Strange-Particle Production in 2.7-GeV/c $\pi^- p$ Interactions*

D. H. Miller, A. Z. Kovacs, R. McIlwain, T. R. Palfrey, and G. W. Tautfest
Department of Physics, Purdue University, Lafayette, Indiana
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A total of 1514 strange-particle events have been analyzed in a sample of 30 000 pictures of incident 2.7-GeV/c π^- in the 72-in. hydrogen bubble chamber. Strong resonance production is observed, particularly $K^*(888)$, $Y_1^*(1385)$, and Y_0^*(1405 and 1520). In general, baryon systems are peaked sharply backward in the center-of-mass system, consistent with peripheral production. Partial cross sections and a study of all final states are presented. The total strange-particle cross section at this energy is calculated to be 1.49±0.07 mb.

I. INTRODUCTION

PREVIOUS experiments[1–4] on $\pi^- p$ interactions producing strange particles have shown that the nature of these interactions is changing in the range from 1.8 to 3 GeV/c. The reactions at the higher momenta are more peripheral and certain channels like the production of Y_1^{*-} are depressed while the production of more complicated final states involving two resonances is becoming significant. This experiment was undertaken to study such effects, to look for strange-particle decays of known and possible undiscovered resonant states, and to measure partial cross sections for strange-particle production.

A run of 30 000 pictures was made with the 72-in. L.R.L. hydrogen bubble chamber at the Bevatron of $\pi^- p$ interactions at 2.7 GeV/c. The film was scanned twice and from the original total of 2000 possible strange-particle events 1514 were accepted for final analysis. From events in which all particles in the final state were seen, a full width at half-height of 28 MeV/c was obtained for the beam momentum.

Special attention was paid during the analysis to the $K\pi\pi$ system in the four-particle final states. This has been reported elsewhere.[5]

The results reported below are in good agreement with those obtained at neighboring energies.[3,4]

II. CROSS-SECTION DETERMINATION

The film was scanned twice for events showing neutral or charged decays which could possibly have come from kaon or hyperon decays. Scanned events were measured on two digitized microscopes and processed by a PACKAGE programming system. A total of 1514 events was accepted within the fiducial volume.

Prints taken of each event were used to obtain ionization estimates as an aid to choosing the correct fit. Events were considered ambiguous if no choice of kinematic hypothesis could be made on the basis of χ^2, ionization, scatters, etc., and two or more hypotheses were successful and had probabilities less than a factor of 10 apart. These ambiguous events were remeasured several times, and ambiguity was removed from a few events. Out of the total sample, 49 events remained ambiguous. In addition, 39 events were considered unmeasurable, these latter occurring in the main in the lower constraint classes of one prong with one seen neutral decay, or two prongs with one charged decay. A scatter or steeply dipping track was usually responsible in reducing any possible interpretation to at best zero constraints. A few of these were handfitted (scatters of neutral V's) from geometry output. Ambiguous or unmeasurable events were not used in any angular distributions or effective mass plots. They were, however, distributed over all possible final-state channels from which they could have been a part, in the ratio of the unambiguous events in those channels. This

TABLE I. Partial cross sections in microbarns for strange-particle production in 2.7-GeV/c $\pi^- p$ interactions.

	σ	$d\sigma$		σ	$d\sigma$
$\Lambda^0 K^0$	120	11	$\Lambda K^+\pi^-\pi^0$	77	9
$\Sigma^0 K^0$	85	12	$\Lambda K^0\pi^+\pi^-$	83	9
$\Sigma^- K^+$	31	5	$\Sigma^0 K^0\pi^+\pi^-$	32	7
$\Lambda^0 K^0\pi^0$	132	18	$\Sigma^+ K^+\pi^-\pi^-$	14	3
$\Lambda^0 K^+\pi^-$	97	10	$\Sigma^+ K^0\pi^-\pi^0$	17	6
$\Sigma^0 K^+\pi^-$	75	9	$\Sigma^- K^0\pi^+\pi^0$	22	7
$\Sigma^+ K^0\pi^-$	51	7	$\Sigma^- K^+\pi^+\pi^-$	12	3
$\Sigma^- K^0\pi^+$	118	10	$\Lambda^0 K^0$(>1 neutral)	116	18
$\Sigma^- K^+\pi^0$	40	6	$\Sigma^- K^+$(>1 neutral)	3	2
$K_1^0 K_1^0 n$	33	7	$\Lambda K^0\pi^+\pi^-\pi^0$	11	4
$pK^- K^0$	81	13	$\Lambda K^+\pi^-\pi^+\pi^-$	2	1
$nK^+ K^-$	84	47	$\Sigma^- K^+\pi^+\pi^-\pi^0$	4	2
$K_1^0 K_1^0$(>1 neutral)	6	3	$\Sigma^- K^0\pi^+\pi^-\pi^+$	4	2
$K_1^0 K_2^0 n$	23	10	$\Lambda K^+\pi^-$(>1 neutral)	14	4
$pK^0 K^-\pi^0$	12	5			
$nK^+ K^0\pi^-$	20	7	1514 accepted events		
$nK^0 K^-\pi^+$	9	5	total cross section		
$pK_1^0 K_1^0\pi^-$	4	2	for strange particle		
$pK^+ K^-\pi^-$	12	9	(1.45±0.07) mb.		
$pK_1^0 K_2^0\pi^-$	2	2			
$pK^0 K^-$(>1 neutral)	2	2			

* Work supported in part by the U. S. Atomic Energy Commission.

[1] G. Alexander, L. Jacobs, G. R. Kalbfleisch, D. H. Miller, G. A. Smith, and J. Schwartz, in *Proceedings of the 1962 Annual International Conference on High-Energy Nuclear Physics at CERN*, edited by J. Prentki (CERN, Geneva, 1962), p. 320.

[2] G. Alexander, G. R. Kalbfleisch, D. H. Miller, and G. A. Smith, Phys. Rev. Letters **8**, 447 (1962).

[3] T. P. Wangler, A. R. Erwin, and W. D. Walker, Phys. Rev. **137**, 414 (1965).

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set was examined for possible biases but no significant correlations were found. These events were used for all cross-section determinations.

All event classes were checked for systematic errors. Known branching ratios of charged to neutral decays were used to compare the one-V event rates to the two-V event rates. In addition to this all two-V events were measured as two one-V events, with one decay and then the other left out. These 'fake' events were then subjected to criteria used for one-V events and possible misinterpretations were looked for. From these studies it was clear that any misassignments such as Λ^0, Σ^0 ambiguities which had been assigned uniquely were at most 2%, i.e., much smaller than the statistical errors present.

Lifetime (length/momentum) distributions of kaons (K_1^0), lambdas, and sigmas gave no indication of significant losses out of the chamber. Projected length distributions indicated a significant loss of very short $\Sigma^\pm$ (when no K_1^0 was seen) and of very short Λ and K_1^0 (when only one decay was seen in the event). A cutoff of 5 mm in projected path length was therefore imposed

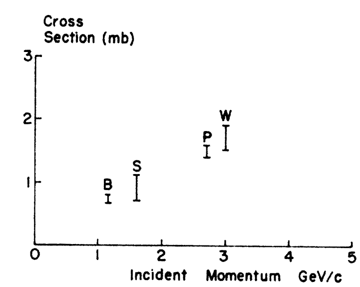

FIG. 1. Strange-particle cross section for π^-p collisions versus incident-pion momentum in the laboratory from the following experiments. B—Ref. 7, p. 271. S—Ref. 8, p. 375. P—Data from this experiment (1965). W—T. P. Wangler *et al.* Phys. Rev. **137**, 415 (1965).

on all single-V or single charged-decay events, and each event was weighted accordingly.

Each event was weighted for the unobservable decays. Branching ratios were taken from Rosenfeld *et al.*[6] In the case of K^0K^0 production the cross section is not quoted for $K_2^0K_2^0$ final states.

The total pion path length for interaction was obtained by a beam-track count every twentieth frame. Comparison of the azimuthal distribution of these beam tracks and of accepted events permitted a sufficiently sharp cutoff to eliminate a large part of the muon contamination in the beam. Separate scans were made for very high (>200-MeV/c) delta rays. A maximum likelihood estimate of the muon contamination using these events gave a contamination of 3.4±1.8%.

In Table I, we give the cross sections obtained. The errors shown reflect only the statistical uncertainties for each event class. Uncertainties in the beam-track count, contamination, hydrogen pressure, etc., add an error of 2.5% to each partial cross section.

The cross section quoted for Λ^0K^0(>1 neutral) includes $\Sigma^0K^0\pi^0$. The ratios of Λ to Σ^0 production in the two- and three-body events which could be fitted were both 1.4. If this is used together with the $\Lambda^0K^0\pi^0$ cross section, then the $\Sigma^0K^0\pi^0$ cross section is $\sim$80 μb.

TABLE II. Cross sections for resonance production in microbarns.

	σ	$d\sigma$		σ	$d\sigma$
$\Lambda K^{*0}\binom{K^+\pi^-}{K^0\pi^0}$	53	8	$Y_1^{*-}K^0\pi^+$	8	2
$\Sigma^0K^{*0}(K^+\pi^-)$	52	8	$Y_1^{*+}K^0\pi^-$	4	1
$\Sigma^-K^{*+}\binom{K^+\pi^0}{K^0\pi^+}$	50	6	$Y_1^{*0}K^+\pi^-$	3	1
			$Y_0^*K^0\pi^0$	6	3
$K^0Y_1^{*0}(\Lambda\pi^0)$	62	13	$Y_0^*K^+\pi^-$	4	2
$K^+Y_1^{*-}(\Lambda\pi^-)$	16	3	$Y_0^*K^+\pi^-$	1	1
$K^0Y_0^*\binom{\Sigma^+\pi^-}{\Sigma^-\pi^+}$	37	4	$K^{*+}\Lambda\pi^-$	4	1
			$K^{*0}\Lambda\pi^0$	12	2
$K^0Y_0^*(1520)\begin{pmatrix}\Sigma^+\pi^-\\ \Sigma^-\pi^+\\ pK^-\end{pmatrix}$	42	7	$K^{*+}\Sigma^0\pi^-$	6	2
			$K^{*0}\Sigma^+\pi^-$	5	2
$Y^{*-}K^{*+}$	10	2	$K^{*0}\Sigma^-\pi^+$	5	2
$Y_1^{*0}K^{*0}$	10	2			
$Y_0^*K^{*0}$	16	5			

The total cross section for hyperon production is 1.16±0.04 mb. For all strange-particle production, exclusive of $K_2^0K_2^0$ final states, the cross section is 1.45±0.07 mb. If the further assumption is made that $\sigma(K_2^0K_2^0)=\sigma(K_1^0K_1^0)$, then the total strange-particle cross section is 1.49±0.07 mb. Figure 1 shows the variation of total strange-particle cross section with momentum up to 3 GeV/c from this and other experiments.[3,7,8]

In Table II resonance cross sections are shown. These apply for the observed decay modes which are indicated in parentheses in the table. The cross sections were obtained by finding the best fits to effective-mass plots using Breit-Wigner shapes for the resonances plus phase-space background.

III. TWO-BODY FINAL STATES

Events with single decays and double decays were used in this analysis.

The production angular distributions in the c.m. system are shown in Fig. 2. In the Λ^0K^0 and Σ^0K^0 final states, the K^0 is peaked strongly forward indicating the importance of peripheral interactions. The other possible state Σ^-K^+ is quite different, however, as the K^+ is peaked (not so strongly) backward. This could be due to baryon exchange.

Examination of the up-down asymmetry in the Λ^0 decay in the final state Λ^0K^0 gives $\alpha\bar{P}=0.3\pm0.26$.

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[8] J. Alitti, J. P. Baton, A. Berthelot, A. Daudin, B. Deler, O. Goussu, M. A. Jobial, A. Rogozinski, and F. Shively, in *Proceedings of the Aix-en-Provence International Conference on Elementary Particles*, 1961 (Centre d'Etudes Nucléaires de Saclay, Seine et Oise, 1961), p. 375.

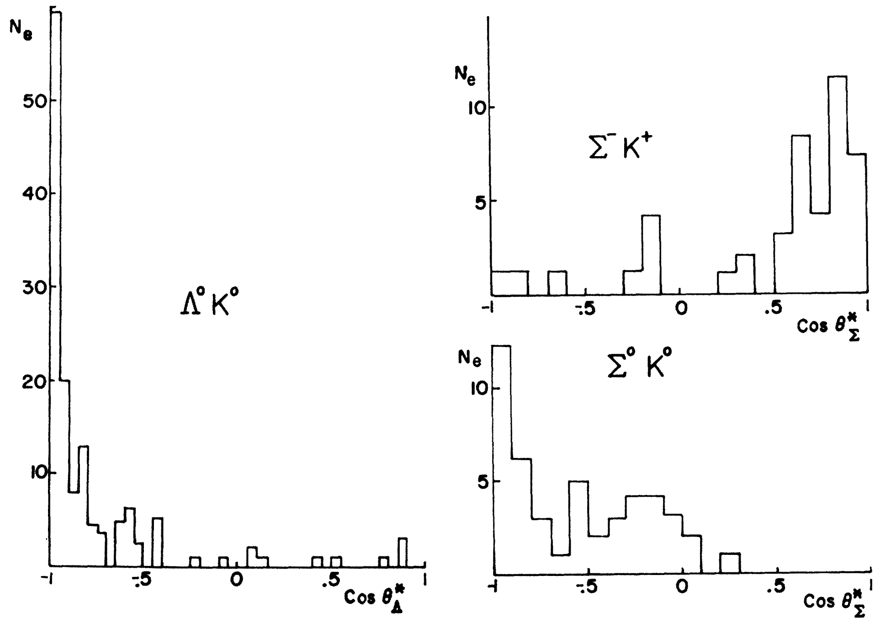

FIG. 2. Angular distribution of the hyperon in the center-of-mass system with respect to the incident pion for two-body production.

IV. THREE-BODY FINAL STATES

The reactions of the type $YK\pi$ are dominated at this incident energy by $K^*(888)$, $Y^*(1385, 1405$, and $1520)$, particularly at small production angles. There is evidence in several of these states for the production of higher mass Y^* and $N^*(1688,1920)$. The production cross sections for these latter resonances via strange-particle channels were estimated to be a few microbarns. Detailed analysis was not possible due both to the smallness of these cross sections and overlapping bands of the more firmly established lower mass resonances.

In order to estimate cross sections for resonance production, fits were made to the mass distributions using phase-space plus the Breit-Wigner curves for the resonances. Our data were consistent with widths of 50 MeV for $K^*(888)$ and $Y^*(1405)$; 30 MeV for $Y^*(1385)$; and 20 MeV for $Y^*(1520)$.

A Dalitz plot is shown for the reaction $\Lambda K^+\pi^-$ in Fig. 3(a) with the mass projection showing strong K^* production. Other relevant mass projections are shown in Figs. 3(b) through 3(i). The partial cross sections for resonance production are given in Table II.

The decay branching ratios of the resonances are shown in Table III and in general disagree with the expected values calculated with Clebsch–Gordon coefficients. This is at least in part due to other resonances being produced in one channel and not the other. In the case of $\Sigma^-\pi^+K^0$, $K^*(888)$ is formed quite strongly whereas in the channel $\Sigma^+\pi^-K^0$ it can not be. Although the branching ratio $\sum^+\pi^-/\Sigma^-\pi^+$ of the $Y_0^*(1405)$ is in disagreement with the expected value, at $\cos\theta^* < -0.5$ (where θ^* is the angle between the outgoing $\Sigma\pi$ system and the incident π^-) agreement is better (0.8 ± 0.3). In this angular region K^* production is very much suppressed. Similarly the presence of Y_1^{*0} affects the ratio of $K^* \rightarrow K^+\pi^-/K^0\pi^0$.

The observed shift of the central value of the $Y^*(1405)$ to 1380 MeV is not due to the presence of K^* events but is seen also outside the crossing region.

The $\Sigma^0K^+\pi^-$ channel was examined for evidence of K or K^* exchange in the manner of Smith *et al.*[9] The $\Sigma^0K^+\pi^-$ is useful in this respect as no strong resonance has been observed in the $\Sigma^0\pi^-$ system. The results are only qualitative because of the small numbers of events in the K^* region but our value of 0.5 ± 0.3 for the ratio of K/K^* exchange is in agreement with previous results.[3,9]

The production angular distributions for these resonant states are shown in Fig. 4 with ~15-20% background. The strong forward peaking is consistent with peripheral interactions.

TABLE III. Branching ratios into observable modes of $K^*(888)$, $Y^*(1385, 1405, 1520)$.

		Measured	Expected
ΛK^*	$K^*(888) \rightarrow (K^+\pi^-)/K^0\pi^0)$	8 ± 2	2
Σ^-K^*	$K^*(888) \rightarrow (K^0\pi^+)/(K^+\pi^0)$	3 ± 0.5	2
K^0Y^*	$Y^*(1405) \rightarrow (\Sigma^+\pi^-)/(\Sigma^-\pi^+)$	0.5 ± 0.15	1
$K^0Y_0^*$	$Y_0^*(1520) \rightarrow (\Sigma^+\pi^-)/(\Sigma^-\pi^+)$	3 ± 1.5	1

V. FOUR-BODY FINAL STATES

The cross sections for resonance production have been given in Table II.

The two most abundant of the four-particle final

[9] G. A. Smith, J. Schwartz, D. H. Miller, G. R. Kalbfleisch, R. W. Huff, O. I. Dahl, and G. Alexander, Phys. Rev. Letters **10**, 138 (1963).

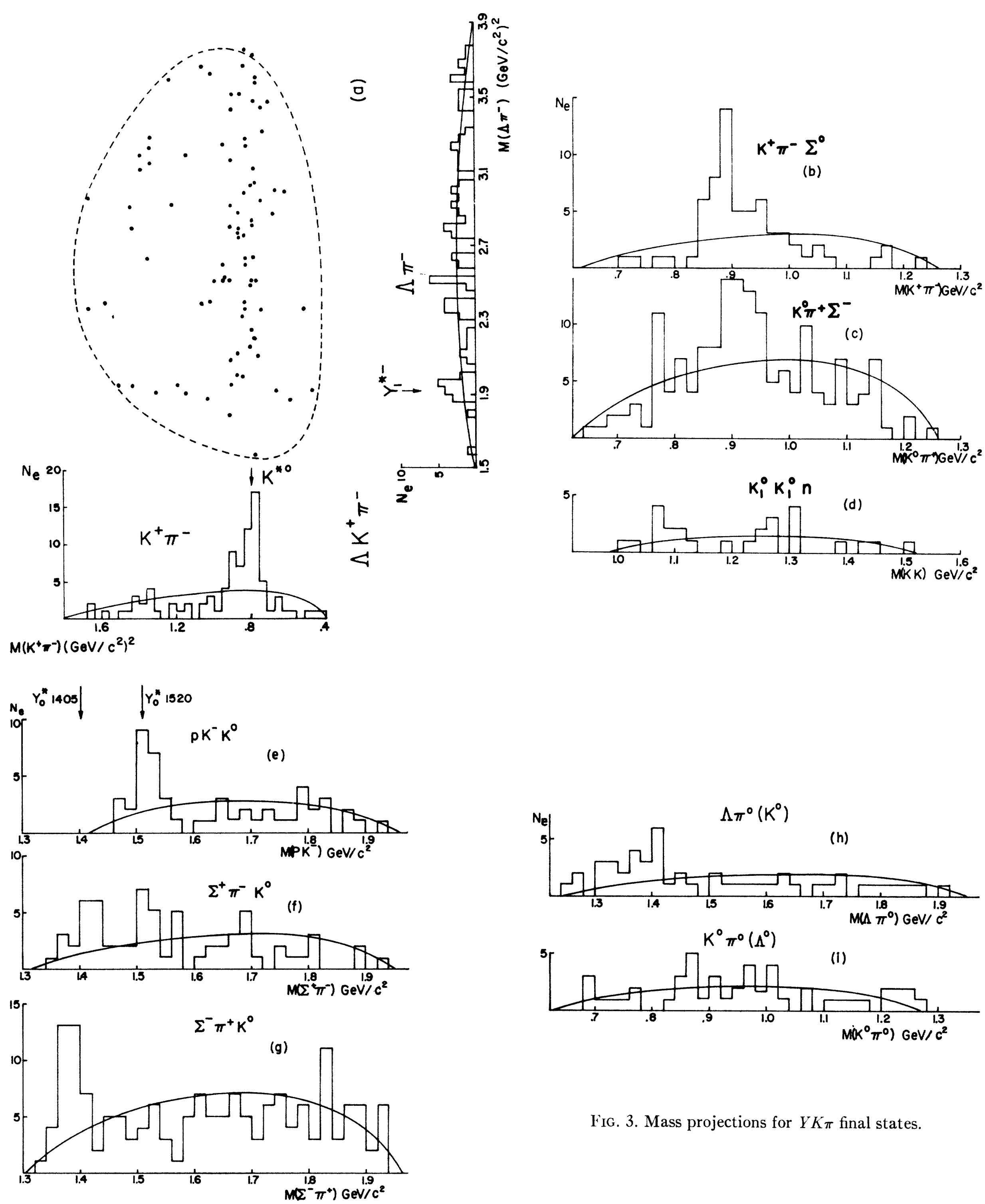

FIG. 3. Mass projections for $YK\pi$ final states.

states are $\Lambda K^0\pi^+\pi^-$ (95 events) and $\Lambda K^+\pi^-\pi^0$ (75 events). Three scatter plots are shown for these final states. Figure 5(a) shows the mass of $\Lambda\pi^-$ against the mass of $K^+\pi^0$ in the $\Lambda K^+\pi^-\pi^0$ states. Figure 5(b) shows the mass of $\Lambda\pi^0$ against the mass of $K^+\pi^-$ in the same states. Figure 5(c) shows the mass of $\Lambda\pi^-$ against the mass of $K^0\pi^+$ in the $\Lambda K^0\pi^+\pi^-$ system. Indication of Y^*K^* production may be seen in these figures. Examination of the subset of events in the simultaneous $Y_1^*K^*$ region is severely limited by statistics. For ex-

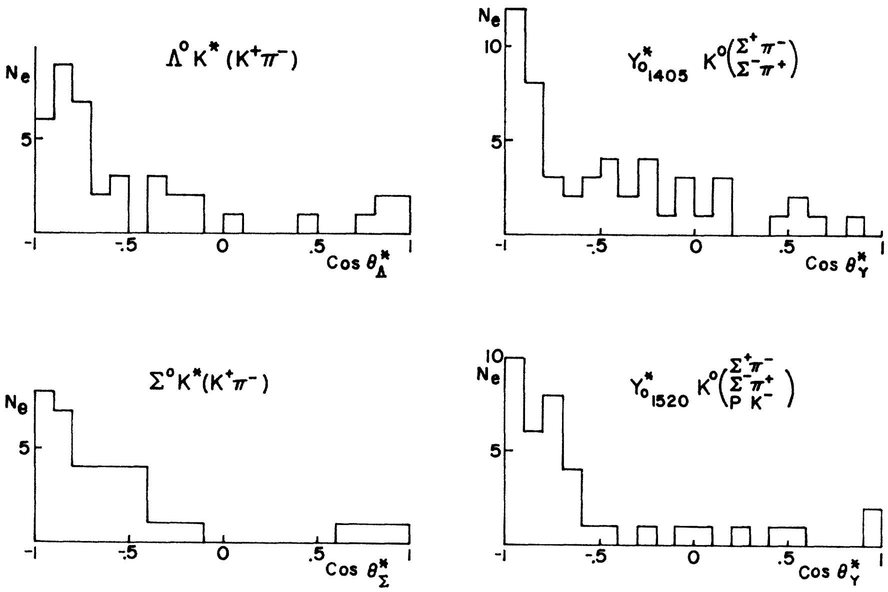

FIG. 4. Angular distributions of the hyperon or hyperon system in the final states YK^* or Y^*K.

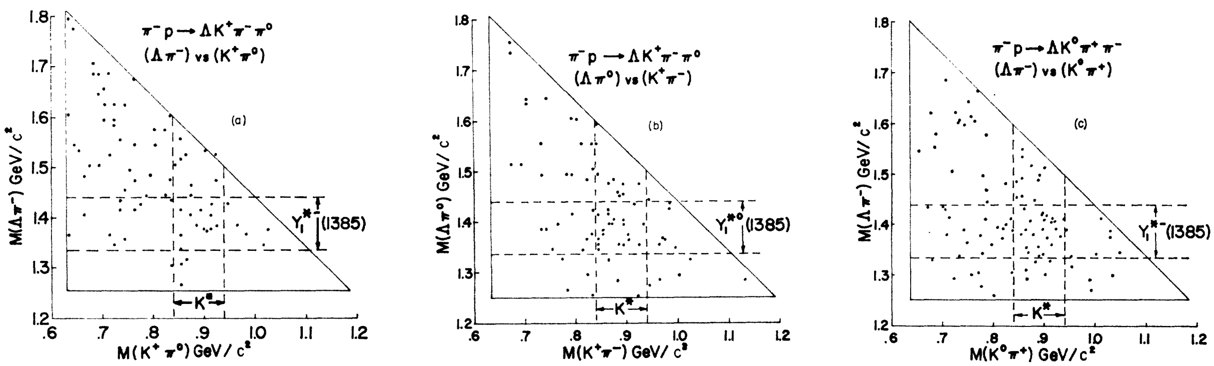

FIG. 5. Distributions of $\Lambda\pi_1$ versus $K\pi_2$ for the final states $\Lambda K\pi_1\pi_2$.

ample, the angular distribution of Y_1^{*0} in K^*Y^* shows a forward to backward ratio of 7:16 in the center-of-mass system, while the Y_1^{*-} has a forward to backward ratio of 22:14. Neither angular distribution has the peaking expected if the interaction were peripheral, a fact which could be attributable to the nearness to threshold. The c.m. energy available is 2.44 GeV, while Y^*K^* amounts to 2.27 GeV.

The ΣK and $YK\pi$ mass distributions were examined for $N_{3/2}^*(1920)$ and $N_{1/2}^*(2190)$. In Fig. 6 where all ΣK combinations are plotted together, there is no evidence for $N_{3/2}^*(1920)$ above background. Phase space in the $YK\pi$ system peaks near 2190 MeV, and falls off from the peak with a width not unlike the reported width of the $N_{1/2}^*(2190)$, making analysis difficult. As can be seen on Fig. 7, 1920 MeV is near the bottom of the

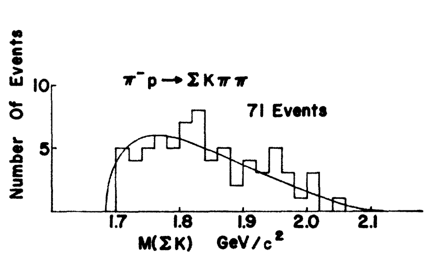

FIG. 6. ΣK mass distribution for all events of the type $\Sigma K\pi_1\pi_2$.

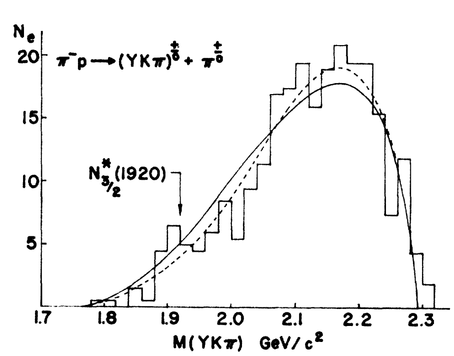

FIG. 7. $YK\pi$ mass distributions for all events of the type $YK\pi_1\pi_2$.

$YK\pi$ phase space, and, if all possible charge combinations are taken, there is at most a small amount of $N_{3/2}^*(1920)$ above phase space. The solid curve is the appropriate sum of $\Lambda K\pi$ and $\Sigma K\pi$ phase space. The dashed curve is the sum of $\Lambda K\pi$ and $\Sigma K\pi$ phase spaces, ΛK^* and ΣK^* phase spaces normalized to the observed number of K^*.

VI. FIVE-BODY FINAL STATES

Only 11 events were identified as five-particle final states with no more than one missing neutral. Cross sections from these events are given in Table I. No statistically significant remarks can be made.

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Exact Bootstrap Solutions to the Low Equation*

KERSON HUANG AND ALFRED H. MUELLER†
Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
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We inquire whether the Low equation for meson-baryon scattering in the static one-meson approximation possesses bootstrap solutions, defined to be those solutions satisfying Levinson's theorem of potential scattering. The Low equation is allowed to have arbitrary subtractions and arbitrary bound states, except that the baryon must be the lowest bound state. A two-parameter family of cutoff functions, including the case of no cutoff, is introduced. We consider 2×2 and 4×4 crossing matrices of certain general forms, with the Chew-Low theory included as a special case of the latter. To answer the question raised, a simple technique is used based on the crossing relation on the imaginary energy axis. It is shown that for all the crossing matrices considered the unsubtracted Low equation does not possess a bootstrap solution, regardless of the choice of bound states and cutoff function. We further study the case of one subtraction for 2×2 crossing matrices and find some necessary bootstrap conditions. These restrict the crossing matrix, determine the form of the cutoff function, and require that in the baryon channel the baryon be the only bound state, while in the other channel there be at most one bound state. These results are generalizations of those obtained earlier by Huang and Low.

1. INTRODUCTION

THE Low equation[1] in the static one-meson approximation, as first applied by Chew and Low[2] to the problem of π-N scattering is the simplest example of a dispersion relation that combines the requirements of unitarity, crossing symmetry, and analyticity. To write down the Low equation, one has to decide beforehand the number of bound states present in each scattering channel, their locations, and their coupling constants. For any given choice of bound states, there exists an infinite number of solutions to the Low equation, as first shown by Castillejo, Dalitz, and Dyson[3] for the charged scalar theory. In the Chew-Low theory, in which the nucleon was taken to be the only bound state, a unique solution was defined by the requirement that it possess a power-series expansion in the pion-nucleon coupling constant, a requirement motivated by an underlying Lagrangian field theory, which was what Chew and Low undertook to study. Since it is a current point of view that unitarity, crossing symmetry, and analyticity might be taken as basic postulates, there is a need for an independent criterion to render the solution to the Low equation unique, given the bound states, or even a criterion to determine the choice of bound states. A criterion that hopes to achieve both purposes is the bootstrap requirement, which expresses in a definite way the idea that no particle is elementary, but all are composite states of one another. This paper, which is an extension of an earlier one,[4] is concerned with the existence and uniqueness of bootstrap solutions to the Low equation.

It was shown in Ref. 4 that in the context of the Low equation, the bootstrap is equivalent to Levinson's theorem of potential scattering, which states that in any scattering channel the difference between the phase shift at infinite energy and at threshold must be equal

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