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STRANGE-PARTICLE PRODUCTION

IN

8 BEV/C PROTON-PROTON INTERACTIONS

by

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IN NUCLEAR SCIENCE ABSTRACTS

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Ph.D. Thesis
Department of Physics
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Urbana, Illinois
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STRANGE-PARTICLE PRODUCTION IN 8 BEV/C PROTON-PROTON INTERACTIONS

Morris William Firebaugh, Ph.D.

Department of Physics

University of Illinois, 1966

An experiment has been performed in which 37,000 pictures were obtained of the 80 " Brookhaven hydrogen bubble chamber exposed to 8 BeV/c protons. All 2, 4, 6, and 8 prong events with one or more associated kinks or V's were scanned for and 7,300 candidates for strange particle events were found. Of these, 3,600 were successfully measured and, of these, 1,260 strange particle events were identified.

A fiducial region was selected and the partial cross section for 33 different final states calculated. This corresponds to a corrected cross section for identified strange particle events of $950 \pm 95 \mu\text{b}$. The total strange particle production cross section is estimated to be 1.8 mb.

Evidence for $N^*(1236)$, $Y_1^*(1385)$, $Y_0^*(1405)$, and $Y_1^*(1660)$ formation is presented. Data concerning the existence of reported di-baryon resonances in the ΛN final state is presented, and the conclusion is drawn that no such resonances appear in the ΛN and ΣN mass distributions of this experiment.

Finally, the 3 body final states are examined in detail. An anomalous peaking is observed in the $K^+\Lambda$ invariant mass in the $K^+P\Lambda$ final state. The simple one pion exchange model does not seem to predict adequately the distribution observed. The OPEM also predicts a cross section for this final state a factor of 2 larger than the measured value of $54 \pm 7 \mu\text{b}$ if no cutoff in 4-momentum transfer to the proton is imposed.

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I. INTRODUCTION

A. Historical Background

There has been remarkably little work done on strange particle production in proton-proton collisions. This is due to the development of improved beams and greater interest in doing the πN and $K N$ experiments which these beams permitted. This experiment attempts to study systematically and in some detail strange particle production from P-P collisions at the highest energy yet reported for this type of analysis.

The first such bubble chamber study^{1/} in which events were systematically identified and studied was done in 1961 at 3.66 BeV/c momentum and observed 98 events. The cross section for strange particle production was measured to be 0.175 ± 0.032 mb and fairly good agreement with the one pion exchange model (OPEM) was obtained, both as it applied to the partial cross sections and the momentum transfer to the baryons.

The next experiment^{2/} was reported in 1964 and was done at 5.52 BeV/c momentum. Only neutral strange particles were studied, and 83 events were identified. The cross section for neutral strange particles is found to rise from $.12 \pm .02$ mb at 3.66 BeV/c^{1/} to $.46 \pm .05$ mb at this momentum, and partial cross sections are given. The cross section for the $K^+ p$ final state is measured to be 42.5 ± 14.4 μ b which this group finds to be a factor 2 smaller than their calculation of the OPEM (101 ± 15 μ b).

The next experiment^{3/}, reported in February, 1966, had an order of magnitude better statistics (1400 events) and was performed at 5 BeV/c momentum. Twelve partial cross sections were measured and the properties of the final state $K^+ p$ were compared to the OPEM and found to agree well, both in magnitude of cross section and shape of invariant mass and angular distributions.

The last detailed study^{4/} with which we are familiar was reported at the Washington meeting of the American Physical Society in April, 1966. This experiment was performed at 6.0 BeV/c momentum and measured a cross section for neutral strange particle production as $.4 \pm .07$ mb. The $K^+P\Lambda$ final state was studied in some detail (about 500 events), and the impression conveyed to this author was that the OPEM did not adequately fit the data.

Other studies have been made of strange particle production at higher energies. These include 25 BeV/c $P + P$ ^{11/}, 10 BeV/c $\pi^- + P$ ^{12,13/}, (6.3 BeV protons, 16.3 BeV/c pions, and 28 BeV/c protons in nuclear emulsions)^{14/}, 11.4 BeV/c $\pi^- + P$ ^{15/}, 16 BeV/c $\pi^- + P$ ^{16/}, 6, 11, and 18 BeV/c $\pi^- + P$ ^{17/}, and 25 BeV/c $P + P$ ^{18/}. However, in all these experiments the statistics were limited (about 250 events or less) and only in references 12 and 13 were attempts made to obtain kinematic fits at the primary vertex. Therefore, only gross features such as the perpendicular component of momentum and angles of various particles were presented in most cases.

B. Objectives of This Experiment

The objectives of this experiment are summarized as follows:

1. The total interaction cross section has been measured and found to be in agreement with previous results.
2. The corrected partial cross sections for 33 different final states have been obtained.
3. General kinematic features such as the degree of peripherality of the baryons as a function of the number of bodies in the final state are presented. We observe that, as the number of bodies in the final state increases, the outgoing baryons become less

peripheral.

4. Data indicating the presence of $N^*(1236)$, $Y_1^*(1385)$, $Y_0^*(1405)$, and $Y_1^*(1660)$ are presented. Fits to the data were performed in which the relative amount of phase space and resonance shape was allowed to vary until a best fit was achieved. These indicated that the first two resonances are formed in about 50 percent of the possible mass combinations. This ratio seems to be independent of the number of bodies in the final state. The last two resonances are formed to a lesser extent.

5. Recent experiments have indicated possible dibaryon resonances in the NA system at 2059, 2098, 2115, 2220, and 2360 MeV/c^2 . Our invariant mass distributions for the NA system are presented. We conclude there is no evidence for any such resonances in the NA or $N\Sigma$ systems in this experiment.

6. Detailed data is presented on the 3 body final states analyzed in this experiment. The $K^+\Lambda$ distribution in the $K^+p\Lambda$ final state indicates a peaking around 1777 MeV/c^2 . The OPEM prediction for this distribution is found to yield quite poor agreement. The OPEM also predicts a cross section a factor of 2 larger than the measured cross section of $54 \pm 7 \mu\text{b}$ if no cutoff on the 4-momentum transfer to the outgoing proton is imposed. Other models are then considered.

II. EXPERIMENTAL PROCEDURE

A. Description of Raw Data

In July, 1964, a total of 37,800 pictures were taken of the Brookhaven 80 inch hydrogen bubble chamber exposed to protons of nominal momentum 8.0 BeV/c. The contamination of the beam by particles less massive than protons was determined by Cerenkov counters (and a subsequent delta-ray count) to be less than 2 %. Such a contamination should not affect the results presented here and is therefore ignored.

Later analysis showed that the actual value of the beam momentum was $(7.873 \pm .010)$ BeV/c which is 1.6 % below the nominal value. The width of the momentum distribution was difficult to determine due to errors inherent in the measuring procedure (see Appendix A). However, the measured width was consistent with a momentum distribution of width $\pm .25$ % of the beam momentum.

B. Scanning Procedure

The entire film was scanned once in all three views and a second time in either two or three views. The purpose of the scan was to detect the presence of strange particles by the observation of their decays: neutral particles by their decay into a "V" and charged particles by their decay into a "kink". The scan was begun by physicists who developed a set of rules (Appendix B) which hourly employees later used to complete the scan.

The scanning apparatus consisted of three scanning tables each equipped with three Italian made Prevost projectors. The film to scanning table magnification was 12, giving an image on the table of .85 life size at the center of the chamber.

An event was defined as any 2, 4, 6, or 8 prong beam interaction with one or more V 's or kinks associated. It was required to originate from a "beam track" interaction, i.e. a track parallel to the other beam tracks to within one part in one hundred. There was no fiducial volume imposed at the scanning level.

As events were found they were assigned an event type according to their topology. The numbering scheme was the following:

$$\text{E.T. \#} = 10(N_p) + 5(N_v) + 3(N_{k-}) + 1(N_{k+})$$

where

- E.T. # $\rightarrow$ event type number
- N_p $\rightarrow$ number of prongs and ≤ 8
- N_v $\rightarrow$ number of V 's and ≤ 3
- N_{k-} $\rightarrow$ number of negative kinks and ≤ 1
- N_{k+} $\rightarrow$ number of positive kinks and ≤ 2

with the additional requirement that

$$N_{k+} + N_{k-} \leq 2 .$$

The record of events consisted of scan sheets and pictures. A typical scan sheet and picture are shown in Fig. 1 and Fig. 2.

In addition to recording the event type, the scanner was required to enter the number of prongs, kinks, and V 's in the appropriate columns to serve as a double check in assigning the event type number. An additional column was provided for "closed V 's" (i.e. electron pairs which will be discussed later) and "Comments" under which π - μ -e and neutron induced reactions were recorded. Comments on the condition of the film (e.g. "too faint", "too many beam tracks", etc.) were also entered in this column.

An additional purpose of the scan sheet was to facilitate comparison of two or more independent scans.

Figure 1

Scanning sheet used to record results of
the scan.

SCANNING FORM

Exp. 03Roll # 9Page # 2
of

Date roll begun _____ Date finished _____

Agent B
9-23-64

FRAME #	PRONGS	✓open	✓closed	KINKS	E.T.	COMMENTS	#
811 430	—						
31	—						
32	—						
33	—						
34	2			✓(2)	21	01	COP
35	6			✓(6)	63		COP
36	—		✓				
37	—						
38	—						
39	2	✓			25		COP
40	—						
41	—						
42	—						
43	2	✓			25		COP
44	—						
45	2, 6	✓			25		COP
46	—		✓				
47	—		✓✓				
48	6+2+2						
49	—						
50	—		✓✓				
51	2	✓	✓		25		COP
52	—						
53	—						
54	—					03	
55	—					03	
56	—						
57	—					04	
58	6+2+2		✓				
59	—						
60	—						
61	6+2+2						
62	6+2+2	✓(6)					
63	—	✓(un)					

Figure 2

Picture of an event made on the scanning table. Such pictures served as a permanent record of the event and a guide to the measurers. The progress of the event through the analysis system was recorded on a form on the back of the picture.

7B
9.23.64
Roll 9
811439
ET25
v.2

The requirement of listing all the important features of an event made the resolution of misinterpretations much easier. For possible later reference, all non-strange interactions with six or more prongs were also listed.

In addition to the entry on the scan sheet, each event was recorded photographically on an 8 1/2 by 11 inch photo-sensitive paper. Indicative information including the date, scanner's initials, roll number, frame number, event type, view number, and event flags were entered in blank spaces in the lower right hand corner of the picture. The event flags were used to record more detailed and less common features of events and are defined in Appendix B.

The chamber was divided into five regions. Region 1 included the area upstream from fiducial 1; region 2, the area between fiducial 1 and fiducial 3, etc. all as observed in view three (see Appendices A and B). Each vertex of the event was indicated by an arrow in which the appropriate region number was entered. This greatly aided locating the event on the frame at later measuring and checking stages.

On the second scan, events were indicated only on the scan sheets. An "error sheet" was then compiled of events caught on one scan but missed on the other. A scanner with considerable experience then refereed these once-missed events and took pictures of the valid ones missed in the first scan.

Throughout the rest of the experiment these pictures served as the primary record of the events. They were filed in notebooks from which they were never removed. As an event was measured, an appropriate record of the measurement was entered on a form on the back of the picture. When a final disposition of the event was made, indicative information was entered in coded form on the back of the picture. Thus, each picture carries a running record of

its history of analysis and final fate.

C. Contamination Due to Scanning

Previous experience had indicated that electron pairs originating from π^0 decays were one of the most common sources of contamination at the scanning level. These were largely eliminated in this experiment by discarding the V if the charged tracks of the V overlapped for more than 0.5 cm or more in all three views on the scanning table. Such Vs were labeled "closed Vs". Only 102 events in which the V was later determined to be an electron pair escaped this criterion.

To estimate how many true lambda hyperons and K^0 mesons were missed by applying such a cutoff, all the closed Vs (i.e. Vs identified as electron pairs) on one roll were examined. There were 281 such Vs. If both tracks of the closed V had a momentum projected in the X-Y plane of greater than 140 MeV/c, the length of each track was determined. For the 88 events meeting this criterion the projected track length totaled 94.6 meters. If one assumes an average total cross section of 40 mb for strong interactions, and that the total track length of the closed Vs was due to strongly interacting particles, 14 strong interactions are expected. None was observed.

Since all closed Vs with one or both prongs of projected momentum less than 140 MeV/c could be identified as $\lambda \rightarrow P + \pi^-$ or $K^0 \rightarrow \pi^+ + \pi^-$ by ionization, we can say that, on this one roll, no such lambda or K^0 decay products underwent strong interactions. Since one expects about one out of seven real (strange) V decay particles to interact, and since we saw none, we conclude that less than seven real Vs were masquerading as closed Vs on this roll.

Another source of contamination at the scanning level was the decay of pions to muons and the small angle scatter

of both pions and protons. As the problem became apparent, new criteria were imposed on the definition of a kink (see MEMO, Appendix B) which greatly reduced the number of proton scatters recorded as kinks. Pion decays and small angle scatters were more difficult to eliminate at the scanning level. Most pion contamination tracks had a characteristic high curvature and low ionization. Physicists could readily detect such pion events from a rapid scan of the picture books. This procedure was adopted midway through the experiment to filter out the most obvious pion contamination. The number of true K mesons and Σ hyperons lost due to this filtering is completely negligible.

D. Scanning Results

The scanning procedure described above produced 7,285 events. An event, at this stage, means a candidate for a strange particle production interaction. Many of these are in fact contamination, and this number is based on treating each possible interpretation of a V with several allowed origins as a separate event. So, for example, one V may have three possible origins. This registers as three events even though only one strange particle interaction exists.

E. Event Measurement

1. Apparatus

The measurement of events was done using two digitized measuring projectors, each equipped with three views. One was an NRI-MPS on which about one third of the data was measured, and the second was an ITEK Hermes on which the remaining two thirds were measured. The machines are very similar in design and performance, the only difference

being that the Hermes has an automatic "track follower". This electronic feedback device aided in the measurement of fiducials and dark tracks.

Both machines have fixed optics and a movable stage. The stage motion is resolved into orthogonal X and Y motion by calibrated screws of pitch 1 mm. These are coupled to DATEX encoders of least count one micron. An estimate of the measuring accuracy possible with the machines is given by making the following check:

1. A straight line is measured, using about 100 points.
2. The points are fitted to the equation of a straight line by the least squares method.
3. The rms deviation of the measured points from the fitted line is calculated.

Such a check, if done with care, yields an rms deviation less than two microns on both machines. This check, called an encoder check, was made at least twice a week throughout the experiment. An abnormally high rms deviation (above 5 microns) indicated trouble in the encoder or associated electronics. When this occurred measuring was halted until the trouble was located and corrected.

The measurement of a point on the film is performed by projecting the point onto the back of a glazed, translucent screen. An illuminated cross hair is projected onto the screen also. The image of the point is moved by moving the stage until it coincides with the image of the cross hair which remains fixed. The measurement is then taken and the X and Y coordinates of the point are punched onto an IBM card. They are given in microns and are five digits each.

2. Measuring Procedure

A detailed description of the measuring procedure used in this experiment is given in Appendix C. This is the set of measuring instructions which was supplied to each measurer. The measurers, like the scanners, were mainly hourly employees with little or no physics background. Most measurers had previously been scanners, so they were aware of the problems encountered in scanning and the most common errors made by scanners.

The measurers used the book of pictures obtained by the scanners as a guide to find the event and to measure it. A summary of the procedure is given below.

1. The frame containing the event was centered in the aperture of the stage in all three views.
2. Indicative information pertinent to the event was punched on the first two IBM cards. This included:
 - a. Measurer ID number
 - b. Date
 - c. Roll number
 - d. Frame number
 - e. Remeasurement number
 - f. Event type number
 - g. Region number (of primary vertex)
 - h. Event flags (if any applied)
3. Two fiducial marks (early in the experiment) or three fiducial marks were measured in each view. These established the coordinate system for later track measurements.
4. A track word was punched which gave the track number and view in which it was to be measured.
5. Each track was measured in the two best stereo views. From 4 to 10 points were taken in each view. The track numbering scheme is given in Appendix B.
6. An end word was punched to indicate there were no

more measured points associated with that event.

The magnification of the measuring machines was 12. Experience had indicated that the reproducibility with which most measurers measured a point was about 4 microns. This corresponds to an uncertainty in real space at the center of the chamber of 60 microns. This is the number for the uncertainty in position of the measured point which was used in subsequent processing of the events.

A preliminary computer analysis to be described later indicated the quality of the measurements. If for some reason an event did not meet the criteria of this analysis it was remeasured. If it did pass the criteria the card image of the event was loaded onto a magnetic tape for later processing.

As a result of four passes of measurement 3,607 successful measurements of events were loaded onto the magnetic tape. These include many remeasurements, events with two or more interpretations for one V, and events which have not been analyzed for this experiment. A breakdown of this number by event type is given in Table 1.

TABLE 1

Measured Event Type Breakdown

Event Type #	Topology of Event	# of Events	% of Total
21	2 Pr + pos kink	595	16.5
22	2 Pr + 2 pos kinks	26	0.7
25	2 Pr + V	1215	33.7
26	2 Pr + V + pos kink	154	4.3
30	2 Pr + 2 V's	174	4.8
31	2 Pr + 2 V's + pos kink	1	- -
41	4 Pr + pos kink	487	13.5
42	4 Pr + 2 pos kinks	14	0.4
43	4 Pr + neg kink	321	8.9
44	4 Pr + pos kink + neg kink	11	0.3
45	4 Pr + V	429	11.9
46	4 Pr + V + pos kink	49	1.4
47	4 Pr + V + 2 pos kinks	1	- -
48	4 Pr + V + neg kink	16	0.4
61	6 Pr + pos kink	54	1.5
63	6 Pr + neg kink	46	1.3
65	6 Pr + V	14	0.4
Totals		3607	100.0

F. Computer Analysis

The purpose of the computer analysis was to determine which possible final states were consistent with energy and momentum conservation. It consisted of the following logical steps:

1. Reconstruction of the coordinates of points along tracks in X,Y, and Z from two stereo sets of X,Y coordinates.
2. Use of the known value of magnetic field* at the track to calculate the vector momentum.
3. Assignment of masses to the various tracks corresponding to possible final states.
4. Testing the final state hypotheses for energy and momentum conservation.

In actual practice the computer analysis was carried out in two separate stages. In the first stage, called the "scratch run", the analysis was carried through step 3 above, and stringent geometric criteria were applied. If the event passed criteria of the first stage it was loaded on magnetic tape. The magnetic tape accumulated well measured events and was later reprocessed through all four steps described above.

Stage One Criteria

The spatial reconstruction program used was the **EUCLID** system developed by Professor G. Ascoli of the University of Illinois. Briefly, the system operates as follows:

* A summary of the procedure used in fitting the magnetic field of the 80 inch chamber is given in Appendix A.

1. For each measured X-Y point in view 1 a corresponding X-Y point in view 2 was found by fitting groups of three points in view 2 to circles and projecting the point in view 1 parallel to a line joining the cameras till it intersected the circle.

2. From these pairs of corresponding points the Z coordinate (depth in the chamber from the inside surface of the chamber window) was calculated.

3. The X-Y points were fitted to a circle.

4. The track was broken into three segments and the magnetic field was calculated at the center of each segment. From these magnetic field values the momentum at the center of the track was calculated.

5. To calculate the dip of the track (Z dependence), the X-Y-Z points were projected onto a cylinder about the Z axis and a least squares fit made to a straight line.

6. A correction to the circle due to the mass dependence of the true curve was made by use of the range-energy curves. The momenta at the beginning and end of the track were recalculated for each mass hypothesis requested.

7. The final output of the EUCLID program was the calculated value of the momentum at the beginning and end of the track, for each mass hypothesis, given in terms of new coordinates: ϕ , $\tan \lambda$, and $k = 1/(p \cos \lambda)$

where ϕ = the angle between the projection of the track on the X-Y plane and the X axis

$\tan \lambda$ = the tangent of the dip angle the track makes with the X-Y plane

$k = 1/(p \cos \lambda)$ proportional to the curvature projected on the X-Y plane. (p = momentum)

8. In addition to these six coordinates for each track, the three by three error matrix for the coordinates at the

beginning and end of the track was calculated.

During the reconstruction the input format of the data cards was checked for measurer errors. In addition, the following tests were made on the quality of the measurement:

1. If more than one point seriously deviated from the fitted curve for the track the event was rejected.
2. If the r.m.s. deviation of the points from the fitted X-Y curve was not less than 5 standard deviations for at least one mass hypothesis the event was rejected.
3. If the r.m.s. deviation of the points from the fitted straight line for the Z dependence (dip) was greater than 5 standard deviations for all mass hypotheses the event was rejected.
4. The tracks were extrapolated to the vertex, and the distance of closest approach of each track to the vertex was calculated. A chi-squared was calculated* which indicated how well the tracks met in space. If this chi-squared was greater than 4 the event was rejected.

Several other tests were performed to insure the quality of the measurements. A complete list of tests and their corresponding reject numbers is given on the last pages of Appendix D.

As a result of the measuring and first stage of computer analysis, 3607 good measurements were recorded on magnetic tape. These correspond to more than 3072 separate events, the difference being due to a) more than one independent measurement of the same event and b) two or more measurements corresponding to a V with two or more possible origins.

*This chi-squared was based on $\Delta X = \Delta Y = 0.017$ cm, $\Delta Z = 0.110$ cm. These parameters were chosen by scaling those developed for the BNL 20" chamber to the 80" chamber.

An average event contained six measured tracks with four to seven points per track measured in each view. Thus, an average event had over 50 measured points in addition to 9 measured fiducial points (3 fiducials in 3 views). The rate at which events passed the above criteria varied from about 50 % early in the experiment to about 70 % near the end. The measuring speed varied from 1.5 to 2.5 events an hour averaged over a 2 week period.

Stage Two - Hypothesis Testing

The purpose of stage two in the computer analysis was to test each measured event for all possible verifiable final states. Verifiable final states are defined as those with at most one neutral unseen particle.

ILLFIT, the program used to test these hypotheses, was developed by Raymond Hanft and Professor Ascoli. This program is similar, in principle, to the Yale program GUTS. It imposes the conditions of energy and momentum conservation between the initial and final state. In doing so it generates a new set of "fit coordinates" ϕ_f , $\tan \lambda_f$, and k_f which differ from the input measured coordinates ϕ_m , $\tan \lambda_m$, and k_m as little as possible while conserving energy and momentum.

The input to ILLFIT was essentially the output of EUCLID, namely the mass dependent coordinates of momentum at the beginning and end points of each track along with their error matrices. The details of the method used in hypothesis testing are similar to those described by Berge, Solmitz, and Taft.^{7/}

The fitted values of the momenta are such that the function, χ^2 is minimized while conserving energy and momentum. χ^2 is defined by

$$\chi^2 = \sum_{i,j=1}^I (x_i - x_i^m) G_{ij} (x_j - x_j^m)$$

where

x_1 = fit value of ϕ for track 1

x_2 = fit value of $\tan \lambda$ for track 1

x_3 = fit value of k for track 1

x_4 = fit value of ϕ for track 2

etc.

x_1^m = measured value of ϕ for track 1

etc.

$G_{ij}^{-1} = \langle \delta x_i^m \delta x_j^m \rangle$ = error matrix

$I = 3n$ where n = number of measured tracks.

Thus, it is apparent that the χ^2 function is a measure of the "goodness of fit" for a given mass hypothesis.

Sequential Vertex Fitting

The measured events consisted of 2, 4, and 6 prong interactions with one or more associated kinks or V's. The kink or V decay vertex contains information which is useful in two regards. First, the fit at the kink or V vertex helps identify the decaying particle. Second, the fit value of the momentum of the decaying strange particle is generally much more accurate than the measured value.

The program used to control the fitting sequence was called FITRAN and was developed by Mr. Raymond Hanft of the University of Illinois. The general procedure used for fitting strange particle events was the following:

1. All possible fits for the V or kink were attempted. If the fit was successful (criteria to be described below), the fit momenta were stored.
2. For a kink, the momentum was "swum" back to the primary vertex, i.e., the change in momentum due to curvature of the track and energy loss was calculated and the resulting momentum of the strange particle at the primary vertex obtained. For a V, the fit value of the momentum at the decay vertex was assumed to be the same at the primary vertex.

3. These fitted momentum values of the outgoing strange particle were treated identically to other measured tracks in the subsequent fits attempted at the primary vertex.

Strange Particle Decay

The following decay hypotheses were attempted:

1. For V's

- a) $\Lambda \rightarrow p + \pi^-$
- b) $K^0 \rightarrow \pi^+ + \pi^-$
- c) $\tilde{\Lambda} \rightarrow \pi^+ + \tilde{p}$ (for 2 prong + V's only)

2. For positive kinks

- a) $K^+ \rightarrow \pi^+ + \pi^0$
- b) $K^+ \rightarrow \mu^+ + \nu$
- c) $\Sigma^+ \rightarrow p + \pi^0$
- d) $\Sigma^+ \rightarrow \pi^+ + n$

3. For negative kinks

- a) $K^- \rightarrow \pi^- + \pi^0$
- b) $K^- \rightarrow \mu^- + \nu$
- c) $\Sigma^- \rightarrow \pi^- + n$
- d) $\Xi^- \rightarrow \pi^- + \Lambda$

Constraint Classes: V's

First, let us consider V decay. The direction of the V line of flight is determined from the measured position of the primary interaction vertex and the decay vertex. It is assumed to be a straight line since the magnetic field will not affect the motion of neutral particles. In addition, both the magnitudes and directions of the momenta of the two decay tracks of the V are determined at the vertex from measurement. Therefore, if one assumes a 2-body decay of the V, the only undetermined kinematic quantity is the magnitude of the momentum of the strange particle.

In assuming a particular hypothesis for the decay, one assigns mass values to each of the three particles involved

in the decay. There are four equations of motion (energy, three-momentum conservation) which can be applied at the decay vertex. Since there are four equations and only one unknown (magnitude of strange particle momentum) one can do a three constraint fit (3-C fit).

Such 3-C fits were tried for all V's for the mass hypotheses shown above. When the fit was successful for a particular hypothesis ($\chi^2 < \sim 30$) the fit momentum of the strange particle was stored and used in subsequent fits at the primary vertex.

Two additional constraint class fits were attempted for each V. One was a 1-C fit in which the incoming direction of the strange particle was ignored. This is equivalent to calculating the invariant mass of the strange particle from the momenta and masses of the decay products.

The purpose of this calculation was to identify the strange particle independently of the position of the assumed origin. The χ^2 generated in this fit was a measure of how well the calculated mass agreed with the known mass of the strange particle being considered. The fit was useful in resolving events with more than one possible origin, events with very short neutral tracks (where errors on ϕ and $\tan \lambda$ may lead to artificially high three constraint χ^2), and events where the neutral strange particle had scattered.

The second additional constraint class of fits tried on V's was a 2-C fit. In the 2-C fit, momentum conservation was used to calculate what the momentum of the strange particle must be. This was then compared to the 2 measured parameters of strange particle momentum ($\phi, \tan \lambda$). In the process of requiring these to agree, a 2-C χ^2 was generated. The purpose of such a fit was to indicate how well a particular V was associated with the particular origin being considered.

In summary, the following fits, to answer the following questions, were tried for all V's:

- 1-C Does the invariant mass of the V agree with that of a K^0 , Λ , or $\bar{\Lambda}$ assuming 2-body decay ?
- 2-C Is the sum of the momenta of the decay particles consistent with the V originating from the vertex being tested ?
- 3-C Does the V being tested have both the correct mass for the present hypothesis and the correct direction to be associated with the primary vertex being tested ?

Constraint Classes: Kinks

In the decay of a charged strange particle into a charged particle and a neutral particle, the neutral particle is unobservable. Thus, with 4 constraint equations and 3 missing variables (p_x , p_y , p_z of the neutral), the best one can hope for is a 1-C fit at the kink vertex.

Experimentally, since the lifetime of the sigma hyperons is $\approx 10^{-10}$ seconds and that of the charged K mesons is $\approx 10^{-8}$ seconds, nearly all the sigma hyperons decay in the chamber while only a small fraction of the K mesons do. The mean life of the sigma hyperons leads to a characteristic path length in the chamber of only a few centimeters. As a result, the arc length of the measured strange particle was often too short to yield a well determined value for the momentum. In fact, if the track was so short that its curvature was not apparent ($\lesssim 2$ cm) the measurers were instructed to measure only the end points. The resulting two point track yields only the direction of the strange particle and gives no information on its momentum magnitude.

In such a case of poorly measured or unmeasured momentum magnitude, one has 4 constraint equations and 4 missing variables. Therefore, the kinematics are completely determined and one can calculate the momentum magnitude of the strange particle. Such a calculation will be referred

to as a 0-C fit.

Three distinct situations may exist for this calculation. We call p_{cm} the momentum of the decay products in the center of mass system of the strange particle, $p_{\perp}$ the component of measured lab momentum of the charged decay particle which is perpendicular to the direction of the decaying strange particle, and p the measured momentum of the charged decay particle. Then the three conditions are:

1. $p_{\perp} > p_{cm}$ In this case, to conserve energy, we must reduce $p_{\perp}$ to p_{cm} . In the process, a chisquare is generated which indicates how much of a change was required in the measured value in order to conserve energy.
2. $p_{\perp} < p_{cm}$ This case corresponds to two distinct, equally valid mathematical solutions for the lab momentum of the strange particle. The first solution, p_1 , arises if the c.m. angle, θ_1 , between the outgoing decay product and the strange particle is less than 90° . The second solution, p_2 , arises if this angle is $\theta_2 = 180^\circ - \theta_1$. It is clear that $p_2 > p_1$. These two values of the momentum are referred to as the two roots of the 0-C fit. (It is assumed in this case that $p > p_{cm}$.)
3. $p < p_{cm}$ This case can correspond only to the strange particle decaying backward in its c.m. and thus corresponds to a single 0-C solution for the strange particle momentum.

In the cases of well measured charged strange particles and in cases 1 and 3 above, the single fitted value of the strange particle 3-momentum was stored for subsequent fitting at the primary vertex. In case 2 above, both roots were stored and used independently in subsequent vertex fits.

Diagnostic Decay Vertex Fits

As previously mentioned, the main sources of contamination among the kink events were pion decays and pion and proton elastic scatters in which the recoil proton was too short to be observed. To help identify and filter out such contamination, the following fits were attempted:

On 4 prong plus positive kink,

On 4 prong plus negative kink,

On two prong plus V events, the prongs of the V were assumed to be electrons and the invariant mass of the system calculated. A zero result indicated that the V was an electron pair rather than a strange particle.

None of the results of the above fits were saved for use in later fitting at the primary vertex.

Diagnostic Primary Vertex Fits

In addition to the above fits at the decay vertex, the following diagnostic fits were tried at the primary vertex:

On all 2 prong events,

On all 4 prong events,

* This use of parentheses, e.g. (π^0) , indicates "This particle is unseen and thus unmeasured".

Such fits were very helpful in filtering out the elastic scattering and pion production contamination from the valid strange particle events. Among the 1543 2-prong plus V(s) events, 45 such contamination events were identified; among the 1637 4-prong plus kink or V events, 216 were identified.

Primary Vertex Fits

The fits tried at the primary vertex consist of the following constraint classes:

1-C Fits - This group of fits includes all final states in which there is one unseen neutral outgoing particle. ILLFIT calculated the missing mass for the unseen outgoing object from the measured values of momentum of the observed particles. If the missing mass squared was within 5 standard deviations of the mass squared of the assumed neutral particle, a 1-C fit was attempted. If the missing mass squared was outside this limit, the result was printed out but no fit was attempted. Such a procedure economized on computer time required to fit an event.

4-C Fits - Such fits were tried for all final states in which it was assumed that all the outgoing particles had well measured momenta. If one of the outgoing particles had poorly measured momentum ($(\Delta p/p)^2 > 50\%$), this momentum magnitude information was ignored and a 3-C fit was attempted.

The only exception to this procedure occurred in the fits attempted for hypotheses including an outgoing Σ^0 when a Λ decay was observed. The Σ^0 hypothesis was tested by the following two step procedure:

1. A 1-C fit was tried at the primary vertex in which the outgoing unseen particle was assumed to be a Σ^0 . If the fit was successful ($\chi^2 < 30.0$), the fit value of Σ^0 momentum was stored.

2. Using this fitted value of the Σ^0 momentum and the 3-C fit value of the Λ momentum the following 1-C fit for the decay of the Σ^0 was tried:

$$\Sigma^0 \rightarrow \Lambda + \gamma$$

Such a 2 step procedure allowed fitting Σ^0 hypotheses in which no other unobserved neutral particle was produced. (Thus, e.g., final states containing $\Sigma^0 + \pi^0$ are intractable.)

G. Event Analysis

The scope of the experiment to be discussed in this thesis is the analysis of all 2 prong and 4 prong strange particle events with these exceptions: the 2 prong plus kink topology and 4 prong topology where there was more than one strange particle decay associated.

There were two reasons for omitting the two prong plus kink topology. First, there are no two body strange particle final states. Thus, there could be no 4-C fits in the 2 prong plus kink topology. There are four possible three body final states, $P\Sigma^+(K^0)$, $K^+\Sigma^+(n)$, $K^+P(\Sigma^0)$, and $K^+P(\Lambda)$. Using the cross sections to be given in Table 3 one can easily estimate the expected number of these events in the experiment to be 16, 16, 2, and 5 respectively. Therefore, there are also very few possible 1-C fits. Most of the valid strange particle events have more than one invisible particle and therefore are not tractable.

The second reason for omitting the 2 prong plus kink topology is that there is a large contamination of π decays and π and P scatters among the kinks. This makes sorting out the valid 1-C strange particle fits quite difficult.

The subsequent analysis will consider only the following event types: 25, 26, 30, 41, 43, and 45. (See Table 1, page

16 for the topology definition and the number of measured events in each topology.) This sample includes 77.1 % of the 3607 successfully measured strange particle event candidates. The 595 2-prong plus kink events constitute 16.5 % of the total sample. The remaining 6.4 % of the successfully measured events were more complicated topologically and have been omitted.

In addition to the above 3607 well measured candidates, 61 events of complex topology were measured but not processed through stage 1 of the computer analysis. (Event types 50, 62, 64, 66, 67, 68, 81, 82, 83 - see Appendix B for definitions.)

A complete list of all the verifiable final states is shown under FIT LIST of Appendix D. All of the fits listed were attempted with the exception of the 2 prong plus kink hypotheses. There is some redundancy due to the various alternative decay modes of a particular final state. For example, the final state containing $\pi^+ PK^0 \Lambda$ may be observed in 3 possible configurations:

$\pi^+ PK^0 (\Lambda)$	K^0 decay observed; Λ decay not
$\pi^+ P\Lambda (K^0)$	Λ decay observed; K^0 decay not
$\pi^+ PK^0 \Lambda$	both decays observed.

Since this corresponds to 3 different observational situations, it is necessary to try three distinct fits.

Analysis Procedure

Since the experiment was of only moderate size it was decided that each event should be examined by a physicist on the scanning table. The film from cameras 1 and 3 was loaded on the Prevost scanning table. Using the book of pictures as an index, and with the computer output for the measured events which had passed stage 1 at hand, each strange particle event candidate was closely examined. The final determination of the identity of the event, insofar as it was possible, was made at this time. If the event appeared to be

a valid strange particle event but had not yet been successfully measured, or if the existing measurement appeared to yield inconclusive results, a request for remeasurement was made.

All the information which could be obtained from the event was entered on the back of the picture in a numerically coded form (to be described below).

Bookkeeping System

Each event was represented by a picture. A form on the back of the picture served as a record of measurements and, as mentioned above, a record of conclusions reached concerning the event.

To facilitate sorting and listing events according to their final identification , an IBM card file was generated with one card per event. This card contained the appropriate indicative information for the event. The numerically coded information entered on the picture at the time of the event analysis was transcribed onto these scan cards for sorting purposes.

Numerical Code - Event Words

It became evident early in the experiment that there were certain general categories into which many events would fall. (e.g., "Well measured, uniquely identified event of the final state $K^+PA.$ ") It also became apparent after analyzing several events at the scanning table that there were also many other events for which the conclusion could not be as clear cut and simple to record.

As a result, the " Event Card Handling Instructions" (4th page of Appendix D) were developed in which the numbers from 11 → 99 were used to correspond to various pertinent comments concerning the event. The list of these comments was originally set up to include the most obvious categories of comments and developed throughout the experiment as the

need for more comments became apparent.

The following are two examples of words used in particular situations. Uniquely identified events were identified with word 83, and, in addition, they carried a fit number which identified the final state. If, for instance, the kink on an event was identified as a scattered proton, the event was given a word 11.

Thus, it became a relatively simple task to obtain lists of all events with any given (numerically identified) characteristic. This system greatly simplified the analysis of the experiment.

Analysis Criteria

The following analysis procedure was developed after examining a large number of events and applies generally throughout the experiment. (See "Exp. 03 Event Analysis System", Appendix D, for details.)

1. Each event was examined in cameras 1 and 3 by the physicist for additional information not implicit in the event type number and event words. Such information included the presence of 3 prong τ decay of K mesons, small angle scatters or kinks not observed by the scanners, electron pairs associated with the primary vertex, and proton recoils near the vertex which could be associated with a neutron or Λ from the vertex.

2. Each track was identified by comparison with the measured values of θ and p as given in the computer output. The computer also calculated the relative ionizations ($I_r / I_{\min} = 1 / \beta^2$) for each charged track assuming various possible mass hypotheses. The ionization for each track was estimated visually and compared to the predicted values. When possible the track was uniquely identified (e.g. as a π^+ or a K^+ or a P); when this was not possible, certain hypotheses were eliminated (e.g. the track may be a π^+ or K^+ but not a P); when the track had a momentum ≥ 1.5 BeV/c

no mass distinction was possible on the basis of ionization.

3. The summary of the strange particle decay fits was examined in the light of the ionization information. When possible, the strange particle identification was made at this stage, and only those primary vertex fits which were consistent with the identified strange particle were considered in subsequent fits.

4. Next the summary of the attempted primary vertex fits was examined and those consistent with the above mass hypotheses were considered as candidates for unique final states. At this point the following χ^2 criteria were applied.

- a. Any event which had a single fit with 1-C $\chi^2 < 10$ or a 3-C or 4-C $\chi^2 < 20$ was considered uniquely identified.
- b. If an event had more than one fit satisfying criterion a, the probability for each χ^2 was read from a graph and if the low χ^2 had a probability > 3 times that of any other, it was considered the unique fit.
- c. If several fits satisfied criterion a, and the two lowest χ^2 fits had probabilities within a factor 3 of each other, the event was assigned to a 2-fold ambiguous category.
- d. If several fits satisfied criterion a and none of the above categories applied, the event was considered completely ambiguous.
- e. One exception to the above criteria occurred when both a 1-C fit and a 4-C fit satisfied criterion a. To compensate for the difficulty in getting "good" (i.e., low χ^2) 4-C fits, the probability for the 4-C fit was weighted by a factor of 2 in comparing to the probability of the 1-C fit.

f. An additional variation occurred for Σ^0 fits. For this case, the 1-C χ^2 from the primary vertex fit was added to the 1-C χ^2 from the $\Sigma^0 \rightarrow \Lambda + \gamma$ fit to give a number which was used to calculate the probability from a 2-C curve. This probability was the one used in the previous steps.

5. In making the identification, the lifetime of the strange particle was considered in the following way. Any event for which the lifetime of the fit strange particle was greater than 5 mean lives was re-examined. In addition, fits which included a Σ^+ which was not observed to decay were tested by calculating the lifetime from the observed path length and momentum. If the lifetime was more than 5 mean lives, it was assumed to be an incorrect identification. This helped eliminate several potential fits.

Additional Criteria

In fitting the decay vertex of kink events, no rigorous χ^2 test was applied. The values of χ^2 for 1-C kink vertex fits were used only to confirm the most likely primary vertex interpretation.

In fitting the decay vertex of V events, an attempt was made to identify the strange particle independently of the primary vertex fit. It was not always possible to resolve the K^0 decay hypothesis from the Λ hypothesis on the basis of χ^2 alone. To investigate the composition of the sample of events which is ambiguous between the K^0 and Λ interpretation (i.e., have 3-C χ^2 's within a factor of 3 of each other), we consider the following argument. Assume one has a sample of pure $K^0 \rightarrow \pi^+ + \pi^-$ decays. Now assume the following fits are tried for these events.

1. $K^0 \rightarrow \pi^+ + \pi^-$
2. $\Lambda \rightarrow p + \pi^-$
3. $\tilde{\Lambda} \rightarrow \pi^+ + \tilde{p}$

All the events should fit hypothesis 1. But some events may also fit hypothesis 2 or 3 due to measurement error and kinematic ambiguity. The important point is that as many $\tilde{\Lambda}$ as Λ ambiguities should occur due to the symmetry of the K^0 decay.

Experimentally, in an unbiased sub-sample in which 48 K^0 - Λ ambiguities occurred, only 3 K^0 - $\tilde{\Lambda}$ ambiguities occurred. All three of these latter ambiguities were identified as K^0 decays by ionization information on the negative prong of the V. These numbers indicate that only about 7 % of the K^0 - Λ ambiguity sample are really K^0 decays and that the remainder are Λ decays. This confirmed the validity of the following procedure used throughout the experiment. For the cases of K^0 - Λ ambiguity, the V as assumed to be a Λ .

An additional verification of the validity of this procedure is obtained by the following argument. One expects a flat distribution for the cosine of the decay angle of positive prongs in the c.m. of the strange particle for both Λ and K^0 particles. One finds experimentally that all Λ - K^0 ambiguities (assumed to be Λ 's by the above argument) when interpreted as K^0 's have $\cos \theta_{cm}(\pi^+) > .85$. Figure 3 shows the distributions for these angles for events identified by the above procedure. Both distributions appear reasonably flat. If the Λ - K^0 ambiguities had been resolved as K^0 's, the $K^0 \cos \theta$ distribution would be grossly distorted in the .8 - 1.0 bin. This flat distribution gives us confidence in the above procedure.

Figure 3

Distributions for cosine of the decay angle of the positive prong in the center of mass of neutral strange particles. Note: any $\Lambda - K^0$ ambiguous V's when plotted in the K^0 graph would appear in the .8 - 1.0 bin.

H. Efficiencies

The overall efficiency for finding and identifying strange particle events was estimated by evaluating the efficiency for each step of the analysis. These efficiencies were then assumed to be independent and the overall efficiency was taken to be the product of the individual efficiencies. Efficiencies were calculated for the following steps:

1. Scanning
2. Successful measurement
3. Successful computer fit
4. Decay detection probability

1. Scanning Efficiency

Two complete scans were performed over the entire film. A record was kept on the scan cards as to which scan detected the event. Only events with unique or 2-fold ambiguous fits were used for this calculation.

At the point at which the calculation was performed, the pertinent numbers were:

N_{obs} = number observed in scan 1 or 2 or both = 1480
 N_1 = number observed in scan 1 = 1267
 N_2 = number observed in scan 2 (unknown)
 N_{21} = number observed in scan 2 but not in scan 1 = 213
 N_{12} = number observed in scan 1 but not in scan 2 (unknown)
 dN = number missed in both scans
 N = total number of events.

It is reasonable to assume

$$N_1 = N_2 \quad \text{and} \quad N_{21} = N_{12}.$$

If one assumes uncorrelated scanning efficiencies for scan 1 and 2, then we have:

$$dN = \frac{N_{21}}{N} N_{21} \approx \frac{(N_{21})^2}{N_{\text{obs}}} \quad \text{since } N_{\text{obs}} \approx N.$$

$$dN = 31 \text{ events}$$

Therefore, $N = N_{\text{obs}} + dN = 1511 \text{ events}$.

The percentage of events not found after two scans is

$$\% \text{ lost} = dN / N = 2.0 \%$$

Therefore the overall scanning efficiency is 98 %. This number seemed to be relatively independent of topology and is used for all event types.

It should be pointed out that insofar as certain pictures may have been photographically poor or overcrowded with tracks, and insofar as bubble chamber conditions may have been systematically worse in certain parts of the experiment, scanning losses were not due only to random inefficiency. Nevertheless, the evidence is that this was the principal source of losses, so the above calculation is believed to be meaningful.

2. Measurement Efficiency

Due to difficulties encountered, some events were never successfully measured. To account for these events, a physicist scanned the pictures upon completion of the last pass of measurement and assigned the appropriate comment (word 59) to those events which appeared to be valid strange particle events but had no successful measurement. There were 48 such events found in the fiducial region of the film (to be described later), and this number was compared to the 1220 successfully measured and identified strange particle events in the same fiducial region. This corresponds to a 96 % efficiency for successful measurement.

3. Computer Analysis Efficiency

Due to inaccuracy and undetected errors in measurement, the computer analysis may lead to erroneous conclusions about the final state. Two questions which immediately arise

are: How many events of a particular final state are missed because the χ^2 for that fit is erroneously high? How many events in one particular final state have been misidentified and really belong in another final state?

One could obtain statistical answers to these questions if one had two independent measurements for every event. In actual practice a second measurement was called for only in those cases in which the first measurement gave inconclusive results. However, we can use such events to give a rough estimate of the answers to the above questions.

Twice measured events in the final states $K^+P\Lambda$ (10 events), $K^+P\Sigma^+\pi^-$ (5 events), and $\pi^+K^+P\Sigma^-$ (6 events) were examined. Of the $K^+P\Lambda$ events, 7 pairs of measurements gave agreement, 2 pairs had one measurement which had a reject preventing the correct fit from being obtained, and 1 pair of measurements had one measurement yielding a $K^+P\Lambda/\Sigma^0$ ambiguity. Of the 5 pairs of measurements of $K^+P\Sigma^+\pi^-$ final state events, all 5 pairs agreed. Of the 6 $\pi^+K^+P\Sigma^-$ events, 4 pairs agreed and 2 pairs had one measurement with a reject fatal to this interpretation.

All 4 of the measurements with fatal rejects were detected as defective measurements and had resulted in requests for a remeasurement. The remeasurement yielded the indicated final state fits.

In addition, all of the events (54) on rolls 1 $\rightarrow$ 10 which had 2 or more measurements were examined. Of these, 32 gave clearcut agreement, and of the 22 events with disagreeing interpretations, 9 were events for which one measurement gave a unique fit while the other gave a 2-fold ambiguity which included the unique fit. On the remaining 13 events the first measurement simply permitted no conclusion due to the V not fitting or other fatal rejects, and remeasurements were requested.

It is extremely difficult to draw any quantitative conclusions from the above statistics because the remeasured events are not an unbiased sample. However, it is estimated

that not over 5 % of the events which should have obtained unique fits failed to do so at the analysis stage. For purposes of later calculations it will be assumed that the computer analysis efficiency is 95 %.

III. RESULTS - CROSS SECTIONS

A. Fiducial Region of Film

Because of experimental difficulties encountered in generating film for this experiment, the film was rather uneven in quality. On several rolls the tracks were too faint to either scan or measure efficiently, and on two rolls the cameras were operating improperly, producing multiple exposures.

The number of beam tracks crossing a line perpendicular to the beam* was counted on every tenth frame in the experiment. The number of identified events per unit track length on each roll was compared to the number of adverse comments (e.g. "cannot measure - event too faint") assigned to events on the roll by the physicist scan. From this correlation the best 29 of the 41 rolls were chosen for cross section calculation purposes. (Omitted are rolls # 2, 9, 10, 12, 13, 14, 21, 34, 35, 37, 39, and 40.)

To determine a reasonable fiducial volume within the chamber, the distribution of a sub-sample of primary vertices of identified events as a function of X was plotted. (See Fig. 4) The fiducial region was chosen to be $-80.0 \text{ cm} < X_{\text{primary vertex}} < +70.0 \text{ cm}$. It is apparent that there is some fall off near the +70 cm end due to escape of strange particles out the end. This effect will be compensated for by calculating the detection efficiency for K^0 , Λ , and $\Sigma^{\pm}$ independently.

The primary vertex position of every measured event was examined and the appropriate word entered on the scan card if the vertex fell outside the fiducial volume. The total number of events in each final state was then obtained by

* The line used was parallel to the "coat hangers" at fiducial 3 and is defined by $(Y, X = -35.5, Z = 35.0 \text{ cm.})$.

Figure 4

Distribution of primary vertices as a function of X in the bubble chamber. X is essentially parallel to the beam direction.

DISTRIBUTION OF PRIMARY VERTEX vs X

sorting the scan cards for events which had fits and lay on the fiducial rolls and in the fiducial volume.

B. Total Cross Section

Over a short section of the film the number of beam tracks crossing fiducial 3 and the number crossing fiducial 7 (see Appendix A for picture) were counted. From the geometry of the bubble chamber and beam, it can be shown that this corresponds to a path length of 104 cm. Then, using

$$\begin{aligned}\frac{dN(x)}{dx} &= \frac{\text{Prob of interaction}}{\text{unit } x} \cdot N(x) \\ &= \frac{\rho (\text{gm/cm}^3)}{M_H (\text{gm})} \sigma_T (\text{cm}^2) N(x)\end{aligned}$$

we get

$$N(x) = N_0 \exp(-\rho \sigma x / M)$$

Solving for σ_T in terms of the number of tracks at two points, x_1 and x_2 , we have

$$\sigma_T = (M_H / \rho \cdot (x_2 - x_1)) \cdot \ln(N(x_1)/N(x_2))$$

Experimentally, we have

$$N(x_1) = 6533$$

$$N(x_2) = 5595$$

$$x_2 - x_1 = 104 \text{ cm}$$

$$M_H = 1.673 \times 10^{-24} \text{ gm}$$

$$\rho = 0.0629 \text{ gm/cm}^3.$$

Using these values we obtain for the total cross section

$$\sigma_T = 39.6 \pm 1.3 \text{ mb.}$$

The error is due to the statistical error on $N(x_1) - N(x_2) = 938$ events. This cross section is in agreement with that given by Galbraith et al. ^{10/}

* The density measurement is discussed in Appendix A

C. Partial Cross Sections for Strange Particle Production

From the number of beam tracks on the fiducial rolls crossing the $X = -35.5$ cm line (362,700), and the cross section of 40.0 mb, we can calculate the number of tracks crossing the $X = -80.0$ cm and the $X = +70.0$ cm lines. From a graphical solution we find

$$N(X = -80.0 \text{ cm}) = 385,500$$

$$N(X = +70.0 \text{ cm}) = 309,500.$$

The total track length in the fiducial region is then

$$L = \int_0^{150} N(x) dx$$

$$L = 518,000 \text{ meters}$$

Using this value of L in the equation

$$\sigma_i = (M_H / (L \rho)) \cdot N_i$$

where

$$M_H = 1.673 \times 10^{-24} \text{ gm} = \text{mass of hydrogen atom}$$

$$\rho = 0.0629 \text{ gm / cm}^3 \quad (\text{Appendix A})$$

$$N_i = \text{corrected number of events in the } i \text{ th final state}$$

we find

$$\sigma_i = (.513 \mu\text{b}) N_i$$

Efficiency - Analysis Corrections

To calculate the corrected number of events we need to consider losses from two sources. First are the losses of events from inefficiency in the scanning, measuring, and analysis procedure. These have been discussed previously and can be considered as a weight by which all the raw numbers of events should be multiplied to correct for scanning, measuring, and analysis losses. This weight, W_a , may be written:

$$W_a = \frac{1}{e_1} \times \frac{1}{e_2} \times \frac{1}{e_3}$$

where

e_1 = scanning efficiency = .98

e_2 = measuring efficiency = .96

e_3 = analysis efficiency = .95

This leads to

$$W_a = 1.12.$$

Efficiency - Decay Corrections

In addition to the three overall efficiency corrections calculated above, there are several other corrections which depend on the strange particle being considered. These corrections have been considered by computing the efficiency associated with the correction and forming a weight for the i th strange particle, W_{di} , defined by

$$W_{di} = \prod_{j=4}^9 (1/e_{ji})$$

These efficiencies are tabulated in Table 2, page 64, and are defined for the i the strange particle as follows:

- j=4 Ratio of visible, verifiable decays to all decays.
- j=5 Detection efficiency for decay inside the fiducial volume.
- j=6 Detection efficiency for tracks being long enough to be observed and measured.
- j=7 Detection efficiency as a function of angle in the strange particle center of mass.
- j=8 Efficiency for final states decaying into the topologies analyzed.
- j=9 Efficiency for resolving $1-C \Sigma^{+-}$ final states.

We now describe in detail how values for the above effi-

ciencies were obtained.

i=4

The ratios of visible, verifiable decay modes to all decay modes were obtained from UCRL-8030 (Revised March, 1965). The efficiencies tabulated are for the $\pi^+\pi^-$ decay of the K^0 , the π^-p decay of the Λ , the $\pi^-(n)$ decay of the Σ^- , and the $\pi^+(n)$ decay of the Σ^+ .

The events with the $P(\pi^0)$ decay of the Σ^+ will not be used calculating cross sections for the following reason. One expects a 50:50 ratio between $\pi^+(n)$ and $P(\pi^0)$ decays for Σ^+ . Experimentally, we observe a ratio of 62:35. This means that $\Sigma^+ \rightarrow P(\pi^0)$ decays are being systematically lost. This is a result of the fact that, in the laboratory, the proton from Σ^+ decay tends to retain most of the Σ^+ momentum. This causes the kink angle between the Σ^+ and P tracks to be small and thus easily missed in scanning. The $\Sigma^+ \rightarrow \pi^+(n)$ decay mode, on the other hand, should be observed with the same efficiency as the $\Sigma^- \rightarrow \pi^-(n)$ mode. Therefore, we will calculate the cross sections for the Σ^+ events on the basis of the $\Sigma^+ \rightarrow \pi^+(n)$ decays alone.

i=5

To calculate the efficiency for detecting the decay of strange particles in the chamber, the following (approximately valid) assumptions were made:

1. All strange particles go straight forward in the chamber. Figure 5, showing the cosine of the angle between the beam track and the outgoing strange particle, indicates the degree to which this assumption is valid.

2. The production vertices are evenly distributed in X from $X=-80.0$ cm to $X=+70.0$ cm. In addition, it is assumed that the decay is detectable if it occurs within $-80.0 < X < +80.0$. This assumption was verified by a plot

Figure 5

Cosine of the angle between the beam
and outgoing strange particle in the
lab.

NUMBER OF EVENTS

COS θ_{LAB} BETWEEN BEAM
AND OUTGOING STRANGE PARTICLE

of the decay vertex point as a function of X .

3. The momentum distribution is unaffected by the loss of high momentum particles. The degree to which this assumption is valid can be tested by the following argument. Particles of high laboratory momentum correspond to particles going forward in the center of mass, whereas particles of low laboratory momentum correspond to backward going particles in the center of mass. Therefore, if one were losing many high lab momentum particles, a plot of $\cos \theta_{cm}$ should show a depletion in the $+\cos \theta$ region. Figure 6 shows the experimental distribution of the center of mass cosine of the angle between the incident proton and the outgoing strange particle. This assumption is valid to the degree to which the distributions are symmetric about zero.

For the i th strange particle, the probability that it decays in the detectable region during its flight time t (in its center of mass) is given by

$$P_i = \frac{\int_0^t \exp(-t/\tau_i) dt}{\int_0^\infty \exp(-t/\tau_i) dt}$$

One can correct for relativistic time dilation and convert a time integral into a space integral by noting

$$t = (x_d - x) \times (m/p)$$

where

x_d = end of the decay region = +80.0 cm.

m = mass of the strange particle

p = momentum of the strange particle.

Then

$$P = \frac{m}{p\tau_i} \times \int_{x_b}^{x_d} \exp(-(x_d - x)m/p\tau_i) dx$$

where

x_b = beginning point of flight path.

Figure 6

Cosine of the angle between the beam and the outgoing strange particle in the overall center of mass. The beam is nearly parallel the X axis in the chamber.

It is seen that this probability depends on the beginning point of the particle's flight path and its momentum. To calculate the average probability for observing the decay of the strange particle, one must average this expression over the primary vertex fiducial region and weight it by the observed momentum distribution. So

$$\langle\langle p \rangle\rangle = \frac{\int_0^{p_{\max}} N(p) dp \int_{-80}^{+70} p dx_b}{N (150 \text{ cm})}$$

where

$N(p)$ = observed momentum distribution

N = total number of particles.

Upon doing the space integral, one obtains

$$\langle\langle p \rangle\rangle = 1 - \frac{c \tau_i}{150 \text{ mN}} \times \int_0^{p_{\max}} N(p) F(p) p dp$$

where

$$F(p) = \exp(-10 \text{ m}/p\tau_i c) - \exp(-160 \text{ m}/p\tau_i c)$$

Neglecting the second exponential term, converting the integral to a sum, and letting

$$f(p) = p \times \exp(-10 \text{ m}/p\tau_i c)$$

we can write

$$\langle\langle p \rangle\rangle = 1 - \frac{c \tau_i}{150 \text{ mN}} \times \sum_{j=1}^n f(p_j) N(p_j)$$

This is a convenient form for doing the integral numerically, using n bins to represent the momentum spectrum. With 1 BeV/c wide bins (6 or 7 bins), the calculation yields the strange particle detection efficiencies e_{5i} summarized in Table 2.

An additional check on this calculation is suggested in the assumption 3 above. If this assumption is valid, i.e. if only strange particles emitted in the forward hemisphere in the center of mass are lost out the end of the chamber, the efficiency for detecting the decay in the chamber will be $(L + R) / 2L$ where L = the number of strange

particles emitted in the backward hemisphere and $R =$ the number of strange particles emitted in the forward hemisphere. When we do this calculation we get agreement with the above calculation to within 2 percent for K^0 mesons, 1 percent for Σ^{+-} hyperons (the π^+ decay of the Σ^+ in the $K^+p\Sigma^+\pi^-$ final state events were used for the Σ^+ calculation), and perfect agreement for the Λ hyperons. This gives us some confidence in the above method of efficiency calculation. It does, however, ignore any differences between final states.

j=6 Short track loss detection efficiency:

When the flight path of the strange particle is very short (< 1 cm) it becomes increasingly difficult to find the event at the scanning stage. To estimate the efficiency due to such losses, the number of events decaying per unit time versus the proper time was plotted for an unbiased subsample of the Σ^+ and Σ^- events. (See Figure 7 for the Σ^+ curve.)

Assuming for Σ^+ and Σ^- hyperons that all decays with $.5\tau < t < 3.0\tau$ were detected, one can calculate what the number, N_0 , of the total parent distribution would be by integrating dN / dt in this region. Then one can calculate the expected number in the $0 < t < .5\tau$ region and compare to the actual number. This procedure leads to short track detection efficiencies for Σ^+ and Σ^- hyperons of .860 and .945 respectively.

To get the short track detection efficiency for K^0 and Λ particles, the number of events decaying per unit length was plotted. (See Figure 8 for the Λ distribution.) For purposes of estimating the loss of short tracks, the curve was assumed to be an exponential and was fitted by eye. The resulting efficiencies for K^0 and Λ particles are .955 and .968 respectively.

Figure 7

Number of Σ^+ particles decaying per .5 mean lives as a function of time.
Note falloff in 0 - .5 bin due to inability to detect short kink tracks.

Figure 8

Number of Λ s decaying per 2 cm as a function of length of path. Depletion in the first bin is interpreted as due to losses in scanning and inability to measure accurately observed short neutrals.

j=7 Angular decay detection efficiency:

Figure 9 shows the angular distribution of the outgoing pion in the center of mass of the hyperon for the decays of Σ^{+-} particles. It is likely that events are lost at small angles due to inability to detect small angle kinks. To estimate the effect of this loss, only events such that $|\cos \theta| < .92$ were used to calculate cross sections, and, since the $\cos \theta$ distributions should be flat, the angular detection efficiency was assumed to be .92.

j=8 Topological decay restriction efficiency:

Four prong events were analyzed only if they had only one strange particle decay. Thus, final states such as $K^+ p \Sigma^+ \pi^-$ or $\pi^+ K^+ p \pi^- \Lambda$ were omitted from the analysis if the K^+ decayed in addition to the shorter lived strange particle.

To take this loss into consideration, the probability of K^{+-} decaying in the chamber was calculated by two independent methods. The integration over the chamber and momentum spectrum described earlier (j=5) gave .092 for the detection efficiency for K^{+-} decaying in the chamber. The experimental ratio of observed K^+ decays to all K^+ events of the 2 prong plus V topology gives a detection efficiency of .0905 for K^+ decay in the chamber. We will assume that .091 of all K^{+-} mesons decay in the chamber. This yields an efficiency of .909 that the 4 prong final state containing a K^+ does not have a K^+ decay and hence falls into the topologies considered.

j=9 $1 - C \Sigma^{+-}$ correction factor:

In addition to the analysis efficiency, e_3 , discussed previously, it was felt that an additional correction

Figure 9

Cosine of the angle between the outgoing decay pion and the flight direction of the Σ as observed in the c.m. of the Σ hyperon. Corresponding graphs for Λ and K^0 decays are given in Figure 3.

factor was necessary for 1-C Σ^+ and Σ^- final states. The need for this factor arises for the following reason. To test the three 1-C hypotheses

$$\begin{array}{ll} \pi^+ p \Sigma^+ \pi^- (K^0) & a) \\ K^+ p \Sigma^+ \pi^- (\pi^0) & b) \\ \pi^+ K^+ \Sigma^+ \pi^- (n) & c) \end{array}$$

requires 2^4 different fits to be attempted (2 positive track permutations $\times$ 4 Σ^+ roots for each hypothesis).

To test the three 1-C hypotheses

$$\begin{array}{ll} \pi^+ \pi^+ p \Sigma^- (K^0) & d) \\ \pi^+ K^+ p \Sigma^- (\pi^0) & e) \\ \pi^+ \pi^+ K^+ \Sigma^- (n) & f) \end{array}$$

also required 2^4 different fits to be attempted.

Since the information obtained from the Σ^{+-} decay vertex fit usually had relatively large errors, the 1-C fits in general were not sufficient to determine the correct hypothesis. In fact, there were often several equally probable chisquare fits for each such event.

Most of the 1-C Σ^{+-} events which were identified were done so using the additional information provided by the ionization of the tracks. When ionization information was not sufficient to identify the event, it was assigned words to indicate that there were several fits and what the most probable interpretation of the strange particle involved in the kink decay was.

The number of events in the fiducial volume of the film identified as final states a), b), or c) above was 34. The number of events for which the kink appeared to be a Σ^+ , but for which the final state hypothesis was ambiguous, was 27. To get an estimate of what the efficiency for obtaining the proper 1-C Σ^+ vertex fit is, we can let

$$\begin{aligned} e_9(1-C \Sigma^+) &= 34 / (34 + 27) \\ &= .56 \end{aligned}$$

For $1-C \Sigma^-$ fits, the appropriate numbers are 46 for the number of events identified as d), e), or f) above and 13 for the number of events containing probable Σ^- hyperons but with ambiguous hypotheses. This leads to

$$\begin{aligned} e_g(1-C \Sigma^-) &= 46 / (46 + 13) \\ &= .78 \end{aligned}$$

These numbers will be used subsequently in obtaining the corrected number of events for the above 6 reactions.

A summary of the above efficiency calculations is given in Table 2 on the next page. These are the numbers used to obtain the decay weight, W_{di} , which in turn is used to compute the total weight, $W = W_a \times W_{di}$, by which the raw number of events in the fiducial volume is to be multiplied to obtain the corrected number of events. ($W_a = 1.12$ is the analysis weight).

Table 3 on the following page presents the partial cross sections for the various final states analyzed. All final states with two or more events are listed and this yields 33 measured partial cross sections. The values for σ_i are obtained from the corrected number of events, N_i , by the equation $\sigma_i = (0.513 \mu b) \times N_i$ where N_i is obtained from the raw number of events, n_i , by the equation $N_i = W n_i$. The weight, W , has been defined previously.

When a final state may be observed via 2 or more different decay modes (e.g. $\pi^+ PK^0 \Lambda$), the number N_i is a weighted average of the N_i predicted by each mode. This weighted average for L different decay modes is given by

$$\langle N_i \rangle = \sum_{j=1}^L (n_{ij} / N_{ij}) / \sum_{j=1}^L (n_{ij} / N_{ij}^2)$$

Events in the 2-fold ambiguous category are apportioned to the two final states involved in the ratio in which the final states are populated with uniquely identified events. While this method is subject to possible kinematic biases it is felt that the errors introduced will be small since the number of events in the 2-fold ambiguous category is small.

TABLE 2

Decay Efficiencies

Strange Particle	e_4	e_5	e_6	e_7	e_8^*	$e_9^{\dagger}$
K^0	.345	.977	.955	1.00	.909	1.00
Λ	.669	.915	.968	1.00	.909	1.00
Σ^+	.500	.990	.860	.920	.909	.560
Σ^-	1.00	.965	.945	.920	.909	.780

where

e_4 = Visible decay to all decay ratio

e_5 = Fiducial volume detection efficiency

e_6 = Detection efficiency due to short track loss

e_7 = Detection efficiency due to small angle loss

e_8 = Efficiency for final states being in analyzed topologies

e_9 = Efficiency for resolving 1-C Σ^{+-} final states.

* Note: e_8 applies only to event types 41, 43, and 45 (4 prong plus kink or V) and final states which include a K^+ particle.

$\dagger$ Note: e_9 applies only to the six 1-C final states discussed in the text under $j=9$.

TABLE 3

Partial Cross Sections

Final State	Fit* No.	Raw No.	Weight	Corrected No.	$\sigma(\mu\text{b})$
$K^+ P \Lambda$	252	43	1.89	106	54.4 ± 7.3
	263	6			
	922	<u>7</u>			
		56			
$K^+ P \Sigma^0$	254	20	1.89	49.2	25.2 ± 5.0
	269	2			
	922	3			
	923	<u>1</u>			
		26			
$K^0 P \Sigma^+$	246	1	3.48	27.8	14.3 ± 5.1
	261	<u>7</u>			
		8			
$P P K^0 K^0$	243	8	2.44	19.7	10.4 ± 3.3
	304	2	12.1	<u>24.2</u>	
				20.3	
$K^+ P K^0 (n)$	244	11	3.48	48.6	25.0 ± 6.7
	267	1			
	926	<u>2</u>			
		14			
$\pi^+ P K^0 \Sigma^0$	242	5	7.38	44.3	29.5 ± 7.0
	302	12	6.57	78.8	
	924	1		<u>57.6</u>	
$\pi^+ \Sigma^+ K^0 (n)$	245	2	3.48	41.7	21.4 ± 6.2
	265	<u>10</u>			
		12			
$P \Sigma^+ K^0 (\pi^0)$	247	1	3.48	34.8	17.9 ± 5.7
	262	<u>9</u>			
		10			
$K^+ P \Sigma^+ \pi^-$	411	23	3.18	73.0	37.4 ± 7.8
$\pi^+ K^+ P \Sigma^-$	431	41	1.47	61.7	31.6 ± 4.9
	952	<u>1</u>			
		42			

TABLE 3
(continued)

Final State	Fit No.	Raw No.	Weight	Corrected No.	$\sigma(\mu\text{b})$
$\pi^+ K^+ \Lambda(n)$	255	93	1.89	196	101 ± 10.3
	268	7			
	925	3			
	927	<u>1</u>			
		104			
$\pi^+ p K^0 \Lambda$	241	13	7.38	140	72.4 ± 7.4
	251	54	2.65	164	
	301	16	6.57	105	
	921	6			
	924	4			
	925	2			
	926	2			
				<u>141</u>	
$K^+ p \Lambda(\pi^0)$	253	63	1.89	151	77.5 ± 8.7
	264	7			
	921	8			
	923	1			
	927	<u>1</u>			
		80			
$\pi^+ p K^0 K^0(n)$	307	4	12.1	48.4	24.8 ± 12.4
$K^+ p p \pi^- K^0$	451	5	3.83	19.1	9.8 ± 4.4
$\pi^+ p p K^- K^0$	455	7	3.83	26.8	13.8 ± 5.2
$K^+ p \Sigma^+ \pi^- (\pi^0)$	412	4	5.62	33.7	17.3 ± 7.1
	953	<u>2</u>			
		6			
$\pi^+ p \Sigma^+ \pi^- (K^0)$	413	3	7.17	28.7	14.7 ± 7.4
	953	<u>1</u>			
		4			
$\pi^+ K^+ \Sigma^+ \pi^- (n)$	414	9	5.62	56.2	28.8 ± 9.1
	958	<u>1</u>			
		10			
$\pi^+ K^+ p \Sigma^- (\pi^0)$	432	19	1.88	43.2	22.2 ± 4.6
	951	2			
	955	1			
	957	<u>1</u>			
		23			

TABLE 3
(continued)

Final State	Fit No.	Raw No.	Weight	Corrected No.	$\sigma(\mu\text{b})$
$\pi^+\pi^+\rho\pi^-(K^0)$	434	20	2.41	48.2	24.7 ± 5.6
$\pi^+\pi^+K^+\pi^-(n)$	433 957	6 $\frac{1}{7}$	1.88	13.2	6.8 ± 2.6
$\pi^+K^+P\pi^-\Sigma^0$	475 941 942	16 2 $\frac{2}{20}$	2.08	41.6	21.4 ± 4.8
$\pi^+PK^0\Lambda(\pi^0)$	303	20	6.57	131	67.4 ± 15.0
$\pi^+\pi^+K^0\Lambda(n)$	308	6	6.57	39.4	20.2 ± 8.3
$\pi^+K^+P\pi^-\Lambda$	471 941	40 $\frac{6}{46}$	2.08	95.7	49.0 ± 7.2
$\pi^+PP\pi^-\pi^0(K^0)$	453	5	2.44	12.2	6.3 ± 2.8
$\pi^+K^+P\pi^-\pi^0(n)$	454	4	3.82	15.3	7.8 ± 3.9
$\pi^+PPK^-\pi^0(\pi^0)$	456	3	3.82	11.5	5.9 ± 3.4
$\pi^+\pi^+PK^-\pi^0(n)$	457	2	3.82	7.6	3.9 ± 2.8
$\pi^+\pi^+P\pi^-\pi^0\Lambda$	470 473 954	3 26 1	7.38 2.65	22.1 71.5	
				$\overline{45.0}$	23.1 ± 4.2
$\pi^+K^+P\pi^-\Lambda(\pi^0)$	472 942 954	34 1 $\frac{2}{37}$	2.08	77.0	39.5 ± 6.3
$\pi^+\pi^+K^+\pi^-\Lambda(n)$	474	19	2.08	39.6	20.3 ± 4.7
Total				946	± 40

* Fit numbers define the topology of the event for numbers < 900 and the 2-fold ambiguous category for numbers > 900. They are identified in Appendix D.

Σ^0 / Λ Resolution

One of the most common ambiguities in this experiment is between events containing Λ hyperons and those containing Σ^0 hyperons. This occurs because of the relatively small mass difference between Λ and Σ^0 particles (76.9 MeV). To give some idea of the resolution with which these can be distinguished, we can examine the square of the missing mass of the object X for the assumption $P + P \rightarrow K^+P(X)$.

This we have done for the final states identified as

$$\begin{aligned} &K^+P\Lambda \\ &K^+P\Sigma^0 \\ &K^+P\Lambda(\pi^0). \end{aligned}$$

Note that the calculation uses only the measured momentum values of the K^+ and P, i.e. the measured Λ momentum is not used at this stage. Figure 10 shows the histogram of the missing mass squared of X for these events. The separation of the Λ and Σ^0 peaks is not large but they are clearly resolved. The ratio of $K^+P\Lambda$ to $K^+P\Sigma^0$ to $K^+P\Lambda/\Sigma^0$ (2-fold ambiguous) is 77 : 37 : 12 in this experiment. This corresponds to resolving about 90 percent of the $K^+P\Lambda$ or Σ^0 events.

While $K^+P\Lambda(\pi^0)$ events can be fit, $K^+P\Sigma^0\pi^0$ events cannot (6 missing variables). If one considers a $K^+P\Lambda(\pi^0)$ fit as essentially a measure of how well the missing mass X in the reaction

$$P + P = K^+P\Lambda(X) \quad a)$$

agrees with that of a π^0 , the question arises of what the missing mass of X would be for the reaction

$$P + P = K^+P\Sigma^0\pi^0 \quad b)$$

when interpreted as reaction a). If we think of reaction b.) as the same as a) except now there is both a π^0 and a gamma-ray unseen, then

$$MM^2(X) = m_{\pi}^2 + 2 \vec{p}_\gamma \cdot (E_{\pi} - \vec{p}_{\pi})$$

Figure 10

Missing mass squared for the object X in the reaction

$$P + P \rightarrow K^+ P (X)$$

from the measured values of K^+ and P momentum. These events were determined to be in the final states indicated.

where $\vec{p}_\gamma \cdot E_\eta$ is understood to mean $p_\gamma E_\eta$. It is clear that there are 2 cases for which $MM^2(X) \simeq m_\eta^2$; a) when $\vec{p}_\gamma$ is very small and b) when $\vec{p}_\gamma$ is parallel to $\vec{p}_\eta$ and $\vec{p}_\eta$ is large. This is true because $(E_\eta - p_\eta) \rightarrow .5 m_\eta^2/p_\eta$ for large p_η .

Thus it is possible that the events identified as $K^+P\Lambda(\pi^0)$ contain a sizable contamination of $K^+P\Sigma^0\pi^0$ events. We have not calculated the size of this effect but simply note the possibility of such contamination.

A final comment should be made concerning the errors quoted in Table 3. These errors are based entirely on the statistical errors in the raw number of events. A more realistic evaluation of the errors should take into account the effects of systematic errors involved. However, it is unlikely that the value of the total identified strange particle cross section can be trusted to more than 10 percent. Thus, a better estimate for the identified strange particle cross section would be $946 \pm 95 \mu\text{b}$. The error quoted in Table 3 is simply the square root of the sum of the squares of the individual errors.

Total Strange Particle Cross Section

In addition to the uniquely identified strange particle production listed in Table 3, there are three other general categories of strange particle production which we need to consider to estimate the total strange particle production cross section.

1. First are the uniquely identified charged K pair events. This category is identified by the decay of the K^+ or K^- alone. The three final states involved are

$$\begin{array}{ll} K^+ PPK^- & a) \\ K^+ PPK^- (\pi^0) & b) \\ \pi^+ K^+ PK^- (n) & c) \end{array}$$

There were 2, 1, and 9 respectively of these events identified in the fiducial region. Using .091 as the probability of each K decaying, we get a weight

$$W = .5 \times 1.12 \div .091 = 5.10$$

for each event. So the cross section for a), b), and c) are 5, 3, and 23 μb respectively.

2. There were many events which yielded no good 4-C or 1-C fit but which had missing mass larger than the one called for in one of the 1-C fits. This corresponds to several neutral particles being created at the primary vertex and no fit is possible. As many of the tracks as possible were identified by ionization and usually the strange particle was identified by the decay vertex fit.

In order to get an estimate of what the cross section for production of these events with more than one neutral is, we will list the number of events according to the strange particle decay and calculate the cross section. The weighting scheme will be similar to that used in Table 3 except that the efficiency e_4 for Σ^+ decays is .78 instead of .50 and all Σ^+ decays are counted $\dagger$. Table 4 gives the results.

TABLE 4

Events With More than One Neutral

Strange Particle	Raw No.	Weight	Corrected No.	$\sigma (\mu\text{b})$
Λ	244	1.89	462	237
K^0	100	3.48	348	178
$K^0 + \Lambda$	15	6.57	99.0	51
$K^0 + K^0$	2	12.1	24.2	12
K^0 or Λ	6	1.89 [*]	11.3	6
K^+	8	12.3	99.0	50
Σ^+	19	1.69	32.1	16
K^-	2	12.3	24.6	13
Σ^-	7	1.23	8.6	4
K^+ or Σ^+	16	1.69 [*]	27.0	14
K^- or Σ^-	10	1.23 [*]	12.3	6
Total				587 μb

* Assumes all K^0 / Λ ambiguities are Λ and all K^{+-} / Σ^{+-} ambiguities are Σ s.

† In an unbiased sample, 35 $\Sigma^+ \rightarrow p + \pi^0$ and 62 $\Sigma^+ \rightarrow n + \pi^+$ were found. Assuming $2 \times 62 = 124$ real Σ decays occurred, only $(35 + 62) \div 124 = .78$ were found due to loss of $\Sigma^+ \rightarrow p + \pi^0$ events.

3. The third general category of events which should be included in the calculation of the total strange particle cross section is that of the topologies not considered in the analysis. This includes 2 prong plus kink (Type 21) and 6 prong plus positive kink (Type 61), 6 prong plus negative kink (Type 63), and 6 prong plus V (Type 65).

One can obtain a rough estimate of the cross section contributed by these topologies by making the following assumption: the strange particle cross section contributed by 2 prong plus positive kink (Type 21) events compared to that of the 4 prong plus positive kink (Type 41) events will be proportional to the measured number of Type 21 events and Type 41 events respectively. Using such arguments and the numbers from Tables 1, 3, and 4 we can estimate the cross sections for strange particles produced in Types 21, 61, 63, and 65 to be 218 μb , 20 μb , 14 μb , and 7 μb respectively. This corresponds to an additional 259 μb of cross section from topologies not analyzed and takes into account the bulk of such contributions.

Summary of Strange Particle Cross Sections

To summarize the strange particle cross sections and estimate the total strange particle cross section we list the various contributions in Table 5.

TABLE 5
Cross Section Summary

Category	$\sigma(\mu\text{b})$	Percent
Fit events (Table 3)	946	51.9
Missing mass too large (Table 4)	587	32.2
Topology not tried estimate	259	14.2
K^{+-} pair events	31	1.7
Total Strange Particle $\sigma =$	1823 μb	100.0

IV. RESULTS - GENERAL KINEMATIC FEATURES

In this section we present some of the most prominent general kinematic features of the data. The subset of data included in this analysis differs somewhat from that included in the cross section calculations.

First, events from all 41 rolls of film are included and no fiducial region is imposed. Second, all 2-fold ambiguities are omitted. Third, all events with track interchange ambiguity are omitted. These were included in the cross section calculation since, e.g. the cross section for $\pi^+K^+\Lambda(n)$ does not depend on the distinguishability of the π^+ and K^+ . (Often the $\pi^+K^+\Lambda(n)$ and $K^+\pi^+\Lambda(n)$ hypotheses gave comparable fits.) However, the kinematic analysis does depend on this information. So only events for which every track was identified were used. Table 6 presents the list of such events used in the subsequent analysis.

A. Method

As events were identified, the numerically coded information was entered on scan cards (discussed previously). At the conclusion of the identification stage of the experiment, these scan cards were used to generate a set of event cards for the uniquely identified events. The event cards were then sorted by final state and used to reprocess the events, grouping them by final state.

From the reprocessed data, cards were generated (one card per track) on which the frame number, mass code number, final state code number, and three fit momenta coordinates of the track appeared. These cards served as a very convenient form of the data for later analysis.

The system of analysis programs was developed by the author. These programs operated on the track cards described above and computed the standard kinematic quantities such as

TABLE 6

Events Used in Kinematical Analysis

K-Y EVENTS

NO. BODIES	FINAL STATE	NO. EVENTS	NO. BODIES	FINAL STATE	NO. EVENTS
3	$K^0 P \Sigma^+$	10	5	$\pi^+ K^+ \Sigma^+ \pi^- (n)$	24
3	$K^+ P \Delta$	75	5	$\pi^+ K^+ P \Sigma^- (\pi^0)$	21
3	$K^+ P \Sigma^0$	37	5	$\pi^+ \pi^+ K^+ \Sigma^- (n)$	7
	TOTAL	122	5	$\pi^+ \pi^+ P \Sigma^- (K^0)$	28
4	$\pi^+ P K^0 \Delta$	120	5	$\pi^+ K^+ P \pi^- \Delta$	65
4	$K^+ P \Delta (\pi^0)$	95	5	$\pi^+ K^+ P \pi^- \Sigma^0$	21
4	$\pi^+ K^+ \Delta (n)$	100	5	$\pi^+ P K^0 \Delta (\pi^0)$	24
4	$K^+ P \Sigma^+ \pi^-$	50	5	$\pi^+ \pi^+ K^0 \Delta (n)$	9
4	$\pi^+ K^+ P \Sigma^-$	62		TOTAL	219
4	$\pi^+ P K^0 \Sigma^0$	26	6	$\pi^+ K^+ P \pi^- \Delta (\pi^0)$	39
4	$P \Sigma^+ K^0 (\pi^0)$	11	6	$\pi^+ \pi^+ P \pi^- K^0 \Delta$	32
4	$\pi^+ \Sigma^+ K^0 (n)$	18	6	$\pi^+ \pi^+ K^+ \pi^- \Delta (n)$	25
	TOTAL	482	6	$\pi^+ \pi^+ \Sigma^+ \pi^- K^0 (n)$	2
5	$K^+ P \Sigma^+ \pi^- (\pi^0)$	7	6	$\pi^+ \pi^+ P \pi^- K^0 \Sigma^0$	1
5	$\pi^+ P \Sigma^+ \pi^- (K^0)$	13		TOTAL	99

K- $\bar{K}$ EVENTS			SUMMARY		
NO. BODIES	FINAL STATE	NO. EVENTS	CATEGORY	NO.	%
4	PPK ⁰ K ⁰	13	3-B K-Y	122	12.1
4	K ⁺ PK ⁰ (n)	13			
4	K ⁺ PPK ⁻	5	4-B K-Y	482	47.6
5	PPK ⁰ K ⁰ (π^0)	1			
5	π^+ PK ⁰ K ⁰ (n)	7	5-B K-Y	219	21.6
5	K ⁺ PPK ⁻ (π^0)	4			
5	π^+ K ⁺ PK ⁻ (n)	11	6-B K-Y	99	9.8
5	K ⁺ PP π^- K ⁰	6			
5	π^+ PPK ⁻ K ⁰	12			
6	K ⁺ PP π^- K ⁰ (π^0)	1	4-B K- $\bar{K}$	31	3.1
6	π^+ PP π^- K ⁰ K ⁰	6			
6	π^+ K ⁺ P π^- K ⁰ (n)	6	5-B K- $\bar{K}$	41	4.1
6	π^+ PPK ⁻ K ⁰ (π^0)	3			
6	$\pi^+\pi^+$ PK ⁻ K ⁰ (n)	2	6-B K- $\bar{K}$	1.8	1.8
		<u>90</u>	TOTAL	<u>1012</u>	<u>100.1</u>

invariant masses, 4-momentum transfer, decay angles, etc. and presented the data as histograms or scatter plots. Typical running time on the computer for one of these programs operating on a typical final state was 20 - 30 seconds.

B. General Features

1. Angular distributions

Figure 11 shows the cosine distribution for the angle between the beam direction and the outgoing particle in the overall center of mass for all 4-body final states. Since the distributions are similar for all charged states of a given particle, all the charge states have been combined for the graph. The interesting feature which is clearly evident is the peripheral nature of the scattered baryons. The distribution for π mesons, on the other hand, is nearly flat. The K meson distribution lies somewhere between the π mesons and baryons. These distributions indicate that the degree of peripherality of the outgoing particle depends strongly upon its mass.

A second general feature is apparent from the data presented in Figure 12. Here we show the center of mass angular distribution for all lambda particles as a function of number of bodies in the final state. The behavior of the distributions as the number of final state particles increases is typical of all the baryons. The conclusion is that, as the number of particles in the final state increases, the baryons tend to lose their directional information due to large 4-momentum transfer necessary to create new particles, the increasing number of final state interactions possible, and a closer approximation to the "statistical model" picture of the interaction. This interpretation is consistent with the assumption of Gottfried and Jackson^{21/} that the more complex, highly inelastic reactions absorb the lower partial waves.

Figure 11

Distributions of cosine of the angle between the beam direction and the outgoing particle in the over-all center of mass for various mass particles.

C.M. ANGULAR DISTRIBUTIONS FOR 4-BODY FINAL STATES

Figure 12

Distributions of cosine of the angle between the beam and the outgoing Λ in the overall center of mass for final states containing various numbers of particles.

$\cos \theta_{CM} (\Delta)$
wrt INCIDENT BEAM

3 BODY

5 BODY

4 BODY

6 BODY

That is, incident protons with small impact parameters (i.e. "central collisions") tend to give rise to many body final states and the resulting baryons tend to "forget" the beam direction.

2. Isobar Production

Data are now presented on the extent to which $N^*_{33}(1236)$, $Y_1^*(1385)$, $Y_0^*(1405)$, and $Y_1^*(1660)$ isobars are present in our experiment. Figure 13 shows all π^+p and π^-n combinations present in the data, grouped by the number of bodies in the final state. These are the combinations in which the isospin $3/2$ N^* resonances should appear, and it is clear that the $N^*(1236)$ is the dominant resonance in these mass combinations.

To determine the amount of N^* present, the histograms shown were fitted to a 4 parameter curve defined by $\dagger$

$$y = A \times \frac{\text{Ph. Sp.}}{(M_0^2 - W^2)^2 + M_0^2 \Gamma^2} + B \times \text{Ph. Sp.}$$

where

- W = invariant mass of the πN system
- A = fraction of events in resonance curve above
- B = fraction of events in phase space
- M_0 = mass of resonance
- Γ = full width at half maximum of resonance.

Table 7 presents the results of such fits. Two interesting features are apparent. One is that, as the number of bodies in the final state increases, there is no strong change in the fraction of N^* formation. It seems to remain constant at about 50 percent of the total. The second feature is that the average value over the 4 categories fitted for the mass position, M_0 , is $1213 \text{ MeV}/c^2$. Jackson^{22/} has calculated the shift in the peak position due to the energy dependence of the width and finds, for the $N^*(1238)$, a shift of $-23 \text{ MeV}/c^2$. Our shift is $1213 - 1236 = -23 \text{ MeV}/c^2$.

TABLE 7

Fits to Isobar Production

Final State	Isobar	Percent Ph. Sp.	Percent Isobar	Fit M_0 Fit Γ	Chisquared Constraints
4 body $\pi^+ p$	$N^*(1236)$	48 ± 7	52 ± 7	$1.213 \pm .011$ $.136 \pm .027$	12.7 25-c
5 body $\pi^+ p$	$N^*(1236)$	43 ± 8	57 ± 8	$1.213 \pm .010$ $.140 \pm .026$	13.7 20-c
6 body $\pi^+ p$	$N^*(1236)$	50 ± 13	50 ± 13	$1.210 \pm .007$ $.063 \pm .026$	20.9 17-c
5,6 body $\pi^- n$	$N^*(1236)$	23 ± 16	77 ± 17	$1.216 \pm .013$ $.107 \pm .027$	7.2 20-c
4 body $\pi \Lambda$	$Y^*(1385)$	54 ± 7	46 ± 6	$1.374 \pm .008$ $.113 \pm .029$	24.5 26-c
5 body $\pi \Lambda$	$Y^*(1385)$	58 ± 13	42 ± 10	$1.368 \pm .036$ $.154 \pm .094$	19.4 20-c
6 body $\pi \Lambda$	$Y^*(1385)$	47 ± 24	53 ± 29	$1.33 \pm .04$ $.26 \pm .15$	18.6 16-c
4 body $\pi \Sigma$	$Y^*(1405)$	70 ± 8	30 ± 8	fixed fixed=.05	31.3 13-c
5 body $\pi \Sigma$	$Y^*(1405)$	80 ± 8	20 ± 5	fixed fixed=.05	29.2 22-c

† The fitting program used was MINMASS, written by Dr. W.P. Swanson, now at DESY, Hamburg, Germany.

Figure 13

Invariant mass distributions for the
isospin $3/2$ πN systems grouped by number
of particles in the final state.

Figure 14 presents the data on possible Y_1^* resonances in final states containing $\pi\Lambda$ combinations. The $Y_1^*(1385)$ is clearly present in 4, 5, and 6 body final states, and the 4 and 5 body final states have a suggestion of $Y_1^*(1660)$.

Four parameter fits similar to those described above were made to these histograms to determine the fraction of $Y_1^*(1385)$ present. In the 4 and 5 body final states, the 1660 MeV/c² region (bins 11 and 12) was omitted from the fit since it is likely that the $Y_1^*(1660)$ contributes some to this region. In the six body final state, fits were done both on all the data and then on all the data except bins 6 and 7, a region in which the $\pi^+\Lambda$ contributes an anomalously large number of points. The numbers in Table 7 are based on this second fit.

Again, as in the case of the $N^*(1238)$, there seems to be a rather constant (about 50 percent) formation of the $Y_1^*(1385)$. The resolution of the fit is not able to confirm the predicted shift in peak position of -4.5 MeV/c² but it is in the right direction.

Figure 15 gives the data on the isospin < 2 $\Sigma\pi$ combinations in the 4 and 5 body final states. While no resonance is dominant, there is some indication that the $Y_0^*(1405)$ may be present. For purposes of fitting, the bin size on the 4 body graph was doubled. Four parameter fits to the 4 and 5 body histograms were not able to converge on the $M_0 = 1405$ MeV/c² value. Therefore, 2 parameter fits were tried in which only the amount of phase space and resonance curve fractions are varied while holding $M_0 = 1405$ MeV/c² and $\Gamma = 50$ MeV/c². The results of these fits are presented in Table 7.

Figure 14

Invariant mass distributions for all $\pi\Lambda$ combinations, grouped according to the number of particles in the final state.

Figure 15

Invariant mass distributions for $\pi\Sigma$ combinations with isospin < 2 . For fitting purposes, the bin size for the 4 body final states was doubled. Dashed curves are phase space predictions.

3. Di-baryon Resonances

There have been possible $N\Lambda$ resonances reported at 2059 MeV/c² 224/, 2098 MeV/c² 25/, 2115 MeV/c² 5.6/, and 2360 MeV/c² 23/.* These have been observed in

$P + P \rightarrow K^+ + X(2059)$	(Counter experiment)
$\Sigma^- + He^4 \rightarrow \Lambda + n + H^3$	(Λ n bump at 2098)
$K^- + d \rightarrow \Lambda \pi^- P$ and $\Lambda \pi \pi N$	(Λ P peak at 2115)
$\pi^+ + d \rightarrow \Lambda PK(\pi)$	(Λ P peak at 2115)
$P + P \rightarrow K^+ + X(2360)$	(Counter experiment).

It is interesting to note that in the 4 previous $P + P \rightarrow$ strange particles in a bubble chamber (at 3.66, 5.0, 5.5, and 6.0 BeV/c), no evidence for such resonances was found.

The evidence concerning these possible $N\Lambda$ resonances in this experiment is presented in Figure 16. The $n\Lambda$ and $P\Lambda$ distributions are similar in shape and have been combined for the graph. The 2059, 2098, and 2360 MeV/c² positions are noted. The conclusion we draw is that there is no evidence for any $N\Lambda$ resonances in this experiment.

The pronounced peaking at the high end of phase space may be interpreted as the result of the peripheral nature of the two baryons (discussed previously). Since they tend to come out of the reaction with small changes in direction and momentum from the initial beam protons, the two baryons are back-to-back and have high relative energy. This causes the peaking at high invariant masses in the di-baryon system.

The mass distributions for $N\Sigma$ combinations were also examined. They indicated that di-baryon resonance production in the $N\Sigma$ final state is negligible.

* In addition to the 4 resonances reported above, Buran et al. (Ref. 26) see a ΛP enhancement at 2220 MeV in K^- capture in a heavy liquid bubble chamber.

Figure 16

Invariant mass distributions for $N \Lambda$ combinations in 3, 4, 5, and 6 body final states. Phase space is indicated by dashed curves.

M (N, Λ) BeV/C²

4. Other Resonances

The mass distributions for the neutral and positive πK combinations indicated that little, if any, $K^*(890)$ is produced in this experiment.

Of the 13 events in the PPK^0K^0 final state, 5 had $M(K^0K^0)$ in the ϕ meson region.

The $(KN)^0$, $(KN\pi)^0$, and $(KN\pi)^{+-}$ spectra were examined for evidence of the reported ^{19/} 2097, 2299, and 1942 MeV/c^2 resonances, and none was found.

V. RESULTS - THREE BODY FINAL STATES

We now wish to consider in some detail the properties of the three body final states:

$K^0 P \Sigma^+$	10 events	1)
$K^+ P \Sigma^0$	37 events	2)
$K^+ P \Lambda$	75 events	3)

A. KPΣ Final States

In Figure 17 we show the Chew-Low and Dalitz plots for reactions 1) and 2). Although the number of events is small, there seems to be no striking difference between reactions 1) and 2).

The phase space predictions for the invariant mass distributions are shown in Figure 18 together with the invariant mass distributions for the 37 $K^+ P \Sigma^0$ events. It appears that a description of the experimental distributions must involve more than a statistical distribution and constant matrix element.

The most radical departure from phase space in the $K^+ P \Sigma^0$ final state seems to be in the $M(K^+ \Sigma^0)$ distribution. If one assumes this deviation is due to a $K^+ \Sigma^0$ resonance and fits the mass histogram shown in the manner described in section IV, B, 2, the results are

$$\begin{aligned}
 \text{Fraction phase space} &= .33 \pm .18 \\
 \text{Fraction resonance} &= .67 \pm .18 \\
 M_0 &= 1.920 \pm .025 \text{ BeV}/c^2 \\
 \Gamma &= .175 \pm .109 \text{ BeV}/c^2 \\
 \text{Chisquare}(12-c) &= 7.0
 \end{aligned}$$

The inclusion of the 10 $K^0 P \Sigma^+$ events in the fit alter the fitted values very slightly and reduce the errors on the fractions to about .15 and the error on the width to

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.07 BeV/c².

To see how the assumption of a resonance matrix element in the invariant mass of the $K^+\Sigma^0$ would influence the other two invariant mass distributions, a Monte Carlo calculation was performed.^{27/} In this calculation, events are generated according to phase space and then weighted according to any desired kinematic quantity. In the above calculation, the invariant mass of the $K^+\Sigma^0$ system, M , was used to generate a weight for the event using a simple Breit-Wigner equation

$$WT = \frac{\Gamma^2 / 4}{\Gamma^2 / 4 + (M - M_0)^2}$$

The values used were $M_0 = 1.924$ and $\Gamma = .170$.

The smooth curves in Figure 18 were generated by adding, in a ratio 70:30, the result of the above calculation and phase space. The agreement with the data is seen to be quite good.

One is tempted to draw the conclusion that we are observing the known $N^*(1924)$ which has a width of 170 MeV, $J = 7/2$, and $I = 3/2$. If one assumes the production is occurring via one pion exchange (see Figure 19, a for the Feynman graph), an obvious quantity to examine is Δ^2 , the 4-momentum transfer to the outgoing proton. Figure 20 presents the data for the $K^+\Sigma^0$ and $K^0\Sigma^+$ final states combined. The curve is a Monte Carlo calculation assuming the $K\Sigma$ system was pure 1924 Breit-Wigner and weighting the Δ^2 distribution by a factor $\Delta^2/(\Delta^2 + \mu^2)^2$ which is the OPEM prediction for the Δ^2 dependence. The agreement of this calculation with the data is quite adequate.

An additional, amusing argument relating the $K^+\Sigma^0$ and $K^0\Sigma^+$ cross sections follows from the assumption that $K\Sigma$ production is proceeding via the $I = 3/2$ channel. Assume again that the production is via OPE. Then the lower vertex in Figure 19, a will be the same for both reactions. The cross sections involve the matrix element at the upper

Figure 18

Invariant mass distributions for the $K^+P\Sigma^0$ final state. Smooth curve is Monte Carlo calculation based on a fit to the $M(K^+\Sigma^0)$ data described in the text. Dashed curve is phase space prediction.

$P + P \rightarrow K^+ P \Sigma^0$
 37 EVENTS
 CURVE = MONTE CARLO
 CALCULATION WITH
 30% PHASE SPACE
 70% $N^*(1924)$ BREIT-WIGNER

Figure 19

- (a) Feynman diagram for one pion exchange in three body final states.
- (b) Feynman diagram for one kaon exchange in three body final states.
- (c) Definition of the "Jackson angles" for the KY system. These angles are measured in the KY center of mass with θ being the angle between the outgoing heavy particle and the incident proton and ϕ being the standard azimuth angle in the coordinate system defined by X and Y as shown.

(a)

(b)

(c)

$$\hat{Z} = \vec{P}_1 / |\vec{P}_1|$$

$$\hat{Y} = \vec{P}_2 \times \vec{P}_3 / |\vec{P}_2 \times \vec{P}_3|$$

$$\hat{X} = \hat{Y} \times \hat{Z}$$

vertex, and therefore we can write

$$\frac{\sigma(\pi^0 p \rightarrow \pi^0 p)}{\sigma(\pi^0 p \rightarrow \pi^+ \pi^-)} = \frac{\sigma(\pi^0 p \rightarrow \pi^0 p)}{\sigma(\pi^0 p \rightarrow \pi^+ \pi^-)}$$

If we ignore the very slight mass differences between charged and neutral K's and Σ 's, the phase space (kinematic) factors for these reactions are identical. The only difference, then, between the reactions is the way in which the charge is arranged in the final state, i.e. the isospin dependence.

We may write the initial and final states as linear combinations of total isospin and Z component of isospin states $|I, I_z\rangle$ as follows

$$\begin{aligned} |\pi^0, p\rangle &= \sqrt{2/3} |3/2, 1/2\rangle - \sqrt{1/3} |1/2, 1/2\rangle \\ |K^0, \Sigma^+\rangle &= \sqrt{1/3} |3/2, 1/2\rangle + \sqrt{2/3} |1/2, 1/2\rangle \\ |K^+, \Sigma^0\rangle &= \sqrt{2/3} |3/2, 1/2\rangle - \sqrt{1/3} |1/2, 1/2\rangle \end{aligned}$$

Using these functions and the equation

$$\frac{\sigma(\pi^0 p \rightarrow \pi^0 p)}{\sigma(\pi^0 p \rightarrow \pi^+ \pi^-)} = \frac{|\langle \pi^0 p | f | K^0 \Sigma^+ \rangle|^2}{|\langle \pi^0 p | f | K^+ \Sigma^0 \rangle|^2}$$

we get

$$R = \frac{\sigma(\pi^0 p \rightarrow \pi^0 p)}{\sigma(\pi^0 p \rightarrow \pi^+ \pi^-)} = \frac{2|f_{3/2}^2| + 2|f_{1/2}^2| - 4\text{Re } f_{3/2}^* f_{1/2}}{4|f_{3/2}^2| + |f_{1/2}^2| + 4\text{Re } f_{3/2}^* f_{1/2}}$$

where

$f_{3/2}$ = amplitude for reaction going through isospin $(1/2)$ $3/2$ channel.

Now let us examine the data.

<u>P(BeV/c)</u>	<u>Ratio($K^0 \Sigma^+ / K^+ \Sigma^0$)</u>	<u>Ref.</u>
3.66	$\frac{30 \pm 10}{13 \pm 7} = 1.76 \pm .63$	1
4.95	$\frac{17 \pm 3}{25 \pm 3} = .68 \pm .2$	3
7.87	$(14 \pm 5) / (25 \pm 5) = .56 \pm .40$	This exp.

Figure 20

Four-momentum transfer (Δ^2) to the outgoing proton in $Kp\Sigma$ events. Curve is Monte Carlo calculation assuming all $K\Sigma$ combinations are in a Breit-Wigner resonance of width 170 MeV and that the Δ^2 distribution is that predicted by the OPEM.

Thus, although the errors are large, the last two experiments have ratios not inconsistent with $1/2$. If we set the above equation for R equal to $1/2$ one obvious solution occurs for $f_{1/2} = 0$. (The other solution, if $f_{3/2}$ and $f_{1/2}$ had the same phase, would be $f_{1/2} = 4 f_{3/2}$.) The first solution would, in fact, be the case if all the $K\Sigma$ production was through the $N^*(1924)$ channel which has isospin $3/2$. If, on the other hand, the dominant amplitude were $f_{1/2}$, the measured ratio would be 2 instead of $1/2$.

These arguments are consistent with the formation of the $N^*(1924)$ in the $K^+\Sigma$ final states. Further evidence for such formation should be present in the decay angular distributions (defined by Jackson ^{22/} and in Figure 19, c). Figure 21 presents these distributions for the K^+P and $K^+\Sigma^0$ systems in the $K^+\Sigma^0$ final state.

First, let us consider the $K^+\Sigma^0$ system as an $N^*(1924)$. Parity conservation in strong decays requires the $\cos \theta$ distribution for the Σ^0 to be symmetric about $\cos \theta = 0$, and the OPEM (spin 0 exchange) requires the ϕ distribution to be flat. The first requirement is rather poorly satisfied and the second seems unsatisfied also (left-right ratio of 12:25). In addition, a pure $J = 7/2$ state, initially populated with only $m = \pm 1/2$ as pertains in the $\pi^0 P$ system, has a characteristic decay distribution peaking up at $\cos \theta = \pm 1$ with secondary bumps at $\cos \theta = \pm .5$. No such peaking appears evident in this data. Slicing the data to include events only in the 1924 MeV region does not seem to affect the distributions.

To summarize the arguments based on the decay distributions: 1) The $\cos \theta$ distribution appears to cast doubt on $N^*(1924)$ as the predominant mechanism in $K^+\Sigma^0$ production, and 2) the ϕ distribution does not seem to be consistent with 100 percent OPE.

Figure 21

Decay angular distributions for the
 $K^+\Sigma^0$ and K^+P systems in the $K^+P\Sigma^0$
final state.

DECAY DISTRIBUTIONS FOR $K^+P\Sigma^-$ EVENTS

It is difficult, on the basis of the data presented here, to make any definite claims concerning the production processes involved in the $K\rho\Sigma$ final states. We can say, however, that the Δ^2 distribution is consistent with the OPEM and that the mass distribution of the $K\Sigma$ system peaks around $1920 \text{ MeV}/c^2$.

B. $K^+P\Lambda$ Final State

The most obvious kinematic features of the $K^+P\Lambda$ final state are displayed in Figures 22 and 23. They can be summarized as follows: 1) There appears to be a strong tendency for events to have low $K^+\Lambda$ invariant masses, and 2) events with such low masses have low Δ^2 to the $K^+\Lambda$ system. Projections of the 3 invariant mass combinations and the Δ^2 distribution to the outgoing proton (equivalent to the Δ^2 to the $K^+\Lambda$ system) are shown in Figure 24 along with the 3 body phase space predictions. Again, the striking feature is the large deviation of the $K^+\Lambda$ invariant mass from phase space in the $1.8 \text{ BeV}/c^2$ region. The peaking at high invariant mass of the $P\Lambda$ system will be shown to be a result of the $K^+\Lambda$ peaking at $1.8 \text{ BeV}/c^2$.

1. OPEM Predictions

The logical first step in an attempt to fit the data is to compare it to the predictions of the one pion exchange model. The OPEM essentially specifies the cross section on the Chew-Low graph (Figure 23) and is of the form ^{20/}

$$\frac{dg}{d\Delta^2 dW^2} = \frac{1}{8\pi} \cdot \left(\frac{G^2}{4\pi} \right) \cdot \frac{g(W)}{(PE)^2} \cdot F_1(\Delta^2) \cdot F_2(W)$$

where

$$\begin{aligned} G^2/4\pi &= \text{pion-nucleon coupling constant} \\ &= 14.24^+ \end{aligned}$$

$$F_1(\Delta^2) = \Delta^2 / (\Delta^2 + \mu^2)^2$$

$$\Delta = 4\text{-momentum transfer to the proton}$$

$$\mu = \text{exchange pion mass} = 135 \text{ MeV}/c^2$$

⁺ This value obtained by $G^2/4\pi = (4M^2/\mu^2) \cdot f^2$ with $f^2 = .0788 \pm .003$ (Ref. 30)

Figure 22

Dalitz plot of $M(K^+P)$ vs $M(K^+\Lambda)$ for the
 $K^+P\Lambda$ final state

Figure 23

Chew-Low plot for the $K^+\Lambda$ system in the
 $K^+\Lambda$ final state.

Figure 24

Invariant mass distributions and momentum transfer distribution for the K^+pA system. The dotted curves are the 3 body phase space predictions.

$$F_2(W) = \frac{1}{2}(W^4 - 2W^2(M^2 + \mu^2) + (M^2 - \mu^2)^2)^{1/2}$$

W = invariant mass of the $K^+\Lambda$ system

M = proton mass

$\sigma(W)$ = cross section for $\pi^0 p \rightarrow K^+\Lambda$

P = initial center of mass momentum

E = total center of mass energy.

There are several assumptions used in the OPEM calculation. First is that the cross section for a virtual π^0 in the interaction $\pi^0 p \rightarrow K^+\Lambda$ is $1/2$ the measured cross section for a real π^- plus p going to $K^0\Lambda$. The factor $1/2$ comes from isospin considerations. The measured cross section for $\pi^- p \rightarrow K^0\Lambda$ is well determined up to $W = 2.3 \text{ BeV}/c^2$ 28,29/. For this calculation a linear interpolation was made from this point to the point of Bigi et al 12/ at $W = 4.43 \text{ BeV}/c^2$.

The second assumption is that the Feynman diagram in Figure 19, a and the same diagram with P_1 and P_2 interchanged do not interfere, thus permitting the calculation of the total cross section as the sum of the (identical) cross sections of each graph separately. This assumption is experimentally verified by our ability to identify which incident proton is scattered into the outgoing proton. The c.m. forward-backward peaking of the protons in this final state is even more pronounced than that of the 4 body final states shown in Figure 11. If the forward outgoing protons are former beam protons and the backward ones are former target protons this procedure is justified. This is a logical assumption to make.

The OPEM equation above suggests 3 comparisons of the theory to the data. First we can integrate over kinematically allowed values of Δ^2 , leaving us with the OPEM prediction for $d\sigma/dW^2$. (Actually, $d\sigma/dW$ was calculated, using $dW^2 = 2W dW$.)

Next, we can integrate out the dependence of the $K^+\Lambda$

invariant mass, leaving the OEM prediction for $d\sigma/d\Delta^2$. Finally, both these distributions can be integrated again, giving the OEM prediction of the partial cross section for $P + P \rightarrow K^+ \Lambda$.

The author has written a computer code to evaluate the above distributions for arbitrary beam momentum. One of the first observations apparent is the strong dependence of the partial cross section on the choice of Δ^2 cutoff imposed.

The necessity of such a cutoff can be interpreted physically as follows: in assuming that the cross sections from the separate Feynman graphs can be added, we have assumed an ability to identify which incident proton was deflected into the outgoing proton. The separation apparent in the c.m. angular distributions corresponds to an equally apparent separation in the Δ^2 distribution. There are two values of Δ^2 calculated for each event. One corresponds to $\Delta^2(p_1, p_3)$ and the second to $\Delta^2(p_2, p_3)$ (see Figure 19, a). We assume the smaller value to be the physically valid value.

The imposition of a Δ^2 cutoff in the calculation corresponds to taking this experimental separation into account in the theory. Figure 25 shows the experimental Δ^2 distribution and our choice of Δ^2 cutoff of 2.4 (BeV/c)^2 . Only one point lies above this value so it appears to be a reasonable choice.

The experimental $M(K^+ \Lambda)$ distribution and OEM prediction corresponding to this cutoff is shown in Figure 26. Three conclusions can be drawn from these graphs. First, the shape of the theoretical and experimental Δ^2 distributions agree well. Second, the absolute magnitude of the experimental distributions are in quite good agreement with the theory. (Note: both theoretical curve and experimental points are in $\mu\text{b.}$) Finally, there is definite disagreement between the experimental and theoretical $M(K^+ \Lambda)$ distributions. This disagreement will be commented upon again later.

Figure 25

Experimental distribution of Δ^2 to the outgoing proton. Curve is the OPEM prediction for this distribution with the cut in Δ^2 used. Both theory and data are in absolute units; no normalization has been done.

Figure 26

Experimental distribution of $M(K^+\Lambda)$ in units of $\mu\text{b}/\text{BeV}/c^2$ and the prediction of the OPEM in the same units. The calculation was done using a cut in Δ^2 at $2.4 \text{ BeV}^2/c^2$.

The OPEM prediction for the partial cross section for a Δ^2 cutoff of 2.4 (BeV/c)^2 is $76 \text{ } \mu\text{b}$. Our measured value is 54 ± 7 . To see how the theoretical number depends on the choice of cutoff we present Figure 27. It can be seen that a cutoff at about 1.25 (BeV/c)^2 would give σ in agreement with our measurement.

It is also interesting to note another general feature of the partial cross section for $P + P \rightarrow K^+ \Lambda$. Figure 28 shows the measured values reported in the three previous experiments as well as the result of this experiment. Our calculation of the OPEM prediction as a function of beam momentum is also shown. The upper curve is the result of integration over the whole Chew-Low graph (no Δ^2 cutoff) while the lower curve is generated using a cutoff of $\Delta^2 = M^2 = .8803$. Cuts at larger Δ^2 give families of curves lying between these two. This lower value of .8803 was suggested in the original paper for the case of $P(\text{beam}) = 3.66 \text{ BeV/c}$ ^{20/}. However, it should be pointed out that the choice of cutoff should depend on the beam momentum since the distribution of the lower Δ^2 root will get wider for higher $P(\text{beam})$.

Several observations may be made concerning Figure 28. First, there seems to be no energy dependence in the measured cross section for this final state. All 4 measurements give $50 \text{ } \mu\text{b}$ to within their errors. Second, the OPEM with a cut at $\Delta^2 = .88$ reproduces the measurements quite well, at least at lower energies. However, as has been pointed out, more realistic (higher) Δ^2 cuts should be made at higher momenta, and this would result in OPEM predictions somewhat higher than experiment.

We should like to comment on the three previous calculations of the OPEM at 3.66 BeV/c ^{20/}, 4.95 BeV/c ^{3/}, and 5.5 BeV/c ^{2/}. The calculation at 3.66 BeV/c involved using a cross section $\sigma(\pi^- P \rightarrow K^0 \Lambda) = 500 \text{ } \mu\text{b} = \text{constant}$. Actually, this cross section peaks very sharply at $W = 1688 \text{ MeV/c}^2$ with a width of about 80 MeV/c^2 and a height of

Figure 27

Partial cross section for $P + P \rightarrow K^+ pA$
at 7.87 BeV/c as a function of Δ^2 cutoff
in the OPEM.

Figure 28

Measured partial cross section for $P + P \rightarrow K^+ p \Lambda$ as a function of incident beam momentum. Curves are the prediction of the OPEM for two values of Δ^2 cutoff.

CROSS SECTION FOR

 $P + P \rightarrow K^+ p \Delta$

X = REF. 1

□ = REF. 2

○ = REF. 3

Δ = THIS EXP.

CURVES = OPEN

1.00 - 1.10 mb. It is therefore perhaps fortuitous that the range on W was such as to bracket this region in such a way as to cause the above calculation to agree exactly with our calculation using σ as a function of W .

The experiment at 4.95 BeV/c measures a cross section of $48 \pm 4 \mu\text{b}$ and presents an OPEM calculation of $42 \pm 6 \mu\text{b}$. Our calculation of 50 μb seems to be in slightly better agreement with their data.

Finally, the experiment at 5.50 BeV/c measures the cross section to be $42.5 \pm 14.4 \mu\text{b}$ and calculates $101 \pm 15 \mu\text{b}$. Our calculation (using a cut at $.88 (\text{BeV}/c)^2$) is 49 μb . We speculate that the factor of 2 between their calculation and ours may be due to their imposing no Δ^2 cut in their calculation. Our calculation with no Δ^2 cut gives 103 μb which is very close to their prediction.

Further evidence on the applicability of the OPEM to this reaction is shown in Figure 29 in which the decay angular distributions for the $K^+\Lambda$ system are presented. The ϕ distribution, which should be flat if the OPEM applied, appears to be peaked in the $\pm 90^\circ$ regions. If one assumes a smooth background of 6 events in these regions, then there are 15 events in both regions combined above the combined background of 12 events. This is about 3 standard deviations from flatness in this region. A mass cut to examine the events in the region of the peak at $1.8 \text{ BeV}/c^2 M(K^+\Lambda)$ gives the distributions indicated by dotted lines. To test the agreement of the OPEM with the $\cos \theta$ distribution it would be necessary to add the experimental $\pi^- p \rightarrow K^0 \Lambda$ distributions for various values of W , weighted by the number of events at each W . This has not yet been done.

Our conclusions concerning the OPEM are that the predicted Δ^2 distribution and the partial cross section are not inconsistent with the data. However, the predicted $M(K^+\Lambda)$ and ϕ distributions are not in agreement with the data.

Figure 29

Decay angular distributions for the $K^+\Lambda$ system in the $K^+\Lambda$ final state. The dotted data are the result of events in the region of the $M(K^+\Lambda)$ peak at $1.8 \text{ BeV}/c^2$.

2. Other Models

In an attempt to understand more about this final state we have tried several approaches.

One was to assume that the matrix element depended only on the mass of the $K^+\Lambda$ system and to find a function which fit this distribution reasonably well. If one fits the $M(K^+\Lambda)$ data to a resonance curve as described previously, leaving out bins 6, 7, and 8 where $N^*(2190)$ may be contributing, one finds that the parameters $A = .93$, $B = .07$, $M_0 = 1.777$ BeV, and $\Gamma = .345$ give a 9-C chisquare of 2.65. This says that a broad Breit-Wigner shape fits the $K^+\Lambda$ distribution extremely well.

To see if such a distribution in the $K^+\Lambda$ system was responsible for the other mass distributions, a Monte Carlo calculation was done in which it was assumed that the $K^+\Lambda$ was 100 percent Breit-Wigner of $M_0 = 1.777$ and $\Gamma = .345$. Figure 30 shows the results of this calculation. The data are seen to be in fine agreement with the calculation.

The Δ^2 dependence predicted by such a model is a rather square curve obtained from the projection of a slice of the Chew-Low plot at $M(K^+\Lambda) = 1.777$ on the Δ^2 axis. However, a $\Delta^2/(\Delta^2 + \mu^2)^2$ dependence can be inserted in the matrix element. This results in agreement with the Δ^2 distribution without disturbing the agreement with the mass projections.

We would like to point out that this calculation verifies that a model which correctly predicts (and depends only on) the $K^+\Lambda$ invariant mass will automatically give the correct prediction for the other two mass distributions. A second conclusion, reached through several Monte Carlo calculations, is that the Δ^2 dependence observed experimentally is not sufficient to generate the mass distributions observed. In fact, a matrix element depending only on Δ^2 (with the OPEM dependence) predicts invariant mass distributions indistinguishable from phase space.

Figure 30

Resonance model prediction for the $K^+ p \Lambda$ final state in which the $M(K^+ \Lambda)$ distribution is assumed to be a Breit-Wigner with $M_0 = 1.777$ and $\Gamma = .345$. The Δ^2 dependence is that predicted by the OPEM.

A second attempt to interpret the data involved a calculation using the one kaon exchange model (Figure 19,b). In this model, the theoretical dependence on momentum transfer, t_1 , from P_1 to the Λ is used at the lower vertex. At the upper vertex the measured dependence on the 4-momentum transfer, t_2 , to the proton as obtained from K^+P scattering is used. This dependence may be parametrized in the region of interest by an $\exp(-4.0 t_2^2)$ dependence. Although preliminary Monte Carlo calculations are incomplete, the rapid falloff in t_2^2 predicted by this model does not agree well with the observed distribution.

An additional limit on the degree to which the OKEM is applicable to this final state is apparent in Figure 31. If the OKEM were the only mechanism at work, the $K^+P \rightarrow \Lambda$ distribution would be flat. This is seen to be clearly not the case. We therefore conclude that OKE is not present to any considerable extent.

3. Conclusion

Our conclusion concerning the $K^+P \rightarrow \Lambda$ final state is that the kinematics seems to be dominated by a peak in the $K^+\Lambda$ distribution at $1.777 \text{ BeV}/c^2$. This distribution does not appear to agree with the OPEM as other authors have found.^{3/} The decay angle θ of the Λ in the $K^+\Lambda$ system likewise does not seem consistent with OPE as the only mechanism at work. The 4-momentum transfer to the proton and the value of the partial cross section, on the other hand, seem to agree fairly well with the OPEM. Further analysis and better statistics will hopefully clear up these discrepancies.

Figure 31

Decay angular distribution of the P in
the K^+P system of K^+PA events.

DECAY DISTRIBUTION FOR $\bar{p}$ IN

$K^+ \bar{p}$ SYSTEM IN $K^+ \bar{p} \Delta$

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APPENDICES

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NOTE ON APPENDICES

It should be pointed out that the "Camera Constants" section of Appendix A and Appendices B, C, and D in their entirety are as nearly reproductions of the original communications as was feasible. While this practice increases the bulk of the Appendices and sometimes results in redundancy, it was felt to be desirable for the following reasons.

In modern, high energy experiments it is quite easy to lose track of the complex analysis procedures which go into producing identified events, once these events become available. Summaries of such procedures may conceal fine points in analysis or basic errors which may significantly effect the results and their interpretation. Presenting actual instructions used at the scanning, measuring, and analysis stages of the experiment should clarify such fine points and facilitate detection of basic biases.

Secondly, it is a matter of personal satisfaction to the author to preserve this record of "How one experiment was done". It is felt that such Appendices may provide useful references in the future for both the author and, hopefully, other graduate students.

APPENDIX A: EXPERIMENTAL CONSTANTS

1. Camera Constants

The camera constants necessary for spatial reconstruction of the measured bubble chamber tracks are provided in the Brookhaven "Provisional Optical Constants" presented below. Some of the numbers required by EUCLID are read directly off this memo and others are obtained from the memo numbers by the transformation program, CHAMBER.

2. Magnetic Field Fit

Professor G. Ascoli has fit the magnetic field of the 80" bubble chamber with a series of spherical harmonics. Using measurements provided by B. B. Culwick* of Brookhaven, he obtained excellent agreement to the measured field points using only even m and $L_{\max} = 10$. The r.m.s. deviation between the fitted and measured field values are 66 gauss in B_x , 56 gauss in B_y , and 24 gauss in B_z for the 1377 points fitted. A test was performed on the absolute magnitude of the field using the dependence on the field of the calculated masses in neutral V decay. Using 32 K^0 's and 136 Λ 's, no error in the nominal field value was detected.

* For the results of an independent fit see B. B. Culwick, 80" Bubble Chamber Provisional Magnetic Field Fit, Bubble Chamber Report 05-2-G, Brookhaven Nat. Lab. (1964)

BROOKHAVEN NATIONAL LABORATORY

BY HOC & BLH DATE 7/9/64 SUBJECT Provisional Optical Constants SHEET No. 1 OF 3
 CHKD. BY DATE For New Window "A" JOB No.
 DEPT. OR PROJECT BQ' Bubble Chamber BG = 01 - 2 - C

NOTES: Window installed March 1964
 Dim'ns are tentative

COORDINATES

<u>Fiducial No</u>	<u>"X"</u>	<u>"Y"</u>	<u>Corrected for Temp. Deg. K</u>
1	0.000cm	0.000cm	27
2	7.551	37.997	"
3	37.954	0.000	"
4	63.295	37.932	"
5	88.725	0.038	"
6	119.099	37.996	"
7	126.357	0.072	"

Camera Lens No

1	31.429cm	50.745cm	none
2	94.929	50.745	"
3	94.929	-12.755	"
4	31.429	-12.755	"

"Z" Dimension (at $N_D = 1.0$)

2 (Back Fiducial)	64.318cm	(~ Behind Lens #2	27
4 (" ")	64.208	(~ " " #4	27

See Sheet 2 for Sketch

BROOKHAVEN NATIONAL LABORATORY
 BY H.O. Courtney DATE 6/25/64 SUBJECT Fiducial Coordinates
Window "A"
 CHKD. BY _____ DATE _____ DEPT. OR PROJECT 80" Bubble Chamber

SHEET NO. 2 OF 3
 JOB NO. _____

BROOKHAVEN NATIONAL LABORATORY

BY.....DATE..... SUBJECT..... SHEET No. 3 OF 3
 CHKD. BY.....DATE..... JOB No.....
 DEPT. OR PROJECT.....

Dist. from Fiducial Plane to Front Principle Plane of Lens:

$$L_o \quad 77 \frac{21}{32}'' \text{ "Optical"} \quad 77.6563 \times 2.54 = 197.247 \text{ cm.}$$

$$L_p \quad 81 \frac{11}{32}'' \text{ "Physical"} \quad 81.3437 \times 2.54 = 206.613 \text{ cm}$$

$$\text{where } L_o = L_p - (L_g - L_g/n_g)$$

$$L_g = 10.75'' \text{ Total Glass thickness} \times 2.54 = 27.305 \text{ cm.}$$

$$n_g = 1.5223$$

Dist. from film plane to back principle plane of lens

View # 1	16.452 cm
2	16.475
3	16.455
4	16.672 (not normally used)

Lenses on $25 \pm .001''$ Square

TO TRANSFORM TO FOL/MAG. FIELD COORD
 TRANSFORM WINDOW FID ORIGIN TO CENTER OF
 CAMERA SQUARE.

3. Density and Index of Refraction of Hydrogen

The density of hydrogen in the bubble chamber was determined by two independent methods.

First, the range of μ^+ mesons from the decay of π^+ mesons was measured. Using the relationship

$$\rho \text{ (mg/cm}^3\text{)} = \frac{(65.0 \pm .3) \text{ mg/cm}^2}{\langle L \rangle} *$$

the density can be determined directly in terms of the average length of μ^+ track, $\langle L \rangle$. Only μ 's which had a dip angle $< 45^\circ$ and measured length $.85 \text{ cm} < L < 1.15 \text{ cm}$ were used. Each μ was measured in each of 3 possible camera pairs. The result of 150 measurements on 51 μ 's was the following:

$$\langle L \rangle = (1.019 \pm .005) \text{ cm}$$

$$\delta L_{\text{rms}} = .058 \text{ cm}$$

Correcting this length by a factor 1.0031 to take into account the curvature of the μ gives a corrected $\langle L \rangle$ of $(1.022 \pm .005) \text{ cm}$ and a density

$$\rho = (63.58 \pm .43) \text{ mg/cm}^3.$$

The second method used to determine the density was to calculate it from the recorded chamber pressure and temperature. This calculation was performed by Professor Sard and resulted in the value for the density ranging from 62.5 mg/cm^3 to 63.1 mg/cm^3 with a mean of

$$\rho = 62.9 \text{ mg/cm}^3.$$

The agreement of these two independent methods to within 1 percent is considered satisfactory.

* This numerical value was provided by Professor R. D. Sard, Private Communication.

Using the range of density noted above, Professor Sard calculated the corresponding indices of refraction to be 1.0996 and 1.101 with a weighted mean of 1.100. This is the value used in the bulk of the experiment.

4. Beam Momentum Determination

The momentum of the beam at the center of the chamber was determined as follows. Events which had been fit as $K^+p\Lambda$, $\pi^+p\pi^-$, and elastic PP scattering were refit, using only the measured value of the beam (normally the beam was weighted by a nominal value). Only those events were used which had fit beam momentum error $\delta k/k < 1$ percent and with $7.7 \text{ BeV/c} < p_{\text{fit}} < 8.0 \text{ BeV/c}$. The fit momentum was corrected for energy loss to the $X = 0$ position in the chamber. The weighted average for the 105 events used was

$$p(X=0) = (7.873 \pm .007) \text{ BeV/c}$$

$$\delta p_{\text{rms}} = 68.8 \text{ MeV}$$

The average of each of the above final states taken separately agreed with the overall average to within 3 MeV. This gives us confidence that the method used is relatively free of bias.

APPENDIX B: SCANNING DICTIONARY--EXP. 03

I. Events of interest

1. Events are 2,4,6, and 8 prong interactions with associated open V's and kinks.
2. Such events may occur anywhere in the chamber.
3. Six, eight, and higher prong interactions with NO associated open V or kink are not events and are listed only on the SCANNING FORM under PRONGS. Simple two and four prong interactions are not listed at all.
4. V's are associated with a certain origin only if they point to it. See Definition 9 for details.
5. Secondary interactions such as a two prong on some track of a two prong plus V event are indicated by means of an appropriate EVENT FLAG.

II. Recording events

1. Photograph all events according to the procedure outlined under Rules for Prints.
2. List each frame number on the SCANNING FORM regardless of whether or not it contains an event.
3. For events, list the number of prongs under PRONGS, and enter a check in the appropriate V or KINK column.
4. Six and higher prong interactions which are not events should be recorded only on the SCANNING FORM.

III. Flags

The only flags used in Exp. 03 are EVENT FLAGS (E.F.).
Event flags are two digit numbers and are defined as follows:

<u>E.F. No.</u>	<u>Description</u>
01	A closed V points to the beam track interaction.
02	A closed V points to an interaction or kink on secondary track.
03	An e^+e^- pair (looks like a closed V) occurs at the beam track interaction.
04	A 3-prong V points to the beam track interaction.
05	There are 2 or more identical event types in this region of this frame.
12	Track 2 has a $\mu^+ \rightarrow e^+$ decay.
13	Track 3 has a $\mu^+ \rightarrow e^+$ decay.
**	
19	Track 9 has a $\mu^+ \rightarrow e^+$ decay.
10	Track 10 has a $\mu^+ \rightarrow e^+$ decay.
22	Track 2 has an additional kink not covered in the E.T.
23	Track 3 has an additional kink not covered in the E.T.
**	
29	Track 9 has an additional kink not covered in the E.T.
20	Track 10 has an additional kink not covered in the E.T.
32	A secondary interaction (2,3,4, etc. prong) occurs on track 2.
**	
30	A secondary interaction (2,3,4, etc. prong) occurs on track 10.

IV. Rules for Prints

1. No track numbering or view pair labeling necessary.
2. Use arrows to indicate all interaction points, e.g., initial beam interaction, kinks, vertices of V's, secondary interactions, and stopping points.
3. Do not use dotted lines for neutrals.
4. In the lower right hand corner of the print place the following information:

Your initials

Date

Roll No.

Frame No.

Event Type

View

(E.F. if any)

For Example

M.F.

7/23/64

Roll 18

644872

E.T. 21

V. 2

E.F. 32

5. Events for which there are more than one interpretation (e.g., a V with 2 possible origins*) should be put on one picture as far as possible. Label the arrow to the nearest interaction to read

INT. 1

etc.

and if the event types involved are different,

E.T.₁ = 25

E.T.₂ = 45

etc.

*To be considered an alternate origin, the second interaction must be within 12 inches of the V.

6. The bubble chamber may conveniently be divided into 5 regions by use of the fiducials located along the left hand side of the picture. Label the arrows which point to the interactions with the region number in which the interaction occurs in View 1.

V. Changes from previous experiments

1. All prongs occur in the even numbers and there are always 2 more positive prongs than negative prongs. Thus there are no 0 prong beam track interactions.
2. If an apparent odd number of prongs occurs on a beam track interaction, examine the vertex closely for a short prong or an overlapping V.
3. "Closed V's" need overlap only .5 cm to qualify as closed (in all three views, as usual).
4. No track numbering or view labeling is necessary.
5. Only three cameras numbered 1, 2, and 3 were used, so there is no question of missing camera numbers (M.C. No.). Load all three rolls.
6. There are no spectator protons in Exp. 03. So, for example, all simple 4 prong interactions are still just 4 prongs, NOT event types.
7. The incident particles are protons instead of pi mesons and are much higher momentum (8 BeV/c instead of 2.5 BeV/c). So to detect small angle kinks, great care must be used in sighting along the prongs.

Definitions (Exp. 03)

1. Beam tracks--The nearly parallel, light ionization, high radius of curvature tracks in a bubble chamber. (See 4 beam tracks in Fig. 1 labeled a.) The Exp. 03 beam tracks are protons.
2. Non-beam tracks--Single tracks which are usually not parallel to the beam tracks and often darker ionization and smaller radius of curvature than beam tracks. (See 1 non-beam track, labeled b in Fig. 1.)

a) Beam tracks

b) Non-beam track

Fig. 1

3. Knock-on protons--Dark ionization tracks which seem to start in free space in the chamber and are often short. They are positively charged particles; that is, they curve to the right in Exp. 03. (See 2 knock-on protons, labeled a, in Fig. 2).
4. Electrons--Very light ionization particles which usually have a small radius of curvature and spiral down into very small circles. They are frequently produced when other tracks hit atoms and are also called delta-rays. (See a high-momentum (large radius) and low-momentum electrons, labeled b, in Fig. 2).

Fig. 2

- a) Knock-on protons
- b) Electrons (delta-rays)

5. Ionization--The number of bubbles per unit length on a track. Fast particles like electrons have a very low number of bubbles per cm and are called minimum ionization particles. Beam tracks also have minimum ionization. Slower particles have more bubbles per cm and hence appear darker. Very slow particles like knock-on protons have a high bubble density and hence appear as a solid dark line.

6. Prongs--When particles interact with the protons in the bubble chamber, new particles are created. The charged particles created fly out from the point of interaction and appear as tracks which we call PRONGS. In this experiment an even number of prongs are made by beam track interactions and there are always two more positive prongs than negative prongs. (See the 2 prong, a, and the 4 prong, b, interaction in Fig. 3.) Prongs can appear in any configuration.

Fig. 3

- a) 2 prong interaction
- b) 4 prong interaction

7. Open V--An open V is the decay of a neutral particle into a positive and a negative particle. These particles usually make an angle of between 3° and 90° with each other. They appear to start in free space in the chamber. (See the 2 open V's labeled a in Fig. 4.)

8. Closed V--A closed V is similar to an open V except that the opening angle between the positive and negative particles is so small that they appear to overlap .5 cm or more. Closed V's are usually electron pairs and so have minimum ionization. (See the closed V labeled b in Fig. 4.)

a) Open V's

b) Closed V

Fig. 4

9. Associated V--all V's are produced in interactions. Usually the interaction point is in the chamber and can be identified as a 2,4,6, etc. prong interaction. If the line of flight between the interaction vertex and the vertex of the V lies within the prongs of the V when extended through the vertex of the V, the V is ASSOCIATED with that interaction. If the line of flight lies outside the prongs of the V, the V is not associated with that interaction. (See Fig. 5. The V labeled a is associated with the 2 prong shown while that labeled b is not associated with the 2 prong.)

Fig. 5

a) Associated V

b) V not associated

10. Kinks--A kink is the decay of a charged particle into another charged particle. It appears as a distinct change in the direction of a charged track. Usually there is a change in ionization apparent between the incoming track and the outgoing track. The incoming track becomes gradually darker in ionization till it may become solid at the point of the kink. The outgoing track is quite light in ionization. There often is a difference in curvature between the incoming and outgoing track of the kink also. A kink in one prong of a two prong is illustrated below in Fig. 6. Kinks on Exp. 03 often are very small angles.

Fig. 6

A kink in a two
prong

11. Radius of curvature--The path of most particles in the bubble chamber is very nearly a circle or the arc of a circle. The electron is an exception because its path is clearly a spiral. Particles which go nearly straight like beam particles have a large radius of curvature and large momentum. Particles with small momentum have a small radius

of curvature and sometimes turn nearly a complete circle in the bubble chamber.

VI. Event Type Numbering

For Event Types 21-90 the Event Type number (E.T.#) is given very simply by the equation:

$$\text{E.T.}\# = 10 \times \text{NP} + 5 \times \text{NV} + 1 \times \text{Npos} + 3 \times \text{Nneg}$$

where

NP = number of prongs

NV = number of open V's

Npos = number of positive kinks

Nneg = number of negative kinks

and $\text{Npos} + \text{Nneg} \leq 2$

≤ 8
 ≤ 3
 ≤ 2
 ≤ 1

Sketches of Event Types

23

24

28

29

33

34

38

39

40

Event types 71-90 follow the above system.

Irregular Event Types

01

02

03

04

05

Determination of Stopping Tracks

Definition of Fiducial Marks:

There is a top glass window on the bubble chamber. On this window are etched markings called "fiducial marks". These marks can be seen on the film in all cameras. The shape and relative positions of these marks are shown below.

Stopping prongs

Positive prongs occurring on events (reactions which have a special event number) and do not fade out of sight on the edges of the camera's field of view and do not end with a kink or secondary event must be tested for stopping.

There is a simple test for determining whether an abruptly ending prong has hit either the top or bottom of the chamber. Should this test show that the particle has not hit either the top or bottom, then it must have stopped within the chamber.

If the track leaves via the top, the end of the track will be exactly the same distance on all three views from any one top fiducial. If it is not equidistant in all 3 views, it does not leave through the top window. Similarly one may test to see whether the particle has left through the bottom of the chamber. If it does not leave through either top or bottom, or fade out at the edge, it is a stopping track and should be labeled as such. However, no negative track should ever be labeled "stopping". Tracks leading to a $\pi^+\mu^+e^+$ (E.T. 04 and sometimes E.F. 12-20) stop if and only if the μ^+ (second track) is only about one-half inch long.

Memo To Scanners of Experiment 03 Concerning E.T. 21:

ON TWO PRONGS WITH ONE VERY DARK PRONG THAT KINKS, PLEASE APPLY THE FOLLOWING CRITERIA:

If track 3 is more than 4 inches long and heavily ionizing, do not call it a 21 unless there is a distinct change in ionization at the kink. In all such cases, track 3 will make a greater angle with the beam track than track 2.

If track 3 is less than 4 inches, even if track 4 is dark also, it is to be treated as an event.

Not a 21.

Record as PP21 in
"comments" column.

Record as a valid
21.

Note: This applies only to tracks which are very dark.

Memo Concerning Positive Kinks in Exp. 03:

This memo includes the criteria of the E.T. 21 memo and extends them to all positive kinks. It also includes additional, more restrictive, criteria.

From now on, for an interaction to qualify as a positive kink, it must meet the following criteria: (See Fig.)

1. If track b is a lightly ionizing track, it is always a good positive kink.

2. If both a and b are heavily ionizing (dark) tracks, they must satisfy the following criteria:

a) Track a must be shorter than 4 inches in all three views.

b) Track b must be longer than 1 inch in at least one view if b stops in the chamber.

c) Track b must be longer than track a in at least one view.

If the criteria 2) a, b and c are satisfied, the interaction is called a positive kink. Otherwise, it is nothing and no event can be based on it alone.

M.F. 12-11-64

APPENDIX C: MEASURING INSTRUCTIONS FOR BROOKHAVEN

80" FILM ON HERMES AND NRI

These instructions are for the measuring of film from the third U. of I. experiment run at the Brookhaven National Laboratory (BNL). There are some 35,000 pictures of the Brookhaven 80" X 25" X 25" hydrogen bubble chamber as exposed to a beam of 8 BeV/c protons from the Alternating Gradient Synchrotron. There are approximately 42 rolls of the 70 mm film.

To obtain the photographs, three cameras were positioned in a square some seven feet in front of the chamber. A light source between the cameras flashed simultaneously with the beam pulse, causing the trails of bubbles left by charged particles passing through the liquid hydrogen to be recorded as black lines on the film.

The measurer's job is to make precise measurements of the fiducial positions and points on the bubble tracks. He must use the proper words and measure the tracks in the proper sequence so the computer can process the data. The photographic print, commonly called the "picture", is designed to aid the measurer in accomplishing this. There is, however, no guarantee that the picture will always be entirely correct, so it is essential that the measurer be a good scanner as well.

Machine Description

Two machines are currently being used to measure BNL film: the Hermes and the NRI. There is a considerable difference between the two machines as far as the type of controls, their position, and the manner in which the film is loaded is concerned.

The three rolls of film are projected onto the screen singly on the Hermes and either singly or multiply on the NRI. Controls on the console allow the operator to move the stage to which the film is attached, resulting in a change of position of the projection. The reticle, a projected crosshair, remains stationary at the center of the screen. A change in the position of the stage causes the x-axis and y-axis encoders to output a different set of co-ordinates, which are punched onto cards by the IBM card punch when the DATA RECORD button is pushed.

Measuring

When starting a shift, perform an encoder check if it has been requested. If the film is not already loaded, load film in accordance with the instructions given in a later section. If it is loaded correctly, measuring may begin. Turn on the projection lamps and vacuum pumps.

1. Load cards in the card punch to insure an adequate supply for your shift (three to four inches). If no cards can be found in the measuring room, there are more in the west closet in room 436A and in closet 4C16 in the hall.
2. If EVENT button is lit, push EVENT button and then END button to clear the card counter. If event button is not lit, just push END button (EVENT button should light up-- if it doesn't, try pushing it, the bulb may be burned out).
3. Obtain the frame number from the picture and advance the film to that frame in all three views. Center them in the field of view so that the whole chamber is visible in all three views. The view number lies between the correct frame and its frame number. After centering, flip the "film clamp" switch down (light out) on the NRI; there is no such switch on the Hermes.

4. Each machine has a panel with seven sets of ten data switches. For reference in the following paragraphs they will be numbered as follows:

The switches of rows 1L, 2L, and 3L should be set up as follows:

	1	2	3	4	5	6	7	8	9	10
<u>Row</u>										
1L	4	0	3	← Meas# →	← Month →	← Day →	← Year			
2L	3	1	0	0	0	0	0	← Roll No. →		
3L	2	Int	← Frame No. →				← Rem		Event Type	

5. The switches of rows 1R, 2R, and 3R as follows:

	1	2	3	4	5	6	7	8	9	10
<u>Row</u>										
1R	5	Region	← E.F. →	← E.F. →	← E.F. →	← E.F. →				
2R	6	0	0	0	0	0	0	0	0	0
3R	7	0	0	0	0	0	0	0	0	0

6. Push EVENT button to enter the data sets 1L, 2L, and 3L on the first card. Pushing this button always enters the contents of rows 1L, 2L, and 3L of the data board in columns 11-40 of the card. The first ten columns are taken up by a history word consisting of a machine identification character in column 1 (an H or N), interpretation number in column 2, frame number in columns 3-7 and a card count number in columns 9-10.

7. After waiting for the card punch to complete the punching of the event data, push the FLAG button. It is important that the punching of the event data be completed before pushing FLAG. This causes a new card to be started with a history word in columns 1-10 and the contents of rows 1R, 2R, and 3R of the data board in columns 11-40.

8. Measure the position of the fiducials in the following order: Fiducial A in view 1, then view 2, then 3; followed by fiducial D in view 1, then view 2, then 3, then F in view 1, then view 2, then 3. See figure below for the identification of A, D, and F.

The measurement is made by setting the center of the reticle on the crossing point of the fiducial lines and then punching DATA RECORD or depressing the foot switch. It is very important that these fiducial measurements be made with the greatest possible precision, as the fiducial readings are basic to the analysis of the event since they provide reference points for reconstruction of the event. The instructions in a following section for the operation of each machine will tell how to obtain the most accurate possible measurement.

The first four of the six fiducial measurements appear in columns 41 through 80 of the second card, and the last two appear in columns 11 through 30 of the next (third) card. When the sixth fiducial measurement is recorded, the track button should light up.

9. Set up the fourth (bottom) row of the data board as

shown below. This row is always used for the track word. The first digit is always 1, and need never be changed. On the punched card, the view number (1, 2, or 3) will appear in the second position of the track word. The M.C. switch (position 3) should always be set to 4. The remaining seven switches are to be set as shown:

	1	2	3	4	5	6	7	8	9	10
Fourth Row	1	x	4	←Track →				LSN		ION
4L										

The settings for the switches are determined as follows:

4 and 5 Track number (= 01 for first track) as per scanning dictionary.

6 and 7 = 00

8 LSN = 0, except

 = 1, if track is (or should be marked STOP on picture.

 = 2, for neutral tracks (invisible track from origin to V)

9 = 0

10 ION if indicated on the picture. Neutral tracks-ionization zero. Visible tracks have ionization between A and F. (Ionization 0 on all tracks if none is indicated)

10. Set "illumination" switch (NRI) or "view" switch (Hermes) to the first view number indicated in the section on "View Pairs". Then push the TRACK button. Pushing the TRACK button always releases the card and prints the contents of the fourth row of the data board (track word) in columns 11 through 20 (the view number appears in column 12).

11. Measure co-ordinates of points on track 1, first view (always the lower of the two view numbers to be used). Do

this by setting the center of the reticle on the center of the track and then punching DATA RECORD or the foot switch. Always move in the direction the particle is going, thus downstream (right to left) for track 1. Never punch in the same point twice. Don't skip back and forth. The number of points to be measured and their locations is discussed in the section on track measuring.

12. Now switch to the second view for track 1, push TRACK and measure the co-ordinates for that track in the view.

13. Next go to the second track of the event (02), and repeat steps 11 and 12 with appropriate changes in track word and illumination or view switch settings. Remember to push the TRACK button every time that you switch views or start measuring another track.

14. When finished with all the numbered tracks, push the END button and fill out the appropriate 4 columns on the back of the picture. Continue from step 3 with the next event.

15. At the end of a measuring session, complete step 14 for the event just measured, advance the last card into the hopper (by pushing SPACE on the Hermes or REL (release) on the keyboard of the card punch), and transfer your deck of cards to the box marked either BNL-Hermes Exp. 03 or BNL-NRI Exp. 03. Do not leave in blank cards. Do not turn off the measuring machine or card punch unless it is out of order. Do turn off the projection lamps and turn off or unplug the vacuum pump. Fill in the schedule sheet on the bulletin board behind the machine.

Track Measuring

Selection of View Pairs

As mentioned before, the three cameras are located at

the corner of a square. When viewed on the measuring machines, their position is:

For the computer to be able to reconstruct the tracks, the proper cameras must be chosen. The criterion is that at no point may the track be parallel to the stereo axis. A line drawn between the two cameras being used will give you the stereo axis. Always choose the pair of cameras most nearly perpendicular to the track. On tracks that curve greatly, remember that no part of the track (beginning, middle or end) may be parallel to the stereo axis. On such tracks it may be necessary not to measure the entire length of the track. Just measure points to where the track comes within about 30° of the stereo axis, then go on to the next view.

Selection of Data Points

When measuring points, always move in the direction that the track particle is going, thus downstream (right to left) for Track 1. Never punch the same point twice. Don't skip back and forth.

On Track 1 choose the first point where the track becomes clearly visible. The last point of Track 1 and the first point of all tracks radiating from this vertex should be as close as possible to the vertex. Do not try to measure the vertex, except for neutral tracks. Measure the first bubble that is clearly visible on the desired track.

If, as is often the case, the track has no bubbles within 5 mm of the vertex, measure the first bubble on the track. The computer can project the track for short

distances. This method of selection of beginning and ending points for tracks should also be used in the case of V's, kinks, and secondary interactions.

The number of points to be measured on charged tracks is more or less arbitrary within the following limits. There must be at least three points and not more than twenty points, (with one exception specified below). Of course if the track is partly obscured in a portion of its path, that region may be skipped unless you can choose bubbles that are clearly on the proper track. If the track is longer than about three inches on the screen, measure between 5 and 10 points. For shorter tracks, 3 or 4 points may be used. The more a track curves, however, the more points should be measured.

The exception mentioned is this: on neutral tracks (from vertex to V) or on short stopping tracks (less than about one centimeter on the screen) it is permissible to measure only two points. In this case the two points must be the beginning and end points of the track in both views (i.e. vertex and vertex, or vertex and end of track). Stereo axis considerations do not apply when only two points are to be measured. Choose which ever views provide the clearest picture of the event. It is illegal to measure two points in one view and more than two in the other.

If a stopping track is .5 centimeters or longer, 6 points must be measured or the event will reject. If the track is less than 1 centimeter and no curvature is visible, measure only the beginning and end in the two views.

Numbering Conventions

Interpretation: This is used only when there is a V with two or more possible origins. The V should be measured with each possible origin using the proper E.T. for that possible origin. The different interpretations should be labelled 1, 2, 3, etc., and Int. 1, 2, etc. noted on the picture.

Int. 0 is used only when there is only one possible origin; it is not to be used for any interpretation if there is more than one interpretation.

Unmeasurable Events

Occasionally, the measurer will encounter events that cannot be measured. Common reasons are invisibility of some tracks on the entire event in one or more views. Sometimes the proper view or portion of it containing a fiducial may be missing from the film due to an error in splicing.

If there has been a splicing error, and that view is not required to measure the tracks, the event may still be measured. To obtain fiducial points for the missing view, just punch in a dummy data point at the appropriate time. If the event cannot be measured without the absent view, proceed as below.

If a track cannot be measured in the proper view pairs, it may be possible to use another pair, remembering to apply the stereo axis considerations. Remember that the track must be measured in two views. If the orientation of the track with respect to the stereo axis prevents this, or if for some other reason you have decided that the event cannot be measured, you may reject the event.

Fill in the usual information on the back of the picture and write REJECT and give a reason. If a track is not visible in some camera, say "not visible in camera 3".

If a picture is found to be scanned or labeled incorrectly please change the mistakes on the pictures to agree with the way you have measured the event.

Error Correction

It may happen that you may make errors of various sorts: punching the wrong button at the wrong time, setting the

data board wrong, etc. Several correction techniques may be used.

The most simple is to push the ERROR button (# 9 on the NRI) and start the whole event over again. This is most easily used if only the fiducials have been measured. Otherwise, it can be very time consuming.

If an error is made after this point and noticed at the time it occurs, the easiest thing to do is to push TRACK again and remeasure the track. Be sure to pull out the bad card as it comes through. Do not leave it in the output.

The most versatile correction technique involves the use of the card punch keyboard and can be used at any time. First push the toggle switch that says "AUTO-SKIP" down and push down on the right side of the blue lever switch above the center areas where the card is visible. Now, remove cards from the visible area by alternately pushing "REL" and "REG" (for release and register). Put the bad card in the right space so that it lies flat. Register the card (i.e. push "REG"). Now duplicate (push "DUP") the good portion of the card. The cards have the column number printed on them and the rotating drum has numbers to indicate how far the card has gone. Now type in the correction (holding down the "NUM" button) or, if the situation is such, reset the toggle switch plus the blue switch and continue measuring. (It may be necessary to push "FEED" after the rest of the card has been punched).

Jamming of the card punch keyboard can usually be corrected by pushing the release button or the backspace control, which is below the center card area.

Encoder Check Rules

1. Load the 35 mm straight line photograph on your machine in any view.

2. Type an I.D. card according to the following format:
*(1st column), your initials, machine, data, short comment if needed. Release the card. Example: *MTP HYDEL 1 3/24/64
AFTER CLEANING ENCODERS.
3. Type a "(1st column) DIAGONAL" card and release. (If only the diagonal track is being measured the word "diagonal" may be written as a comment on the I.D. card).
4. On the Hydel#1, punch the measurer word.
5. On all machines push the event button with the event word switches set in the normal manner.
6. Measure 100 to 200 points along the track then push the end button.
7. If you have been asked to measure the vertical or horizontal tracks, repeat steps 3, 4, 5, 6, making the appropriate changes.
8. Write your name, the date and the machine on the first card, place a rubber band around the deck and place it in the ENCODER CHECK slot in the mailbox.
9. Comments may be placed in the deck if desired by placing an asterisk in the first column of a card and typing the comment on that card.

APPENDIX D: EXP. 03 EVENT ANALYSIS SYSTEM

1. Check frame number, event type, interpretation number on picture, film and output.
2. Follow all tracks on film to their end, checking for kinks, 3-prong decays (K mesons), and scatters. Examine the event in both view 1 and 3.
3. Identify each track using measured values of momentum, ϕ begin, and $\tan(\lambda)$. Remember, short tracks (like kinks) have poorly determined momentum and hence poorly determined ionization calculation. Check kinematics for the size of error when in doubt.
4. Estimate the ionization for each charged track and enter it just above the (ionization from measured data) columns.
5. Using estimates, cross out impossible track interpretations (by an x), check the positively identified interpretations, and when several are allowed, bracket them. When one is more probable than another, number your choices 1, 2.
6. Using the track-wise ionization identifications, sort through the ionization summary of the fits, eliminating as many fits as possible.
7. When the eliminating is finished, check the remaining fits against their chi-squares.

Rules For Chi-Square Selection

1. All fits with 1-C chi-square less than 10.0 and 3-C and 4-C chi-square less than 20.0 are candidates for consideration as final fits.
2. If there is more than one candidate for the final fit, look up the probabilities corresponding to the chi-squares in question. Then use the following criteria in making your choice:
 - A. For two good 1-C fits, if $P(J)$ is greater than $3.0 \times P(I)$ choose J as the final fit. Otherwise place event in 2-fold ambiguous category and assign the proper fit number.
 - B. For three or more good 1-C fits, if $P(J)$ is the probability corresponding to the lowest chi-square and $P(I)$ are the probabilities of the others, choose J if $P(J)$ is greater than $3.0 \times P(I)$. Otherwise place in ambiguous category.
 - C. Apply criteria A and B for two or more 4-C fits.
 - D. With mixed 1-C and 4-C fits, weight the 4-C fits twice as heavily as the probability curve indicates and proceed as in A and B.
 - E. For Σ^0 fits, add the chi-square from the 1-C vertex fit to the chi-square from the Σ^0 decay fit to get a 2-C chi-square. Use the 2-C probability curve to get its probability.

Additional Information

1. When the flight path of V's is very short (less than 2 cm), the measured angles are often in error enough to give artificially high chi-squares on the 2-C and 3-C V fits. Do not worry about such events unless the 3-C chi-square is greater than 20.0.
2. When a V fits both as a K^0 and a lambda, check the $\cos(+)_\text{cm}$ of the positive prong of the decay fit. If it is greater than +0.86, choose the lambda decay as the correct fit. (True lambdas will often give good K^0 fits with $\cos(+)_\text{cm} = +0.87$).
3. Remember, Σ and cascade hyperons have short half lives (about 10^{-10} sec) and so go only about 3 cm (times G). G can be estimated by dividing P (momentum) by mass. E.g. for a 3 BEV/c Σ , $G=3.0$ ($3.0/1.1189$)
4. Enter appropriate words, fit number, date and your initials on both the picture and the output.

(This completes the analysis instructions as compiled by MWF on 7/11/65)

Event Card Handling Instructions

9th Edition

The following instructions are to be updated, and the corresponding date-care entered as per below. These instructions are valid up to--
9/11/65 by M. Firebaugh.

Information will be entered on the scan cards, hereafter called event cards, as follows:

Column	Entry
53-54	Lowest word
55-56	Next lowest word
57-58	Etc.
Etc.	
75-76	Highest possible word
77-79	Fit number (for words 83 and 84)

Word List-Rejects (No. 11-40)

Number	Definition
11	No event--really pp E.T., not E.T. (kink is pp)
12	Kink is really π -mu decay or π scatter
13	No event--track 1 is not a beam track
14	No event--V not associated with correct vertex.
15	No event--V really an electron pair (closed V)
16	No event--V not valid, i.e., V is 2 prong, etc.
17	No event--V associated with secondary vertex
18	No event--imaginary kink
19	No event--kink occurs at top or bottom of chamber
20	No event--kink is a scatter
21	Cannot meas--event cannot be seen
22	Cannot meas--kink not visible
23	Cannot meas--flare blocks event

24	Cannot meas--beam track confused
25	Cannot meas--film multiply exposed
26	Cannot meas--event too faint
27	Cannot meas--some tracks not visible in correct stereo views
28	Cannot meas--too near edge
29	Cannot meas--too near end
30	Cannot meas--too many tracks are too short
31	Cannot meas--kink angle too small
32	Cannot meas--necessary views not available
33	Cannot meas--spliced
34	Cannot meas--late event
35	
36	
37	
38	No event--V associated with neutral beam interaction
39	No event--invalid E.T.
40	

Word List--Additional Information (No. 41-50)

Number	Definition
41	Event flag in position 1 added at this stage
42	Event flag in position 2 added at this stage
43	Event flag in position 3 added at this stage
44	Event flag in position 4 added at this stage
45	Duplicate cards
46	Primary vertex outside fid. vol. (-80cm to +70cm)
47	
48	
49	
50	This event would make a good slide

Word List--Conclusion (No. 51-60)

Number	Definition
51	This 1-C fit OK but there may be N π^0 's associated in addition
52	This class B event looks valid
53	There is more than one independent measurement on tape for this event
54	
55	
56	
57	
58	
59	Black flag (Looks good, not measured OK, count in cross-section)
60	Green flag

Word List--Changes (No. 61-70)

Number	Definition
61	Event flag 1 changed to present value
62	Event flag 2 changed to present value
63	Event flag 3 changed to present value
64	Event flag 4 changed to present value
65	Frame number changed to present value
66	Event type changed to present value
67	Interpretation number changed to present value
68	Region number changed to present value
69	Fit number has been changed
70	

Word List--Conclusion (No. 71-99)

Number	Definition
71	V is a K^0 associated with this vertex
72	V is a lambda associated with this vertex
73	V fits this vertex and is either a K^0 or lambda
74	See recoil proton at proper angle
75	Kink is from a K meson
76	Kink is from a Σ hyperon
77	Kink is from a K or Σ
78	See tau decay of K prong
79	No fit agreeing with ion estimate exists
80	Ambiguous
81	Event properly scanned, event card correct, and event should be measured
82	Scan, card, and measurement all A-OK
83	Same as 82 plus event fitted uniquely
84	Same as 82 plus fitted down to two ambiguities
85	Same as 82 plus event partially fitted (i.e. some tracks identified)
86	Same as 82, event completely ambiguous--no fit
87	Remeasure
88	Event one of two or more interpretations. This one incorrect. No E.T.
89	Same as 82 but intractable for some reason
90	Error in measurement--LSN wrong, etc. Change cards and re-edit
91	Meas. OK, event valid, but no fit--outside fid. volumn (75 cm)
92	Remeasure to check interpretation assignment
93	Refit as a special event type
94	V may be leptonic decay or 3 π decay
95	Ambiguous--too many fits
96	Positive MM for best ion fit

- 97 Negative MM for best ion fit--try π^+ , K^+ , beam
 98 Remeasure as special event type (one prong scatters
 etc.)
 99 Particle ambiguity within one physical category (fit)

If an event gets a word 83 entered, the fit number should be listed in columns 77-79. It is assumed that only physicists will make entries with words 83 and above and only in columns 71 and above.

Fit List

Fit No. Definition (Pos, Neg, Measured Neut, then
 unseen particles)

*** 3TP20--Two Prong

200	P	P		(Elastic)
201	P	P	(π^0)	
202	π^+	P	(N)	

*** 3TP21--Two Prong Plus Kink

211	P	Σ^+	(K^0)	
212	K^+	Σ^+	(N)	
213	K^+	P	(Σ^0)	
214	K^+	P	(LMB)	

*** 3TP25--Two Prong Plus Open V

241	π^+	P	K^0	(LMB)
242	π^+	P	K^0	(Σ^0)
243	P	P	K^0	(K^0)
244	K^+	P	K^0	(N)
245	π^+	Σ^+	K^0	(N)
246	P	Σ^+	K^0	
247	P	Σ^+	K^0	(π^0)

248	K+	P	K°	(CI°)
-----	----	---	----	-------

249				
-----	--	--	--	--

250				
-----	--	--	--	--

251	π^+	P	LMB	(K°)
-----	---------	---	-----	------

252	K+	P	LMB	
-----	----	---	-----	--

253	K+	P	LMB	(π^0)
-----	----	---	-----	-------------

254	K+	P	Σ^0	
-----	----	---	------------	--

255	π^+	K+	LMB	(N)
-----	---------	----	-----	-----

256	P	P	LMB	(ALMB)
-----	---	---	-----	--------

257	P	P	ALMB	(LMB)
-----	---	---	------	-------

3TP26--Two Prong Plus Kink Plus Open V

261	P	Σ^+	K°	
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262	P	Σ^+	K°	(π^0)
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263	K+	P	LMB	(π^0)
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264	K+	P	LMB	(π^0)
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265	π^+	Σ^+	K°	(N)
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266	K+	P	K°	(CI°)
-----	----	---	----	-------

267	K+	P	K°	(N)
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268	π^+	K+	LMB	(N)
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269	K+	P	Σ^0	
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270	π^+	P	K°	(Σ^0)
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271	π^+	P	K°	(LMB)
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3TP30--Two Prong Plus Two V's

301	π^+	P	K°	LMB
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302	π^+	P	K°	Σ^0
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303	π^+	P	K°	LMB	(π^0)
-----	---------	---	----	-----	-------------

304	P	P	K°	K°
-----	---	---	----	----

305	P	P	K°	K°	(π^0)
-----	---	---	----	----	-------------

306	π^+	P	K°	K°	(CI°)
-----	---------	---	----	----	-------

307	π^+	P	K°	K°	(N)
-----	---------	---	----	----	-----

308	π^+	π^+	K°	LMB	(N)
-----	---------	---------	----	-----	-----

309	P	P	LMB	ALMB
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310	P	P	LMB	ALMB	(π^0)
311	K+	P	K 0	(CI 0)	

*** 3TP41---Four Prong Plus Positive Kink

411	K+	P	Σ^+	π^-	(π^0)
412	K+	P	Σ^+	π^-	(π^0)
413	π^+	P	Σ^+	π^-	(K 0)
414	π^+	K+	Σ^+	π^-	(N)
415	K+	P	P	K-	
416	K+	P	P	K-	(π^0)
417	K+	P	P	π^-	(K 0)
418	π^+	K+	P	K-	(N)
419	π^+	K+	P	π^-	(LMB)
420	π^+	K+	P	π^-	(Σ^0)
421	K+	K+	P	π^-	(CI 0)
422	π^+	K+	P	Σ^-	
423	π^+	K+	P	Σ^-	(π^0)
424	K+	K+	P	CI-	
425	K+	K+	P	CI-	(π^0)
426	π^+	K+	P	CI-	(K 0)
427	π^+	K+	K+	CI-	(N)
428	π^+	π^+	K+	Σ^-	(N)
401	π^+	P	P	π^-	
402	π^+	P	P	π^-	(π^0)
403	π^+	π^+	P	π^-	(N)

*** 3TP43---Four Prong Plus Negative Kink

431	π^+	K+	P	Σ^-	
432	π^+	K+	P	Σ^-	(π^0)
433	π^+	π^+	K+	Σ^-	(N)
434	π^+	π^+	P	Σ^-	(K 0)
435	K+	P	P	K-	
436	K+	P	P	K-	(π^0)
437	π^+	K+	P	K-	(N)

438	π^+	P	P	K ⁻	(K ⁰)
439	K ⁺	K ⁺	P	CI ⁻	(π^0)
440	K ⁺	K ⁺	P	CI ⁻	(N)
441	π^+	K ⁺	K ⁺	CI ⁻	(K ⁰)
442	π^+	K ⁺	P	CI ⁻	(π^0)
443	π^+	P	P	π^-	(N)
444	π^+	P	P	π^-	(π^0)
445	π^+	π^+	P	π^-	(N)

*** 3TP45--Four Prong Plus Open V

451	K ⁺	P	P	π^-	K ⁰
452	K ⁺	P	P	π^-	K ⁰
453	π^+	P	P	π^-	K ⁰
454	π^+	K ⁺	P	π^-	(N)
455	π^+	P	P	K ⁻	K ⁰
456	π^+	P	P	K ⁻	(π^0)
457	π^+	π^+	P	K ⁻	(N)
458	π^+	P	Σ^+	π^-	(π^0)
459	π^+	P	Σ^+	π^-	(N)
460	π^+	π^+	Σ^+	π^-	(π^0)
461	π^+	π^+	P	Σ^-	(N)
462	π^+	π^+	P	Σ^-	(π^0)
463	π^+	π^+	π^+	Σ^-	(N)
464	π^+	K ⁺	P	CI ⁻	(π^0)
465	π^+	K ⁺	P	CI ⁻	(N)
466	π^+	π^+	K ⁺	CI ⁻	(K ⁰)
467	π^+	π^+	P	CI ⁻	(CI ⁰)
468	π^+	K ⁺	P	π^-	(Σ^0)
469	π^+	π^+	P	π^-	(LMB)
470	π^+	π^+	P	π^-	(π^0)
471	π^+	K ⁺	P	π^-	(K ⁰)
472	π^+	K ⁺	P	π^-	(N)
473	π^+	π^+	P	π^-	(π^0)
474	π^+	π^+	K ⁺	π^-	(K ⁰)
475	π^+	K ⁺	P	π^-	(N)

Ambiguity Classes

No.	Ambiguous Between			
921	π^+	P	LMB	(K^0)
	K^+	P	LMB	(π^0)
922	K^+	P	LMB	
	K^+	P	Σ^0	
923	K^+	P	Σ^0	
	K^+	P	LMB	(π^0)
924	π^+	P	K^0	(LMB)
	π^+	P	K^0	(Σ^0)
925	π^+	P	LMB	(K^0)
	π^+	K^+	LMB	(N)
926	π^+	P	K^0	(LMB)
	K^+	P	K^0	(N)
927	π^+	K^+	LMB	(N)
	K^+	P	LMB	(π^0)
941	π^+	K^+	P	LMB
	π^+	K^+	P	Σ^0
942	π^+	K^+	P	Σ^0
	π^+	K^+	P	LMB
943	π^+	P	P	(π^0)
	π^+	π^+	P	(N)
951	π^+	K^+	P	(N)
	π^+	K^+	P	(π^0)
952	π^+	P	P	(K^0)
	π^+	K^+	P	Σ^-
953	π^+	P	Σ^+	(K^0)
	K^+	P	Σ^+	(π^0)

954	π^+	P	K^+	π^-	LMB	(π^0)
	π^+	π^+	P	π^-	LMB	(K^0)
955	π^+	P	P	K^-		(K^0)
	π^+	K^+	P	Σ^-		(π^0)
956	π^+	K^+	P	π^-	LMB	(π^0)
	π^+	K^+	P	π^-	Σ^0	(π^0)
957	π^+	π^+	K^+	Σ^-		(N)
	π^+	K^+	P	Σ^-		(π^0)
958	π^+	P	Σ^+	π^-		(K^0)
	π^+	K^+	Σ^+	π^-		(N)

List of Event Flags Used In Exp. 03 And Their Definitions

E.F. No.	Description
01	A closed V points to the beam track interaction
02	A closed V points to an interaction or kink on secondary track
03	An electron pair (Dalitz pair) occurs at the beam track interaction
04	A three prong V points to the beam track interaction
05	There are two or more identical E.T. in this region of this frame
06	An additional open V was not measured
07	Data cards altered (points deleted, etc.)
10	Track 10 has a mu-electron decay
12	Track 2 has a mu-electron decay
13	Track 3 has a mu-electron decay
etc.	
19	Track 9 has a mu-electron decay
20	Track 10 has an additional kink not covered in the event type.

- 22 Track 2 has an additional kink not covered in the event type.
- 23 Track 3 has an additional kink not covered in the event type.
- etc.
- 29 Track 9 has an additional kink not covered in the event type.
- 30 A secondary interaction (2, 3, 4 etc. prong) occurs on track 10.
- 32 A secondary interaction (2, 3, 4 etc. prong) occurs on track 2.
- 33 A secondary interaction (2, 3, 4 etc. prong) occurs on track 3.
- etc.
- 39 A secondary interaction (2, 3, 4, etc. prong) occurs on track 9.

Tag Color Code For Event Pictures

Black	-	Remeasure
Green	-	Attention, Physicists
Yellow	-	Attention, Sedna
White	-	Attention, Tom Buchman--New Words to Enter

Reject List

Illfit Errors

- 1 Too many bad tracks
- 2 MV=4 not allowed (i.e. there are 4 missing variables.)
- 3 Four missing momenta
- 4 Input error matrix not positive definite
- 5 DF/DY singular
- 6 Momenta parallel
- 7 Unmeasured momentum negative
- 8 Negative energy in MMD=3 case.
- 9 Chi-square too large
- 10 Too many cuts
- 11 Too many steps
- 12 Constraint error matrix singular
- 13 No root in MV=4 case
- 14 No energy balance MV=4
- 15 Energy part. group negative
- 16 Negative momentum in MQ=1 case
- 17 Bad tracks in MQ=1 case (poorly measured track doesn't allow MM calc.)
- 18
- 19
- 20 MM squared too large--fit not tried

Star Rejects (Vertex Rejects)

- 201 XMass for stopping primary
- 202 Primary not first
- 203 Range discrepancy (RDISC) too large
- 204 Space point reject at vertex
- 205 DEVR or DEVZ too large (above 5.0)
- 206 Not beam track

207 Too few tracks
208 Fitted range wrong
209 Cannot swim
210 Cannot swim LCR=3
211 Divide check
212 AC FPT overflow

Euclid Rejects (In Space Reconstruction)

Event Errors

200 NWHICH incorrect (program error)
201 Negative X-Y word (program error)
202 Positive track word (program error)
250 No spectator found by XSAW
260 Excise could not remove a vertex (program error)
270 Divide check during Euclid
271 FPT overflow during Euclid

Vertex Errors

301 Too many steps
302 Tracks are parallel
303 Chi-square at vertex too large (tracks do not meet)
304 Type not in topsy table
305 Track measured beyond vertex
306 Error in topsy table
307 Negative square root occurred in reconstruction

Input Errors

- 1 Event type not listed
- 2 More than 9 or less than 6 fiducials
- 3 Missing camera number is wrong (not 1,2,3, or 4)
- 4 Track number incorrect
- 5 Missing camera number changed during input of one event
- 6 LSN number not 0,1,2, or 3
- 7 Track word changed between first view of one track and what should have been second view of same track
- 8 Too few points in a track. Either less than 2 points in either view, or 2 points in one view and more than 2 points in other view.
- 9 More than 20 points for one view of one track
- 10 More tracks in event than event type requires
- 11 Record for one event is complete, but end word missing.
- 12 Event incomplete, interrupted by end word
- 13 Ditto, event word
- 14 Ditto, error word
- 15 Ditto, illegible magnetic tape (key punch error)
- 16 Ditto, illegible paper tape (blank work)
- 17 Ditto, P-card
- 18 Ditto, Q-card
- 19 LSN=3 and points have been measured on the track

Track Errors

- 100 Rejected by check, more than one had point in one view, or one end point is bad.
- 101 Rejected by check, track makes too small an angle to stereo axis.
- 111 Wrong view number (not 1,2,3, or incorrect order)
- 112 Fiducial separation too large
- 113 Fiducial separation too small

- 114 Fiducials reversed or out of line.
- 120 Average deviation in X-Y from fitted circle too large. (DEVR)
- 130 To avoid excessive extrapolation in second view a point in the first view should be rejected, but only two points are left.
- 131 Iteration in space reconstruction fails to converge to interpolated point in second view after ten tries.
- 132 Corresponding points in two views of a two point track are off more than $1/2$ mm.
- 133 There is no mate in second view to a point in view 1. (Occurs only if track becomes parallel to stereo axis)
- 134 Failure in fitting circle to 3 consecutive points in second view. Should occur only if a point and its second next neighbor are identically equal.
- 140 Computational difficulty in S-Z fit.
- 141 Average deviation in S-Z too large.
- 160 R^{*2} fitted by spiral is negative.

Track Errors Found by Test

- 280 Magnet current incorrect (not 0.0 or 1.0)
- 281 DVB .GE. 0.100 for EXP 03.
- 282 DVA .GE. 0.100 for EXP 03.
- 283 PCIRCLE incorrect on a stopping track with more than three points in each view.
- 284 PCIRCLE incorrect on a stopping track with exactly three points in each view.
- 285 PCIRCLE incorrect on a non-stopping track which has only a small error in momentum.
- 286 A stopping track ends within two centimeters of either window.

- 287 Not enough stopping tracks. (EXP 02 only)
- 288 Wrong number of neutral tracks.
- 289 FTN not equal 0.
- 290 LSN not equal 0 on track 1.
- 291 LSN not equal 0 on a negative track.
- 292 LSN not equal 2 on a neutral track.
- 293 LSN equals 2 on a positive track.
- 294 Track 1 not measured in Cam. 2 and 3 in EXP 03 only.