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Internal Report

Some 5.0 GeV/c π^-p Cross Sections

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I. Introduction

We determine the cross sections for several channels involving 4-prong and 6-prong π^-p interactions at 5 GeV/c π^- beam momentum by means of normalizing to the total cross section measured in a counter experiment. The interactions were observed in the SLAC 82" HBC. The exposure consisted of $\sim 100,000$ pictures.

II. ProcedureA. Description

We first obtained the cross section for 4-prong interactions, σ_{4p} , by normalizing to the known total cross section σ_T . This was done by counting (and correcting for scanning errors and biases) all interactions in 6 rolls (~ 3900 frames). The 6 rolls have a sufficient number of events so that statistical errors are the order of a few percent. We will refer to this scan as the normalization scan. For σ_{4p} we have

$$\sigma_{4p} = \sigma_T \frac{N_{4p}}{N_T}$$

where N_{4p} and N_T are the total number and the number of 4-prong events occurring in the 6 rolls.

The 6-prong channel does not have as many events in the normalization scan as does the 4-prong channel so in order to reduce statistical errors for σ_{6p} , we counted the number of 6-prong events in the entire exposure and normalized to σ_{4p} above. In general, if N_A is the number of events of any channel A found in the entire exposure, the cross section for channel A, σ_A is

$$\sigma_A = C_{\mu} \cdot N_A = (\sigma_{4p} / N_{4p}^T) \cdot N_A$$

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where C_{μ} is the microbarn equivalent (if σ_{4p} is given in microbarns) and N_{4p}^T is the total number of 4 prongs occurring in the entire exposure.

B. Normalization Scan

Each of the 6 rolls of film were scanned twice and the scans were compared. A physicist investigated and resolved all discrepancies. Table I shows the results of the scan. The various quantities are defined as

n_{AB}^- = number found in scan A but not in B.

n_{AB}^+ = number found in B but not in A.

n_{AB} = number found in both A and B.

n_F = total number found.

$N = (n_{AB}^- + n_{AB}^+) / n_{AB} =$ total number

$\sigma_N = (\sigma_A^2 + \sigma_B^2)^{1/2} =$ uncertainty in N.

$\sigma_A = (N \epsilon_A (1 - \epsilon_A))^{1/2} =$ standard deviation of $(n_{AB}^- + n_{AB}^+)$ about its expectation value.

$\sigma_B = (N \epsilon_B (1 - \epsilon_B))^{1/2}$

$\sigma_{AB} = (N \epsilon_A \epsilon_B (1 - \epsilon_A \epsilon_B))^{1/2}$

$\epsilon_A = (n_{AB}^- + n_{AB}) / N =$ efficiency of A.

$\epsilon_B = (n_{AB}^+ + n_{AB}) / N =$ efficiency of B.

A full discussion and derivation of these quantities is given in Ref. 1.

Several comments are in order for some of the event types.

a) Since 0-prongs (ET20's) are difficult to detect in scanning, 15% of the frames in the 6 rolls were carefully rescanned by a physicist. This rescan indicates the other two scans were only 92.8% efficient instead of the 97.2% given by the above equations or 256 $\pm$ 20 ET20's are expected. We will use the latter number as the best estimate of the ET20's.

b) Table I includes some odd numbered prong event types. A physicist examined all such events; all appear to be legitimate events. Apparently one prong is missing because

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- i) a negative prong has a 0-prong interaction very close to the vertex,
- ii) a positive prong scatters or interacts very close to the vertex, or
- iii) the momentum transfer to the proton is too small to allow it to travel far enough to be seen. We found that most of the ET23's were of type i) or iii) and should be counted as 4-prongs (ET24) and we include them in the total number of 4-prong interactions for the purpose of finding the 4-prong cross section.

Examination of the seven 1-prong (ET21) events reveal that four events most likely are small (laboratory) angle π^-p elastic scatters with momentum transfer Δ^2 to the proton too small for the recoil proton to be visible in the chamber. Since we will correct for low Δ^2 elastic events (described below), we will count only the other three ET21's in the total number of interactions in the 6 rolls. We arbitrarily assign an uncertainty of one event to the 1-prong events.

C. Elastic Correction to 2-Prong Events

Elastic scatters with low Δ^2 are difficult to detect in scanning but since the behavior of the differential cross section, $d\sigma/dt$ goes as e^{Bt} , we can correct for this loss. In the following we briefly describe the procedures.

All ET22's found in the normalization scan were measured, reconstructed and fitted. The 305 failing events were remeasured and refitted and the 156 of these events that again failed were examined on the scanning table by a physicist. Only 30 of the 156 looked as if they could be elastic scatters and these were reconstructed with the criteria for passing reconstruction relaxed. Thirteen events still failed. Since the elastic correction is only 13% of the total seen elastic events, assuming the 13 failing events are all elastic means the correction is only 2 additional events and if none are elastic there is no correction. At any rate, the uncertainty arising from failing to count all elastic scatters is negligible compared to the total number of events in the 6 rolls (~ 5700) and

the statistical error associated with it (70 events). The other 126 repeat failures were considered legitimate events and were counted as such.

We found a total of 942 fitted elastic events, the dN/dt distribution of which is given in Fig. 1. It is clear that low $|t|$ events are lost. Using the maximum likelihood method, we fitted dN/dt to e^{Bt} in the range $-t_L < -t < .50$ $(\text{GeV}/c)^2$, for various values of t_L , to get a slope B . We then normalized the distribution to the number of events in the fitting range and integrated from $-t = 0$ to $.50$ $(\text{GeV}/c)^2$ to get the total number with $-t < .50$ $(\text{GeV}/c)^2$. The difference between this number and the actual observed number is the elastic correction for small $|t|$. Table I and Fig. 2 show the result of these fits as a function of $|t_L|$. (The error of ± 20 for N for $-t_L = .04$ $(\text{GeV}/c)^2$ was found by finding N for those values of B which reduced the maximum likelihood by one unit (still normalizing to the fitting range)).

We choose to use $N = 1061$ ($-t_L = .055$ $(\text{GeV}/c)^2$) because

- a) it has the highest χ^2 probability and
- b) it is near the average (1057) of the N 's for $-t_L > .04$ $(\text{GeV}/c)^2$ and to use $\Delta N = \pm 22$ for the error. The curve in Fig. 1 represents this fit. Thus the elastic correction is 165 ± 22 events. The 44 fitted events with $-t > .50$ $(\text{GeV}/c)^2$ make $1105 \pm \pi^-p$ elastic events in all in the 6 rolls. This value of B , $8.32 \pm .40$ $(\text{GeV}/c)^{-2}$, is consistent with the value $7.93 \pm .17$ $(\text{GeV}/c)^{-2}$ found by counter techniques^{2/} for 5.03 GeV/c.

We also investigated the azimuthal angle of the scattering plane about the beam and found no evidence for azimuthal losses for $-t > .055$ $(\text{GeV}/c)^2$ whereas there are indications for such losses for $-t < .03$ $(\text{GeV}/c)^2$.

Using only ET22's without stopping tracks we find the two scans are 99.8% efficient in detecting 2 prongs implying a scanning correction of 6 ± 1 events. Also, as a result of the measuring, 7 of the 3181 ET22's found by the scanners were rejected because they were not legitimate events. Table III summarizes the ET22 events.

In Table IV we summarize the results of scanning and measuring for the normalization scan. The uncertainty in the totals are the result of quadratic addition. The uncertainty is a systematic error arising from being unable to count events correctly namely due, in the case of non-ET22's, to uncertainty as to whether or not an interaction is on a beam track.

One further correction not included in Table IV since it is a result of measuring and analyzing the ET24's is that approximately 6 events called 4-prongs by the scanners are really 2-prongs with a Dalitz pair. Thus the number of 3- or 4-prongs is 1779 ± 6 , while the total number of all events stays the same.

D. Cross Section for 3- and 4-Prong Events

The 3- or 4-prong cross section σ_{4p} is given by $\sigma_{4p} = \sigma_T \cdot \frac{N_{4p}}{N_T}$ where

$$\sigma_T = 29.155 \pm 0.10^{+0.150}_{-0.200} \text{ mb} = \text{total cross section for 5 GeV/c } \pi p \text{ interactions}$$

$$N_T = 5780 \pm 76 \pm 29 = \text{total number of events in the 6 rolls.}$$

$$N_{4p} = 1779 \pm 42 \pm 6 = \text{number of 3- and 4-prong events in the 6 rolls.}$$

The first error is statistical and the second is systematic. We get

$$\sigma_{4p} = 8.973 \pm 0.242^{+0.196}_{-0.118} \text{ mb}$$

where the first error is statistical, arising mostly from N_{4p} and the second is systematic arising mostly from σ_T .

E. Microbarn Equivalent

To get a microbarn equivalent for the entire exposure, we need to divide σ_{4p} by the total number of 3- and 4-prong events in the entire exposure.

In the regular scan, most rolls were scanned for 3-, 4-, 5-, and 6-prongs only; the presence of a V or kink was ignored and the events were called event types 23, 24, 25, or 26. Fourteen of the rolls however were scanned for all event types (except ET20, 21, and 22). In these rolls, which included the 6 rolls of the normalization scan, events with a V or kink were called the appropriate event type.

All events called ET24 or 26 were measured (two passes were made); reconstructed, and fitted. ET23's with two negative and one positive prongs were also measured in an attempt to get low Δ^2 events. Events with constrained fits were ionized; at this stage some events were rejected for various reasons: non-beam track; two prongs were actually a Dalitz pair; high energy δ -ray on the beam track, etc.

To verify that the normalization scan was equivalent to the regular scan, we compared the two scans for the 3-, 4-, 5-, and 6-prongs for the 6 rolls used in the normalization scan. Table V shows the comparison for the numbers recorded. The agreement is quite good; the difference in the total 3- and 4-prongs and in the total 5- and 6-prongs is much less than 1%. Thus, the scans are equivalent with respect to the number of 3- and 4-prongs and to the number of 5- and 6-prongs recorded. In addition, an event by event comparison of the 3- and 4-prongs was made. Some events recorded by one scan were not recorded by the other but upon imposing the decisions of the measurers and ionizers with regard to rejects, 98.7% of the remaining events were seen by both scans. Most of the difference between the two scans is due to missed events in the regular scan. We conclude that the normalization scan and the regular scan are equivalent with regards to the same events being recorded.

In the entire exposure, scanners recorded 43,468 ET24's, 125 ET23's, and 118 other 3- and 4-prong events. Two measuring passes were made on the ET24's; those events failing the first pass were remeasured. One measuring pass was made on the ET23's and none on the others. Those events which had constrained fits were examined at the scanning table for ionization information. Measurers could and did reject events they believed were not legitimate events. Ionizers also provided information which led to rejection of some events. We now briefly discuss these rejects.

Events rejected by the measurers in the first pass were subject to the second pass. Of the 595 events rejected in the first pass 422 were also re-

rejected in the second; we consider these valid rejects. The other 173 events were actually measured and 41 failed reconstruction or fitting. Another 63 events, which failed reconstruction in the first pass were rejected in the second. We estimate that $\sim 1/2$ of the 41+63 events, or ~ 52 events should be rejected and assign an uncertainty of 20. There are 239 events rejected in the first pass but never remeasured; they are apportioned in the same ratio as those events going through two passes, i.e., 186 ± 15 rejects. The total number of ET24's rejected is 660 ± 25 .

Only events having constrained fits were ionized and we assume the unionized events have the same percentage of rejects. Approximately 25,000 events were ionized and 801 of these were rejected (non beam track, two prongs are a Dalitz pair, not a legitimate event, or high energy δ -ray on the beam track). This rejected number scales to 1370 ± 27 events for all the events (estimated 2% uncertainty).

Since only about half of the 125 ET23's (the 2 negative plus one positive prongs) and none of the 118 4-prongs with kinks or V's were measured in the regular measuring passes, we will assume the same percentage of rejects as for the ET24's. The number of accepted events then became 119 and 112 respectively.

Also, measurement of the 6-prong events indicates 33 ± 1 events are actually 4-prongs with a Dalitz pair.

The final total of all 3- and 4-prong events is 41,702. A summary is given in Table VI. We have combined the various uncertainties to give an overall systematic uncertainty of 50 events. The statistical error is 204 events, large compared to the systematic error. Dividing σ_{4p} by this number, $41702 \pm 204 \pm 50$, we have the microbarn equivalent of

$$(.2152 \pm .0059^{+.0049}_{-.0030}) \mu\text{b/event}.$$

The first error is statistical, coming mainly from N_{4p} of the normalization scan and the second error is systematic, mostly from σ_T .

F. Cross Section for 4C - 4-Prong Events

A total of 7647 $\pi^- p \pi^+ \pi^-$ events were found in the two measuring passes on the 3- and 4-prongs. All but 15 are best fits and these 15 are second best fits but the best fit is not a 4C fit. In the 7647 events there appears to be no loss of events due to highly dipping protons. This was investigated by examining the azimuthal distribution of the proton about the beam direction; the distribution was flat.

Approximately 2000 3- and 4-prong events failed reconstruction or were unmeasurable for various reasons. A third measuring pass was made on 99 of these 4-prongs to get an estimate of the number of $\pi^- p \pi^+ \pi^-$ events in this class of events. Eighteen events had a fit to this final state; 58 other events which reconstructed did not fit this final state, and 23 events failed for various reasons. These 23 were examined on the scanning table and this examination revealed that 13 of them could not be $\pi^- p \pi^+ \pi^-$ events. We assume that $5+3$ of the other 10 events are $\pi^- p \pi^+ \pi^-$ events for a total of $23+3$ $\pi^- p \pi^+ \pi^-$ events out of 95 good events (4 of 99 were rejects). Scaling this ratio to all the failures results in an estimate of $492+64$ $\pi^- p \pi^+ \pi^-$ events. We also estimate that there are $20+10$ such events in the ET23's which were not measured or which failed measurement.

There is a possibility of $\pi^- p \pi^+ \pi^-$ events occurring in the kinked 4-prong events. 18 such events were measured (those in the normalization scan rolls); only two had a fit to $\pi^- p \pi^+ \pi^-$. This scales up to 5 for all kinked 4-prongs. (We assumed the presence of a V is an indication of a K^0 or Λ so the 4-prong plus V events could not be $\pi^- p \pi^+ \pi^-$ events).

Table VI includes a summary of the $\pi^- p \pi^+ \pi^-$ events. We estimate an overall (systematic) uncertainty of 67 events. The total number of $\pi^- p \pi^+ \pi^-$ events in the exposure then is $8164+90+70$ events where again the first error is statistical and the second is systematical coming mainly in estimating $\pi^- p \pi^+ \pi^-$ events in the

unmeasured and failing ET24's. Multiplication by the microbarn equivalent produces a cross section of

$$\sigma(\pi^- p \pi^+ \pi^-) = (1.757 \pm .050^{+.055}_{-.040}) \text{ mb.}$$

The statistical error still comes mainly from N_{4p} in the normalization scan and the systematic error comes mainly from σ_T . A reasonable folding of the errors is .07 mb, and so $\sigma = 1.76 \pm .07 \text{ mb.}$

G. 6-Prong Cross Section

For the 6-prong events, we essentially followed the same procedure as for the 4-prong events. A total of 4414 6-prongs were recorded by the scanners in all the rolls. Estimated operator rejects and ion rejects are 159 ± 13 and 157 ± 5 , respectively or, 4098 ± 15 good 6-prong events (estimate of systematic error). The statistical error is ± 66 events. The 5-prong events number 52 ± 5 after removal of estimated operator rejects (2) and ionizer rejects (2). The statistical error is ± 7 . Assuming the 5-prong events are 6-prong events with a very short proton or a negative prong interacting in a 0-prong very close to the vertex, we have a total number of $4150 \pm 67 \pm 18$ 6-prong events. This indicates a cross section of $(893 \pm 28^{+25}_{-16}) \text{ } \mu\text{b}$ where the first error is statistical and the second is our estimate of the systematic errors.

All 6-prongs were measured and fitted; those having constrained fits were ionized. After two measurement passes we had a total of 3628 events which had good fits or missing mass hypotheses leaving a remainder of 470 ± 15 acceptable events which failed reconstruction or fitting.

Only 5 hypotheses were tried in kinematic fitting:

- $\pi^- p \rightarrow 3\pi^- 2\pi^+ p$ a)
- $\rightarrow 3\pi^- 2\pi^+ p \pi^0$ b)
- $\rightarrow 3\pi^- 2\pi^+ p$ missing mass c)
- $\rightarrow 3\pi^- 3\pi^+ n$ d)
- $\rightarrow 3\pi^- 3\pi^+$ missing mass e)

We attempted to estimate the number of strange particle events by observing that only one 6-prong plus V and only one 6-prong with a kink were found in the 6 rolls used in the normalization scan which projects to 25 V's and 25 kinks in the exposure. If we assume equal numbers of K_S^0 and Λ 's produced we would see only half of all V's because of the various decay modes. There should be therefore ~ 50 V's. The corrections to the charged strange particle events are estimated to be a factor of three; most Σ 's would decay in the chamber but the K's would escape. We therefore estimate ~ 75 charged strange particles. Taking associated production into account we estimate the total number of strange particle events to be ~ 100 . The error will be large; we assign an uncertainty of ± 50 . The cross section for 100 ± 50 strange particle events in the 6-prong events is $22 \pm 13 \mu\text{b}$.

We now have 434 ± 100 events to distribute among the five final states. We distribute them according to the previous distribution. The result is given in Table VI along with the cross section in microbarns. Table VII also includes the statistical errors and our (rough) estimate of what the systematic errors are. Most of the systematic error arises from distributing the events which failed reconstruction. We took the error for any one channel to be 25% of the events being distributed in the channel. Finally Table VIII gives the cross section for the various 6-body final states and the estimates of statistical and systematic errors.

References

1. M. L. Shen, Nucl. Inst. and Methods 65, 157 (1968).
2. Fellingner et al., Phys. Rev. D2, 1777 (1970).

TABLE I. Results of Normalization Scan

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EVENT TYPE	$\frac{n}{AB}$	$\frac{n}{AB}$	$\frac{n}{AB}$	$\frac{n}{F}$	N	$8N$
20	17	63	157	237	244	16.2
21	0	6	1	7	7	21.6
22	45	197	2939	3181	3184	
23			5	5	5	-
24	7	6	1702	1715	1716	4.3
25			3	3	3	1.9
26	1	0	171	172	172	
28			3	3	3	-
30			36	36	36	-
32	3	0	89	92	92	2.4
33			1	1	1	-
34			34	34	34	-
36			1	1	1	-
40	1	0	17	18	18	-
42			15	15	15	-
44			1	1	1	-
50			1	1	1	-
62			3	3	3	-
64			2	2	2	-
72			9	9	9	-
74			1	1	1	-
82			9	9	9	-
83			1	1	1	-
84			7	7	7	-
88			1	1	1	-
92			27	27	27	-
94			16	16	16	-
96			1	1	1	-
ZOON	1		1	2	2	-
TOTAL (excluding ET21 & 22)						
	30	69	2314	2413	2421	17.1
3&4 Prongs	7	6	1770	1783	1784	4.3
Non-stopping ET22	40	74	2487	2605	2610	15.9

TABLE II. Fits to $dN/dt \sim e^{Bt}$

-13-

$ t_L $	Number between $ t_L $ and .50	B	N	χ^2	Prob. %	Degrees of Freedom
.025	822	7.896 $\pm$.341	1005.7	23.4	32.3	21
.030	792	7.933 $\pm$.350	1010.0	28.6	12.3	21
.035	763	7.973 $\pm$.359	1014.8	19.2	57.5	21
.040	742	8.123 $\pm$.370	1033.8 $\pm$ 22	22.2	38.6	21
.045	713	8.146 $\pm$.380	1036.7	20.4	43.2	20
.050	698	8.389 $\pm$.392	1070.3	19.5	49.2	20
.055	665	8.325 $\pm$.402	1060.9	14.5	80.6	20
.060	643	8.437 $\pm$.414	1077.4	18.4	55.9	20
.065	609	8.303 $\pm$.425	1056.8	19.6	41.7	19
.070	578	8.189 $\pm$.436	1038.9	18.3	50.1	19
.075	558	8.273 $\pm$.448	1052.5	14.4	75.9	19
.080	534	8.261 $\pm$.461	1050.1	18.1	51.6	19
.085	510	8.218 $\pm$.475	1043.1	19.5	36.0	18
.090	498	8.455 $\pm$.489	1084.1	16.5	55.9	18
.095	475	8.411 $\pm$.503	1076.0	14.0	73.0	18

Table III. Event Type 22

Total formed by scanners	3181
Rejected by measurers	7
Fitted elastics	942
Inelastics	2232
Elastic correction	163+22
Correction from unfitted possible elastics	<u>1+1</u>
TOTAL	3338+23
.2% scanning correction	<u>6+1</u>
TOTAL ET22's	3344+23

Table IV. Results for Normalization Scan

Event type	Number Found	Corrections	Total	Uncertainty
20	237	19	256	17
21	3	0	3	1
22	3181	163	3344	23
23	5	0	5	5
24	1715	1	1716	
25	3	0	3	1
26	173	0	173	
Other non 3- or 4-prongs	216	0	216	3
Other 3- or 4- prongs	<u>64</u>	<u>0</u>	<u>64</u>	<u>1</u>
TOTAL N_T	5597	183	5780	29
Total 3- or 4- prongs = N_{4p}	1784	1	1785	6

TABLE V. Inter-Scan Comparison

<u>Event Type</u>	<u>Number found in Normalization Scan</u>	<u>Number found in Regular Scan</u>
23	5	9
24	1715	1710
25	3	1
26	172	175
33	1	0
34	34	36
36	1	1
44	1	1
64	2	1
74	1	1
83	1	1
84	7	7
94	16	11
96	1	1
4-prong zoons	1	3
Total 3-prongs	7	10
Total 4-prongs	1777	1770
Total 5- and 6-prongs	177	178
Total Others	214	202

TABLE VI. Summary of 3- and 4-Prongs

	23	24	Others	Total
Recorded by Scanners	125	43468	118	43711
Operator Rejects	<u>2+1</u>	<u>660+25</u>	<u>2+1</u>	<u>664</u>
Good for Measurement	<u>123+1</u>	<u>42808+25</u>	<u>116+1</u>	<u>43047</u>
Ion Rejects	<u>4+2</u>	<u>1370+27</u>	<u>4+2</u>	<u>1378</u>
Contributions from 6-prongs	<u>--</u>	<u>33+1</u>	<u>--</u>	<u>33</u>
Total Good Events	<u>119</u>	<u>41471</u>	<u>112</u>	<u>41702+48</u>
<hr/>				
Fitted $\pi^- p \pi^+ \pi^-$	5	7642	--	7647
Estimated in unmeasured or failing events	<u>20+10</u>	<u>492+64</u>	<u>5+1</u>	<u>517</u>
TOTAL $\pi^- p \pi^+ \pi^-$	<u>25</u>	<u>8134</u>	<u>5</u>	<u>8164+70</u>

TABLE VII. Summary of 6-Body Final States

State	Unamb.	NUMBER OF EVENTS				Sum	ERROR	
		Self Ambig	Best of Ambig	Kycd-3	Failures		Statis.	System
4C	1025	34	3	0	128	1190	35	39
1C π^0	1020	37	72	76	144	1349	37	110
1Cn	228	0	22	17	32	299	18	28
π^0 mm	374	15	182	38	73	682	27	128
n mm	369	0	74	30	57	530	23	66
Strange Particle						100	10	50

TABLE VIII.
Cross Sections

State	Cross Section		
	σ	Δ_{stat}	Δ_{syst}
4C	256	7.5	8.3
1C π^0	290	8.0	24.0
1Cn	64.5	3.9	6.0
π^0 mm	147	5.8	28.0
n mm	114	5.0	14.0
Strange Particle	21.5	2.2	11.8

11/02

$\frac{dN}{dt}$ vs t

942 EWE 1173

~ @ 8325t

-t (6.1V/16)²

1.44

1.00005

Figure 1

Figure 2