1982

Study of \([\pi\pi \rightarrow KK]\) and \([\pi\pi \rightarrow KK\,\ast]\) scattering at 10 GeV/c

Dwight Lee Denney

Iowa State University

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STUDY OF PI-PI \rightarrow KAON-KAON AND PI-PI \rightarrow KAON-EXCITED KAON SCATTERING AT 10 GEV/C

Iowa State University  Ph.D.  1982

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Study of $\pi \pi \rightarrow K\bar{K}$ and $\pi \pi \rightarrow K\bar{K}^*$ scattering at 10 GeV/c

by

Dwight Lee Denney

A Dissertation Submitted to the
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CHAPTER I

INTRODUCTION

Since its proposal in 1964 by Gell-Mann\(^1\) and Zweig\(^2\), the Quark Model of hadrons has been a very useful tool in describing the mass spectra of hadrons. However, even with the many successes of recent years there are still a number of undetected states that are predicted by the Quark Model\(^3\). The goal of this study is to look for meson resonances that are coupled to the Quark Model state of two strange quarks, i.e., $s\bar{s}$, and thus can decay into $K\bar{K}$ or $K^*\bar{K}$ final states. The detection and measurement of these states would give information relevant to the particle mass splitting due to radial and orbital excitations and spin-orbit couplings of the constituent quarks. This information could then be used to test various proposed theories of how hadrons are constructed out of quarks.

In the light quark model, the meson resonance states are identified with the states of the SU(3) group given by the $3 \otimes \bar{3} = 8 \oplus 1$ representation and are referred to as a nonet. The octet states are made up of an $I = 1$ triplet: $u\bar{d}$, $d\bar{u}$, and $(u\bar{u} - d\bar{d})/\sqrt{2}$; two $I = 1/2$ doublets $u\bar{s}$, $s\bar{u}$, $d\bar{s}$, $s\bar{d}$; and an $I = 0$ singlet $(u\bar{u} + d\bar{d} - s\bar{s})/\sqrt{6}$. The remaining nonet state is an $I = 0$ singlet denoted by $(u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$. In practice, the three observable hadron states with $I_3 = 0$ are found to be mixtures of the three $I_3 = 0$ quark model states, thus giving three states in each nonet which can, in principle, couple to an $s\bar{s}$ quark state\(^4\).
A given quark model state is labeled by its total angular momentum \( J = L + S \), (where \( L \) is the orbital angular momentum and \( S \) is the total spin angular momentum), total isotopic spin \( I \), parity \( (P = (-1)^{L+S}) \), charge conjugation parity \( (C = (-1)^{L+S}) \), and, for states with integer isotopic spin, \( G \) parity \( (G = (-1)^{L+S+I}) \). A schematic for a typical state is shown in figure 1.1. Figure 1.2 is a convenient way of showing the expected quark model states based on a harmonic oscillator potential. The states are categorized in this figure by \( I, J^P \), \( L \) and \( n \) the radial excitation number, as a function of mass-squared. Each row of four boxes represents a nonet of the quark model, with each box representing the separate isospin multiplets. The bottom row of each block represents those states with \( S = 0 \), and the upper rows (or row for \( L = 0 \)) represent the states with \( S = 1 \). The boxes corresponding to observed states have been labeled. Of these states, the best established are those in the upper row of each set of boxes, known as the leading natural spin-parity states; where leading is defined as the lowest mass state with a given spin-parity assignment, and natural parity is defined as \( P = (-1)^J \). Similarly, unnatural parity is defined as \( P = (-1)^{J+1} \).

As one can clearly see there are still many states yet to be detected.

This study will be concerned with the reactions

\[
\pi^+ p \rightarrow K^+ K^- n
\]  

1.1

and

\[
\pi^+ p \rightarrow K^+ K^- \pi^+
\]  

1.2

diagramed in figure 1.3. In order to study the virtual reactions

\[
\pi^+ \pi^- \rightarrow K^+ K^-
\]  

1.3
Figure 1.1. $\bar{q}q$ meson system and its quantum numbers

Parity ($P$), charge conjugation ($C$), and $G$ parity determined by the orbital angular momentum ($L$), total spin ($S$) and total isospin ($I$) of the $\bar{q}q$ system.
\[ J = L + S \]
\[ P = (-1)^{L+1} \]
\[ C = (-1)^{L+S} \]
\[ G = (-1)^{L+S+I} \]
Figure 1.2. Light quark meson spectrum prior to this analysis. Circled states are those accessible to this analysis.
Figure 1.3. Pion exchange diagrams for the reaction studies.

Top - $\pi^+ n + X^0 n \rightarrow K^+ K^- p$ with an exchanged $\pi^-$

Middle - $\pi^+ p + X^0_{\Delta^{++}} \rightarrow K^+ K^- \pi^+ p$ with a $\pi^-$ exchanged

Bottom - $\pi^+ p + X^0 p \rightarrow K^+ K^- \pi^+ p$ with a $\pi^0$ exchanged
the low -t kinematic region is selected. The variable t is defined as the square of the magnitude of the four-momentum transfer from the initial baryon to the final baryon, and is equal to the square of the mass of the exchanged virtual particle (in this case a pion). The low -t region is selected because this is the kinematic region nearest to the pion pole. Thus, the cross section for reactions 1 and 2 are expected to be dominated by events with single pion exchange in the low -t kinematic region\(^{(6)}\). For reactions 3 and 4, a consideration of G parity shows that only those states of even G parity can be produced at the meson vertex (upper vertex of the diagrams in figure 1.3). Also, an examination of conservation of angular momentum and parity imply that only states with natural spin-parity are allowed, i.e., only states with \(J^P = 0^+, 1^-, 2^+\), etc. can be produced. The unnatural parity states require that a particle with \(J \geq 1\) such as a \(\rho\) be the exchanged particle.

The development in recent years of particle detectors with nearly \(4\pi\) acceptance and high event rate capabilities (such as the Multiparticle Spectrometer (MPS) at Brookhaven, the OMEGA Spectrometer at CERN, and the Large Aperture Solenoid Spectrometer (LASS) at SLAC) has allowed the collection of large data samples which nearly cover the full angular distribution for the decaying particles. This allows for a more accurate determination of a resonance's mass width and spin-parity than could be done in previous experimental apparatus, such as forward spectrometers, which could take high event rates but had limited angular acceptance, or bubble chambers which have good angular acceptance but
low event rates. The essential new ingredients in these new spectrometers are the high statistics which allow for the determination of states produced with low cross section and the nearly complete geometrical acceptance which is essential for a determination of the spin-parities of many states.

The data described in this analysis were taken in May and June of 1978, and are part of an experiment run on LASS at the Stanford Linear Accelerator Center (SLAC) in California\(^7\). The experiment was a collaborative effort of the experimental High Energy Physics Group at Iowa State University and a group from the University of Michigan. This exposure of the LASS apparatus resulted in approximately 11 million events being recorded on magnetic tape, about 5.2 million of which satisfied our primary physics trigger. The data were later processed through programs for track reconstruction, geometrical fitting, and kinematic selection on the ISU High Energy Physics Group's DEC VAX 11/780 computer giving the raw data sample.

In order to obtain the decay angular distributions, the raw data sample had to be corrected for the non-uniformity of the angular acceptance of the apparatus. This required the use of an intricate Monte Carlo simulation package for the generation of the angular acceptance arrays. The raw data sample was then processed through an analysis routine which determined the acceptance corrected angular distributions and spherical harmonic moments. An analysis of these moments can give insight into the nature of the leading natural spin-parity resonances. To get information on the other states one needs
to fit the data using a procedure known as a partial wave analysis.

It needs to be noted, that there have been other experiments performed with the LASS apparatus and thus, some of the computer routines used for this analysis were originally developed at SLAC. Specifically, the event reconstruction routines, the geometry fitting routines, and the Monte Carlo routines were originally developed at SLAC for use with this apparatus and suitably modified for our experiment.

In Chapter II, there is a discussion of the various detection devices used in the LASS apparatus. In Chapter III, there is a discussion of the fast trigger logic and data acquisition system. In Chapter IV, the event reconstruction package and the production procedure are described. In Chapter V, there is a description of the raw data sample, the various backgrounds, and the resolution of the data. In Chapter VI, there is a description of the moment calculation, the acceptance corrected data and also a physics interpretation of the moment distributions.
CHAPTER II

EXPERIMENTAL APPARATUS

Introduction

The experiment was performed by exposing the Large Aperture Solenoidal Spectrometer (LASS), located at the Stanford Linear Accelerator Center (SLAC), to a 10 GeV/c positive pion beam incident on a liquid deuterium target. The trigger was designed to select events in which the particles produced in the forward direction were likely to be kaons. The LASS facility was designed and built by experimental group B at SLAC, with some of the apparatus built by groups from the Johns Hopkins University and the California Institute of Technology. A diagram of the facility is shown in figure 2.1. Since the apparatus was not constructed by the Ames Laboratory high energy physics group, the description of the apparatus will be brief in the following sections; for more detailed information see references 8 - 18.

The LASS facility was used, for this experiment, because it has nearly complete $4\pi$ geometrical acceptance as well as good resolution in both transverse and longitudinal momenta. The solenoidal magnet provided a means of measuring momenta of those particles with large-angle trajectories and relatively low momenta. And, the dipole magnet provided a means to measure the momenta of the small-angle high-momentum particles by joining track segments found in the downstream (dipole) chambers to track segments found in the region between the two magnets and solenoid region via an extrapolation through the dipole field.
Figure 2.1. Plane view of the LASS spectrometer.
Particle identification was accomplished with the time-of-flight scintillation counter array and the two Cherenkov counters (C1 and C2). The coordinate system, used in this experiment, was defined with the positive z-axis along the beam direction (left to right in figure 2.1), the positive y-axis upward perpendicular to the surface of the earth, and the x-axis forming a right-handed coordinate system.

**Beam**

For our experiment, we used a 10 GeV/c secondary pion beam supplied by the main accelerator to beam line 20-21 (shown in figure 2.2). During the data taking period, the main accelerator's 21 GeV/c electron beam was run at 180 pulses per second with each pulse 1.6 μs long. The electron beam was focused on a 0.22 radiation length copper radiator for enhancement of the electron shower, and then onto a 0.85 radiation length beryllium target. By using the dipole magnet, 20D1, we were able to select the beam momentum with a momentum spread of Δp/p ≈ 2% at FWHM, and with a dispersed focus at the P-hodoscope scintillator we were able to measure the momentum of a given beam particle to approximately 0.25%. Beam line 20-21 also contains lead filters which reduced the electron contamination of the pion beam to the level of 10^-6 electrons per pion. There are also two RF mass separators available but these were not used since 94% of the particles left in the beam line after the lead filters were pions. The identification of beam particles is supplied by two Cherenkov counters, C_π which fired only on pions, and C_κ which fired on pions and kaons; both counters were insensitive to
Figure 2.2. LASS beam line.
protons. Thus, a pion identification required that both \( C_{\pi} \) and \( C_{K} \) fire in coincidence.

The beam track finding elements of the detector consisted of the \( \theta-\phi \) scintillation hodoscope, the x-y scintillation counter, the beam PWCs and the SE scintillation counter. The \( \theta-\phi \) scintillation hodoscope was located 14 meters upstream of the target and consisted of 24 1.27 cm wide strips, with one-half arranged vertically and one-half arranged horizontally. The SE scintillation counter located at the point where the beam entered the LASS building approximately five meters upstream of the target was made of a single scintillator. All beam and device timing was done with respect to the signal from this counter. The x-y scintillation counter located one meter in front of the target was made of four small scintillators arranged in a square, and were used to veto an event when two beam particles were incident on the target within ±32 nanoseconds of each other. The ring counter surrounding the x-y counter was used to veto on the beam halo. The beam PWCs were located one and two meters in front of the target. The first beam PWC was constructed with 4 wire planes, XYEP (vertical, horizontal, and \( \pm 45^\circ \) to the vertical) and gave a spatial resolution of \( \pm 1 \text{ mm} \). The second beam PWC was constructed with 5 wire planes (2X, 2Y and an E) and also had a spatial resolution of \( \pm 1 \text{ mm} \). The magnets in the beam line were controlled by a computer monitoring system, called Yardmux, which consisted of a Data General Nova Computer and its associated current monitoring devices. This system monitored and adjusted the currents of all the magnets used in the beam line plus the dipole magnet...
which was part of the spectrometer. The final setting for the beam current gave the equivalent of 2.5 pions per beam pulse.

**Target**

For this experiment, we used a liquid deuterium target, located at the upstream end of the solenoid magnet. The target was contained in a cylinder 91.4 cm long and 5.24 cm in diameter, through which the liquid deuterium was continuously circulated (see figure 2.3). The temperature and pressure of the cell were recorded at the beginning of each run, and were later used to compute the density of the deuterium in the target.

**Magnets**

The LASS spectrometer used two magnets, a superconducting solenoidal magnet, and a normal dipole magnet. The superconducting solenoidal magnet consisted of four liquid helium cooled coils separated by 15.24 cm gaps which allowed for the insertion of capacitive diode (C-D) and proportional wire chambers (PWCs). The coils were enclosed by an iron casing which acted as a flux return; both ends of the magnet were capped with flux return mirrors. The magnet had an over-all length of 465 cm and an inside diameter of 185 cm. For this experiment, the current was run at 1600 amps giving a uniform field along the cylinder axis of 22.4 Kilogauss with an approximate non-uniformity of only 1%. The dipole magnet was a normal iron-core magnet with a one meter vertical gap, a 2 meter wide horizontal opening, and a field region of
LIQUID HYDROGEN TARGET

Mylar Window
Target Cell

2 1/16' Mylar Cylinders
Platinum Resistor

Vapor Pressure Bulb
Vacuum
Resistor Wire Leads

LH$_2$ Flow
LH$_2$ Return Flow
Mylar Window

Figure 2.3. The liquid deuterium target.
2.4 meters in the beam direction. For this experiment, the dipole magnet was run at 7050 amps giving an integrated flux of 39 Kilogauss-meters.

**Detection Devices**

In this section, the various detection devices will be described starting with those devices located in the solenoid region, followed by devices in the region between the solenoid and dipole magnets, referred to as the twixt region, and finally the devices located downstream of the dipole magnet.

**Solenoid region**

The solenoid region is that area of the detector located inside the solenoid magnet. The devices in this region are the cylindrical spark chamber package, the planar C-D chambers and associated proportional wire plug chambers, the full-bore proportional wire chambers, and the proportional wire trigger chambers.

**Cylinder chamber package** The cylinder chamber package consisted of a cylindrical proportional wire chamber (PWC) and five cylindrical capacitive diode (C-D) chambers concentric to the target region of the solenoid magnet, with the PWC chamber being closest to the target. All of the cylindrical chambers had a 2 mm wire spacing except the largest which had a 4 mm wire spacing. For the PWC chamber, there was one readout plane with wires parallel to the cylinder axis, giving an accurate \( \phi \) angle determination but no \( z \) information. This chamber also had good time resolution and was used to eliminate wide-angle out-of-time tracks. For the C-D chambers, there were two gaps
with three readout planes (see figure 2.4). One set of wires was parallel to the z-axis and the other two sets were strung at angles of ±5.7° to the z-axis, giving a helical path to the wires. The wires parallel to the z-axis gave a precise $\phi$ information. And the wires at an angle to the z-axis gave a precise $\phi$ and approximate $z$ information. Thus, a track passing through all cylinder chambers could have eleven $\phi$ measurements and six $z$ measurements. The readout system for these chambers is described in the data readout section in this chapter.

Planar chambers In the solenoid region, there are twelve planar devices, three full-bore capacitive diode readout spark chambers with their accompanying proportional-wire-chamber (PWC) plugs; three full-bore PWC chambers and three PWC trigger chambers, also full-bore. Each of the C-D chambers was constructed with four wire planes and two gaps. The wires for the planes were spaced at 0.907 cm intervals with one plane of wires oriented horizontally, one vertically, and one at each of ±30° to the vertical; referred to as X, Y, E, and P, respectively. Due to the long memory time of spark chambers, the central region of each C-D chamber was desensitized by a circular styrofoam plug 21.6 cm in diameter, and this desensitized region was covered by a proportional wire 'plug' chamber. These small chambers were hung over the center of the C-D chamber frames and their active area was somewhat larger than the desensitized region of the associated C-D chamber. The plug chambers had three wire planes, X, Y, and E, (horizontal, vertical, and $\pm35^\circ$ to vertical) and a wire spacing of 1.016 mm. The full-bore PWC chambers had an active area which filled the aperture of the solenoid
Figure 2.4. Cylindrical chamber package
(a) Cut away view of the entire package.
(b) Detail of wire orientation of each gap.
magnet. They were constructed with three wire readout planes; X, Y, and E (horizontal, vertical and $+45^\circ$ to the vertical), and a wire spacing of 2 mm. The three PWC trigger chambers, referred to as TA, TB, and TC, were also full-bore chambers. They were constructed with one wire plane and an etched foil cathode readout which provided radial and azimuthal information with a $\Delta \phi$ of 2.81$^\circ$ except for the inner region of TA which had a $\Delta \phi$ of 4.62$^\circ$. These chambers were used solely for in-time corroboration and not track finding. (Figure 2.5 shows the orientation of the wires for the various PWC readout planes.)

**Twixt region**

The twixt region is that area between the two spectrometer magnets. The devices in this region are the Cherenkov counter CI, the time-of-flight counter, two planar MS chambers, two planar C-D chambers and associated PWC plug chambers, and two PWC hodoscopes.

**Cherenkov counter CI** The counter CI (see figure 2.6 and 2.7 for diagram) is a thirty-eight cell segmented Cherenkov counter. The cells were arranged in three concentric rings of twelve cells each with the two remaining cells centered along the beam axis. The mirrors were made of aluminized mylar, which reflected the light into the extension arms where it was focused on the phototube for that cell by a Fresnel lens. Extension arms placed the phototubes outside most of the fringe magnetic field of the solenoid. The phototubes were shielded from the remaining fringe field by iron and mu-metal cylindrical shielding and were also fitted with coils to compensate for any remaining field along
Figure 2.5. The readout planes of the proportional wire chamber (PWC) system.
Figure 2.6. Plane view of the Cherenkov counter C1 looking down beam.
Figure 2.7. Side view of Cherenkov counter Cl.
the cylindrical shielding axis. The inner surfaces of each cell and extension arm were coated with aluminized mylar to improve the light collecting properties. All cells of CI were oriented so they would point back to the center of the target, this was done to increase the probability that fast tracks would pass through only one cell. For this experiment, the counter was filled with Freon-12 at atmospheric pressure, giving a threshold $\beta$ of 0.9989, and corresponding to a threshold momentum of 3.0 GeV/c for pions, 10.6 GeV/c for kaons, and 21.1 GeV/c for protons. The discriminated signals from all the cells were summed and the resulting signal was used as a veto in our primary physics trigger to be described in the next chapter.

Time-of-flight counter (TOF) The time-of-flight counter was located at the downstream face of the first Cherenkov counter. The TOF counter consisted of twenty-four scintillation counters arranged azimuthally (see figure 2.8), with two paddles matching the cell boundaries of CI, and four counters located in the center (referred to as the quad counters). The twenty-four pie shaped counters were connected to time-to-digital converter modules (TDCs), and were used to calculate particle masses based on the time-of-flight to the counter and the measured track parameters. The quad counters were not connected to TDCs because few of the tracks passing through them were of low enough momentum that the time resolution of the counters could distinguish between particle types. The discriminated signals from each of the twenty-eight counters were summed and used as part of our physics trigger.
Figure 2.8. Time-of-flight hodoscope array.
Planar spark chambers  Also in the twixt region were two C-D spark chambers with their corresponding PWC plug chambers (identical to those in the solenoid region), two magnetostrictive (MS) spark chambers, and two PWC hodoscope chambers (referred to as JHXY and JHUP). The MS chambers were constructed with four wire planes: XYEP (horizontal, vertical, and ±30° to the vertical), with a wire spacing of 0.907 mm, and two gaps. The central region of each chamber was desensitized to the beam region due to long chamber memories. The MS readout wands were fitted with biasing coils to counter the effects of the fringe fields from the solenoid and dipole magnets. The JHXY PWC hodoscope had one vertical wire plane with a wire spacing of 4 mm and a 2.8 cm horizontal cathode readout strip. This chamber was used in track finding and in providing discrimination between in-time and out-of-time tracks. The JHUP PWC hodoscope was not used in this experiment because of technical problems.

Dipole region

The dipole or downstream region is the area downstream of the dipole magnet. The devices in this region were a PWC hodoscope, four magnetostrictive spark chambers, two scintillator hodoscopes, and a Cherenkov counter (C2).

Planar chambers  The PWC hodoscope, referred to as JH down, had one wire plane with a 4 mm wire spacing. It gave an x-coordinate readout with good time resolution. The chamber was used in the primary physics trigger and in elimination of out-of-time dipole track segments.
The four MS chambers were constructed identically to the MS chambers in the twixt region. These chambers were shifted to the left when facing downstream along the beam so the unscattered beam would pass through the desensitized region.

Scintillation hodoscopes

The two scintillation hodoscopes, HA and HB, were constructed with the scintillators placed in a side-by-side picket fence arrangement. For each device, there were two such fences referred to as top and bottom (as shown in figure 2.9). For each row of HA, there were twenty 20.3 cm x 83.8 cm counters and a 10.2 cm x 83.8 cm counter in the center. The narrower counters in the center were shifted vertically to give a 10.2 cm x 10.2 cm hole through which unscattered beam particles could pass. For HB, there were a total of thirty-eight 10.2 cm to 15.2 cm x 81.3 cm counters in each row with the center counters shifted vertically to give a 10.2 cm x 10.2 cm beam hole. The hodoscopes were shifted similarly to the MS chambers so the unscattered pion beam would pass through the 10.2 cm x 10.2 cm holes. These counters provided in-time tracking information and were used in coincidence with the PWC hodoscope JH down as part of the primary physics trigger. They were also used as corroboration for downstream track segments. Attached to the frame of HB was a small circular scintillator referred to as LP3 which covered the beam hole and was used as part of the beam straight-through trigger.

Cherenkov counter C2

The last detection device in the system was a large pressurized Cherenkov counter referred to as C2. This
Figure 2.9. HA and HB scintillation hodoscope arrays
Top is HA, bottom is HB.
counter had eight mirrors, divided into two horizontal rows, with each mirror configured as shown in figure 2.10. Each mirror had its own phototube, and associated coils and magnetic shielding. The counter was filled with Freon-12 at a pressure of one atmosphere, giving the same thresholds as for Cl. The information from this counter was used as a veto in one of the secondary physics triggers and provided information on the efficiency of Cl which was used as a veto in the primary physics trigger.

Data Readout Systems

This section briefly describes the various systems for data readout; for more details see references 8-18. For the C-D chambers, each wire was attached to a capacitive-diode discriminator. The output of these discriminators was stored in a shift register, which was then strobed into the data acquisition system (to be described in Chapter 3). For the PWC chambers, an amplitude discriminator circuit was attached to each wire. The discriminated output was then strobed at 49 MHz into a thirty-two bit random access memory, or RAM, giving a thirty-two bit time profile which allowed for timing in software rather than in hardware. The contents of the RAM were then read into the data acquisition system. For the MS chambers, the arrival time of signals generated by the fiducials and sparks were measured, digitized and then sent to the data acquisition system. For the Cherenkov counters, the dynode signal for each phototube was amplified and fed into an analog-to-digital (ADC) converter, and the anode signal after discrimination was stored in an
Figure 2.10. Side view of Cherenkov counter C2.
event-gated latch called a "buffer strobe module". Both sets of
discriminated signals were then read into the data acquisition system.
For the scintillation counters the output of each phototube was dis­
criminated and sent to ADC modules. In addition, the twenty-four outer
paddles of the time-of-flight counter were also read-out to time-to-
digital (TDC) converter modules. All ADC and TDC modules were then
read into the data acquisition system.

Device efficiency and resolutions  The efficiencies and spatial
resolutions of the various detection devices are summarized in tables
2.1 through 2.5. These values were obtained from track reconstruction
and detection efficiencies recorded as part of the end run summary
output from the track reconstruction program to be described in Chapter
IV. Other values of interest are listed for comparison purposes.
Table 2.1 LASS Cylindrical Chamber Device Summary

<table>
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<th>Readout Type^a</th>
<th>Cylinder Radius</th>
<th>Typical Trackfinding Efficiency</th>
<th>Typical Spatial Resolution</th>
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<td>φ</td>
<td>5.2 cm</td>
<td>98%</td>
<td>0.07 cm</td>
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<td>CD Cylinders:</td>
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<td>φ</td>
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<td>91%</td>
<td>0.10 cm, 0.80 cm</td>
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<td>3</td>
<td>φ</td>
<td>12.7 cm</td>
<td>96%</td>
<td>0.10 cm</td>
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<tr>
<td>4</td>
<td>φ</td>
<td>15.7 cm</td>
<td>92%</td>
<td>0.06 cm, 0.74 cm</td>
</tr>
<tr>
<td>5</td>
<td>φ</td>
<td>17.8 cm</td>
<td>93%</td>
<td>0.17 cm</td>
</tr>
<tr>
<td>6</td>
<td>φ</td>
<td>20.8 cm</td>
<td>93%</td>
<td>0.06 cm, 0.71 cm</td>
</tr>
<tr>
<td>7</td>
<td>φ</td>
<td>22.9 cm</td>
<td>24%</td>
<td>0.12 cm</td>
</tr>
<tr>
<td>8</td>
<td>φ</td>
<td>31.0 cm</td>
<td>86%</td>
<td>0.13 cm, 0.71 cm</td>
</tr>
<tr>
<td>9</td>
<td>φ</td>
<td>32.0 cm</td>
<td>87%</td>
<td>0.13 cm</td>
</tr>
<tr>
<td>10</td>
<td>φ</td>
<td>56.4 cm</td>
<td>70%</td>
<td>0.18 cm, 1.50 cm</td>
</tr>
<tr>
<td>11</td>
<td>φ</td>
<td>57.4 cm</td>
<td>74%</td>
<td>0.25 cm</td>
</tr>
</tbody>
</table>

^a Radii vary but all cylinders are 91.3 cm in length.
### Table 2.2 LASS Planar Chamber Device Summary

<table>
<thead>
<tr>
<th>Device Name</th>
<th># Chambers In System</th>
<th># Planes Per Chamber</th>
<th>Wire Spacing</th>
<th>Approximate Active Area (In cm)</th>
<th>Typical Trackfinding Efficiency</th>
<th>Typical Spatial Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PROPORTIONAL WIRE CHAMBERS:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Chambers</td>
<td>2</td>
<td>4 and 5</td>
<td>1 mm</td>
<td>6.4 x 6.4</td>
<td>99%</td>
<td>0.28 mm</td>
</tr>
<tr>
<td>Plug Chambers</td>
<td>5</td>
<td>3</td>
<td>1 mm</td>
<td>25.6 x 25.6</td>
<td>94%</td>
<td>0.28 mm</td>
</tr>
<tr>
<td>Full Bore Chambers</td>
<td>3</td>
<td>3</td>
<td>2 mm</td>
<td>128 x 128</td>
<td>95%</td>
<td>0.55 mm</td>
</tr>
<tr>
<td>Trigger Chambers</td>
<td>3</td>
<td>2</td>
<td>cathode readout</td>
<td>71 cm radius circle</td>
<td>97%</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>JHU</td>
<td>1</td>
<td>1</td>
<td>4 mm</td>
<td>200 x 175</td>
<td>98%</td>
<td>3.0 mm</td>
</tr>
<tr>
<td>JHXY (X plane) (Y plane)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1</td>
<td>1 X</td>
<td>4 mm</td>
<td>200 x 175</td>
<td>99%</td>
<td>2.5 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Y</td>
<td>28 mm</td>
<td>200 x 175</td>
<td>84%</td>
<td>8.0 mm</td>
</tr>
<tr>
<td>JHD</td>
<td>1</td>
<td>1</td>
<td>4 mm</td>
<td>200 x 120</td>
<td>92%</td>
<td>2.5 mm</td>
</tr>
<tr>
<td><strong>SPARK CHAMBERS:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td>5</td>
<td>4</td>
<td>0.9 mm</td>
<td>160 x 160</td>
<td>87%</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>MS (Twixt) (Downstream)</td>
<td>2</td>
<td>4</td>
<td>0.9 mm</td>
<td>400 x 200</td>
<td>92%</td>
<td>0.9 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>0.9 mm</td>
<td>300 x 150</td>
<td>97%</td>
<td>0.6 mm</td>
</tr>
</tbody>
</table>

<sup>a</sup>Y plane has 28 mm spaced cathode readout pads.
<table>
<thead>
<tr>
<th>Name of Device</th>
<th>Number of Elements</th>
<th>Approximate Active Area</th>
<th>Typical Track-finding Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-of-Flight</td>
<td>28</td>
<td>145 cm rad. circle</td>
<td>99%</td>
</tr>
<tr>
<td>HA</td>
<td>42</td>
<td>420 x 166 cm</td>
<td>95%</td>
</tr>
<tr>
<td>HB</td>
<td>76</td>
<td>459 x 162 cm</td>
<td>93%</td>
</tr>
<tr>
<td>LP3 (veto)</td>
<td>1</td>
<td>9.8 cm rad. circle</td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>
Table 2.4  Cl Efficiency Checking Both ADC and BUF

(If either the ADC or BUF fired, it is considered a hit)

<table>
<thead>
<tr>
<th>A</th>
<th>Eff</th>
<th>Err</th>
<th>B</th>
<th>Eff</th>
<th>Err</th>
<th>C</th>
<th>Eff</th>
<th>Err</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68.8</td>
<td>8.2</td>
<td>1</td>
<td>95.0</td>
<td>1.2</td>
<td>1</td>
<td>98.2</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>66.7</td>
<td>9.6</td>
<td>2</td>
<td>96.3</td>
<td>1.1</td>
<td>2</td>
<td>97.8</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>74.2</td>
<td>7.9</td>
<td>3</td>
<td>89.7</td>
<td>1.8</td>
<td>3</td>
<td>96.0</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>71.9</td>
<td>8.0</td>
<td>4</td>
<td>93.5</td>
<td>1.4</td>
<td>4</td>
<td>96.2</td>
<td>0.9</td>
</tr>
<tr>
<td>5</td>
<td>61.5</td>
<td>9.5</td>
<td>5</td>
<td>84.0</td>
<td>2.0</td>
<td>5</td>
<td>97.0</td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>40.6</td>
<td>8.7</td>
<td>6</td>
<td>78.1</td>
<td>2.1</td>
<td>6</td>
<td>94.3</td>
<td>1.0</td>
</tr>
<tr>
<td>7</td>
<td>60.0</td>
<td>9.8</td>
<td>7</td>
<td>77.4</td>
<td>2.3</td>
<td>7</td>
<td>91.2</td>
<td>1.3</td>
</tr>
<tr>
<td>8</td>
<td>70.4</td>
<td>8.8</td>
<td>8</td>
<td>93.2</td>
<td>1.4</td>
<td>8</td>
<td>93.3</td>
<td>1.2</td>
</tr>
<tr>
<td>9</td>
<td>59.0</td>
<td>7.9</td>
<td>9</td>
<td>95.0</td>
<td>1.2</td>
<td>9</td>
<td>90.9</td>
<td>1.4</td>
</tr>
<tr>
<td>10</td>
<td>67.9</td>
<td>8.8</td>
<td>10</td>
<td>84.4</td>
<td>2.0</td>
<td>10</td>
<td>91.7</td>
<td>1.2</td>
</tr>
<tr>
<td>11</td>
<td>42.1</td>
<td>8.0</td>
<td>11</td>
<td>84.9</td>
<td>1.9</td>
<td>11</td>
<td>89.8</td>
<td>1.4</td>
</tr>
<tr>
<td>12</td>
<td>76.9</td>
<td>8.3</td>
<td>12</td>
<td>96.6</td>
<td>1.0</td>
<td>12</td>
<td>97.3</td>
<td>0.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ring</th>
<th>Eff</th>
<th>Err</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>62.5</td>
<td>2.6</td>
</tr>
<tr>
<td>B</td>
<td>88.8</td>
<td>0.5</td>
</tr>
<tr>
<td>C</td>
<td>94.5</td>
<td>0.3</td>
</tr>
<tr>
<td>D</td>
<td>26.7</td>
<td>6.6</td>
</tr>
</tbody>
</table>

CI Overall Efficiency 90.8 ± 0.3
Table 2.5  C2 Overall Efficiency using 4.5 and 5.5 GeV/c data

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>84.7 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>Center</td>
<td>94.1 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>Edge</td>
<td>77.5 ± 1.7</td>
<td></td>
</tr>
<tr>
<td>Corner</td>
<td>70.9 ± 6.1</td>
<td></td>
</tr>
</tbody>
</table>

C2 Overall Efficiency using 10 GeV/c data

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>98.2 ± 1.8</td>
<td></td>
</tr>
<tr>
<td>Center</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>Edge</td>
<td>96.3 ± 3.6</td>
<td></td>
</tr>
<tr>
<td>Corner</td>
<td>100.0</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER III

TRIGGER LOGIC AND DATA ACQUISITION

Trigger Logic

For this experiment, there were five different "triggers" defined, each of which could trigger the fast electronics and data acquisition systems to record the information from an event onto magnetic tape. Two of the triggers (T0 and T4) were for physics studies, and the remaining three triggers (T1, T2, and T3) were for monitoring, calibration, normalization, and other studies of the system. Specifically, T0 was our primary physics trigger, T1 a general interaction trigger, T2 an elastic trigger, T3 a beam particle trigger, and T4 a secondary physics trigger. (This last trigger was changed several times during the data taking period and data from this trigger will not be used in this analysis.) The T2 triggered events were used for beam-momentum calibration and resolution as well as for dipole-track momentum-resolution studies. The T3 triggered events were used for normalization and beam property studies. The T1 triggered events were intended to be used for normalization studies, but other methods proved to be superior. The high trigger rates for the T1, T2, T3, and T4\(^{(19)}\) events required us to implement a scheme whereby only a fraction of these events actually triggered the apparatus, in order to avoid the excessive dead-time associated with too high a rate of secondary triggers. This was accomplished through the use of trigger rate equalizer modules, which allowed the experimenters to choose what fraction of these events would be
recorded by the system. The TO trigger, however, was not subject to any rate reduction, except for intrinsic dead-time limitations. Thus, any TO trigger that occurred in principle always activated the data acquisition system. This activation was termed an event trigger and locked out any further triggers during the device firing and readout sequence. All five triggers were operating simultaneously to insure that the calibration and normalization triggers were subject to the same conditions as the physics triggers.

At various points during the data taking, runs were made with special triggers for the purpose of determining values for the alignment constants of the various chambers to be used in the event reconstruction program, for determining the event rate for events not occurring in the D₂ target (called target empty runs), and for efficiency studies of the two Cherenkov counters and the time-of-flight hodoscope.

**Physics Trigger**

**TO logic**

The TO logic was designed to select events for π⁺p interactions which had at least one fast-forward particle with a mass greater than the pion mass. This logic consisted of five parts: (1) pion beam logic, (2) PWC 1.5 cluster logic, (3) first Cherenkov counter logic, (4) TOF counter logic, and (5) downstream hodoscope logic.

**Beam logic** The beam logic (see figure 3.1 for schematic) was
Figure 3.1. The beam logic.
designed to produce a logical 'true' signal when one identified pion was
detected in the SE and XY scintillation counters during a beam spill
with no other particles within ±32 ns\(^{(17)}\). The symbolic notation for
the pion beam trigger is:

\[
PION = SE \cdot \bar{ZR} \cdot (\Sigma Y = 1) \cdot C_π \cdot C_K
\]

The ring counter vetoed the beam halo and the proper \(C_π - C_K\) combination
insured that the particle was a pion. The \(\Sigma Y = 1\) signal indicated that
one and only one of the XY scintillation counters was on. But \(\Sigma Y = 1\)
could also occur as a result of a second beam particle entering the same
quadrant as the first at approximately the same time. Thus, a small
percentage of PION beam triggers actually permitted two beam particles,
an effect that had to be corrected for in the normalization calculations.
(This effect was less than a 1.0% correction.)

1.5 PWC cluster logic

The 1.5 PWC cluster logic was designed
to count "clusters" in each of the 1.5X and 1.5Y proportional wire planes.
A cluster was defined as one or more consecutive wires that produced
signals. For example, if five consecutive wires were on, it would count
as one cluster, but if there were sequentially two on, one off, and two
on, that would count as two clusters. The region of the 1.5 PWC chamber
within 1.6 cm of the central axis of the solenoid was not included in the
cluster logic in order to reduce triggers in this region due to un-
scattered beam particles and small angle elastically scattered particles.
The effect of this logic was to insure that two or more charged tracks
were produced in the solenoid region.
**Cl logic**  The Cl logic summed all the cells in the upstream Cherenkov counter that detected light. This signal was then used in the TO trigger in a veto mode. The event sample satisfying the CI veto logic was enriched with events having kaon or baryon pairs.

**TOF logic**  The TOF logic counted the number of individual TOF counters which recorded a signal. For the TO trigger, two or more counters were required to be on. This logic selected events with two or more tracks, as did the 1.5 PWC cluster logic, but the better time resolution of the TOF counter (\(\sim 1.5\) ns vs \(\sim 50\) ns) helped reduce the number of out-of-time tracks which could satisfy the PWC 1.5 cluster logic.

**Downstream hodoscope logic**  The downstream hodoscope logic involved the three downstream hodoscope counters JHD, HA and HB. The logic circuit was designed to sum the number of hits in each chamber separately. This was accomplished in JHD by summing the number of wires that recorded a signal, and for HA and HB by summing the number of individual scintillators detecting a signal. It was then required that one or more hits be recorded in each of these three devices. For testing purposes, we made ten runs with this coincidence set at "2 out of 3" devices. This setup was not used in general because the "3 out of 3" requirement insured that the downstream track passed through the aperture of the dipole magnet, while the "2 out of 3" setup would allow tracks that passed through the iron of the dipole magnet (and were thus very likely to have been scattered) to hit HA and HB thus triggering the
apparatus. This part of the TO trigger insured that at least one track passed through the dipole aperture, and therefore, had a momentum greater than approximately 3 GeV/c. It took a momentum of at least 3 GeV/c for a particle to cross from the upstream to the downstream region. This effect, combined with the Cl veto logic, allowed the apparatus to be triggered on events which produced 'fast' (greater than 3 GeV/c) forward tracks likely to be primarily kaons. The notation for the TO trigger logic was:

\[
\text{TO} = \text{PION} \cdot ((E1.5X \geq 2 \text{ OR } E1.5Y \geq 2) \cdot (\Sigma C1 > 1) \cdot (\Sigma TOF > 2) \cdot (\Sigma JHD > 1 \cdot \Sigma EHA > 1 \cdot \Sigma EHB > 1))
\]

The ratio of the number of triggers to the numbers of pion beam triggers, or trigger rate, for each of the event triggers, is shown in table 3.1. There was a large overlap between the events satisfying the final T4 trigger and the events satisfying the TO trigger. Thus, the total trigger rate was approximately 3%. A diagram of the TO trigger logic is shown in figure 3.2.

**Event Trigger**

The event trigger\(^{(8-18)}\) was a signal for the various spectrometer devices to readout their data which was then to be transferred to the mass storage units (magnetic tape).

This trigger consisted of one of the equalized data triggers being satisfied (most frequently TO) in coincidence with a PDP-11 Ready signal. This would cause the following series of events:

(1) PDP-11 Ready is turned off.
<table>
<thead>
<tr>
<th>Trigger Type</th>
<th>Raw Rate</th>
<th>Trigger Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>TO triggers/PION triggers</td>
<td>1.5%</td>
<td>not trigger rate</td>
</tr>
<tr>
<td>T1 /PION</td>
<td>16%</td>
<td>equalized</td>
</tr>
<tr>
<td>T2 /PION</td>
<td>8.6%</td>
<td>.17%</td>
</tr>
<tr>
<td>T3 /PION</td>
<td>73%</td>
<td>.18%</td>
</tr>
<tr>
<td>T4 /PION (runs 6289 - end)</td>
<td>1.8%</td>
<td>not trigger rate</td>
</tr>
</tbody>
</table>

Equalized Rate
Figure 3.2. TO trigger logic.
47

PWC 1.9, PWC TOF TOF TOF SPARK CHAMBER ENABLE SPARK CHAMBER ENABLE SPARK CHAMBER TRIGGER EVENT GATE TO TRIGGER

1.5x PWC

1.5y PWC

TOF 1 TOF 2 TOF 3 TOF 24 QUAD 1 QUAD 4 TO TRIGGER

CI-1 CI-2 CI-38 B.S. CI >1

JHD 1 JHD 2 B.S. 

HA 1 HA 2 HA 42 B.S. 

HB 1 HB 2 HB 76 B.S.

\[ \Sigma 1.5x \geq 2 \]

\[ \Sigma 1.5y \geq 2 \]

\[ \Sigma \text{TOF} \geq 2 \]

\[ (\Sigma \text{CI} \geq 1) \]

\[ \Sigma \text{JHD} \geq 1 \]

\[ (\Sigma \text{JHD} \geq 1 \text{ and } \Sigma \text{HA} \geq 1) \]

\[ \Sigma \text{HA} \geq 1 \]

\[ \Sigma \text{HB} \geq 1 \]

And

\[ \Delta \]

Discriminator

\[ \vartriangleright \]

Or
(2) Scintillation and Cherenkov counters strobed to buffer.

(3) PWC wire signal time slot records transferred to storage buffer.

(4) Spark chambers fired.

(5) Spark chambers readout to buffer.

(6) Data buffers written to magnetic tape.

(7) PDP-11 Ready turned on.

The time consumed for the data transfer was approximately 21 ms, which could overlap anywhere from zero to three beam pulses depending on the beam pulse rate which was set for various runs at between 80 and 180 pulses per second.

**Monitoring System**

There were three separate systems that allowed for monitoring of the performance of the apparatus\(^{(8-18)}\): the scaler system, the digital volt meter system, and the magnet monitoring system.

The scaler system was divided into two subsets of scalers, those that were run gated and those that were event gated. Run gated scalers counted all events during a run, whereas event gated scalers counted only those events which occurred while the event gate was on. For example, the run gated scaler that counted the number of beam triggers counted all beam triggers that occurred from the beginning of the run to the end of the run, while the event gated scaler for beam triggers, counted only those beam triggers which, if they interacted, could cause the data acquisition system to be activated. The difference between the two scalers would be the number of beam triggers that occurred during the system dead time, i.e., the number of beam particles that arrived during
the 21 ms periods required to write events to tape.

The digital volt meter system digitized and displayed the voltages that were being supplied to the phototubes, and the currents being supplied to the bucking coils around phototubes in the fringe fields of the magnets.

The magnet monitoring system, consisting of a Nova computer and digital amp meters, monitored the currents being supplied to the beam line magnets and the two spectrometer magnets. All systems were strobed to tape at the beginning and end of each run and at regular intervals during the run. The scalers were reset to zero at the beginning of each run.

**Data Acquisition System**

The data acquisition system\(^{8-18}\) stored the raw data on magnetic tape and sampled the events for monitoring the hardware performance. Figure 3.3 is a schematic diagram of this system. The system consisted of seven readout systems each with device controllers and direct memory access (DMA) modules to gain control of the PDP-11/20 unibus. Six of the readout systems were used on each event. These were the two systems for the planar C-D chambers, one for the cylindrical C-D chambers, one for the PWC chambers, one for the MS chambers, and one for the ADC, TDC, and buffer strobe systems. The seventh readout system was used to periodically transfer the scaler, DVM, and magnet monitor quantities to the PDP-11/20 memory. Once each of the devices had completed the data transfer to its respective DMA, the PDP-11/20 would then allow each DMA in turn to take control of the unibus to transfer its data.
Figure 3.3. Overview of the data acquisition system.
Figure 3.4. A typical device controller interface with the PDP-11/20 data acquisition computer.
to an IBM Sys/7 high speed data link (see figure 3.4), which then passed the data to a high speed input port of the SLAC computer facility, consisting of two IBM 370/168s and one IBM 360/91 (called the TRIPLEX). The data were then transferred from the port to the realtime program which was resident in one of the two IBM 370 CPUs. The realtime program had the primary task of writing the data to one of the fast 6250 bpi tape drives, and a secondary task of sampling the events as time allowed. The sampled data could then be displayed on a graphics terminal in the LASS control room. The graphs to be displayed could be initialized, deleted, or added to by use of the subprocess called the command task. A diagram of the realtime network is shown in figure 3.5. In case the triplex was not useable, there was a back up system in the LASS control room which consisted of an IBM 1800 and its associated tape drives. The triplex was the preferred CPU system, because there were many fewer monitoring capabilities on the 1800, and the tape drives on the 1800 were slower and of a lower density (800 bpi).
Figure 3.5. The LASS Realtime Network.
CHAPTER IV

EVENT RECONSTRUCTION

Overview

Event reconstruction was performed by a set of computer routines, herein referred to as LASSCODE. The reconstruction of an event began with the unpacking of the raw input event record which was followed by point reconstruction for the wire planes of the PWC and spark chambers. In an effort to speed production, a cut (to be described in more detail in the section on software cuts) was imposed on the number of points found in the cylindrical C-D chambers. The next step was the construction of 'match points' which were three dimensional space points with two or more corroborating wire plane coordinates from a single chamber. Then, pairs of match points from different chambers were used to form trial track segments. The parameterization of these trail track segments depended on which of the regions of the spectrometer the track segment was in, and will be described in the section on track reconstruction. Each trial track segment was retained as a track only if enough points along the predicted trajectory of the trial track were found in the other chambers of the appropriate region. After the individual tracks were reconstructed, the next step was to form a trial vertex using these tracks. At this stage the coordinate banks, track banks, ADC, and TDC information, and trial vertex coordinates were written to magnetic tape in order to provide an intermediate data set of reconstructed events. These tapes, called LGTs, for LASS geometry
tapes, were later read as input to vertex-finding and geometry fitting packages known as VHUNT and MVFIT. The first step of these routines was to find candidate vertices which were then to be fitted by the geometry fitting routine MVFIT. All events for which a vertex was found were again readout to tape, and any event which was successfully fitted, (where success is defined as having a convergent $\chi^2$) also had the fitted track parameters and vertex coordinates written to tape. This tape then provided a complete set of all reconstructed events in the experiment. Condensed versions of these tapes called data summary tapes or DSTs were used for the subsequent physics analysis.

**Coordinate Determination and Match Points**

There were three types of raw coordinate information:\(^{(17, 18)}\):

1. Time slot profiles for each wire in the PWC chambers
2. Wire numbers for each wire that fired in the C-D chambers
3. Time delays between fiducial pulses and spark pulses in the MS chambers

For each PWC wire, there was a time slot mask, which, when compared to the time slot record for that wire, determined whether or not that wire's signal was in-time. Each wire was thus given a yes or no signal assignment for that event. The wire numbers for those wires with in-time signals were then converted into distances measured from the end of the wire plane by use of the known wire spacing. For the C-D chambers, the wire number information was converted into a distance using the wire spacing in the wire cloth. This distance was then corrected.
for any non-linearity in the cloth planes. For both the C-D and PWC chambers, points were then clustered into groups of adjacent wires which were then converted into an average coordinate. These wire clusters were limited to a maximum size which depended on the chamber. For the MS chambers, the time delay information was converted into a distance measurement by using the calculated signal propagation velocity in the MS wires.

The distance measurements for the various chambers were then converted into coordinates as follows. For the x and y readout planes, the distances were directly converted into x and y coordinates, respectively. The E and P readout planes were first rotated about the z-axis to be parallel to the x-axis and then the procedure for determining an x plane coordinate was allowed after which the plane was rotated back to its original position. For the cylindrical chambers, there were two types of planes, those with their wires parallel to the z-axis and those whose wires were in a helical path centered on the z-axis. For the wires parallel to z, the wire numbers were converted directly into the φ angle, whereas for the helical wires, the φ and z coordinates were calculated using the wire number, wire spacing and crossing angle information. To calculate accurately these coordinates, a procedure for determining the shift of the chambers from their nominal positions (described later) was followed.

Once all the point coordinates had been calculated, they were clustered into match points. A match point was defined as two or more corroborating coordinates within a single multi-plane chamber. They
were found by taking one coordinate from each of two different planes and determining if one or more of the remaining planes had a corroborating coordinate within some tolerance of the point defined by the first two coordinates. These match points were then used in track reconstruction described in the next section.

**Track Reconstruction**

The first region in which tracks were to be reconstructed was the beam region, the second was the dipole region, which was followed by the solenoid region. The reason for doing the dipole region prior to the solenoid was that for particle identification purposes we required at least one reconstructed track downstream of the dipole. Therefore, if there were no track segments found in the downstream region we stopped processing the event and avoided the time consuming solenoid track reconstruction. Also, if a dipole track segment was found it was swum upstream through the solenoid region to the target. This eliminated some of the many possible solenoid track candidates formed from match point combinations with match points on this particular track, thus saving even more computer time.

In all sections of the spectrometer, trial tracks were constructed using an iterative tube search method. This method entailed first choosing two match points, not in the same device, to define a trial track. Then, a cylindrical tube of radius $r$ centered on this trial track was defined. Next the number of plane points inside the tube was determined and if there were more than a minimum number of points in
the tube the trial track parameters (described below) were fitted to those points using a $\chi^2$ minimization procedure. After a track is fitted, those points farthest from the fitted track could be discarded and the track then refitted to the remaining points. This procedure resulted in a fitted track with minimum errors. The tube radius, minimum number of points, and point discard criteria were determined for each region of the spectrometer and type of chamber from detailed track finding studies.

The parameterization used for track fitting depended on the region of the spectrometer in which the track segment was found. For track segments in the beam, twixt, and dipole regions, the bending of tracks due to stray magnetic fields was less than the resolution of the chambers. Therefore, the track segments in these regions were fit to straight lines, which were parameterized by the five variables $x^o$, $y^o$, $z^o$, $dx/dz$, and $dy/dz$, where $x^o$, $y^o$, and $z^o$ are the track coordinates at a reference plane and $dx/dz$ and $dy/dz$ are the $x$ and $y$ slopes relative to $z$. The $x$ and $y$ coordinates on a track at any value of $z$ are then given by

$$x(z) = x^o + (z - z^o) \frac{dx}{dz}$$
$$y(z) = y^o + (z - z^o) \frac{dy}{dz}$$

The solenoid-region track segments were parameterized with the six variables describing a helix, $x^o$, $y^o$, $z^o$, $r$, $\phi^o$, and $dy/dz$, where $x^o$, $y^o$, $z^o$ are the coordinates of the helix axis in the reference plane, $r$ is the radius of the circular projection of the helix in the $x$-$y$ plane, $\phi^o$ is the azimuthal angle of the track relative to the center of the helix at the reference point, and $dy/dz$ is the slope in the $\phi$, $z$
plane. The x and y coordinates are then given as functions of z by

\[ x(z) = x_0 + r \cos(\phi_0 + (z - z_0) \frac{dy}{dz}) \]
\[ y(z) = y_0 + r \sin(\phi_0 + (z - z_0) \frac{dy}{dz}) \]  

4.2

From the fitted track parameters in the solenoid region, we determine
from Maxwell's equations that the track momentum is given by

\[ P_x = q B r \sin(\phi_0 + (z - z_0) \frac{d\phi}{dz}) \]
\[ P_y = q B r \cos(\phi_0 + (z - z_0) \frac{d\phi}{dz}) \]
\[ P_z = z B/(d\phi/dz) \]  

4.3

where \( q = 2.998 \times 10^{-4} \text{ GeV/(KG-cm)} \) and B is the magnetic field strength.

**Beam tracks**

The beam region was the first area in which track reconstruction
was attempted in an event. This was done because beam tracks took
little time to reconstruct, and if no reconstructible beam tracks were
found the entire event could be immediately discarded. A trial beam
track was found by choosing a match point from each of the two beam PWCs.
The track parameters for a straight line through these two points were
calculated, and an iterative tube search involving all nine planes of
the beam PWCs was performed. If the trial track was successfully fitted
in the tube search, it was then extrapolated upstream into the \( \theta-\phi \)
scintillation counter hodoscope, and downstream into the x-y scintil-
lation counter to check for in-time corroboration. The resulting
momentum measurement, track parameters, and error matrix from the tube
search fit were then stored for later use. If more than one beam track
was found, the routine discarded the event and went on to the next event.
This happened for less than one percent of the events.
Dipole tracking

Once a beam track was found and there were no other candidate beam tracks, the track reconstruction program looked for track segments in the downstream or dipole region of the spectrometer. The devices used for track reconstruction in this region were the four downstream MS chambers and the JHD PWC hodoscope. As with beam tracking, match points were formed and trial tracks were made from pairs of match points in different chambers. The iterative tube search method was employed to fit track candidates to the plane points in the tube. Once the track was fitted, it was required to have corroboration from two of the three downstream in-time devices, namely JHD, HA, and HB. All coordinates and track parameters for these segments were stored for later use. At this time, if no downstream track segment had been found, the reconstruction routine would skip out and go to the next event. This happened for 15% of the events.

For those events with downstream track segments, the routine then proceeded to extrapolate the track through the dipole field region. This was done with a standard Runge-Kutta routine which used the dipole magnetic field map and the differential equations of motion to approximate the path of the particle through the magnetic field. Since the correct momentum of the track was not known at this time, this method could only be used iteratively. A successful crossing of the dipole occurred when the downstream segment could be joined up to a point in the twixt region which resulted in a good twixt track segment (again found by an iterative tube search). In such a case, the parameters for
the joined track segments were stored for later use. If no dipole track segment could be joined up to a track segment in the twixt region, the reconstruction for this event stopped. The successfully joined track segments were then swum through the solenoid fringe field, using the Runge-Kutta method mentioned earlier and the solenoid magnet fringe field map, into the solenoid region. Once in the solenoid region, the standard helix parameters were calculated using the track momentum as determined in the dipole crossing, with the downstream end of the solenoid as the reference plane. An iterative tube search in the solenoid region was performed, and the results stored for later use. A dipole track which was successfully joined up in the twixt region and then swum into the physical target was referred to as a matched track. At least one matched track was required to be found for an event to continue to be reconstructed.

**Solenoid tracks**

For the reconstruction of those tracks which were contained within the solenoid region, there were two track reconstruction algorithms used. The first algorithm started with trial tracks made in the planar chambers of the solenoid region, and the second started with trial tracks in the cylindrical chamber package. In either case the trial tracks were allowed to use points from both regions. The procedure for the planar chambers started by constructing trial tracks using pairs of match points from the planar chambers. It then proceeded to collect the track coordinates with an iterative tube search through all of the planar
and cylindrical chambers. Most of the trial tracks were due to combinations of match points which were actually on different tracks. These erroneous combinations generally resulted in tracks with very few coordinates and were eliminated by requiring that each track be detected in a certain minimum number of devices. The surviving tracks were then fitted to a helix with a least-squares procedure. These fitted tracks were also required to have a minimum number of PWC in-time corroborations. Trial tracks were also tested against a maximum allowable number of coordinates missing from the fitted track trajectory. Because of these requirements on the number of points a track must have, there were real tracks that were shortened because of in-flight decays, absorption, or wide-angle scattering during flight. These tracks could not be reconstructed because they did not have enough points or were missing too many points along their expected line of flight. This effect was included in the Monte Carlo acceptance calculation to be described later.

In the cylinder track finding algorithm, a trial track was defined with three match points rather than two. Trial tracks were again constructed with an iterative tube search procedure using coordinates from both the cylinder and planar regions. The resulting trial tracks were subjected to a similar set of constraints on the minimum number of points and PWC in-time corroboration requirements. Surviving tracks were then fitted by a least-squares method to a helix. Since both algorithms used coordinates in both the planar and cylindrical chambers, the two resulting sets of tracks had some overlap. One of the duplicate
tracks was then eliminated by a routine which checked for the uniqueness of points on tracks. Primarily, this routine required that each pair of tracks have no more than three shared coordinates. After duplicate track elimination, all track parameters and associated coordinates were stored for later use. After track reconstruction was finished, a preliminary primary vertex was determined by LASSCODE and all results were written to magnetic tape.

Software Trigger Cuts

In the course of LASMCODE track reconstruction, there were several cuts made on the data (several of which were briefly mentioned earlier). These cuts were designed to further select against events with too large a charge multiplicity and without identifiable strange particle production. There were six software cuts used, the first of which was a cut on the maximum number of points in the cylinder chambers, called the clean cut. This cut selected against high multiplicity events which were of little interest for this study, and could be made early in the processing, thus saving a large portion of the time spent on event reconstruction. The second cut (discussed earlier) was a requirement that a downstream track segment be found. This helped purify the sample of events in which a fast forward track was produced, which made it into the downstream spectrometer system. In the third cut, at least one downstream track segment was required to become a matched track (described earlier) further purifying the sample of events with a fast forward track. Fourth, we required that the momentum
of the fastest track found, in each event, be greater than 3 GeV/c, thus putting it above the Cherenkov light threshold for a pion. Fifth, we required that no light be seen in the downstream Cherenkov counter C2. This was necessary to further purify the sample of events with fast forward particles which were heavier than pions. If a track with momentum above 3 GeV/c hit C2 and did not give any light, then a sixth requirement was not tested. Otherwise, we required that one track with a momentum greater than 3 GeV/c pass through an efficient region of C1 and give no light in the appropriate region of C1. This combination of requirements greatly enhanced the likelihood that those events which were reconstructed would contain identifiable strange particles. A summary of the effects on the data of each cut is given in table 4.1.

**Vertex Finding And Event Topology Determination**

The problems of finding an event vertex and the determination of an event topology are complex and interdependent. These problems were handled by a package of routines known as VRHUNT which found trial primary vertices and primary plus secondary vertex combinations using the track parameters found by the track reconstruction routine LASSCODE. A vertex was determined by minimizing the quantity

\[ d^2 = \sum_j (x^j_v - x^j_i)^2 \]

where \( x^j_i \) is the \( j^{th} \) coordinate of the point of closest approach to the vertex, \( x^j_v \) of the \( i^{th} \) track. The vertices found were classified as OK, good, or excellent depending on the magnitude of \( d^2 \), defined to be the sum of the distances squared \( (D^2) \) divided by the number of tracks.
Table 4.1  Software TO production cuts

<table>
<thead>
<tr>
<th>Cuts imposed on data</th>
<th>Sequential percentage losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>TO trigger</td>
<td>53%</td>
</tr>
<tr>
<td>Clean</td>
<td>7%</td>
</tr>
<tr>
<td>Dipole track</td>
<td>15%</td>
</tr>
<tr>
<td>Matched dipole track</td>
<td>28%</td>
</tr>
<tr>
<td>Dipole track with momentum &gt; 3.0 GeV/c</td>
<td>36%</td>
</tr>
<tr>
<td>C2 (no light)</td>
<td>30%</td>
</tr>
<tr>
<td>Track through efficient part of C1 or through C2</td>
<td>15%</td>
</tr>
</tbody>
</table>
associated with the vertex. VRHUNT first tried to form a vertex for
an event out of the n tracks found by the track reconstruction routine.
If the n-prong vertex was not found to be excellent, VRHUNT then tried
all possible n-1 prong vertices followed by all possible n-2 plus one
Vee vertex combinations, etc. This continued until either an excellent
vertex combination was found or until all N-prong combinations with up
to three tracks removed and all N-prong plus one Vee combination with
up to two tracks removed were tried where N is the number of tracks
used in the primary vertex. If an excellent vertex combination was
found, the routine stopped searching and saved only the quantities for
that vertex. Otherwise, the parameters for the best N-prong vertex
(where N = n-1, n-2, or n-3) and the three best N-prong plus one Vee
vertices (where N = n-2, n-3, or n-4) were saved. If no vertices were
found the event was discarded. It should be pointed out that no track
parameters were varied in this procedure, i.e., no fitting is done in
VRHUNT. It is solely an algorithm for finding possible vertices.

Event Fitting

The vertex combinations found by VRHUNT along with the track
parameters and point coordinates found by LASSCODE were then input to
a multi-vertex fitting package known as MVFIT. This package used an
iterative Lagrange multiplier method to minimize the $\chi^2$ sum of the
track residuals for all coordinates including corrections for approximate
energy loss in the target and for multiple scattering effects. Its
function was to determine the optimum helix parameters for the outgoing
tracks and vertex positions. If the $\chi^2$ converged or reached a minimum within 20 iterations, the fitted track parameters, vertex position, and error matrix were saved, otherwise, the vertex was discarded. For purposes of this analysis, only the geometry fits were used, i.e., no kinematic constraints were imposed on the data in the fitting by MVFIT. The selection of events for the various final states was performed by appropriate cuts on the data and will be discussed in Chapter V.

Data Processing Job

The approximately 11 million events recorded during the data taking period were stored on 197 magnetic tapes at a density of 6250 bpi. The TO trigger data were then processed through the track reconstruction package LASSCODE and its associated software cuts. The events, for which tracks were successfully reconstructed, were recorded on 37 magnetic tapes at a density of 6250 bpi. These tapes were then read as input by the vertex finding and geometry fitting packages VRHUNT and MVFIT. VRHUNT successfully found one or more vertices for 65% of the input events. MVFIT was then able to make successful geometry fits to 83% of all of the vertices found by VRHUNT (this includes those events which were ambiguous to the point of having four possible vertices). The output of the VRHUNT-MVFIT package was stored on 18 magnetic tapes at a density of 6250 bpi. These output tapes were then read by a short routine which made a condensed version of the full event reconstruction tapes, called a data summary tape or DST. The event records on the DST tape contained the fitted vertex location, track parameters, and
Cherenkov and TOF information for particle identification. At this stage, there were about 686,000 events that had been fully reconstructed. From this master DST, smaller DSTs were made which contained only the data sample needed for a particular study, such as all 3-prong events or all events with a V°, etc.

**Alignment**

A first order approximation of the chamber alignment was made with an optical survey performed after the data taking period. This approximation was then improved by analysis of three separate data samples, two with both the solenoid and dipole magnets off and one with both magnets on. The analysis procedure for all three samples consisted of fitting tracks with an appropriate set of parameters (to be described later) and then calculating the residuals for the track in each chamber. These residuals for each chamber were histogrammed and their mean value for a chamber was used as the alignment error for that chamber. This value was then used to correct the offset constant used in coordinate reconstruction. For the two magnet off data samples, the tracks were reconstructed using a straight line iterative tube fitting procedure and for the third data sample the standard track reconstruction procedure was followed. The first data sample was made with the target empty, and thus consisted of non-interacting beam tracks. This sample aligned only those chambers through which a beam track would ordinarily pass, i.e., all of the planar chambers except the C-D and MS twixt chambers which had been desensitized in the beam region. For the second data sample
the target was filled, and thus it contained events with large-angle tracks. These events were used to align those planar chambers not aligned by the first sample, namely the C-D and twixt region MS chambers. For this data set, the iterative tube searches were started with match points found in the chambers that were aligned in the first set. The third data set was used to align the cylinder chambers. This was done by first aligning the cylinders with respect to each other, and then, by aligning the cylinder package to the rest of the detector. The first step was performed by fitting large-angle tracks which were primarily in the cylinder region to helices. The second step was accomplished by fitting tracks with both planar and cylinder points first to the planar points and then extrapolating into the cylinders to get rotation and pitch constants for the cylinder package. The third data sample also allowed us to make any final corrections to the alignment of the planar chambers due to the magnetic fields. The edges of the scintillation counters were determined by making x-y plots of track positions at the scintillator location for tracks which had scintillator corroboration. From this plot, the edges of the scintillators could be determined and the corrections to their positions made.
CHAPTER V

EVENT SELECTION AND DATA DISTRIBUTIONS

Introduction

This study was conducted in order to measure the mass, width, and spin-parity of resonance meson states which decay to $K\bar{K}$ and $K\bar{K}^*$ final states. To accomplish this, we had to apply various cuts aimed at meeting requirements from basic physics concepts such as conservation of charge and conservation of momentum and energy. Other cuts were applied to the data with the aim of reducing the background to the reactions of interest. The data sample surviving these cuts, referred to as the raw data sample, was then corrected for the event loses due to the acceptance of LASS and for the effects of the various cuts as determined by a Monte Carlo simulation program. The acceptance corrected data sample was then used in the moment analysis to determine resonance parameters.

The following sections will each be divided into three parts corresponding to the three scattering reactions considered, namely $\pi^+ n \rightarrow K^+ K^- p$, $\pi^+ p \rightarrow K^+ K^- \Delta^+$, and $\pi^+ p \rightarrow K^+ K^- p$. The first section will deal with the cuts applied to arrive at the 'raw' data samples and present the distributions for these samples. The second section will briefly describe the Monte Carlo used to determine the acceptance corrections. (The Monte Carlo simulation program will be described in more detail in Appendix.) And the third section will describe the acceptance corrected data distributions.
Selection of Events and the Raw Data Sample

The cuts applied to the data samples were used to reduce the backgrounds due to reactions with neutral particle production and to reactions such as \(\pi^+ n \rightarrow K^+ K^- \pi^+(p)\) where the proton did not have enough energy to get out of the target, and thus was not detected. The cuts most useful for reducing this type of background are those on the missing momenta, missing energy and missing mass squared. The next level of background to be addressed was that due to events such as \(\pi^+ n \rightarrow \pi^+ \pi^- p\), \(\pi^+ n \rightarrow pp p\) and \(\pi^+ p \rightarrow \pi^+ \pi^- \pi^+ p\). These types of events would pass the missing momenta cuts and some, due to the finite resolution of the momenta, could also pass the missing mass squared and missing energy cuts. A useful variable for estimating the background due to events of these types is \(M^2(x)\), which is the mass squared of the two tracks forming an oppositely charged equal mass pair. This variable was determined by scaling the z components of the momenta of the outgoing tracks so that the momentum in this direction was conserved for this event. Then, one used the equations for conservation of energy and the presumed masses of the recoil track (3 prongs) or tracks (4 prongs) to calculate the square of the mass of the individual tracks in the pair. This variable was then used to reduce the background due to \(p\bar{p}\) and \(\pi^+ \pi^-\) pair production. The third level of background to the \(\pi\pi\) scattering is that due to legitimate \(K^+ K^-\) and \(K^+ K^- \pi^+ p\) final states which are produced through channels other than one-pion exchange, such as associated strangeness production like \(\pi^+ n \rightarrow K^+ \Lambda(1520) \rightarrow K^+ K^- p\). Background due to events of this type are generally reduced by examining
the two body mass distributions and discarding those regions where known resonances occur. One can also reduce backgrounds due to misidentification of tracks by studying the appropriate two body mass distribution, and making cuts to eliminate any resonances.

KKp cuts

The \( K^+K^-p \) raw data sample was selected first by requiring the events to have exactly three charged tracks with a net charge of +1. Next, we required that the missing transverse momentum\(^{(21)} \) be less than 0.02 (GeV/c)\(^2 \) (shown in figure 5.1a) and that the magnitude of the missing longitudinal momentum be less than 0.5 GeV/c (shown in figure 5.1b). These two requirements eliminated most of the background due to events with 'fast' unreconstructed tracks. Further constraints were applied by allowing only events with the square of the missing mass (defined as the missing energy squared minus the missing momentum squared) less than 0.1 GeV\(^2 \) (shown in figure 5.1c), and allowing only events with the magnitude of the missing energy less than 0.3 GeV (shown in figure 5.1d). These cuts helped reduce the background due to misidentified tracks. To restrict ourselves to the kinematic region dominated by one pion exchange, we imposed a requirement that the magnitude of the four-momentum transferred from the incident pion to the outgoing \( K^+K^- \) system \( t = (p_\pi - p_K^+ - p_K^-)^2 \) be less than 0.2 (GeV/c)\(^2 \). This cut could have been set slightly higher, but we have a drop in the \( t \) acceptance for this final state above this value. The \( t \) distribution before this cut is shown in figure 5.2. After this cut, the major
Figure 5.1. Kinematic variable constraints for the reaction $\pi^+ n \rightarrow K^+ K^- p$
(shaded area is region discarded).

a) Missing transverse momentum squared
b) Missing longitudinal momentum
c) Missing mass squared
d) Missing energy
Figure 5.1 (Continued)
Figure 5.1 (Continued)
Figure 5.1 (Continued)
Figure 5.2. Momentum transfer distribution.
(The dashed line indicates the location of the cut.)
competing exchange channel to pion exchange is K exchange, in which a
K⁺ is produced at the upper vertex of a t-exchange diagram (see figure
1.3) and a Σ⁰ * or Λ⁰ * decaying into K⁻ p is produced at the lower vertex.
Examination of the K⁻ p mass plot in figure 5.3a shows a large peak in the
low K⁻ p mass region. On closer examination (figure 5.3b), we see that this
peak is actually made up of two resonances, one is the Λ⁰(1520) with a
FWHM of 15 MeV. The second peak is due to events where the Λ⁰(1115)
decayed so close to the primary vertex that the vertex finding package
could not distinguish the secondary Vee vertex from the primary vertex,
and the slow π⁻ from this decay has been misidentified as a K⁻. The
Λ⁰(1115) events are removed by requiring the K⁻ p mass be greater than
1.455 GeV. The Λ⁰(1520) events are removed by discarding the events in
the K⁻ p mass region between 1.510 GeV and 1.535 GeV. The final cut
applied to the KKp data was a cut on the mass squared of the equal mass
forward pair, M²(x) (shown in figure 5.4). This cut removed most of the
remaining p⁻ p̄ pair background. The event losses due to each cut are shown
in table 5.1.

**KKp raw data distributions**

The event sample left after the cuts mentioned above constitutes
our raw data sample for the K⁺K⁻ p events. In figure 5.5, the uncorrected
K⁺K⁻ mass distribution is shown. We see a large enhancement, due to
production of the f meson 1.3 GeV and a smaller enhancement for the
g meson at 1.65 GeV. There is no evidence for anything new in this
plot. In figure 5.6, we show the distribution for cos θ⁰ GJ, where θ⁰ GJ
Figure 5.3. \( K^- p \) mass distribution for the \( K^+ K^- p \) final state.

a) full distribution, dashed lines indicate the location of the cuts

b) Expanded distribution of the low mass region, shaded area indicated region discarded
Figure 5.3 (Continued)
Figure 5.4. $M^2(x)$ distribution for the reaction $\pi^+ n \rightarrow K^+ K^- p$.
(Shaded area is region discarded.)
Table 5.1. Percentage of events lost for event selection cuts for the reaction $\pi^+ n \rightarrow K^+ K^- p$.

<table>
<thead>
<tr>
<th>CUT</th>
<th>% LOST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Missing $P_T^2$</td>
<td>33%</td>
</tr>
<tr>
<td>Missing $P_L$</td>
<td>12%</td>
</tr>
<tr>
<td>Particle id consistent with $K^+ K^- p$</td>
<td>51%</td>
</tr>
<tr>
<td>Missing mass squared</td>
<td>28%</td>
</tr>
<tr>
<td>Missing energy</td>
<td>18%</td>
</tr>
<tr>
<td>Momentum transfer</td>
<td>57%</td>
</tr>
<tr>
<td>$K^- p$ mass</td>
<td>5%</td>
</tr>
<tr>
<td>$M^2(x)$</td>
<td>33%</td>
</tr>
</tbody>
</table>
Figure 5.5. Uncorrected $K^+K^-$ mass distribution for the reaction $\pi^+n \rightarrow K^+K^-p$. 
EVENTS/0.05 GeV

M(K^+K^-) 1GeV

0 50 100 150 200
Figure 5.6. Uncorrected $\cos \theta_{GJ}$ distribution of the meson vertex for the reaction $\pi^+ n \rightarrow K^+ K^- p$. 
EVENTS/0.05 IN COS $\theta$
is the angle from the incident pion momentum direction to the $K^+$ momentum direction in the $K^+K^-$ center of momentum frame; this reference frame is commonly referred to as the Gottfried-Jackson frame. The forward backward asymmetry of the plot is expected. The asymmetry is due to diffractive dissociation of the incident pion into a fast forward $K^+$ and a slower $K^-$, and acceptance affects. In figure 5.7 the $K^+p$ mass distribution is shown. This distribution, within statistical errors, is the expected phase space $K^+p$ mass distribution for one pion exchange events. $K^+K^-p$ data will be discussed further after the discussion on the acceptance corrections to be applied to the data.

$K^+K^-\Delta^{++}$ cuts

The $K^+K^-\Delta^{++}$ sample of events was first required to have exactly four reconstructed tracks associated with the primary vertex, no secondary vertices, and a net charge of +2. The missing momentum, missing mass squared and missing energy requirements for this data sample were the same as those for the $K^+K^-p$ data sample; namely $\Delta p_T^2 < 0.02 \text{ (GeV/c)}^2$, $|\Delta p_z| < 0.5 \text{ GeV/c}$, $|MM^2| < 0.1 \text{ GeV}^2$ and $|AE| < 0.3 \text{ GeV}$. The distributions for these variables are shown in figures 5.8a through d. In order to select events in the $\Delta^{++}$ region of the $\pi^+p$ mass (plotted in figure 5.9), we required the $\pi^+p$ mass to be less than 1.35 GeV. The pion exchange dominated region was selected by requiring that the magnitude of the momentum transfer from the incident pion to the $K\bar{K}$ system be less than 0.5 $\text{ (GeV/c)}^2$. (The $t$-distribution is shown in figure 5.10.) This cut is larger than in the $KKp$ final state because the minimum allowed $t$ for a $K^+K^-\Delta^{++}$ state is larger than for the $K^+K^-p$. 
Figure 5.7. $K^+p$ mass distribution for the reaction $\pi^+n \rightarrow K^+K^-p$. 
Figure 5.8. Kinematic variable constraints for the reaction $\pi^+_p \rightarrow K^+ K^- \pi^+_p$. (The dashed line indicated the location of the cuts.)

a) Missing transverse momentum
b) Missing longitudinal momentum
c) Missing mass squared
d) Missing energy
Figure 5.8 (Continued)
Figure 5.8 (Continued)
Figure 5.8 (Continued)
Figure 5.9. Uncorrected $\pi^+ p$ mass distribution for the reaction

$$\pi^+ p + K^+ K^- \pi^+ p.$$ (Dashed line indicates the location of the cut.)
Figure 5.10. Uncorrected momentum transfer distribution for
the reaction $\pi^+_p \rightarrow K^+ K^- \pi^+_p$. (Dashed line indicates
the location of the cut.)
state. The larger cut will also allow for more background due to $\rho$ exchange events. In the $K^+p$ mass plot (figure 5.11) we see a small bump at low mass interpreted as a reflection of the $\Lambda^{++}$, where the $\pi^+$ from the decay has been misidentified as a $K^+$. We therefore, require the $K^+p$ mass be greater than 1.6 GeV. In the $K^-p$ mass distribution (shown in figure 5.12) we again see a small enhancement in the low mass region, identified as $\Lambda^0(1115)$ and $\Lambda^0(1520)$ and therefore, require the $K^-p$ mass be greater than 1.535 GeV. The final cut on the $K^+K^-\Delta^{++}$ data set was on the mass squared of the equal mass pair, $M^2(x)$, as shown in figure 5.13. This cut was designed to remove most of the remaining events with misidentified $\pi^+\pi^-$ and $pp$ pair events. The event losses due to each cut are shown in table 5.2.

$K^+K^-\Delta^{++}$ raw data distributions

The raw $K^+K^-$ mass distribution is shown in figure 5.14. Just as for the $K^+K^-p$ final state we see a large $f$ meson signal at 1.3 GeV and smaller enhancements for the $f'$ and $g$ mesons at 1.5 and 1.65 GeV, respectfully. The $\cos \theta_{GJ}$ distribution is shown in figure 5.15 and has the same general features as the $K^+K^-p$ angular distribution. In figure 5.16, we see the $K^-\pi^+$ mass distribution and notice that there is little indication of the $K^*(890)$ meson resonance. This indicates that we are selecting events with the two kaons coming from the upper vertex of the exchange diagram.
Figure 5.11. Uncorrected $K^+ p$ mass distribution for the reaction $\pi^+ p \rightarrow K^+ K^- \Delta^{++} \rightarrow K^+ K^- \pi^+ p$.

(Dashed line indicates the location of the cut.)
Figure 5.12. Uncorrected $K^-p$ mass distribution for the reaction
$\pi^+ p \rightarrow K^+ K^- \Delta^{++} \rightarrow K^+ K^- \pi^+ p$. (Dashed line indicates
the location of the cut.)
Figure 5.13. \( M^2(x) \) for the reaction \( \pi^+ p \rightarrow K^+ K^- \Delta^{++} \rightarrow K^+ K^- \pi^+ p \).

(Dashed line indicates the location of the cut.)
Table 5.2. Percentage of events lost for event selected cuts for the reaction $\pi^+ p \rightarrow K^+ K^- \Delta^+ \rightarrow K^+ K^- \pi^+ p$.

<table>
<thead>
<tr>
<th>CUT</th>
<th>% LOST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Missing $P_T^2$</td>
<td>21%</td>
</tr>
<tr>
<td>Missing $P_L$</td>
<td>10%</td>
</tr>
<tr>
<td>Particle id consistent with $K^+ K^- \pi^+ p$</td>
<td>36%</td>
</tr>
<tr>
<td>Missing mass squared</td>
<td>27%</td>
</tr>
<tr>
<td>Missing energy</td>
<td>13%</td>
</tr>
<tr>
<td>$\pi^+ p$ mass</td>
<td>71%</td>
</tr>
<tr>
<td>Momentum transfer</td>
<td>45%</td>
</tr>
<tr>
<td>$K^+ p$ mass</td>
<td>3%</td>
</tr>
<tr>
<td>$K^- p$ mass</td>
<td>7%</td>
</tr>
<tr>
<td>$M^2(x)$</td>
<td>23%</td>
</tr>
</tbody>
</table>
Figure 5.14. Uncorrected $K^+ K^-$ mass distribution for the reaction

$$\pi^+ p + K^+ K^- \Delta^{++} \rightarrow K^+ K^- \pi^+ p.$$
Figure 5.15. Uncorrected $\cos \theta_{GJ}$ distribution for the reaction 

$$\pi^+ p \rightarrow K^+ K^- \Delta^{++} \rightarrow K^+ K^- \pi^+ p.$$
Figure 5.16. Uncorrected $K^-\pi^+$ mass distribution for the reaction

$$\pi^+_p \rightarrow K^+K^-\Delta^{++} \rightarrow K^+K^-\pi^+_p.$$
The initial data sample for the $K^+K^-\pi^+p$ final state and the $K^+K^-\Delta^{++}$ final state were the same and thus the cuts for the two final states for missing momentum, missing energy and missing mass squared are the same. The cut on the $\pi^+p$ mass was the converse of the cut for the $K^+K^-\Delta^{++}$ final state, namely the $\pi^+p$ mass is now required to be greater than 1.35 GeV. The locations of these cuts are shown in figure 5.8a through d and figure 5.9. In figure 5.17, we show the $t$ distribution, and impose the requirement that $|t| < 0.5 (\text{GeV/c})^2$, again selecting the low $-t$ region for enhanced pion exchange. The final cut on the $KK\pi p$ data was a requirement that $M^2(x)$ be greater than 0. This reduced the background due to misidentified pions, and from the distribution shown in figure 5.18, we see little contribution due to $pp$ pair production. The losses due to these cuts are summarized in table 5.3.

$K^+K^-\pi^+p$ raw data distributions

The $K^+K^-\pi^+$ mass distribution is shown in figure 5.19. In this distribution, we see a broad enhancement in the 1.5 to 1.8 GeV region corresponding to the $g$ meson resonance. There is one reported observation of an $I = 1$ resonance with a mass of 2.307 GeV and spin-parity of $5^-(22)$. This resonance is not seen in this plot. There may also be an enhancement around 2600 MeV. For this data sample the angular distributions are defined with the same coordinate system described in the $KKp$ section, but the vector used as the angular momentum analyzer in this case is the normal to the $K^+K^-\pi^+$ decay plane in the $KK\pi$ center of momentum.
Figure 5.17. Uncorrected momentum transfer distribution for the reaction $\pi^+ p \rightarrow K^+ K^- \pi^+ p$. (Dashed line indicates the location of the cut.)
Figure 5.18. $M^2(x)$ distribution for the reaction $\pi^+_p \to K^+K^-\pi^+_p$.

(Dashed line indicates the location of the cut.)
Table 5.3. Percentage of events lost for event selection cuts for the reaction $\pi^+ p \rightarrow K^+ K^- \pi^+ p$.

<table>
<thead>
<tr>
<th>CUT</th>
<th>% LOST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Missing $P_T^2$</td>
<td>21%</td>
</tr>
<tr>
<td>Missing $P_L$</td>
<td>10%</td>
</tr>
<tr>
<td>Particle id consistent with $K^+ K^- \pi^+ p$</td>
<td>36%</td>
</tr>
<tr>
<td>Missing mass squared</td>
<td>27%</td>
</tr>
<tr>
<td>Missing energy</td>
<td>13%</td>
</tr>
<tr>
<td>$\pi^+ p$ mass</td>
<td>33%</td>
</tr>
<tr>
<td>Momentum transfer</td>
<td>74%</td>
</tr>
<tr>
<td>$M^2(x)$</td>
<td>35%</td>
</tr>
</tbody>
</table>
Figure 5.19. Uncorrected $K^+K^-\pi^+$ mass distribution for the reaction $\pi^+p + K^+K^-\pi^+p$. 
system. The normal to the decay plane \( \hat{\mathbf{n}} \) is given by

\[
\hat{\mathbf{n}} \sim (\hat{\mathbf{p}} + \hat{\mathbf{p}}').
\] 5.1

The distribution for \( \cos \beta \), where \( \beta \) is the angle from the z-axis to the normal \( \hat{\mathbf{n}} \) is shown in figure 5.20. Notice that this distribution peaks at \( \cos \beta = 0 \), which does not correspond to \( \cos \theta_{GJ} = \pm 1 \) where the two body decay angular distributions peaked. This difference is expected from the kinematics of the four body state and the method of analysis.

Figure 5.21 is the \( K^+ K^- \) mass distribution for these events showing a strong peak in the 1.3 GeV region corresponding to the \( \Lambda_2^o \). And in figure 5.22, we show the \( K^- \pi^+ \) mass distribution which features a strong \( K^*(890) \) signal. These plots indicate that the decay tends to progress through the intermediate states \( \Lambda_2^o \pi^+ \) and \( K^+ K^*o \). For comparison, we also show the \( K^+ p, K^- p, \) and \( K^+ \pi^+ \) mass distributions in figures 5.23 through 5.25.

For all three final states, the distributions in the azimuthal angle about the beam direction in the meson vertex center of momentum frame are flat to within statistical errors, and are not shown.

**Measurement Resolutions**

The mass, \( t, \cos \theta_{GJ} \) (or \( \cos \beta \)), and \( \phi \) resolutions were determined, for this experiment, by use of the Monte Carlo simulation routine described in the Appendix. This program was designed to simulate closely the event reconstruction and fitting procedures used to a high degree of accuracy. Both device efficiency and resolution were used in the track reconstruction simulation, and many studies were made to verify that the
Figure 5.20. Uncorrected $\cos \beta$ distribution for the reaction

$$\pi^+ + p \rightarrow K^+ K^- \pi^+ p.$$
Figure 5.21. Uncorrected $K^+K^-$ mass distribution for the reaction

$$\pi^+p + K^+K^-\pi^+p.$$
Figure 5.22. Uncorrected $K^- \pi^+$ mass distribution for the reaction $\pi^+ p \rightarrow K^+ K^- \pi^+ p$. 
Figure 5.23. Uncorrected $K^+ p$ mass distribution for the reaction

$$\pi^+ p \rightarrow K^+ K^- \pi^+ p.$$
Figure 5.24. Uncorrected $K^- p$ mass distribution for the reaction $\pi^+ p \rightarrow K^+ K^- \pi^+ p$. 
Figure 5.25. Uncorrected $K^+\pi^+$ mass distribution for the reaction

$\pi^+ p \rightarrow K^+ K^- \pi^+ p$. 
program accurately simulated all important aspects of track reconstruction. Once these Monte Carlo studies were done, we could then determine the approximate resolution for the quantities of importance to this analysis. Because of the division of the acceptance correction function into bins in mass, \( t \), \( \cos \theta \), and \( \phi \), where \( \theta \) and \( \phi \) are the polar and azimuthal angles, one needs to know that an event generated in one bin is not likely to be measured in another bin. The results of this Monte Carlo study gave the errors for these quantities shown in Table 5.4. These values would allow for a small amount of crossover near bin edges, but this was found to have no significant effect as the important physics quantities were found to vary slowly from bin to bin.

**Acceptance Corrections and Acceptance Corrected Distributions**

To get the produced mass and angular distributions for an experiment, one must correct the raw distributions, on an event by event basis, for the geometrical acceptance of the apparatus, the inefficiencies of the detection chambers, and the inefficiencies of the event reconstruction programs and for the effects of the cuts on the data\(^{(24)}\). For this experiment, the acceptance correction matrix, \( A(\Omega, x) \) where \( \Omega \) refers to the angular dependence, and \( x \) to kinematic variable dependence, was determined by use of the Monte Carlo simulation program. The acceptance was determined for bins in meson vertex mass \( M \), momentum transfer \( t \), azimuthal angle \( \phi \), and \( \cos \theta_{GJ} \) for \( K^+K^-p \) and \( K^+K^-\Delta^{++} \) or \( \cos \beta \) for \( K^+K^-\pi^+p \), and all other variables were integrated over. For the \( K^+K^-p \) final state the array \( A \) was constructed with 20 bins in \( \cos \theta_{GJ} \) of width 0.1, 5 bins of \( 72^\circ \) in \( \phi \), 4 bins of 0.05 (GeV/c)^2 in \( t \), and 85
Table 5.4 Kinematic Variable Resolutions

<table>
<thead>
<tr>
<th>Variable</th>
<th>KKp</th>
<th>KKa</th>
<th>KKπp</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{</td>
<td>t</td>
<td>}$</td>
<td>0.013 (GeV/c)^2</td>
</tr>
<tr>
<td>$\sigma_M$</td>
<td>0.009 GeV</td>
<td>0.006 GeV</td>
<td>0.020 GeV</td>
</tr>
<tr>
<td>$\sigma_\theta$</td>
<td>0.10 radians</td>
<td>0.11 radians</td>
<td>0.08 radians</td>
</tr>
<tr>
<td>$\sigma_\phi$</td>
<td>0.13 radians</td>
<td>0.15 radians</td>
<td>0.21 radians</td>
</tr>
</tbody>
</table>
bins of 30 MeV in mass. For the $K^+K^-\Delta^{++}$ and $K^+K^0\pi^+$ states, the number of bins for each variable was the same as for $K^+K^-p$, and the angular and mass bin widths were the same as for $K^+K^-p$ but the bin width in $t$ was changed from $0.05 \ (GeV/c)^2$ to $0.125 \ (GeV/c)^2$ due to the higher $t$ cut used for these states. For the $K^+K^-\pi^+p$ final state there are three more variables needed to determine the state of an individual event, namely two two-body submasses $M(K^+K^-)$ and $M(K^-\pi^+)$ and the angle about the normal to the decay plane $\gamma$. The angle $\gamma$ will give no added information about the spin-parity of an observed resonance$^{(23)}$ and was, therefore, integrated over in the acceptance. The acceptance as a function of the submasses was studied and found to be flat within a bin of the meson mass, and, therefore, these were also integrated over. The acceptance correction weight for a given event is the reciprocal of the contents of the mass, $t$, $\cos \theta$ and $\phi$ bin in which that event would fall. Due to statistical uncertainties and the fact that the model of the apparatus used was not perfect, any event with a weight greater than 50.0 was discarded. The weighted events were then used in plotting the acceptance corrected distributions. In figures 5.26 through 5.28, contour plots for the acceptance as a function of the resonance mass and $\cos \theta$ are shown for the $K^+K^-p$, $K^+K^-\Delta^{++}$, and $K^+K^-\pi^+p$ final states.

Corrected distributions

$K^+K^-p$ Acceptance Corrected Distributions

Of the 1732 events passing the event selection, 232 were discarded because they were in bins where the acceptance was less than 2%. This left 1491 events
Figure 5.26. Contour plot of the acceptance as a function of $K^+K^-$ mass and $\cos \theta_{GJ}$ for the reaction $\pi^+n \rightarrow K^+K^-p$. 
Figure 5.27. Contour plot of the acceptance as a function of the $K^+K^-$ mass and $\cos \theta_{GJ}$ for the reaction $\pi^+ p \rightarrow K^+K^-\Delta^{++} \rightarrow K^+K^-\pi^+ p$. 
Figure 5.28. Contour plot of the acceptance as a function of the $K^+K^-\pi^+$ mass and $\cos \beta$ for the reaction $\pi^+p \rightarrow K^+K^-\pi^+p$. 
giving an acceptance corrected equivalent total of 11,471 events. This gives an average acceptance correction weight of 7.69 or an average acceptance of 13.0%. Figure 5.29 shows the corrected $K^+K^-$ mass distribution in which we see strong signals in the 1.3 GeV and 1.7 GeV regions, corresponding to the known meson resonances $f(1270)$ and $g(1700)$. Also, we see a weak signal at 2.0 GeV corresponding to the $h(2040)$ resonance. The mass and widths of these resonances as determined from a fit to a cubic polynomial background and three Breit-Wigner resonance structures are,

\[
\begin{align*}
M_f &= 1.344 \pm 0.014 & \Gamma_f &= 0.305 \pm 0.042 \\
M_g &= 1.664 \pm 0.015 & \Gamma_g &= 0.207 \pm 0.048 \\
M_h &= 2.005 \pm 0.021 & \Gamma_h &= 0.180 \pm 0.014
\end{align*}
\]

with a $\chi^2$ of 20.71 for 20 degrees of freedom. The errors are from the fitting procedure and do not include any systematic error estimate. The fitted mass and width for the $f$ meson are high. Contributing factors to this are the large statistical fluctuation in one of the mass bins above the resonance, the fact that we have not included the $f'(1515)$ (which is seen in the moment plots discussed in the next chapter), and background due to p exchange production of the $A_2(1310)$. In figure 5.30, the angular distribution is shown and we note that the general shape of the distribution has changed little from the raw data distribution. In figure 5.31, we show the acceptance corrected $t$ distribution. Due to the location of the cut on $t$, a slope for this distribution was not determined.
Figure 5.29. Acceptance corrected $K^+K^-$ mass distribution for the reaction $\pi^+n \rightarrow K^+K^-p$. 
Figure 5.30. Acceptance corrected $\cos \theta_{GJ}$ distribution for the reaction $\pi^+_n \rightarrow K^+ K^- p$. 
Figure 5.31. Acceptance corrected momentum transfer distribution for the reaction $\pi^+ n \rightarrow K^+ K^- p$. 
passing the event selection cuts, 82 were in bins with an acceptance less than 2% and were thus discarded. This left a total of 2037 events giving an acceptance corrected equivalent total of 25,104 events. This gives an average weight of 12.32 or an average acceptance of 8.1%. Figure 5.32 shows the $K^+K^-$ mass distribution in which we see a strong signal in the 1.3 GeV region, a weaker signal for the 1.7 GeV region, and a weak signal in the 2.0 GeV region, corresponding to the $f(1270)$, $g(1700)$, and $h(2040)$ meson resonances, respectively. This distribution was also fitted to a cubic polynomial background and three Breit-Wigner resonance structures giving mass and width measurements of

$$
M_f = 1.321 \pm 0.008 \quad \Gamma_f = 0.118 \pm 0.011 \\
M_g = 1.640 \pm 0.017 \quad \Gamma_g = 0.112 \pm 0.029 \\
M_h = 2.040 \pm 0.169 \quad \Gamma_h = 0.150 \pm 1.414
$$

with a $\chi^2$ of 44.32 for 19 degrees of freedom. The errors represent a change of one in the $\chi^2$ and do not include any estimate of the systematic errors. The mass for the $f$ and $g$ mesons have apparently been shifted to compensate for the $f'(1515)$ which is seen in the moment plots. The $h$ meson parameters were not changed from their initial values and the strength for this Breit-Wigner was consistent with zero in the fit. In figure 5.33, we show the corrected $\cos \theta_{GJ}$ distribution and note that the general shape is unchanged from the raw data distribution. In figure 5.34, we show the corrected $t$ distribution, but again the location of the cut prevents the determination of the exponential slope for one pion exchange.
Figure 5.32. Acceptance corrected $K^+K^-$ mass distribution for the reaction $\pi^+p \rightarrow K^+K^-\Delta^{++} \rightarrow K^+K^-\pi^+p$. 
Figure 5.33. Acceptance corrected $\cos \theta_G$ distribution for the reaction $\pi^+ p \rightarrow K^+ K^- \Delta^{++} \rightarrow K^+ K^- \pi^+ p$. 
EVENTS/0.05 IN COS θ

COS θ_{GJ}
Figure 5.34. Acceptance corrected momentum transfer distribution for the reaction $\pi^+ p \rightarrow K^+ K^- \Delta^{++} \rightarrow K^+ K^- \pi^+ p$. 
passing the event selection cuts, 643 events were discarded because they were in bins where the acceptance was less than 2%. This left 969 events giving an acceptance corrected equivalent total of 15,699 events. This gives an average weight of 16.2 corresponding to an average acceptance of 6.1%. The large number of events lost by the acceptance cut indicates that either there is some problem in the Monte Carlo in modeling this final state, or more likely, that even after the event selection cuts have been made, there is still a large background from other production channels. In figure 5.35, we show the corrected $K^+K^-\pi^+$ mass distribution noting the signal at 1.7 GeV which corresponds to the g(1700) resonance, and a smaller broad bump around 2.7 GeV. Noting that the model mentioned in Chapter I indicates that the next leading natural spin-parity states expected to contribute to this distribution would have a mass of 2.3 and 2.7 GeV one might suspect this enhancement to be a new state. This distribution was fitted with a fifth degree polynomial background and three Breit-Wigner shapes (one for the g meson, one for the bump at 2.7 GeV, and one for the broad spin one background seen in the moment plots). The results of the fit are

$$M_g = 1.714 \pm 0.0114, \quad \Gamma_g = 0.1583 \pm 0.5135$$
$$M_X = 2.747 \pm 0.0318, \quad \Gamma_X = 0.1500 \pm 0.0749$$

with a $\chi^2$ of 28.29 for 33 degrees of freedom. Our mass and width for the g(1700) meson are consistent with those of Aderholtz, et al. (26) The strength of the Breit-Wigner fitting the enhancement at 2.72 GeV is $254.7 \pm 83.5$. The spin 5$^-$ state seen by Alper, et al., would fall in the area between these two resonances. This distribution was also fit to a polynomial plus one Breit-Wigner shape at 1700 MeV, and to a
Figure 5.35. Acceptance corrected $K^+K^-\pi^+$ mass distribution for the reactions $\pi^+p \rightarrow K^+K^-\pi^+p$. Upper curve is from a fit to fifth degree polynomial and three Breit-Wigner shapes. Middle curve is the polynomial background plus the Breit-Wigner for the spin background. Lower curve is the polynomial background.
polynomial plus two Breit-Wigner shapes (one at 1700 MeV and one for the spin one Deck background). The one Breit-Wigner fit gave a $\chi^2$ of 44.15 for 39 degrees of freedom, and the two Breit-Wigner fit, gave a $\chi^2$ of 34.90 for 36 degrees of freedom. In either case, the five bins between 2.65 and 2.85 GeV have a $\chi^2$ contributions of approximately 1.5 per bin. So that, even though the overall $\chi^2$ for these fits was acceptable, the fit in the 2.65 to 2.85 GeV region was poor without the Breit-Wigner for this region. Figure 5.36 is the acceptance corrected $K^-\pi^+$ mass distribution, in which we see a strong $K^*(890)$ signal. And in figure 5.37, the corrected $K^+K^-$ mass distribution is shown. We observe a strong $\Lambda_2(1300)$ signal and weaker signals in the $g(1700)$ and $h(2040)$ regions. These two plots indicate that the meson produced at the upper vertex tends to decay via one of the two two-step processes $\chi^+ \rightarrow K^+K^0(890) \rightarrow K^+K^-\pi^+$ or $\chi^+ \rightarrow f^0\pi^+ \rightarrow K^+K^-\pi^+$. In either case, there are other channels through which the $K^*$ or $f^0$ resonances could decay and these would not have been detected in this experiment. These other decay modes would have to be included if an absolute cross section rather than a cross section times branching ratio were to be calculated. Figure 5.38 shows the corrected $\cos \beta$ distribution which is of the same general shape as the raw data distribution. And in figure 5.39, the corrected $t$ distribution is shown; again, the exponential slope was not calculated due to the location of the $t$ cut.
Figure 5.36. Acceptance corrected $K^-\pi^+$ mass distribution for the reactions $\pi^+_p \rightarrow K^+K^-\pi^+_p$. 
Figure 5.37. Acceptance corrected $K^+K^-$ mass distribution for the reactions $\pi^+p \rightarrow K^+K^-\pi^+p$. 
EVENTS / 0.05 GeV

M (K+K⁻) GeV
Figure 5.38. Acceptance corrected cos $\beta$ distribution for the reaction $\pi^+ p + K^+ K^- \pi^+ p$. 
Figure 5.39. Acceptance corrected momentum transfer distribution for the reaction $\pi^+ p \rightarrow KK^- \pi^+ p$. 
CHAPTER VI

MOMENT ANALYSIS

To determine the spin and parity of an observed state we must examine the spherical harmonic moments as functions of mass. The moments presented in this paper were calculated from the acceptance corrected data sample and are not the result of a fit of the spherical harmonics to the angular distribution. For this analysis, the unnormalized angular moments were calculated using

\[ N_i \langle Y_1^m \rangle = \sum_{j=1}^{N_i} A_i(\Omega_j, x_j) Y_1^m(\Omega_j) \]

where \( N_i \) is the number of events in the \( i^{\text{th}} \) mass bin, \( \Omega_j \) and \( x_j \) refer to the angles and kinematic variables for the \( j^{\text{th}} \) event in the \( i^{\text{th}} \) mass bin, \( A_i(\Omega_j, x_j) \) is the acceptance for this event, and \( Y_1^m \) is the relevant spherical harmonic. One convenient result of using the angles in the Gottfried-Jackson frame, is the z component of the orbital angular momentum of the incident pion with the exchanged pion is zero, and since the individual pions have zero intrinsic spin the z component of the total angular momentum is also zero. Thus, in this frame one expects only the \( Y_1^0 \) moments to be appreciably different from zero\(^{27} \). Also, since we see no structure in the \( \Phi \) distribution, only the \( Y_1^0 \) moments are presented here. The moments are plotted in 50 MeV wide mass bins, and in the bins where moments are not shown the moments are found to be consistent with zero. A resonance of mass \( M \) and spin \( J \) will appear in the first \( l = 2J \) moments with a peak-like structure at mass \( M \), and will
give no contribution for higher $l$ values. In the case of a leading resonance, one would expect the $l = 2J$ moment to be consistent with zero for masses less than $M$ and the moments for $l > 2J$ to be consistent with zero through $M$. With these criteria in mind, we now examine the moments.

Moments

**KKp moments**

The KKp moments are shown in figure 6.1. The $Y_0^0$ moment is not shown as it differs from the acceptance corrected mass distribution by only a multiplicative constant. Using the criteria described above, we see evidence for the spin-parity $2^+ f(1270)$ meson from the peak in the $Y_4^0$ moment at 1.25 GeV. Also, there is evidence for the spin-parity $3^- g(1700)$ meson from the peak at 1.7 GeV in the $Y_6^0$ moment plot. From the peak in the $Y_4^0$ moments centered at 1.5 GeV, and noticing that the same mass region is consistent with zero for higher $l$ values gives evidence for the spin-parity $2^+ f'(1515)$ meson. From the small peak in the $Y_8^0$ moment plot, we have some evidence for a contribution from the spin-parity $4^+ h(2040)$ meson.

Further support for this interpretation of the moments is found in looking at the odd $l$, $m = 0$ moments. In these moments, interference between states of differing angular momentum can be seen as a slight drop and sudden rise in the mass region between resonances. An example of this can be seen in the mass region between $f'(1515)$ and $g(1700)$ resonances in the $Y_3^0$ moment, indicating the interference between these
Figure 6.1. Unnormalized spherical harmonic moments for the reaction

\[ \pi^+ n \rightarrow K^+ K^- p. \]
two states.

\[ K^+K^- \Delta^{++} \text{ moments} \]

Figure 6.2 displays the KK\(\Lambda\) moments as a function of \(K^+K^-\) mass. For this data sample, we see evidence for the \(f(1270)\) and \(f'(1515)\) in the \(Y_{\Delta}^0\) moment, consistent with previous results. However, the errors in the \(Y_{\Delta}^0\) and \(Y_{\Delta}^0\) moments are such that no firm conclusions can be drawn in this experiment.

\[ K^+K^- \pi^+p \text{ moments} \]

Figure 6.3 displays the moments for the KK\(\pi p\) final state as a function of the \(K^+K^-\pi^+\) mass. Consideration of the conservation of angular momentum, \(g\)-parity and parity implies that only states with isospin \(I = 1\) and \(J^P = 1^-, 3^-, 5^-, 7^-\) will contribute to the \(\pi^+\pi^- \rightarrow K^+K^-\pi^+\) reaction. The \(Y_{\pi}^0\), \(Y_{\pi}^0\), and \(Y_{\pi}^0\) moments are consistent with a large spin-one deck type background similar to that seen in \(3\pi\) analyses \(^{28}\). The known states that fit these criteria are the spin-parity \(3^-\) \(g(1700)\) and a resonance reported by Alper, et al., with spin-parity \(5^-\) at a mass of 2307 MeV. From the \(Y_{\pi}^0\) moment we note a peak in the 1700 GeV region corresponding to the \(g(1700)\) resonance. But in the \(Y_{\pi}^0\) moment, we see only slight, if any evidence for a 2.3 GeV spin-parity \(5^-\) state. Due to the limited statistics and large acceptance errors, the enhancement at 2.7 GeV is not statistically significant in each moment separately. Thus, the moments are used only to determine the spin of this state. In each of the \(Y_{\pi}^0\), \(Y_{\pi}^0\), \(Y_{\pi}^0\), and \(Y_{\pi}^0\) moments, the enhancement at 2.7 GeV appears. From this, the enhancement appears to be a spin
Figure 6.2. Unnormalized spherical harmonic moments for the reaction
\[ \pi^+_p \rightarrow K^+ K^- \Delta^+ \rightarrow K^+ K^- \pi^+_p. \]
Figure 6.3. Unnormalized spherical harmonic moments for the reaction

$$\pi^+ p + K^+ K^- \pi^+ p.$$
Figure 6.3 (continued)
7^- object interfering with the large spin 1 background shown in Y^0. Again, the errors on these moments are large but they are dominated by the statistical errors and thus, fitting the moments to the data would probably not give a marked improvement in the moment distribution.

The moment distributions, seen in this experiment, for the K^+K^-p final state are consistent with those seen elsewhere\(^{(22, 29-34)}\). The moment distributions for the K^+K^-\pi^+\pi^- final state are also consistent for the region of K^+K^- mass less than 1.6 GeV. The interpretation of the moment distributions for the K^+K^-\pi^+p final state is consistent with the partial wave analysis done by G. Otter, et al.,\(^{(35)}\) in the low mass region showing a wide Deck type background. The moment analysis of the K^+K^-\pi^+ mass above the g meson resonance region is unique to this study.

**Summary of Results**

In this study, we have presented evidence for observation of the spin-parity 2^+ states f(1270) and f'(1515), the spin parity 3^- state g(1700) and the spin-parity 4^+ state h(2040) in the K^+K^-p and K^+K^-\Delta^{++} final states. We also see evidence for the spin-parity 3^- state g(1700). We also see some evidence for a new state with spin-parity 7^- at 2747 MeV with a width of 150 MeV. This new state is the highest observed spin state for a meson resonance to date.

In terms of the quark model, this new state would be an isospin I = 1 state consisting of a ud quark anti-quark pair. The measured mass agrees within errors, with the mass predicted by the model presented in Chapter I. This state also indicates the existence of at least eight
new meson octets, one set of four octets with a $q\bar{q}$ orbital angular momentum of 5 which would not contribute to the final state studied in this experiment, and one set of four octets with a $q\bar{q}$ orbital angular momentum of 6, with only the $J^P = 7^-, I = 1$ state seen in this experiment. On a Chew-Frantchi plot (figure 6.4), the new state is seen to fall on the $\rho$ trajectory. The new state is the sixth observed state of the seven possible through spin 7.
Figure 6.4. Chew Frantchi plot of the leading non-strange mesons.
THIS EXPERIMENT

TOTAL ANGULAR MOMENTUM J

MASS$^2$ GeV$^2$

P(1770) f(1270) ρ(1770) h(2040) p(2100) p(2720)

ω(1782) A(1300) ω(1700) h(2040) p(2307)
APPENDIX

LASS MONTE CARLO

In this section, the application of the Monte Carlo simulation to our experiment will be described, for more details on the program structure see reference 18. This simulation program was used to calculate the acceptance correction factors for the reactions of interest, to determine the spectrometer resolution for the kinematic variables, and to study the distributions for backgrounds.

To meet these goals the guidelines followed by the programmers as listed by A. Honma were to:

1. Generate events with kinematic distributions as close as possible to the true physics distributions.
2. Accurately simulate the geometrical acceptance of the spectrometer including physical boundaries, detector active areas or volumes, proper magnetic field tracking, simulation of hardware trigger, absorption, etc.
3. Include device inefficiency effects.
4. Simulate the data event reconstruction programs (software tracking algorithms).
5. Reproduce track resolution.
6. Create a large sample of Monte Carlo events that can be easily processed to obtain acceptance.

There were four sections of code that were rewritten to apply to our experiment. The first was a replacement of the event generating
routine by a standard event generating routine, referred to as SAGE. The standardized routine was much more flexible than the event generator used by group B at SLAC, and was easily adapted to the final states studied in our experiment. The second change was the inclusion of routines that would simulate the efficiencies of the 2 Cherenkov counters. Since group B at SLAC were engaged in experiments not particularly dependent on good particle identification, this part of the spectrometer had not been modeled by them. The third change was to replace the SLAC group B hardware trigger simulation routine with one which modeled our own hardware trigger. The fourth difference was the replacement of the SLAC output routine with one of our own design fitted to our particular needs.

In addition, each final state studied required the writing of two routines, one for the control of the event generation package, and the other to plot the variables necessary for monitoring the performance of the program.

The processing of a Monte Carlo event started by reading in the parameters for a beam track from a file of actual reconstructed beam tracks taken from the real event sample. The momentum of this track was then modified to account for the Fermi motion of the nucleons in the downstream target. The modification of the beam parameters was based on the Hulthen model of the proton as described in the reference. The modified beam parameters were then used as input to the event generation routine and the individual generated track parameters were readout and stored. The generated tracks were then swum through the
detector generating points for each chamber hit, based on the chamber's efficiencies and point resolutions determined from the track reconstruction program. During this process, the program properly accounted for energy loss effects on track direction, effects due to scattering off of the material in the detector, particle decays and absorption of particles in the material making up the various devices. Next, the various chambers included in the actual trigger were checked to see if the event would satisfy our hardware trigger. Once the chamber points had been generated for the tracks, the track reconstruction simulation routine decided whether or not the individual tracks could be reconstructed, and assigned a detection probability weight to each event. The events were then subjected to the requirements of the software trigger cuts applied to the data. The next stage was to do a geometry fit to the reconstructed tracks for each of the remaining events. There were counters at every point in the processing where events could be lost, which monitored the efficiencies of the various parts of the experiment. The results of this analysis are shown in table A-1.

For each event generated, an output record was made and written to magnetic tape. For those generated events which were declared undetectable, not reconstructable, or were discarded by the software trigger cuts, the output record consisted of only the generated event parameters.

The Monte Carlo output tapes were then read by routines which included all the kinematic and mass cuts that were applied to the particular real data sample under study. The acceptance matrix was determined by
Table A.1. Apparatus event detection efficiency.

<table>
<thead>
<tr>
<th>REASON FOR EVENT NOT BEING DETECTED</th>
<th>PERCENTAGE OF EVENTS LOST</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>KKp</td>
</tr>
<tr>
<td>Vertex outside target</td>
<td>0.1%</td>
</tr>
<tr>
<td>Track not vertex associated</td>
<td>0.3%</td>
</tr>
<tr>
<td>Track not out of target</td>
<td>18.2%</td>
</tr>
<tr>
<td>Particle absorbed in solenoid region</td>
<td>9.3%</td>
</tr>
<tr>
<td>Did not satisfy hardware trigger</td>
<td>89.1%</td>
</tr>
<tr>
<td>Track not reconstructable</td>
<td>22.3%</td>
</tr>
<tr>
<td>Did not satisfye hardware trigger after PWC 1.5 efficiency taken into account</td>
<td>2.9%</td>
</tr>
<tr>
<td>Clean cut</td>
<td>0.0%</td>
</tr>
<tr>
<td>Dipole track</td>
<td>0.0%</td>
</tr>
<tr>
<td>Matched dipole track</td>
<td>8.0%</td>
</tr>
<tr>
<td>Maximum momentum less than 3GeV/c</td>
<td>0.0%</td>
</tr>
<tr>
<td>C2</td>
<td>0.6%</td>
</tr>
<tr>
<td>C1</td>
<td>6.2%</td>
</tr>
</tbody>
</table>
\[ A(\Omega, x) = \frac{\sum_{i=1}^{N_A(\Omega, x)} W_{G_i} \cdot W_{D_i}}{\sum_{j=1}^{N_G(\Omega, x)} W_{G_j}} \]

where \( \Omega \) and \( x \) indicate the angular and kinematic bin, \( N_A(\Omega, x) \) is the number of events accepted in that bin, \( N_G(\Omega, x) \) is the number of events generated in that bin, \( W_{G_j} \) is the generation weight for the \( j^{th} \) generated event, and \( W_{D_i} \) is the detection weight for the event. The acceptance matrix was then stored on disk to be used by the appropriate analysis program.
BIBLIOGRAPHY

3. Two of many review articles on the subject are:
4. General discussions of the Quark Model can be found in:
   a) Kerson Huang, Quarks, Center for Theoretical Physics, Publication #629.
   b) Bernard T. Feld, Models of Elementary Particles, (Blaisdell Publishing Company, Waltham, Massachusetts, 1969), Part III.
6. For a discussion of one-pion-exchange see:
   b) R. A. Leacock, An Introduction To One-Pion Exchange Calculation In High Energy Reactions, Institute of Atomic Research and Department of Physics, Iowa State University, Ames, Iowa (1966).


19. T4 triggered events were trigger rate equalized for runs 6100-6289. The trigger was then changed and the rate for the new trigger was low enough that no equalization was needed.


21. Transverse momentum is defined as the component of momentum perpendicular to the beam direction, and longitudinal momentum is the component along the beam direction. For this experiment, transverse momentum is essentially the component of the momentum in the x-y plane and longitudinal momentum the component along the z-axis.


23. For a discussion of the 3-body decay problem see:
   a) S. M. Berman and M. Jacob, Phys. Rev. 139B, 1023 (1965).


28. For example see: