A STUDY OF
THE NEUTRAL MESON SPECTRUM
NEAR 1000MeV

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Ph.D. Thesis submitted to Iowa State University

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A study of the neutral meson spectrum near 1000 MeV

by

Ramon Joe Leeper

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A study of the neutral meson spectrum near 1000 MeV

Ramon Joe Leeper

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The non-strange neutral meson spectrum from 0.75 to 1.23 GeV/c has been studied in the reaction negative pion plus proton goes to neutron plus missing mass at incident beam momenta of 1.98 and 2.41 GeV/c. Neutrons produced by beam interactions in the liquid hydrogen target were detected in the near forward direction in an array of plastic scintillation counters. The missing mass of the remaining particles produced in the final state was determined by a measurement of the neutron time-of-flight. In the case of genuine two-body processes, $\pi^- p \rightarrow n + \text{meson}$, the observed neutron corresponded to mesons produced forward in the center of mass system. Forward going secondary charge particles produced in the hydrogen target were detected and momentum analyzed by the Argonne Effective Mass Spectrometer. This allowed the isolation of several constrained final states. Arrays of scintillation detectors surrounding the target gave charged particle information and enabled the data to be differentiated into various topological subsamples. The well-established ω^0 meson was detected. In addition, a sharp break in the $\pi^+ \pi^- n$ mass spectrum and

a rapid rise of the K^+K^-n spectrum just above threshold was observed. Both of these effects were associated with the S^* meson. Finally, the absence of four previously observed narrow mesons is discussed.

SECTION I. INTRODUCTION

In recent years the area of meson spectroscopy has been of considerable importance in the study of strong interactions. A careful analysis of mesons produced by high-energy collisions indicate that there exists a series of excited states of the low mass mesons, i.e. the π , K, and η mesons.¹ These excited states or resonances are referred to by various letters: ρ meson, ω meson, and so on, of which the π , K, and η mesons are the ground state levels. These quantum states are directly analogous to the quantum energy level excitations of the atom and nucleus. In fact the meson spectrum along with the complementary baryon spectrum have been referred to by Weisskopf² as the third spectroscopy. The states of the third spectroscopy form a level spectrum in which excitation energies are measured in billions of electron volts, not in millions of electron volts as in nuclei, or in electron volts as in atoms. This level spectrum shows regularities similar to those of the other spectra, and the same quantum numbers appear, plus a new one introduced by Gell-Mann³ and independently by Nakato and Nishijima,⁴ the hypercharge or strangeness. Also just as in the case of atoms and nuclei, transitions between the levels occur with the emission or absorption of light quanta and lepton pairs. But in addition a new form of energy exchange was found: the absorption and emission of mesons. As Weisskopf points² out, the existence of this third spectroscopy strongly indicates that baryons and mesons have an internal structure in the same sense that atoms and nuclei have an internal structure. Hopefully, as progress is

made in the third spectroscopy, new insights will be obtained into the meaning of commonly used concepts such as particle, field, mass, interaction, and charge.

The presently known baryon and meson spectra exhibit certain regularities which allows them to be classified by certain irreducible representations or multiplets of the special unitary group of order 3, denoted $SU(3)$.^{5,6} The multiplets of $SU(3)$ can in turn be generated from two fundamental multiplets which contain three members each.⁷ The members of one of these two triplets are identified with three particles with half-integer spin called the u , d , and s type quarks while the second triplet's members are identified with $\bar{u}$, $\bar{d}$, and $\bar{s}$ antiquarks. In terms of this model, baryons are considered to be a bound state of three quarks, while mesons are considered to be a bound quark-antiquark pair. Mesons in this model are then the quantum states of a quark-antiquark system in direct analogy to positronium, which is an electron-positron system. A bound quark-antiquark pair can be created by, and annihilated into, other forms of energy. Hence this model is a suitable picture for a meson which is absorbed or emitted in transitions between excited states of the baryons.

Although many experimental observations can be explained by assuming the existence of, quarks, a fundamental understanding of why the theory works so well is lacking. Furthermore, quarks have never been observed even in nucleon collisions of the highest available energy.

This thesis is concerned with an experimental investigation of the meson spectrum in the mass region 0.75 to 1.23 GeV. Recent reviews of our present experimental knowledge of the meson resonances may be found in several conference proceedings.^{8,9,10} For the most part, our understanding of the meson spectrum is fragmentary and, in some cases, confused. For example, in the 1.00 GeV region alone, some seven or eight narrow resonances have been suggested and all are in need of confirmation (see table 3 of Ref.⁸).

To carry out our investigation we studied neutral, nonstrange meson production in the reaction $\pi^- p \rightarrow X^0 n$ where X^0 is a meson resonance. Final state neutrons and the charged particles from the decay of the X^0 were detected. The momentum of the neutron was measured by using the time-of-flight technique in conjunction with a bank of thirty scintillation counters. Charged secondary particles were detected and momentum analyzed by the Argonne Effective Mass Spectrometer. The neutrons were detected near 0° in the laboratory and for two-body processes the events corresponded to forward meson production.

The knowledge of the momentum of the neutron and the momentum of the incident π^- allowed the mass of the X^0 to be determined from conservation of energy and momentum. Also the knowledge of the momentum of the charged secondaries made it possible to select various decay channels of the X^0 . These decay channels will be discussed later in Section III.

The primary emphasis of the experiment was to confirm or disprove the existence of four previously reported meson resonances,^{11,12,13} the

$M^0(940)$, $\delta^0(963)$, $M^0(1030)$, and the $M^0(1150)$. In order to accomplish this goal, the present experiment accumulated approximately an order of magnitude more data than the original experiment. An additional goal of the experiment was to make a high statistics study of the previously reported^{1,14,15,16,17} $S^*(993)$ meson in both the $\pi^+\pi^-n$ and K^+K^-n decay channels.

Data reported in this thesis were taken at two different incident π^- momenta, namely 1.98 and 2.41 GeV/c. The 1.98 GeV/c data spanned the missing mass region from approximately 0.750 to 1.080 GeV. The 2.41 GeV/c data spanned the missing mass region from approximately 0.840 to 1.230 GeV.

In Section II the experimental apparatus and the online data acquisition system are described. In Section III the details of how the data were analyzed is presented. This section also presents discussions of the kinematics of the reaction $\pi^-p \rightarrow X^0n$, the offline program, the kinematic constraints, the vertexing of tracks and the geometric acceptance of the apparatus. The major results of the experiment are given in Section IV. These results consist mainly of mass spectra for various constrained final states. In addition, the position of the pole associated with the S^* meson is extracted from an analysis of the $\pi^+\pi^-n$ and K^+K^-n mass spectra.

SECTION II. APPARATUS

In this section a detailed discussion of the experimental apparatus will be presented. This will include a discussion of the secondary beam, the Argonne Effective Mass Spectrometer, the neutron counters, various other counters and tags, the trigger scheme, and the shielding used to reduce the number of background neutrons. In addition, the data collection and online data analysis system will be explained. But before proceeding to this discussion of the apparatus, a short chronology of the experiment will be given.

The amount of time needed to execute the experiment reported in this thesis was extensive. From January, 1972 to July, 1972 Monte Carlo studies were performed to determine the experiment's feasibility. In July, 1972 a proposal¹⁸ written by M. T. Buttram, H. B. Crawley, R. C. Lamb, R. J. Leeper, and F. C. Peterson, Iowa State University, and S. L. Kramer, Argonne National Laboratory, was submitted to the Zero Gradient Synchrotron (ZGS) programming committee at Argonne National Laboratory. After the programming committee approved the experiment in late August, 1972 work towards getting the required experimental equipment designed and built was begun. The equipment was completed in June, 1973 at which point it was transported to Argonne.

During the months of June, July, and August, 1973, the equipment and the required fast digital electronics were setup, tested, and integrated with the Argonne Effective Mass Spectrometer. An online data acquisition system was also completed and debugged during this time.

Beam was delivered to the experiment in late August for two weeks for initial testing and tuning of the equipment. During a two-week period in late September, 1973 a data taking run was performed. From October, 1973 until March, 1974 an offline data analysis program was developed and debugged. This offline system was then used to analyze the data taken the previous September along with part of the data taken the previous August.

During the months of March and April, 1974 we took data almost continuously and generated some three hundred magnetic computer tapes. These tapes were then analyzed using the offline system during the period May, 1974, to May, 1975.

Beam

The apparatus was located in an unseparated beam which for negative momenta consisted mainly of pions. The details of the beam floor plan are shown in Figure 1. Protons of 12.33 GeV/c momentum were extracted from the main accelerator ring of the ZGS Synchrotron into External Proton Beam 1 and then brought to a focus on a 0.64 cm x 0.64 cm x 10.2 cm long copper production target. Pions, kaons, and anti-proton produced at this target were then incident on a series of collimators (denoted by Ω Col., ϕ Col., and θ Col. in Fig. 1) which restricted the production angles of the accepted particles to be centered at 4.25° with respect to the proton beam line. The ϕ and θ collimators were variable and could be used to adjust the beam intensity.

The first stage of the beam consisted of a pair of quadrupole magnets, Q1 and Q2, and a pair of bending magnets, B1 and B2, which

Figure 1. Floor plan of the pion beam.

brought the beam to its first focus at the six element momentum hodoscope, labelled p in Fig. 1. This hodoscope tagged the individual particle momenta to $\pm 0.25\%$.¹⁹ The total momentum spread of the beam was $\pm 1.5\%$.

The second stage of the beam consisted of a pair of bending magnets, B3 and B4, and four quadrupole magnets, Q3 - Q6. This stage was designed to recombine momenta at the final focus which was located at the center of the 38.1 cm long liquid hydrogen target. The spot size of the final focus was approximately circular with a diameter of about 2.54 cm. The position and angles of incident beam particles for events of interest were measured to better than ± 1 mr by three K0 spark chambers upstream of the hydrogen target.

A beam signature consisted of the coincidence between the three beam defining counters, labelled S1-2 and B in Fig. 1, the momentum hodoscope P, and six beam defining anticoincidence counters, labelled A1-5 and VI. Symbolically this beam signature may be written $P \cdot S1 \cdot S2 \cdot B \cdot \overline{A1-5} \cdot \overline{VI}$ where the dot indicates a coincidence requirement and the superscripted bar indicates the logical complement. Two ethylene-gas threshold Cerenkov counters labelled C2 and C4 in Fig. 1 provided tagging information to label incident beam particles as pions. The two Cerenkov counters labelled C1 and C3 were at atmospheric pressure and were not used in the present experiment.

Beam composition varied with momentum, but a typical $\pi^-/K^-/\bar{p}$ ratio was 127/1/0.5 for the range of momenta used in the present experiment as measured by D. S. Ayres.²⁰ The incident pion beam was corrected for

μ -e contamination since the beam Cerenkov counters could not distinguish π 's from μ 's and e's. This correction amounted to approximately 4% of the pion flux in the case of e's. This correction amounted to approximately 2% of the pion flux in the case of μ^- 's.²⁰

The total incident particle flux was typically kept in the range from 2.5×10^5 to 3.5×10^5 per 700 msec beam spill of the ZGS. This was done in an attempt to assure the equality of accidental coincidences and other rate effects.

Spectrometer

Fig. 2 shows a plan view of the Argonne Effective Mass Spectrometer,¹⁹ the basic component of which was a large dipole magnet, with an aperture 2 m wide by 0.66 m high. The magnet had a central field of 11.4 KG, and effective length of 1 m, and an $\int \vec{B} \cdot d\vec{l}$ which was constant to about 20% over the aperture. The vertical and horizontal components of the field were measured over an 84000-point grid and the fitted results, as described by a 2800 parameter field-generating computer program, were accurate to 0.9% of the central value.

The five sets of wire spark chambers K1 through K5 measured the angles and momenta of forward going secondary charge particles produced in the hydrogen target. The readout of the wire chambers was provided by 40 magnetostrictive lines with electronics which could record up to six sparks per readout for the chamber sets K1 and K2, and up to four sparks per readout for the chamber sets K0, K3, K4, and K5. Each chamber was constructed from two foils 1 cm apart, each consisting of

Figure 2. Plan view of the apparatus.

25 μ flattened aluminum wires epoxied to 75 μ Mylar sheets with 15 μ aluminum foil backing. Wire spacing ranges from 1.2 mm (K0, K4) to 0.6 mm (K1, K2, K3), giving a total of 60000 wires; the density of a typical chamber is 0.07 gm/cm² (0.002 radiation lengths). The six K5 chambers are divided into two overlapping sets of three, so that the total area matches the spectrometer acceptance. The active areas of all the chambers are presented in Table I.

The K0, K4 and K5 spark chambers each had planes of horizontal and vertical wires. The K1 and K2 chambers both had a plane of vertical wires and planes of wires at ± 30 degrees to the vertical. These non-orthogonal planes were used to resolve ambiguities in multiple track events. The K3 chamber had only a plane of vertical wires which were extended outside the magnet enabling the readout to be located in a low field region. The spatial resolution of the chambers was approximately ± 0.5 mm.

A gas mixture composed of approximately 89% neon, 10% helium, and 1% ethanol was circulated through the chambers and through a purifier at about 30 ft³ per hour. The ethanol concentration was kept constant by bubbling the gas through liquid alcohol at - 5°C and 2 psig, and monitored with a gas chromatograph which was also sensitive to air contamination to the level of a few ppm. A 50 V dc clearing field was applied to all chambers except K3 where an 80 V dc field was applied. With these clearing fields and the above gas mixture the chambers had a sensitive time of about 710 nsec. High voltage pulses of 7.5 kV amplitude were applied to chambers K0, K1, K2, K3, and K4 while chamber K5

Table 1. Nominal active areas of the spark chambers.

Spark Chamber	Nominal Active Area
K0	8" x 16"
K1	15" x 36"
K2	21" x 48"
K3	21" x 79.5"
K4	30" x 78"
K5	46.5" x 176"

had 6.5 kV pulses applied. These pulses had a full-width half maximum of 60 nsec and were applied by thyratrons, which discharged storage capacitors across the chambers about 470 nsec after an event of interest had occurred. The high voltage pulse was followed by a pulsed clearing field of 170 V and 6 msec duration. The resulting dead time was approximately 20 msec. The single-track efficiencies are estimated to be about 96% for this experiment.

Neutron Counters

Neutrons produced in the target and arriving in the appropriate time interval subsequent to an interacted beam particle were detected 5.30 m downstream by an array of thirty neutron counters, labelled N in Fig. 2. This time interval corresponded to neutrons whose speeds were within the interval $0.17c$ to $0.42c$. A fuller description of this time interval will be given in the kinematic subsection of Section III of this thesis. The array was centered on the beam line as shown in Fig. 3a and subtended angles up to 12.50° . The total solid angle subtended by the neutron counter array was 0.098 sr.

Each of the neutron counters consisted of a 30 cm x 30 cm x 15 cm deep block of plastic scintillator, viewed from the downstream end by an Amperex 58 AVP 5" diameter photomultiplier tube. For each counter the threshold amplitude was determined by a 100 mV threshold discriminator whose input signal was the next-to-last dynode of the 58 AVP photomultiplier. The arrival time of the output pulse of each counter was determined by a 200 mV threshold discriminator whose input signal was the anode of the photomultiplier. This method, which is convention-

TI COUNTER ARRAY

Figure 3. The neutron and TI counter arrays.
 (a) End view of neutron counter array looking downstream.
 (b) End view of TI counter array looking downstream.

ally called the high-low technique, enables accurate timing as well as precise threshold discrimination to be achieved.

As described in R. W. Jacobel's thesis,²¹ the efficiency of the neutron counters is dependent on the threshold level. In the present experiment, the high voltages of the photomultipliers were set and maintained so that the 2.75 MeV gamma ray from a Na²⁴ source gave a maximum pulse height from the Compton spectrum of approximately 200 mV on the dynode output. Variable attenuations in the dynode signals were then adjusted so that the thresholds on the discriminators corresponded to 3.5 MeV electron equivalent energy. For a 3.5 MeV threshold, neutron detection efficiencies ranged from 16% to 18% depending on neutron kinetic energy.²¹

The thirty neutron anode signals were timed with respect to each other to an accuracy of ± 0.2 nsec using interacted beam particles. With this system, the time of flight spectrum for charged particles and gamma rays in the beam showed a peak at $\beta = 1$ of 1.40 nsec full width at half maximum (FWHM) for all 30 detectors.

Slow neutral particles detected by the neutron counters were assumed to be neutrons although slow neutral kaons could be present. These neutral kaons do not present a problem since it is known that the flux of slow K⁰L's is less than one percent of the neutron flux and is therefore negligible. It should also be noted that gamma rays from beam interactions in the target may be eliminated by virtue of their velocity.

Decay and Trigger Counters

Surrounding the hydrogen target in the form of a box was a forty-one element scintillation counter hodoscope which detected charged particles and gamma rays produced in an interaction. In Fig. 2 these counters are denoted by T1 and H. The hodoscope T1 is constructed from eleven counters which are arranged as shown in Fig. 3b and whose sizes are given in Table II. The element of T1 which is located at the center of the hodoscope and labelled #10 in Fig. 3b is a so-called double pulse height counter (DPH). The threshold of the discriminator associated with this counter was set at a level that corresponded to approximately 1.5 times the most probable pulse height due to one minimum ionizing particle. In this way the double pulse height counter could then be used to select those events which had two charged particles simultaneously passing through the counter. The T1 hodoscope was also used in triggering the apparatus.

The hodoscope H is made of two subunits, one of which is constructed of sixteen elements and detects wide angle charged particles. The second subunit, located to the outside of the first, is a fourteen element hodoscope. It was used to detect electron showers due to the conversion of gamma rays in two radiation lengths of lead positioned between the two subunits. The sizes of all counters which constituted hodoscope H are given in Table III.

The hodoscopes T1 and H provide a measurement of the approximate direction and multiplicity of charged particles originating in the hydrogen target. It was then possible to differentiate events into

Table II. T1 counter sizes.

# of Counters of T1 this size	Counter Size (Width x Length x Thickness)
2	5 1/2" x 12" x 1/8"
2	3" x 12" x 1/8"
2	2" x 12" x 1/8"
2	1 1/2" x 12" x 1/8"
2	3" x 4 1/2" x 1/8"
1	3" x 3" x 1/16"

Table III. H counter sizes

# of Counters of H this size	Counter Size (Width x Length x Thickness)
8	8" x 20" x 1/8"
8	6" x 20" x 1/8"
8	4" x 20" x 1/8"
4	3" x 20" x 1/8"
2	13 9/32" x 11 15/16" x 1/2" with 2 1/8" radius cutout

various topological subsamples. This in turn allowed near duplication of of two previous experiments performed in the 1 GeV mass region which were designed to search for narrow mesons.^{11,12,13,22,23}

A forty element hodoscope located at the spectrometer magnet exit and labelled by T2 in Fig. 2 was used to trigger the apparatus. The counters of this hodoscope were made of 3-mm thick scintillator and were arranged in rows of twenty 10-cm wide counters above and below the mid-plane.

Other Counters and Tags

In addition to the detectors discussed thus far, there were several other sets of counters used in the experiment. Triggers from non-interacting beam particles were eliminated by a 7-cm square beam veto counter labelled as V_2 in Fig. 2. Eight large veto counters that lined the magnet aperture allowed the possibility of suppressing events with extra charge particles. These counters, however, were not used in the analysis presented in this thesis. An eleven element hodoscope located immediately upstream of the neutron counters and labelled by V_3 in Fig. 1 was used to veto charged particles. This hodoscope completely covered the bank of thirty neutron counters.

Trigger Scheme

Two different methods of triggering the apparatus were used during the course of the experiment. The first trigger was the so called "3-Fold" trigger whose purpose was to trigger the apparatus at a low overall rate on events which had one charged secondary particle going

forward all the way through the spectrometer and a second charged particle either going forward or going wide into the hodoscope H. The second trigger was the "2-Fold" trigger which was designed to select those events, again at a low overall rate, with two charged particles forward. The reason for wanting to select events of these two particular topologies will be further explained in Section III on data reduction and event selection.

Specifically, the 3-Fold trigger was a requirement of: (1) an incident beam particle, at least one particle in any counter of T1 except the double height counter located at the center of the array (mentioned earlier), at least one particle in T2 following the magnet, and one and only one neutron counter signal, or (2) an incident beam particle, at least one particle in the double pulse counter of T1, at least one particle in T2, at least one particle in the inner subsection of H, and one and only one neutron counter signal, or (3) an incident beam particle, at least two particles in the double pulse counter of T1, at least one particle in T2, and one and only one neutron counter signal. A potential event was vetoed if any particle was detected in the beam halo counter V_1 , the unreacted beam veto counter V_2 , or that element of the charged particle veto hodoscope V_3 covering the counter which detected the neutron. Symbolically this trigger may be summarized as:

$$(1) \quad IBM \cdot IT1 \text{ (except DPH)} \cdot IT2 \cdot IN$$

or

$$(2) \quad IBM \cdot 1DPH \cdot 1H \cdot 1T2 \cdot 1N$$

or

$$(3) \quad IBM \cdot 2DPH \cdot 1T2 \cdot 1N$$

where BM is an incident beam particle and DPH is the double pulse height counter of the Hodoscope T1.

The 2-Fold trigger was a requirement of: (1) an incident beam particle, at least one particle in any counter of T1 except the double pulse height counter, no particles in H, at least one particle in T2, and one and only one neutron counter signal or (2) an incident beam particle, at least 2 particles in the double pulse height counter, at least one particle in T2, no particles in H, and one and only one neutron counter signal. Once again a potential event was vetoed if any particle was detected in V_1 , V_2 , or that portion of V_3 covering the neutron counter which detected the neutron. Summarizing this trigger symbolically we have:

$$(1) \quad IBM \cdot 1T1 \text{ (except DPH)} \cdot \bar{H} \cdot 1T2 \cdot 1N$$

$$(2) \quad IBM \cdot 2DPH \cdot \bar{H} \cdot 1T2 \cdot 1N$$

A simplified block diagram of the electronic fast logic used to implement the two triggers is given in Appendix I. This appendix also includes a discussion of the neutron time-of-flight logic as well as the methods used to calibrate the time scale.

Shielding

To reduce the number of accidental events due to spurious neutron signals, large amounts of concrete were placed around the apparatus.

This shielding acted to absorb much of the low energy component of background room neutrons and thermalize higher energy room neutrons. In addition, a borax enclosure was built around the neutron counters themselves. Boron, a constituent of borax, has a 759 barn total thermal neutron absorption cross section. The absorption length for this process is 1.3 mm. In the present case, approximately 10 absorption lengths of borax were used in the enclosure and consequently virtually all of the thermal neutrons surviving the concrete were eliminated.

But even with the above shielding, problems with spurious neutron triggers were still experienced. These accidental events are probably due to residual background neutrons and gamma rays produced by secondary interactions of the original reaction products from the hydrogen in the decay counters, walls, etc. It should also be understood that these spurious events can easily be eliminated by the use of kinematic constraints.

Data Collection and On-Line Analysis

The spectrometer was on line to an EMR-6050 computer whose primary function was to collect the data from up to 17 triggers per ZGS pulse and to store the results on magnetic tape during the 3.5 seconds between beam bursts. The raw data were supplied to the computer through the Science Accessories Corporation's Multiple Input Data Acquisition's System (MIDAS). The data consisted of: (1) the contents of six scalers for each of 12 spark chamber readouts and the contents of four scalers for each of 28 spark chamber readouts (2) tag bits indicating which scintillation counters had fired for each event, including the momentum

hodoscope, the beam veto counters, the 40 counters of hodoscope H, the 11 counters of hodoscope T1, the 40 counters of hodoscope T2, the 11 counters of hodoscope V₃, and the 30 neutron counters, (3) tag bits indicating beam particle identity (4) a bit indicating the passage of an extra beam track through the apparatus in the time between the interaction and the spark chamber firing and (5) 12 bits of neutron time-of-flight information. For each event, two-hundred and four 24-bit words were written on magnetic tape.

The computer had 32K of 24-bit word memory, 1.9 μ sec cycle time, floating-point hardware, priority interrupts, an oscilloscope display, two fast tape drives, and other peripherals. In the time between beam pulses, it completely analyzed approximately 35% of the events, monitored spark chamber efficiencies and scintillation counter rates provided an oscilloscope display of the geometrical reconstruction of events and histograms of results, and warned the experimenters of possible spark chamber malfunctions. The powerful diagnostic tool provided by the online computer system²⁴ allowed the experiment to be tuned and debugged quickly, helped maintain a consistently high level of hardware performance during the data taking and made feasible the online study of possible systematic effects.

SECTION III. DATA REDUCTION

The analysis of the 1.98 and 2.41 GeV/c data was performed on an IBM 370/195 computer at Argonne National Laboratory. The data correspond to a total flux of 45.3×10^9 pions incident on the hydrogen target: 8.2×10^9 3-fold triggers at a beam momentum of 1.98 GeV/c, 22.7×10^4 3-fold triggers and 14.4×10^9 2-fold triggers at 2.4 GeV/c. In this section a detailed discussion of the data analysis will be given. This will include a discussion of the off-line data analysis program, the methods used to select events of various constrained final states, the algorithm used to vertex tracks, and the geometric acceptance of the apparatus. But before this detailed description of the analysis system is given, several topics need to be presented which provide essential background. The first of these is the kinematics of the reaction $\pi^- p \rightarrow X^0 n$.

Kinematics

Let us use the symbols M , E , $\vec{p}$, T , and $\beta = v/c$, with an appropriate subscript to denote the mass, total energy, momentum, kinetic energy, and velocity of a particle or combinations of particles. All of these variables are taken to be in the laboratory frame of reference unless indicated otherwise. Applying energy and momentum conservation to the reaction $\pi^- p \rightarrow X^0 n$ we have

$$(MM)^2 = M_{\pi^-}^2 + M_p^2 + M_n^2 + (E_{\pi^-} M_p - E_{\pi^-} E_n - M_p E_n + |\vec{p}_{\pi^-}| |\vec{p}_n| \cos \theta_n) \quad (1)$$

Here MM is the mass of the X^0 and θ_n is the polar angle of the neutron to the beam. The dependence of MM on the three independent variables $|\vec{p}_{\pi^-}|$,

$|\vec{p}_n|$, and θ_n is given by

$$(MM) \frac{\partial(MM)}{\partial |\vec{p}_{\pi^-}|} = |\vec{p}_n| \cos \theta_n - \beta_{\pi^-} (E_n - M_p), \quad (2)$$

$$(MM) \frac{\partial(MM)}{\partial |\vec{p}_n|} = (E_{\pi^-} + M_p) (\beta_c \cos \theta_n - \beta_n), \quad (3)$$

$$(MM) \frac{\partial(MM)}{\partial \theta_n} = - |\vec{p}_{\pi^-}| |\vec{p}_n| \sin \theta_n. \quad (4)$$

β_c is the velocity of the center of mass of the π^- incident on the proton. All mass spectra presented in this thesis are plotted as a function of MM.

In general a high-resolution measurement of MM requires accurate knowledge of $|\vec{p}_{\pi^-}|$, $|\vec{p}_n|$, and θ_n , however certain kinematic regions can be chosen in such a way that one or more of the differential coefficients in (2) are close to zero, thus reducing the required precision of the relevant variables.

In the present experiment the neutron counters were placed near zero degrees with respect to the incident beam direction. This was done for two reasons. First, we desired to duplicate as closely as possible the previous experiment which reported narrow mesons.^{11,12,13} In this experiment the neutron counters were located near zero degrees. Second, the geometric constraints imposed by the layout of the Argonne Effective Mass Spectrometer required the neutron counters to be placed near zero degrees. Neutrons produced at large angles in the hydrogen target pass through the steel of the pole pieces of the spectrometer's magnet. Since the neutrons

are near zero degrees, then by equation (4) $\frac{\partial(MM)}{\partial \theta_n}$ will be nearly zero. Consequently a high-resolution measurement of MM under these kinematic conditions requires only an accurate measurement of the magnitude of the beam and neutron momenta, with only a relatively coarse measurement of the neutron angle. This so-called zero degree region is complementary to the Jacobian peak region where $\frac{\partial(MM)}{\partial |\vec{p}_n|}$ is near zero.²⁵ Here a high-resolution measurement of MM requires only an accurate measurement of the neutron angle, with only a relatively crude measurement of $|\vec{p}_n|$.

For a given laboratory solid angle, the center of mass solid angle subtended near zero degrees is much less than it would be if that same laboratory solid angle were located at the Jacobian peak. Often this feature of the zero-degree region is partially off-set by the fact that production cross sections are higher at zero degrees than at the larger polar angles present in the Jacobian peak region. In addition, with the neutron detectors near zero degrees, one must be careful that the beam does not interfere with the apparatus after passing through the target region.

Figure 4 shows the calculated relationship between MM and the neutron time-of-flight for a 1.98 GeV/c incident pion and a neutron flight path of 529.8 cm centered on the beam line. Figure 5 shows the same plot at 2.41 GeV/c. The two values of time-of-flight at a given mass value corresponds to the neutron going forward or backward in the center of mass system. In the present experiment, only events with neutron time-of-flight values in the interval 42 to 103 nsec were accepted. The 42 nsec cut off in the time-of-flight at both 1.98 and 2.41 GeV/c means that only those neutrons emitted near 180° in the center of mass

Figure 4. Missing mass versus neutron time-of-flight for a 1.98 GeV/c pion beam.

Figure 5. Missing mass versus neutron time-of-flight for a 2.41 GeV/c pion beam.

system were detected. Consequently in the case of two-body processes these neutrons correspond to the X^0 system being produced at essentially 0° .

The range of θ accepted by the neutron detectors may be converted to a range of t , the squared four momentum transfer from the target proton to the recoil neutron:

$$t = (\tilde{p}_p - \tilde{p}_n)^2 = (M_n - M_p)^2 - 2T_n M_p \quad (5)$$

where $\tilde{p}_p$ and $\tilde{p}_n$ are the four-momenta of the proton and neutron. The value of t where $\theta=0^\circ$ is referred to as t minimum²⁵ (t_{MIN}) since it corresponds to the smallest physical value of t . Presented in Figs. 6 and 7 are plots of t versus MM for the two extreme angles of the neutron detectors at 1.98 and 2.41 GeV/c respectively. The lower curve corresponds to a laboratory angle of 0.0° ($t = t_{\text{MIN}}$) and the upper curve to an angle of 12.5° . The essential point of these two figures is that the data are taken at t values very nearly equal to t_{MIN} , but the t values do vary as a function of MM .

Mass Uncertainty and Mass Resolution

Experimental mass uncertainty and mass resolution are both quantities which enter into the data analysis. Uncertainty in the mass scale arises because of three independent effects: (1) the absolute uncertainty in the TOF measurement, (2) the absolute uncertainty in the length of the flight path over which the time-of-flight measurement was made, and (3) the absolute uncertainty of the beam momentum. In the present experiment the error in the time-of-flight is mass dependent and is estimated on the

Figure 6. t versus missing mass in the reaction $\pi^- p \rightarrow X^0 n$ at 1.98 GeV/c for laboratory angles corresponding to the center and outer edges of the neutron counter array.

Figure 7. t versus missing mass in the reaction $\pi^- p \rightarrow X n$ at 2.41 GeV/c for laboratory angles corresponding to the center and outer edges of the neutron counter array.

basis of the calibration procedure described in Appendix I to be in the case of the 1.98 GeV/c data ± 0.18 ns at the ω^0 meson mass (783 MeV) and ± 0.11 ns at the K^+K^- threshold (987 MeV). At 2.41 GeV/c the error in the time-of-flight was estimated to be ± 0.19 ns at 840 MeV and ± 0.14 ns at 987 MeV. At both 1.98 and 2.41 GeV/c the absolute error in the 529.8 cm flight path was estimated to be $\pm 0.25\%$ while the error in the beam momentum was estimated to be $\pm 1\%$. Table IV gives for each of these errors the corresponding error in the absolute mass.

When the 1.98 GeV/c data was first analyzed from the raw data tapes it was processed at a nominal beam momentum of 1.96 GeV/c. At the conclusion of this analysis two facts concerning the mass scale were observed which led us to the conclusion that the beam momentum should be raised by approximately 1%. First, an ω^0 meson signal was observed which was approximately 4 MeV below the accepted ω^0 meson mass of 782.7 MeV. Second, the edge of the K^+K^- threshold was observed to be some 5 MeV below its calculated value of 987.4 MeV. From Table IV it may be seen that a 1% increase in beam momentum would put the threshold edge and the ω^0 mass at nearly their proper values. So we decided to reanalyze the 1.96 GeV/c data from the generated summary tapes and raise the beam momentum 1% (within the error quoted in Table IV) to 1.98 GeV/c. All of the 1.98 GeV/c mass spectra presented in this thesis are from this second analysis.

At 2.41 GeV/c the edge of the K^+K^- threshold was once again observed to be too low in mass. Because of limited statistics this result is not as definitive as in the case of the 1.98 GeV/c data where one can use both the ω^0 and the K^+K^- threshold to establish the mass scale. But a 1%

Table IV. Error sources contributing to absolute mass uncertainty.

<u>Error</u>	<u>Source</u>	<u>Mass (MeV)</u>	<u>Beam Momentum (GeV/c)</u>	<u>Error in Missing Mass (MeV)</u>
± 0.18 nsec	Time-of-Flight	783	1.98	± 0.62
± 0.11 nsec	Time-of-Flight	987	1.98	± 0.78
$\pm 0.25\%$	Flight Path	783	1.98	± 0.84
$\pm 0.25\%$	Flight Path	987	1.98	± 0.94
$\pm 1.0\%$	Beam Momentum	783	1.98	± 3.98
$\pm 1.0\%$	Beam Momentum	987	1.98	± 5.35
± 0.19 nsec	Time-of-Flight	840	2.41	± 0.68
± 0.14 nsec	Time-of-Flight	987	2.41	± 0.80
$\pm 0.25\%$	Flight Path	840	2.41	± 0.92
$\pm 0.25\%$	Flight Path	987	2.41	± 1.03
$\pm 1.09\%$	Beam Momentum	840	2.41	± 4.24
$\pm 1.09\%$	Beam Momentum	987	2.41	± 5.13

increase in beam momentum does seem to be in order for this data. However, a second analysis was not executed due to a lack of operating funds for computer time at Argonne. Consequently, all of the 2.41 GeV/c mass spectra presented in this thesis should be shifted by approximately 5 MeV before any fitting or quantitative work is performed.

Mass resolution was important in the present experiment since it was a search for narrow width meson resonances. Without good mass resolution any such objects would become more difficult to observe. Our mass resolution depended on two independent effects. The first effect was the momentum uncertainty of a particular beam particle. This was due to both the physical size of a single beam momentum hodoscope element and the finite extent of the beam spot. As mentioned earlier in Section II a particular element of our momentum hodoscope could tag an individual beam particle to $\pm 0.25\%$. The other effect contributing to our mass resolution was the momentum uncertainty of a detected neutron. There were two contributions to this uncertainty. The first was the fact that it was not known at what point in the 15 cm deep scintillator the neutron interacted. Thus the exact flight path of the neutron was uncertain. For neutrons near $\beta = 1$ (high mass events) this contribution was of little consequence. For slower neutrons this contribution dominated. The second contribution to the momentum uncertainty of the detected neutron was the time resolution of the thirty neutron detectors. This contribution was 1.40 nsec (FWHM) as determined from the width of the previously mentioned (in Section II) $\beta = 1$ peak. This latter contribution becomes dominant at high values of MM. The total resulting resolution of these two effects are presented in Table V for several values of MM.

Table V. Total mass resolution for several different mass values.

Missing Mass(MM) (MeV)	Beam Momentum (GeV/c)	Mass Resolution MeV(FWHM)
800	1.98	7.4
900	1.98	9.0
1000	1.98	11.1
900	2.41	8.5
1000	2.41	10.3
1100	2.41	12.5

Off-line Analysis - Program EMSOF

To process the data a modified version of the program EMSOF²⁶ was used. EMSOF is an off-line program to reconstruct tracks through the wire spark chambers of the Argonne Effective Mass Spectrometer. In its most general form, EMSOF contains over 60 subroutines, totalling about 7000 card images. It is written almost exclusively (except for tape-reading routine which is in assembler language) in Fortran IV for the IBM 370/195. For the purposes of the present experiment, several changes and modifications to EMSOF were made. Programming instructions were added which implemented a new vertexing algorithm, a new histogramming package, a completely new subroutine that picked good "physics" events, and a subroutine which handled some one hundred new scintillation counters. Also many of the standard EMSOF subroutines were somewhat modified to meet the needs of the experiment.

The overall flow of the program is illustrated in Fig. 8. The main program, EMSOF, reads in the data deck and initializes the run. OFLINE is then called to read in one record, containing one buffer of input data, from the magnetic data tape. OFLINE returns to EMSOF only at the end of a run, at which point histograms are generated, new chamber constants from the alignment routine may be printed, and spark chamber efficiencies are calculated. After each record is read, OFLINE calls CALC to process each event in the record. CALC contains a series of subroutine calls²⁷ to various subroutines that make up the calculation sequence. This sequence is shown in Figs. 9 and 10. After the spatial reconstruction of the tracks is complete and as the last step in the calculation sequence for

Figure 8. Overall program flow.

Figure 9. First part of the calculational sequence for each event (subroutine CALC).

Figure 10. Second part of the calculational sequence for each event (subroutine CALC).

each event, the kinematic fitting subroutine EXAMIN is called. This subroutine sorts events according to topology and makes final state hypothesis tests. EXAMIN also calls a summary tape writing subroutine for selected "good" events.

In addition to the basic track reconstruction routines, which form the major portion of the program, other packages are included that run concurrently and perform specific tasks, among them, (1) a chamber alignment package²⁸ (ALIGN-FUDGE), (2) a chamber efficiency package (EFFIC), and (3) a histogram package (ADD1, ADD2, HISTO).

Input to the EMSOF programs is from (1) a magnetic tape, each record of which contains counter information and spark coordinates for all the events recorded in one ZGS pulse, and (2) a data deck containing user defined options, experiment constants, a list of histograms to be plotted and other miscellaneous information. Output from the package consists of (1) histograms, printed at the end of each run, and (2) a summary tape containing pertinent information for all "good events" as selected by the subroutine EXAMIN. If alignment was requested, new chamber constants are also outputed.

Event Selection

The major functions of the subroutine EXAMIN was to divide events according to topology type and make a final state hypothesis selection. There were three event classes of interest: (1) class 1 events had two charged particles of opposite polarity momentum analyzed in the spectrometer (2) class 2 events had one charged particle momentum analyzed and a second particle had only its polar and azimuthal angles measured in the

spark chamber sets K1 and K2. (3) class 3 events had one momentum analyzed track and no further spectrometer information. For each event class, various final state hypothesis assignments were attempted.

Any event is classed as a certain constraint type depending upon the number of energy and momentum constraints that can be applied at the vertex. These constraints are:

1. Conservation of momentum in the x direction (P_x).
2. Conservation of momentum in the y direction (P_y).
3. Conservation of momentum in the z direction (P_z).
4. Conservation of energy.

The coordinate system used in this thesis is shown in Fig. 11.

In terms of polar coordinates the maximum amount of kinematic information that may be obtained about a particle trajectory is its polar angle, azimuthal angle, and the magnitude of its momentum. For an event to be completely measured, every particle in the event must have these three variables measured. When variables are poorly measured or missing, then the number of constraints that can be applied to test a hypothesis will be four minus the number of poorly measured or missing variables.

The constrained final states examined in the present experiment were:

$$\pi^- p \rightarrow \pi^+ \pi^- n \quad (6)$$

$$\pi^- p \rightarrow K^+ K^- n \quad (7)$$

$$\pi^- p \rightarrow \pi^+ \pi^- \pi^0 n \quad (8)$$

Figure 11. Coordinate system used.

$$\pi^- p \rightarrow K_s^0 K^0 n \quad (9)$$

$$\pi^- p \rightarrow \pi^+ \pi^- \eta^0 n \quad (10)$$

Class 1 events having two momentum analyzed tracks through the spectrometer were investigated as possible candidates for all five of the above reactions. But Class 2 and 3 events in which only one particle was momentum analyzed could only be examined as possible candidates for reactions 1 and 2.

In the case of class 1 events, reactions 1 and 2 have four constraints since all of the kinematic variables were measured in the final state.

The four constraints (4C) were calculated by considering the reactions to proceed either as

$$\pi^- p \rightarrow \pi^+ \pi^- n M_N \quad (11)$$

or

$$\pi^- p \rightarrow K^+ K^- n M_N \quad (12)$$

where M_N is a hypothesized missing neutral particle whose three-momentum and energy are denoted by

$$P_{M_N} = (P_{M_N}^x, P_{M_N}^y, P_{M_N}^z),$$

and E_{M_N} respectively. Then for events which are actually of reactions 1 or 2 it must be true in the ideal case that

$$p_{M_N}^x = 0, p_{M_N}^y = 0, p_{M_N}^z = 0,$$

and

$$E_{M_N} = 0$$

by energy and momentum conservation. These four conditions then form a possible set of constraints that may be used to select events of reactions 1 or 2. However in the present experiment the condition that $E_{M_N} = 0$ was replaced by the equivalent condition that the neutron mass squared as calculated from the beam and meson 4-vectors be centered at its value of 0.883 GeV^2 .

The four constraints for the 1.98 and 2.41 GeV/c data are given in Figs. 12a,b,c,d and 13a,b,c,d. In Fig. 12a the missing neutral x momentum (x is the longitudinal direction) is not centered exactly at zero as it should be. Also the neutron mass squared in the Fig. 12b is not centered at exactly 0.883 GeV^2 as it should. The reason for these two peaks being slightly offset is due to the fact that the spectrometer was aligned at a beam momentum of 1.96 GeV/c. As mentioned previously, the data was later reanalyzed with the beam momentum increased to 1.98 GeV/c. This had the effect of offsetting those constraints which were coupled strongly to the beam momentum. In the case of the 4C constraints, both the missing neutral x momentum and the neutron mass squared constraints couple strongly to the beam momentum and consequently are offset.

Figure 12. The four constraints used to select the 40 $\pi^+\pi^-n$ events at 1.98 GeV/c.

Figure 13. The four constraints used to select the $4C \pi^+ \pi^- n$ events at 2.41 GeV/c.

The offset constraints (the present ones as well as ones to be presented later) do not represent a problem in the present experiment since these constraints are used solely to select the various final states and do not in any way enter into the definition of the mass scale. The mass scale is determined exclusively by the beam momentum and the neutron's momentum which are completely independent of the spectrometer. So if a particular constraint is shifted, the cuts used to select the data sample are also shifted.

At the beam momentum of 1.98 GeV/c, the four cuts used to select the data sample for reactions (1) and (2) required $P_{M_N}^x$ to be within the interval -0.06 to 0.10 GeV/c, $P_{M_N}^y$ to be within the interval -0.04 to 0.04 GeV/c, $P_{M_N}^z$ to be within the interval -0.04 to 0.04 GeV/c, and the neutron mass squared to be within the interval 0.86 to 0.96 (GeV/c²)² as shown by the arrows in Figs. 12a,b,c,d. At 2.41 GeV/c the cuts used required $P_{M_N}^x$ to be within -0.08 to 0.08, $P_{M_N}^y$ to be within -0.04 to 0.04, $P_{M_N}^z$ to be within -0.04 to 0.04, and the neutron mass squared to be within 0.79 to 0.97 (GeV/c²)² as shown once again by the arrows in Figs. 13a,b,c,d.

In the case of 4C events of reactions (1) and (2) the invariant mass of the $\pi^+\pi^-$ or K^+K^- system may be calculated in two independent ways. First, one may use the beam and neutron four-vectors to establish the missing mass of the $\pi^+\pi^-$ or K^+K^- system. Second, one may use the four-vectors of the pions or kaons as measured by the spectrometer to establish the effective mass of the $\pi^+\pi^-$ or K^+K^- system. Figs. 14 and 15 show this effective mass minus the missing mass for the 1.98 GeV/c $\pi^+\pi^-$ and K^+K^- .

Figure 14. The difference between the spectrometer measurement of the dipion mass and the missing mass for the reaction $\pi^- p \rightarrow \pi^+\pi^-n$ at 1.98 GeV/c.

Figure 15. The difference between the spectrometer measurement of the dikaon mass and the missing mass for the reaction $\pi^- p \rightarrow K^+ K^- n$ at 1.98 GeV/c.

systems. The off-centered peaks are due in part to the previously mentioned fact that the spectrometer was misaligned at 1.98 GeV/c. But even when this is taken into account, there is still a relative shift between the $\pi^+\pi^-$ system and the K^+K^- system of approximately 10 MeV. This is probably due to the fact that most of our acceptance for $4C\ K^+K^-n$ events occurs just above K^+K^- threshold where the amount of energy available to an individual K is low. This means that they have a high probability of getting transformed forward through the spectrometer. It also means that just above threshold the opening angle of the K^+K^- pairs are small. These small opening angles are likely causing a systematic shift in the effective K^+K^- mass as measured by the spectrometer that is causing the relative shift between Figs. 14 and 15.

Figs. 16 and 17 show the effective mass minus the missing mass for the 2.41 GeV/c $\pi^+\pi^-$ and K^+K^- systems. Once again there is a relative shift between the $\pi^+\pi^-$ and K^+K^- peaks of approximately 10 MeV which is again probably due to the small opening angles of the K^+K^- pairs as discussed above.

Class 1 events were then analyzed as possible candidates for reactions 3, 4, and 5. The three reactions in this case have only one constraint since the polar angle, azimuthal angle, and the magnitude of the momentum of the π^0 , K^0 , or η^0 were not measured. The one constraint in the case of the $\pi^+\pi^-\pi^0n$ final state at 1.98 GeV/c was calculated by considering the reaction to proceed as

$$\pi^-p \rightarrow \pi^+\pi^-\pi^0B \quad (13)$$

Figure 16. The difference between the spectrometer measurement of the dipion mass and the missing mass for the reaction $\pi^-p \rightarrow \pi^+\pi^-n$ at 2.41 GeV/c.

Figure 17. The difference between the spectrometer measurement of the dikaon mass and the missing mass for the reaction $\pi^-p \rightarrow K^+K^-n$ at 2.41 GeV/c.

In Eq. (13) the $\pi^+\pi^-\pi^0$ is hypothesized and from energy and momentum conservation and the knowledge of the velocity β of the detected baryon B, it was possible to calculate the mass of the baryon. In Fig. 18 the mass of B is plotted for the 1.98 GeV/c data. The final event selection was made by requiring the mass of B to be in the range appropriate to the neutron, 0.925 to 0.980 GeV/c². The ω^0 meson (to be discussed later in Section IV) was observed in this event sample.

The constraint for the $\pi^+\pi^-\eta^0n$ final state at 1.98 GeV/c was calculated in exactly the same manner as the $\pi^+\pi^-\pi^0n$ state, except of course the $\pi^+\pi^-\eta^0n$ state was hypothesized. Fig. 19 shows the baryon mass B plotted for the 1.98 GeV/c data. Again the final event selection was made by requiring the baryon mass to be within the range 0.925 to 0.980 GeV/c².

The constraint for the $\pi^+\pi^-\pi^0n$ final state at 2.41 GeV/c was calculated by considering the reaction to proceed via equation (11). The constraint was just the requirement that the mass of the missing neutral meson squared (M_N^2) be equal to the π^0 mass squared ($(0.0182(\text{GeV}/c^2)^2)$). Fig. 20 shows M_N^2 for the $\pi^+\pi^-\pi^0n$ final state. The final event selection was made by requiring M_N^2 to be within the interval -0.004 to 0.044 (GeV/c²)².

The constraint for the $\pi^+\pi^-\eta^0n$ final state at 2.41 GeV/c was calculated in exactly the same manner as the 2.41 GeV/c $\pi^+\pi^-\pi^0n$ state, except M_N^2 was required to be equal to the η^0 mass squared ($(0.301 \text{ GeV}/c^2)^2$). Fig. 21 shows M_N^2 for the $\pi^+\pi^-\eta^0n$ final state. In this case M_N^2 was required to be within the interval 0.281 to 0.321 (GeV/c²)².

Figure 18. The constraint used to select the $\pi^+\pi^-\pi^0n$ final state at 1.98 GeV/c.

Figure 19. The constraint used to select the $\pi^+\pi^-\eta^0n$ final state at 1.98 GeV/c.

Figure 20. The constraint used to select the $\pi^+\pi^-\pi^0n$ final state at 2.41 GeV/c.

Figure 21. The constraint used to select the $\pi^+\pi^-\eta^0n$ final state at 2.41 GeV/c.

The constraint for the $K_s^0 K_n^0$ final state was calculated differently. The K_s^0 decays to $\pi^+ \pi^-$. So the actual final state considered was

$$\pi^- p \rightarrow \pi^+ \pi^- K^0 n \quad (14)$$

By energy and momentum conservation the mass squared of the K^0 was calculated. This forms the constraint and is plotted for both momenta in Figs. 22 and 23. The final event selection was made by requiring the constraint to be within the interval 0.215 to 0.281 $(\text{GeV}/c^2)^2$ 1.98 GeV/c and within the interval 0.218 to 0.278 $(\text{GeV}/c^2)^2$ at 2.41 GeV/c .

Class 2 events had one particle momentum analyzed and a second particle which only went through the spark chamber sets K1-K2. This second particle had its polar and azimuthal angles measured, but no measurement of the magnitude of its momentum. Consequently, three constraints were available that could be applied to class 2 events to select reactions 1 and 2.

The three constraints used require some explanation. From the neutron information the energy (E_{X^0}) and the three-momentum ($\vec{P}_{X^0}$) of the X^0 were calculated for each event. Now assume in the following diagram that pion #1 (π_1) was the momentum analyzed particle.

Figure 22. The constraint used to select the $K^0 K^0 n$ final state at 1.98 GeV/c.

Figure 23. The constraint used to select the $K^0 K^0 n$ final state at 2.41 GeV/c.

Then by assuming energy and momentum conservation and the measured value of θ_1 , $\theta_1^{\text{measured}}$, it was possible to calculate both θ_2 and $|\vec{p}_1|$. The variables

$$\Delta \theta = \frac{\cos \theta_2^{\text{measured}} - \cos \theta_2^{\text{calculated}}}{\sin \theta_2^{\text{calculated}}} \quad (15)$$

and

$$\Delta P/P = \frac{|\vec{p}_1|^{\text{measured}} - |\vec{p}_1|^{\text{calculated}}}{|\vec{p}_1|^{\text{calculated}}} \quad (16)$$

were then formed. This allowed a comparison between predicted and measured values to be made. $\Delta \theta$ and $\Delta P/P$ formed two of the three constraints.

Since the decay of the X^0 into either $\pi^+\pi^-$ or K^+K^- was a two-body decay, then the angle between the planes formed by the vectors $\vec{p}_{X^0}$, $\vec{\pi}_1$ and $\vec{p}_{X^0}$, $\vec{\pi}_2$ must have been zero to insure the conservation of momentum where $\vec{\pi}_1$ and $\vec{\pi}_2$ are unit vectors in the directions of pion #1 and pion #2 respectively. The vectors $\vec{p}_{X^0}$, $\vec{\pi}_1$ and $\vec{\pi}_2$ were then coplanar. This was the third constraint, the coplanarity angle $\Delta \phi$.

$\Delta \theta$, $\Delta P/P$, and $\Delta \phi$ are shown in Figs. 24 and 25 for the two beam momenta. The final event selection at 1.98 GeV/c was made by requiring $\Delta \theta$ to be within the interval -0.07 to 0.03 rad, the coplanarity angle to be within the interval -0.07 to 0.08 rad, and $\Delta P/P$ to be within the interval -0.05 to 0.03. At 2.41 GeV/c, $\Delta \theta$ was required to be within

Figure 24. The three constraints used to select the $3\pi^+\pi^-\pi^0$ events at 1.98 GeV/c.

Figure 25. The three constraints used to select the 30 $\pi^+\pi^-\eta$ events at 2.41 GeV/c.

the interval -0.10 to 0.10 rad, $\Delta\phi$ to be within the interval -0.10 to 0.10 rad, and $\Delta P/P$ to be within the interval -0.10 to 0.10 .

Class 3 events had one momentum analyzed track and no further spectrometer information. For reactions 1 and 2 they are 1-constraint, the constraint used being the $\Delta P/P$ constraint described above for class 2 events. Additional counter data were also used with class 3 events from reactions 1 and 2 to reduce their signal-to-noise ratio. The unseen second meson was required to have been detected either in the T1 counters or in the 16 counter hodoscope H which surrounded the target on its remaining five sides. Furthermore, the particular counter predicted using energy and momentum conservation was required.

In Figs. 26a and 26b $\Delta P/P$ is presented for the 1.98 GeV/c data with and without the correct counter requirements. Figs. 27a and 27b present $\Delta P/P$ for the 2.41 GeV/c data. In both cases the final event selection required the correct counter to have been struck and $\Delta P/P$ to have been within the interval -0.04 to 0.02 at 1.98 GeV/c and within the interval -0.03 to 0.03 at 2.41 GeV/c.

The signal-to-noise ratio of a constraint plot is of primary significance. This ratio indicates how cleanly a given final state could be separated. Table VI presents the signal-to-noise ratio of all constrained final states at both 1.98 and 2.41 GeV/c.

Target Vertex

The vertexing of momentum analyzed tracks was performed by the minimization of a χ^2 defined for the hypothesis that all the tracks originated at one point. An attempt was first made to vertex the beam,

Figure 26. The constraint used to select the $10 \pi^+ \pi^- n$ events at 1.98 GeV/c. (a) The constraint without the correct T1 or H counter being required. (b) The constraint with the correct T1 or H counter being required.

Figure 27. The constraint used to select the 10 $\pi^+\pi^-$ events at 2.41 GeV/c. (a) The constraint without the correct T1 or H counter being required. (b) The constraint with the correct T1 or H counter being required.

Table VI. Signal to noise ratios for various constrained final states.

Final State	Constraint Class	Beam Momentum	Signal to Noise Ratio
$\pi^+ \pi^- n$	4C	1.98	179.80
$\pi^+ \pi^- n$	3C	1.98	22.31
$\pi^+ \pi^- n$	1C	1.98	9.73
$K^+ K^- n$	4C	1.98	7.13
$\pi^+ \pi^- \pi^0 n$	1C	1.98	0.80
$K_S^0 K^0 n$	1C	1.98	0.18
$\pi^+ \pi^- \eta^0 n$	1C	1.98	0.20
$\pi^+ \pi^- n$	4C	2.41	58.70
$\pi^+ \pi^- n$	3C	2.41	13.04
$\pi^+ \pi^- n$	1C	2.41	3.14
$K^+ K^- n$	4C	2.41	6.71
$\pi^+ \pi^- \pi^0 n$	1C	2.41	0.49
$K_S^0 K^0 n$	1C	2.41	0.43
$\pi^+ \pi^- \eta^0 n$	1C	2.41	0.13

any momentum analyzed track, and any neutral tracks from K^0 decays. If the χ^2 of the fit was greater than 50, the worst track was eliminated and the fit repeated.

An attempt was then made to vertex any lines found in the chamber sets K1 - K2 with the beam. The method used was the distance of closest approach. Any lines whose distance of closest approach with the beam was greater than 0.4 inch was immediately rejected. A mean vertex was then calculated which was the average value of the vertex formed by any of the momentum analyzed tracks and the vertices formed by the K1 - K2 lines and the beam. Any K1 - K2 line whose distance from this mean vertex was greater than 1.0 inch was eliminated. A new mean vertex was calculated and the above procedure repeated. The mean vertex where all of the K1 - K2 lines were within the cutoff distance of 1 inch formed the final vertex.

The distribution of vertices for the 1.98 and 2.41 GeV/c class 1 events and the location of the liquid hydrogen target are shown in Figs. 28 and 29. In both cases interactions in the 0.16 cm thick double pulse height counter of the T1 array are clearly evident just beyond the downstream edge of the target. The rise in the number of events across the target in Figs. 28 and 29 is a reflection of the acceptance of the spectrometer. The acceptance for events produced at the downstream edge of the target is about a factor of two higher than the acceptance for events produced at the upstream edge. All events used in the analysis were required to vertex within the target, thereby eliminating non-hydrogen associated events.

Figure 28. The distribution of vertices and the location of the liquid hydrogen target for class 1 events at 1.98 GeV/c.

Figure 29. The distribution of vertices and the location of the liquid hydrogen target for class I events at 2.41 GeV/c.

Geometric Acceptance

A Monte Carlo calculation of the spectrometer acceptance was performed in the case of the $\pi^+\pi^-n$ final state for each of the three topology classes mentioned above. At discrete values of MM, events were generated to populate uniformly the neutron counters as the data were observed to do. Decay pions from the X^0 which was assumed to be spin zero were propagated through the spectrometer and assigned to classes 1 through 3 or undetectable depending on which spark chambers intercepted the trajectories. For purposes of field integration, a square field with vertical focusing was found to be adequate after comparison with a sample of events processed using a full inhomogeneous field integration. Corrections for in-flight decays were important.

The successfully detected $\pi^+\pi^-n$ events by class were then transformed into the X^0 Gottfried-Jackson (GJ) rest frame. For our highly peripheral events, the Lorentz transformation to the GJ rest frame was essentially along the beam direction. Class 1 events were found to populate a π^+ polar angle $\theta_{GJ}^{\pi^+}$ region near 90° in the X^0 rest frame. After transformation into the laboratory frame, the π^+ and π^- are forward going and symmetric with respect to the beam line which is required to get two trajectories passing through the spectrometer. The detection efficiency drops as the transverse momentum increases which means that the acceptance falls with MM at a given rest frame polar angle. Class 3 events are produced with the π^+ either parallel or anti-parallel to the beam direction. This gives one particle through the spectrometer while the second misses altogether. The acceptance for class 3 events is nearly MM indepen-

dent. The class 2 acceptance is intermediate between the other two classes in angle. It falls with MM although more slowly than the class 1 acceptance. The distribution in $\cos\theta_{GJ}^{\pi^+}$ for the three classes of Monte Carlo generated $\pi^+\pi^-n$ events is given in Fig. 30a,b,c. Figs. 30 and 31 present the acceptance of the Monte Carlo generated events as a function of MM integrated over θ_{GJ} for the two beam momenta of 1.96 and 2.40 GeV/c.

Efficiencies were also generated for non-zero X^0 spin states. The general result is that spin projection zero states, whose angular distributions peak near $\theta = 0^\circ$ and 180° , tend to populate class 3 whereas non-zero projections are more important to class 2.

Figure 30. The distributions in $\cos \theta_{GJ}^{\pi^+}$ for the three classes of Monte Carlo generated $\pi^+ \pi^- n$ events at 2.40 GeV/c.

MONTE CARLO EVENTS

Figure 31. The acceptance versus mass for Monte Carlo generated $\pi^+\pi^-n$ events at 1.96 and 2.40 GeV/c.

SECTION IV. RESULTS

In this section we survey the mass spectra for the constrained final states at both 1.98 and 2.41 GeV/c. An ω^0 meson signal observed in the mass spectrum of the 1.98 GeV/c $\pi^+\pi^-\pi^0n$ final state is presented. In addition, a sharp break in the $\pi^+\pi^-n$ mass spectrum and a rapid rise of the K^+K^-n spectrum just above threshold are observed and are associated with the S^* resonance. From fits to the $\pi^+\pi^-n$ and K^+K^-n spectra the position of the S^* pole is then determined. Finally, the absence of four previously observed narrow mesons is discussed.

Mass Spectra

As discussed in Section III selection criteria (cuts) may be imposed on the data in an effort to isolate various final states. Table VII lists the numbers of events which satisfied these cuts for each final state category.

We will first consider the mass spectra obtained from the data taken at a beam momentum of 1.98 GeV/c. The distribution in MM for the 10 $\pi^+\pi^-n$ events is shown in Fig. 32. The data show a flat spectrum at high and low MM with a rapid transition over the 40 MeV/c² interval between 940 and 980 MeV/c². We associate this dramatic drop in the cross section with the previously reported S^* resonance.^{1,14,15,16,17} The normally large ρ meson signal is not apparent. Given the 11.5-to-1 signal-to-noise ratio we expect 24 background events per 5 MeV/c² in Fig. 32.

Table VII. Number of events for various constrained final states.

Final State	Constraint Class	Beam Momentum	# of Events in this Category
$\pi^+ \pi^- n$	4C	1.98	441
$\pi^+ \pi^- n$	3C	1.98	3226
$\pi^+ \pi^- n$	1C	1.98	17977
$K^+ K^- n$	4C	1.98	52
$\pi^+ \pi^- \pi^0 n$	1C	1.98	937
$K_S^0 K^0 n$	1C	1.98	34
$\pi^+ \pi^- \eta^0 n$	1C	1.98	148
$\pi^+ \pi^- n$	4C	2.41	946
$\pi^+ \pi^- n$	3C	2.41	8016
$\pi^+ \pi^- n$	1C	2.41	32688
$K^+ K^- n$	4C	2.41	418
$\pi^+ \pi^- \pi^0 n$	1C	2.41	11101
$K_S^0 K^0 n$	1C	2.41	352
$\pi^+ \pi^- \eta^0 n$	1C	2.41	1941

Figure 32. Mass spectrum of the 10 $\pi^+\pi^-n$ events at 1.98 GeV/c. The solid curve is the best S^* fit to the data as described in the text. The dashed curve is the best fit if the non-resonant s-wave phase is held at 90° .

The 3C and 4C $\pi^+\pi^-$ MM spectra are presented in Figs. 33 and 34 respectively. There are significantly fewer events in these spectra since the acceptance for these two constraint classes is much lower than for the 1C constraint class. The events are also concentrated at low mass since the acceptance for each spectrum falls sharply with increasing MM. However, a pronounced break is still apparent in both spectra near 950 MeV/c².

The MM distribution for the 1.98 GeV/c 4C K^+K^-n events is presented in Fig. 35. The previously reported²⁹ rapid rise of the KKn spectrum near threshold is apparent. As was mentioned previously, we have a check on the MM scale as the MM spectrum for the 4C K^+K^-n events is found to be consistent within experimental resolution with a threshold at $2M_{K^+}$. An attempt was made to isolate 1C and 3C K^+K^-n events. No 1C K^+K^-n signal was observed. A 3C K^+K^-n signal was observed, but the events were sufficiently contaminated to make them not useful to the analysis presented in this thesis.

Another check on the MM scale and resolution was provided by the observation of the ω^0 meson. Fig. 36 shows the 1C $\pi^+\pi^-\pi^0n$ mass spectrum at 1.98 GeV/c. An ω^0 signal is evident. Even though this peak is located near our low mass acceptance limit, an examination of our mass acceptance shows that it is essentially constant through the region of the figure and does not distort the ω^0 signal. The data in Fig. 36 was fitted to a Gaussian signal plus a constant background. The width of the ω^0 from the fit is $\Gamma = (13 \pm 3)$ MeV/c². After correction for our experimental resolution we find the ω^0 natural

Figure 33. Mass spectrum of the 30 $\pi^+\pi^-$ events at 1.98 GeV/c. The curve is the best S^* fit.

Figure 34. Mass spectrum of the 4C $\pi^+ \pi^- n$ events at 1.98 GeV/c.

Figure 35. Mass spectrum of the 40 K^+K^-n events at 1.98 GeV/c. The curve is a one parameter (g_K) fit to the data with the S^* pole held at the $\pi^+\pi^-n$ best value.

Figure 36. ω^0 meson signal in the $\pi^+\pi^-\pi^0$ final state from data at 1.98 GeV/c. The curve is a fit to a constant plus a Gaussian ω^0 .

width to be (9 ± 3) MeV/c² consistent with the tabulated world average.¹ The ω^0 peak is centered at (781 ± 2) MeV/c², slightly below but consistent with the tabulated value of 782.7 MeV/c².

The 1C $K_S^0 K_S^0 n$ MM distributions is presented in Fig. 37. This event sample is small and there is no evidence of structure.

We now turn our attention to the mass spectra at 2.41 GeV/c. The 1C, 3C, and 4C $\pi^+ \pi^- n$ MM distributions at this beam momenta are presented in Figs. 38, 39, 40, 41, and 42. Fig. 39 shows that portion of Fig. 38 and Fig. 41 shows that portion of Fig. 40 over which fits to the data were performed. The 1C data of Figs. 38 and 39 show a flat spectrum at low missing mass and a slowly rising spectrum at higher mass. Between 940 and 980 MeV/c² the 1C spectrum falls rapidly and then makes a recovery between 980 and 1020 MeV/c². The 3C MM distribution of Figs. 40 and 41 has a pronounced drop over the interval 940 to 980 MeV/c². The 4C MM spectrum presented in Fig. 42 also shows some evidence of falling in the 940 to 980 MeV/c² region. For all three spectra we associate this rather dramatic behavior in cross section near 960 MeV/c² with the S^* resonance.

The MM spectrum for the 2.41 GeV/c 4C $K^+ K^- n$ events is presented in Fig. 43. Once again the rapid rise of the spectrum near the $K^+ K^-$ threshold is apparent. A low background level is present.

The MM distribution for the 2.41 GeV/c $\pi^+ \pi^- \pi^0 n$ and the $K_S^0 K_S^0 n$ final states are shown in Figs. 44 and 45 respectively. No structure is apparent in any of these event samples.

Figure 37. Mass spectrum of the $K^0\bar{K}^0n$ final state.

Figure 38. Mass spectrum of the $1C \pi^+ \pi^- n$ events over the full mass region accepted at 2.41 GeV/c.

Figure 39. Mass spectrum of the 2.41 GeV/c 1C $\pi^+ \pi^- n$ events over a restricted mass region. The curve is the best S^* fit to the data as described in the text.

Figure 40. Mass spectrum of the 3C $\pi^+ \pi^- n$ events over the full mass region accepted at 2.41 GeV/c.

Figure 41. Mass spectrum of the 2.41 GeV/c 3C $\pi^+ \pi^- n$ events over a restricted mass region. The curve is the best S^* fit.

Figure 42. Mass spectrum of the $4C \pi^+\pi^-n$ events at $2.41 \text{ GeV}/c$.

Figure 43. Mass Spectrum of the 4C $K^+ K^- n$ events at 2.41 GeV/c.

Figure 44. Mass spectrum of the $\pi^+ \pi^- \pi^0 n$ final state at 2.41 GeV/c.

Figure 45. Mass spectrum of the $K^0 \bar{K}^0 n$ final state at 2.41 GeV/c.

Fig. 46 shows the MM distribution for the $\pi^+\pi^-\eta^0n$ final state where the 1.98 GeV/c data has been added to the 2.41 GeV/c data. The mass scale of the 2.41 GeV/c data was shifted 5 MeV before the distributions were added in accordance with the discussion on mass scales presented in Section III. The 0.955 to 0.965 bin of this mass distribution exhibits an enhancement of approximately 3σ above the background. We identify this enhancement as the η' meson whose mass (957.6 ± 0.3 MeV) and width (<1 MeV) are consistent with our observations.

The S^* Resonance

Both the rapid drop in the cross section for the process

$$\pi^- p \rightarrow \pi^+ \pi^- n \quad (17)$$

near dipion mass $960 \text{ MeV}/c^2$ and the rapid rise above threshold for the reaction

$$\pi^- p \rightarrow K^+ K^- n \quad (18)$$

have been explained in terms of a pole in the $\pi\pi$ scattering amplitude near the KK threshold.^{1,14,15,16,17} The opening of the KK threshold alone is not sufficient to cause the effect. As references 30, 31, and 32 point out, any threshold effect not produced by a pole is usually too weak to be observable. Therefore an observable effect around threshold is due to the presence of a pole in the complex mass plane. In the present case this pole, the S^* , has been shown to occur in the dipion s-wave.^{14,16,17} The study of this resonance typically

Figure 46. Mass spectrum of the $\pi^+\pi^-\eta^0n$ final state. This spectrum is the sum of the $\pi^+\pi^-\eta^0n$ events at 1.98 and 2.41 GeV/c. The enhancement in the 0.955 to 0.965 bin we identify with the η' meson.

has proceeded either through a fit of a Breit-Wigner resonance form to the mass spectra for dimeson production reactions^{14,15} or through a complete partial wave analysis that incorporates a K or M-matrix parametrization.^{16,17} A primary advantage of the full partial wave analysis is its use of angular information to separate the s-wave contribution to the cross section from the contributions of higher partial waves. For the purpose of studying the S^* these higher partial waves may be considered a background. The largest such background typically comes from the ρ resonance in the p-wave although the d-wave has also been shown to be important.

The analysis procedure used in this thesis is the minimization of the χ^2 for the hypothesis that the $\pi^+\pi^-\pi$ mass spectra in Figs. 32, 33, 39, and 41 are of the form

$$\frac{dN_c(MM)}{dMM} = J(MM)F(t,MM) [\epsilon_c^0 |T_\pi^0(MM)|^2 + \epsilon_c^1 |T_\pi^1(MM)|^2] + B_c(MM) \quad (19)$$

$N_c(MM)$ is the number of events of constraint class C as a function of MM. $J(MM)$ is the solid angle subtended by the neutron counters in the overall center-of-mass frame multiplied by a normalization factor. ϵ_c^0 is the s-wave Monte Carlo efficiency for constraint class C; T_π^0 is the s-wave $\pi\pi$ scattering amplitude. ϵ_c^1 and T_π^1 are the corresponding p-wave functions. We have tried fits including corresponding d-wave functions in the form of the f meson and have found their contribution

to be consistent with zero. Note that Eq. (19) implicitly assumes that an integration over angles (in the rest frame) has been performed. The cross term between s and p-waves cancels in this integration because the calculated efficiency is symmetric about 90° .

In a $\pi\pi$ scattering analysis of reactions 1 and 2, $F(t, MM)$ contains the virtual pion propagator and describes the nucleon vertex. Several forms of F were examined including this one pion exchange (OPE) form, an exponential factor $e^{7tM_{\pi N}}$, and the product $F(t, MM) J(MM)$ equal to a constant. For the $\pi^+\pi^-n$ data presented, neither the s-wave cross section nor the overall quality of our fits (χ^2 probability) is a function of the choice among these three options. Results presented in this thesis have been obtained using the OPE form.

The s-wave amplitude was parameterized by³³

$$T^\circ_\pi(MM) = \frac{2}{3} \left[\frac{e^{2i\delta}-1}{2i} + \frac{e^{2i\delta}\Gamma_\pi M_O}{M_O^2 - MM^2 - iM_O(\Gamma_\pi + \Gamma_K)} \right] \quad (20)$$

$$\Gamma_\pi = g_\pi \sqrt{\frac{1}{4}MM^2 - M_{\pi^+}^2} \quad (21)$$

$$\Gamma_K = g_K \left[\sqrt{\frac{1}{4}MM^2 - M_{K^+}^2} + \sqrt{\frac{1}{4}MM^2 - M_{K^0}^2} \right] \quad (22)$$

where δ , M_O , g_π , and g_K are the adjustable parameters; M_{π^+} , M_{K^+} , and M_{K^0} are the masses of the π^+ , K^+ , and K^0 . Γ_K is the sum of the partial widths for decay to the final states K^+K^- (Γ_{K^+}) and $K^0\bar{K}^0$ (Γ_{K^0}). Below $K\bar{K}$ thresholds the positive imaginary square root is implied. Here the $T^\circ_{\pi\pi}(MM)$ amplitude is the sum of a background amplitude plus a Breit-Wigner. The drop occurs in the $\pi^+\pi^-n$ spectra because the phase change across the rela-

tively narrow S^* is superimposed on a constant background phase δ . According to this view, it is then the interference between the background amplitude and the S^* Breit-Wigner that causes the sharp edge in the data. In addition, the 2π amplitude does not fully recover above the S^* because of strong absorption by the $2K$ channel. The position of the S^* pole is by definition the complex zero of the denominator of the second term of $T^\circ_\pi(MM)$

For the p-wave contribution either we use a ρ Breit-Wigner multiplied by the Monte Carlo generated efficiency or we include the p-wave effects in the background term $B(MM)$. The former case will be referred to as the physical background, the latter as the polynomial background. In the physical background the ρ amplitude is a parameter and $B(MM)$ is taken to be a constant. In the polynomial background, $B(MM)$ is taken as a linear or quadratic function of MM depending on the particular fit. The final form of equation (19) contains either 7 or 8 adjustable parameters, the overall normalization, 4 s-wave parameters, and 2 or 3 background parameters. Not all of the s-wave parameters can be determined from the $\pi^+\pi^-n$ data. The reason is illustrated in Table VIII where fits are made to the IC 1.98 GeV/c $\pi^+\pi^-n$ data after fixing g_K at various values. Excellent fits are obtained independent of g_K . In fact the $\pi^+\pi^-n$ data by themselves are consistent with the hypothesis $g_K = 0$ which implies no coupling to the $K\bar{K}$ system. The remaining parameters of the s-wave amplitude are strong functions of g_K , but if the position of the S^* pole is extracted, it is nearly independent of g_K . The procedure was then to fix g_K , fit the data sets to the

Table VIII. S^* pole positions for various values of g_K .

g_K	χ^2 Probability %	g_π	M_π (MeV/c ²)	s-wave Background Phase (degrees)	Pole Position (MeV/c ²)
2.5	95	$0.71 \pm .14$	745 ± 23	61 ± 6	$(971 \pm 5) - i(23 \pm 5)$
0.5	97	$0.20 \pm .04$	917 ± 8	62 ± 5	$(971 \pm 5) - i(22 \pm 5)$
0.25	95	$0.15 \pm .03$	942 ± 6	61 ± 5	$(967 \pm 5) - i(22 \pm 5)$
0.06	94	$0.11 \pm .02$	959 ± 4	57 ± 5	$(965 \pm 5) - i(21 \pm 5)$
0.00	93	$0.09 \pm .02$	964 ± 4	55 ± 4	$(964 \pm 5) - i(21 \pm 5)$

expression in Eq. (19), and then extract the pole parameters. The 1.98 GeV/c K^+K^- data was then fitted to find g_K .

We have already noted the independence of the pole position on the form of $F(t,MM)$. To check its dependence on background we list in the first four rows of Table IX the pole position from fits made to the 1.98 GeV/c data in Figs. 32 and 33 using the physical and polynomial backgrounds. The χ^2 probabilities for the various fits are given in column 4 of Table IX. The 1C fits are excellent and the 3C fits are acceptable. The fits from rows 1 and 2 of Table IX are shown as the solid curves in Figs. 32 and 33 respectively.

The results of fits to the 1C and 3C $\pi^+\pi^-n$ events at 2.41 GeV/c are presented in Table X. The χ^2 probabilities for the fits are given in column 4. All fits are seen to be acceptable. The fits of the 2.41 GeV/c data of Table X are shown as solid curves in Figs. 39 and 41.

There is an obvious consistency between fits to the data at 1.98 GeV/c and 2.41 GeV/c and an independence from the background parameterization. The overall normalizations are also consistent within errors serving to check the Monte Carlo efficiencies. For example, for the two physical background fits at 1.98 GeV/c, the normalizations are 578 ± 37 and 640 ± 67 . The computed pole position is found to be independent of the form of the background within the computed errors. The pole parameters also display an independence from the rest frame decay angles since the data from the two constraint classes sample different angular ranges.

Table IX. S^* pole positions for various fits to the 1.98 GeV/c data.

<u>Data Class</u>	<u>MASS Range (MeV/c²)</u>	<u>Background Form</u>	<u>χ^2 Probability %</u>	<u>s-wave Background Phase (degrees)</u>	<u>Position (MeV/c²)</u>
1-C	770-1070	Linear	94	57 ± 5	$(965 \pm 5) - i(21 \pm 5)$
3-C	770-1070	Quadratic	9	49 ± 14	$(970 \pm 6) - i(13 \pm 6)$
1-C	770-1070	Physical	94	57 ± 5	$(966 \pm 4) - i(21 \pm 4)$
3-C	770-1070	Physical	2	51 ± 7	$(972 \pm 6) - i(24 \pm 5)$
1-C	890-1015	Constant	86	59 ± 9	$(973 \pm 6) - i(26 \pm 5)$
3-C	900-1015	Constant	87	35 ± 14	$(962 \pm 10) - i(27 \pm 7)$

Table X. S^* pole positions for two fits to the 2.41 GeV/c data.

Data Class	MASS Range (MeV/c ²)	Background Form	χ^2 Probability %	s-wave Background Phase (degrees)	Pole Position (MeV/c ²)
3C	840-1070	Quadratic	54.1	45 ± 16	$(972 \pm 6) - i(11 \pm 5)$
1C	840-1070	Quadratic	27.0	46 ± 15	$(965 \pm 6) - i(12 \pm 6)$

To complete the analysis we fit the sample of 4C 1.98 GeV/c K^+K^-n data shown in Fig. 35. The fitting function used was

$$\frac{dN_K}{dMM} = F(t, MM) J(MM) \epsilon_K^\circ(MM) |T_K^\circ(MM)|^2 \quad (23)$$

$$T_K^\circ(MM) = \frac{M_O \sqrt{\Gamma_\pi \Gamma_{K^+}} / \sqrt{3}}{M_O^2 - MM^2 - i M_O (\Gamma_\pi + \Gamma_{K^+})} \quad (24)$$

Eq. (23) is the analog of Eqs. (19) and (20) with the p-wave omitted and the s-wave amplitude replaced by the inelastic amplitude T_K° for the process $\pi^+\pi^- \rightarrow K^+K^-$. The efficiency $\epsilon_K^\circ(MM)$ is the Monte Carlo generated K^+K^- acceptance. In fitting with this function we hold the S^* pole at the value given above from the $\pi^+\pi^-$ fits. We hold the overall normalization at the $\pi^+\pi^-$ value. This leaves one free parameter, g_K . Because of non-zero MM resolution there are some K^+K^-n events below threshold. To fit these data it is necessary to include our $\sigma = 4 \text{ MeV}/c^2$ resolution in the fit. Likewise even a small mass shift can affect the fits enormously. We have already observed that the mass of our ω^0 signal is low. A $3 \text{ MeV}/c^2$ upward shift of the mass scale near K^+K^- threshold is made in compensation. We obtain the 75% confidence level fit shown in Fig. 35 for $g_K = 0.5 \pm 0.05$. The values for g_π , M_O and ϕ are found by refitting the $\pi^+\pi^-n$ class 3 data for $g_K = 0.25$. The resultant values are $g_\pi = 0.14 \pm 0.03$, $M_O = 943 \pm 6 \text{ MeV}/c^2$, and $\phi = 60^\circ \pm 5^\circ$. From these results, the position of the S^* pole is $(967 \pm 5) - i (22 \pm 5) \text{ MeV}/c^2$, on the second sheet.

Our nonresonant s-wave background phase is markedly different from previous observations which have either been near 90° ¹⁴ or near 0° .¹⁵ Likewise, the real part of our S^* pole position is approximately $26 \text{ MeV}/c^2$ below the world average.¹ We do observe from our fits that the position of the S^* pole is correlated with the background phase. If we fix the background phase at 90° in agreement with Ref. 14 the pole moves to $(996 \pm 2) - i(35 \pm 6) \text{ GeV}/c^2$ giving a real part of the pole position in agreement with the world average and an imaginary part too large by a factor of two. The quality of the fit also suffers as the fitting function is no longer able to reproduce the sharpness of the S^* as is shown by the dashed curve in Fig. 32.

Before quoting a best value for the S^* pole we acknowledge a potential systematic mass shift in our data of $3 \text{ MeV}/c^2$ as evidenced by the positions of the K^+K^- threshold and the ω . This lies within our experimental resolution. The effect of such a shift is to lower the real part of the S^* pole by $3 \text{ MeV}/c^2$ while leaving the imaginary part unchanged. Including this shift we find the best value for the S^* pole position to be $(970 \pm 5) - i(22 \pm 5) \text{ MeV}/c^2$ and the associated background phase to be $60^\circ \pm 5^\circ$.

A possible explanation of the discrepancy between this number and the world average would be the inadequacy of our model which holds the background phase constant over our entire mass range. However, fits over a restricted mass range (rows 5 and 6 of Table IX) show that the best fit background phase does not change when data far from the S^* edge are eliminated. A background phase substantially below 90° is

required to match the data near $950 \text{ MeV}/c^2$. A slow variation in this phase at other masses could be absorbed in the background terms from higher partial waves. These results still hold for fits to even smaller mass ranges although the parameter errors become large rapidly.

Previous to the results reported in this thesis, there have been three high precision measurements of the S^* pole position (z).^{15,16,17} They are consistent among themselves and with our result for $\text{Im}(z)$. Two of the measurements, Binnie, et al.,¹⁵ and Protopopescu, et al.,¹⁶ report significantly greater precision in their determination of $\text{Re}(z)$ than does the third.¹⁷ Binnie, et al., report $\text{Re } z = 987 \pm 7 \text{ MeV}/c^2$ based on fits to the dipion mass spectrum for the reaction $\pi^- p \rightarrow \pi^+ \pi^- n$ at threshold. Interestingly they find $\text{Re}(z) = 977$ for the reaction $\pi^- p \rightarrow \pi^+ \pi^- n$ at threshold, but this data sample has a poor signal-to-noise ratio and was disregarded. In both cases the background phase is 0° . Protopopescu, et al., find $\text{Re}(z) = 997 \pm 7$ in a partial wave analysis of the reaction $\pi^+ p \rightarrow \Delta^{++} \pi^+ \pi^-$ at $7.1 \text{ GeV}/c$. The same group in an earlier analysis of their data¹⁴ found a background phase near 90° . We at $1.98 \text{ GeV}/c$ lie in phase between the threshold and $7.1 \text{ GeV}/c$ results and in $\text{Re}(z)$ we lie below both other results. Because of our relatively low momentum we share with Binnie, et al., a potential problem due to s-channel effects. However, because these effects are expected to vary slowly with MM we expect our value for the S^* pole position to be unaffected by processes in the s-channel.

Search for Narrow Neutral Meson Resonances

As was mentioned in the introduction, evidence of the production of four narrow neutral mesons has been previously reported.^{11,12,13} Subsequent experiments by another group^{22,23} have failed to confirm these resonances. The present experiment was designed to reproduce the results of Ref. 11, 12, and 13 as closely as possible with significantly more data and to have the ability, not present in Ref. 11, 12, 13, 22, and 33 to reconstruct constrained final states. No evidence of the existence of these four mesons is seen in either the constrained final states or the mass spectra that used the same particle multiplicity and angle cuts used to enhance the effects seen in Ref. 11, 12 and 13. A paper (to be published) is presented in Appendix II which contains these topologically duplicated mass spectra.

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APPENDIX I

A simplified block diagram of the detector electronics is shown in Fig. 47. The modules consisted primarily of NIM-standard fast logic. In the figure the symbol "T" denotes a fast logic discriminator or "trigger". The modules labelled "AND" were fast logic coincidence units and the "VETO" signifies a signal which was in anti-coincidence. Note that in order to have a "START" or "STOP" signal sent to the time to amplitude converter (TAC) both a beam particle and a neutron were required by the logic.

Many of the modules have been left out of the figure or greatly simplified for clarity. There were critical timing relationships between the various pulses entering a module and these relationships have been unspecified for the same reason. Also, there were many detectors and electronic signals which "tag" various types of events that have not been shown. These were not a part of the event signature but enter the computer in coincidence with a "good event" signal.

The pulse height of the output signal of a TAC module is directly proportional to the time interval between the "START" and "STOP" input signals. In the present experiment this pulse height was digitized by a linear analog to digital converter (ADC). The resulting digital number (let's denote it as NADC) was the ADC channel number that corresponded to the time interval between the START and STOP signals input to the TAC. To convert NADC to an

Figure 47. A simplified block diagram of the detector electronics.

absolute value of time-of-flight (TOF) in nsec it was necessary to know the number of nsec per ADC channel (denoted by SCALE) and the ADC channel that corresponded to particles traveling at speeds $\beta = v/c = 1$ (denoted by FCHBI). Then the absolute TOF in nsec could be calculated by

$$\text{TOF} = (\text{SCALE}) \times (\text{NADC} - \text{FCHBI}) + \text{TOFBI} \quad (25)$$

where TOFBI is the time in nsec required for a $\beta = 1$ particle to travel the 529.8 cm flight path. To establish FCHBI special runs were made where the logic was set up to accept gamma rays in the beam. The resulting spectrum gave a narrow, 1.40 nsec (FWHM), peak corresponding to $\beta = 1$ time-of-flights. The absolute center of this peak could be established to ± 2 ADC channels. To establish SCALE a crystal controlled oscillator accurate to a few parts in 10^6 was used to input well-known absolute time intervals into the TAC-ADC system. The resulting number of ADC channels that corresponded to the well-known time interval allowed the calculation of SCALE. SCALE could be inferred to ± 2 ADC channels/100 nsec. The mass dependent errors in TOF quoted in Table VII correspond to FCHBI being known only to ± 2 ADC channels and SCALE being uncertain to ± 2 ADC channels/100 nsec.

APPENDIX II:

A SEARCH FOR NARROW NEUTRAL MESON RESONANCES NEAR

MASS $1 \text{ GeV}/c^2$ [†]

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A SEARCH FOR NARROW NEUTRAL MESON RESONANCES NEAR
MASS 1 GeV/c^{2†}

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ABSTRACT

We examine the reaction $\pi^- p \rightarrow X^0 n$ at 2.4 GeV/c for evidence of the production of the previously reported narrow neutral mesons $M^0(940)$, $\delta(963)$, $M^0(1033)$, and $M^0(1150)$. Strong evidence against the existence of these states is presented.

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Evidence for four new narrow meson resonances was reported from a missing mass (MM) experiment by an Iowa State University - Argonne National Laboratory - Purdue University collaboration studying the reaction $\pi^- p \rightarrow X^0 n$. The MM is defined to be the X^0 mass. Subsequent experiments by another group⁴⁻⁵ have failed to confirm these resonances. In the present Letter we present the results of an experiment designed to reproduce the results of Ref. 1-3 as closely as possible with significantly more data and to have the ability, not present in Ref. 1-5, to reconstruct constrained final states.

The experiment was performed at the Argonne National Laboratory Zero Gradient Synchrotron (ZGS). A plan view of the apparatus is shown in Fig. 1a. Thirty plastic scintillator neutron detectors of the type employed in Ref. 1-3 (30 cm x 30 cm x 15 cm deep) were used in conjunction with a magnetostrictive wire spark chamber system, the Effective Mass Spectrometer (EMS)⁶ at the ZGS. This letter presents data not analyzed for constrained final states. For the present analysis the EMS was used to measure the angles of any final state charged particles passing through its front spark chambers K1 and K2. These data were taken at a π^- beam momentum of 2.4 GeV/c analyzed to $\pm .25\%$. Neutrons were detected after a 5.33 meter flight path from a 38.1 cm liquid hydrogen target. The neutron detectors were arranged about the beam line in an array which intercepted neutron angles up to 12.5° . Only signals corresponding to neutrons with times-of-flight (TOF) in the interval 38 to 100 nsec were accepted. Such slow forward going neutrons are produced very close to 180° from the beam direction in the reaction

center-of-mass frame. For the geometry of this experiment and for X^0 masses near $1 \text{ GeV}/c^2$, $|t - t_{\min}|$ is less than $0.003 \text{ (GeV}/c)^2$. The MM, as calculated from the beam and neutron momenta, is almost independent of the neutron angle under these circumstances. The MM and its error are most sensitive to the neutron TOF measurement. The allowed TOF's for this experiment correspond to MM in the range 0.85 to $1.25 \text{ GeV}/c^2$. The MM resolution was $\sigma = 0.004 \text{ GeV}/c^2$ at $1 \text{ GeV}/c^2$.

This experiment was designed to permit a reasonable reproduction, consistent with the addition of the spectrometer, of the charged particle multiplicity and angle cuts used to enhance the effects seen in Ref. 1-3. As previously mentioned, angles of forward going particles were measured in the spectrometer's front chambers. For particles produced at wider angles a sixteen counter hodoscope H surrounding the target gave an angular measure sufficient to reproduce the desired cuts. Outside of these counters was 0.64 cm of lead backed by an additional fourteen counters which were used to select events involving γ rays. Forward going γ rays were detected in the neutron counters.

Between the target and the spark chambers was an 11-counter hodoscope T1 made of 0.33 cm scintillator which completed a 4π solid angle detector about the target. A typical trigger required at least one particle in T1, at least one in a hodoscope T2 following the magnet, an incident beam particle and one and only one neutron counter signal in the allowed time interval. A potential event was vetoed if any particle was detected in the beam halo counter V_1 , the unreacted beam veto counter V_2 , or that element of the charged particle veto hodoscope V_3 covering

the counter which detected the neutron. In order to avoid incorrect TOF data from the association of a neutron signal with the wrong beam particle, a potential event was eliminated if another beam particle arrived within 400 nsec of the beam particle of interest.

A total of 33.5×10^9 beam particles yielded a set of 2.58×10^6 events satisfying the trigger logic. These events form a sample approximately 10 times that of Ref. 1-3. It should be noted that the requirement of one particle through the spectrometer provides an acceptance versus MM which is slightly different from that of Ref. 1-3. However for the present data this is not important as it will not bias a search for narrow structures.

The spectrometer was used to check the MM as calculated from beam and neutron parameters for the constrained final state $^7 \pi^+ \pi^- n$. This was possible because the spectrometer alignment procedure decoupled its measurement of the X^0 mass from the corresponding missing mass measurement. The difference between the two measurements is displayed in Fig. 1b. Note that the position of the peak indicates that the two mass measurements agree within a few MeV/c^2 . The width of the peak is consistent with the stated MM resolution ($\sigma = 0.004 \text{ GeV}/c^2$) and the expected spectrometer resolution ($\sigma = 0.007 \text{ GeV}/c^2$). A two dimensional histogram (not shown) of MM versus spectrometer mass shows that there is no systematic variation between the two mass scales over the range of the experiment.

In fig. 2a we present our mass spectrum with cuts equivalent to those applied to produce the spectrum in Fig. 3b of Ref. 1. Two resonances were reported in Ref. 1, the $M^0(940)$ and the $\delta(963)$. Both

were seen in final states involving two charged particles. The former was seen in final states containing missing neutrals. The latter was not seen in final states containing missing neutrals. Events in Fig. 2a contain two charged particles in the final state, one with $0^\circ < \theta_{\text{LAB}} < 17^\circ$ and the other with $\theta_{\text{LAB}} > 17^\circ$ where θ is the polar angle. In Fig. 2b we present subsets of the data in Fig. 2a which cannot be the result of two body decays. The shaded portion of the figure contains events for which the difference in azimuthal angles between the two charged particles $\Delta\phi$ lies in the range 147° to 180° but which also have a γ in the final state. The unshaded portion of Fig. 2b contains the shaded portion plus events with $0^\circ < \Delta\phi < 33^\circ$. No evidence is apparent in either figure for the $M^0(940)$ or $\delta(963)$.

In Fig. 3a we present our mass spectrum which is equivalent to Fig. 2a of Ref. 2. Events in Fig. 3a have two charged particles in the final state with $79^\circ < \Delta\phi < 180^\circ$ and the larger polar angle between 11° and 17° . Fig. 3b which reproduces Fig. 2c of Ref. 2 shows two charged particle events with $169^\circ < \Delta\phi < 180^\circ$ and one polar angle in the range 6.5° to 17° while the other polar angle is greater than 17° . Neither spectrum shows evidence for the $M^0(1033)$.

In Fig. 3c we present our mass spectrum equivalent to Fig. 3b of Ref. 3 which reported the resonance $M^0(1150)$. The $M^0(1150)$ was seen in final states involving two charged particles after removal of pure two body final states. Events in Fig. 3c have two charges, $79^\circ < \Delta\phi < 146^\circ$ and both polar angles less than 17° . Again there is no evidence for the $M^0(1150)$.

As a measure of the disparity between the present results and those of Ref. 1-3, we present in Table 1 estimates of the number of events we would have expected based on the published production cross sections for these four mesons $\frac{d\sigma}{dt}$ at 0° (column 2 of Table 1). The number of expected events (column 3) is given by

$$N = \rho A L B \epsilon \frac{d\sigma}{dt} \Delta t \quad (1)$$

where ρ is the density of liquid hydrogen ($.0708 \text{ gm/cm}^3$), A is Avagadro's number, L is the target length (38.1 cm), and B is the total beam ($33.5 \times 10^9 \pi^-$). The momentum transfer interval Δt is the range of 4-momentum transfers squared corresponding to the neutron angles subtended by the neutron counters. The efficiency ϵ is the product of 3 terms. The first is the detection probability of a neutron in a 15 cm thick neutron counter, $18 \pm 4\%$.

The second term is the probability of getting one charged particle through the spectrometer. Since this factor depends upon the decay of the X^0 , we use what seems to be a conservative underestimate of 33% based on Monte Carlo studies of s-wave dipion decays. We find 33% to be the probability that one pion passes through the spectrometer while the other pion misses the spectrometer's front spark chambers altogether. For events involving no missing neutrals this estimate is conservative because the actual probability of getting one particle through the spectrometer independent of what happens to the other is some what larger than 33%. This would lead to larger expected event estimates in even greater disagreement with the present data. For final states involving

missing neutrals we expect the probability of getting one particle through the spectrometer to be even greater than it is in the dipion case from Q-value considerations. Since the forward going neutron requirement in the present experiment compels the X^0 to go forward, the probability of getting one particle through the spectrometer increases as the Q value for the X^0 decay decreases. For example in the decay of a spin 0 X^0 into two pions the calculated efficiency increases with decreasing MM from a limit of 33% at high MM. It should also be noted that all the angle cuts of Ref. 1-3 involve at least one forward going particle. An event satisfying these cuts then has an enhanced probability of getting a particle through the spectrometer. This makes the 33% efficiency even more conservative.

The third and final factor in the efficiency is the probability that the decay products of the X^0 will satisfy the angle cuts. As in Ref. 1-3, we take this probability to be unity. The justification for this procedure in Ref. 1-3 was that the only significant effect of the cuts imposed was to reduce the background level under the respective signals.

With the assumptions given above we calculate the number of events expected (column 3 of Table 1) for each of the four mesons and observe that there is no evidence for effects of this magnitude in any of the figures. We believe that if the cross sections of Ref. 1-3 were correct we would have seen obvious effects. We therefore conclude on the basis of an event sample approximately ten times larger than but otherwise very similar to that of Ref. 1-3 that there is no evidence for the production of the $M^0(940)$, $\delta(963)$, $M^0(1033)$, or $M^0(1150)$ in our reaction. This confirms the results of Ref. 4-5.

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TABLE CAPTION

Table 1 presents in column 3 the number of events we would have expected for the mesons listed in column 1 assuming their production cross sections as given in Ref. 1-3. These differential cross sections at polar angle (θ) equal zero are given in column 2.

TABLE I

<u>Meson</u>	$(\frac{d\sigma}{dt})_{\theta=0}$ <u>mb/(GeV/c)²</u>	<u>Number of Events Expected</u>
$M^0(940)$	0.52	3300 (Fig. 2a)
$\delta(963)$	0.49	3600 (Fig. 2a)
$M^0(1033)$	0.07	860 (Fig. 3a)
	0.22	2600 (Fig. 3b)
$M^0(1150)$	0.025	670 (Fig. 3c)

A fraction of the data (39%) was obtained with a trigger which suppressed the detection of events satisfying the cuts of Fig. 2a and Fig. 3a. The corresponding numbers given in column 3 do not include any correction for this suppression. The size of the correction is at most 39%.

FIGURE CAPTIONS

- Fig. 1. a) Plan view of the experimental layout. K0 - K5 are magnetostrictive wire spark chambers. B, V₁, and V₂ are counters, T1, T2, H and V₃ are hodoscopes, and N are the neutron detectors.
- b) Histogram of the difference between the missing mass and the dipion mass measured by the spectrometer for the reaction $\pi^- p \rightarrow \pi^+ \pi^- n$.

- Fig. 2. a) Histogram of the missing mass for events with two charged particles, one with $0^\circ < \theta_{\text{LAB}} < 17^\circ$ the other with $17^\circ < \theta_{\text{LAB}} < 100^\circ$.
- b) Subsets of the events in a) which cannot result from two pion decays of the χ^0 . The shaded events have a γ ray and azimuthal angle difference ($\Delta\phi$) between 147° and 180° . The unshaded events include the shaded plus events with $0^\circ < \Delta\phi < 33^\circ$.

- Fig. 3. a) Histogram of the missing mass for two charge events with one polar angle less than 17° and the other in the range 6.5° to 17° . The azimuthal angle difference $\Delta\phi$ is between 79° and 180° .

- Fig. 3. b) Two charge events with polar angles in the ranges $6.5^\circ < \theta_1 < 17^\circ$ and $17^\circ < \theta_2 < 100^\circ$ and with $\Delta\varphi$ in the range $169^\circ < \Delta\varphi < 180^\circ$. The cuts for a) and b) enrich the data in pure dimeson final states.
- c) Two charge events with both polar angles in the range $0^\circ < \theta < 17^\circ$ and $79^\circ < \Delta\varphi < 146^\circ$. These cuts eliminate pure dimeson final states.

Fig. 1.

Fig. 2.

Fig. 3.