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PRODUCTION OF Σ HYPERONS IN K^-p INTERACTIONS*

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We report the observation of the production in high-energy K^-p interactions of four Σ hyperon states, the $\Sigma(1385)$, $\Sigma(1660)$, $\Sigma(1940)$, and $\Sigma(2280)$. The properties of the $\Sigma(1385)$ and $\Sigma(1660)$ are in good agreement with previous observations. The $\Sigma(1940)$, in contrast to previous evidence, has a strong $\Sigma\pi$ decay mode which agrees with its assignment to the SU(3) $\frac{5}{2}^+$ octet. Finally, the existence of the $\Sigma(2280)$ has been confirmed and some of its decay modes exhibited.

Experimental information on $I = 1$ hyperons with masses greater than ~1800 MeV is still very fragmentary, the reason for this being the lack of high statistics formation or production experiments above the threshold for the production of such resonances. Evidence for such high-mass Σ resonances has been reported by Cool et al.,[1] who observed enhancements in the isospin-1 part of the total K^--nucleon cross section at masses of 1915, 2040, and 2260 MeV. These structures were also observed in the K^-p total cross-section measurements by Davies et al.[2] It should be noted that the interpretation of enhancements observed in this type of experiment is strongly dependent upon the unfolding procedure adopted to deal with the Fermi motion and shadowing effects of the nucleons in the deuteron. Numerous other experiments have reported weak supporting evidence for the existence as well as the spin and parity of the $\Sigma(1915)$. They have suffered from either a small coupling to the modes under observation[3,4] or from insufficient energy for producing the resonance,[4] in the latter cases only the effects of the Breit-Wigner tail manifesting themselves. In this Letter we present positive evidence for the existence of two Σ hyperons with masses $M_1 = 1940 \pm 20$ MeV, $M_2 = 2280 \pm 20$ MeV and widths $\Gamma_1 = 100 \pm 30$ MeV, $\Gamma_2 = 120 \pm 30$ MeV, respectively. Of particular importance in the SU(3) formulation of a $J^P = \frac{5}{2}^+$ octet[5] is the observation of the $\Sigma(1915) \to \Sigma\pi$ which hitherto had been unobserved.

The data for this study come from two separate K^-p exposures in the Brookhaven National Laboratory 80-in. hydrogen bubble chamber at the alternating-gradient synchrotron. The beam momenta in the first exposure were 4.6 and 5.0 GeV/c, most of the exposure being at 4.6 GeV/c, whereas in the second exposure the beam momenta were set to values of 3.9 and 4.6 GeV/c in approximately equal amounts. The sensitivity of the experiment, when all the exposures are added together, amounts to ~14 events/μb. This is apportioned among the three energies as follows: 2.9 events/μb at 3.9 GeV/c, 8.9 events/μb at 4.6 GeV/c, and 2.2 events/μb at 5.0 GeV/c.[6] In the ensuing analysis, data from the three energies have been added together, since with the statistics available there are no discernible differences between them. Results from the first experiment have been discussed elsewhere,[7] so that we will, in the following, limit our discussion of the processing and kinematical fitting of the data to the events occurring in the second exposure. From the latter, about 33 000 two-prong-plus-V events have been measured on the Brookhaven flying spot digitizer. The two reactions of interest are

$$K^-p \to \Sigma^0\pi^+\pi^-, \qquad (A)$$

$$K^-p \to \Lambda^0\pi^+\pi^-, \qquad (B)$$

the former being a two-constraint and the latter a four-constraint fit. The events were processed using the Brookhaven National Laboratory QLOD programming system. Only events fitting Reaction (A) with a χ^2 probability >5% and Reaction (B) with a χ^2 probability >1% were retained. Furthermore, the ionization of all charged tracks, either as measured by the flying spot digitizer or visually estimated by the scanning personnel, had to be consistent with that predicted by the production hypothesis. In this manner 455 events unambiguously fit Reaction (A), 447 events unambiguously fit Reaction (B), and 627 events were ambiguous between the two reactions. In order to resolve this ambiguity, use was made of Σ^0 decay correlations. In particular, for the true Σ^0 events the decay distribution of the Λ^0 (or the γ) decaying from the Σ^0 is expected to be isotropic as measured in the Σ^0 rest system. To this end we have investigated this decay with respect to $\hat{n}$, the unit normal to the production plane defined as $\hat{n} = \hat{p}_{K^-} \times \hat{p}_{\Sigma^0}$. The particular correlation chosen was $\hat{n}\cdot\hat{\Lambda}^0$, where $\hat{\Lambda}^0$ is a unit vector along the Λ^0 direction in the Σ^0 rest frame. This distribution is shown in Figs. 1(a) and 1(b) for the unique Σ^0 events and the ambiguous events, respectively. The contrast is striking, the distribution for the unique Σ^0 events being isotropic while that for the ambiguous events being sharply peaked at zero, clearly indicating the preponderance of $\Lambda\pi^+\pi^-$ final states.[8] For the ensuing analysis we have retained only the unique Σ^0 events for Reaction (A) and placed both unique and ambiguous Λ^0 events in Reaction (B). This results in a total of 704 events for Reaction (A) and 1969 events for Reaction (B) from both exposures combined.

In Fig. 2(a) we plot the $\Sigma^0\pi^+$ effective mass from the $\Sigma^0\pi^+\pi^-$ final state and in Fig. 2(b), the $\pi^+\pi^-$ effective mass from the same reaction.[9] It can be seen that Reaction (A) is dominated by $\rho(750)$, $f^0(1250)$, and $\Sigma(1660)$ production. Some evidence for $\Sigma(1385) \to \Sigma^0\pi^+$ is also evident. This is more clearly seen in the shaded events of Fig. 2(a),

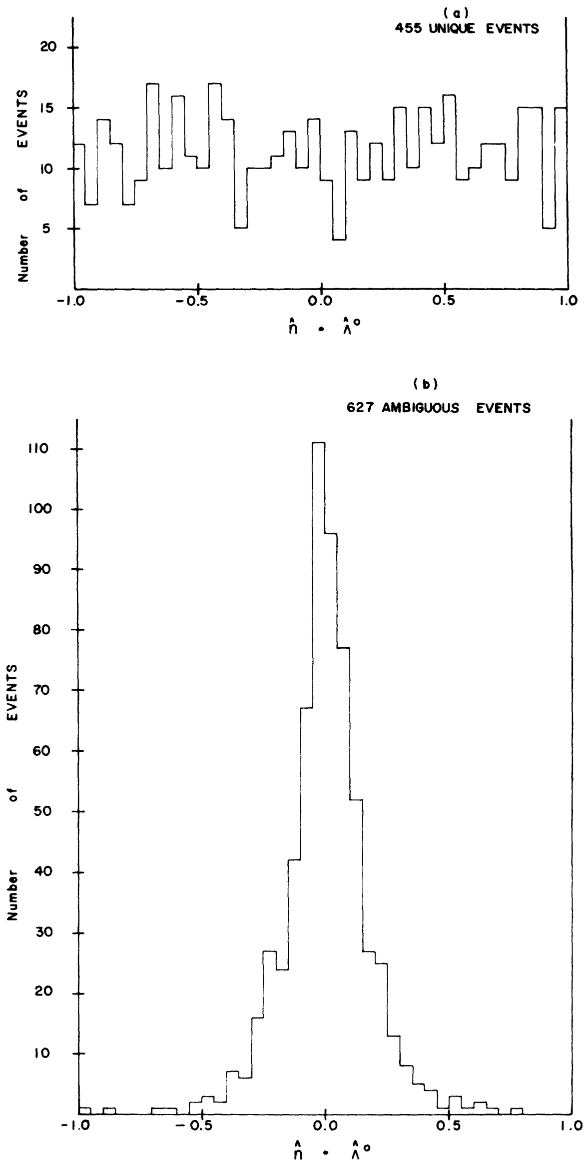

FIG. 1. Distribution of the quantity $\hat{n}\cdot\hat{\Lambda}^0$, where $\hat{\Lambda}^0$ is a unit vector along the Λ^0 direction in the Σ^0 rest frame and the normal $\hat{n}$ to the Σ^0 production plane is defined as $\hat{n} = (\hat{p}_{\text{beam}} \times \hat{p}_{\Sigma^0})$, (a) for unique Σ^0 fits having a χ^2 (probability) >5% and (b) for Σ^0 fits ambiguous with the $\Lambda\pi^+\pi^-$ final state.

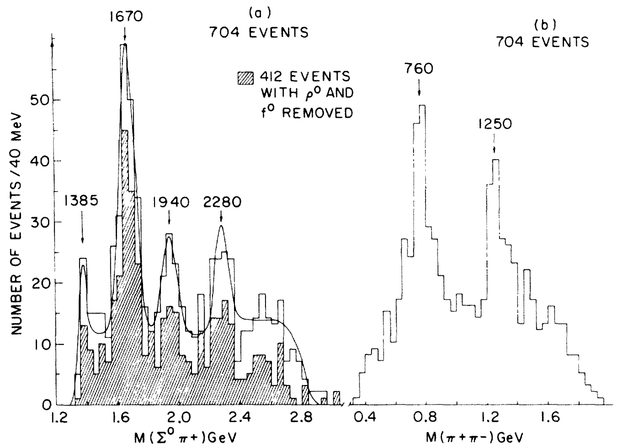

FIG. 2. (a) $\Sigma^0\pi^+$ mass spectrum for Reaction (A). The solid curve is a fit with four resonances. (b) $\pi^+\pi^-$ effective-mass distribution for Reaction (A).

where the events containing a ρ or f^0 have been removed. Two additional clear enhancements are evident, with or without ρ and f^0 removal, at masses of 1940 MeV (3.0- to 3.5-standard-deviation effect) and 2280 MeV (4- to 5-standard-deviation effect). The smooth curve shown in Fig. 2(a) is a fit to all the data assuming four resonances superimposed on a smooth background. The mass and width of the $\Sigma(1385)$ were kept fixed at their accepted values[10] and the masses and widths of the remaining three resonances were allowed to vary. An acceptable fit[11] was obtained with the following best values: $M_1 = 1670 \pm 10$ MeV, $\Gamma_1 = 95 \pm 20$ MeV; $M_2 = 1940 \pm 20$ MeV, $\Gamma_2 = 100 \pm 30$ MeV; and $M_3 = 2280 \pm 20$ MeV, $\Gamma_3 = 120 \pm 30$ MeV. A fit was also made to the overall Dalitz plot, assuming no interference between any of the Σ resonances and the ρ and f^0 bosons.[12] The results were essentially the same as the above.

The widths of the $\Sigma(1660)$ and $\Sigma(1940)$ are broader, and the $\Sigma(2280)$ narrower, than previously reported.[10] The apparent increased width of the $\Sigma(1660)$ may in fact be due to the presence of the newly found $\Sigma(1616)$,[13] or the $\Sigma(1700)$, or both. The discrepancy in the widths of the higher mass resonances is not serious in view of the large errors involved in the total cross-section measurements due to both the small magnitude of the effect as well as the difficulties in the unfolding procedures.

We now turn to a discussion of the decay branching ratios of the Σ hyperons, namely $\Lambda\pi/\Sigma\pi$ and $\bar{K}N/\Sigma\pi$. These numbers for the $\Sigma(1660$, 1940, and 2280) are shown in Table I. In most cases

Table I. Tabulation of the $\Lambda\pi/\Sigma\pi$ and $\bar{K}N/\Sigma\pi$ branching ratios for the $\Sigma(1660)$, $\Sigma(1940)$, and $\Sigma(2280)$ hyperons. The quoted upper limit corresponds to 1 standard deviation.

Hyperon	Branching ratios	
	$\Lambda\pi/\Sigma\pi$	$\bar{K}N/\Sigma\pi$
$\Sigma(1660)$	0.52 ± 0.09	<0.06
$\Sigma(1940)$	<0.28	<0.37
$\Sigma(2280)$	<0.18	<0.18

no signal was observed in $\Lambda\pi$ or $\bar{K}N$ channels and only upper limits (corresponding to 1 standard deviation) are quoted. It is noted that all these three Σ hyperons decay predominantly via the $\Sigma\pi$ mode. This is to be contrasted to the $\Sigma(1385)$ which decays mainly via the $\Lambda\pi$ mode, the branching fraction measured in this experiment being equal to $[\Sigma(1385)\rightarrow\Sigma\pi]/[\Sigma(1385)\rightarrow\Lambda\pi] = (6\pm3)\%$, in good agreement with the world average of $(9 \pm 3)\%$.[10] The previously published[10] decay modes of the $\Sigma(1660)$ are in a rather confused state due to the proximity of the $\Sigma(1700)$. The value reported here for $\Sigma(1660)\rightarrow\Lambda\pi$ should be considered as an upper limit since all events in the $\Lambda\pi$ mass region were attributed to the $\Sigma(1660)$ due to the inability to separate the $\Sigma(1700)$ contribution to this mass plot.[14] The numbers presented here for the decay of the $\Sigma(1660)$ are in reasonable agreement with the recent CERN-Heidelberg-Saclay (CHS)[15] measurements which reported a ratio of $\Sigma\pi/\Lambda\pi \approx 5/3$. On the other hand, if we identify the structure that we observe at a mass of 1940 MeV with the previously reported[1-4] $\Sigma(1915)$, a strong disagreement is found with the CHS measurement of the decay branching ratio for this state. In particular the only detectable decay mode in our production experiment is $\Sigma(1940)\rightarrow\Sigma\pi$, the two other sought-for modes, $\Lambda\pi$ and $\bar{K}N$, being an order of magnitude less frequent. This is to be contrasted to previously observed couplings of the $\Sigma(1910)$ to $\Lambda\pi$ and $\bar{K}N$ of 8-10% each with that for $\Sigma\pi < 1\%$.[3,4] Either one or more of the experiments is in error or there are two hyperons with approximately the same mass[16] but a different decay frequency for each of the possible decay modes. The $\Sigma(2280)$ has previously been observed in total-cross-section measurements only and therefore the branching fractions presented here are new information.

As has been suggested before,[5] the $\Sigma(1940)$ is a prime candidate for inclusion into a $J^P = \frac{5}{2}^+$ octet, the other members being the $N(1688)$, $\Lambda(1815)$, both of whose spin parities are well defined, and the recently discovered $\Xi(2030)$.[17] An SU(3) analysis of this octet[5,17] gave excellent agreement between the experimental and theoretically predicted rates with the exception of the $\Sigma(1940) \rightarrow \Sigma\pi$ rate. The predicted width for $\Sigma(1940)\rightarrow\Sigma\pi$ was 64 MeV to be compared with the previously accepted experimental rate of ≈2 MeV.[4] This discrepancy with SU(3) is now removed provided there are no other major decay modes of the $\Sigma(1940)$. It should be noted that the predicted SU(3) coupling of the $\Sigma(1940)$ to $\bar{K}N$ is very small, ≈3 MeV, so that it is not surprising that it has been more readily experimentally observed in a production rather than a formation type of experiment.

We conclude by commenting that four Σ hyperon states have been observed in this experiment. The results are in agreement with the properties of two previously well-established states, the $\Sigma(1385)$ and $\Sigma(1660)$. The existence of a $\Sigma(1940)$ with a strong $\Sigma\pi$ coupling has been established. This has removed a major discrepancy in previous SU(3) formulations of a possible $J^P = \frac{5}{2}^+$ octet. In addition, the existence of the $\Sigma(2280)$ has been confirmed and some of its decay modes exhibited.

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[4]R. Armenteros et al., Phys. Letters 24B, 198 (1967), and Nucl. Phys. B3, 592 (1967); R. Tripp et al., Nucl. Phys. B3, 10 (1967).

[5]R. Tripp et al., Nucl. Phys. B3, 10 (1967); M. Goldberg et al., Nuovo Cimento 45A, 169 (1966); J. Alitti et al., Phys. Rev. Letters 21, 1119 (1968).

[6]These numbers refer to the sample of two-prong plus V events.

[7]M. Primer et al., Phys. Rev. Letters 20, 610 (1968).

[8]In a bubble chamber, directions are determined in general to a much better accuracy than absolute momenta. For a $\Lambda\pi^+\pi^-$ final state, therefore, the production plane (i.e., the plane containing the beam and the vector resultant of the two pions) is very well determined. An additional (fake) Σ^0 must therefore lie in the same plane. But if the final state is really $\Lambda\pi^+\pi^-$, then the measured Λ will also lie in this plane (and in most cases will be nearly parallel to the "fake" Σ^0). Therefore $\hat{n}\cdot\hat{\Lambda}$ will have a distribution peaked around zero for those ambiguous events that do really belong to the $\Lambda\pi^+\pi^-$ final state. The two samples differ moreover in the other respect that the ambiguous Σ^0 events show a sharp enhancement in the $\Sigma^0\pi^+$ effective mass distribution (not shown) at a mass of ≃1440 MeV. This is consistent with the effect expected from $\Sigma(1385)\rightarrow\Lambda^0\pi$ events where the Λ^0 is misidentified as a Σ^0. This again confirms the correctness of the adopted separation criteria.

[9]The $\Sigma^0\pi^-$ effective mass distribution (not shown) exhibits no significant structure.

[10]A. Rosenfeld et al., University of California Lawrence Radiation Laboratory Report No. UCRL-8030, 1968 (unpublished).

[11]A 60% goodness of fit was achieved for the data shown in Fig. 2(a).

[12]This assumption is quite reasonable for the $\Sigma(1385)$, $\Sigma(1660)$, and $\Sigma(1940)$ since the excess of events above background with and without ρ and f^0 [see Fig. 2(a)] are quite similar while the comparable number is only slightly different for $\Sigma(2280)$.

[13]D. Crennell et al., Phys. Rev. Letters 21, 648 (1968); R. Armenteros et al., as quoted by R. Tripp, in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968, (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 181.

[14]Up to the present time we have not fully measured and analyzed the $\Sigma^{\pm}\pi^{\mp}\pi^+\pi^-$ final state and therefore cannot comment on the crucial decay mode $\Sigma(1660) \rightarrow\Sigma(1405)\pi$.

[15]Armenteros et al., Ref. 13; R. Abrams et al., Phys. Rev. Letters 19, 678 (1967).

[16]There are also minor differences in the precise value for the mass and width of this resonance; however as noted by the previous authors, the mass width as well as elasticity reported in formation experiments are sensitive to the deuteron wave functions used and the presence of nearby K^*N and N^*K thresholds.

[17]J. Alitti et al., Phys. Rev. Letters 22, 79 (1969). It is to be noted that this value for the mass of the Σ is in better agreement with the Gell-Mann–Okubo formula, predicting a Ξ at a mass of 2010 ± 15 MeV to be contrasted to the measured value of 2030 ± 10 MeV.