Photoproduction of K Mesons in Hydrogen near Threshold*

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The total cross sections near threshold of the three processes: $\gamma+p\rightarrow\Lambda^0+K^+$, Σ^0+K^+, Σ^++K^0, have been calculated as a function of the incident photon energy in the laboratory system under the assumptions that the hyperons have spin $\frac{1}{2}^+$ with positive anomalous magnetic moments and that the K meson has spin $0\pm$ and is coupled to the baryon field by direct Yukawa interaction. A pseudoscalar K meson gives a steep increase of the cross section for neutral production and at the same time gives a large K^0/K^+ production ratio compared to that for a scalar K meson.

THERE is no evidence for the failure of parity conservation in strong interactions[1] and it is reasonable to assume that the K meson behaves as a scalar *or* as a pseudoscalar particle in strong interactions. It is therefore of interest to examine processes which may throw light on the parity behavior of K mesons (with respect to the relative parity of nucleon and hyperon) in strong interactions. It will be recalled that in the pion case, it was the occurrence of the slow-pion reaction $\pi^-+d\rightarrow 2n$ which fixed the parity of the pion.[2] Unfortunately, there is no analog of this reaction for K mesons (insofar as absolute selection rules can be invoked) and one must be satisfied with a less incisive type of experiment. It turns out that the magnitude and energy dependence of the cross section for the photoproduction of K mesons in hydrogen depends rather sensitively on the parity of the K meson provided the anomalous magnetic moments of the proton and the hyperon are taken into account.

We have calculated the total cross sections for the processes: $\gamma+p\rightarrow\Lambda^0+K^+$, $\gamma+p\rightarrow\Sigma^0+K^+$ and $\gamma+p\rightarrow\Sigma^++K^0$ for scalar and pseudoscalar coupling and both with and without the anomalous moments of the baryons.[3] A Born-approximation calculation was carried out from the threshold energy of 0.909 Bev to 1.2 Bev for the Λ process and from the threshold energy of 1.04 Bev to 1.5 Bev for the Σ processes. The diagrams which are taken into account are exhibited in Fig. 1; we note that the transitions $\Sigma^0\rightleftarrows\Lambda^0+\gamma$ have been considered and indeed have taken equal to $\Sigma^0\rightleftarrows\Sigma^0+\gamma$ and $\Lambda^0\rightleftarrows\Lambda^0+\gamma$. The anomalous moments of the Σ hyperons were taken from the paper Marshak *et al.*[4] where the observed mass differences among the components of the Σ triplet were used to derive information concerning the anomalous moments. In particular, the values $\mu(\Sigma^0)=1.44$, $\mu(\Sigma^+)=1.33$ hyperon magnetons were used. The anomalous moment of Λ^0 was taken equal to that for Σ^0; this follows[5] if one assumes equal coupling of the Σ and Λ to the nucleon and if one neglects the mass difference between Σ and Λ.

Figures 2–4 contain the results for the total cross sections as a function of energy in the laboratory system. The cross sections are given in units of $g^2/4\pi$ microbarns, where g is the appropriate coupling constant for the $(p\Sigma^0K^+)$ interaction; the coupling constant equals $\sqrt{2}g$ for the $(p\Sigma^+K^0)$ interaction if one assumes that the fundamental interaction is a scalar in isotopic-spin space. It is seen that the anomalous moments lead to a very marked enhancement of the K^0 cross section (by a factor exceeding 10) when the coupling is pseudoscalar in contrast to scalar coupling where the increase is only a factor of 2. The energy dependence of the cross section (with anomalous moments) is also much more rapid in the pseudoscalar than in the scalar case for K^0 production.

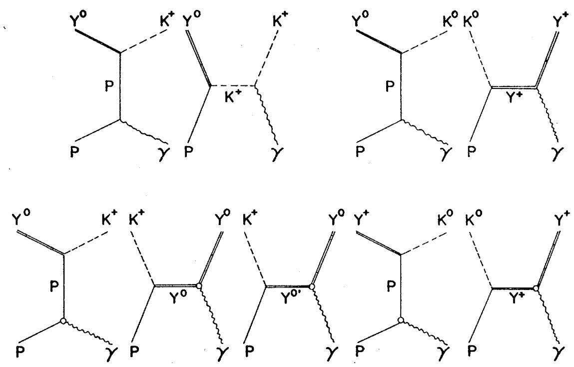

FIG. 1. Feynman diagrams. The small circle stands for an interaction through an anomalous magnetic moment.

The difference can be understood qualitatively as follows: in the pseudoscalar case the current contribution of Σ^+ to the cross section is relatively small because of the large mass. When the anomalous moments are

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

[2] B. Ferretti, in *Report on the International Conference on Low Temperatures and Fundamental Particles, Cambridge, 1946* (The Physical Society, London, 1947), p. 75.

[3] Similar calculations have been carried out by M. Kawaguchi and M. J. Moravcsik, preceding paper [Phys. Rev. **107**, 563 (1957)]. The two articles were coordinated prior to publication in order to avoid duplication.

[4] Marshak, Okubo, and Sudarshan, Phys. Rev. **106**, 599 (1957).

[5] In lowest order perturbation theory one can show that the interaction diagrams $(\Sigma^0\Sigma^0\gamma)$, $(\Lambda^0\Lambda^0\gamma)$ and $(\Sigma^0\Lambda^0\gamma)$ give equal contributions under the two assumptions mentioned in the text. S. Okubo has informed us that $(\Sigma^0\Sigma^0\gamma)=(\Lambda^0\Lambda^0\gamma)$ to all orders under the same two assumptions.

included, $\mu(p)$ and $\mu(\Sigma^+)$ add constructively because a spin flip of the baryon is associated with the p-wave emission of the K^0 meson (cf. next to last Feynman diagram of Fig. 1). In the scalar case, the s-wave emission does not involve a spin flip and there is destructive interference between $\mu(p)$ and $\mu(\Sigma^+)$. The effect of the anomalous moments on the K^+ production is much less striking because the current contribution of the charged K meson is already substantial. It is interesting to note that the pseudoscalar theory (with anomalous moments) predicts a K^0/K^+ production ratio considerably in excess of 1; the scalar theory predicts a K^0/K^+ ratio <1.

We believe that the general features of the total cross section curves in Figs. 2–4 have qualitative meaning (despite Born approximation) although we place less reliance on the differential cross sections (which have also been calculated and are not given here).[3] Support for this statement is drawn from the

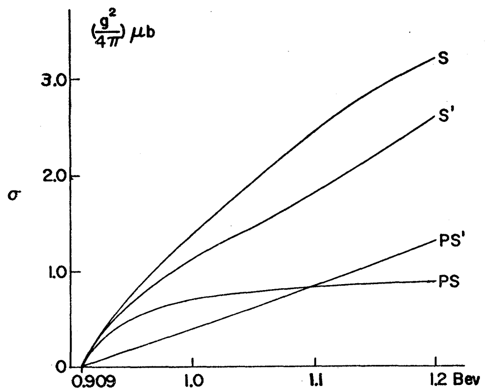

FIG. 2. The total cross section [in units of $(g^2/4\pi)$ microbarns] for $\gamma+p\rightarrow\Lambda^0+K^+$ as a function of photon energy in the laboratory system. The primed curves include anomalous moments, the unprimed curves do not.

pion situation where the more rigourous Chew-Low theory of photopion[6] production is not in gross disagreement with the Born-approximation calculations provided the nucleon anomalous moments are included. For example, Kaplon's Born-approximation treatment of neutral pion production[7] and the Chew-Low theory agree roughly with respect to magnitude and energy dependence but disagree with regard to the angular distribution of the photoproduced neutral pions [because of the importance of the $(\frac{3}{2},\frac{3}{2})$ resonance]. In the K^0 meson case, the situation is less promising because the baryon recoil contribution is relatively more important and the static magnetic moments are assumed to operate at much higher energies. On the other hand, the K meson coupling constant may be

[6] G. F. Chew and F. E. Low, Phys. Rev. **101**, 1579 (1956).
[7] M. F. Kaplon, Phys. Rev. **83**, 712 (1951); R. E. Marshak *Meson Physics*, Chap. 1 (McGraw-Hill Book Company, Inc., New York, 1952).

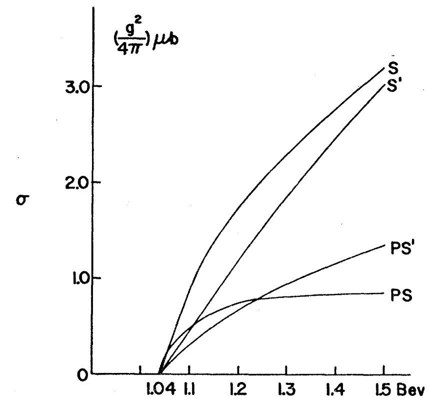

FIG. 3. The total cross section [in units of $(g^2/4\pi)$ microbarns] for $\gamma+p\rightarrow\Sigma^0+K^+$ as a function of photon energy in the laboratory system. The primed curves include anomalous moments, the unprimed curves do not.

smaller than the pion coupling constant and resonance effects, if any, may be less important than for pions.[8] The magnitude and energy dependence of the cross section for charged pion production near threshold is also not given too badly by Born approximation and in this case even the differential cross section contains several essential features of the Chew-Low theory (and experiment). It is perhaps not rash to entertain the hope that some of the gross properties of the experimental data on the photoproduction of K mesons in hydrogen near threshold will help decide whether the K meson behaves as a scalar or a pseudoscalar particle in strong interactions.

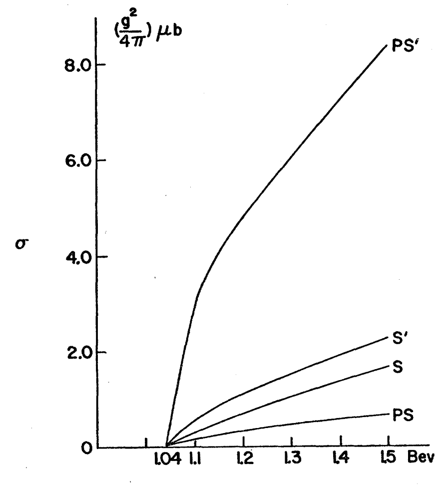

FIG. 4. The total cross section [in units of $(g^2/4\pi)$ microbarns] for $\gamma+p\rightarrow\Sigma^++K^0$ as a function of photon energy in the laboratory system. The primed curves include anomalous moments, the unprimed curves do not.

[8] S. Okubo (private communication) gives support for this statement on the basis of a dispersion-theoretic calculation of the photoproduction of K mesons. He finds that the leading term is the renormalized Born approximation with anomalous moments.

APPENDIX

For purposes of reference, the total cross sections for K^+ and K^0 production in hydrogen are given in this appendix. The total cross section for K^+ production is

$$\sigma^{(+)}=\left(\frac{e^2}{4\pi}\right)\left(\frac{g^2}{4\pi}\right)\frac{1}{M_0^2}\frac{\pi}{2}\{F_0^{(+)}(\xi)+(\alpha\mp2\beta)F_1^{(+)}(\xi)+(\alpha\mp2\beta)^2F_2^{(+)}(\xi)\pm2\alpha\beta F_3^{(+)}(\xi)\},$$

where

$$F_0^{(+)}(\xi)=\frac{(M\pm M_0)^2-m^2}{M_0^2}\frac{1}{\xi^2}\left[A(\xi)L_1(\xi)-\frac{2R(\xi)}{\xi}\right]+\frac{2R(\xi)}{\xi(1+2\xi)}\left[1-\frac{\xi A(\xi)}{1+2\xi}\right]$$

$$F_1^{(+)}(\xi)=\frac{2R(\xi)}{\xi(1+2\xi)}\left[1-\frac{\xi A(\xi)}{1+2\xi}\pm\frac{M}{M_0}\right],$$

$$F_2^{(+)}(\xi)=\frac{R(\xi)}{2\xi(1+2\xi)}\left[\frac{(M\pm M_0)^2-m^2}{M_0^2}+\frac{2\xi^2A(\xi)}{1+2\xi}\right],$$

$$F_3^{(+)}(\xi)=\frac{R(\xi)}{\xi}\left[1-\frac{\xi A(\xi)}{1+2\xi}\right]-\frac{1}{2}\frac{M^2}{M_0^2}\frac{L_2(\xi)}{\xi}.$$

The total cross section for K^0 production is

$$\sigma^{(0)}=\left(\frac{e^2}{4\pi}\right)\left(\frac{g^2}{4\pi}\right)\frac{1}{M_0^2}\frac{\pi}{2}\{F_0^{(0)}(\xi)+(\alpha\mp\beta)F_1^{(0)}(\xi)+(\alpha\mp\beta)^2F_2^{(0)}(\xi)\pm\alpha\beta F_3^{(0)}(\xi)\},$$

where

$$F_0^{(0)}(\xi)=\frac{(M\pm M_0)^2-m^2}{M_0^2}\frac{1}{\xi^2}\times\left[\left(2+\frac{1}{\xi}-A(\xi)\right)L_2(\xi)-\frac{2R(\xi)}{\xi}\right]+\frac{L_2(\xi)}{\xi}-\frac{2R(\xi)}{\xi(1+2\xi)}\left[1+\frac{\xi A(\xi)}{1+2\xi}\right],$$

$$F_1^{(0)}(\xi)=\frac{-2R(\xi)A(\xi)}{(1+2\xi)^2}\pm\frac{M}{M_0}\frac{1}{\xi}\left[\frac{2R(\xi)}{1+2\xi}-L_2(\xi)\right],$$

$$F_2^{(0)}(\xi)=F_2^{(+)}(\xi),$$

$$F_3^{(0)}(\xi)=F_3^{(+)}(\xi).$$

The auxiliary functions are defined by

$$A(\xi)=1+\frac{-M^2+M_0^2+m^2}{2M_0^2}\frac{1}{\xi},$$

$$R(\xi)=\left(\left[\xi-\frac{(M+m)^2-M_0^2}{2M_0^2}\right]\left[\xi-\frac{(M-m)^2-M_0^2}{2M_0^2}\right]\right)^{\frac{1}{2}},$$

$$L_1(\xi)=\log\left|\frac{\xi A(\xi)+R(\xi)}{\xi A(\xi)-R(\xi)}\right|,$$

$$L_2(\xi)=\log\left|\frac{1+2\xi-\xi A(\xi)+R(\xi)}{1+2\xi-\xi A(\xi)-R(\xi)}\right|,$$

where $\xi=\omega/M_0$, ω = incident photon energy in the laboratory system, M_0 = nucleon mass, M = hyperon mass, and $m=K$ meson mass.

The upper and lower signs refer to the $S(S)$ and $PS(PS)$ cases, respectively; α and β are the anomalous magnetic moments of the proton and hyperon, respectively, both in units of *nuclear* magnetons.