life of[12] $(1.24\pm0.02)\times10^{-8}$ sec was used, and it was assumed that no K mesons which decayed would be detected. A rough estimate of the probability of counting one of the products of K-meson decays indicates that this is a very small effect.

It may be seen from Table I that over the angular and energy region investigated in this experiment, no very significant variations in the cross section were observed. In fact, all except the highest and lowest values fall within their errors at a value 1.5×10^{-31} cm^2/sterad, and these two exceptions are only about $1\frac{1}{2}$ standard deviations from this value. With this limitation, it might still be remarked that the angular distribution at 1060 Mev seems to be peaked forward, whereas that at 1000 Mev does not. However, if one compares these data with the value $\sigma(\theta)=0.89\times10^{-31}$ cm^2/sterad obtained at Cornell by Silverman, Wilson, and Woodward,[5] at 990 Mev and $\theta_{\text{c.m.}}=155°$, the angular distribution at 1000 Mev also seems to fall at backward angles.

The excitation curve at $\theta_{\text{c.m.}}=90°$ seems rather flat between 960 and 1060 Mev according to the values of Table I, although again the errors are unfortunately large. This behavior would be expected in general if the K mesons are produced in S waves near the threshold.

Several theoretical treatments of K-particle photoproduction have been given,[13] but in view of the uncertainties in the theories and the large errors in the experimental data, it would probably be premature to draw detailed conclusions about the K-hyperon interaction. A rather general conclusion from the magnitude of the cross sections has already been pointed out and used in a theory of the strange-particle interactions, by Gell-Mann.[14] This is that the K-Λ^0 coupling is perhaps weaker than the pion-nucleon one.

The measurements of K^+-meson photoproduction by the general method reported here are being continued with some improvements by Brody, Wetherell, and Walker.[7] The results obtained thus far are in good agreement with those reported here, but the errors are comparable. It would be especially desirable now to obtain more accurate data.

7. ACKNOWLEDGMENTS

We wish to thank Mr. H. M. Brody and Mr. F. P. Dixon for assisting in the performance of this experiment, and Mr. E. B. Emery for the maintenance of the liquid hydrogen target. We are indebted to the entire staff and to graduate students of the Synchrotron Laboratory for contributing to the operation and maintenance of the synchrotron.

[12] See for example L. W. Alvarez, *Proceedings of the Seventh Annual Rochester Conference on High-Energy Nuclear Physics* (Interscience Publishers, Inc., New York, 1957).

[13] M. Kawaguchi and M. Moravcsik, Phys. Rev. **107**, 563 (1957); A. Fujii and R. Marshak, Phys. Rev. **107**, 570 (1957); D. Amati and B. Vitale, Nuovo cimento **6**, 394 (1957); B. T. Feld and G. Costa, Phys. Rev. **110**, 968 (1958).

[14] M. Gell-Mann, Phys. Rev. **106**, 1296 (1957).

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Pion-Hyperon Scattering and K^--p Reactions*

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A brief survey is made of the consequences of the universal pion-baryon interaction on production of hyperons with pions. In particular, a pion-hyperon resonant scattering state similar to the $p_{\frac{3}{2}}$, $T=\frac{3}{2}$ pion-nucleon state should exist. Possible effects of this state are examined. It is found that the large low-energy K^--p cross sections cannot be associated with it. Other experiments are suggested in order to search for this state, especially K^--p reactions at higher energy and pion production in hyperon-nucleon scattering.

INTRODUCTION

In addition to its attractive simplicity, the assumption of a pion-baryon interaction of universal strength and form[1] has led to some agreement with hyperon nucleon forces.[2] The purpose of this paper is to find a qualitative test of this assumption in hyperon production. This, it is hoped, may be of some value in suggesting experimental possibilities. It shall be assumed that the pion-baryon interaction is somewhat stronger than the K-particle interactions. In order to avoid great involvement in these unknown K interactions we shall examine here the effects of pion-hyperon scattering. In particular we shall consider the most prominent effect: the $p_{\frac{3}{2}}$ resonance in pion-hyperon scattering which is the counterpart of the $T=\frac{3}{2}$, $p_{\frac{3}{2}}$ low-energy resonance in pion-nucelon scattering. This is not to be directly observed, of course, but it should have a substantial effect on processes involving production

* Supported in part by the National Science Foundation.

[1] M. Gell-Mann, Phys. Rev. **106**, 1296 (1957); J. Schwinger, *Proceedings of the Seventh Annual Rochester Conference on High-Energy Nuclear Physics, 1957* (Interscience Publishers, Inc., New York, 1957), Session IX.

[2] D. B. Lichtenberg and M. H. Ross, Phys. Rev. **107**, 1714 (1957); **109**, 2163 (1958); and M. H. Ross and D. B. Lichtenberg, Phys. Rev. **110**, 737 (1958). N. Dallaporta and F. Ferrari, Nuovo cimento **5**, 111 (1957); R. H. Dalitz and B. W. Downs, Phys. Rev. **111**, 967 (1958).

of a pion and hyperon. Many aspects of such final state interaction effects are very simple. If it can be assumed that the production interaction, here the K interactions, can be treated in perturbation theory further properties can be deduced. Many of the arguments to be used here (e.g., branching ratios and energy dependence of the production) do not depend on the accuracy of perturbation theory. More explicit assumptions about the production interaction are not necessary.

Let us write the cross sections in terms of the T matrix[3]:

$$\sigma_{i\to j}=\frac{2\pi}{v_i}|T_{ji}|^2\rho_j. \tag{1}$$

It is convenient to make a partial wave expansion:

$$T_{ji}=\sum_\Gamma \phi_\Gamma^\dagger(\Omega_j)(t_{ji})_\Gamma\phi_\Gamma(\Omega_i). \tag{2}$$

Here the sum ranges over all normalized angular momentum isotopic spin states ϕ_Γ. The coordinate Ω_i includes the momentum direction k_i and spin polarization m_i with respect to an arbitrary axis, and in addition, the various charge coordinates. For elastic scattering,

$$-\frac{\pi\rho_i'}{4\pi}(t_{ii})_\Gamma=e^{i\delta_\Gamma}\sin\delta_\Gamma,\quad \text{with}\quad \rho'=\frac{4\pi k^2dk}{(2\pi)^3dE}.$$

Let us assume that the interaction consists of two parts, H_π and H_K, the latter a production interaction to be treated in perturbation theory. We then write[4] for the production process:

$$T_{ji}=(\psi_j^{(-)}, H_K\psi_i^{(+)}), \tag{3}$$

where the ψ's are eigenfunctions of the Hamiltonian excluding H_K. Into a particular two-body channel, the partial wave expansion of $\psi_j^{(-)}$ is

$$\psi_j^{(-)}=\sum_\Gamma C_{JLM}(\hat{r},\sigma)\phi_\Gamma(\Omega_j)e^{-i\delta_\Gamma}\times[\cos\delta_\Gamma\, j_L(kr)+\sin\delta_\Gamma\, f_L(kr)], \tag{4}$$

where $j_L(kr)$ is the regular spherical Bessel function, f_L is asymptotically equal to the irregular function, and where for spin-$\frac{1}{2}$ particle plus spin-zero particle, C_{JLM} is chosen so that

$$\sum_\Gamma C_{JLM}(\hat{r},\sigma)\phi_\Gamma j_L(kr)=e^{i\mathbf{k}\cdot\mathbf{r}}\chi^m(\sigma)\xi,$$

χ and ξ being the desired spin and isotopic spin functions.

On the basis of (4) we can express the production process in the form:

$$t_{ji}=e^{i(\delta_j-\delta_i)}\{B\cos\delta_i\cos\delta_j+A\cos\delta_i\sin\delta_j+A'\sin\delta_i\cos\delta_j+A''\sin\delta_i\sin\delta_j\}. \tag{5}$$

The subscript Γ is dropped here and in some other relations. If we assume that there are only the two channels i and j, then the A's and B are real as a result of time reversal.[5] If there is no scattering due to H_π in the initial state [keeping in mind the process (9)], then

$$t_{ji}=e^{i\delta}(B_{ji}\cos\delta+A_{ji}\sin\delta). \tag{6}$$

The main point of an expression such as (6) is that in most situations the A's and B are essentially independent of the phase-shift behavior. In particular we can expect these quantities to vary smoothly through the region of a phase-shift resonance. From (4) we can deduce the following momentum dependence for A and B due to the centrifugal barrier[6]:

$$B_{ji}\sim k_j^{L_j}k_i^{L_i},\quad A_{ji}\sim k_j^{-L_j-1}k_i^{L_i}. \tag{7}$$

Since these results arise from the expansion in kr of the Bessel functions, they do not apply when k becomes large. If the size r of the interaction region is such that kr is small, it is indicated that $A\gg B$. In the expressions (5) or (6) only the phase depends on the accuracy of lowest order perturbation theory.

In the presence of a resonance in the state j we may, to obtain a crude picture, assume that the enhancement term A dominates the Born approximation term B, and indeed that it dominates contributions from other partial waves. This will be our basic assumption. It may also be interesting to consider that elastic scattering in the initial state i [having in mind here the process (10)] occurs only as a byproduct of the enhancement of production, i.e., only through the intermediate resonant state j. The exact form of the matrix element (3) contains the initial state $\Psi_i^{(+)}$, an eigenfunction of the full Hamiltonian. It is readily deduced that in second order in H_K we have

$$T_{ij}=\left(\psi_i^{(-)}, H_K\frac{1}{E-H_0+i\epsilon}H_K\psi_i^{(+)}\right).$$

In the crude picture proposed above, the scattering involves summing over energies of the intermediate resonant state j:

$$t_{ii}(E)=-\frac{1}{\pi}\int dE_j\, t_{ij}t_{ji}\frac{1}{E-E_j+i\epsilon}\left(\frac{\rho_j'}{4\pi}\right), \tag{8}$$

which is to be substituted in the (total) cross-section formula:

$$\sigma_{ii}=\frac{\rho_i'}{2}\frac{1}{v_i}|\phi_\Gamma(\Omega_i)|^2|(t_{ii})_\Gamma|^2.$$

The expression (8) for the elastic scattering is certainly less reliable than the expressions above for the production. But it is something that can be evaluated.

Perhaps the most interesting reaction to study in order to look for a $\pi-Y$ resonance is, as suggested by

[3] We use units $\hbar=c=1$.

[4] M. Gell-Mann and M. Goldberger, Phys. Rev. **91**, 398 (1953).

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

[6] K. M. Watson, Phys. Rev. **88**, 1163 (1952).

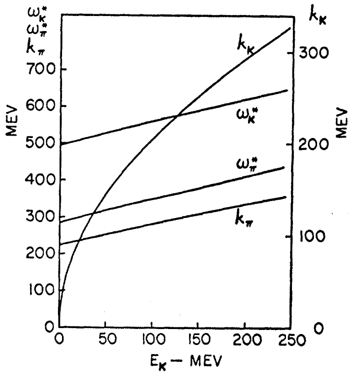

FIG. 1. Kinematics of $\bar{K}+N\rightarrow Y+\pi$. See text. The mass of the hyperon was set at the intermediate value of 1150 Mev to calculate these curves.

Gell-Mann[1]:

$$\bar{K}+N\rightarrow\pi+Y, \tag{9}$$

and the associated elastic scattering:

$$\bar{K}+N\rightarrow\bar{K}+N. \tag{10}$$

Here and throughout this paper Y and the word hyperon denote either Λ or Σ, and N denotes a nucleon. For orientation some kinematics of (9) are presented below: Let k_K and k_π be the center-of-mass momenta in the initial and final states of (9). Let $\omega_K{}^*$ and $\omega_\pi{}^*$ be the total center-of-mass rest energies less the rest energy of the appropriate baryon (actually we shall not bother to distinguish between ω^* and the energy of the boson alone, in our crude expressions). Let E_K be the *kinetic* energy of the K in the laboratory. Then

$$M_Y+\omega_\pi{}^*=M_N+\omega_K{}^*=((M_N+M_K)^2+2M_NE_K)^{\frac{1}{2}}. \tag{11}$$

Denoting the *total* laboratory energy of the K as ω_K and the similar quantity for the π (assuming a stationary hyperon target) as ω_π, we have

$$2M_Y\omega_\pi=(M_K{}^2-M_\pi{}^2+M_N{}^2-M_Y{}^2)+2M_N\omega_K, \tag{12}$$

or $\omega_\pi=353+0.842E_K$ Mev, for Λ production, and, $\omega_\pi=251+0.785E_K$ Mev, for Σ production. In Fig. 1, k_π, k_K, $\omega_\pi{}^*$ and $\omega_K{}^*$ are plotted as a function of E_K, for convenience.

PION HYPERON SCATTERING

The π-Λ and π-Σ isotopic spin states are given in Table I. Both the universal pion-baryon interaction and the K interactions are assumed to conserve isotopic spin. The former interaction is readily given in terms of the π-N Hamiltonian if we express the hyperons in terms of nucleon fields and another noninteracting entity, δ. This δ has the properties of spin 0 and isotopic spin $\frac{1}{2}$. The components δ^+ and δ^- correspond to changes 0 and -1. Thus

$$\Lambda=(1/\sqrt{2})(p\delta^--n\delta^+),$$
$$\Sigma^+=p\delta^+,\quad \Sigma^0=(1/\sqrt{2})(p\delta^-+n\delta^+),\quad \Sigma^-=n\delta^-. \tag{13}$$

The relation (13) does not involve a special model; it is just one device which may be used to specify the universal pion-baryon interaction.[7] We are now, for the time being, neglecting baryon mass differences and any renormalization differences of the pion-baryon coupling constant that will occur on account of the K interactions. It is also noted that in this universal theory we assume equal parity for Λ and Σ.

From (13) it is readily seen that pion-hyperon scattering can be expressed in terms of the isotopic spin $\frac{1}{2}$ and $\frac{3}{2}$ π-N scattering cross sections, σ_1 and σ_3. In Table II the various π-Y states and the corresponding π-N cross sections that apply are shown. Thus $T=\frac{3}{2}$ π-N scattering corresponds to diagonal scattering of $T=2$ π-Σ states and of the following $T=1$ π-Y states:

$$\begin{aligned}&-(\tfrac{2}{3})^{\frac{1}{2}}\pi^+\Lambda+(\tfrac{1}{6})^{\frac{1}{2}}(-\Sigma^0\pi^+-\Sigma^+\pi^0),\\&(\tfrac{2}{3})^{\frac{1}{2}}\pi^0\Lambda+(\tfrac{1}{6})^{\frac{1}{2}}(-\Sigma^-\pi^+-\Sigma^+\pi^-),\\&(\tfrac{2}{3})^{\frac{1}{2}}\pi^-\Lambda+(\tfrac{1}{6})^{\frac{1}{2}}(\Sigma^-\pi^0-\Sigma^0\pi^-).\end{aligned} \tag{14}$$

These are the final states associated with the low-energy resonance.

The simple result (14) is the most important one. We can, however, attempt to explore some details of the π-Y resonance. As a result of the baryon mass differences and possible differences between pion-baryon coupling constants, at what energy will the $T=1$ and $T=2$ resonances lie? Also, what will be the actual Λ/Σ probability ratio as compared to 2 in the $T=1$ case? Present theories of π-N scattering agree on certain features of the $p\frac{3}{2}$, $T=\frac{3}{2}$ resonance. It is generally agreed that it is difficult to predict its position with any reliability. To review the indications as to the resonance energy let us, for the present, ignore the Λ-Σ mass difference and simplify the question by equating the cutoff of nonrelativistic theories with the baryon mass M. Let g be the relativistic coupling constant in the PS theory, and f the PV coupling constant. In these relations $M_\pi=1$.

TABLE I. Pion-hyperon isotopic spin states.

T	T_3	
0	0	$(1/\sqrt{3})(\pi^-\Sigma^+-\pi^0\Sigma^0-\pi^+\Sigma^-)$
	1	$-\pi^+\Lambda$
1	0	$\pi^0\Lambda$
	-1	$\pi^-\Lambda$
	1	$(1/\sqrt{2})(-\pi^+\Sigma^0-\pi^0\Sigma^+)$
1	0	$(1/\sqrt{2})(-\pi^+\Sigma^--\pi^-\Sigma^+)$
	-1	$(1/\sqrt{2})(\pi^0\Sigma^--\pi^-\Sigma^0)$
	2	$-\pi^+\Sigma^+$
	1	$(1/\sqrt{2})(-\pi^+\Sigma^0+\pi^0\Sigma^+)$
2	0	$(1/\sqrt{6})(\pi^-\Sigma^++2\pi^0\Sigma^0-\pi^+\Sigma^-)$
	-1	$(1/\sqrt{2})(\pi^0\Sigma^-+\pi^-\Sigma^0)$
	-2	$\pi^-\Sigma^-$

[7] A consistent convention must be used in forming isotopic spin invariant operators and isotopic spin wave functions. We have constructed here the (unique) isotopic forms for the Hamiltonian having in mind a certain definition of the various multiplets. In the sign convention of Condon and Shortley [E. U. Condon and G. H. Shortley, *Theory of Atomic Spectra* (Cambridge University Press, Cambridge, 1935)], our multiplets are (p,n), $(-\pi^+,\pi^0,\pi^-)$, $(\Sigma^+,\Sigma^0,\Sigma^-)$. This definition agrees with Lichtenberg and Ross (reference 2) and differences in the sign of Σ^+ from that used by Gell-Mann (reference 1).

For the relativistic dispersion relations[8] there is no definite prediction, but the theory is consistent with results obtained from nonrelativistic dispersion theory.

The nonrelativistic dispersion relations[9] (Chew-Low theory) yield, in the one-meson approximation, the resonance energy

$$\omega_r^* \approx M/g^2,$$

or

$$\omega_r^* \approx 1/f^2 M.$$

It is convenient to quote similar results associated with the Tamm-Dancoff approximation as it has been applied to π-N scattering. Here one has an integral equation for an amplitude corresponding to $\tan\delta$ on the energy shell:

$$f(k) = f_B(k) + g^2 \int L(k,s) f(s) ds.$$

The equation becomes convenient for discussion of the resonance if we make the gross approximation:

$$\int L(k,s) f(s) ds = f(k) \int L(k,s) ds \equiv f(k) I(k), \qquad (15)$$

so that

$$f(k) = f_B(k) / [1 - g^2 I(k)].$$

We then have crudely, in either the relativistic[10] or nonrelativistic[11] theories,

$$kr/\omega_r^{*\frac{1}{2}} \sim M^{\frac{1}{2}}/g^2,$$

or

$$kr/\omega_r^{*\frac{1}{2}} \sim 1/f^2 M^{\frac{3}{2}}.$$

Even in the framework of these crude results, we are, at present, in no position to predict the resonance energy or merely the direction of the shift (although that could be examined in perturbation theory). A shift of, say, 100 Mev in ω_r^* would not be surprising. Or it can be put that such a shift would not deter us from using the language of the universal pion-baryon interaction. In the π-N system $\omega_r^* \approx 295$ Mev.

The Λ/Σ ratio in the $T=1$ resonant state will deviate somewhat from 2. Using the Tamm-Dancoff approach we will have coupled equations:

$$f_\Lambda = f_{\Lambda B} + g^2 \int L_\Lambda f_\Lambda ds + g^2 \int L_{\Lambda\Sigma} f_\Sigma ds,$$

$$f_\Sigma = f_{\Sigma B} + g^2 \int L_\Sigma f_\Sigma ds + g^2 \int L_{\Lambda\Sigma} f_\Lambda ds.$$

Here the Λ-Σ mixture (and $f_{\Lambda B}/f_{\Sigma B}$) is determined by solution for the diagonal states. Using (15) and assuming $I_{\Lambda\Sigma}^2 = I_\Lambda I_\Sigma$, for simplicity, we obtain the two pairs of solutions:

$$f_\Lambda^{(1)} = f_{\Lambda B}^{(1)} / (1 - I_\Lambda' - I_\Sigma'),$$
$$f_\Sigma^{(1)} = f_{\Sigma B}^{(1)} / (1 - I_\Lambda' - I_\Sigma'),$$
$$f_\Lambda^{(1)} / f_\Sigma^{(1)} = I_\Lambda' / I_{\Lambda\Sigma}' = (I_\Lambda'/I_\Sigma')^{\frac{1}{2}},$$

and

$$f_\Lambda^{(2)} = f_{\Lambda B}^{(2)},$$
$$f_\Sigma^{(2)} = f_{\Sigma B}^{(2)},$$
$$f_\Lambda^{(2)} / f_\Sigma^{(2)} = -I_\Sigma' / I_{\Lambda\Sigma}'.$$

Here the coupling constants have been absorbed into the I''s. The ratio of Λ's to Σ's produced is

$$\rho_\Sigma |f_\Lambda|^2 / \rho_\Lambda |f_\Sigma|^2 = \rho_\Sigma I_\Lambda' / \rho_\Lambda I_\Sigma' = 2 \frac{g_\Lambda^2}{g_\Sigma^2} \left(\frac{\omega_\Sigma}{\omega_\Lambda}\right)^{\frac{3}{2}} \left(\frac{M_\Sigma}{M_\Lambda}\right)^{\frac{1}{2}}$$

or

$$2 \frac{f_\Lambda^2}{f_\Sigma^2} \left(\frac{\omega_\Sigma M_\Lambda}{\omega_\Lambda M_\Sigma}\right)^{\frac{3}{2}}$$

in the resonant state. We can probably say that the qualitative feature of more Λ's than Σ's will not be altered.

K^--p CAPTURE AT LOW ENERGY

The K^--p reactions have been relatively extensively examined. Large cross sections are observed at low energy. Let us assume that there is a $p_{\frac{3}{2}}$ resonance which is shifted (relative to its energy in the π-N system) so that it occurs near zero K-particle energy. Since the final state is $p_{\frac{3}{2}}$, the initial state must be

$d_{\frac{3}{2}}$ for scalar K, or $p_{\frac{3}{2}}$ for pseudoscalar K.

Here the hyperon parity is set by convention equal to nucleon parity. The threshold cross section energy dependence for production is k_K^{2l-1} and for elastic scattering k_K^{4l}. It is not necessary to go into the details of either this theory or of experiment. Looking at the results of Alvarez *et al.*[12] and of emulsion data,[13] we see that the scant information on cross-section energy dependence indicates s-wave processes. Actually the

TABLE II. Pion-hyperon states and the pion-nucleon cross section to be used to describe the pion-hyperon scattering.

π-Y state	π-N cross section
$T=2$	σ_3
$T=0$	σ_1
$(2/3)^{\frac{1}{2}}(\pi\text{-}\Lambda)+(1/3)^{\frac{1}{2}}(\pi\text{-}\Sigma)_{T=1}$	σ_3
$-(1/3)^{\frac{1}{2}}(\pi\text{-}\Lambda)+(2/3)^{\frac{1}{2}}(\pi\text{-}\Sigma)_{T=1}$	σ_1

[8] Chew, Goldberger, Low, and Nambu, Phys. Rev. **106**, 1337 (1957).
[9] G. F. Chew and F. E. Low, Phys. Rev. **101**, 1570 (1956).
[10] Dyson, Ross, Salpeter, Schweber, Sundaresan, Visscher, and Bethe, Phys. Rev. **95**, 1644 (1954).
[11] G. F. Chew, Phys. Rev. **95**, 1669 (1954).
[12] Alvarez, Bradner, Falk-Vairant, Gow, Rosenfeld, Solmitz, and Tripp, University of California Radiation Laboratory Report UCRL-3775, (unpublished), and Nuovo cimento **5**, 1026 (1957).
[13] See M. Ceccarelli, *Proceedings of the Seventh Annual Rochester Conference on High Energy Nuclear Physics, 1957* (Interscience Publishers, Inc., New York, 1957), Session VI.

data are readily fitted with this assumption. An apparent rise in elastic scattering and a rise faster than $1/k_K$ in inelastic scattering with decreasing energy over the energy range $0<E_K<100$ Mev can be well fitted with s waves in a variety of ways.[14] On the other hand, it might be thought that this energy dependence is, instead, coupled with final-state resonance effects. Actually the resonance picture is awkard in this respect. The observations are, however, not necessarily inconsistent with a p-wave process as the resonance will quickly change the energy dependence, and could yield a very-low-energy peak falling off (slowly) on the high-momentum side. The d-wave process seems definitely incorrect.

The hyperon ratios provide more useful information. It has been found by Alvarez *et al.* that, in flight,

$$\Sigma^+:\Sigma^-=4:10$$

(the actual number of events is shown). Meanwhile, in-flight plus at-rest events yield, with fairly good statistics:

$$\Sigma^+:\Sigma^0:\Sigma^-:\Lambda=4:4:8:1.$$

If we can assume that a substantial fraction of at-rest events proceed by the same $p_{\frac{3}{2}}$ process involved for the in-flight events, then we see that the Λ-Σ ratio is completely wrong. This is indeed the case. A Brueckner-Serber-Watson[15] analysis shows that capture from the $p_{\frac{3}{2}}$ atomic orbit completely dominates radiative decay to the s orbit if there is a large low-energy $p_{\frac{3}{2}}$ cross section[16] (here the capture cross section rises to about 100 mb at $k_K\approx 100$ Mev). We conclude that the π-Y resonance does not play a role in K^--p reactions near zero energy.

It should be noted that the very small Λ-Σ ratio is quite puzzling. It may indicate that the two hyperons are basically of different character instead of very similar as assumed in this paper.

K^--p REACTIONS AT HIGHER ENERGY

If we assume that the π-Y resonance occurs at an energy such that $kr\lesssim 1$, where r is the range of interaction, presumably of the order $1/M_K$, then we may expect that the T-matrix element for production has the energy dependence

$$t_{ji}\sim\frac{k_\pi^{-2}k_K^{L(K)}}{\omega_\pi^*\omega_K^*}\sin\delta, \tag{16}$$

where $L(K)$ is equal to 2 or 1 for scalar or pseudoscalar K, respectively. The ω factors generally appear in field theory. Thus the production energy dependence near the resonance, neglecting all other partial waves and neglecting the B term of (6), is as follows:

For pseudoscalar K:

$$\sigma_{\text{prod}}\sim\frac{M_K^2k_K\sin^2\delta}{k_\pi^3\omega_\pi^*\omega_K^*}. \tag{17}$$

For scalar K:

$$\sigma_{\text{prod}}\sim\frac{k_K^3\sin^2\delta}{k_\pi^3\omega_\pi^*\omega_K^*}. \tag{18}$$

The expressions (17) and (18) are plotted in Fig. 2 for a resonance at $E_K=150$ Mev ($\omega_r^*=415$ Mev for Λ and 335 Mev for Σ), curves A and B. The $\sin\delta$ factor was taken from the approximate expression[9]

$$e^{i\delta}\sin\delta=\frac{\lambda k_\pi^3/\omega_\pi^*}{-i\lambda k_\pi^3/\omega_\pi^*+(1-\omega_\pi^*/\omega_r^*)}, \tag{19}$$

where $\lambda=\frac{4}{3}f^2$, $f^2=0.076$ in the π-N case, and $M_\pi=1$. It is noted that if one uses (19), which has some theoretical justification,[17] the width of the resonance increases considerably with higher resonance energies, if λ is kept fixed. In Fig. 2, curves A and B (but not C), λ has been reduced arbitrarily while ω_r^* is higher than in the π-N case. It is seen in Fig. 2 that the curves for scalar K are very broad.

The production into the π-Y resonant system occurs, of course, in the $T=1$ state. The hyperon ratio should be roughly

$$\Lambda:\Sigma^+:\Sigma^0:\Sigma^-=4:1:0:1. \tag{20}$$

If a peak is also observed in elastic scattering, it may be permissible to attempt to explain this elastic scattering as a second-order effect via the intermediate resonant state. This will be $T=1$ scattering. The energy dependence of the matrix element (8) can be roughly evaluated using (16). One finds that the δ-function contribution in the integration dominates if the energy is within, say, 50–100 Mev of the resonance. For this

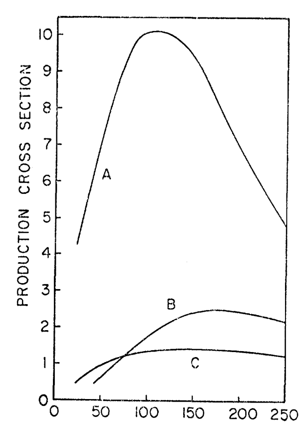

FIG. 2. Cross sections for $\bar{K}+N\rightarrow Y+\pi$ in the $T=1$ state. The right-hand side of Eq. (17) is plotted as curve A, and of Eq. (18) is plotted as curves B and C. The curves A and B correspond to a $\pi-Y$ resonance at $E_K=150$ Mev, while curve C applies to a $\pi-Y$ resonance at $E_K=0$. The units of the ordinate are 10^{-6} Mev^{-2}. An intermediate value of 1150 Mev was used for the hyperon mass.

[14] Ascoli, Hill, and Yoon, Nuovo cimento **9**, 813 (1958); Jackson, Ravenhall, and Wyld, Nuovo cimento **9**, 834 (1958).

[15] Brueckner, Serber, and Watson, Phys. Rev. **81**, 575 (1951).

[16] R. Gatto, Nuovo cimento **3**, 1142 (1956).

[17] A more complicated but more justifiable expression than (19) would involve a larger and more accurate value for f^2 [Professor R. Serber, quoted by S. Lindenbaum and L. Yuan, Phys. Rev. **100**, 306 (1955)]. The difference is inconsequential for this work.

process, then, the total elastic cross section in the $T=1$ state is

$$\sigma_{el} = (k_K^2/8\pi)(\sigma_{prod})^2. \quad (21)$$

DISCUSSION

Assuming that the universal pion-baryon interaction is essentially correct, we can say that a principal feature of this interaction may be a $T=1$ peak in $\bar{K}+N\rightarrow\pi+Y$ processes with more Λ's produced than Σ's. This peak cannot be identified with the large cross section already observed near zero energy, but may yet be found at higher energy. We have found that only if the π-Y resonance lies at a relatively high energy and if the K is pseudoscalar is there likely to be a definite peak.

It is quite possible, instead, that the π-Y resonance lies below the corresponding π-N resonance, and below the threshold for $\bar{K}$-N processes. In this case we would have to examine more complicated situations in order to detect it.

K^--deuteron processes might be easy to examine experimentally. There are many processes with a variety of features.[18] It would be difficult to disentangle the postulated π-Y resonance. We can expect that most of the K^- production reactions with deuterium will be reactions with individual slow nucleons. The large low-energy s-wave K^--N processes should dominate. The π-Y resonance would be associated with K^- absorption by high-momentum nucleons in deuterium. These relatively rare events will, of course, be strongly influenced by interactions with the second nucleon. The interpretation would be difficult.

Also complicated is the process

$$\pi+N\rightarrow K+Y+\pi,$$

which can occur *above* 1.3 Bev (π kinetic energy in the laboratory) with the π-Y system in resonance at an energy $\omega_\pi^*=300$ Mev. The peak would at least be broadened by the 3-body final state. We would no longer have just the $T=1$ π-Y state but also $T=2$. Only for a $T=\frac{1}{2}$ initial state would the $T=1$ π-Y resonant state alone appear. It will be difficult to make much use of the hyperon ratios unless $T=\frac{1}{2}$ and $T=\frac{3}{2}$ processes could be separated.

High-energy Y-N processes might be easier to analyze theoretically. The processes

$$\Lambda+N\rightarrow N+\pi+Y, \quad (22)$$

$$\Sigma+N\rightarrow N+\pi+Y, \quad (23)$$

should be similar to the

$$N+N\rightarrow N+N+\pi \quad (24)$$

[18] See, for example, Case, Karplus, and Yang, Phys. Rev. **101**, 358 (1956).

TABLE III. Laboratory energies (in Mev) required for production of pions in hyperon-nucleon and (for comparison) nucleon-nucleon scattering [processes (22), (23), and (24)].

Process	Λ→Λ	Λ→Σ⁻	Σ⁻→Λ	Σ→Σ	$N\rightarrow N$
Threshold	317	507	138	329	290
Threshold plus 150 Mev[a]	678	882	501	705	625

[a] The lab energy required to yield 150-Mev kinetic energy in the center-of-mass system.

processes which have been analyzed with considerable success in terms of the N-π final-state resonant interaction.[19] In all probability there is no bound state for the Λ-N system, although there may well be such a state for the Σ-N system.[2,20] This is unfortunate because production of deuterons in (24) has been the most useful of all processes (24). Various laboratory energies of interest for (22) and (23) are presented in Table III. It is seen that only production of Λ's by Σ's can occur at relatively low energy. In the latter reaction we already have some possibility to detect a π-Y p-state resonance. It would be indicated by enhancement of production of p-wave mesons in the $T=\frac{1}{2}$ state. For this purpose the processes

$$\Sigma^-+p\rightarrow\begin{cases}\Lambda+\pi^-+p\\ \Lambda+\pi^0+n\end{cases} \quad (25)$$

can be examined. We can assume that the predominant ΛN states will be ^1S and ^3S. The production of p-wave pions should dominate except very near threshold, at least in the $T=\frac{3}{2}$ state. In this state the strong π-N final-state interaction is effective. If it is indeed found that the excitation function for the $T=\frac{3}{2}$ process indicates strong production of p-wave pions, we can look to see if the production in the $T=\frac{1}{2}$ state is comparable. There the enhancement would have to come from the π-Y interaction. The $T=\frac{1}{2}$ production can be detected by comparing (25) with $\Sigma^++p\rightarrow\Lambda+\pi^++p$, or by examining the deviation of the production ratio $(\pi^-+p)/(\pi^0+p)$ from $\frac{1}{2}$.

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[20] F. Ferrari and L. Fonda, Nuovo cimento **6**, 1027 (1957).