PRODUCTION OF STRANGE PARTICLES IN p-p COLLISIONS (*) AT 2.85 BeV

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I. INTRODUCTION

The production of hyperons and *K*-mesons in nucleon-nucleon collisions has received little attention. Since three or more particles are necessary in the final state, the experimental analysis of these processes becomes very much more difficult than in pion-nucleon interactions at about 1 BeV in which typically there are only two particles in the final state.

Near 3 BeV kinetic energy three previous experiments investigated the cross sections for strange particle production. One of these experiments [1] used a hydrogen gas filled diffusion chamber through which a " pencil " beam of protons was passed. Severe limitations in the knowledge of the geometrical efficiency in this experiment lead to an uncertain conclusion that the total cross section for hyperon production was 40 microbarns. It was concluded, after allowing for statistical fluctuations, that it was unlikely that the cross section would be larger than about 200 microbarns.

The second experiment [2] was a nuclear emulsion experiment using a hydrogen target, which counted K^+ mesons leaving the target with a momentum of 280 MeV/c and at 0° in the laboratory system. A total cross section for K^+ production was calculated from this differential cross section assuming a statistical momentum distribution and an isotropic angular distribution for the K^+ particles. This calculation gave about 200 microbarns for the total K^+ production cross section.

The third experiment [3] was a counter experiment which detected γ rays considered to be decay products from π^0 mesons produced in the neutral decay modes of the K^0 and Λ^0 particles. The total cross section deduced from the detected γ rays was similar to that from the diffusion chamber experiment. It should be noted that all three of these experiments had severe limitations with respect to deducing total cross sections. In the present experiment using a liquid hydrogen bubble chamber it has been possible to obtain more direct information on the total cross section and on the partial cross sections for the various production channels.

II. EXPERIMENTAL DETAILS

Protons of 2.85 BeV kinetic energy, produced by the Cosmotron at Brookhaven National Laboratory, were passed through a $20'' \times 10'' \times 9''$ liquid hydrogen bubble chamber, the 20″ dimension being along the beam direction. The chamber was operated in a magnetic field of 17,000 gauss.

The proton beam, was produced by scattering the circulating beam of the Cosmotron from an internal target of carbon. Protons scattered at 4.2° passed out of the vacuum tank through shims and were subsequently deflected a total of about 11° by two $18'' \times 36''$ magnets. Two slits located before the bending magnets were used to collimate the beam. The momentum spread of the beam was 1%. The main momentum analysis of the beam occurred in the 40° deflection produced in one quadrant of the Cosmotron. The subsequent 11° deflection in the two external magnets removed neutral particles and lower

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energy, slit scattered, charged particles. A beam duration of a few microseconds was obtained using the Rapid Beam Ejector to perturb the circulating beam and cause it to strike the carbon target. Approximately 65,000 useful photographs were taken, having on the average about one *p-p* reaction per picture.

All photographs have been scanned for strange particle events. These events were measured on a film measuring instrument which employs automatic track following. Coordinates are read-out onto punched paper tape. Geometrical reconstruction of each event has been done on either a Royal McBee LGP-30 desk-size computer or on an IBM 704.

The events were identified by adjusting momenta until the computed missing mass in production events had the desired value and until computed *Q*-values for any neutral *V*'s were consistent with that for the decay process being checked. These computations were performed using the LGP-30 computer. Visual estimates of bubble density were used as a guide to the identification of particles, and, in some cases, a gap count method was used to obtain a better estimate of particle velocity. With these procedures most events could be identified fairly definitely.

III. RESULTS

At 2.85 BeV the strange particle reactions having three particles in the final state are:

$$pp \to \Lambda^0 K^+ p \quad (1)$$

$$\to \Sigma^+ K^+ n \quad (2a)$$

$$\to \Sigma^+ K^0 p \quad (2b)$$

$$\to \Sigma^0 K^+ p \quad (2c)$$

and those having four particles are

$$pp \to \Lambda^0 K^0 p\pi^+ \quad (3a)$$

$$\to \Lambda^0 K^+ p\pi^0 \quad (3b)$$

$$\to \Lambda^0 K^+ n\pi^+ \quad (3c)$$

$$\to \Sigma^0 K^0 p\pi^+ \quad (4a)$$

$$\to \Sigma^0 K^+ p\pi^0 \quad (4b)$$

$$\to \Sigma^0 K^+ n\pi^+ \quad (4c)$$

$$\to \Sigma^- K^+ p\pi^+ \quad (5)$$

$$\to \Sigma^+ K^+ n\pi^0 \quad (6a)$$

$$\to \Sigma^+ K^0 p\pi^0 \quad (6b)$$

$$\to \Sigma^+ K^+ p\pi^- \quad (6c)$$

$$\to \Sigma^+ K^0 n\pi^+ \quad (6d)$$

$$\to K^+ K^- pp \quad (7a)$$

$$\to K^+ \bar{K}^0 pn \quad (7b)$$

$$\to K^0 \bar{K}^0 pp \quad (7c)$$

The thresholds for these reactions are shown in Table I.

Table I. Thresholds for strange particle production

Reaction	Laboratory kinetic energy for incident proton (BeV)
ΛKN	1.58
ΣKN	1.78
$\Lambda KN\pi$	1.96
$\Sigma KN\pi$	2.17
$K\bar{K}NN$	2.49

Table II is a summary of the total event count, the events analyzed as of August 15, 1960 and a breakdown into the various observed production processes. We have chosen coordinate limits within which an event must occur, and we have imposed limits on the angle which the incident proton must have in order to be considered a true beam particle. The number of events satisfying these restrictions are shown separately from those events which did not. Only those within the prescribed limits are used for cross section determinations. In attempting to assign an event to a production process we have considered the following:

(1) For events with Λ^0 or K^0 decays we have adjusted the momenta of the decay particles until the desired *Q*-value is obtained. The momentum components of the neutral particle are then also known. At the production vertex we use momentum and energy balance to obtain the missing neutral mass and momentum. The results from these two computations are compared and the measured momenta are adjusted until agreement is reached.

Table II. Summary of event count and breakdown into production channels

Number of strange particle production events	162
Number analyzed as of 8/15/60	110
Number analyzed and within fiducial volume and beam angle limits	94
Number having hyperon decay	91
Number having *K*-decay only	3

Reaction	Inside Limits	Outside Limits
Σ^+K^+n	23-$^{1}/_{2}$	2
Σ^+K^0p	19-$^{1}/_{2}$	
Σ^0K^+p	7-$^{1}/_{3}$	4-$^{1}/_{6}$
Λ^0K^+p	22-$^{5}/_{6}$	5-$^{1}/_{6}$
$\Sigma^-K^+p\pi^+$	4	1
$\Sigma^+K^+n\pi^0$	2-$^{1}/_{2}$	
$\Sigma^+K^0p\pi^+$	$^{1}/_{2}$	
$\left.\begin{matrix}\Lambda^0\\ \Sigma^0\end{matrix}\right\} K^0p\pi^+$	6	
$\left.\begin{matrix}\Lambda^0\\ \Sigma^0\end{matrix}\right\} K^+p\pi^0$	5-$^{5}/_{6}$	3-$^{2}/_{3}$
$\left.\begin{matrix}\Lambda^0\\ \Sigma^0\end{matrix}\right\} K^+n\pi^+$	2	
	94	16

(2) In Σ decay events, the Σ decay length is too short for a direct determination of the Σ momentum. The decay particle is used to obtain the Σ momentum and then a neutral mass and momentum calculation is carried out for the production event. Some events naturally are ambigous as to the production process. If an event fits two or more processes within our prescribed limits on adjusting measured momenta, then each process is weighted appropriately. 17% of the events are so divided. Most difficult is the separation of Λ^0, Σ^0 processes.

In calculating the total production cross section from the events occurring within the coordinate and angle limits we have proceeded as follows:

(1) Only those events showing a hyperon decay (91) are used.

(2) A correction is made for those events not counted because the decay occurred outside the chamber.

(3) Since the $\Sigma^+\to p+\pi^0$ decay has in general a small decay angle and thus a sizeable fraction of these events are missed, we have included only events with $\Sigma^+\to\pi^++n$ decays, and have used the experimental information [4] that $\Sigma^+\to p+\pi^0$ decays occur with equal frequency.

(4) For Λ^0 decays we have taken the charged decay mode to occur $^2/_3$ of the time [5].

(5) During scanning, all 4-prong production were recorded, hence the ratio of hyperon production was determined.

(6) For a smaller fraction of pictures all *p-p* interactions were recorded so that the ratio of 4-prong to all *p-p* interactions was found.

(7) The total *p-p* cross section at this energy is 43.1 mb [6]. In scanning, the small angle (<3.5°) elastic scattering events are easily missed. We have estimated that this amounts to roughly 10% of the total cross section and therefore have used 39 mb in our cross section calculation. These considerations lead to a total cross section for hyperon production

$$\sigma_{\text{hyperon}} = 130\pm30 \text{ microbarns.}$$

Table III gives the partial cross sections as well as a comparison with the theoretical predictions of Ferrari [7] which will be discussed in the next section. We point out again that experimentally the separation of Λ^0K^+p and Σ^0K^+p channels is difficult. The relative frequency of these two channels is thus subject to substantial error. No case of *K*-pair production has been identified as yet.

IV. DISCUSSION

The firmest result of the present experiment is the total cross section for hyperon production, 130±30 microbarns. The error which is quoted includes the statistical error and a generous factor for uncertainties in scanning efficiency and correction factors which have not yet been thoroughly investigated. This cross section is approximately a factor of 5-6 smaller than the $\pi^-p\to$hyperon production cross section at 1.4 BeV/c [8].

We note also from Table III that the processes with four particle final states (production of an extra π-meson) represent about 20% of the total cross section even though their thresholds are significantly above the three particle thresholds.

Table III. Partial cross sections for hyperon production processes (microbarns). The brackets in the last column indicate an extrapolation by the present authors.

Reaction	Experimental Value	Ferrari I	Ferrari II
$\Sigma^- K^+ n$	31 ± 8	69	96
$\Sigma^+ K^0 p$	21 ± 7	52	[10]
$\Sigma^0 K^+ p$	12 ± 7	11	79
$\Lambda^0 K^+ p$	38 ± 9	56	125
$\Sigma^+ K^+ p\pi^+$	4 ± 2		
$\Sigma^+ K^+ n\pi^0$	4 ± 3		
$\left.\begin{matrix}\Lambda^0\\ \Sigma^0\end{matrix}\right\} K^0 p\pi^+$	8 ± 4		
$\left.\begin{matrix}\Lambda^0\\ \Sigma^0\end{matrix}\right\} K^+ p\pi^0$	10 ± 5		
$\left.\begin{matrix}\Lambda^0\\ \Sigma^0\end{matrix}\right\} K^+ n\pi^+$	2 ± 2		
Total	130 ± 30		

The fact that no K-pair production events have been found is surprising since the reactions

$$pp \to K^+ \bar{K}^0 pn \tag{7b}$$

$$pp \to K^0 \bar{K}^0 pp \tag{7c}$$

should be easily identified. The third K-pair reaction

$$pp \to K^+ K^- pp \tag{7a}$$

is included in about 10,000 4-prong events and will be difficult to separate from the frequent pion production processes, such as

$$pp \to \pi^+ \pi^- pp \tag{8}$$

An attempt to separate these reactions is being undertaken. In any case it is already clear that $K\bar{K}$ production is less frequent than K-hyperon production at 2.85 BeV.

Triangular inequalities resulting from charge independence have been given by Feldman [9] and Feldman and Mathews [10] for the processes

$$pp \to \Sigma^+ K^+ n \tag{2a}$$

$$\to \Sigma^+ K^0 p \tag{2b}$$

$$\to \Sigma^0 K^+ p \tag{2c}$$

These inequalities are satisfied by the present data.

The total cross sections for the processes (2) as well as

$$pp \to \Lambda^0 K^+ p^+ \tag{1}$$

have been investigated theoretically by Ferrari [7] using two simple models, which consider the exchange of one intermediate π-meson (Model I) or K-meson (Model II). In Model I the p-p cross sections are related to the cross sections for

$$\pi^+ p \to \Sigma^+ K^+ \tag{9}$$

$$\pi^- p \to \Sigma^- K^+ \tag{10a}$$

$$\pi^- p \to \Sigma^0 K^0 \tag{10b}$$

$$\pi^- p \to \Lambda^0 K^0 \tag{10c}$$

While in Model II they are related to the cross sections

$$K^+ p \to K^+ p \tag{11}$$

$$K^+ n \to K^+ n \tag{12a}$$

$$K^+ n \to K^0 p \tag{12b}$$

The K^+ scattering data is limited and so the predictions of II must be considered tentative. In Table III the present experimental data are shown together with the results of the two models of Ferrari. We note that the calculated and experimental values are of the same order of magnitude. Perhaps of more significance are the ratios of cross sections, since these will not depend upon assumed coupling constants. Table IV shows the ratios of the predicted cross sections to the experimental cross sections.

Table IV. Ratios of calculated to experimental cross sections

	Model I experimental	Model II experimental
$\Sigma^+ K^+ n$	2.2	3.0
$\Sigma^+ K^0 p$	2.5	0.5
$\Sigma^0 K^+ p$	1.0	6.6
$\Lambda^0 K^+ p$	1.5	3.3

This comparison shows that Model I appears to fit the data rather well, whereas Model II shows large differences for the Σ^+K^0p and $\Sigma^0K^+p^+$ reactions. Now using the predictions of Model I only we compare two more points. Experimentally, the ratio of the cross sections of K^+/K^0 is ~ 3.9, I predicts a ratio ~ 2.5. Second, remembering the difficulty in separating Σ^0K^+p and Λ^0K^+p processes, we find the experimental ratio $\Sigma^+/\Sigma^0+\Lambda^0$ to be ~ 1, while I predicts a ratio ~ 2.

One other new piece of information on strange particle production in *p-p* collisions comes as a by-product of an experiment on pion production by 2.05 BeV protons carried out by Pickup, Robinson, and Salant.[11] There were 11 events of the reaction (1) found, giving a cross section of about 14 microbarns. The Ferrari model I gives about 13 microbarns, model II gives about 16 microbarns.

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DISCUSSION

CHUVILO: What is the angular distribution of the hyperons?

RAU: The geometrical corrections have not been fully computed. We do not have that information.