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A SEARCH FOR THE E MESON IN AN 11 GeV/c K^-p EXPERIMENT

by

F. G. OAKHAM

A thesis submitted to the faculty of graduate studies in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Carleton University

Ottawa Ontario

1981

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ABSTRACT

An 11 GeV/c K^-p experiment undertaken at the Large Aperture Solenoid Spectrometer facility at the Stanford Linear Accelerator Centre is described. A large number of events were taken (40 million) using a trigger that selected most of the non-elastic cross section. From this data sample a 10,400 event $(K\bar{K}\pi)^0$ data sample was selected which had a sensitivity of 35 and 31 events/ μb for the $\bar{K}^0 K^+ \pi^-$ and $K^0 K^- \pi^+$ channels respectively. The selection was made by reconstruction of the $K^0(\text{short}) \rightarrow (\pi^+ \pi^-)$ decays and the identification of the charged kaons by the LASS particle identification system. Observation of the recoil baryon was not required experimentally; however a missing mass cut of 1 to 4 $(\text{GeV}/c^2)^2$ was made opposite the $K\bar{K}\pi$ system.

No clear evidence was found in the $K\bar{K}\pi$ mass spectrum for any narrow structure. Applying a 6 cut to the $K\bar{K}$ invariant mass did produce a broad bump at low mass ($1.45 \text{ GeV}/c^2$) in the $K\bar{K}\pi$ system. However using events generated by a Monte Carlo technique, this was shown to be in large part due to a kinematic enhancement. A channel separation analysis revealed that the $K\bar{K}\pi$ sample consisted of 3-body phase space and the two body decay mode K^*K . No evidence is found for a $\delta\pi$ decay mode. Events in the K^*K channel forms a broad structure between 1.4 and 1.6 GeV/c^2 . There was

also a difference between the proportion of the K^* charged and the K^* neutral channels in this region. This is indicative of interference between resonances or a resonance and a non-resonant $K\bar{K}\pi$ background. A moments analysis revealed that at low mass the $K\bar{K}\pi$ system was consistent with a J^P assignment of 1^+ .

Thus the analysis performed so far on this data sample provides no clear evidence for an E meson, nor does it exclude its existence. A partial wave analysis is suggested as the best method of understanding the mechanisms responsible for the production of the broad structure at low $K\bar{K}\pi$ mass in the K^*K channel.

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Chapter I

INTRODUCTION

One of the fundamental areas of physics research is an exploration of the nature of matter; a determination of its constituents and the forces that act between them. The study of this subject has led to the concept that matter is made up of atoms which have a size of about 10^{-10} m. Atoms consist of a small (10^{-15} m) but finite sized nucleus, surrounded by point-like electrons. The electrons are bound to the nucleus by the electro-magnetic force; the interaction being described by the theory of Quantum Electrodynamics (QED). The nuclei of atoms contain protons and neutrons which are bound together by the so called strong force. Protons and neutrons are members of a large class of sub-atomic particles called hadrons. Hadrons also appear to have structure; which indicates that they are made up of still smaller particles called quarks.

To explain the known hadron spectrum one must assume that five different types of quarks exist. The types of quarks are known as flavours and they are labelled up, down, strange, charm, and bottom. In addition each flavour of quark has one of three colour charges. All observed hadrons can be constructed by combinations of 3 quarks to form bar-

yons or a quark-antiquark pair to form mesons. Many states predicted by the quark model have not been experimentally observed. This is true of many of the meson states containing one or two strange quarks. Thus one of the goals of meson spectroscopy is to look for these missing states.

The description of the forces holding quarks together is known as Quantum Chromo-Dynamics or QCD. In this theory the colour charges play a role similar to the electric charges in QED. The forces between quarks arise from the exchange of a particle known as the gluon which also carries colour charges. One of the interesting features of this theory is the prediction that gluons can bind together to form particles known as glueballs. The observation of a glueball would be direct evidence for QCD. Unfortunately the characteristics of these particles (mass and decay width) are predicted to be similar to those of many mesons. Thus a thorough understanding of the experimentally observed states and their relation to the hadronic spectrum is essential for the observation of a glueball.

One experimental state that is currently under scrutiny in the search for a glueball is the 'E' meson. The measured properties of this meson are consistent with it being a standard hadronic state of mass $1.42 \text{ GeV}/c^2$ composed of a strange quark-antiquark pair. Recently a state with quite similar properties has been seen in an experimental situation in which a glueball was expected. This has focussed new interest on the E meson, and its properties.

The current status of meson spectroscopy leads to great interest in mesons with strange quark content, particularly the E. One experimental method for obtaining information on meson states is the bombardment of a target (usually liquid hydrogen) with a beam of high energy particles. Some of the energy available in this process appears as new particle states. These states are detected by the observation of the particles into which these states decay. By using a strange particle beam it is expected that particles with strange quark content would be preferentially produced. This thesis describes such an experiment and the analysis of that experiment to look for the E meson and similar meson states.

The experiment in question was carried out at the Stanford Linear Accelerator Centre (SLAC) using a magnetic spectrometer known as LASS (Large Aperture Solenoid Spectrometer). The experiment was conducted by a collaboration between a SLAC experimental group and a Canadian group drawing personnel from Carleton University and the National Research Council of Canada.

A negative kaon beam of 11 GeV/c momentum was used in this experiment and the LASS target was filled with liquid hydrogen. The detector was triggered to collect data when K^-p interactions occurred. (Elastic scattering events were excluded from the main trigger.) Information about the events was collected from a large number of detecting devices that were situated in and around two momentum ana-

lysing magnets. The data was stored on magnetic tape for later computer analysis; forty million useable events were recorded.

Since the trigger requirements were so broad, a wide variety of final states could be examined using this data. The beam particles (kaons) contained one strange quark, so the experiment was well suited to an examination of K^* , ρ and L particles which each contain one strange quark. It was also anticipated that the data would contain mesons consisting of a strange quark-antiquark pair including the Ξ meson. One of the final states in which these mesons can be observed is a neutral three particle state consisting of a neutral kaon K^0 , a charged K and a charged pion ($K\bar{K}\pi^\pm$)⁰. This is the final state that is studied in this thesis.

Extracting this final state from the raw experimental data required a series of analysis and data reduction programs. There were three analysis programs. The first extracted track information from the raw coordinates stored on the original data tape. The second was used to select good tracks and then reconstruct vertices using these tracks. The third program performed an analytic fit on the whole event to the measured points. Interspersed with the analysis programs was a series of selection jobs that used vertex and particle identification information to extract the sample of 10,400 $K\bar{K}\pi$ events.

The $K\bar{K}\pi$ data sample was examined for evidence of meson states particularly for evidence of the E meson. The results of this study were ambiguous. There was no clear evidence in the $K\bar{K}\pi$ mass plots for the narrow structure usually associated with the E . On the other hand the data does not rule out the presence of the E in association with a non-resonant $K\bar{K}\pi$ system with or without other resonances present. This latter conclusion was based on the observation of the two body channel K^*K in the data. This channel is the principal decay mode of the E . The angular decay properties of the K^*K system in the region of the E were consistent with the accepted spin and parity assignments of the E . Even though the current result of the analysis is ambiguous the data sample is of sufficient size and quality that a Partial Wave Analysis could possibly resolve the ambiguity.

1.1 GUIDE TO THESIS

Chapter 2 of this thesis contains a guide to QCD and the quark model. The meson states predicted by this model are mapped out and compared to the observed meson spectrum. Meson-like states that arise from QCD are also considered. The relevance of this experiment to our understanding of the meson spectrum is discussed with particular emphasis on the E meson and other mesons containing strange quarks.

The LASS spectrometer is described in Chapter 3. Many features of this device have been described elsewhere. (See ref. [1] and the references given therein.) Chapter 3 is in essence a summary of the features of the spectrometer. The particle identification devices used in LASS are highlighted in this description. In the latter half of the chapter the way the spectrometer was used to take the experimental data and the specific triggering arrangements are discussed.

Chapter 4 describes the analysis and the data reduction process. The track finding program is summarized, with more details again being contained in ref. [1]. The second analysis program is described in more detail. Particular emphasis is put on the way good tracks were selected and the operation of the vertex searching algorithm. Much of the work of analysing the particle identification information was done at this stage. The results of these studies for the three particle identification devices, the Time Of Flight hodoscope (TOF) and the two Čerenkov counters C1 and C2, are described in detail.

The extraction and analysis of the $K\bar{K}\pi$ data sample is described in chapter 5. That chapter also contains a description of the Monte Carlo programme used to calculate the resolution and acceptance of the spectrometer. The backgrounds present in the data sample are discussed in detail. The two numerical analyses used on the data are

described; these were a channel separation analysis and a moments analysis. The moments analysis extracted the spherical harmonic content of the $K\bar{K}\pi$ angular distributions. Also included in this chapter is a review of the experimental evidence for the E meson with a comparison between the data from this experiment and one in which the E meson was clearly seen. Finally the results are summarized along with suggestions for further analysis.

Chapter II

THEORETICAL BACKGROUND AND EXPERIMENTAL REVIEW

" Consider all substances; can you find among them any enduring "self"? Are they not aggregates that sooner or later will break apart and be scattered?"

The teachings of Buddha

2.1 QUARKS AND GLUONS

In ancient Greece a topic often debated was the question of whether matter was continuous or made from very small particles. No doubt the adherents to the continuous matter theory would ask what the very small particles were made from. The adherents to the particle theory would claim nothing; they are fundamental. The question that was probably not addressed by either side (they were after all philosophers), was how a fundamental particle would be recognized if found. The latter question is certainly important in light of our current understanding of the constituents of matter.

The picture of matter consisting of atoms made up of a nucleus with a cloud of electrons around it is a familiar

one. The nucleus is known to consist of particles named protons and neutrons. Experiments with these 'fundamental' particles (protons, neutrons and electrons), revealed that many more proton-like particles existed. They were given the name hadrons (heavy particles). This is to be contrasted with electron-like particles named leptons (light particles). Further experiments in which protons (in liquid hydrogen) were bombarded with high energy electrons (ref. [2]) indicated that the proton had structure. This demonstrated that the proton was not a fundamental particle, and raised questions about the properties of the constituents of the proton, (and all other hadrons). The scheme that fits the observed particle spectrum best is one in which all hadrons are made up of three fractionally charged particles called quarks. Quarks come in five flavours known as up (u), down (d), strange (s), charm (c) and bottom (b). The properties of the five quarks are listed in table 1. Quarks combine in three different ways to form hadrons. three quarks combine to form a subset of hadrons known as baryons, three antiquarks combine to form antibaryons and a quark can combine with an antiquark to form mesons. One of the early difficulties with this theory was that a free quark was not observed experimentally. At present it is not clear whether they have or have not been observed (ref. [3]). In any case the quark model has been successful in explaining so many aspects of hadron spectroscopy, that the existence of quarks is no longer an issue.

TABLE 1.

Quantum Numbers Associated with the Quarks

Quark flavour	Effective mass GeV	Charge Q	Strangeness S	Charm C	Bottom B
u	0.3-0.4	2/3	0	0	0
d	0.3-0.4	-1/3	0	0	0
s	0.5	-1/3	-1	0	0
c	1.5	2/3	0	1	0
b	5	-1/3	0	0	1

Atomic forces are well understood using the theory of Quantum Electro-Dynamics (QED). In this theory the force between charged particles arises from the exchange of virtual photons between them. These photons do not interact directly with each other, and because of the infinite range of the electromagnetic force the photon has to be massless. QED is an extremely successful theory giving rise to agreement between theory and experiment for the energy levels of atoms to many significant figures. QED has also been shown to be valid over a wide range of distances, from macroscopic values down to 10^{-14} m.

To explain forces between quarks the concept of a colour charge is used. The property of colour was originally assigned to quarks to correct an anomaly in the way quarks

were combined to form baryons. To give baryons the correct spin, quarks had to have half integral spin. However in some hadrons all three quarks had to have identical quantum numbers. This violated the well established Pauli exclusion principle, which forbids identical half integral spin particles to be in the same state. By allowing quarks to have one of three colours this difficulty is overcome. The forces between quarks originate from the exchange of a particle known as a gluon. There are eight different types of gluons and they each carry a colour charge and an anti-colour charge. Thus absorption or emission of a gluon by a quark can change its colour, see figure 1. All known particles can be constructed to be colourless in the sense that as each of the quarks in a baryon has to have a different colour (red, yellow , blue), then the overall baryon is colourless, using the analogy of the addition of primary colours. Similarly if one assigns one of the quarks in a meson to have the anti-colour of the other, the mesons are also colourless. The fact that all hadrons can be constructed to be colourless and that there have been no confirmed sightings of a free quark, indicates that the exhibition of free colour is restricted by some mechanism.

An empirical method of describing the quark-quark forces is to look for quark-quark potentials that fit the known spectra of particles. This is more easily done using the meson spectra as only two quarks are involved. Poten-

GLUON SELF - INTERACTION

Figure 1: Gluon and Quark Interactions

tials have been found that fit the radially excited $c\bar{c}$ spectrum associated with the Υ , Υ' , Υ'' , ... and χ mesons very well. When these same potentials are applied to the $b\bar{b}$ spectrum of the Υ , Υ' , Υ'' mesons, the fit was also very good. A potential that goes as $1/r$ at small r and $\log(r)$ or r at large r provides a good fit to both spectra (ref. [4]). In these potentials the term for large r is included to provide confinement or inhibition of free quark states. Application of such potentials to the light quark spectrum (those containing only u, d and s quarks) have been less successful. The main reason for this is that as the mass of these quarks is lower, the relativistic and spin-orbit coupling effects are more significant. Despite these difficulties recent success has been reported fitting bottom, charmed and strange meson spectra using a potential with the form $A + Br^{0.1}$ (ref. [5]).

A more fundamental approach to describing the quark-quark force is to use a theory based on the exchange of gluons. This theory is an extension of the principles used to formulate QED and is known as Quantum Chromo Dynamics or QCD. There is a fundamental difference between the two theories namely that in QCD the exchange particle, the gluon, carries the colour charge. Thus the gluon itself can emit and absorb more gluons. Unfortunately this self-interaction of gluons makes numerical calculations with QCD extremely difficult. In principle to establish the theory one would

want to use it to fit the masses and decay widths of the observed hadron spectrum. This would involve using the known properties of the hadron spectrum to calculate the masses of the quarks and the coupling constants that give the strengths of the quark-gluon and gluon-gluon interactions. Unfortunately the necessary calculations have not been done yet. However the gluon self-interaction lead to the interesting possibility that two or three gluons could form a stable particle. These have been given the tentative name of glueballs. The observation of a glueball would be dramatic evidence for the existence of gluons and therefore for QCD.

So at our current level of understanding the 'indivisible particles' sought by the Greeks are the quarks and the leptons. Currently six leptons are known, the electron, muon, tau, and their associated neutrinos. Both the charmed and bottom quarks and the tau particles have been discovered quite recently (in the past seven years.) There is currently no compelling evidence that all quarks and leptons have been discovered nor that there is a limit to the number of them. This situation forces one to wonder, are quarks and leptons really fundamental? Many theorists have wondered about this too, resulting in a number of schemes in which both quarks and leptons are made from a few more elementary particles ref. [6]. Some tentative names for these particles are preons (or richons. So far these schemes can

be used to explain the general characteristics of quarks and leptons in a fairly convincing manner. However the dynamics of the theories are far from being solved. And will richons be fundamental? Unfortunately this question and a number of others can not be answered by the experiment that is being described here. The realm of the K^-p experiment is an exploration of the section of the meson spectrum composed of u , d and s quarks.

2.2 THE QUARK MODEL AND THE MESON SPECTRUM

The quark model described in the previous section does a remarkably good job in providing a qualitative explanation of the known hadron spectrum. No particle has yet been seen that cannot be assigned to an allowed $q\bar{q}$ or three quark state. An alternative test of the theory is to ask how many of the predicted states have been observed. The heavy quark spectra, those containing charmed and bottom quarks, are well understood with sufficient radially excited states to allow a fit of a quark-quark potential. This is not true for the strange quark states. In fact there are many missing states in the light quark spectrum. Before discussing them it is necessary to map out the spectrum predicted for the light quarks.

There are nine ways of arranging the u , d and s quarks and their antiquarks into $q\bar{q}$ combinations. The $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ combinations have identical quantum numbers. In general any two states with the same quantum numbers can mix. Thus

the observed particles may be formed from linear combinations of such states. A symmetry scheme $SU(3)$ is used to define a set of such linear combinations and to classify the nine resulting meson states in an octet and a singlet representation. The states and their quark content are shown in figure 2. Each of the mesons has a definite value of isospin I . In the $SU(3)$ octet there is an $I=1$ triplet, an $I=0$ singlet and two $I=1/2$ doublets. The particles in isospin multiplets have similar masses and are considered to be different states of the same particle. The $SU(3)$ singlet state contains one symmetric $I=0$ particle. The $I=0$ octet state has a higher strange quark content than the singlet state. The observed $I=0$ meson states are not pure $SU(3)$ states but are a mixture of the singlet and the octet state. When the experimental meson states have properties consistent with them being pure $s\bar{s}$ and pure $(u\bar{u}+d\bar{d})$, magic mixing is said to occur.

The quarks carry half integral spin $\frac{1}{2}$. In a meson they can have a relative angular momentum $\bar{L}$ leading to a total angular momentum $\bar{J} = \bar{L} + \bar{S}$. This and the definition of the three other quantum numbers associated with the $q\bar{q}$ system are shown in figure 3. They are the parity P , C-parity C , and G-parity G . The mesons fall into super-multiplets with a fixed value of L . Each $I=0$ meson is in a C-parity eigenstate. The octet and singlet of a given nonet are usually labelled with the C-parity of its $I=0$ member (JPC). It is also possible for radially excited states to exist.

SU(3) OCTET

17

SU(3) SINGLET

Figure 2: Meson Classification Scheme. The quark assignments for the SU(3) symmetry scheme are shown and the application of this scheme to the pseudo-scalar mesons is illustrated.

$$J = L + S$$

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$

$$G = (-1)^{L+S-1}$$

10-80
3942 A 57

Figure 3: Quantum Numbers Associated with Mesons

Using this notation the known light quark meson spectrum is shown in table 2. For $L=0$, only two nonets of states are possible with $J=0$ and 1. For $L>0$, four sets are possible, $J=L$ for $S=0$ and $J=L-1, L, L+1$ for $S=1$. The radially excited states are shown in the boxes on the right. If $SU(3)$ were an exact symmetry one would expect the masses of all the particles in an octet to be the same. In fact, $SU(3)$ is a badly broken symmetry. The masses of the mesons are more easily understood in terms of their quark content. For instance, the difference in mass between the pion, kaon and η can be understood in terms of the proportion of strange quark content, assuming the strange quark mass is significantly greater than the u and d quarks.

In the meson spectrum the states with the highest value of J in a given supermultiplet are the best determined. These are known as the leading spin-parity states. All the $L=0$ states are well known and there are even some candidates for the radially excited $L=0$ states. There are candidates for most of the states in the $L=1$ supermultiplet and a fair number of these are well established mesons. In this supermultiplet the $I=1/2$ mesons have been found and amongst the $I=1$ states the A_2 and the B are well established. The existence of the A_1 meson has proved difficult to confirm and the mass and width of this meson has varied greatly since it was first observed. The δ resonance is seen as a threshold enhancement in $K\bar{K}$ spectra. Because it has a mass

TABLE 2
Status of the Meson Spectrum

+ L=2 or L=0 radially excited state
? Needs experimental verification
Questionable assignment

SU(3)		OCTET		SINGLET	
J ^{PC}	S	I=1/2	I=1	I=0	I=0
4 ⁺⁺	1	K [*] (2070)	A ₄ (1900)		h(2040)
3 ⁺⁺	1				
2 ⁺⁺	1				
3 ⁺⁻	0				
L=3					
3 ⁻⁻	1	K [*] (1780)	g(1700)		ω(1670)
2 ⁻⁻	1	L(1700)?	A ₃ (1660)		
1 ⁻⁻	1	K [*] (1700) ⁺	ρ ⁺ (1660) ⁺		
2 ⁺⁻	0	L(1700)?			
L=2					
2 ⁺⁺	1	K [*] (1430)	A ₂ (1310)	f'(1520)	f(1270)
1 ⁺⁺	1	Q _a (1340)	A ₁ (1230)	E(1420)	D(1285)
0 ⁺⁺	1	κ(1420)	δ(980)?	S [*] (980) [#]	ε(1300)
1 ⁺⁻	0	Q _b (1340)	B(1235)		
L=1					
1 ⁻⁻	1	K [*] (895)	ρ(770) _k	φ(1020)	ω(783)
0 ⁺⁻	0	K(497)	π(135)	η(549)	η'(958)
L=0					

I=1/2	I=1	I=0	I=0
κ ⁺ (1900)?			
K [*] (1700) ⁺	ρ ⁺ (1600) ⁺		
K ⁺ (1400)?	π ⁺ (1270)?		

FIRST RADIAL EXCITATION

below threshold, its mass and width have also been difficult to determine. As explained earlier, the experimentally observed $I=0$ states are in general mixtures of the $I=0$ $SU(3)$ octet and singlet states. The observed $I=0$ state with the larger $s\bar{s}$ content is assigned to the octet state. The $s\bar{s}$ content of a meson is determined partly by the relative masses of the two $I=0$ states and partly by the decay mode of the mesons. A selection rule operates on the decay of states known as the Zweig rule that prohibits discontinuous quark lines. This is illustrated in figure 4. The operation of this selection rule on a pure $s\bar{s}$ state which arises when the $I=0$ states are magically mixed requires the decay products to include at least two strange mesons. Thus, of the $IJP=02^+$ mesons, the f' is assigned to the octet as it has the larger mass and decays predominantly to $K\bar{K}$ while the f goes mainly to $\pi\pi$. The D is well established and has decay properties suitable for its $SU(3)$ singlet assignment. Its companion the E decays mainly to K^*K which puts it into the octet slot, however there has been great difficulty with both the observation and subsequent JP determinations for this state. These will be discussed later. The meson assignments for the 0^+ nonet are basically unsatisfactory. The masses of the states do not fit together with either the $SU(3)$ model or the quark model. Possible explanations for this are discussed in the next two sections.

Less than half of the $L=2$ supermultiplet states have possible meson assignments; there are even fewer for $L=3$. Note that there are no unambiguous assignments to the radially excited states. Both the $K^*(1700)$ and the $\rho'(1600)$ could be assigned either to the $L=0$ radially excited supermultiplet or to the orbitally excited $L=2$ supermultiplet. The $K'(1400)$ has not yet been observed in a second experiment. Evidence for a $K'(1900)$ has been found in this experiment. If confirmed it will be the first unambiguous radially excited K' , or strange state. The scarcity of these states is somewhat surprising in view the large number of radial excitations seen in the π ($c\bar{c}$) and Υ ($b\bar{b}$) spectra.

As already indicated the K^-p experiment was intended to provide new data mainly on mesons with a strange quark content. In the next section the status of these mesons is examined in more detail.

2.3 MESONS WITH STRANGE QUARK CONTENT

There are two classes of strange quark mesons, the $I=1/2$ mesons which contain one strange quark and the $I=0$ mesons which have a certain percentage of $s\bar{s}$ content. In general the $I=1/2$ mesons are better established than the $I=0$ mesons, and amongst the $I=1/2$ mesons the ones with natural spin parity are the best understood. The reason for these differences is mainly the simplicity of the channels in which the mesons can be studied.

ZWEIG ALLOWED PROCESS (no discontinuous quark lines)

ZWEIG SUPPRESSED PROCESS

RADIATIVE DECAY OF J/ψ

Figure 4: Example of Zweig Allowed and Zweig Forbidden Processes

The natural spin parity $I=1/2$ mesons, generically labelled K^* , are best studied in channels such as:-

$$K^-p \rightarrow K^-n + n$$

The most recent study of this channel is the one using the data from this K^-p experiment. The results of this analysis can be found in ref. [1] and [7]. In this analysis all established states were confirmed and new ones were discovered. There are now four leading K^* resonances for values of $L=0,1,2$ and 3. Parameters of these resonances are shown in the upper half of table 3. Only the $K^*(890)$ and the $K^*(1430)$ are visible as resonances in the Kn mass spectrum. The other K^* states were observed by determining the spherical harmonic moments of the Kn decay angular distributions and then performing a partial wave analysis (PWA). The $K^*(2070)$ was observed for the first time in this experiment. The $K^*(1780)$ is confirmation of a state observed by a previous experiment, ref. [8]. Three underlying resonances have also been discovered in this Kn data. The results of this experiment for these states are shown in the bottom half of table 3. Interpretation of the data is more difficult for these resonances, so it is not possible to give precise masses and widths for them, although clear resonant behaviour is observed. The $0^+(1420)$ is confirmation of a K^* first seen by Estabrooks et al., ref. [9]. The $0^+(1900)$ and

$1^-(1700)$ are new effects. The significance of these to the quark model has been discussed in the previous section.

TABLE 3

K^* Resonances Found in $K\pi$ Analysis of ref. [1]

LEADING RESONANCES

JP	Mass MeV/c ²	Width MeV/c ²	Elasticity
1^-	894.6 ± 0.8	49.8 ± 1.2	-
2^+	1428 ± 3	98 ± 8	0.43 ± 0.01
3^-	$1753 \begin{smallmatrix} +.25 \\ -18 \end{smallmatrix}$	$300 \begin{smallmatrix} + 170 \\ - 80 \end{smallmatrix}$	0.16 ± 0.01
4^+	$2070 \begin{smallmatrix} +100 \\ - 40 \end{smallmatrix}$	$240 \begin{smallmatrix} +500 \\ -100 \end{smallmatrix}$	0.17 ± 0.01

UNDERLYING RESONANCES

0^+	1420	240	0.85
0^+	1900	230	0.35-0.45
1^-	1700	200	0.35

The unnatural spin-parity $I=1/2$ resonances are best studied in the reactions:-

$$K^-p \rightarrow K^-n^+n^-p$$

$$K^-p \rightarrow K^0n^+n^-n$$

Plots of the $\bar{K}\pi\pi$ mass spectra in these reactions reveal a broad bump between 1.2 and 1.4 GeV/c² that is known as the Q region. There is another broad bump around 1.7 GeV/c² that is known as the L region. Neither the Q nor the L region are open to simple interpretation and detailed analysis is necessary to extract resonance information. Two main decay modes have been established in the Q region: they are (K, ρ) and (K^*, π) . A number of independent partial wave analyses have been performed using data from different experiments. From these the Q region is best interpreted as two resonances $Q_1(1280)$ and $Q_2(1400)$ decaying mainly to (K, ρ) and (K^*, π) respectively. Because the quantum numbers for the two $J^P=1^+, I=1/2$ mesons are the same, mixing occurs between the two possible SU(3) states to produce the experimentally observed mesons. The SU(3) states are labelled as Q_a and Q_b . In an analysis by Carnegie et al. (ref. [10]), the mixing angle θ_q is calculated to be 45° using SU(3) symmetry. This leads to masses for Q_a and Q_b of about 1.34 GeV/c².

There is evidence for a $0^- K^*(1400)$ from a PWA of $\bar{K}\pi\pi$ data, ref. [11]. This resonance if confirmed would be classified as a radially excited K. The status of the L region is at present uncertain. It is anticipated that the L=2 orbital excitations of the K will lie in this region.

In comparison to K^* and Q-L spectroscopy the status of the I=0 mesons is much worse. Mesons have been found for all the I=0 ground states of the quark model. Of these the ρ and η are identified with the SU(3) octet states. The ϕ

appears as a prominent peak in the $K\bar{K}$ mass spectrum just above $K\bar{K}$ threshold with a decay width of $4 \text{ MeV}/c^2$. Application of mass rules and $SU(3)$ symmetry to the pseudo-scalar mesons indicates that the $I=0$ members are not magically mixed, i.e. the η is not in a pure $s\bar{s}$ state. It is also clear that they are not pure $SU(3)$ states. It is thought that relativistic and spin orbit forces are a major factor in the energy levels of this nonet.

In the $L=1$ nonet good candidates exist for the $I=0$ states in the leading nonet 2^{++} , the f and the f' . In fact on all grounds this nonet is an ideal example. The masses of the constituent particles are consistent with their quark content, they also work well with $SU(3)$ symmetry if one assumes magic mixing. The f and the f' decay predominantly to $K\bar{K}$ and $\pi\pi$ respectively. For the remaining $L=1$ mesons the situation is less clear. There are good candidates for the $SU(3)$ singlet states in the 1^+ and 0^+ nonets: the D and the $\epsilon(1300)$. The D has been seen in a number of decay modes (η, π, π) , (K^*, K) , (ϕ, π) , (ρ, π, π) . In practice because of the kinematics involved it is difficult to distinguish between the (ϕ, π) and (K^*, K) decay modes. The averaged mass and width of the D is 1285 and $26 \text{ MeV}/c^2$ respectively. However a recent phase shift analysis on the (η, π, π) channel gives a much narrower width for the D , ref. [12]. They also found evidence for underlying resonances in the D region that apparently inflated the observed width of the raw peak. The

ϵ is seen in phase shift analysis of the $(\pi\pi)^0$ and $(K\bar{K})^0$ systems. There is a fairly detailed review of this subject which includes a discussion of the S^* in the particle property tables ref. [13].

The remaining observed $I=0$ meson that fits into the $L=1$ multiplet is the E meson. This meson has had a checkered history. It was first observed in $p\bar{p}$ collisions at low p momentum in bubble chamber experiments, ref. [14]. In nearly all cases the E was seen in the $K\bar{K}\pi$ channel. The E signal was found to be enhanced by requiring that the decay proceed via either of the two body decays (δ, π) or (K^*K) . In fact, as will be discussed in chapter 5, if the predominant decay mode is K^*K , making a δ cut on the $K\bar{K}$ mass will enhance the E on purely kinematic grounds. The early analysis of the E meson were made with poor statistics and often with the assumption that the principal decay mode was $\delta\pi$. This led to many contradictory results. A recent higher statistics π^+ production experiment by Dionisi et al, (ref. [15]), has indicated that the decay is predominantly K^*K and that the JP assignment of this meson is 1^+ . The $K\bar{K}\pi$ spectrum obtained in this experiment is shown in figure 5. The cuts used to obtain this spectrum are shown on the plot. The E meson is the prominent peak visible just above K^*K threshold. The observed mass and width of the E in this experiment were 1426 and 40 MeV/c² respectively. A branching ratio of

$$E \rightarrow (K^*K + c.c.) / (\delta\pi + K^*K + c.c) = .86 \pm .12$$

was obtained. Note that the E has not been seen in the (η, π, π) channel which should arise from the other observed decay mode of the S . The experimental status of the E is considered again in chapter 5, at which point a comparison is made between the $n\bar{p}$ experiment of ref [15] and this experiment. The current evidence from production experiments points to the E as being a conventional 1^+ meson containing mainly $s\bar{s}$ quarks.

Recently an E like state (mass=1440, width=50 MeV/c²) has been observed in radiative decays of the Υ ($\Upsilon \rightarrow E\gamma$), ref. [16]. There are insufficient events in the measurement of the E in Υ decays to determine the spin-parity of the state. The observation of the E in this manner has raised great interest because it is anticipated that if glueballs do exist they would be seen in this process and at the mass of the E . This topic is discussed in more detail in the next section.

2.4 MULTI-QUARK STATES AND GLUEBALLS

In addition to the regular $q\bar{q}$ and qqq combinations, adherents of QCD have predicted a number of other possible multi-quark states and states in which gluons are more manifest. This theory has a significant impact on the number of meson like states that are anticipated to exist. A review of this subject with extensive references can be found in ref. [17].

The multiquark meson-like states consist of four quarks, $qqq\bar{q}$. Thus at a certain level they can be considered to be a combination of two standard mesons. As such

Figure 5: $K\bar{K}\pi$ Spectrum from 4 GeV π^-p Experiment of Ref. [15]

they can literally fall apart providing that the angular momentum between the two mesons is 0. The only way such a decay could be narrow is if it is below threshold. There are two ways of calculating the properties of the four quark system, one is to use the MIT bag model and the other is to use the baryonium model. The bag model is solvable only if all quarks are confined in the bag in s-waves. This leads to three possible spin-parity assignments $0^+, 1^+, 2^+$ and an enormous number of states. The masses of these states span the standard meson spectrum. See table 4.

If these states exist they can go a long way in explaining some of the puzzles and difficulties with the $q\bar{q}$ system, particularly those of the 0^+ nonet, ref. [18]. The δ and S^* could both be four quark systems. Their masses are below the $K\bar{K}$ threshold and so would have a relatively narrow mass for a four quark state. This would leave the $\kappa(1420)$ and the $\epsilon(1300)$ in the 0^+ nonet. To complete this nonet one would need a $\delta'(1300)$ (ref. [19]) and an excited S^* at a mass of about 1500 MeV/c². The other effect of the states predicted by the bag model would be a large number of very broad resonances from 1 to 2.5 MeV/c². These could cause a large background to the $q\bar{q}$ meson spectrum. This could explain why some of the $q\bar{q}$ mesons have been so hard to find.

The baryonium model consists of a $q\bar{q}$ pair coupled with a $q\bar{q}$ pair at high orbital angular momentum. One of the key predictions of this model is that some of these states are

TABLE 4

Mass Predictions for $q\bar{q}q\bar{q}$ from the MIT Bag Model

from Cashmore (ref. [17])

0^+			1^+		
SU(3) multiplet	State	Mass (MeV)	SU(3) multiplet	State	Mass (MeV)
<u>9</u>	C^0	650	<u>9</u>	C^0	1200
	C_K	900		C_K	1400
	C^S, C_T^S	1100		C^S, C_T^S	1600
<u>36</u>	E_{TK}, C_T, C^0	1150	<u>18</u>	C_T	1250
	E_{TK}, C_K	1350		E_{TK}, C_K	1450
	$E_{(KK)}^1, C_T^S, C^S$	1550		$E_{(KK)}^0, C_T^S, C^S$	1650
	C_K^S	1750		C_K^S	1850
	C^{SS}	1950	<u>36</u>	E_{TK}, C_T, C^0	1450
<u>9^*</u>	C^0	1450		E_{TK}, C_K	1600
	C_K	1600		$E_{(KK)}^1, C_T^S, C^S$	1800
	C^S, C_T^S	1800		C_K^S	1950
<u>36^*</u>	E_{TK}, C_T, C^0	1800		C^{SS}	2150
	E_{TK}, C_K	1950	<u>18^*</u>	C_T	1650
	$E_{(KK)}^1, C_T^S, C^0$	2100		E_{TK}, C_K	1800
	C_K^S	2200		$E_{(KK)}^0, C_T^S, C^S$	1950
	C^{SS}	2350		C_K^S	2100

 2^+

SU(3) multiplet	State	Mass (MeV)
<u>9</u>	C^0	1650
	C_K	1800
	C^S, C_T^S	1950
<u>36</u>	E_{TK}, C_T, C^0	1650
	E_{TK}, C_K	1800
	$E_{(KK)}^1, C_T^S, C^S$	1950
	C_K^S	2100
	C^{SS}	2250

expected to have a narrow width. Their masses would be higher than those of the bag model or $q\bar{q}$ ground states. There is currently no evidence for narrow baryonium states.

One of the features of QCD is that gluons interact with each other leading to the possibility of two or three gluon states. The masses of these states can also be estimated using the bag model. The predicted masses along with the possible spin-parity assignments for glueballs are shown in table 5. Once again the masses of these states are within the standard meson range. Glueballs are expected to have fairly narrow decay widths as the decay represents one half of a Zweig forbidden process. One possible candidate for a glueball is the S^* except that the S^* does not have equal branching ratios to $K\bar{K}$ and $\pi\pi$. One would expect the decay of a glueball to be flavour independent. The other possible evidence for a glueball is in the radiative decays of the $\bar{E}$, where the E like object mentioned in the previous section has been observed. In these decays one expects a two gluon state which does not permit the E 's JP assignment of 1^+ . In the radiative decay process sufficient data does not exist for a spin parity determination of the E like object. This is quite a crucial measurement. If the assignment is 1^+ then the particle is probably a standard E meson. The coupling to $\bar{E}$ could be explained by the E having a sizable $c\bar{c}$ content, ref. [20].

TABLE 5

Glueball Spin-Parity and Mass Assignments

	0^{++}	2^{++}	980 MeV/c ²
	0^{-+}	1^{-+} 2^{-+}	1290 MeV/c ²
	0^{++}	2^{++}	1590 MeV/c ²
3g	1^{--}		1460 MeV/c ²

from Cashmore ref. [17]

It is also anticipated that $q\bar{q}g$ states can exist. Nearly all spin-parity combinations are possible in this case. The decays of such states would be narrow due to Zweig suppression of the decay of the gluon. There is no experimental evidence for these states.

Given QCD, the possibility exists of a large number of meson like states arising from multiquark combinations and states containing gluons. To determine whether such states really exist it is essential that a better experimental understanding of the meson spectrum is obtained. The application of the K^-p experiment to this problem is discussed in the next section.

2.5 K^-p AND THE MESON SPECTRUM

As the 11 GeV/c K^-p experiment employed a non-specific interaction trigger, many final states can be examined for evidence of new meson states. Due to the use of a kaon beam the data is particularly useful for looking for states with strange quark content.

An analysis has already been performed on the K^-n^+ channel, giving rise to new information on K^* states. An analysis of the $K^-n^-n^+$ and $\bar{K}^0n^-n^+$ channels is underway to study the Q and L regions. A third channel of great interest is $(K^0K\pi)^0$. In this channel one expects to see the unnatural parity, $I=0$ mesons, particularly those with large $s\bar{s}$ content. This includes the E meson and its B nonet counterpart. One could also hope to see the $L=2$ analogue of these states. Additional information on the E meson is particularly important in light of its possible observation in radiative π decay, and the historical difficulty in clearly establishing quantum numbers and decay modes for it.

The rest of this thesis is devoted to a description of how the K^-p experiment was used to look for the E meson in the $K^0K^+n^-$ channel.

Chapter III

DESCRIPTION OF EXPERIMENT

3.1 INTRODUCTION TO THE LASS SPECTROMETER

The LASS spectrometer is a device for investigating high energy particle physics reactions. It is situated at the end of the two mile long Stanford linear accelerator. In a typical physics reaction a high energy particle from the accelerator hits a particle in the target producing a number of secondary particles. By detecting and measuring the properties of these secondary particles it is possible to reconstruct the underlying physics event. A large number of such physics events provides the data needed for the experimenter to investigate the properties of a large number of sub-atomic particles.

The main function of the spectrometer is to measure the momentum and position of particles within the device, and to uniquely identify as many of them as possible. The LASS spectrometer system uses two magnets; a solenoid and a dipole (see fig. (6)), with a large number of detectors in and around the magnets for measuring the position of particles. The super-conducting solenoid which produces a field of 22.4 kilogauss surrounds the liquid hydrogen target. The down beam end of the solenoid is covered by two particle

identification devices, a 38 cell Čerenkov counter (C1) and a 28 element Time Of Flight/trigger hodoscope (TOF). Because of the magnetic field, particles move along helical paths within the solenoid, with the axis of the helix oriented in the direction of the field. A measurement of the helix parameters allows the momenta of the particles to be calculated. The majority of particles get trapped within the bore of the solenoid and travel down to the particle identification devices. Particles with large momenta are usually produced at small angles and are not well measured in the solenoid, but are generally measurable in the dipole section of the spectrometer. The dipole has an aperture of 1 m (vertical) by 2 m (horizontal) and a depth (in the direction of the beam) of 2 m. The effective field of the dipole is 30 kg-m. There are detectors on either side of the dipole. A measurement of the bending of the particle's path as it passes through the dipole allows a measurement of the particle's momentum. Identification for particles in the dipole region is provided by an 8 cell Čerenkov counter (C2).

The use of both a solenoid and a dipole in the LASS configuration gives the device a large angular acceptance. In practice it should be noted that not all tracks are observable. Tracks that have small momenta are often not detected and those that are seen are less likely to get to the particle identification devices. These devices also have a non-uniform spatial acceptance and operate in limited

Figure 6: Diagram of Spectrometer

momentum ranges. There are also no devices to detect neutral particles (n^0, γ). Despite these shortcomings the angular acceptance of LASS provides a considerable improvement over spectrometers used in previous experiments.

There are a number of different detectors used in the LASS system. The types of devices and their characteristics are shown in table 6. Spark chambers give good positional information but have poor timing characteristics. Scintillation counters, which are combined to form arrays called hodoscopes, give good timing resolution but limited positional information. In the case of the TOF hodoscope the timing resolution is deliberately enhanced. Spatial resolution of scintillation hodoscopes is determined by the segmentation of the array. Cerenkov counters have similar resolution characteristics to scintillation counters. Proportional chambers have both good timing and spatial resolution.

The key characteristic of all these devices is that the information they provide (spatial and timing) is in an electronic form. This makes it possible to select events of interest and to record the experimental information on magnetic tape for immediate or later computer analysis. For the LASS system encoding the information from the detector into a compact record for transfer to magnetic tape took about 21 ms. Thus the spectrometer could accept data at the rate of up to 50 events/sec. In practice data was taken at

TABLE 6

-Characteristics of Devices Used in LASS

DEVICE	RESOLUTION		DEADTIME
	TIME	SPATIAL	
SPARK CHAMBER	1 μ sec	0.5 mm	10 msec
PROPORTIONAL CHAMBER	75 nsec	0.3 mm	-
SCINTILLATION HODOSCOPE	0.5-5 nsec	~cm	-
CERENKOV COUNTERS	as for scintillation counters		
TOF	1.3 nsec	~cm	-

a much slower rate (about 15 events per second). In comparison with a bubble chamber LASS does not provide the same uniform angular acceptance and resolution. This is compensated by the higher data rate that can be achieved with the spectrometer, the ability to trigger events, and the convenient form of the data record. The remainder of this chapter describes LASS and its use in detail.

3.2 ACCELERATOR AND BEAM LINE

The accelerator at SLAC produced an electron beam with an energy of 21 GeV/c. This beam was delivered in discrete 1.5 μ sec pulses at a rate of up to 180 pulses/sec. For experiments with LASS, the electron beam was directed via the beam switchyard to a copper/beryllium target located within a shielded blockhouse, (End Station 'B'). This produced a

large number of secondary particles of different types. From this shower of particles, negative kaons of momentum 11 GeV/c were selected by the secondary beam line, transported to the LASS spectrometer, and focused on a region at the end of the liquid hydrogen target within the spectrometer. For details of the beam transport system see figure 7.

3.2.1 Secondary beamline

The secondary beamline focus is maintained by a system of quadrupoles. There are three intermediate focussed beam positions in addition to the main focus at the target labelled F1, F2, F3, F4 in figure 7. Momentum selection is achieved using dipole magnets and collimators. The particles emerging from the electron beam target are mainly electrons and pions, with a small number of kaons and protons. Electrons are removed with a thin lead absorber. To select kaons two Radio-Frequency (R.F.) separators are used. These reduce the pion contamination to less than 5%. All other contaminations are negligible.

3.2.2 Beam line monitoring devices

The beam line monitoring devices are shown in figure 7. The momentum of beam particles was measured by the P scintillation counter hodoscope located at the horizontally dispersed focus F3. This hodoscope provided a momentum resolution of 25 MeV/c. The position of the beam near the LASS target was measured using the theta/phi hodoscope and two sets of Pro-

TABLE 7

Parameters of Beam

Secondary K ⁻ beam momentum	11 GeV/c
Momentum dispersion (dp/p)	1.5%
Momentum hodoscope resolution	0.35%
Beam pulse rate	<180 hz
Beam pulse duration	1.6 μ sec
Number of kaons per pulse	2.5
Pion contamination of beam	5%
Radius of beam spot at target	< 0.5 cm

portional Wire Chambers (PWCs). The beam PWCs had a total of nine planes of wires with 1mm wire spacing. Three of the planes were oriented at 45° to the vertical to remove match point ambiguities. (See section 4.2.1). Beam position information for the trigger was provided by the XY-R scintillation counters. The XY counters were used to ensure that events were initiated by a single beam particle. In addition, if in an event one or more particle hit the ring counters, the event was not recorded. This had the effect of reducing the beam halo. Beam identification was provided by two pressurized Čerenkov counters CK and Cn. CK was filled with carbon dioxide and Cn was filled with hydrogen. The pressure in these counters was adjusted so that a kaon of 11 GeV/c gave light in CK but not in Cn. Finally, a small 10 by 10 cm scintillation counter labelled SE was located just inside the LASS building. This counter provided the timing signal for the spectrometer. It was also

used as the start counter for the TOF system. A summary of the beam parameters can be found in table 7.

3.3 SOLENOIDAL PART OF SPECTROMETER

3.3.1 Solenoid

A detailed diagram of the solenoidal part of the spectrometer can be found in figure 8. The solenoid was made up of four sets of superconducting coils. The upbeam end was covered by a thick iron flux return plate. The target fitted into a central hole in the plate; the hole also provided an entry point for the beam. There was an iron ring at the down-beam end of the solenoid to improve field uniformity. The internal bore of the solenoid had a radius of 92 cm and an internal length of 3.5 m. Prior to the installation of the track finding devices the field was measured in and around the magnets so that a field map could be created. The region of the solenoid in which particle tracks were detected and measured had a field of 22.4 kg that was uniform to within 1%. In the region of the Čerenkov counter C1 and the twist region,¹ the field was far from uniform and of considerable strength. To describe the paths of tracks in this region it was necessary to employ a Runge-Kutta integration technique in conjunction with the field map.

¹ The region between the solenoid and the dipole magnet was known as the twist region.

- LH₂ Target
- ▨ Plug Proportional Chamber (Plug 1,2,3)
- ▩ Tracking / Trigger Chamber (Trig A,B,C)
- Capacitive-Diode (CD) Chamber (CD 1-3)
- Cylindrical Proportional Chamber (Cyl 1)
- ▨ Full Bore Proportional Chamber (1.5, 2.5, 3.5)
- · · Cylindrical C-D Chamber (Cyl 2-11)
- ▩ Polyurethane Foam Plugs

Figure 8: Detail of solenoidal part of Spectrometer

The coordinate system used in this experiment was one in which the z axis was defined to lie along the solenoid axis in the direction of the beam. The y axis was chosen to be vertically upwards and x was then chosen to define a right handed coordinate system. In discussions of the cylindrical chambers and the Čerenkov counter C1, a cylindrical system of coordinates r, ϕ, z , is often used in place of x, y, z .

3.3.2 Target

The target was a mylar tube 91.6 cm long and 2.62 cm in radius, filled with liquid hydrogen. (See figure 9). The target was supported by an evacuated aluminum cylinder. The liquid hydrogen was constantly circulated and cooled to prevent it from boiling. The temperature and pressure of the liquid in the target was monitored during the experiment so that the effective density could be calculated for the whole experimental run.

3.3.3 Cylindrical chamber system

The target was surrounded by a cylindrical chamber system which consisted of one proportional chamber and five spark chambers. The system was used to detect tracks that emerged from the target at a wide angle. The Proportional Wire Chamber (PWC) was the innermost one and had wires strung in the z direction. The good time resolution of the PWC chamber (75 nsec) allowed the rejection of out of time tracks.

Figure 9: Diagram of Target

TABLE 8

Characteristics of Cylinder Package

cylinder number	readout type	cylinder radius†	typical trackfinding efficiency	typical spatial resolution
PWC Cylinder:				
1	φ	5.2 cm	98%	0.07 cm
CD Cylinders:				
2	φ	10.7 cm	91%	0.10 cm
	Z			0.80 cm
3	φ	12.7 cm	96%	0.10 cm
4	φ	15.7 cm	92%	0.06 cm
	Z			0.74 cm
5	φ	17.8 cm	93%	0.17 cm
6	φ	20.8 cm	93%	0.06 cm
	Z			0.71 cm
7	φ	22.9 cm	24%	0.12 cm
8	φ	31.0 cm	86%	0.13 cm
	Z			0.71 cm
9	φ	32.0 cm	87%	0.13 cm
10	φ	56.4 cm	70%	0.18 cm
	Z			1.50 cm
11	φ	57.4 cm	74%	0.25 cm

† Radii vary but all cylinders are 91.3 cm in length

However it only provided one ϕ co-ordinate. Each of the spark chambers consisted of three sets of wires, one in the z direction, one at $+5.7^\circ$ to the z direction and one at -5.7° to the z direction. Thus each cylinder provided two ϕ and one z co-ordinate. Details about the cylinder package are given in table 8.

3.3.4 Plane chambers

The arrangement of plane chambers within the solenoid can be seen in figure 8. In each of the gaps between the coils of the solenoid was a spark and proportional chamber package. The spark chambers, known as CD chambers due to the capacitive diode readout method used, had two gaps and four sets of wire planes. The sets were oriented horizontally, vertically, and at $\pm 30^\circ$ to the vertical. Each spark chamber was 160cm by 160cm and had a central region of radius 10.8cm that was deadened with a styrofoam plug. This was to prevent the high count rate in the central region overloading the wires that passed through it which would have caused many match point ambiguities. Fortunately the good time resolution of PWCs allowed them to be used in the central region. So mounted with each CD chamber there was a PWC 'plug' chamber that covered the deadened region of the spark chamber. The plug had an active area of approximately 26cm by 26cm and had 3 sets of wires oriented horizontally, vertically and at 35° to the vertical.

TABLE 9

LASS Planar Chamber Devices Summary

device name	# chambers in system	# planes per chamber	wire spacing	approximate active area (in cm)	typical trackfinding efficiency	typical spatial resolution
PROPORTIONAL WIRE CHAMBERS:						
Beam Chambers	2	4 and 5	1 mm	6.4 x 6.4	99%	0.28 mm
Plug Chambers	5	3	1 mm	25.6 x 25.6	94%	0.28 mm
Full Bore Chambers	3	3	2 mm	128 x 128	95%	0.55 mm
Trigger Chambers	3	2	cathode readout	71 cm radius circle	97%	Not Applicable
JHU	1	1	4 mm	200 x 175	98%	3.0 mm
JHXY (X plane) (Y plane)	1	1 X	4 mm	200 x 175	99%	2.5 mm
		1 Y	28 mm*	200 x 175	84%	8.0 mm
JHD	1	1	4 mm	200 x 120	92%	2.5 mm
SPARK CHAMBERS:						
CD	5	4	0.9 mm	160 x 160	87%	1.2 mm
MS (Twist) (Downstream)	2	4	0.9 mm	400 x 200	92%	0.9 mm
	4	4	0.9 mm	300 x 150	97%	0.6 mm

* Y plane has 28 mm spaced cathode readout pads

Inside each of the three small solenoid coils was a full bore proportional chamber and a cathode foil readout 'trigger' proportional chamber. Each proportional chamber had three sets of wires oriented horizontally, vertically and at 45° to the vertical. The cathode foils of the trigger chambers consisted of three concentric rings of cathode foils divided into many segments. They were originally designed to provide fast trigger information. In this experiment they were used as corroborating hodoscopes.

Details about all the planar devices in the spectrometer can be found in table 9.

3.3.5 Particle identification devices

A diagram of the Čerenkov counter C1 and its location within the solenoid can be found in figure 10.

C1 was filled with Freon 114 at atmospheric pressure. This meant that the threshold for pions producing Čerenkov light in the counter was 2.6 GeV/c. The downstream part of the counter was segmented by foil dividers into 38 cells, consisting of three rings of 12 cells and two central cells. The labelling convention for C1 cells is given in figure 11. The upstream section (C1 extension) was unsegmented. Light produced in the counter was reflected by a set of mirrors down long air filled light guides to a set of phototubes at the ends of the C1 arms. The phototubes had to be oriented to allow for shielding from the fringe field of the solenoid; so at the end of each light guide there was a second

Figure 10: Diagram of C1 Counter

Figure 11: C1 Cell Numbering Convention. The position of the TOF scintillator segments is shown for comparison

mirror, along with a Fresnel lens for focussing the light onto the phototube. The central region of the counter was deadened using a helium filled cylindrical bag that was 7.6 cm in diameter. The helium bag was used to reduce the incidence of fast forward particles interacting with the dense freon gas, and also to reduce the number of double hits in the two innermost cells. Identification for these fast particles was provided by the Čerenkov counter C2. A more detailed account of C1 can be found in ref [21].

The TOF counter was attached to the downbeam end of C1. The arrangement of scintillator segments can be found in figure 12. The location of the counters with respect to the C1 cells can be seen in figure 11. The active area of the counter was roughly circular with an outer diameter of 2.9 m. There was a central hole in the counter of diameter 7.6cm. The four inner quadrant counters (25-28) were used for triggering purposes only. The twenty-four larger pie shaped counters (1-24) were used for particle identification. Light from the 1cm thick scintillator was collected by plastic light guides and directed to 56AVP phototubes. Cathode and dynode voltages for these phototubes were optimized for good time resolution. The phototubes were oriented and shielded to neutralize the effects of the solenoid fringe field. The resolution of the TOF array is approximately 0.55 nsec. Details of the TOF system can be found in ref [22].

Figure 12: Diagram of TOF Counter

3.4 DIPOLE SECTION OF SPECTROMETER

Situated down-beam from the solenoid was a standard dipole spectrometer (figure 6), consisting of a dipole magnet with a large number of particle detection devices on either side of it. The region between the solenoid and the dipole was known as the twixt region and the region downstream of the dipole was known as the downstream region.

3.4.1 Description of dipole

The dipole magnet produced a field in the vertical direction with a field integral along z of .30 kg-m. In the track finding process an integration technique is used to project track segments found downstream of the dipole into the twixt region; thus the field map described in section 3.3.1 included the dipole region. In addition to the standard field map, other field maps were made for various combinations of magnet settings (i.e. dipole only, solenoid only). These were for use with special alignment runs.

3.4.2 Twixt chambers

There were a number of different types of planar devices used in the twixt region. These included four spark chambers: 2 large chambers (2 m by 4 m) with magnetostrictive read-out labelled MST1 and MST2, and two smaller C.D. chambers (CD4 and CD5) which were identical in design to the ones used in the solenoid. Each of these spark chambers had

a styrofoam plug to deaden the central region of the chamber as did the spark chambers in the downstream region. There were four proportional devices; two plug chambers and two wire hodoscopes. The plug chambers were similar to the ones in the solenoid except they were mounted independently of the C.D. chambers. The proportional hodoscopes (JHU and JHXY) were made with vertical anode wires that were spaced 4mm apart. The JHXY chamber also had segmented cathode foils giving a y resolution of approximately 3cm. The order of the chambers in the twist region was designed to keep the distance between the two sets of proportional chambers large. The TOF counter was used as a corroborating hodoscope for dipole track finding.

3.4.3 Downstream devices

The downstream tracking devices consisted of four spark chambers (MSD1 - MSD4), one proportional hodoscope (JHD), and two scintillation hodoscopes (HA and HB). The spark chambers had an active area of 1.5 by 3 m and used magnetostrictive read-out. The proportional hodoscope (JHD) had the same design as the JHU hodoscope in the twist region. Details for all the planar devices in the spectrometer can be found in table 9. The two scintillation hodoscopes each consisted of two arrays of paddle shaped scintillator, with phototubes at the top or at the bottom. There was a central hole in each array to form a dead region in the hodoscope (see figure 13). The hodoscopes and the downstream spark

chambers were aligned so that the non interacting beam would pass through the dead regions of the devices. Downbeam from the HB hodoscope there was a beam veto counter (LP3) which used a circular piece of scintillator 9.8 cm in radius. This counter was used in the experimental trigger to veto events in which the beam particle did not interact.

3.4.4 C2: Čerenkov counter

Particle identification for dipole tracks was provided by an 8 cell Čerenkov counter C2, (see figure 14). The counter was filled with FREON 12 at 1.25 atmospheres. This meant that the threshold for a pion to give light in the counter was 2.7 GeV/c. The upbeam end of the counter was covered by a thin aluminum window. Light generated in the volume of the counter is reflected by a set of 8 focussing mirrors at the back of the counter to 8 phototubes at the front. Four of the tubes were located above the entrance window and four below. Five inch 58AVP tubes were used for this counter. There were no physical partitions in the counter. For more details on the design of C2 see ref. [23].

Figure 13: HA and HB Hodoscopes

Figure 14: Diagrams of C2 Counter

3.5 ELECTRONICS

The spectrometer electronics could be roughly divided into two sections, the fast trigger electronics and the data acquisition system. Signals from the proportional system, the scintillation counters and the Čerenkov counters were used to form the trigger. An event was deemed to have occurred if a kaon beam particle was detected during a beam pulse, and an interaction occurred which produced secondary particles satisfying one of the triggers. At this point the data acquisition system was invoked. It consisted of a number of electronic sub-systems associated with the different types of devices. These sub-systems stored and packed the information and loaded it into the memory of a PDP11 computer. When this computer had received data from all the experimental devices the data was transferred to a larger computer, the SLAC triplex system.² This computer was used for writing the events to high density tapes (6250 BPI) and for analysing a small fraction of events to provide a monitor for the experiment. If the triplex was not operating data was recorded using a back up system (an IBM 1800 and two 800 BPI drives) located within the experimental area.

² The SLAC TRIPLEX system consisted of one IBM 360/91 and two IBM 370/168 computers.

3.5.1 Fast triggers

There were four triggers used in the experiment. The main trigger was labelled T0 and was intended to include all non-elastic scattering K⁻p interactions. The other triggers labelled T2, T3 and T4 were used for various studies including calibration, normalization and monitoring. These secondary triggers occurred at a higher rate than the T0 trigger, while only a much smaller fraction of such events were needed. The reduction in rate for T2, T3 and T4 was achieved using a device called the trigger rate equalizer.

The logic to define a beam particle is shown in figure 15. This logic required that one and only one hit be recorded in the XY beam counters and that there should be no hits in the ring counters. There was also a requirement that the SE counter have a signal in time with the XY hodoscope. With this arrangement a small fraction of events still were found to have two beam particles (<3%). For the KAON signal to be logically true there had to be light produced in the Čerenkov counter CK but not in Cn. The logical definition of the KAON signal is given by:-

$$KAON = (XY=1) \cdot (\overline{RING}) \cdot SE \cdot CK \cdot (\overline{Cn})$$

A diagram of the T0 trigger logic can be found in figure 16. The main element of this trigger, after the KAON signal requirement, was an attempt to require at least two

Figure 15: Diagram of Beam Logic

charged particles to be seen in the first full bore proportional chambers, situated just downstream of the target. In practice this involved using an electronic clustering algorithm to group adjacent wires. This is necessary because the passage of a single particle through a wire chamber often causes more than one wire to be on. The signal that was found to be most effective in picking out the desired events was to require that there be two or more clusters in the x plane or two or more clusters in the y plane. The central region (3.2cm across) of the chamber was excluded from the logic to reduce the number of undesirable events. The TOF counter was also used with the trigger because of its good time resolution. The appropriate TOF requirement was found to be a hit in one or more of the 28 elements of the hodoscope. The final condition in the trigger was the requirement that no signal be seen in the LP3 veto counter situated downstream of the HB hodoscope. This was to remove events with a non-interacting beam particle. The logical definition of the T0 trigger was:-

$$T0 = KAON \cdot (\sum (1.5X \geq 2) \text{ or } \sum (1.5Y \geq 2)) \cdot \sum (TOF \geq 1) \cdot \overline{(LP3)}$$

Many different triggers were tested before the T0 trigger described above was selected. Originally an attempt was made to form a non-elastic scattering trigger using the TOF hodoscope and the HA, HB and LP3 counters. However it was

Figure 16: Diagram of T0 Trigger Logic

found that interactions in the solenoidal devices, particularly in the dense freon gas of C1, caused an inflated trigger rate of about 9 or 10%. To avoid this problem the cluster logic was developed for the 1.5 chamber, ref. [24]. As this chamber is much closer to the target than the TOF hodoscope, the triggers from non target interactions were much reduced. The T0 trigger used has a rate of 6.8% of all beam triggers. This is close to the rate expected for an 11 GeV/c K^- beam on the LASS target.

The secondary trigger T2 was a K^-p elastic scattering trigger. It was logically defined by requiring a non-beam downstream track and one other track in the solenoid. T2 events were used mainly to provide very simple and constrained events for track finding studies. T3 was the KAON beam particle trigger that was defined earlier. T3 events were used to provide a sample of beam tracks representative of the whole experiment. This data was used to generate beam particles in the Monte Carlo programme, (see chapter 5). The T4 trigger was defined by requiring two or more hits in the HA and HB hodoscopes and one or more hits in the TOF hodoscope. Events selected by this trigger contained a high proportion of beam (tau) decays ($K^- \rightarrow \pi^+ \pi^- \pi^-$). Tau decays were used in studies of the dipole momentum resolution and to calibrate the beam momentum measurement of the P scintillation hodoscope. The special triggers were used at a reduced rate as mentioned earlier. The event rate (T0 plus reduced T2, T3, and T4 triggers) was 7.7%.

3.5.2 Data acquisition system

When one of the triggers was satisfied the transfer of data from the spectrometer electronics to tape was initiated. There were seven read out systems in the LASS system. There was one for the phototube signals, one for the proportional system, two for the Capacitive diode (CD) spark chambers, one for the CD cylinders, and one for the Magnetostrictive (MS) system. The seventh readout system was activated every 256 events to read the scalers, the magnet settings and the output of the digital voltmeters. Each of these systems had a Direct Memory Access (DMA) to the PDP11 computer. This meant that each read-out device when ready initiated transfer of data to the memory of the PDP11. When all systems had transferred data to the PDP11 the event was sent to the TRIPLEX or 1800 computer for recording on magnetic tape. During the data collection and transfer process the experimental triggers were disabled. The deadtime was set at 21 msec.

The phototube readout system assembled the following information using CAMAC. Pulse heights from phototubes connected to C1, C2 and the TOF counter were digitized using ADC modules. The elapsed time between a signal from the SE counter and a hit in any of the TOF counters was digitized using Time To Digital Converters. On/off information for all scintillation counters (except the large TOF counters) was stored in buffer strobe modules. All this information was transferred using a DMA from CAMAC to the PDP11.

The proportional read-out system consisted of an amplifier and discriminator connected to each of the wires in the system. Every 25 nsec the status of the wires was fed into a memory. At any one time the status for 32 time slots of 25 nsec duration were stored in this memory. After an event occurred the readout system transferred the contents of a 200 nsec portion of the memory to the PDP11. Thus an on/off time profile for each wire in the system was available in the event record. The system was organized this way to remove the need for the difficult job of timing individual wires.

To prevent noise problems in the PWC system the spark chambers were fired after the PWC system information was stored in the buffer. The on/off status of wires in the CD system was stored by a capacitive diode system. This information was then packed and transferred by the CD read-out system. The readout of the magnetostrictive chambers was more involved. Spark current in the chamber wires caused magnetostrictive acoustic pulses to be produced in a sense wire oriented at right angles to the chamber wires. Two reference magnetostrictive pulses were also induced in the sense wire. The position of the wire that fired was found by measuring the time delay of its associated magnetostrictive pulse with respect to the two reference pulses. The MS system digitized this information for transfer to the PDP11. The seventh subsystem read in information that was

used mainly for monitoring. The magnet information included the settings used for the beamline magnets, the dipole and the solenoid. The DVM system was used to record the voltage settings on all the phototubes in the system. The scalers contained information not directly available from the other experimental data.

3.5.3 Data logging and experimental control

The arrangement used for controlling the experiment and for the data transfer is shown in figure 17. The experimental data was split up into a series of runs. An end of run generally occurred when the magnetic tape on which the data was being recorded was full. A run typically contained about 50,000 events and took about an hour to collect at full rate running (180 pulses/sec). A control panel connected to the PDP11 computer was used to start and stop runs.

The normal data collection mode was one in which a complex analysis/data logging task was running on the SLAC triplex system. The PDP11 could access this job through a number of hardware and software links to allow the data to be transferred from the control room to this program. The analysis section of this program reconstructed a small fraction of the events for monitoring purposes. The output of the analysis program could be studied using an IBM graphics terminal in the control room. The back up computer located in the control room was used when the triplex system was out of operation. Use of the triplex system was preferable

Figure 17: Overview of the LASS Control System

mainly because of the superior monitoring capability of that system and its use of high density tape drives.

3.5.4 Monitoring

Various measures were taken while the data was being collected to ensure good quality. At the start of each run the flux and quality of the beam was checked and the pressure of the target was recorded. Once per eight hour shift a hardware check was made. This involved checking a large number of equipment settings such as chamber voltages, gas flows and beam magnet settings.

In addition to these checks a small fraction of events were analysed using an early version of the track finding program. This enabled a number of aspects of the spectrometer to be monitored, such as the chamber efficiencies, while the data was being collected. At the end of each run a summary was created which consisted of a few hundred numbers stored on a disc at the computer centre. These numbers included such things as the number of hits in the various scintillation and Čerenkov counters, the trigger rates and the efficiencies of the spark and proportional chambers. They were then plotted for a series of runs so that long-term variations in performance could be detected.

3.6 K⁻P DATA TAKING WITH THE LASS SPECTROMETER

The data for the K⁻p experiment was taken in the winter months of 1977/78. The data taking process lasted about

seven weeks. There were also two check out runs in June and November of the previous year. Most of the data was taken using the standard trigger combination described in section 3.5.1. In addition a number of special runs were taken. The conditions used for these runs and the number of events taken for each set of conditions is shown in table 10. The first column of this table gives the specific triggering arrangement used for each set of runs. The second indicated whether the target was empty or full and the spectrometer magnet status is given in the third and fourth column. The first entry in this table is the experimental data sample. The next two entries represent samples taken with loose T0 trigger requirements. These were necessary to check for inefficiencies of the standard T0 trigger logic. Some of these special runs were taken in the middle and some at the end of normal running.

When the data taking was completed in March of 1978, a thousand tapes of data had been collected. These contained events generated by approximately 560 million incident beam kaons. A summary was made of all the runs, to document any specific problems and to enable a set of good runs to be selected. Runs that had been taken when major equipment failures occurred were rejected at this stage. This left a data sample of 40 million events suitable for analysis.

TABLE 10

List of Runs Taken

trigger	target	solenoid	dipole	#events
STANDARD MIX	FULL	ON	ON	40,000K
T0=K-.TOP>0.LP3	FULL	ON	ON	916K
T0=K-.TOP>0.CL>1	FULL	ON	ON	455K
T3 ONLY	FULL	ON	OFF	5K
STANDARD MIX	EMPTY	ON	ON	321K
T2. (CL>0)	FULL	OFF	ON	35K
T2 ONLY	FULL	OFF	ON	60K
STANDARD MIX	FULL	OFF	ON	44K
STANDARD MIX (DIFFERENT FOCUS)	FULL	ON	ON	64K
T2. (CL>0)	FULL	ON	ON	51K
T2. (CL>0)	FULL	OFF	ON	40K
T2	FULL	OFF	ON	40K
T3	FULL	OFF	OFF	10K
T0 ONLY	FULL	OFF	ON	20K

Chapter IV

DATA REDUCTION

4.1 / GENERAL

The raw data sample consisted of approximately 40 million events and was stored on 800 high density tapes. The data record contained just the packed information obtained from the spectrometer devices :- spark positions, status of proportional wires and raw ADC and TDC values. The process by which this information was transformed into four momentum vectors of particles was a long and involved one.

The first step in this process was to pass the data through the track finding program known as 'GNUCODE'. It took an average of 1 second to process one event with GNUCODE using an IBM 370/168 computer. Thus to analyse all the data with GNUCODE took approximately 11,000 hours or 440 days of computing time. The next stage 'DSTPRIME' was considerably faster, only 0.2 seconds per event or 100 days of computing. DSTPRIME was used to select good tracks and find topological vertex solutions for the tracks. All data was passed through these two stages.³ GNUCODE and DSTPRIME rejected 18% and 6% of events respectively, (23% in -----)

³ A two prong filter was developed to spin-off events containing K^-n+n physics. These were analysed ahead of the bulk of the data. The results of this analysis can be found in ref. [1] and [7].

combination). This lead to a data sample at the DSTPRIME output level of 31 million events. The DSTPRIME output format was also considerably shorter than the original data record, so these 31 million events fitted onto 119 tapes.

To study this data a series of spin-off tapes were made from the DSTPRIME tapes. At Carleton these included a selected set of nprong data (topology one), events with an observed K^0 (topology 2) and events involving multiple V^0 s or a V^- decay (topologies 5, 6, 7 and 8). To study a given physics channel the relevant events had to be selected from the topology tapes. In the process of studying the extraction of the $K^0K\pi$ channel, it was found necessary to use a Multi-Vertex FITting program, (MVFIT). This program used the original coordinates for tracks to fit an event as an entity to a geometric topology hypothesis. This allowed a better rejection of events that were a background to the $K^0K\pi$ sample. Processing events with MVFIT was again quite slow (0.5 seconds per event). So to reduce computer usage a subset of events were selected from the topology 2 tapes for analysis by MVFIT. A series of programs were then used to select the $K\pi$ sample from the MVFIT output tapes. The extraction of the $K\pi$ sample from the DSTPRIME tapes is described in detail at the beginning of chapter 5.

It may not be immediately obvious why the various LASS analysis programs should be as time consuming as they are. One of the contributing factors is the use of a solenoid.

rather than a dipole as an analysing magnet. It takes more time to find a helical track than a straight line segment, because an extra parameter has to be found. There is also the difficulty that all low momenta particles become trapped within the bore of the solenoid. So delta rays, secondary interactions, decays and in-time backgrounds conspire to give a wash of particles travelling down the solenoid. In this situation it is often difficult and therefore time consuming to extract the relevant features of an event. A second factor is the very large number of detectors used in the LASS system, some of which were marginally efficient. This lead to a large number of permutations for the track finding algorithm to test, which again was very time consuming.

The data was analysed both at SLAC and at Carleton/NRC. At SLAC the TRIPLEX system was used along with a system of dedicated computers known as the 168Es. Data processing for the Carleton/NRC part of the collaboration was carried out using the IBM 3032 at the NRC computer centre. The 3032 had a speed roughly equivalent to the 370/168. One third of the data was processed at NRC and of the two thirds processed at SLAC 20% was processed using the 168E's.

* The 168Es were a set of processors designed at SLAC to speed-up data processing. They used an instruction set similar to the IBM 370/168 to allow easy translation of existing programs to the microprocessors. Ref. [25].

4.2 GNUCODE:THE TRACK FINDING PROGRAM

4.2.1 Track finding

The starting point for the track finding program was the calculation of the coordinates of hits in the various spectrometer devices. This was done using previously found alignment constants. The coordinate system and track parametrization used in the LASS system are shown in figure 18.

The sets of coordinates for each chamber were used to find 3 dimensional (x,y,z) match points. These were found by cycling through two of the sets of coordinates (say x and y) and looking for corroborating coordinates in the other rotated planes. If an additional coordinate came from a set of wires that was at an angle to both the x and y planes the match point was uniquely defined. The set of match points for each chamber was stored for use in track finding.

The track finding method was similar in all sections of the spectrometer and is best understood by considering straight line tracks. For instance in the region downbeam of the dipole there are four spark chambers with four planes each. In this region the magnetic field is sufficiently low that the tracks are straight, within the resolution of the chambers. A trial straight line track is defined by two match points. A tube of a given radius is then defined around this track and all coordinates from all relevant planes that fall within this tube are used to define a new track by making a least squares fit of a line to the points.

STRAIGHT LINE
PARAMETERIZATION

$$X = X_0 + (Z - Z_0) \frac{dX}{dZ}$$

$$Y = Y_0 + (Z - Z_0) \frac{dY}{dZ}$$

HELIX PARAMETERIZATION

$$X = X_0 + R (\cos(\phi_0 + (Z - Z_0) \frac{d\phi}{dZ}))$$

$$Y = Y_0 + R (\sin(\phi_0 + (Z - Z_0) \frac{d\phi}{dZ}))$$

THIS LEADS TO

$$R_x = qBR \cos(\phi_0 + (Z - Z_0) \frac{d\phi}{dZ})$$

$$R_y = qBR \sin(\phi_0 + (Z - Z_0) \frac{d\phi}{dZ})$$

$$R_z = qB / (d\phi/dZ)$$

WHERE $q = 2.998 \times 10^{-4} \text{ GV} / (\text{KG} - \text{cm})$

AND $B = \text{FIELD STRENGTH}$

Figure 18: Coordinate System and Track Parametrization

The procedure is repeated with smaller tube sizes until a stable track is found. The track is then projected to pick up hodoscope on/off information. For a track to be acceptable it had to have more than a specified number of in-time points. There also had to be less than a pre-determined number of missing coordinates from the expected number.

Track finding was first used to look for beam tracks using the beam FWC's. Up to two beam tracks were allowed. The next stage was a search for dipole tracks, looking first for track segments in the region downstream of the dipole. Track finding was attempted first in this region because it was quicker and easier than in the solenoid. This is partly because there are fewer tracks to find and partly because finding a straight track is easier than finding a helical track. Once found the downstream track segments were projected into the twist region using a Runge-Kutta Integration (RKI) technique, ref [26]. Using an iterative procedure (because at this point the track momentum was unknown), an attempt was made to join the track to a twist track segment. When this had been accomplished and if the joined track met the various track acceptance criteria, it was designated and stored as a dipole track. All dipole tracks were projected back into the solenoid using the RKI technique, through the solenoid fringe field region. Coordinates were sought for the track in the solenoid devices using the standard track finding method. If a dipole track could be successfully

projected back to the target region by meeting the acceptance criteria throughout the spectrometer, the track was also classified as a solenoid track and stored as such. While the track was being projected back through the TOP and C1 region, information about the track relative to the TOP and C1 geometry was stored for use in particle identification at the DSTPRIME level. C2 information for dipole tracks was stored with the dipole track parameters.

Solenoid track finding was simplified by removing from consideration coordinates used by dipole tracks. In addition match points that lie within a small cylinder centred on the z axis (radius = 2.5cm) were omitted from the procedure which searched for solenoid track candidates. Tracks were found independently in the plane chambers and in the cylindrical chambers. It was possible for a track to be found by both algorithms. So in defining solenoid found tracks, the two sets of tracks were added together and any duplicates removed. These were then added to any tracks found by the dipole method. Tracks found in the solenoid were projected out to the twist region to obtain particle identification information. The helix parametrization was used as far as the end of the solenoid and beyond that point the RKI technique. A small step size (3cm) had to be used for the RKI because of the low momenta of many of the solenoid tracks. The position at which projected tracks crossed the TOP counter was corrected using information from the

large magnetostrictive spark chambers. Precision in calculating these points was important because they formed the basis for part of the TOF timing correction procedure. Other information derived in the projection included the track length from a fixed z to the TOF counter, and the intersection points of the track with the C1 cells.

In addition to track finding the GNUCODE program contained sophisticated track fitting and vertex finding segments. Both of these steps were repeated at the DSTPRIME level and will be discussed in that section.

4.2.2 Alignment

The alignment of the spectrometer devices was carried out in parallel with the development of GNUCODE. Initially the measured survey positions of all the devices, and the details of their construction were used to create a bank of constants for translating the raw event information into coordinates. Using these constants GNUCODE was run on the data sample that contained beam triggers taken when both the dipole and solenoid were off. (See table 10.) By finding the undeviated beam track throughout the spectrometer and measuring the difference between the expected and measured positions at which the chambers were hit, the chambers could be aligned in x and y . This step aligned only chambers through which the beam passed. The spark chambers in the solenoid and the twist region were aligned using data in which the magnets were off; this provided tracks at a vari-

ety of angles to the beam. In this case the previously aligned chambers were used for track finding and the spark chambers were aligned relative to them.

Finally alignment was repeated using standard TO data with both magnets on. This allowed correction of the alignment constants for magnetic field effects. It also provided a reasonable number of slow recoil particles for aligning the cylindrical system. Cylindrical alignment was done in two stages. First the individual chambers were aligned with respect to one another, and then the whole package was aligned with respect to the other solenoid devices.

The TOF counter was aligned using TO data after the rest of the alignment was completed. Because of the complicated internal geometry of C1, alignment of that counter was found to be impractical and not useful.

4.2.3 Monitoring and production

GNUCODE production test runs were started in October of 1978. Final production was started in January 1979, and this stage was completed in August of 1980. During this period a number of modifications and improvements, mainly involving program speed, were made to the program. Care was taken to keep track of this process and to prevent inconsistencies in the output record. One of the sections of the GNUCODE production program was devoted to monitoring the quality of the output. This involved a check on 34 key quantities such as trigger rates, software failures and the number of tracks found in various parts of the spectrometer.

As indicated earlier 18% of events were rejected by GNUCODE. These failures occurred in one of three areas; data unpacking (7%), beam reconstruction (8%), and track finding (3%). The data unpacking failures arose with data tanks that were incomplete. This was usually due to lack of space in the buffer memory used to pack the original data record, before it was written to tape. A beam reconstruction failure occurred when no beam track was found or too many were found. Track finding errors occurred when the number of tracks generated exceeded the available space in the arrays.

4.3 DSTPRIME: TRACK REFINEMENT AND VERTEX FINDING PROGRAM

4.3.1 Overview

During the period in which GNUCODE production was being run, an intensive effort was made to study the characteristics of the data that the program produced. This included the development of a physics monitor package to check the properties of several different final state reactions contained in the experiment. The characteristics of the tracks found by GNUCODE were also examined to develop definitions of good and bad tracks. This study resulted in a section of the DSTPRIME program that rejected a significant fraction of spurious tracks. In GNUCODE the main vertex finding algorithm required all but two tracks to be included in the vertex. So the removal of bad tracks had a positive effect on the number of vertices found. Thus after the bad tracks

2

were removed from the track banks it was necessary to run the vertex program again. The DSTPRIME program was also used to extract more useful information from the available particle identification data.

In general an effort was made to compress the output record of DSTPRIME as much as possible to reduce tape handling problems at the next stage of data reduction. A flow chart of the DSTPRIME program can be found in figure 19.

4.3.2 Track selection and refinement

Studies of GNUCODE tracks were used to develop a series of tests (discussed below), to separate good tracks from bad tracks. There was a third category of borderline cases labelled grey tracks. About 14% of tracks fell into the bad track category and were rejected from the data sample. This was accomplished by first flagging all bad tracks and removing them from the track bank, along with all references to them in other banks. All pointers to the track banks had then to be updated. In addition all unjoined track segments in the dipole track bank were removed.

Three classes of tracks were defined in the selection procedure. 'DIPOLE' tracks were those found in the dipole and successfully projected back into the solenoid. 'LINK' tracks were those that had no points on beam of the first full bore proportional chamber. The rest of the solenoid tracks were labelled TEASEM tracks. LINK and TEASEM tracks corresponded roughly to those found in the cylinders and

Figure 19: Flow Chart of DSTPRIME Program

planes respectively. The selection procedure was slightly different for the three classes of tracks. The list of selection cuts can be found in table 11. A description of these cuts follows.

TABLE 11
List of Track Selection Cuts

CUTS	% of tracks cut
REMOVAL OF DUPLICATE TRACKS	6.1
PT > 6.7GeV/c	0.2
PL > 12 GeV/c	0.7
PT too small < 27MeV/c THASEM < 67MeV/c LINK	1.3
TOO MANY MISSING COORDINATES	2.3
DUPLICATE CYLINDER TRACKS	2.8

Note 86% of tracks survive cuts

There were a number of duplicate tracks in the solenoid track bank. A duplicate track was defined in terms of the number of coordinates that tracks had in common. The procedure for flagging duplicate tracks was an iterative one. Non-DIPCLE tracks were compared, and of tracks with fewer than 8 unshared coordinates, the track with the fewest unshared coordinates was flagged and omitted from the next iteration. The process was complete when all remaining tracks had at least 8 unshared coordinates.

The next set of cuts applied constraints on the momenta of tracks. The maximum values allowed for the transverse and longitudinal components of momentum (P_T and P_L) were 6.7 and 12 GeV/c respectively. Studies of the data revealed that there was an excess of tracks with small P_T . The excess was due mainly to delta ray production. A minimum momentum cut was made to remove it. The cut was more severe for LINK tracks because the resolution on these tracks was worse.

The criteria for rejecting a track on the basis of the number of missing coordinates, and the number of missing proportional coordinates were studied using the available vertex information. Coordinate information was compared for tracks that were included in vertices, (predominantly 'good' tracks) against those that could not be vertex associated, (predominantly 'bad' tracks). This was done for a number of different topologies using some physics reaction selection procedures. This study produced a new set of slightly more restrictive cuts which removed 2.3% of the tracks.

A track with a longitudinal momentum of 50 MeV/c rotates through 2π radians within 50 cm. Thus it is possible for low momentum tracks to make multiple loops within the cylindrical chambers. The cylindrical track finding program in GNUCODE considered each segment of such a track starting at small r and moving away from the target as a separate track. So tracks with low P_L could be represented by 2 or 3 cylindrical tracks. A piece of code was included

in DSTPRIME to retain only the initial segment of such a track.

When bad tracks had been removed from the track bank the remaining non-dipole tracks were subjected to the track fitting program 'TRKFIT'. TRKFIT was re-run at the DSTPRIME stage because studies on the GNUCODE data had led to a better knowledge of the errors on the track coordinates. TRKFIT used these errors to calculate the χ^2 contribution of each coordinate to the track. This significantly improved the fit of the track. The output of TRKFIT included the fitted track parameters and an error matrix of the track parameters. The error on the track momentum as a function of momentum is shown in figure 20. Three distinct bands are visible which correspond to tracks found in the dipole, the planes and the cylinders. This plot shows that dipole tracks (lowest band), have small errors over the whole momentum range. Cylindrical tracks (top band), have relatively large errors which increase rapidly with increasing momentum. The DSTPRIME version of TRKFIT had the ability to throw away up to three coordinates. If the track fitting procedure failed at the DSTPRIME level the old GNUCODE fit values were retained.

Events with no tracks, after bad tracks had been rejected, were discarded by the DSTPRIME programme. This resulted in the 6% rejection of events as stated in section 4.1.

Figure 20: Track Momentum Errors as a Function of Momentum

4.3.3 Particle identification programs

particle identification information for the Čerenkov counter C1 and the TOF hodoscope was stored in one bank called the swimbank. It contained data for each 'swim' track, i.e. one that was projected through C1 and the TOF counter using the RKI technique. Data on bad tracks in this bank were removed from the swimbank at the track selection stage. The information on the remaining tracks was analyzed, compressed and stored as two data banks, one for the C1 counter and one for the TOF hodoscope.

The following set of restrictions was applied to swim bank tracks before inclusion in the C1 bank for transfer to the DSTPRIME output tape.

1. Tracks passing through the helium bag were rejected ($r < 3.81$ cm).
2. Tracks had to be seen in the TOF hodoscope (including the inner four trigger counters).
3. Momenta of tracks had to be greater than 2.5 GeV/c.
4. Track length in C1 had to be greater than 115 cm.
5. Track had to pass through ≤ 2 cells.
6. Double hit ambiguities were removed.

For each track passing these cuts the C1 bank contained the total pulse height, the number of cells hit, which cells were hit and the position of the track at the centre of its trajectory in each cell. The total pulse height was the sum of the pulse heights recorded in the cells the track passed through. If a track was within 2cm of the edge of a cell the pulse height of the neighbouring cell was checked. If the pulse height in the neighbouring cell was non-zero it was added to the total pulse height for the track.

The last cut listed above was needed to deal with the ambiguities that arise if two tracks pass through the same cell. If, when this happens, no light is seen in the cell there is no problem as both tracks can be assigned a kaon identification, all other spatial cuts being satisfied. If, however, light is seen in the cell, one or both tracks could be pions and no identification is possible for either. In the latter case both tracks are excluded from the swim bank. Similar tests were applied when a track passed through the edge region of a cell. If another track passed through the neighbouring cell and there was light in that cell, then no identification was possible for the track in the neighbouring cell.

Information on all tracks in the swim bank that were seen in the large TOF counters was included in the DSTPRIME TOF bank. Double hits in the TOF counters were flagged and the time of flight for tracks from $Z=0$ to the TOF counter

was calculated. This was done by correcting the measured TDC value for the position the track hit the counter and for the pulse height in the counter (see section 4.4.3). The correction procedure was not finalized before DSTPRIME production began so the time of flight and sufficient information to recalculate it was included in the TOF bank. Information for the Čerenkov counter C2 was stored in the dipole bank. Spatial cuts for C2 had already been imposed at the GNUCODE level. However studies at the DSTPRIME level revealed that the counter was inefficient at the extreme upper and lower regions of the counter. Tracks passing through these regions had shorter track lengths which explained the inefficiency. Such tracks were flagged as having no C2 information.

4.3.4 Vertex finding program

The vertex program was used to reconstruct events from the tracks in the solenoid track bank. The program allowed for eight different topological solutions, which are shown in table 12. Topology 1 was a simple nprong vertex in which tracks were associated with a single vertex. Topologies 2 through 4 (V^0 solutions) had one secondary vertex representing the decay of a neutral particle. The primary vertex for these topologies included the neutral track, the beam track and any other associated charged tracks. Decays of K^0 , Λ and $\bar{\Lambda}$ particles were assigned to topologies 2, 3 and 4 respectively. Topology 5 contained candidates for the

decay of charged particles such as the Ξ^- . It consisted of two secondary vertices, one for the decay of the charged particle to a charged and neutral particle and one for the decay of the neutral. The other high topology solutions (6 through 8), consisted of combinations of V^- and V^0 decays.

TABLE 12

Topological Solutions of the Vertex Program

TOPOLOGY NUMBER	TYPE
1	NPRONG
2	V^0 WITHIN K^0 MASS RANGE
3	V^0 WITHIN LAMBDA MASS RANGE
4	V^0 WITHIN LAMBDA EAR MASS RANGE
5	V^- DECAY
6	TWO V^0 S
7	$V^- + V^0$
8	THREE V^0 S

The strategy for finding vertices was different for topologies 1 through 4 from that used for topologies 5 through 8. For the lower topologies an attempt was made to find a solution using all solenoid tracks. If a good solution could not be found a track was discarded and a new solution sought using the remaining tracks. Up to two tracks could be discarded for an nprong and one for a V^0 topology. For the higher topologies the specific decay process was looked for first; e.g. if three tracks could be

linked to form a V^- decay chain and the projected track of the V^- came within a certain tolerance of the beam track, then a V^- solution was deemed to exist. Similarly a topology six solution existed if there were two or more V^0 vertices, and the neutral parent particles of two of the V^0 s formed a vertex with the beam particle. After a higher topological solution was found, unused solenoid tracks were added to the primary vertex. Finding the position of the primary vertex and adding the extra tracks was an iterative process.

The procedure used to actually find vertex positions was quite simple. A trial vertex position was selected for a given set of tracks. The tracks were then approximated to straight lines by taking the tangent to each track at the z of the trial vertex. A new vertex was then found by minimizing the sum of the d^2 of these straight lines to a new point vertex. (The quantity d^2 represents the square of the perpendicular distance from each line segment to the point vertex.) This procedure was repeated, with the new vertex being used as the trial vertex, until the vertex position stabilized. This usually occurred after 2 or 3 repetitions. An iterative technique was used to compensate for the fact that the tracks were really helices. The quantity $Q = \sum(d^2)/(N-1)$ where N is the number of charged tracks in the vertex solution was used extensively in selecting vertex solutions. The value of Q was transferred to the output record as a measure of the quality of the solution. A sec-

ond version of the vertex program was developed that used the track errors in finding vertices which gave a χ^2 analogue of Q . In practice this version was found to add little to the vertex finding process and it was considerably more time consuming. The d^2 version was used in DSTPRIME.

A flow diagram of the vertex search procedure can be found in figure 21. The branch points in the flow were determined by a set of cuts which are described in table 13. The second column of table 13 gives the abbreviations used in figure 21 for these cuts. The first action of the vertex program was to look for an nprong vertex using all the solenoid tracks. Such a solution existed if Q was less than $OK1$. If the vertex was also an excellent one ($Q < EX$) the vertex seeking program terminated. If no excellent nprong existed all possible pairs of a positive and a negative track were tested to see if they formed a secondary V^0 vertex. The test for a V^0 vertex was $Q < V^0TEST$. An attempt was then made to look for primary vertices using each of the neutral particles calculated from the V^0 solutions and the remaining solenoid tracks. The overall Q for a topology included the d^2 of secondary vertices. There were three tests used to define a V^0 topology. The first was a Q test ($Q < OK2$), the second a decay length test and the third a test to ensure the secondary vertex was 'downstream' of the primary vertex. If there was an excellent V^0 solution no further vertex searches were made. It was however necessary to

pick the best V^0 solutions and assign them to the 3 V^0 topologies (2,3 and 4). The V^0 solutions were assigned to a topology by making cuts on the invariant mass of the tracks that comprised the V^0 . The mass cuts used are in table 13. The mass cuts were set much wider than the measured width of the V^0 to allow a measurement of the background underneath the V^0 . (The K^0 width was dominated by the spectrometer resolution.) For a given event it was possible to have a solution for each of the V^0 topologies using the same or different V^0 s. The process by which V^0 solutions were chosen and assigned to a topological solution was always the last step in the vertex program, unless an excellent nprong was found using all tracks.

If no excellent nprong or V^0 solution existed a search was made for higher topologies. Whether or not higher topological solutions were found the search procedure for nprong and V^0 solutions continued. The flow for this processes shown in figure 21 is fairly straightforward. It should be noted that the procedure for choosing between, for example, an nprong and an (nprong-1) was a test on the value of Q . If Q improved by the constant DIFF by throwing away one track the (nprong-1) vertex was selected as the best vertex. The value of DIFF was the same for nprong and V^0 vertices.

The determination of the vertex cuts was made by repetitive running of the vertex program with the cuts set to different values. The vertex solutions found were written

Figure 21: The Vertex Searching Algorithm

TABLE 13

Cuts Used in the Vertex Program

CUT	SYMBOL	VALUE
EXCELLENT VERTEX.	EX	0.01
VERY GOOD NPRONG	VG1	0.2
O.K. NPRONG	OK1	2.0
VERY GOOD V^0	VG2	0.02
O.K. V^0	OK2	4.0
V^0 CANDIDATE	V0TEST	1.0
COMPARISON BETWEEN VERTICES	DIFF	0.5
K^0 MASS CUT		0.425 $\rightarrow$ 0.575 (GeV/c ²)
LAMBDA MASS CUT		1.085 $\rightarrow$ 1.145 (GeV/c ²)
DECAY LENGTH CUT		2.0 cm

to tape for further analysis. This analysis included an examination of the general properties of the solutions and how the variations in cuts affected known physics signals. The topology one cuts were tuned by looking at the charge balance, missing mass and momentum conservation of the solutions. In addition the $K\pi\pi$ and $K\pi\pi\pi$ channels were examined and the number of K^* events, and events in the Q region were tallied. The excellent cut was kept small because satisfying this cut terminated the event finding process. There were more cuts to tune for the V^0 topologies. However it was possible to use the signal to background ratios of the K^0 and lambda in these cases. (No Λ signal was seen at this stage of the experiment.) One of the key cuts for the V^0 topology was the decay length cut. Due to the finite

resolution of the spectrometer, as the decay length cut was reduced the number of V^0 solutions increased dramatically. The decay length cut was set at the point at which the number of background events started to rise rapidly. The values of V^0 TEST and the OK2 cuts were set by examining the signal and background of the K^0 and Λ as a function of the two variables. The cuts chosen were a compromise between rejecting real events and retaining a lot of background events.

The last stage of the vertex finding process was a reassessment of the tracks at the primary vertex. The errors on track parameters varied considerably depending on the type of track, (see figure 20). DIPCLE tracks were very well determined- within one millimeter or so; on the other hand LINK tracks could have an uncertainty of the order of a centimeter. By using the d^2 method just described, tracks with large errors tended not to be included in the vertex. Histograms of the weighted d^2 (the weight being proportional to the error in d^2), revealed a cut could be established to determine whether or not a track was vertex associated (figure 22). The hump at the lower end of these histograms corresponds to vertex associated tracks. Using this information a routine was created to add and subtract tracks to the primary vertex.

Figure 22: Weighted d^2 of TRSOL, LINK and TEASEM Tracks

4.4 PARTICLE IDENTIFICATION RESULTS

In order to use the particle identification devices to select rare processes it is important to know their efficiencies. For instance in this experiment there are about seven times more K^0_{nn} events than $K^0K\pi$ events. If the efficiency of C1 is 90% then 10% of pions in the K^0_{nn} sample will be mis-identified as kaons giving rise to a background which is 1.4 times the size of the real data sample. Clearly careful study of particle identification is warranted.

4.4.1 C1

The condition for a particle of velocity v to produce Čerenkov radiation is given by :-

$$v \geq c/n$$

Where n is the refractive index of the medium, and c is the velocity of light. C1 was filled with FREON-114 at atmospheric pressure giving an $(n-1)=1.45 \times 10^{-3}$. This meant that the threshold for pions and kaons giving light in C1 was 2.6 and 9.2 GeV/c respectively.

Pions from secondary K^0 decays were used to study the efficiency of C1. To be able to calculate absolute efficiencies for the counter it was important to understand the K^0 background. The K^0 spectrum consisted of a prominent peak on a relatively flat background, with a signal to noise ratio of about 4:1. The background arose from other reac-

tions and was therefore a source of particles other than pions, most of which did not give light in C1. The effect of the background was therefore to reduce the measured efficiency. To minimize this effect a method was developed to reduce the background in the K^0 data sample by tight geometric cuts and additional cuts on the quality of the topology two and topology one vertex (if any). Using these cuts a 400,000 event K^0 sample was generated from a subset of the available topology two data. This K^0 sample had a signal to background ratio of 10:1. The advantage of using the $K^0 \rightarrow \pi\pi$ decay to study C1 was that it was possible to measure the size and characteristics of the K^0 background, using the wings of the K^0 mass distribution. Thus from a measurement of the C1 efficiency for the K^0 signal and for the K^0 background, it was possible to calculate the percentage of background particles not giving light, and therefore to calculate absolute efficiencies for C1. To check this calculation, a second K^0 data sample (72,000 events) was defined from the first using momentum and missing mass cuts. This data sample had a K^0 signal to background ratio of 20:1. The absolute efficiencies calculated for the two different data samples agreed within statistical error.

The overall absolute efficiency of C1 for tracks with momenta greater than 4.5 GeV/c was 90%. This was inadequate for selecting the $K\bar{K}\pi$ data sample. It was known that the efficiency of C1 had a strong spatial dependence. Thus to

develop a means of improving the overall efficiency, a study was made of the efficiency of C1 as a function of the position of tracks within the counter. The counter was mapped using pions from the large (400,000 event) data sample with momentum greater than 4 GeV/c. This momentum cut removed pions with momenta in the threshold region of the counter. The position of each track at the centre (in z) of the cell was calculated in terms of the cylindrical coordinates (r, ϕ) . The efficiency was then mapped as a function of these two variables.

In general the spatial efficiency of C1 as a function of ϕ was fairly uniform. The exception was the two innermost D cells (37 and 38), which were only efficient in a small region around the x - z plane. There was also one other cell (27) which showed a strong ϕ dependence; cell 27 was inefficient along an azimuthal edge. (For C1 cell numbering convention see figure 11.) The efficiency of cells as a function of radius r is shown in figures 23 and 24. Note that in these figures the radial axis is offset at the C1 ring boundaries. It can be seen in these figures that the efficiency of many cells has a strong dependence on r . Many cells are inefficient along their inner radial boundary. This is particularly true for the lower C cells 29, 30 and 31. A major reason for this effect is the different optical system used for the lower three sets of cells, see fig 10.

Figure 23: Efficiencies of C1 Cells as a Function of Radius.

Figure 24: Efficiencies of C1 Cells as a Function of Radius

Using this information on the spatial efficiency of C1 to exclude inefficient regions of C1, it was possible to raise the overall absolute efficiency of C1 from 90% to as high as 99%. Such a spatial cut however removed 50% of the data. In most applications in this experiment 99% efficiency is unnecessary so a series of cuts of gradually increasing severity was developed. These cuts and the effect they have on overall efficiency and data reduction are shown in table 14. These results will change slightly for other reactions. The cuts for individual cells were chosen to exclude regions of the cell where the efficiency dropped below the cut level. Information on the integrated cell efficiency was also used in establishing these cuts.

TABLE 14

C1 Efficiency Cuts

CUT LEVEL	ABSOLUTE EFFICIENCY	DATA PASSED
95%	98.4%	55%
93%	97.9%	65%
90%	97.1%	75%
80%	96.0%	85%
NO CUTS	90.0%	100%

Figure 25 gives the absolute efficiency of C1 as a function of momentum for the various cuts. (Points for the 93% cut have been omitted for clarity as have the error bars on the 95% and 80% points.) For the first four cuts the

Figure 25: Efficiency of C1 as a function of Momentum

plateau efficiencies are remarkably similar. There are larger differences in the threshold region of the counter. The curves shown here can be used to calculate the background caused by C1 inefficiency as a function of momentum.

In practice the C1 counter was used by selecting a set of spatial cuts and a minimum momentum cut.

4.4.2 C2

The Čerenkov counter C2 was filled with FREON-12 at 1.25 atmospheres which has a refractive index given by $(n-1) = 1.35 \times 10^{-3}$ at that pressure. This meant that the threshold for pions and kaons giving light in C2 was 2.7 and 9.5 GeV/c respectively. This counter had been used in a previous experiment and studied extensively at that time.⁵ These studies showed that within the active region of the counter its efficiency was about 98% and was quite uniform. The uniformity is attributable to the fact that there were no physical divisions between the cells and that the counter had a relatively simple optical system. These design features prevented inefficiencies at cell boundaries. However, there were differences in the use of C2 in this experiment that meant that previous results for overall efficiencies were not directly transferable. In the LASS system the counter was subjected to the fringe field of the solenoid.⁶

⁵ SLAC experiment number E-75, K⁻ 13 GeV/c, Ref. [23].

⁶ The downbeam fringe field of the solenoid was very large due to the lack of a flux return path at that end. At C2 the field was dominated by the solenoid rather than the

The orientation of the large (10cm) C2 phototubes was not optimal for shielding in this field. The counter was also operated at a lower pressure than in the previous experiment. Both of these effects had the potential for reducing C2 efficiency.

For this experiment the efficiency of C2 was measured using pions from K^0 decays. The efficiency as a function of y -position and of momentum is shown in figure 26. The overall efficiency for seeing pions between 4 and 9 GeV/c was found to be 94%. It should be noted that this number and the points plotted in figure 26 are raw efficiencies without corrections for the K^0 background. There are no detectors downstream of C2, thus there is no way of knowing whether a particle was absorbed before crossing the C2 active volume. The 2% inefficiency observed in the previous experiment was attributed to absorption. To summarize the efficiency of C2, it is in the 94%-98% region above 4 GeV/c.

Above the threshold for kaons to give light, identification in both counters is more difficult. If a Čerenkov counter is reasonably efficient, n/K identification is still possible on the basis of pulse height. This was studied for the C2 counter and it was found that some separation could be achieved over a limited momentum range by comparing the pulse height to the variable

dipole. Even at the downbeam end of the LASS building a phototube would not work without some form of magnetic shielding.

Figure 26: Efficiency of C2 as a Function of Y Coordinate and Momentum

$$PHCUT = A + B*(P-PTH)$$

where A and B are constants. P is the momentum of the particle and PTH is the threshold momentum for a kaon to give light. A similar cut was developed for C1.

The effective ranges of C1 and C2 overlapped. Information from the two counters was combined in the following way. If both counters provided identification for a track and the identification was consistent, then the track was assigned the common identification. If the information was inconsistent the track was flagged as being unidentifiable. If only one counter provided identification, that identification was accepted.

4.4.3 TOF

The information provided by the TOF readout system was the time delay between the SE counter firing and the TOF counters firing along with pulse heights for the individual counters. This information was used to calculate the Time Of Flight of stable secondary particles (π , K and p), from the production vertex to the TOF counter hodoscope plane. The TOF of secondary particles is given by

$$T = TDC*CAL + TK + TV + TR + TP + TD$$

where TDC is TDC value

CAL is TDC channel number to time calibration

TK is TOF of the beam particle from SE
to the primary vertex

TV is TOF of V^0 and/or V^- particles

TR is a correction for the position the secondary

particle hits the counter.

TP is correction for P.H.

TD is a fixed offset constant that is different for each counter.

The value of CAL was determined during the running of the experiment. TK and TV were calculated using the measured beam momentum and the reconstructed vertex information. The correction TR was necessary to allow for the time it took light to propagate along the scintillator. Because of the focussing effect of the wedge shaped pieces of scintillator the major correction was a non-linear one in r , the radial distance from the spectrometer z axis. The pulse height correction TP is necessary to correct for the time walk introduced by the use of fixed threshold discriminators. More information on the nature of the position and pulse height corrections can be found in ref. [22].

The functions used for the corrections TR, TP and TD were:-

$$\begin{aligned} TR+TD &= C1 + (40 - r) \times C2 + C3 \times (r-80.0)^2 \text{ for } r > 40 \\ &= C4 + (40 - r) \times C5 + C6 \times (r-27.5)^2 \text{ for } r < 40 \\ TP &= C7 \times (1 - \text{EXP}(C8 \times PH)) \end{aligned}$$

These corrections were investigated using tracks with momenta greater than 3 GeV/c. For such tracks, the calcu-

lated time is independent of the type of secondary particle, within the resolution of the counter. To determine the counter resolution, the difference (DT) between the measured time and the expected time was calculated. The width of a distribution of DT for a large number of tracks is then a measure of the resolution of the counter. The set of constants C1 through C8 were found by minimizing this width. This was done iteratively using a multi-parameter fitting program called MINUIT. MINUIT was also used to investigate different functional forms for the corrections. These included linear and quadratic functions with or without different parameters for large and small r . The functional forms shown on the previous page allowed a good representation of the dependence of the measured time delay on the position and the pulse height, and their use provided optimal resolutions for the individual counters. The resolution (σ) was calculated for each counter, for large and small r for use in the particle identification process.

The values of the TOF correction constants varied during the course of the experiment. Major changes were found to occur when either of the magnets had been turned off and on. The problem was due to hysteresis effects in the iron phototube magnetic shields. These were difficult to prevent even with the use of the bucking coils in the TOF magnetic shields. To minimize the effects of these variations, the correction program was run on data taken after each off/on

cycle of the magnets. This information was used to produce a set of run dependent correction constants.

Plots of DT for tracks with momenta greater than 3 GeV/c using the run dependent time of flight constants are shown in figure 27. The tracks used in these plots were of X^+ and X^- particles from the 155,000 data and background sample defined in chapter 5. Histograms are shown for all counters, for the six smaller counters and for the eighteen standard sized counters. (See figure 12.) The resolution for the smaller counters is considerably better than the standard sized counters. This is simply due to the reduction in light losses in the scintillator and light pipes of the smaller counters. The resolution for the whole array is 1.3 nsec FWHM which is equivalent to a sigma of .55 nsec.

Time of flight information was useful for particle identification below about 2.4 GeV/c. It was used by calculating the value of the expected TOF minus the measured TOF (DT) for the three hypothesis; pion, kaon and proton. The expected time is given by :-

$$T(\text{exp}) = (S \times E) / (P \times c)$$

where S is the track length

E is the energy of the particle

P is the momentum

Figure 27: Time Resolution of the TOF Array

a) Positive tracks

b) Negative tracks

Figure 28: Time Difference Versus Momentum for TOP.
 $\Delta T = (\text{Measured Time} - \text{Expected Time})$.

Plots of the quantity (DT) versus momentum for the KAON hypothesis can be found in figure 28. The upper and lower plots are for positive and negative tracks respectively. The tracks used for these plots came from the same data sample as those used for figure 27. In the top plot one can clearly see proton and pion 'arms' branching off to the top and bottom of the plot at low momentum. Kaons are to be found around DT=0. A kaon is deemed to have been identified if the following three conditions are satisfied :-

$$\begin{aligned} |DT(KAON)| &< N(K,K) \times \sigma \\ |DT(PION)| &> N(K,\pi) \times \sigma \\ |DT(PROT)| &> N(K,p) \times \sigma \end{aligned}$$

Where the sigma used is that of the counter and the values of the 3 by 3 matrix N are chosen to allow for optimal separation of signal from background. Similar sets of conditions are used to select pions and protons. There are very few $\bar{p}$ in this data sample so separation of negative particles is between pions and kaons.

The standard use of the TOP system is to set the N-matrix so that there are 3 sigma bands around the proton and pion and a 2 sigma band around the kaon.

4.5 MVFIT AND K^0 TOPOLOGY SELECTION

At the beginning of the previous section it was stressed how important the efficient identification of the charged kaon was to the selection of the $K\bar{K}\pi$ data sample. An equally important aspect to the selection of this data sample is the identification of events that also contain a neutral kaon. This involves the general problem of the separation of single vertex events (topology one), from those events having topological solutions with an additional secondary V^0 (topology two). The problem was essentially deferred at the DSTPRIME vertex reconstruction stage, by choosing fairly liberal cuts, and retaining both candidate hypotheses. However during the investigation of the K^0 data sample it was found that when a K^- particle was identified in an event the K^0 background was larger than for other events. This is illustrated by figure 29. The top plot shows the raw K^0 signal and the centre plot shows what happens when a K^- is required. The reason for the deterioration in the signal to background ratio is that there are many more $K^-\pi\pi X$ events than $K^-K^0 X$ events. In order to study rare events involving a K^0 and an additional kaon an improved definition of a K^0 was necessary.

In the discussion that follows the K^0 background is defined as topology 2 V^0 events with a V^0 mass between 0.439 and 0.453 or 0.541 and 0.555 GeV/c^2 . A K^0 signal is topology 2 V^0 events with a V^0 mass between 0.483 and 0.511 GeV/c^2 minus the background.

a) K^0 Mass plot for $K^0 X^+ X^-$ events in which an X^+ or X^- can be identified

b) K^0 Mass plot when X^- is identified as K^-

c) K^0 Mass plot when K^- is identified and K^0 is selected with $\text{PARAM} = 10$

Figure 29: Effect of K^- Selection on K^0 Mass Spectrum

Various algorithms were developed to reduce the K^0 background using the information on the DSTPRIME tapes. There were two types of cuts that were effective, a geometry cut and a cut on the value of Q for the topology one and topology two solutions. (Note $Q = \sum(d^2)/(N-1)$.) The geometry cut was based on the decay length and the lab opening angle of the K^0 (θ). The background was found to preferentially populate regions of small θ and decay length. Quality cuts were based on the topology 2 quality being good (small Q), the topology 1 quality being poor (large Q), and the Q of the topology one solution not being significantly better than that of the topology 2 solution. With these cuts a substantial reduction in background was possible, but at a cost of 50% reduction of real K^0 events. This type of cut was used to define the K^0 data samples for C1 studies.

There was an alternative method available to separate topology one from topology two events. This was to fit both topological solutions using the multi-vertex fitting program MVFIT. The MVFIT program fitted the event as a whole using the track coordinates and the topological solution as a constraint. It had the potential of improving K^0 selection as it provided errors on the decay length. The visible effects of the program included small changes in the track momenta, K^0 mass and vertex positions. After running MVFIT one had the confidence level of the fit and information on the errors of the fit, including errors on the decay length

and the total visible momentum of the event. It was possible to run MVFIT constraining the masses of the V^0 and V^- or not as required.

To use MVFIT for V^0 selection it was run on the topology 2 solution without mass constraints. It was also run on any topology 1 solution that contained all the tracks at the primary vertex of the topology 2 solution. The selection procedure involved a comparison of the confidence levels of the topology one and topology two solutions (C^1 and C^2). Events in which C^1/C^2 was less than 10.0 were not used. The other part of the selection was a cut on the decay length divided by its error ($L/\delta L$). Events in which $L/\delta L$ was less than the value of the program parameter (PARAM) were rejected. The effect of various values of the selection parameter (PARAM) can be found in figure 30. This figure shows plots of the K^0 signal versus the K^0 background for different values of PARAM. Two plots are given. The upper one is for events without additional identification constraints, and the lower one is for events in which a K^- was also required to be seen. These plots also contain a point which represents the non-MVFIT cut which gave the best signal to background ratio. One can see that the use of MVFIT leads to a 50% increase in K^0 signal without significantly affecting the signal to background ratio.

Figure 30: Data Versus Background Reduction for V^0 Cuts

Chapter V

RESULTS

The subject of this thesis is the study of the $K^0 K^+ \pi^-$ final state in the 11 GeV/c $K^- p$ experiment. In Chapter 3, the spectrometer and data taking process for this experiment were described. The first stages of the analysis of this data were then presented in Chapter 4. Chapter 4 also contained descriptions of the methods developed for charged and neutral kaon identification. These methods were of vital importance to the selection of the $K K \pi$ sample.

The subject of this chapter is the extraction and analysis of the $K^0 K^+ \pi^-$ data sample. The aim of this analysis as described in chapter 2 is a search for the E meson.

5.1 $K K \pi$ DATA SAMPLE SELECTION

The DSTPRIME data sample consisted of 31 million events. To study any physics reaction, events of interest had to be selected from this data sample. The two sections at the end of the previous chapter described the efficiencies of the particle identification system and the effectiveness of MVFIT in defining K^0 particles. This information was used in the selection of the $K^0 K \pi$ data sample. A clean $K^0 K \pi$ sample depends crucially on charged K identification to reject the much larger $\bar{K}^0 \pi \pi$ sample. Similarly neutral K identification

is equally crucial for separating the $K^0 K_n$ reaction from the $K^- n n n$ background. The process by which the $K K_n$ sample was extracted from the DSTPRIME tapes is shown in a flow chart in figure 31. Note that up until the last selection stage $K^0 n n$ events were included in the data sample; this was to allow studies of the background to be made.

The first step in the data reduction process was the creation of the topology tapes. Three streams of these were defined at Carleton. Topology 1, topology 2 and a high topology tape containing events with any of topology ~~5, 6, 7~~ or 8. The thirty topology 2 tapes contained all events with a topology two solution. There were 5.2 million of these events. The analysis described here was done with 4.87 million of these events.

To optimize K^0 selection it is necessary to have processed the data with the MVFIT program. Since MVFIT takes a lot of computer time, it was used after the data had been passed through a preliminary set of cuts (data compression 1 and 2). The first of these cuts was used to select events with a meson system of a K^0 and at least one positive and one negative particle ($K^0 X^+ X^-$), with no requirement on the baryon recoil system. The difficulty encountered in selecting $K^0 K_n$ events is that the recoil system is a strange baryon, which in the majority of cases gives rise to a long lived neutral baryon such as a lambda or Σ^0 particle. These neutral baryons are poorly reconstructed in the spectrom-

Figure 31: Data Reduction Process

ter, because their decay products, which have low longitudinal momentum, are detectable mainly by the cylindrical system alone. For a cylindrical track to exist it had to have a coordinate on the inner proportional cylinder. If the neutral baryon decayed outside this chamber, reconstruction of its decay products was impossible. Thus it was expected that $K^0 K^0$ events would be contained in events with three or more appropriately charged tracks at the primary vertex. The forward charged meson system ($X^+ X^-$) was chosen by selecting the positive and negative track with the largest z component of momentum. If there were 4 or more tracks at the primary vertex the sum of the momenta of the meson system was required to be greater than 8 GeV/c. The next cuts were on the position of the primary and secondary vertices. A missing mass cut was made assuming pion masses for the two X particles. Cuts 4 and 5 were made to remove the background reactions ($\bar{K}^0 n p$), ($\bar{K}^0 n p n^0$) and ($\Lambda X^+ X^-$). The last requirement was that one of the charged mesons (X^+ or X^-) be identifiable as a π or a K. For TOF identification to be possible the momentum had to be less than 2 GeV/c. For positive particles a cut of 2 sigma was applied to the kaon hypothesis and a cut of 3 sigma applied to the pion and proton hypothesis. For negative particles 3 sigma cuts were used for both the pion and kaon hypothesis. Standard cuts were used for C2. C1 was used with the 80% level spatial cuts on tracks with momentum > 3 GeV/c.

Figure 32: Effects of Data Reduction Cuts

The first stage of selection cuts removed 91% of events. The remaining 443,000 events were processed by MVFIT in the manner described in section 4.5. A second set of cuts were applied to the MVFIT output data to create one tape containing $K^0 K^n$ and $\bar{K}^0 n n$ events for use in background studies. There were 155,000 events on the data plus background tape. The first cut applied was to require that MVFIT had converged and that the solution satisfied the K^0 selection criteria with a cut parameter (PARAM) of 5, (see figure 30). The next three cuts were re-application of cuts used in the first selection stage. The MVFIT program produced small changes in track parameters. In borderline cases the calculated charge of a track can change. It is therefore necessary to check that a $K^0 X^+ X^-$ solution still exists after MVFIT. $\bar{K}^0 n n$ events for which the K^0 mass lies outside the standard K^0 mass cuts (see figure 31) were removed as they are not useful for background calculations. The K^0 mass spectrum for $\bar{K}^0 n n$ events before and after these cuts is shown in figure 32a. They are removed at this point rather than before MVFIT because the K^0 mass can change significantly in the fitting process. The last cut was to tighten the C1 requirement to tracks with momentum greater than 3.2 GeV/c and to require the 90% C1 cuts. The tape produced by these cuts was used for the signal and background studies described later in this chapter. It was also used for many of the plots shown in the previous chapter.

For detailed studies of the properties of the data a $K^0K\pi$ data sample of 14,500 events was defined and stored on a single data tape. The cuts used to define this data only sample are shown in the last box in figure 31. A track resolution cut was made using the error on the total visible momentum as calculated in MVFIT. The major cut at this level was the removal of the $K^0K\pi$ background events by applying K^0 mass cuts and the requirement that there be a K^+ or K^- particle (not both). Thus $\bar{K}^0\pi\pi$ and K^0KK events were removed at this point. C2 and TOF cuts were the same as those applied earlier and C1 was used with the 93% cuts. The effects of this set of cuts on the spatial acceptance of C1 is shown in figure 33. There was an additional momentum cut on kaons identified by the Čerenkov counters of $3.4 < p < 9.25$.

The remaining data sample had two other known contaminations. The first of these occurred in the $K^0K^-\pi^+$ channel. In some of these events the π^+ was actually a proton. This can be seen in figure 32c which gives the TOF information for the positive mesons of this channel on the kaon hypothesis. Pions are contained in the band that extends to the bottom of the plot at low momentum. A clear proton band is also visible extending to the top. The particles that are positively identified as protons are shown in the right hand plot. Twenty four percent of positive mesons identifiable by the TOF were found to be protons. Events in which the

Figure 33: Spatial Acceptance of C1 with 93% Cuts

positive meson was identified as a proton were rejected from the data sample. The other background was in the $\bar{K}^0 K^+ \pi^-$ channel where the K^+ was labelled by one of the Čerenkov counters. In the momentum range selected for K identification in the Čerenkov counters, it was not possible to discriminate between protons and kaons, using either the Čerenkov counters or the TOF hodoscope. To study the proton background to the K^+ signal the $p\pi^-$ invariant mass for the $X^+ X^-$ mesons was plotted, (see figure 32b). This figure revealed a significant lambda signal. Events with a $p\pi^-$ invariant mass close to the lambda mass were removed from the data sample. (See figure 32b. bottom plot.) About 4% of the $\bar{K}^0 K^+ \pi^-$ events fell in to this category.

In studies of the $K\bar{K}\pi$ data sample a cut was applied on the missing mass opposite the $K\bar{K}\pi$ system. This reduced the data sample to 10,400 events. A description of the missing mass spectrum and the cuts used is given in the next section.

5.2 FEATURES OF THE $K\bar{K}\pi$ DATA SAMPLE

The $K^0 K\pi$ invariant mass spectrum after the missing mass cut of 1 to 4 $(\text{GeV}/c^2)^2$ has been applied is shown in figure 34. The $K^0 K\pi$ spectrum rises slowly above the $K\bar{K}\pi$ threshold, until the $K^* K$ threshold is reached just below $1.4 \text{ GeV}/c^2$. At this point there is a sharp increase in the number of events per 20 MeV/c^2 bin. The spectrum is flat and fairly smooth between 1.5 and 1.9 GeV/c^2 . At higher masses the

Figure 34: $K\bar{K}\pi$ Spectrum

number of events per bin gradually declines, with less than 3% of events having an invariant mass greater than 3 GeV/c². There is no evidence of narrow structure in the spectrum, in particular there is not a statistically significant peak in the E region.

Resonances within the $K\bar{K}\pi$ system are assumed to have been produced in the manner shown in figure 35a. This shows the hypercharge exchange K^+p reaction producing a meson A^{123} at the top vertex and a baryon recoil particle B at the bottom vertex. Studies of the meson system A^{123} do not require the observation of the baryon in the experiment. The parent meson A^{123} is assumed to decay via a two step process involving a secondary resonance A^{23} . Thus the invariant masses formed from any two of the three final state particles are also of interest.

Plots of these invariant masses are shown in figure 36. In both the $M(K^0\pi^+)$ and the $M(K^+\pi^0)$ plots a prominent peak is seen at the mass of the $K^*(890)$. The invariant mass of the $K\bar{K}$ system $M(K\bar{K})$ shows a sharp rise at the $K\bar{K}$ threshold. If a two body decay mode did exist via the $K\bar{K}$ system, then one would expect the secondary resonance A^{23} to be the $\delta(980)$ which has a mass just below the $K\bar{K}$ threshold. The mass plot in figure 36 for the $K\bar{K}$ system is not as strongly peaked at threshold as one might expect for δ production. However it does not preclude the existence of a δ . Thus the appearance of the 2 body invariant mass plots encourages the

a)

A = MESON
B = BARYON

b)

mode	2	3
A^{23}	K^{*0}	K^{*+}
A^1	K^0	K^+
A^2	K^+	K^0
A^3	π^+	π^+
A		

c) (In overall centre of mass reference frame)

Figure 35: Three Body Decay Process

Figure 36: Two Body Mass Spectra for KKn Data

investigation of the following three decay modes; $K^* \rightarrow K^0$, $K^{*+} \rightarrow K^+ \pi^-$ and 8π . The notation used for these decay schemes is shown in figure 35b. In this notation the invariant mass of the parent and secondary resonances (M^{123} and M^{12}) respectively are given in terms of the particle's four vectors P by :-

$$\begin{aligned} (M^{123})^2 &= |P^1 + P^2 + P^3|^2 = (M(K\bar{K}\pi))^2 \\ (M^{23})^2 &= |P^2 + P^3|^2 = (M(K\bar{K}))^2 \\ &\text{etc.} \end{aligned}$$

Three other quantities that are used extensively throughout the analysis are the missing mass squared $(MM)^2$, the four momentum transfer t , and the quantity $t' = t - t(\min)$. These are defined in the following way. The missing mass and t are given by

$$\begin{aligned} (MM)^2 &= |P(\text{beam}) + P(\text{target}) - P^1 - P^2 - P^3|^2 \\ t &= (P(\text{beam}) - P^1 - P^2 - P^3)^2 \end{aligned}$$

The quantity t' is readily calculated in the form

$$|t'| = 2 \times |p(\text{beam})| \times |p^{123}| \times (1 - \cos\theta)$$

where $p(\text{beam})$ and p^{123} are the momentum of the beam and the parent meson in the centre of mass reference frame for the reaction. The angle θ is the production angle of the parent meson as defined in figure 35c.

The missing mass spectrum opposite the $K\bar{K}\pi$ sample is shown in figure 37a. It is consistent with a strange baryon recoil system, as the leading edge of the resolution broad-

a)

b)

Figure 37: Missing Mass-Squared Distributions

Figure 38: T-Prime Distribution

ened distribution is just below the lambda mass. The spectrum is limited at high mass by the 8 GeV/c momentum cut imposed on the forward meson system during the event selection process. The observed MM^2 spectrum is fairly flat between 1 and 4 (GeV/c²)² with no dominant recoil baryons. The missing mass spectrum for events that have good overall momentum resolution ($\Sigma(\Delta P_z)^2 < 0.05$) is shown in figure 37b. In this plot a clear peak is observed corresponding to Λ and Σ^0 recoil baryons. The t' dependence of the reaction is shown in 38. The exponential decrease of events with t' for the whole data spectrum is given by

$$N(t') = a \times \exp(b \times t')$$

$$\text{where } b = -2.21 \pm 0.16$$

Thus in general the $K\bar{K}\pi$ data sample shows no strong evidence for structure indicating the presence of $K\bar{K}\pi$ resonances. There is however evidence for the K^*K decay mode. The missing mass opposite the $K\bar{K}\pi$ sample indicated the presence of a number of strange recoil baryons with no one particle dominating. The number of events as a function of t' is a smooth and exponentially decreasing function.

5.3. MONTÉ CARLO

To interpret the results of the experiment, it is important to know both the acceptance and the resolution of the spectrometer. In any device such as LASS the acceptance depends on a large number of variables. Variations in acceptance can have a large effect on many physics distributions such

as decay angular distributions. If the acceptance is known these effects can be allowed for. The spectrometer resolution is important as well, as it determines the class of phenomena that can be investigated. For instance, a meson with a width of $40 \text{ MeV}/c^2$ will be difficult to observe in a mass plot if the mass resolution is only $100 \text{ MeV}/c^2$. Due to the complexity of the problem it is difficult to determine the acceptance and resolution analytically. Fortunately another technique exists, that is, the use of an event simulation program or Monte Carlo (MC).

The MC program was used to generate $K^-p \rightarrow K^0 K^+ n^+ B$ events originating throughout the hydrogen target and then to simulate the response of the spectrometer. The trajectories of each of the outgoing mesons were followed through the spectrometer to see if they were measurable, and in the case of the charged K, identifiable by the particle identification devices. The MC events were written to tape in a format that was similar to the data records after they had been passed through MVFIT. This enabled the compression and analysis programs used on the MVFIT data records to be used on Monte Carlo events. Thus the effect of the compression and analysis programs was equal on both data and MC events. An outline of the Monte Carlo program is shown in figure 39.

Monte Carlo events were generated with the invariant mass of the $K\bar{K}n$ system chosen uniformly between fixed limits. The momenta of the individual mesons K^0, K^+, n^+ were

Figure 39: Summary of Monte Carlo Program

then chosen randomly according to three body phase space. No two body decay modes were imposed. The K^0 was allowed to decay with the characteristic time of the K^0 (short) to $\pi^+\pi^-$. Three different MC event samples were generated in this manner. The first of these was a 100,000 event $\bar{K}^0 K^+ n^-$ sample generated with a $K\bar{K}n$ mass between 1.2 and 1.6 GeV/c^2 and with a lambda recoil baryon. The decay products of the baryon were not tracked through the spectrometer. This sample was used primarily to give the missing mass squared resolution at the lambda mass. The second sample contained 200,000 events with a $\bar{K}^0 K^+ n^-$ mass between 1.2 and 3.0 GeV/c^2 . This was generated with a recoil baryon which had a mass between 1.35 and 1.85 GeV/c^2 . For any given event the upper bound on the baryon mass was fixed by the mass chosen for the $K\bar{K}n$ system and the beam momentum. Given this constraint the baryon mass was chosen uniformly between 1.35 GeV/c^2 and the upper bound. The baryon in this data sample was caused to decay immediately to a proton and a π^- which were then tracked through the spectrometer. Thus the events generated could be used to simulate the effect of the $K\bar{K}n$ system being chosen from particles originating from both meson and baryon decays. The third data sample was a 260,000 event $K^0 K^- n^+$ sample with the same conditions applied to the $K\bar{K}n$ system and the recoil baryon as in the second sample. The second and third MC data samples were used for calculating the acceptance and resolution of the spectrom-

ter for the $K\bar{K}\pi$ system. For all three data samples the four momentum transfer t' was randomized so that the thrown t' spectrum was similar to that of the data. The specific dependence used was $N(t') = \exp(-2.1t')$.

The tracking of charged particles through the spectrometer and the corrections and precautions used in that process are described in detail in ref. [1]. A summary of that process is given here.

For each MC event a beam track was taken from a bank of experimentally measured beam tracks. These were selected from the entire experimental run. The position, direction and momentum of these tracks were randomly changed by a small amount to simulate measurement errors. For each event an interaction point was chosen at random within the target volume, allowance being made for the absorption of the beam by the target. The beam four momentum, vertex position and reaction parameters described above were used to define the four vectors of the 3 outgoing mesons. The K^0 was allowed to decay to 2 charged pions resulting in a total of four charged mesons from the parent meson system. These particles along with particles from the baryon decay (if any) were tracked through the spectrometer until they hit a high mass object which was considered to be a total absorber, or until they successfully passed through all detector elements. Particles were assumed to follow helical paths within the solenoid region and straight lines in the region downstream of

the TOF hodoscope. The RKI technique was used to track the particles through the dipole and the high field region at the end of the solenoid. In the tracking process the probability of absorption by the devices within the spectrometer was taken into account. The energy loss of particles in the target was calculated and the momentum appropriately reduced.

At this point the tracks of the four charged particles within the spectrometer were known. To simulate the track finding program used on the data, it was necessary to simulate coordinate information. This was done using the experimentally measured resolution, and the efficiencies of the spectrometer wire chamber planes. Coordinates were calculated for each device through which the track passed. The coordinate was deemed measurable if a random number between 0 and 1 was less than the fractional efficiency of the device. The resolution of each device was simulated by randomly shifting coordinates. The coordinates were shifted by an amount that reflected the device resolution. Each track was then subjected to tests on the number of proportional coordinates and missing coordinates identical to those used in reconstructing experimental tracks at both the GNUCODE and DSTPRIME level. If a track failed these tests it was labelled unfindable in the MC track banks. A check was also made using the coordinate information to see if the event passed the hardware trigger requirements. If not the MC program was terminated for that event.

After the coordinate simulation the MC event contained much of the information in the GNUCODE output record. To simulate the track fitting and vertex finding performed by the DSTPRIME program, these segments of the event reconstruction program were included in the Monte Carlo. The same thing was done with the MVFIT program which was used to refit the whole event using the simulated coordinate information.

Throughout the MC, checks were made on whether the charged kaon could be identified. Early in the program the momentum of the kaon was compared with the operating ranges of the identification devices. At a later point a determination was made as to whether the particle went through the active regions of one of the counters. If the kaon failed either of these tests the program was stopped for that event. C2 information for the Monte Carlo output was calculated for all 'dipole' tracks. If the track went through the active region of the counter, a fixed pulse height was assigned to the track. The calculation of the C2 active region included the more restrictive DSTPRIME y-cut. The C2 simulation did not include the adjacent mirror checking performed in GNUCODE. Particle identification information for C1 and the TOF was calculated using the same routines found in GNUCODE and DSTPRIME. However in the MC only on/off information was simulated for these devices. The measured TOF was not simulated and the pulse heights and TDC values for the cells of the hodoscopes were assigned fixed values.

The effect of the finite resolution of the TOF counter was simulated in the group of programs that read the MC output record. This was done by creating a measured time by adding to the expected time a random number (in a gaussian distribution) that reflected the time resolution of the individual counter.

The output record of the MC was shorter than the DSTPRIME record and slightly different in format. It was possible however, to run ~~all~~ the existing compression and analysis programs on the MC output event records. The key MC information used in the following analysis was the output of the MVPIT segment of the program, which gave the particles' four vectors, and the particle identification information that was used to simulate the particle identification cuts.

The acceptance of the spectrometer can be understood by comparing distributions of kinematic quantities of events generated by the Monte Carlo, with the appearance of the same distributions for those events that pass all the cuts. In short, a comparison between the 'thrown' and 'accepted' events. Histograms of the thrown and accepted $K\bar{K}\pi$ mass are shown in figure 40a. As described earlier the thrown $K\bar{K}\pi$ spectrum is flat, (top left hand plot). The bottom left hand plot shows the $K\bar{K}\pi$ acceptance spectrum. This plot shows that the acceptance is smooth and fairly uniform for low $K\bar{K}\pi$ masses. As the $K\bar{K}\pi$ mass increases the acceptance

Figure 40: Spectrometer Acceptance from Monte Carlo

falls off. Thus we can interpret the decrease in the number of events at high mass in the $K\bar{K}\pi$ data spectrum as being an acceptance effect. Similar plots for the 2 body invariant masses $K\bar{K}$ and $K^0\pi^\pm$ are also shown in figure 40. Again the acceptance in these variables is quite smooth. The $K^\pm\pi^\pm$ spectra are not shown as they are equivalent to the $K^0\pi^\pm$ spectra. A particularly important feature of these acceptance plots is that the regions of interest for the E meson at $1.4 \text{ GeV}/c^2$ in the $K\bar{K}\pi$ spectrum and at $0.890 \text{ GeV}/c^2$ in the $K\pi$ spectrum have good acceptance with no sharp irregularities. The plots in figure 40 were made with the $K^0K^+\pi$ MC sample. Plots from the $K^0K^-\pi$ sample have similar features. A number of kinematic quantities were examined in this manner and the spectrometer acceptance was generally very good. The one exception was a 'hole' in one of the decay angular distributions. This will be discussed in section 5.7. Of the thrown events in the $K^0K^+\pi^-$ and $K^0K^-\pi^+$ samples of the MC 2.9% and 2.5% respectively passed all the spectrometer and data reduction cuts.

The resolution of the spectrometer is related to the measurement errors of the detecting devices, which in turn determines the measurement errors of the tracks. To check that the MC simulation of the track finding errors was reasonable a plot of the track errors as a function of track momentum was made. This plot was similar in all respects to the same plot made for the data shown in figure 20.

Figure 41: Missing Mass² and $K\bar{K}\pi$ Resolution

The MC program was used to determine the resolution by comparing the kinematics of the thrown events with the changes produced by the spectrometer simulation of the reconstruction program. Thus in the first MC sample the missing mass opposite the $K\bar{K}\pi$ system was fixed at the lambda mass. After passing through all the various stages of the MC programs, the calculated missing mass opposite the $K\bar{K}\pi$ system was as shown in figure 41a. One can see that the original delta function distribution has been broadened to a distribution with a full width at half maximum of $0.35 \text{ (GeV/c}^2\text{)}^2$. This resolution is dependant on the overall $\Sigma(\Delta p_z)^2$ cut as demonstrated in figure 37. Thus the lack of narrow structure in the missing mass spectrum of the data is not surprising. The resolution for the $K\bar{K}\pi$ mass was calculated by examining the difference between the thrown and measured $K\bar{K}\pi$ mass. This is shown for a number of different bins in the $K\bar{K}\pi$ mass spectrum in figure 41b. It is apparent from this plot that the resolution is best at low $K\bar{K}\pi$ mass. The variation in the $K\bar{K}\pi$ resolution as a function of $K\bar{K}\pi$ mass is shown in 41c. From this plot, one can see that the resolution at the mass of the E is about 20 MeV/c^2 . Thus the E with a width of 50 MeV/c^2 should be resolvable by the LASS spectrometer in the $K\bar{K}\pi$ channel.

5.4 BACKGROUNDS AND $K\bar{K}\pi$ CROSS SECTIONS

The $K^0K\pi$ data sample consisted of 0.2 % of all topology 2 candidate events. The potential backgrounds to this channel are therefore high. Before any conclusions can be drawn about the data it is important to determine the size and characteristics of the background. This is done by examining the cleanliness of the $K^0, K\pm$ and $\pi\pm$ selection, and using this information to create a $K^0K\pi$ background spectrum.

The K^0 spectra for events from the data plus background tape when a K^+ or K^- is required are shown in figure 42. The signal (plus underlying background) was defined to lie in the mass range from 0.483 to 0.511 GeV/c^2 . The backgrounds B1 and B2 were defined to be events in the ranges 0.439 to 0.453 and 0.541 to 0.555 GeV/c^2 respectively. These are shown in figure 42. The signal to background ratios defined by $(S-B1-B2)/(B1+B2)$ are 8.9 and 7.3 for the K^+ and K^- selection respectively. It is possible to define a $K^0K\pi$ background spectrum due to K^0 misidentification by plotting the invariant $K\bar{K}\pi$ mass for those events that fall in either of the two background ranges B1 and B2. This is done in figure 43c. Note that this background spectrum is quite smooth.

The particle identification cuts used to select the $K\pm$ mesons have been described in the previous chapter. About 5% of the kaons were identified by the TOP and of the kaons identified by the Čerenkov counters 86% were identifiable by

a) K^0 Mass when
 K^+ selected

b) K^0 Mass when
 K^- selected

Figure 42: K^0 Mass Plots

a) $K\bar{K}\pi$ spectrum
for $K\pi\pi$ events.

b) $K\bar{K}\pi$ spectrum for
 $K\pi\pi$ events
weighted using C1
efficiencies.

c) $K\bar{K}\pi$ spectrum for
events with a K^0
from B1 and B2
regions.

Figure 43: $K\bar{K}\pi$ Background Spectra

C1. The $K^0K\pi$ background due to charged pions being misidentified as $K\pm$ was calculated by weighting those events in the $K\pi\pi$ spectrum in which one of the pions is identifiable by C1 or C2. The weights were given by

$$WT = (1-e)/e$$

where e is the momentum dependent efficiency of C1 for the 93% level cuts. The weights used can be found in table 15. The invariant $K^0K\pi$ mass for events identified as $\bar{K}^0\pi\pi$ is shown in figure 43a. There is a prominent hump in this spectrum just below $1.6\text{GeV}/c^2$ which is a reflection of the $K^*(1420)$. The $K^0K\pi$ background spectrum that arises from these events using the weighting procedure described above is shown in figure 43b. The calculation of the background is approximate as no allowance is made for TOF misidentification, and C2 is assigned the same efficiency as C1. The approximation is a good one due to the major role played by C1. It should also be noted that at low $K\pi\pi$ invariant mass no charged kaons are identified by the TOF hodoscope.

TABLE 15

Weights Used in Determining $K\pm$ Background

MOMENTUM RANGE		WEIGHT
3.4	3.6	0.075
3.6	4.0	0.050
4.0	4.6	0.027
> 4.6		0.020

a) $K\bar{K}\pi$ data spectrum

b) $K\bar{K}\pi$ composite
background spectrum

c) $K\bar{K}\pi$ background
subtracted spectrum

Figure 44: Summary of $K\bar{K}\pi$ Data and Background Spectra

The $K\bar{K}\pi$ background due to charged and neutral kaon misidentification can be combined to form a single composite spectrum. Figure 44 shows the $K\bar{K}\pi$ data spectrum, the composite background spectrum, and the background subtracted $K\bar{K}\pi$ spectrum. The composite spectrum is fairly smooth with a broad maximum at about $1.6 \text{ GeV}/c^2$. Relative to this spectrum the data has an excess of events in the region 1.4 to $1.5 \text{ GeV}/c^2$. This is accentuated in the signal minus background plot at the bottom of the figure.

The $K^{*-}(890)$ resonance was a prominent signal in the $K^0\pi^-$ two body mass plot of the $K^0\pi\pi$ system. As a K^- beam was used in the experiment the K^{*+} is not seen in the $K^0\pi\pi$ system by strangeness conservation. The reflection of the K^{*-} was seen in the K^0K^- 2 body mass plot of the $K^0K^-\pi^+$ data sample. This was caused by charged kaon misidentification. This effect was used to check the charged kaon background calculation. In figure 45 $\bar{K}^0K^+$ and K^0K^- mass plots are shown. The K^0K^- plot (signal) has a sharp peak at low mass which is due to the K^* reflection. There is no such peak in the $\bar{K}^0K^+$ plot. The middle two plots in this figure show the calculated backgrounds for these two invariant masses. The K^{*-} reflection, as expected, is even more prominent in these plots. The bottom two plots show the background subtracted $\bar{K}^0K^+$ and K^0K^- plots which look quite similar to each other with no evidence for the K^* reflection. This indicates that the background calculation is reasonable.

Figure 45: $K^*(890)$ Contamination in $K\bar{K}\pi$ Sample

There are two other major backgrounds to be considered. They both involved inclusion of the proton from baryon decay into the $K^0 K \pi$ system: as a K^+ in the $\bar{K}^0 K^+ \pi^-$ channel and as a π^+ in the $K^0 K^- \pi^+$ channel. Measures taken to reduce these backgrounds were described in section 5.1. However a quantitative estimate of the size of the remaining background is important. The estimate is made using the second and third Monte Carlo event samples, simply by counting the number of misassignments made to the $K \bar{K} \pi$ channel by the channel selection algorithm. These numbers are then corrected for the n/p baryon branching ratios which were estimated from the particle property tables. The backgrounds were 6.5% for the $\bar{K}^0 K^+ \pi^-$ channel and 11% for the $K^0 K^- \pi^+$ channel. Note misassignments of the π^- from the baryon decay to the $\bar{K}^0 K^+ \pi^-$ channel or to the K^- in the $K^0 K^- \pi^+$ channel were negligible (less than 0.3%).

Backgrounds to the $K \bar{K} \pi$ sample are summarized in table 16. It should be noted that the backgrounds from the three different sources are not independent. Thus the baryon decay background is applied to the signal after the effect of the other two backgrounds has been subtracted. This has been allowed for in the calculation of the total background. The error on the total background is partly statistical and partly arises from an allowance for the K^0 background in the $K^0 \pi \pi$ reaction used to calculate the charged K background. The background to the $K^0 K^- \pi^+$ channel is much larger than the

TABLE 16

Signal and Background Sizes for the Data Sample

	$K^0 K \pi$	$\bar{K}^0 K^+ \pi^-$	$K^0 K^- \pi^+$
Charged K background	9.1 %	4.4%	14.8%
Neutral K background	9.3 %	9.1%	9.4%
Baryon decay bgnd.	8.5 %	6.5%	11 %
Total	26. $\pm$ 3.0%	20 $\pm$ 3.5%	34 $\pm$ 3.5%
Number of events			
Observed data i.e.			
Signal+background	10406	5783	4623
Signal	7700 $\pm$ 3%	4626 $\pm$ 3%	3051 $\pm$ 5%

background to the $\bar{K}^0 K^+ \pi^-$ channel. At the bottom of table 16 the number of events that can be associated with signals in the 3 channels is given. These are used to calculate the $K K \pi$ cross sections.

The sensitivity of the experiment depends on the number of beam particles (4.05×10^8), the target dimensions and the weighted average of the target density during the experimental run ($.07082 \text{ gm/cm}^3$). There were also a number of correction factors that had to be taken into account in calculating the sensitivity, such as the trigger deadtime and the beam absorption. These are described in detail in ref. [1]. Given these corrections the sensitivity of the experiment after the losses due to GNUCODE production have been taken into account was

$$S(E) = 1224 \text{ events}/\mu\text{b} \pm 10.1\%$$

To estimate the sensitivity to the $\bar{K}^0 K^+ n^-$ and $K^0 K^- n^+$ channels, the acceptance effects of the spectrometer and the data reduction programs must be taken into account. This can be done using the second and third Monte Carlo samples of events. The average acceptance is given by:-

$$(\text{number of accepted events}) / (3 \times \text{number of thrown events})$$

where the factor of three arises from the assumption in the Monte Carlo that all neutral kaons decay to $n^+ n^-$. This leads to the average sensitivities for $M(K\bar{K}n) < 3 \text{ GeV}/c^2$ and a missing mass between 1 and 2 GeV/c^2 of:-

$$S(\bar{K}^0 K^+ n^-) = 35 \text{ events}/\mu\text{b}$$

$$S(K^0 K^- n^+) = 31 \text{ events}/\mu\text{b} \quad \pm 13\%$$

where the increase in error is mainly associated with the uncertainty in defining the recoil baryon mass range.

5.5 PRINCIPAL RESULTS OF THE DATA

In the previous section the backgrounds present in the $K\bar{K}\pi$ sample were discussed and the magnitude of these backgrounds calculated. In the analysis presented in this and following sections no further attempt has been made to reduce these backgrounds, although their effect is discussed where relevant. The observed $K\bar{K}\pi$ spectrum is shown again in figure 46, with the acceptance derived from the Monte Carlo shown on the same plot (dashed line). This figure shows that the shape of the high mass part of the $K\bar{K}\pi$ spectrum is determined mainly by the spectrometer acceptance. Known factors affecting the shape of the low mass part of the spectrum are the available three body phase space and the existence of the K^*K decay channel. In section 5.2 the evidence for the 2 body decay processes $\delta\pi$, K^0K^0 and $K^{*+}K^-$ were discussed. If these channels result from the decay of a parent meson A^{123} , the parent meson can be enhanced in the $K\bar{K}\pi$ spectrum by making an appropriate cut on the 2 body masses ($M(K\pi)$ etc.). The cuts used in this analysis were:-

$$\begin{array}{ll} \delta\pi & M(K^0K^*) \leq 1.1 \text{ GeV}/c^2 \\ K^0K^0 & 0.841 \leq M(K^0) \leq 0.941 \text{ GeV}/c^2 \\ K^{*+}K^- & 0.841 \leq M(K^{*+}) \leq 0.941 \text{ GeV}/c^2 \end{array}$$

The $K\bar{K}\pi$ mass spectrum when either of the K^* cuts is satisfied is shown in figure 47a. This distribution rises sharply at the K^*K threshold but otherwise does not exhibit

Figure 46: Acceptance for the $K\bar{K}\pi$ Spectrum

a) K^* cut b) ϕ cut Figure 47: $K\bar{K}\pi$ Mass Spectrum with ϕ and K^* Mass Cuts

any narrow peak structure. The $K\bar{K}\pi$ mass spectrum for events that satisfied the δ cut is shown in figure 47b. This plot has a prominent peak at low mass of width 100 MeV/c² in the region of the E meson. The peak is wider than the accepted width of the E (40-50 MeV/c²). Both plots on figure 47 have very few events at high $K\bar{K}\pi$ mass.

There were differences in some of the features of the data between the $K^0K^+\pi^-$ channel and the $K^0K^-\pi^+$ channel. To examine these differences most of the quantities of interest were plotted separately for each channel. $K\bar{K}\pi$ spectra for the two channels with and without two body mass cuts are shown in figure 48. A study of these histograms indicates only slight differences between the two channels. One such difference is the larger number of events at low $K\bar{K}\pi$ mass in the $K^0K^+\pi^-$ channel.

As an aid to the investigation of the data the $K\bar{K}\pi$ mass spectrum was divided up into six regions as shown in table 17. The MM^2 for each of these regions is shown in figure 49. For the 'E region' (b) the MM^2 is remarkably featureless while in the higher mass regions there is evidence for both the lambda and the lambda(1520) recoil baryons. It is clear however that there are no dominant baryon recoil particles in the E region. The t' distributions for the six mass bins are shown in figure 50. The distributions are remarkably similar. When the magnitude of the t' slope parameter is plotted as a function of $K\bar{K}\pi$ mass there is some

Figure 48: $\bar{K}^0 K^+ \pi^-$ and $K^0 K^- \pi^+$ Spectra

evidence that it decreases with increasing $K\bar{K}\pi$ mass. However the statistical significance is marginal.

TABLE 17
Mass Regions of $K\bar{K}\pi$ Spectrum

REGION	$K\bar{K}\pi$ MASS CUT	
a	0	1.36
b	1.36	1.5
c	1.5	1.64
d	1.64	1.8
e	1.8	2.0
f	2.0	2.4

There are a number of simple standard methods for examining data for potential resonances. One of these is a Chew-Low plot in which t' is plotted against the $K\bar{K}\pi$ invariant mass squared. Resonances appear in Chew-Low plots as bands in t' at a given $K\bar{K}\pi$ mass. Such a plot for the $K\bar{K}\pi$ data is shown in figure 51. There are no obvious bands visible in this plot to indicate the presence of a resonance.

A second analysis method is the use of a Dalitz plot, which consists of one of the two body invariant mass squared plotted against another. An informative Dalitz plot was found to be the one with $(M(K\pi)^0)^2$ plotted against $(M(K\pi)^+)^2$. Examples of these can be found for the whole $K\bar{K}\pi$ sample in figure 52, and for the six different $K\bar{K}\pi$ regions in figure 53. The dominant feature of these plots is the

Figure 49: $M_{\pi\pi}$ Plots for the Different $K\bar{K}\pi$ Mass Regions

channel proportions were determined by an iterative technique in which the proportion of each channel was varied until the best fit to the data was obtained, using a method that was equivalent to a maximum likelihood technique. These proportions were then multiplied by the number of events in the bin to give the channel strengths.

The channel strengths calculated in this manner are shown in figure 59. From this plot it can be seen that there is no significant amount of the $\delta\pi$ channel at any $K\bar{K}\pi$ mass. This confirms the qualitative assessment made in the previous section. It is also apparent that at high mass, (above about $1.65 \text{ GeV}/c$) the $K\bar{K}\pi$ sample is largely phase space with a small proportion of the K^*K channel. This effect can also be seen in the Dalitz plots for the data, (figure 53). In the mass region from 1.4 to $1.6 \text{ GeV}/c^2$ the K^*K channel is very strong with a broad peak at about $1.5 \text{ GeV}/c^2$.

One of the intriguing features of the data is that the K^*K signal is not evenly divided between the charged and neutral K^* channels. There are also differences between events from the $\bar{K}^0 K^+ \pi^-$ and $K^0 K^- \pi^+$ channels. This effect is shown in the four plots in figure 60. The cross sections on the right hand side of these plots are calculated using the $\bar{K}^0 K^+ \pi^-$ and $K^0 K^- \pi^+$ sensitivities with the appropriate Clebsch Gordon coefficients for the K^* decay. In the $K^+ \bar{K}^0 \pi^-$ sample the charged K^* signal is very large while the neutral K^*

$$M^2(KOK \pm PI \mp X)(GEV/C^2)^2 \rightarrow$$

Figure 51: Chew-Low Plot for $K\bar{K}\pi$ Data

Figure 52: Dalitz Plot for $K\bar{K}\pi$ Data

Figure 53: Dalitz Plots for Different $K\bar{K}\pi$ Mass Regions

a) All $K\bar{K}\pi$ events b) $K\bar{K}\pi$ events in
mass region b

Figure 54: Dalitz Plots for Monte Carlo Events

bands around a $K\pi$ invariant mass of $0.890 \text{ GeV}/c^2$. This is indicative of the $K^*(890)$ decay mode. Note that the percentage of events in the K^* bands decreases with increasing $K\bar{K}\pi$ invariant mass. Two of these plots are shown for Monte Carlo events in figure 54. As anticipated, these plots do not show the K^* bands as the MC events were generated without any two body mass constraints.

The Dalitz plot for the data for mass bin (b) (the 'E' region), is shown again in figure 55, along with separate plots for the $\bar{K}^0 K^+ \pi^-$ and $K^0 K^- \pi^+$ channels. If a significant number of events decayed via $\delta\pi$ one would expect to see an enhancement in the top right hand regions of these plots. No such enhancements are visible. (As the same Dalitz plot for Monte Carlo events is quite uniform (figure 54b.), one can conclude that acceptance effects are not depleting the $\delta\pi$ events. The $K\bar{K}\pi$ plot is consistent with the decay process being dominated by K^*K . One interesting feature of the data can be seen in the right hand plots of figure 55. They show a marked asymmetry in the K^+ and K^- channels, which are dominated by the K^* charged and K^* neutral resonances respectively. The interpretation of this is not immediately obvious. However what is apparent from this set of plots, is that the $\delta\pi$ decay mode is not a dominant feature of the data. It therefore seems unlikely that the structure observed in the $K\bar{K}\pi$ spectrum when the δ cut is applied is actually related to a $\delta\pi$ decay mode.

Figure 55: Dalitz Plots for Z Region of $K\bar{K}\pi$ Mass Spectrum

(a)
 $M(K\bar{K})$ v $M(K\bar{K}\pi)$

(b)
 $M(K\pi^0)$ v $M(K\bar{K}\pi)$

(c)
 $M(K\pi^+)$ v $M(K\bar{K}\pi)$

a)

b) K^* cut

To gain some insight into the nature of this structure scatter plots of $M(K\bar{K})$ and $M(K\pi)$ against the $K\bar{K}\pi$ invariant mass have proved useful. These plots are shown in figure 56. In plot (56a) ($M(K\bar{K})$ v $M(K\bar{K}\pi)$), it is apparent that for all $K\bar{K}$ masses there is a strong $K\bar{K}\pi$ threshold enhancement. Thus the δ cut extracts a small section of this general enhancement, giving rise to a broad structure at low $K\bar{K}\pi$ mass. To understand the enhancement in the two body plot (figure 56a), it is useful to look at the same plot for Monte Carlo events. (See figure 57a.) This plot appears to be fairly uniform. However when the effect of the K^* channel is simulated by making K^* cuts on the $M(K\pi)$ two body masses, the plot in figure 57b results. In this plot all events are close to $K\bar{K}\pi$ threshold. Thus it would appear that the structure in the $K\bar{K}\pi$ mass plot with a δ cut is to a large extent due to a kinematic reflection of the K^* .

To check this hypothesis a K^* cut and a δ cut were applied to Monte Carlo events. The result can be seen in the $K\bar{K}\pi$ mass plot of figure 58a. Figure 58b is the $K\bar{K}\pi$ spectrum for the data with just the δ cut for comparison. There is indeed a structure induced in the MC distribution, at a slightly lower mass than the structure in the data. The exact shape and position of the peak in the Monte Carlo mass spectrum would change if the correct phase space and K^* Breit-Wigner effects were used. From these plots however it would appear that the anomalous structure in the δ cut $K\bar{K}\pi$ data is due in large part to kinematics.

- a) $K\bar{K}\pi$ invariant mass spectrum for Monte Carlo events with a δ cut and a K^* cut.

- b) $K\bar{K}\pi$ invariant mass spectrum for data with δ cut.

Figure 58: Simulation of Structure in $K\bar{K}\pi$ Mass Spectrum with δ Cut

An examination of the data at this level reveals that there are no dominant resonances in the $K\bar{K}\pi$ spectrum. In particular there is no evidence at this point in the analysis for a narrow E meson. This is quite surprising in the light of previous experiments. Two approaches are possible to investigate the non-observation of the E : the first is to take a more detailed look at the data; examine the angular distributions, channel strengths etc; the second is to make a more detailed comparison between this experiment and previous ones. These approaches are followed in the next sections.

5.6 CHANNEL SEPARATION ANALYSIS

The Dalitz plots for $K\bar{K}\pi$ events were shown in figure 53. These showed clear evidence for the two body decay process K^*K and no evidence was found for the $\delta\pi$ decay channel. It was also clear that the proportion of K^*0K^0 and $K^{*+}K^-$ were not equal. To find which of the two body channels were actually present in the data and to determine their relative proportions, a channel separation analysis was used. For this analysis the data was split up into 100 MeV/c^2 bins, and the proportional content of each of four channels was determined for each mass bin. The four channels considered were phase space, $K^{*+}K^-$, K^*0K^0 , and $\delta\pi$. The K^* and δ resonances were parametrized as Breit-Wigner distributions. The mass and width used for the K^* and δ resonances were $0.890 \pm 0.052 \text{ GeV}/c^2$ and $0.980 \pm 0.052 \text{ GeV}/c^2$ respectively. The

channel proportions were determined by an iterative technique in which the proportion of each channel was varied until the best fit to the data was obtained, using a method that was equivalent to a maximum likelihood technique. These proportions were then multiplied by the number of events in the bin to give the channel strengths.

The channel strengths calculated in this manner are shown in figure 59. From this plot it can be seen that there is no significant amount of the 8π channel at any $K\bar{K}\pi$ mass. This confirms the qualitative assessment made in the previous section. It is also apparent that at high mass, (above about $1.65 \text{ GeV}/c^2$) the $K\bar{K}\pi$ sample is largely phase space with a small proportion of the K^*K channel. This effect can also be seen in the Dalitz plots for the data, (figure 53). In the mass region from 1.4 to $1.6 \text{ GeV}/c^2$ the K^*K channel is very strong with a broad peak at about $1.5 \text{ GeV}/c^2$.

One of the intriguing features of the data is that the K^*K signal is not evenly divided between the charged and neutral K^* channels. There are also differences between events from the $\bar{K}^0 K^+ \pi^-$ and $K^0 K^- \pi^+$ channels. This effect is shown in the four plots in figure 60. The cross sections on the right hand side of these plots are calculated using the $\bar{K}^0 K^+ \pi^-$ and $K^0 K^- \pi^+$ sensitivities with the appropriate Clebsch Gordon coefficients for the K^* decay. In the $K^+ \bar{K}^0 \pi^-$ sample the charged K^* signal is very large while the neutral K^*

3 3

OF / DE

Figure 59: Channel Strengths of $K\bar{K}\pi$ Data as a Function of Mass

signal is almost non-existent. In the $K^-K^0\pi^+$ sample there is a more even distribution of events between the two channels. It is also interesting to note that at higher masses (above about $1.7 \text{ GeV}/c^2$ there are small but statistically significant amounts of K^*K in all four sub-channels.

The differences in the strengths between the four K^*K channels is not easy to interpret, mainly because one of the four channels is so much stronger than the other. Before discussing the possible causes for these differences as phenomena in the $K^0K\pi$ channel it is necessary to examine possible background effects. The discussion in section 5.4 indicates that the backgrounds considered there are higher in the $K^0K^-\pi^+$ channel than the $K^0K^+\pi^-$ channel. Thus if the background produced a strong K^*K signal one would expect it to affect mainly the K^-K^{*+} and $K^0\bar{K}^{*0}$ channels, which is apparently not the case. Another possible background is events in which the three particles $K^0K\pi$, do not originate from the same vertex. This can arise in reactions such as $K^-p \rightarrow \bar{K}^{*0}N^*, N^* \rightarrow \Lambda K^0$ and $K^-p \rightarrow K^{*-}N^*, N^* \rightarrow \Lambda K^+$. The production of such K^* resonances is large in this experiment, however the branching ratio of $N^* \rightarrow \Lambda K$ is very small, (of the order of 2%). Plots of the missing mass opposite $K^0\pi^-$ and $K^+\pi^-$ did not reveal any prominent N^* peaks. One would expect these reactions to contribute to the $K^0\bar{K}^{*0}$ and K^+K^{*-} channels but not to the other two by strangeness conservation. It is difficult to see how the observed channel strengths could be explained by this potential background to the K^*K channels.

Figure 60: K^*K channel strengths

The production of a single resonance which then decays to K^*K would result in equal branching ratios to each of the four K^*K final states. The differing channel strengths suggest that there exists one or more resonances decaying to K^*K in the $K\bar{K}\pi$ mass region from 1.4 to 1.6 GeV/c². It is possible for such resonances to interfere with each other and with a non-resonant background producing different channel strengths. One way to gain more information on the nature of the low mass K^*K structure is to examine the decay angular properties of the $K\bar{K}\pi$ system. This is done in the next section.

The conclusion from this analysis is that the dominant two body process in the $K\bar{K}\pi$ sample is K^*K . There was no evidence for the $\pi\pi$ channel. Based on this, the angular analysis described in the next section was performed only for the K^*K hypothesis.

5.7 ANGULAR DECAY PROPERTIES OF THE $K\bar{K}\pi$ SYSTEM

The two step decay process can be characterized by four angles $\theta^1, \theta^2, \phi^1, \phi^2$. The definition of these angles is illustrated in figure 61. θ^1 and ϕ^1 describe the decay of the parent meson. These angles are defined in the rest frame of the parent meson using the coordinate system x', y', z' . The z' axis is chosen as the beam direction in the rest frame of the parent meson. The y' axis (y') is fixed to be normal to the production plane, which is the plane defined by the directions of the beam and the parent

a)

 $(L^1 m^1)$

$$\hat{Z}' = \hat{K}^- \text{ beam}$$

$$\hat{Y}' = (-\hat{X}') \times \hat{Z}' \text{ (Production Plane)}$$

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

$$\hat{X} = -A^{23} \text{ (In Lab Frame)}$$

IN A^{23} REST FRAME

b)

 $(L^2 m^2)$

$$\hat{Z}'' = -A^1$$

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

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

IN A^{23} REST FRAME

Figure 61: Definition of Angles Used to Describe Decays

meson. This is calculated by defining the vector X in the laboratory reference frame to be the vector opposite that of the $K\bar{K}\pi$ system. The x' axis is chosen to produce a right handed coordinate system. The angles for the decay of the secondary meson A^{23} are calculated in a similar way (see figure 61b), except that the z'' axis is chosen to be in the direction opposite to the A^1 meson in the A^{23} meson rest frame. The kaon was used as the analyser for both K^0 and K^{*+} decays; (compare figures 35 and 61).

For each $K\bar{K}\pi$ event the four angles were calculated for the K^0K^0 and $K^{*+}K^+$ hypothesis. An event was included in a particular K^* channel if the invariant mass of the appropriate two particles was within 50 Mev/c² of the nominal K^* mass. After the K^* cut had been applied the lowest mass bin of table 15 (a) contained too few events to be used. The remaining data was divided into the five mass bins (b) through (f). The angular properties of the $K\bar{K}\pi$ system were represented by four angles for each of four K^*K sub-channels in one of five mass bins. Thus to display this information for both data and Monte Carlo events required 160 histograms. A study of these 160 histograms revealed that the data and MC distributions had many features in common. The $K^{*+}K^-$ channel and the $K^{*-}K^+$ channels had angular distributions that were indistinguishable within the limits of the available statistics. This was also true of the $\bar{K}^{*0}K^0$ and $K^{*0}\bar{K}^0$ channels. Thus in the histograms shown on the follow-

ing pages the four sub-channels are combined into two; $K^*(\text{charged})$ and $K^*(\text{neutral})$.

Figure 62 shows distributions of the four angles for the charged K^* decay mode for the total $K\bar{K}\pi$ sample. The upper plots are for the data, the lower ones for the Monte Carlo. The prominent feature in these histograms is the small number of events with $\cos(\theta^1) > 0.25$. This 'hole' is an acceptance effect as it occurs for both the Monte Carlo and the data events. It appears after the momentum of the charged kaon is required to be greater than 3.4 GeV/c for particle identification by the Čerenkov counters. It can be understood in terms of the momentum cut selecting forward charged kaons which therefore selects backwards K^* particles. In this context forward and backward refer to the directions in the centre of mass of the $K\bar{K}\pi$ system. Another acceptance effect can be seen in the ϕ^2 distributions, in which less events are observed in the $\phi^2 = 0$ region. The same set of histograms for the K^*0 is shown in figure 63. Again, the effect of acceptance is apparent in these plots, particularly for the variables θ^1 and ϕ^2 , although in this channel there are no regions without any events.

In both figures 62 and 63 the trends in the Monte Carlo and data distributions are similar. The small differences visible between the two sets of plots have marginal statistical significance. One of the means of searching for resonance behaviour is to look for marked changes in the angular

a) Data

b) MC

Figure 62: Angular Distributions for Data and MC Events in the Charged K^* Channel

a) Data

b) MC

Figure 63: Angular Distributions for Data and MC Events in the Neutral K^* Channel

distributions as a function of mass. Such plots were studied for all angles for the K^* channels. However as indicated at the beginning of this section, splitting the data up in this way creates a large number of bins. Thus as most of the histograms of data and MC events showed little variation with $K\bar{K}n$ mass only the more striking plots are presented here. These are plots of $\cos\theta^1$ and ϕ^1 for the charged K^* for data and Monte Carlo events, (see figure 64). One of the notable features of these plots is the appearance of events with $\cos\theta^1$ greater than 0.5 for higher $K\bar{K}n$ mass bins. This is due to the detection of slow (backward) charged kaons by the TOP counter. This occurs for both data and MC events. The data and MC plots of $\cos\theta^1$ are generally similar except for the highest mass bin. In this bin there are indications that there are more events at $\cos\theta^1 = \pm 1$ in the data plot compared to the MC plot. In the plots of ϕ^1 there is a gradual and marked change in the distributions of ϕ^1 with mass. This is seen for both the Monte Carlo and data events.

In summary the comparison of the angular distributions of the Monte Carlo and the data leads to no evidence for substantial differences between the two. This is however a qualitative statement based on the subjective appearance of the angular distributions. Quantitative statements can be made by calculating the spherical harmonic content or 'moments' of the angular distributions. Decomposition of a

a) $\cos\theta^1$ Data b) $\cos\theta^1$ MC c) ϕ^1 Data d) ϕ^1 MC

Figure 64: $\cos\theta^1$ and ϕ^1 as a Function of Mass for the Charged K^* Channel

function $I(\theta, \phi)$ into spherical harmonics leads to an infinite series of terms identified by the quantum numbers l and m ($-l \leq m \leq +l$). (Where l is the orbital quantum number and m is the magnetic quantum number). The coefficients of these terms $C(l, m)$ are known as the moments of the function $I(\theta, \phi)$. In the $K\bar{K}\pi$ system there are two coupled angular distributions and the moments are identified by four quantum numbers $C(l^1, m^1, l^2, m^2)$, (see figure 61). These coefficients are given by (ref. [27]) :-

$$C(l^1, m^1, l^2, m^2) = \int d\Omega^1 d\Omega^2 D_{m^1, m^2}^{l^1}(\Omega^1) D_{m^2, 0}^{l^2}(\Omega^2) W(\theta^1, \phi^1, \theta^2, \phi^2)$$

where D stands for standard D functions

$$\Omega^1 = (\theta^1, \phi^1)$$

$$\Omega^2 = (\theta^2, \phi^2)$$

W is the experimentally observed angular distributions and the normalization $C(0, 0, 0, 0) = 1$ has been applied.

The details of the way these coefficients were calculated from the angular distributions can be found in ref. [28]. As initial interest was focussed on states with spin less than or equal to two, the decomposition was limited by restricting the value of l^1 and l^2 to be less than or equal to 4.

With an upper limit of 4 for l^1 and l^2 there are 275 independent moments. For each of these moments the signed real and imaginary parts of the coefficients plus their errors are calculated. The moments program was run on each

of the four sub-channels $K^{*+}K^{-}$, $K^{*-}K^{+}$, $\bar{K}^{*0}K^0$, $K^{*0}\bar{K}^0$ for each of the five mass bins for data and MC events. To select the significant moments from this large array of numbers, all coefficients that had a statistical significance of ≥ 2 sigma were listed separately. These numbers were then examined in detail to make an initial comparison between the data and MC sets of moments and to decide how to proceed. From this set of numbers, the moments for the data that had a significance of greater than 3.5 sigma for any mass bin in a given sub-channel was selected. They were then plotted for both data and MC as a function of mass. There were 8 to 10 of such plots for each sub-channel. The eight most significant of these plots for each channel are shown in figures 65 to 68.

The first overall impression on examining these moments is that the general appearance of the data and Monte Carlo moments are similar. It is notable that for the two charged K^{*} channels (figures 65 and 66) 6 moments appear in both sets of plots. The general appearance of these six moments is also similar in the two channels. As one expects these channels to be similar, this gives confidence that the moments program is working correctly. The same comments can be made about the neutral K^{*} channels in which 5 moments are to be found in both sets of plots. Note also that there is a large difference between the moments for the neutral and charged K^{*} channels. This is due to the different momentum ranges of the charged and neutral kaons.

Note vertical scales are fixed by normalization $C(0,0,0,0)=1$.

Figure 65: Moments as a Function of Mass for K^*+K^- Channel

Note vertical scales are fixed by normalization $C(0,0,0,0)=1$.

Figure 66: Moments as a Function of Mass for $K^{*-}K^+$ Channel

Note vertical scales are fixed by normalization $C(0,0,0,0)=1$.

Figure 67: Moments as a Function of Mass for $\bar{K}^*0K^0$ Channel

Note vertical scales are fixed by normalization $C(0,0,0,0)=1$.

Figure 68: Moments as a Function of Mass for K^*0K^0 Channel

The moments of interest are those in which there are significant differences between the Monte Carlo and the data. For instance, if in one or more moments there is a 4 standard deviation difference between the two for a given isolated mass bin, it would be taken as evidence for the presence of a resonance. In the 32 plots shown here this occurs only in the 0010 moment of the $\bar{K}^0(K^+\pi^-)$ channel, (figure 68). However, in the low mass bin of this channel most of the events come from the other K^* channel, the K^*0 content being quite small in the $\bar{K}^0 K^+\pi^-$ channel. (See the Dalitz plot for the E region given in figure 55). Thus the difference in the 0010 moment in the $\bar{K}^0(K^+\pi^-)$ channel is unlikely to be significant. One interesting feature of the moments is the deviation between the MC and data moments at high mass in the 1000 moment of the $K^{*+}K^+$ channel. (See figure 66). This is accompanied by much smaller effects in the 3000 and 4000 moments. This effect is not as strong in the other K^* channels. Small differences are noticeable at high mass in the 2000, 3000 and 4000 moments in the $K^{*+}K^-$ channel, (figure 65), and the 2000 moment in the $\bar{K}^{*0}K^0$ channel, (figure 67). The simplest interpretation of these effects is that at higher $K\bar{K}\pi$ mass, higher l-states between the K^* and the K become important. This is not necessarily evidence for resonant behavior. One tantalizing feature of the data is a marginally significant difference in the 0020 moment in the $K^{*+}K^-$ channel in the low mass region, (figure

65). The channel separation analysis demonstrated that this channel had the largest K^* content. The significance of this moment is discussed later. In summary, the method of moments has shown that at low $K\bar{K}\pi$ mass ($<1.8\text{GeV}/c^2$) there are no significant differences between the Monte Carlo and data moments, indicating that the orbital angular momentum between the K^* and the K is consistent with $l=0$ or s-wave. At higher masses there are indications of non-zero angular momentum states being present in the K^*K system.

The fact that no significant differences were seen between the moments for data and Monte Carlo events at low mass is at first surprising, particularly since the $JP=1^-$ $K^*(890)$ is seen clearly in the $K\bar{K}\pi$ data. If, for instance, the low mass $K\bar{K}\pi$ system was predominantly 1^+ one might expect the 0020 moment to show strong evidence for the K^* . To see why this is not necessarily so, consider the reaction in which a parent particle $I(J^1M^1)$ with $JP=1^+$ decays to K^*K , ($K^* = I(J^2M^2); J^2=1$). The parent meson can be produced in any of three M states, $-1, 0, 1$. Similarly in the $K^*(890)$ decay the same three M states, can be produced. The expectation value of the angular decay distribution will be given by:-

$$I(\Omega) = \sum_{JM} \psi(J^1, J^2, M^1, M^2) \psi^*(J^1, J^2, M^1, M^2)$$

JM

As the sum JM includes all 8 indices many different moments up to $l^1=2$ can appear in the angular distributions. This means that there need be no single statistically significant moment even though a K^* does exist in the data.

The basic problem with the use of the method of moments is that one resonant state can lead to the population of many moments. This problem is compounded when more than one resonance exists in the same channel at about the same mass. In certain cases where one moment dominates the other, information on J^1M^1 can be obtained directly from one or two moments, (see ref. [7]). However the $K\bar{K}\pi$ system is apparently not that simple. We need to extract the original states $\psi(J^1M^1)$ or amplitudes from the moments or the angular distributions. This is known as an amplitude or Partial Wave Analysis (PWA). The evidence of the channel separation analysis pointed to the existence of a broad structure at low $K\bar{K}\pi$ mass decaying to K^*K containing one or more resonances. The possibility of more than one resonance makes the use of a PWA all the more important for understanding the nature of the low mass enhancement in the K^*K channel.

5.8 COMPARISON WITH PREVIOUS EXPERIMENTS

One of the notable features of the data is the absence of a narrow peak at $1.42 \text{ GeV}/c^2$ that is associated with the ϕ meson. This meson has been seen by a number of π^-p and $\bar{p}p$ experiments since 1965. It is important to ask therefore, whether there is a conflict between this experiment and pre-

vious ones. To address this question a brief review of the experimental evidence for the E meson is presented here, along with a comparison of the results of this experiment with previous ones.

A list (non-exhaustive) of the experiments that had the potential for seeing the E meson is given in table 18. In most of these a hydrogen bubble chamber was used as target and detector. In many of the early experiments the statistics available were quite small, which no doubt explains some of the original conflicting evidence for this meson. In the $n\bar{p}$ experiments the E is observed mainly in experiments in which the n momentum was less than 4 GeV/c. The one case in which the E was observed in an experiment with high incident n momentum ref. [29], the measured mass of the E was anomalously low 1.40 GeV/c². The data for this experiment was taken with the CERN OMEGA spectrometer. There is no experimental evidence for an E in any K^+p experiment.

The best determination of the properties of the E meson comes from the last experiment listed in table 18, ref. [15]. In this experiment the E meson was seen in a high statistics (90 events/ub) $K\bar{K}n$ sample derived from the reaction $n^+p^- \rightarrow K\bar{K}nn$. The E meson appeared as a sharp spike in the raw $K\bar{K}n$ spectrum (see figure 69a). A tight K^* cut and a cut on $\theta(K^*)$ (θ^2 in the notation of this thesis) were used to enhance the E signal which resulted in the spectrum shown

TABLE 18

List of Experiments in which the E Meson could have been Observed

Experiment	Type, beam, p (GeV/c)	Year	E?	Experimenter	Reference
HBC	π^- 1.8-4.3	1965	Y	MILLER	30
HBC	$\bar{p}$ 1.2	1965	N	BLANDLAU	31
HBC	π^- 1.5-4.2	1967	Y	DAHL	32
HBC	$\bar{p}$ 0	1967	Y	BARASH	33
HBC	$\bar{p}$ 0	1967	Y	BAILLON	14
HBC	π^+ 8.0	1969	N	OTWINOWSKI	34
HBC	$\bar{p}$ 0	1969	Y	LORSTAD	35
HBC	π^- 16.0	1971	N	BOESBECK	36
HBC	π^- 13.4	1972	N	THUN	37
HBC	$\bar{p}$ 1.2	1972	Y	DUBOC	38
HBC	$\bar{p}$ 0.7	1972	?	DEFOIX	39
HBC	$\bar{p}$ 1.5	1976	Y	VUILLEMIN	40
HBC	π^- 16.0	1977	N	GRASSLER	41
CNTR	π^- 8.5	1978	N	STANTON	12
OMEG	π^- 12-15	1978	?	CORDEN	29
HBC	π^- 3.9	1980	Y	DIONISI	15

in figure 69b. This spectrum shows a narrow E signal with approximately 100 events in the peak. It is interesting to compare the corresponding uncorrected mass plot for this experiment. This is shown in figure 69c. Use of the tight K^* and angle cut does not produce a sharp peaking at low mass in the K^-p data.

Some features of the data of the two experiments are quite similar. In both experiments the K^*K channel dominates the $K\bar{K}\pi$ data at low mass. In the π^-p experiment a barely significant $\delta\pi$ signal was observed (14%±12% of the K^*K channel). The asymmetry between the K^* charged K^* neu-

$\bar{K}\bar{K}\pi$ spectra from experiment of Dionisi et al, ref. [15].

a)

b)

c) $\bar{K}\bar{K}\pi$ spectrum from this K^-p experiment with kinematic cuts used to produce plot (b).

Figure 69: Comparison of π^-p and K^-p $\bar{K}\bar{K}\pi$ Spectra

tral channels discussed in section 5.6 was also observed in the π^-p experiment. This can be seen in figure 70 which contains the $K\bar{K}\pi$ spectra and Dalitz plots for events with $K\bar{K}\pi$ mass close to the E meson. Unfortunately there is no information in ref. [15] on the division of events between the $\bar{K}^0K^+\pi^-$ channel and the $K^0K^-\pi^+$ channel. Thus the general features of the $K\bar{K}\pi$ sample in this K^-p experiment are similar to those found in the π^-p experiment of ref. [15]. The major difference between the experiments is the lack a narrow structure in the K^-p data.

Given the apparent suppression of E production at higher incident momenta in π^-p experiments, the lack of narrow structure in the 11 GeV/c K^-p experiment should not be interpreted as a conflict with previous experiments. In addition the absence of a sharp peak at the E mass in the K^-p data does not rule out the presence of the E meson within the data. The only way of observing the E and any other resonance present in the data, and separating them from non-resonant $K\bar{K}\pi$ events, is to use a partial wave analysis.

Figure 70: $K\pi$ Mass Spectra-Squared and Dalitz Plots for E Region from Ref. [15].

5.9 SUMMARY AND DISCUSSION OF THE RESULTS

This chapter has described the extraction of a $K\bar{K}\pi$ sample and the analysis of that data sample. In the analysis performed no evidence was found for any specific resonances although a number of aspects of the data point to the existence of underlying structure. In particular no evidence was found for an E meson. In this section the main features of the data are summarised and the steps necessary to extract further information from the $K\bar{K}\pi$ sample are discussed.

The $K\bar{K}\pi$ sample was a small fraction of the 40 million events taken in the K^+p experiment. The extraction of this data sample involved selection of a K^0 (short), by its decay to $\pi^+\pi^-$ and the selection of a charged kaon using the particle identification devices of the spectrometer. The recoil system opposite the $K\bar{K}\pi$ sample was not measured, but was fixed by a missing mass cut of 1.0 to 4.0 $(\text{GeV}/c^2)^2$. The sample contained 10,400 events with a sensitivity of 35 and 31 events/ub for the $\bar{K}^0 K^+ \pi^-$ and $K^0 K^- \pi^+$ channels respectively. The $K\bar{K}\pi$ mass spectrum was basically smooth except for a sharp increase in the number of events at the K^*K threshold at 1.4 GeV/c^2 . The spectrum was well populated to about 2.5 GeV/c^2 . Above 2 GeV/c^2 the number of events per mass bin showed a gradual decline due to the reduction in spectrometer acceptance.

The resolution and acceptance of the spectrometer were studied using a Monte Carlo program. For this program $K\bar{K}nB$ events were generated with characteristics similar to the data. The decay products of the Baryon recoil particle B were simulated in this reaction to study the selection of the $K\bar{K}n$ sample. The $K\bar{K}n$ mass resolution was found to be a function of the $K\bar{K}n$ mass. It varied from 20 MeV/c² at 1.4 GeV/c² to 50 MeV/c² at 2.4 GeV/c². The missing mass squared resolution was found to be 350 (MeV/c²)² for reactions of the type $K^-p \rightarrow E \Lambda$. The acceptance of the spectrometer was generally good particularly in the mass regions relevant to the production of the E meson.

Since no clear evidence was found for resonances in the data, it was important to understand and quantify the backgrounds to the $K\bar{K}n$ sample. There were two different types of background: one was due to the misidentification of the K^0 and K^+ , and the other was due to the inclusion of the proton from the baryon recoil in the $K\bar{K}n$ system. The size of the K^0 background was calculated from the 'wings' of the K^0 mass distribution. The charged kaon background was calculated using the measured efficiencies of the Čerenkov counters. The background due to the selection of a particle from the baryon recoil system was calculated using Monte Carlo events. The combined backgrounds were found to be 25% and 42% for the $\bar{K}^0 K^+ n^-$ and $K^0 K^- n^+$ channels respectively. The calculated $K\bar{K}n$ background spectra were reasonably smooth

and were found not to cause major distortions in the shape of the $K\bar{K}\pi$ data spectra. Thus the backgrounds were not masking any narrow structure in the data.

A wide variety of analysis techniques were employed to study the properties of the $K\bar{K}\pi$ system. These included examining the $K\bar{K}\pi$ spectra after two body mass cuts had been applied ($\delta\pi$, K^*), and producing Chew-Low and Dalitz plots from the data. These methods indicated that the K^*K decay mode was present in the data, but provided little evidence for structure that could be interpreted as resonant. In light of this, two slightly more sophisticated analysis techniques were used; a channel separation analysis, and an examination of the decay angular distributions of the data which included a moments analysis.

In the channel separation analysis the following 2-step decay processes were considered: $\delta\pi$, K^*K and K^*K^0 . The analysis was used to determine the proportion of events in phase space and in each of these channels. The results obtained were checked against the appearance of the Dalitz plots and the invariant masses of the two particle combinations. No evidence was found for the $\delta\pi$ channel, but there was a significant amount of the K^*K channel at all $K\bar{K}\pi$ masses. A plot of the K^*K channel strength versus $K\bar{K}\pi$ mass revealed a broad structure from about 1.4 to 1.6 GeV/c^2 . At high mass the $K\bar{K}\pi$ system was mainly phase space. One of the interesting features of the data was that the strengths of

the K^* charged, and K^* neutral channels were uneven in the $K^0 K^- \pi^+$ channel. One possible interpretation of this fact is that the unevenness is due to resonances producing interference effects. It is noted that the difference in strengths of the K^* charged and K^* neutral channels in the $K\bar{K}\pi$ system was also observed in a recent $\pi^- p$ experiment in which the E was observed, (ref. [15],)

As the channel separation analysis gave no evidence for the $\delta\pi$ channel, the angular decay system of only the $K^* K$ channel was studied. This study was done at first in a qualitative fashion, by examining distributions of the four angles that were used to define the decay process for both the Monte Carlo and data events as a function of $K\bar{K}\pi$ mass. The distributions for the Monte Carlo events revealed that the angular acceptance for the spectrometer was not uniform. This was caused mainly by the momentum cuts imposed on the charged kaons. In general the angular acceptance was good with only one hole in the acceptance in one of the angular distributions. A comparison of the angular distributions for the Monte Carlo and the data revealed that the main features of the distributions were quite similar. There was some evidence for differences in the highest mass bin considered (2.0 to 2.4 GeV/c²). To put the angular analysis on a quantitative footing, the spherical harmonic content or moments of the angular distributions was calculated. Significant moments were then plotted as a function of mass to enable a numerical comparison between the moments to be made. In the

low mass region ($<1.8 \text{ GeV}/c^2$) there was no significant difference between the Monte Carlo and data moments. This indicates that the K^* and the K could be in a relative S-state, which would mean that the $K\bar{K}\pi$ system had $J^P = 1^+$. In the upper two mass bins ($1.8 - 2.4 \text{ GeV}/c^2$) there was evidence for differences between the two sets of moments. This is interpreted as high moments being important at larger values of $K\bar{K}\pi$ mass. There was no evidence for a significant one-mass bin effect that could be interpreted as a narrow resonance.

The major reason for examining the $K\bar{K}\pi$ channel in this experiment was to look for evidence of the E meson. The characteristics of the data that are relevant to the E meson are summarized here. The raw $K\bar{K}\pi$ spectrum did not show the narrow structure that has been associated with the E , although a steep rise in the number of events at the K^*K threshold could be related to the presence of this meson. When the K^*K channel is selected by a $K\pi$ mass cut the $K\bar{K}\pi$ mass spectrum again shows no evidence for narrow structure. However when the $\delta\pi$ channel is selected a broad peak appears around 1.4 to $1.5 \text{ GeV}/c^2$. When the δ cut was simulated with Monte Carlo events, a broad peak also appeared at low $K\bar{K}\pi$ mass. There were slight differences between the details of these peaks that could be interpreted as evidence for the E meson. The channel separation analysis indicated that at the E meson mass there is a strong K^*K component to the data

which is the decay mode favoured for the E . The channel strengths for the charged and neutral K^* channels in the region of the E were uneven indicating the presence of interference effects involving resonances. The angular analysis indicated that in the E region the K^*K channel could be in a relative S-state. Thus the data is not inconsistent with a $JP=1^+$ object decaying to K^*K at the mass of the E . To summarize, at the current stage of the analysis there is no clear evidence for the narrow structure that has been associated with the E meson. On the other hand one cannot rule out the possibility of the E meson being present in the data along with non-resonant $K\bar{K}\pi$ events or one or more other resonances.

Given the current ambiguous result for the E meson, an important question is what could be done to resolve this ambiguity. As indicated in section 5.7 the best method at this point is to use a partial wave analysis technique. For this approach it is important to use a data sample that is as large as possible, consistent with keeping backgrounds to an acceptable level. Thus before performing the partial wave analysis it is necessary to redefine the $K\bar{K}\pi$ data sample making use of what has been learnt from the current one.

The redefinition of the $K\bar{K}\pi$ data sample would involve the following changes. All the data would be used rather than the sub-section (94%) used in the present analysis. The TOF hodoscope would be used to discriminate between π^+

and p at the $K^0 K^- \pi^+$ event selection stage rather than to form cuts on the final data sample. The momentum range for proton discrimination could also be raised above the current limit of 2 GeV/c. The effect of these changes would be to raise the $K^0 K^- \pi^+$ signal size and reduce the $K^0 K^- p \pi$ background. Another area for possible improvement is the use of a graded Čerenkov efficiency cut. In the current charged kaon identification package one set of C1 spatial cuts is used for all particles with momentum greater than 3.4 GeV/c. It would be possible to use different spatial cuts for particles in different momentum regions. By a judicious choice of such cuts it would be possible to lower the momentum cut and increase the number of particles identifiable without greatly increasing the background. Lowering the momentum cut would not only increase the number of events but also reduce the size of the hole in the $\cos\theta^*$ angular distribution. Finally the cuts to remove $K\pi p$ and $K\pi p \pi^0$ events were too severe in the current data selection. They would be relaxed as far as possible.

More Monte Carlo events would be necessary to calculate the acceptance moments for the spectrometer. The current Monte Carlo sample has about twice the statistics of the data. To prevent the FWA results being dependent on the statistical errors of the acceptance moments, one needs about ten times more Monte Carlo events than data events. The moments program itself is in the process of being readied for a combined channel separation and moments analysis.

This involves a procedure in which the moments calculation and the channel extraction are done sequentially and iteratively and the calculated moments are used in the channel extraction. (See ref. [15].) Given both the moments of the revised data and the acceptance moments of the extended Monte Carlo, one is then ready to proceed with the partial wave analysis.

Chapter VI

SUMMARY AND CONCLUSION

Evidence for the E meson was first obtained in 1965. In the past sixteen years large numbers of well established resonant states have been added to the Meson and Baryon spectra. However, many of the original puzzles associated with the E meson are still unsolved. A recent addition to the uncertain status of the E is the possibility that some of the E like states are actually glueballs. That a narrow state at $1.42 \text{ GeV}/c^2$ exists in np production experiments is indisputable in the light of the recent experiment by Dionisi et Al. Whether this state is the same object as seen in pp collisions or in the radiative decay of the $\bar{X}$ is unclear. Whether such a state occurs at all in K^-p reactions is still an open question.

In this thesis production of the E in an $11 \text{ GeV}/c$ K^-p experiment was investigated. No clear evidence was found for such a state. This can be interpreted in one of two ways: either the E meson is not produced in K^-p reactions at $11 \text{ GeV}/c$, or the presence of the E is masked by non-resonant backgrounds. A partial wave analysis would be required to decide between these possibilities.

Although no firm evidence was found for the E meson there were a number of intriguing aspects to the data. There was a steep rise in the number of events in the $K\bar{K}\pi$ mass spectrum at K^*K threshold and a channel separation analysis confirmed that there was indeed a large component of the 2-body decay channel K^*K at low ($<1.65 \text{ GeV}/c^2$) $K\bar{K}\pi$ mass. At high $K\bar{K}\pi$ masses the K^*K component was smaller and the $K\bar{K}\pi$ system was mainly 3-body phase space. There was no evidence for the $\delta\pi$ 2-body decay channel at any $K\bar{K}\pi$ mass. The proportion of $K^{*+}K^-$ and $K^{*0}K^0$ channels was found to be uneven which could be explained as interference between resonances, or interference between a resonance and non resonant $K\bar{K}\pi$ events.

Attempts to produce a narrow E -like structure by using channel and angle cuts were unsuccessful. A broad structure close to the E meson mass was produced when a $\delta\pi$ channel cut was made. When the same cuts were applied to a sample of events generated by the Monte Carlo program, a similar structure resulted. This indicated that the effect was to a large extent due to a kinematic enhancement.

A study was made of the angular decay properties of the K^*K system by examining distributions of the four angles that were defined to represent the decay process. A comparison was made between distributions of these angles for data and Monte Carlo events. These studies were put on a quantitative footing by the calculation of the spherical harmonic

content or moments of the distributions. The conclusions from these studies was that there was no significant difference in the angular distributions between the Monte Carlo and the data below a $K\bar{K}\pi$ mass of $1.8 \text{ GeV}/c^2$. This is consistent with the K^*K system being in a relative S-state at low mass, or the $K\bar{K}\pi$ system having $J^P=1^+$. At higher masses significant divergences were observed between some of the data and Monte Carlo moments. This is indicative of higher angular momentum states existing in the data at high mass.

To summarise the results of this experiment; no evidence was found for the narrow structure associated with the E meson, however the data was not inconsistent with the presence of the E meson plus either other resonances or a sizable non resonant $K\bar{K}\pi$ continuum. From the channel separation analysis there was evidence for a broad region (1.4 to $1.6 \text{ GeV}/c^2$) which was dominated by K^*K . In this region the angular properties of the K^*K system was consistent with the $K\bar{K}\pi$ system having $J^P=1^+$. In addition the observation of differences in the strengths of the charged and neutral K^* channels was indicative of interference effects involving resonances. To understand the broad structure in the $K\bar{K}\pi$ sample and to determine if it does contain the E meson a Partial Wave Analysis would be necessary. Given the wide mass range of the available data sample, this technique also has the potential for extracting resonances at higher $K\bar{K}\pi$ mass.

LIST OF REFERENCES

1. L.S. Durkin, Ph.D. Thesis, Stanford University, (1980)
(SLAC-REPORT-238)
A.K. Honma, Ph.D. Thesis, Stanford University, (1980)
(SLAC-REPORT-235)
2. M. Breidenbach et al., Phys. Rev. Lett. 23, 935 (1969)
G. Miller et al., Phys. Rev. D5, 528 (1972)
3. For the results of a recent quark search experiment,
plus references on the subject see:- J.M. Weiss et al.,
Phys. Lett. 101B(6), 439 (1981)
4. H. Krassman, TH-3036-CERN(1981)
W. Buchmuller et al., FERMILAB-Conf-81/38-THY
5. A. Martin, TH-2980-CERN(1980)
6. I. Bars et al., Phys. Lett. 101B(3), 159(1981)
7. D. Aston et al., Phys. Lett. 99B(6), 502 (1981)
8. S.W. Brandenburg et al., Phys. Lett. 60B(5), 478 (1976)
9. P. Estabrooks et al., Nucl. Phys. B133, 490 (1978)
10. R.K. Carnegie et al., Phys. Lett. 68B(3), 287 (1977)
11. S.W. Brandenburg et al., Phys. Rev. Lett. 36 1239
(1976)
12. N.R. Stanton et al., Phys. Rev. Lett. 42 346 (1979)
13. R.L. Kelly et al., Particle Data Group, Rev. Mod. Phys.
Vol. 52, No.2 (1980)
14. For example: P. Baillon et al., Il. Nuo. Cim. 50A 393
(1967)
15. C. Dionisi et al., Nucl. Phys. B169 1 (1980)
16. D.L. Sharre et al., SLAC PUB 2514 (To be published in
Phys. Rev. Lett.)
17. R.J. Cashmore, Lectures from 16th International school
of Elementary Particle Physics, KUPARI (1980).

18. P. Estabrooks, Phys. Rev. D19 2678 (1979)
19. N.M. Casson et al., Phys. Rev. Lett. 36, 1485 (1976)
R. Baldi et al., Nucl. Phys. B134, 365 (1978)
A.D. Martin et al., Phys. Lett. 74B 417 (1978)
20. K. Ishikawa, DESY REPORT 80/113 (1980)
21. C.L. Woody, Ph.D Thesis, The Johns Hopkins University (1978)
22. F.G. Oakham, M.Sc. Thesis, Carleton University (1977)
23. S.H. Williams, N.I.M. 105 483 (1972)
24. J. Va'vra et al., N.I.M., 163 415 (1979)
25. P.F. Kunz, SLAC-PUB 1723 (1976)
26. For descriptions of the Runge-Kutta method see
A. Ralston, A First course in Numerical Analysis (McGraw-Hill), N.Y., (1965), p191
G. Dahlquist and A. Bjorck, Numerical Methods (Prentice-Hall), N.J., (1974), p 346
27. S.U Chung, Spin Formalisms CERN Lectures 71-8 (1971) p 31
28. B. Franek, The Extraction of Quasi Two body Processes for 3 body final state. RL77-069 (1977)
29. M.J. Corden et al., Nucl. Phys. B144 253 (1978)
30. D.H. Miller et al., Phys. Rev. Lett. 14(26) (1965)
31. Ch. D'Andlau et al., Phys. Lett. 17(3) 347 (1965)
32. O.L. Dahl et al., Phys. Rev. 163(5) 1377 (1967)
33. N. Barash et al., Phys. Rev. 156(5) 1399 (1967)
34. S. Otwinowski et al., Phys. Lett. 29B(8) 529 (1969)
35. R. Lorstad et al., Nucl. Phys. B14 63 (1969)
36. K. Boesbeck et al., Phys. Lett. 34B(7) 659 (1971)
37. R. Thun et al., Phys. Rev. Lett. 28(26) 1733 (1972)
38. J. Duboc et al., Nucl. Phys. B46 429 (1972)
39. C. Defoix et al., Nucl. Phys. B44 125 (1972)

40. V. Vuillemin et al., Il. Nuo. Cim. 33A 133 (1976)
41. H. Grassler et al., Nucl. Phys. B121 189 (1977)

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