1660-MeV Y_1^* HYPERON*

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Recently, Bastien et al. reported the results of an extensive analysis of K^-+p interactions below 1 BeV/c.[1] They found that both the $\Sigma^-\pi^+/\Sigma^+\pi^-$ ratio and the cross sections for production of $\Lambda\pi(\pi)$ and $\Sigma\pi(\pi)$ final states varied rapidly in the region $p_K=760$ MeV/c ($E_{\mathrm{c.m.}}=1681$ MeV). In addition, Alexander et al. examined the two-body effective-mass distribution for $Y\pi K$ states produced in π^-+p interactions at 2.1 to 2.3 BeV/c.[2] They observed an enhancement in the region $M(Y\pi)\approx 1685$ MeV, and tentatively ascribed the effect to a resonance in the $I=1$ $Y\pi$ system.

To obtain additional evidence regarding the existence and properties of such a state, we have studied the three- and four-body final states produced in K^-+p interactions at $p_K=1.51$ BeV/c ($E_{\mathrm{c.m.}}=2025$ MeV). The effective-mass distributions for these events establish the existence of an $I=1$ resonant state, Y_1^*, with mean energy $M^*\approx 1660\pm 10$ MeV and full width at half-maximum $\Gamma\approx 40\pm 10$ MeV. Enhancements in the mass spectra associated with the positive component of Y_1^*(1660 MeV) are particularly strong and have been used to estimate 7:6:4:4:<1 as the relative rates for decay into $\Lambda\pi:\Sigma\pi:\Lambda\pi\pi:\Sigma\pi\pi:\bar{K}N$. Because of interference with the large background of competing mechanisms in each channel, neither the spin nor parity of the resonant state could be inferred. The possible relevance of Y_1^*(1660 MeV) to the recently proposed SU(3) symmetry scheme[3,4] is discussed.

The data were obtained during an extensive exposure of the Lawrence Radiation Laboratory's 72-in. hydrogen bubble chamber to a K^- beam. At the momentum setting of 1.51 BeV/c the observed path length provided 5000 events per millibarn of cross section.[5] After scanning and measurement, events were fitted kinematically by using an IBM program "PACKAGE."

We have studied the effective-mass distributions for the reactions

$$K^-+p\to\Lambda+\pi^++\pi^-, \tag{1a}$$
$$\to\Lambda+\pi^++\pi^-+\pi^0, \tag{1b}$$
$$\to\Sigma^0+\pi^++\pi^-, \tag{1c}$$
$$\to\Sigma^\pm+\pi^\mp+\pi^0, \tag{1d}$$
$$\to\Sigma^\pm+\pi^\mp+\pi^++\pi^-, \tag{1e}$$
$$\to\bar{K}^0+\pi^-+p. \tag{1f}$$

The final states (1a), (1b), (1c), and (1f) appear topologically in the bubble chamber as interactions leading to two prongs plus an associated V. For approximately 98 % of the events, Reaction (1f) could be unambiguously separated from the Λ/Σ^0 final states by kinematic fits to both the decay and the production vertices. The more difficult task of apportioning the two-prong-plus-Λ events among reactions (1a), (1b), and (1c) was performed by using the χ^2 criteria enumerated in Table I.

Events arising from Reactions (1d) and (1e) were obtained by measurement of two- and four-prong interactions having a kink in any track at a distance greater than 0.3 cm from the production vertex. Kinematic fitting resulted in almost unambiguous identification of the $\Sigma^\pm\pi^\mp\pi^0$ and $\Sigma^\pm\pi^\mp\pi^+\pi^-$ final states. The number of events assigned to Reactions (1a) to (1f) is given in the first column of Table II.

Several of the final states studied arise predominantly through production of low-mass resonances in association with one or two additional

Table I. Selection criteria for apportioning V^0 plus two-prong events.[a]

Final state	Constraints	Criteria (1)	Criteria (2)	Criteria (3)
(a) $\Lambda\pi^+\pi^-$	4	$\chi_a^2<40$	$\chi_b^2>10$	$\frac{\chi_a^2}{\chi_c^2}<\frac{4}{2}$
(b) $\Lambda\pi^+\pi^-\pi^0$	1	$\frac{\chi_b^2}{\chi_a^2}<\frac{1}{4}$	$\chi_b^2<10$	$\frac{\chi_b^2}{\chi_c^2}<\frac{1}{2}$
(c) $\Sigma^0\pi^+\pi^-$	2	$\chi_a^2>40$	$\frac{\chi_c^2}{\chi_b^2}<\frac{2}{1}$	$\chi_c^2<20$

[a]The average expected value of χ^2 is proportional to the number of constraints. For an event to be assigned to a given hypothesis, it must satisfy all three χ^2 tests listed in the row associated with that interpretation. Note that the χ^2 criteria are chosen in a manner such that no event can be assigned to more than one interpretation. Furthermore, the highly ambiguous events are not accepted anywhere in this table. This results in rejecting approximately 9 % of the data.

Table II. Summary of data used in determination of Y_1^*(1660-MeV) decay branching ratios.

Final state[a]	Number of events	Estimated number of Y_1^* events Observed	Corrected[b]	Relative decay rate
$\Lambda\pi^+$	1852	130	700	7
$\Sigma^0\pi^+$	504	60	320	6
$\Sigma^+\pi^0$	752	70	280	
$\Lambda\pi^+\pi^0$	1736	90	440	4
$(\Sigma\pi\pi)^+$ visible[c]	1058	180	270	
$(\Sigma\pi\pi)^+$ total			400	4
$\bar{K}^0p$	1223	0	0	<1

[a]We have also examined about 400 events of the type $K^- + p \rightarrow \bar{K}N2\pi$, corresponding to slightly more than half of the entire film sample. No statistically significant enhancement is observed in the region of 1660 MeV in the mass spectra of the $\bar{K}N\pi$ system.

[b]The numbers in this column have been obtained by applying corrections for detection efficiency, neutral decay modes, and amount of path length analyzed for each topology.

[c]Of the four charge states that make up the $(\Sigma\pi\pi)^+$ combination, both $\Sigma^0\pi^0\pi^+$ and $\Sigma^+\pi^0\pi^0$ involve two missing neutrals and thus are inaccessible to us. Because of the three possible $\Sigma\pi$ amplitudes ($I=0$, 1, or 2) which can make up an $I=1$ $\Sigma\pi\pi$ state, the ratio of the two visible modes $\Sigma^+\pi^+\pi^-$ and $\Sigma^-\pi^+\pi^+$ to the other two can vary anywhere from 1:1 to 4:1. As a compromise, we have arbitrarily taken this ratio to be 2:1 in estimating the total rate into $\Sigma\pi\pi$.

particles. Therefore it is difficult to establish the existence of more weakly produced, higher lying resonances, which must appear as superpositions on this large background. The effect is illustrated in Fig. 1, which shows the Dalitz plot for the 1852 events identified as $K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$. This final state is clearly dominated by the sequence $K^- + p \rightarrow Y_1^*(1385 \text{ MeV}) + \pi \rightarrow \Lambda + \pi^+ + \pi^-$. Nevertheless, an enhancement of $\approx$130 events may be observed both on the Dalitz plot and in the projected effective-mass distribution given in Fig. 2(a). No significant effect occurs

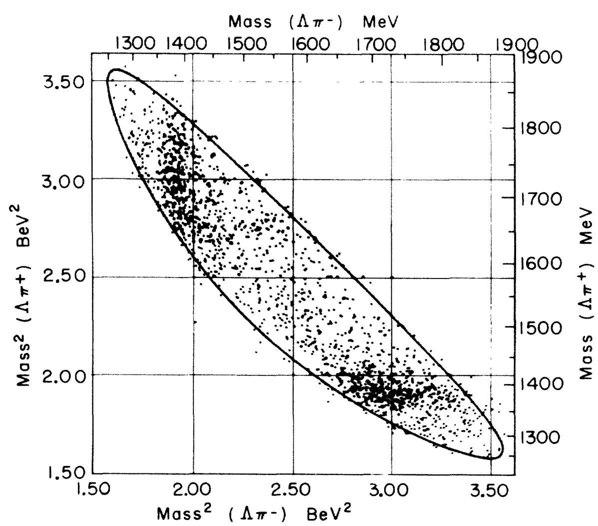

FIG. 1. Dalitz plot of 1852 examples of the reaction $K^- + p \rightarrow \Lambda\pi^+\pi^-$.

in the distribution for $M(\Lambda\pi^-)$.

Effective-mass distributions for the positive charge combinations $\Sigma^+\pi^0$, $\Sigma^0\pi^+$, $\bar{K}^0p$, $\Lambda\pi^+\pi^0$, and $\Sigma^\pm\pi^\mp\pi^+$ are given in Figs. 2(b), (c), (d), and Figs. 3(a) and (b). With the exception of the $\bar{K}^0p\pi^-$ mass spectrum, each distribution shows a significant enhancement in the $M \approx 1660$ MeV region. An examination of the corresponding negatively charged and neutral combinations indicates that enhancement at $M \approx 1660$ MeV is weak or absent. We have considered the possibility that some of the observed enhancements might arise spuriously as the result of kinematic reflections of known $Y\pi$ resonances. The only possibility occurs in the case of the $\Sigma^+\pi^-\pi^0$ channel through projection of the $Y_0^*(1520 \text{ MeV})$ onto the $\Sigma^+\pi^0$ axis; however, the $Y_0^*(1520 \text{ MeV})$ contributes equally strongly to the $\Sigma^-\pi^+\pi^0$ channel, where no significant peak is observed in the $\Sigma^-\pi^0$ distribution. Accordingly, we are led to conclude that the positively charged component of an $I=1$ (since $\Lambda\pi^+$ is pure isospin 1) resonant state with mass 1660 MeV is produced at this energy.[6]

The relative rates for $Y_1^*(1660 \text{ MeV})$ decay into various channels were obtained from suitably corrected estimates for the number of resonance events in each final state. To estimate these numbers in a systematic manner, we fitted the data in the region of the peak with a smooth background curve plus the Breit-Wigner resonance distribution $N(M) = (n_0\Gamma/2\pi)[(M - M^*)^2 + (\frac{1}{2}\Gamma)^2]^{-1}$. Since the final states [(1a) through (1f)] are dom-

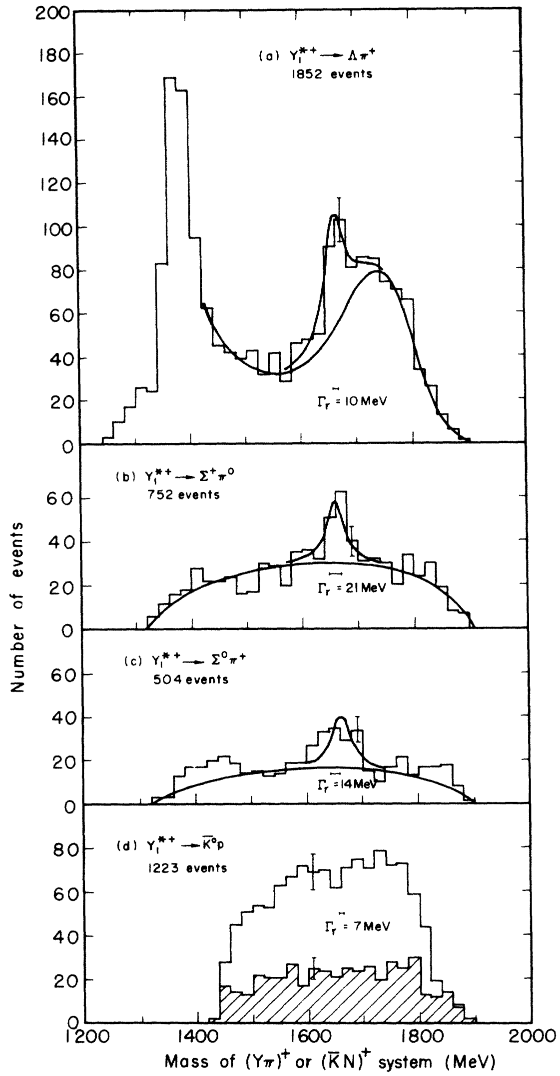

FIG. 2. Two-body decay modes of the 1660-MeV Y_1^{*+}. The dashed portion of Fig. 2(d) includes only non-K^* events [events satisfying the criterion 850 MeV $< M(K\pi) < 940$ MeV have been removed]. The curves represent the best fits of the data to a smooth background curve plus a Breit-Wigner distribution. Here Γ_γ indicates the experimental resolution in the 1660-MeV region.

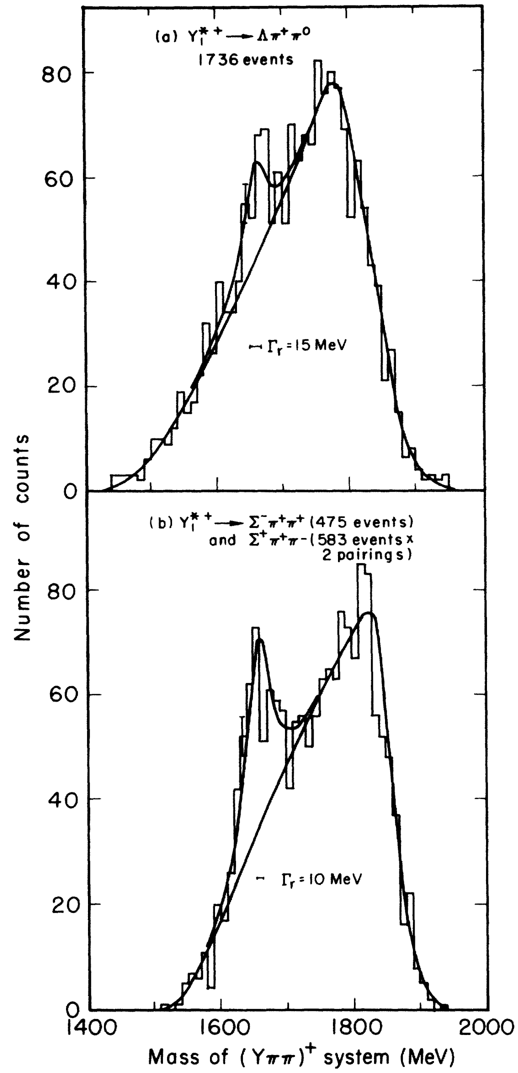

FIG. 3. Three-body decay modes of the 1660-MeV Y_1^{*+}. The curves represent the best fits of the data to a smooth background curve plus a Breit-Wigner distribution. Here Γ_γ indicates the experimental resolution in the 1660-MeV region.

inated by production of low-mass resonances, interference effects may modify significantly the shapes of the distributions observed for Y_1^*(1660 MeV). Figures 2 and 3 suggest that the apparent mean energy and width may vary by as much as ± 10 MeV. Nevertheless, because of the large uncertainties in background and statistical limitations in some channels, a single mass and width have been used. An adequate fit is obtained with $M^* = 1600$ MeV and $\Gamma = 40$ MeV.

The data on the branching ratios of Y_1^*(1660 MeV) are summarized in Table II. It is of interest to note that, within statistics, no enhancement whatever is observed in the $\bar{K}^0 p(\pi^-)$ final state.[7] In addition, an examination of the Dalitz plot (not shown) for the $\Sigma^0\pi^+\pi^-$ events indicates that the asymmetric resonance distribution results from a constructive interference between the overlapping bands for $Y_1^{*\pm}(1660\text{ MeV}) \to \Sigma^0\pi^\pm$. It should be emphasized that purely experimental uncertainties associated with estimating the number of resonant events make the relative branching ratios reliable to only about 25 %. Furthermore, any strong interference effects, either with three- or four-body background or other resonant states could alter these numbers even further.

The numbers quoted in Table II yield a cross section of approximately 0.4 mb for the process $K^- + p \to Y_1^{*+}(1660\text{ MeV}) + \pi^-$. The best estimate for the production ratios $Y_1^{*+}:Y_1^{*0}:Y_1^{*-}$ is 5:<1:<1.

One may attempt to relate $Y_1^*(1660\text{ MeV})$ and other baryon resonances to the approximate symmetry model proposed by Gell-Mann[3] and Ne'eman[4] and discussed further by Glashow and Sakurai.[8] It has been suggested that the stable baryons plus the low-lying resonant states may be accomodated in unitary multiplets of dimensionality 1, 8, 8, and 10.[9] Approximate sum rules for masses result from the additional assumption that violations of unitary symmetry occur in a particular and simple manner. The suggested assignments for low-lying baryon resonances are summarized in Table III. Because of the uncertainty in quantum numbers, several assignments are speculative. However, if the 1385-MeV Y_1^* is called[10] Σ_δ in accordance with recent evidence for $J=\frac{3}{2}^+$ from the $\Lambda\pi$ decay mode,[11] then the only remaining vacancy for the 1660-MeV Y_1^* is Σ_γ with spin $J=\frac{3}{2}^-$. Furthermore, this assignment gives excellent agreement with the equal-mass spacing rule of the δ decuplet if the presently known Ξ^* is a $J=\frac{3}{2}^+$ resonance.

It has already been pointed out that SU(3) requires an $S=-3$ singlet, Ω^-, of mass 1676 MeV, to complete the tenfold δ multiplet.[12,13] We further observe, that if the assignment of Σ_γ for the 1660-MeV Y_1^* is correct, then the predicted mass of the remaining member of the γ octet, an $S=-2$ doublet, Ξ_γ, is approximately 1600 MeV (see Table III). Moreover, Ξ_γ should be very narrow, and hence easy to detect.[14] Accordingly, the theory now predicts the existence and masses of two new particles, both of which can be produced relatively easily using presently available experimental techniques.[15]

The authors are indebted to the operators of the 72-in. bubble chamber and the Bevatron for their skill and patience. Furthermore, this work would have been impossible without the enormous effort of our scanning and measuring staffs.

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[1]P. L. Bastien, J. P. Berge, O. I. Dahl, M. Ferro-Luzzi, J. Kirz, D. H. Miller, J. J. Murray, A. H. Rosenfeld, R. D. Tripp, and M. B. Watson, in Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 373. See also P. L. Bastien and J. P. Berge, following Letter [Phys. Rev. Letters 10, 188 (1963)].

Table III. The SU(3) representation of low-mass baryons. Not shown is the β singlet, whose sole member Λ_β could well be $Y^{*0}(1405\text{ MeV})$. In its $\Sigma\pi$ channel, Λ_β would represent a resonance; in its $\bar{K}N$ channel, it would represent an s-wave bound state. We have used the symbol Λ for the metastable 1115-MeV Λ particle, as well as the two Y_0^* resonances which have the same values for baryon number, strangeness, and isotopic spin. We treat Σ, N, and Ξ similarly, and invent Δ to stand for $N_{3/2}^*$. This notation is further explained in reference 7.

Two octets[a]: $\frac{1}{2}(m_N+m_\Xi)\approx\frac{1}{4}(m_\Sigma+3m_\Lambda)$						One decuplet[a]: equal-mass spacing rule			
α octet $J^P=\frac{1}{2}^+$			γ octet $J^P=\frac{3}{2}^-$			δ decuplet $J^P=\frac{3}{2}^+$			
Baryon	m (MeV)	$2I+1$	Baryon	m (MeV)	$2I+1$	Baryon	m (MeV)	Δm	$2I+1$
Ξ^{b}	1320	2	Ξ (?)	1600	2	Ω (?)	1676		1
Σ	1190	3	$\Sigma^{c}=Y_1^*$	1660	3	$\Xi^{b}=\Xi_{1/2}^*$	1530	146	2
Λ	1115	1	$\Lambda=Y_0^*$	1520	1	$\Sigma=Y_1^*$	1385	145	3
N	939	2	$N=N_{1/2}^*$	1512	2	$\Delta=N_{3/2}^*$	1238	147	4
	Total	8		Total	8			Total	10

[a]The two mass formulas are special cases of Okubo's generalization of Gell-Mann's mass formula [S. Okubo, Progr. Theoret. Phys. 27, 949 (1962)].
[b]This assignment is speculative; neither the spin nor parity is determined.
[c]This assignment is speculative; the parity is yet undetermined; the spin assignment is suggested by the work of Bastien and Berge (see second part of reference 2).

[2]G. Alexander, L. Jacobs, G. R. Kalbfleisch, D. H. Miller, G. A. Smith, and J. Schwartz, in Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 322.

[3]M. Gell-Mann, Phys. Rev. 125, 1067 (1962); California Institute of Technology Report CTSL-20, 1961 (unpublished).

[4]Y. Ne'eman, Nucl. Phys. 26, 222 (1961).

[5]All of the path length was utilized for the $\Sigma 3\pi$ events, whereas other topologies studied in this experiment have been analyzed only in about 40% of the film.

[6]San-Fu Tuan, Phys. Rev. 125, 1761 (1962), has suggested that Peierls's mechanism [see Ronald F. Peierls, Phys. Rev. Letters 6, 641 (1961)] applied to the $\Lambda\pi^+\pi^-$ final state might provide the dynamical basis for Y^* in the 1645-MeV region.

[7]Michael Nauenberg (unpublished) has pointed out that, in general, the observed branching ratios for a resonant state strongly coupled to several channels may depend sensitively upon whether the resonant state is produced in association with other particles or is formed directly from the interaction of two specific particles. In the former case, the final state may be considered to be the result of a set of three-body production processes (e.g., $\Lambda\pi\pi$, $\Sigma\pi\pi$, $\bar{K}p\pi$), followed by coherent rescattering of some groups of particles formed. Since only one of the possible intermediate states will be analogous to formation in the two-body situation, the observed final states may have markedly different properties.

[8]S. Glashow and J. J. Sakurai, Nuovo Cimento 25, 337 (1962).

[9]M. Gell-Mann and S. Glashow (private communication).

[10]For the explanation of this notation, see A. H. Rosenfeld, in Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 325

[11]J. J. Murray, J. B. Shafer, and D. O. Huwe, Bull. Am. Phys. Soc. 8, 22 (1963); see also D. Colley, N. Gelfand, U. Nauenberg, J. Steinberger, S. Wolf, H. R. Brugger, P. R. Kramer, and R. J. Plano, Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Service, Geneva, Switzerland, 1962), p. 315.

[12]M. Gell-Mann, Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 805.

[13]S. Glashow and J. J. Sakurai, Nuovo Cimento 26, 662 (1962).

[14]S. Glashow and A. H. Rosenfeld, second following Letter [Phys. Rev. Letters 10, 192 (1963)].

[15]The threshold for the reaction $K^- + p \rightarrow \Omega^- + K^+ + K^0$ is about 3.2 BeV/c. The threshold for the production of Ξ_γ is only about 1.7 BeV/c, so it is slightly disconcerting that it has not yet been observed.

$K^- - p$ INTERACTIONS NEAR 760 MeV/c[†]

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We present the results of a study of the $K^- - p$ system at incident K^- laboratory momenta of 620, 760, and 850 MeV/c (center-of-mass energies $E_{\rm c.m.}$ of 1616, 1681, and 1723 MeV, respectively). Only the most important features of the interactions have been obtained at each of these momenta. At 620 MeV/c the system is dominated by strong $S_{1/2}$ absorption. At 760 MeV/c, effects due to $Y_1^*(1660)$ are observed.[1] Here the presence of large $\cos^2\theta$ terms and the absence of large $\cos^3\theta$ terms in the angular distributions suggest $\frac{3}{2}$ as a plausible spin assignment for the resonance. Finally, at 850 MeV/c, large $\frac{3}{2}$ or $\frac{5}{2}$ amplitudes have set in.

The Lawrence Radiation Laboratory's 15-in. hydrogen bubble chamber was exposed to a separated K^- beam capable of operating at either 760 or 850 MeV/c.[2] A setting at 620 MeV/c was obtained by degrading the 760-MeV/c beam. A total of 8000 interactions, representing all the available data, were analyzed.

In Table I we summarize the observed total cross sections, having determined the path length at each momentum by counting τ decays.[3] The only significant bias occurs when a Σ^+ decays via the protonic mode; at our energies the laboratory angle between the Σ^+ and its decay proton is usually too small to be detected with good efficiency. For this reason only, Σ^+ decaying via the pionic mode were used to establish both the total and differential cross sections. On the other hand, ambiguities in the interpretation of the events arise when one wants to distinguish between the $\Lambda\pi^0$, $\Sigma^0\pi^0$, $\Lambda\pi^0\pi^0$, and $\Sigma^0\pi^0\pi^0$ final states. The method of separation used in our experiment is the same as that described by Ferro-Luzzi, Tripp, and Watson.[4]

All differential cross sections were fitted to a series of the form

$$(4/\bar{\lambda}^2)d\sigma/d\Omega = A_0 + A_1\cos\theta + A_2\cos^2\theta + \cdots, \qquad (1)$$