable to associated photoproduction of K and Σ particles.

The threshold for the reaction (4) is 0.91 Bev in the laboratory system. For the incident γ-ray energy below 1.05 Bev, we may assume that only s and p waves are important in the final state of the K-Λ system.[7] The

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[1] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).

[2] R. H. Dalitz (private communication), based on the work of the Columbia, Bologna, Brookhaven, and Michigan groups.

[3] Lee, Steinberger, Feinberg, Kabir, and Yang, Phys. Rev. **106**, 1367 (1957). In the following we assume that the spin of the hyperon Y is $\frac{1}{2}$ and that of the K meson is zero as assumed in the above reference.

[4] See, e.g. L. Wolfenstein, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1956), Vol. 6, p. 43.

[5] R. H. Dalitz (private communication); M. Gell-Mann, Phys. Rev. **107**, 1296 (1957).

[6] Budde, Chretien, Leitner, Samios, Schwartz, and Steinberger Phys. Rev. **103**, 1827 (1956); D. A. Glaser *et al.* (to be published),

[7] Note in this connection that any meson field theory predicts a term in the matrix element of the form $\beta_K\sin\theta/(1-\beta_K\cos\theta)$ which arises from the direct "photoelectric" ejection of the K^+

production matrix for the pseudoscalar K meson[8] is identical in structure to that for the pion.[9]

$$T^{(PS)}=iA\boldsymbol{\sigma}\cdot\boldsymbol{\varepsilon}-B[(\hat{k}\times\boldsymbol{\varepsilon})\cdot\hat{q}-i(\boldsymbol{\sigma}\cdot\boldsymbol{\varepsilon}\hat{k}\cdot\hat{q}-\boldsymbol{\sigma}\cdot\hat{k}\boldsymbol{\varepsilon}\cdot\hat{q})]-C[2(\hat{k}\times\boldsymbol{\varepsilon})\cdot\hat{q}+i(\boldsymbol{\sigma}\cdot\boldsymbol{\varepsilon}\hat{k}\cdot\hat{q}-\boldsymbol{\sigma}\cdot\hat{k}\boldsymbol{\varepsilon}\cdot\hat{q})]+\tfrac{1}{2}iD[\boldsymbol{\sigma}\cdot\hat{k}\boldsymbol{\varepsilon}\cdot\hat{q}+\boldsymbol{\sigma}\cdot\boldsymbol{\varepsilon}\hat{k}\cdot\hat{q}]. \quad (5)$$

The formal structure of the production matrix for the scalar K meson can be readily obtained from the above by the transformation

$$\boldsymbol{\varepsilon}\rightarrow\hat{k}\times\boldsymbol{\varepsilon},\quad \hat{k}\times\boldsymbol{\varepsilon}\rightarrow-\boldsymbol{\varepsilon}. \quad (6)$$

Such a transformation amounts to changing the intrinsic parity of the photon leaving the baryon parities unchanged, which is equivalent to considering the meson whose parity is opposite to that of the one before.[10] Thus the production matrix for the scalar K meson is

$$T^{(S)}=iA\boldsymbol{\sigma}\cdot(\hat{k}\times\boldsymbol{\varepsilon})+B[\boldsymbol{\varepsilon}\cdot\hat{q}-i\boldsymbol{\sigma}\cdot(\boldsymbol{\varepsilon}\times\hat{q})]+C[2\boldsymbol{\varepsilon}\cdot\hat{q}+i\boldsymbol{\sigma}\cdot(\boldsymbol{\varepsilon}\times\hat{q})]+\tfrac{1}{2}iD[\boldsymbol{\sigma}\cdot\hat{k}(\hat{k}\times\boldsymbol{\varepsilon})\cdot\hat{q}+\boldsymbol{\sigma}\cdot(\hat{k}\times\boldsymbol{\varepsilon})\hat{k}\cdot\hat{q}]. \quad (7)$$

In (5) and (7), $\boldsymbol{\varepsilon}$ stands for the polarization vector of the incident γ ray; $\hat{k}$ and $\hat{q}$ are unit vectors defined by

$$\hat{k}=\mathbf{k}/|\mathbf{k}|,\quad \hat{q}=\mathbf{q}/|\mathbf{q}|, \quad (8)$$

where $\mathbf{q}$ and $\mathbf{k}$ represent the momenta of the K meson and the photon, respectively. As tabulated in Table I, A, B, C, and D have definite meaning in terms of electromagnetic multipoles. The phases of these coefficients are chosen in such a manner that they would be purely real if both the final state K-Λ interaction and the effect of a virtual pion-nucleon system were negligible, as assumed in the case of lowest order perturbation calculations.

When the initial γ ray is unpolarized, we readily obtain from (5) and (7) the differential cross section $d\sigma/d\Omega$ and polarization $P(\theta)$:

$$d\sigma/d\Omega=N\{|A+(B-C+\tfrac{1}{2}D)\cos\theta|^2+[|\tfrac{3}{2}C+\tfrac{1}{4}D|^2+|-B-\tfrac{1}{2}C+\tfrac{1}{4}D|^2]\sin^2\theta\}, \quad (9)$$

$$P(\theta)d\sigma/d\Omega=-N\sin\theta\,\mathrm{Im}\{A^*(2B+C-\tfrac{1}{2}D)+3B^*(C-\tfrac{1}{2}D)\cos\theta\}, \quad (10)$$

N stands for the relativistic phase factor:

$$N=q\{k[E_p(\mathbf{k})+k][E_\Lambda(\mathbf{q})+\omega_K(\mathbf{q})]\}^{-1}, \quad (11)$$

where

$$E_p(\mathbf{k})=(M_p^2+k^2)^{\frac{1}{2}},\quad E_\Lambda(\mathbf{q})=(M_\Lambda^2+q^2)^{\frac{1}{2}},\quad \omega_K(\mathbf{q})=(\mu_K^2+q^2)^{\frac{1}{2}}. \quad (12)$$

(We take $\hbar=c=1$ throughout.) The differential cross section and the polarization when the incident γ ray is polarized is given in Appendix II for completeness. By substituting (9) and (10) into (2), we obtain for the distribution of the decay pion

$$W(\theta,\xi)d\Omega d\xi=N\{|A+(B-C+\tfrac{1}{2}D)\cos\theta|^2+[|\tfrac{3}{2}C+\tfrac{1}{4}D|^2+|-B-\tfrac{1}{2}C+\tfrac{1}{4}D|^2]\sin^2\theta\}\times d\Omega\tfrac{1}{2}d\xi-\alpha N\sin\theta\,\mathrm{Im}\{A^*(2B+C-\tfrac{1}{2}D)+3B^*(C-\tfrac{1}{2}D)\cos\theta\}d\Omega\xi\tfrac{1}{2}d\xi. \quad (13)$$

Apart from the assumption that only s- and p-wave K mesons are produced, no approximation has been made so far. We note that *near threshold* the momentum dependence of the coefficients A, B, C, and D are likely to be given by the last column of Table I, where η stands for $|\mathbf{q}|/\mu_K$. Then the polarization, if present at all, arises mainly from the interference term between A and $(2B+C-\frac{1}{2}D)$. The maximum polarization is attained at $\theta=\pi/2$ near threshold.

In the photoproduction of pions the application of the Wigner time-reversal establishes the well-known relation between the phase of the photoproduction amplitude and the corresponding scattering phase shift of pion-nucleon scattering.[11,12] Unfortunately the relation is not strictly applicable in associated photoproduction of K and Λ particles where there is a strong interaction between the K-Λ system and a virtual π-nucleon system, since, in the language of reference 12, S_0 (the S matrix before we turn on the electromagnetic interaction) is no longer diagonal because of the *strong interactions* among various "channels."[13] However, the qualitative conclusion drawn from Watson's theorem and from the assumption that the scattering phase shift goes as δ^{2l+1} is probably correct in the sense that the departure from reality of the coefficients is more important for A (s-wave amplitude) than for p-wave amplitudes near threshold. If Watson's theorem were strictly valid in our case, $P(\pi/2)$ would be given by

$$P(\pi/2)=\pm\sin\delta_S^{(K\Lambda)}|2B+C-\tfrac{1}{2}D|/|A|, \quad (14)$$

which leads to an η^2 threshold dependence. $\delta_S^{(K\Lambda)}$ is the s-wave phase shift for K^+-Λ scattering, about which nothing is known. Numerically, if the s-wave contribution to the K^+-Λ scattering cross section at low energies is of the order of 5 mb, the phase shift in question is $\approx0.5\eta$ radians.

In conclusion, we should like to note that the failure to observe any "up-down" asymmetry in the decay of hyperons produced in π-p collisions does not *a priori* imply the impossibility of detecting such an asymmetry

particle, and which contains all angular momenta with relative strength $\beta_K{}^l$ for $l_K\geq1$. This term may be particularly important for the scalar K. See M. Kawaguchi and M. J. Moravcsik, Phys. Rev. **107**, 563 (1957).

[8] As usual, we *define* the intrinsic parity of the Λ hyperon to be the same as that of the proton.

[9] K. Brueckner and K. M. Watson, Phys. Rev. **86**, 923 (1952).

[10] Note the similarity of our problem to that of the Minami ambiguity in pion-nucleon scattering: S. Minami, Progr. Theoret. Phys. Japan **11**, 213 (1954).

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

[12] E. Fermi, Nuovo cimento Suppl. **2**, 17 (1955), Sec. 8.

[13] We are indebted to Dr. P. Kabir for this remark.

TABLE I. Photoproduction amplitudes.

	K pseudoscalar	K scalar	l_K	J	Momentum dependence
A	electric dipole	magnetic dipole	0	$\frac{1}{2}$	constant
B	magnetic dipole	electric dipole	1	$\frac{1}{2}$	η
C	magnetic dipole	electric dipole	1	$\frac{3}{2}$	η
D	electric quadrupole	magnetic quadrupole	1	$\frac{3}{2}$	η

in the case of associated photoproduction of K and Λ particles. Only preliminary measurements of this associated photoproduction cross section have been available, but there is some indication that neither the excitation function nor the angular distribution varies significantly in the region 0.96–1.06 Bev and $60°\leq\theta\leq 90°$, which may indicate the importance of the s-state.[14] Further measurements of the angular distribution, especially in the region $\theta\approx 130°$, will greatly clarify our understanding of the production matrix, and may throw light on the possibility of detecting nonconservation of parity. Once the numerical value of α is determined either from photoproduction or from other experiments, the study of the decay of the Λ particle, which serves as a "natural analyzer," will give vital information on the structure of the production matrix itself, especially at higher energies where the conventional phenomenological approach may break down.

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APPENDIX I

In this section we speculate on the order of magnitude of the asymmetry parameter α from a field-theoretic point of view. We restrict ourselves to a decay interaction of the Yukawa type[15] rather than that of the Fermi type.[16]

$$H_{\text{int}}=\phi_\pi\bar{\psi}_p(g_S+g_S'\gamma_5)\psi_\Lambda+\frac{i}{\mu_\pi}\frac{\partial\phi_\pi}{\partial x_\mu}\bar{\psi}_p(g_V\gamma_\mu+g_V'\gamma_5\gamma_\mu)\psi_\Lambda. \quad (15)$$

For simplicity we ignore the effect of the final state interaction, which is known to be small for the Λ decay due to the smallness of the pion-nucleon phase shift at the corresponding energy.

[14] R. R. Wilson (private communication); P. L. Donaho and R. L. Walker, Bull. Am. Phys. Soc. Ser. II, 2, 235 (1957).

[15] Oneda, Hori, and Wakasa, Progr. Theoret. Phys. Japan **15**, 302 (1956).

[16] M. Gell-Mann, *Proceedings of the Sixth Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1956).

It is evident from (15) that even if we require $g_S=g_S'=0$ *or* $g_V=g_V'=0$, the value of α is completely undetermined. However, in the following special cases, which are somewhat suggested by recent experiments on weak interactions, definite values of α can be obtained.

Case (I). Scalar coupling; $g_S'=|g_S|e^{i\lambda}$ with λ real, $g_V=g_V'=0$. Then

$$\alpha=\frac{2p_\pi(E_p(\mathbf{p}_\pi)+M_p)\cos\lambda}{(E_p(\mathbf{p}_\pi)+M_p)^2+p_\pi^2}. \quad (16)$$

Case (II). Vector coupling; $g_V'=|g_V|e^{i\lambda}$, $g_S=g_S'=0$.

$$\alpha=\frac{2p_\pi(M_\Lambda^2-M_p^2)(E_p(\mathbf{p}_\pi)+M_p)\cos\lambda}{(E_p(\mathbf{p}_\pi)+M_p)^2(M_\Lambda-M_p)^2+(M_\Lambda+M_p)^2p_\pi^2}. \quad (17)$$

In (16) and (17), $\mathbf{p}_\pi$ stands for the momentum of the decay pion in the rest system of the Λ.

If invariance under time reversal is valid, then

$$\lambda=0 \quad\text{or}\quad \pi,$$

and

$$\begin{aligned}\alpha&=\pm 0.10 \quad \text{for Case (I)},\\ \alpha&=\pm 0.89 \quad \text{for Case (II)}.\end{aligned} \quad (18)$$

If invariance under charge conjugation is assumed, then

$$\lambda=\pm\pi/2,$$

and

$$\alpha=0$$

for both cases, to the approximation that the final-state interaction is negligible.

APPENDIX II

In this section we obtain the angular distribution and polarization when the incident γ ray is polarized. We choose our coordinates in such a way that $\hat{q}$ lies in the $x-z$ plane, and $\hat{k}$ is along the z-axis as usual. Let the angle that $\boldsymbol{\varepsilon}$, which always lies in the $x-y$ plane, makes with the x-axis for the pseudoscalar (scalar) K meson be $\varphi(\varphi-\frac{1}{2}\pi)$. Then

$$d\sigma/d\Omega=|A+(B-C+\tfrac{1}{2}D)\cos\theta|^2+\{|B+2C|^2\sin^2\varphi+|-B+C+\tfrac{1}{2}D|^2\cos^2\varphi\}\sin^2\theta. \quad (19)$$

The polarization of the Λ is not necessarily in the direction perpendicular to the production plane.

$$\begin{aligned}\mathbf{P}(\theta)d\sigma/d\Omega&=N\sin\theta\,\mathrm{Im}[\hat{\imath}\{A^*(3C+\tfrac{1}{2}D)+[B^*(3C+\tfrac{1}{2}D)\\&-2C^*D]\cos\theta\}\sin^2\varphi+2\hat{\jmath}\{A^*(B+2C)\\&+[B^*(3C-\tfrac{1}{2}D)-C^*D]\cos\theta\}\sin^2\varphi\\&+2\hat{\jmath}\{A^*(B-C-\tfrac{1}{2}D)+(-B^*+C^*)D\cos\theta\}\cos^2\varphi\\&+\hat{k}\{-3B^*C-\tfrac{1}{2}(B^*+2C^*)D\}\sin 2\varphi]. \quad (20)\end{aligned}$$

In this formula $\hat{\imath}$, $\hat{\jmath}$, $\hat{k}$ are unit vectors along the x, y, z axes, respectively. In particular, $\hat{\jmath}=-(\mathbf{p}_{\text{in}}\times\mathbf{p}_Y)/|\mathbf{p}_{\text{in}}\times\mathbf{p}_Y|$. Averaging over φ, we readily obtain (9) and (10).