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THE NON-STRANGE NEUTRAL MESON SPECTRUM
FROM $\pi^- p \rightarrow M^0 n$ at 2.4 GeV/c

Ph.D. Thesis Submitted to Iowa State University,
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The non-strange neutral meson spectrum from

$\pi^- p \rightarrow M^0 n$ at 2.4 GeV/c

by

Robert William Jacobel

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TABLE OF CONTENTS

	Page
ABSTRACT	vi
SECTION I. INTRODUCTION	1
SECTION II. APPARATUS	5
Incident Beam	5
Liquid Hydrogen Target	8
Beam Detectors and Electronic Logic	9
Neutron Detectors	13
Target Detector Arrays	15
Other Detectors and Tags	19
Shielding	21
On-Line Data System	23
Typical Running Procedures	26
SECTION III. DATA ANALYSIS	28
Kinematics	28
Mass Resolution and Mass Uncertainty	33
Kinematic Reflections	35
Analysis Program	39
General Data Features	41
SECTION IV. MASS SPECTRA	49
Total Mass Spectrum	49
η^0 and ρ^0 Mesons	62
950 MeV Region	65

	Page
1030 MeV Region	73
1150 MeV Region	82
Summary and Conclusions	86
REFERENCES	90

The non-strange neutral meson spectrum from

$$\pi^- p \rightarrow M^0 n \text{ at } 2.4 \text{ GeV}/c$$

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The non-strange neutral meson spectrum from 900 to 1300 MeV has been studied in the reaction negative pion plus proton goes to neutron plus missing mass at an incident beam momentum of 2.4 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 detectors. 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 neutrons corresponded to mesons produced forward in the center of mass system. Arrays of scintillation detectors surrounding the hydrogen target gave charged particle information which was used to separate the missing mass spectra into different final state categories. The well-established η^0 , ρ^0 and η' mesons were detected along with evidence for four previously unreported mesons. These mesons, appearing as narrow enhancements in the missing mass spectrum, were found in subsets of the two-charged final state category at masses of approximately 940, 963, 1033, and 1150 MeV.

SECTION I. INTRODUCTION

In recent years the area of meson spectroscopy has been of considerable importance in the study of strong interactions. The number of particles or states which have been discovered and tabulated (1), and the accumulation of literature in this field are evidence that this is true. In order to consider the strong force in a spectroscopic framework, it is desirable to know which states or particles exist and their quantum numbers.

The spectroscopic information is obtained in bubble-chamber experiments and experiments involving electronic detectors, that is, scintillation detectors and/or spark chambers. These latter techniques have been particularly fruitful in observing particle states with small cross sections (2-4) or for studying with high statistics the properties of known particles (5-8). This thesis describes the results of an experiment which employed scintillation detectors.

Electronic detector experiments in the field of meson spectroscopy fall basically into two categories, those employing effective mass spectrometers and those employing missing mass spectrometers. Experiments using the effective mass technique measure the momentum of outgoing particles in the final state and kinematically reconstruct their effective mass. Missing mass experiments measure the momentum of one particle in the final state and infer the mass of the remaining particles (the "missing mass") by conservation of energy and momentum. This was the technique utilized in this experiment.

Searches for mesons using the missing mass technique were first done

In the mid 1960's (9,10). Using this technique, the non-strange charged meson spectrum has been studied extensively in the reaction $\pi^- p \rightarrow p + \text{missing mass (MM)}$ (2-4,9,11-13) as well as in processes such as $p+p \rightarrow D+\text{MM}$ (14-18). Missing mass studies of neutral non-strange mesons have been slightly less extensive because of the somewhat greater experimental difficulties involved in detecting neutrons in the reaction $\pi^- p \rightarrow n + \text{MM}$. Several experiments have studied neutral mesons from this reaction by measuring the time of flight of the neutron to determine the effective mass of the undetected particles, that is, the missing mass (8,10,19-23). Other experiments have examined neutral mesons in the reaction $\pi^- p \rightarrow \pi^- p + \text{MM}$ (24) and in the reaction $p+D \rightarrow \text{He}^3 + \text{MM}$ (25,26). Although there had been no less than eight experiments which studied neutral mesons at the time this experiment was planned, the mass regions covered by these experiments were only a small fraction of the mass range which is accessible. Studies of the non-strange charged meson spectrum provide information about mesons with isotopic spin one. A neutral non-strange meson search on the other hand, will yield the neutral members of the isotopic spin one multiplets, plus the particles with isotopic spin zero.

In the present experiment the reaction $\pi^- p \rightarrow n + \text{MM}$ was studied. It was the purpose of the experiment to study this neutral meson spectrum over a large mass range. The apparatus was configured so that a relatively large mass range could be covered at one incident beam momentum. Different mass regions were then studied by varying the incident beam momentum. An additional design criterion required that the detector sizes and acceptances be such that meson states with low production cross sections

would be detected with good statistics.

Specifically, the apparatus employed a beam of π mesons, or pions, incident on a target of liquid hydrogen. Neutrons produced in the near forward direction were detected in an array of plastic scintillators located downstream of the target. The missing mass of the particles produced with the neutron was determined by a measurement of the neutron time of flight. A peak in the time of flight or missing mass spectrum indicated neutral non-strange meson production in the two-body process $\pi^- p \rightarrow M^0 n$. Events not associated with a peak corresponded to non-resonant background, that is, three or more body processes. Scintillation detectors surrounding the target detected the charged particles produced with the neutron and information from these detectors was used to subdivide the mass spectra into different final state categories. The use of these detectors was a modification of the standard missing mass technique because it provided additional information about the missing mass.

Data were taken at seven incident π^- momenta spanning the missing mass region 850 to 2450 MeV. Also several low momentum calibration runs were made to detect well-established low mass mesons. In addition, data were taken at one incident π^+ momentum to study so called "exotic" mesons in the reaction $\pi^+ p \rightarrow M^{++} n$. The results of the data obtained at 2.4 GeV/c incident π^- momentum as well as some of the calibration data are presented here. These data span the mass region 850 to 1300 MeV. This work has been published in three Physical Review Letters (27-29) and in the proceedings of the 1972 Philadelphia conference on experimental meson

spectroscopy (30).

Section II of this thesis deals with the experimental setup and details of the apparatus. In Section III the data analysis is described along with some of the general features of the data. Selected meson spectra are presented in Section IV along with evidence of four mesons at masses of approximately 940, 963, 1033, and 1150 MeV which had not been previously established.

SECTION II. APPARATUS

Incident Beam

The experiment was run at the Argonne National Laboratory Zero Gradient Synchrotron in several stages from December, 1970 through September, 1971.

The apparatus was located in an unseparated beam which for negative momenta consisted mainly of pions. The beam had a usable particle intensity over the approximate range 0.8 to 8.0 GeV/c. Protons of 12.33 GeV/c momentum were extracted from the main accelerator ring and were brought to a focus on a 0.64 cm x 0.64 cm x 10.2 cm long Beryllium target. Pions, kaons, and anti-protons produced at this target were bent by a septum magnet which restricted the production angles of the focused particles to be centered at 1.5° to the proton beam line.

The details of the beam floor plan are shown in Figure 1. The first stage of the beam consisted of two septum magnets, SE1 and SE2, a pair of quadrupoles, Q1 and Q2, and a bending magnet B1, which brought the beam to its first focus at the momentum collimator. The horizontal and vertical magnification at this focus were -0.87 and -4.92 respectively. The second stage of the beam consisted of a bending magnet, B2, followed by four quadrupoles, Q3-Q6, operated as a triplet lense. This stage was designed to recombine momenta at the final focus which was located at the center of the liquid hydrogen target. The spot size of the final focus was approximately circular with a diameter of about 1 cm. Horizontal and vertical magnification were +1.03 and +2.09 respectively. The beam divergence was ± 5.7 mr horizontally and + 7.1 mr vertically. These small

Figure 1. Floor plan of the pion beam

divergences allowed the beam to pass easily through a one foot square opening in the neutron detectors 8.5 m downstream of the hydrogen target.

In order to "tune" the beam it is necessary to adjust the magnet settings to optimize particle transmission. Initial magnet settings were obtained using a ray tracing computer program. Small corrections to these values were obtained in the following manner. The momentum transmitted by the second stage was fixed by setting the field strength of bending magnet B2. The value of the field strength was measured with an NMR probe and maintained to better than 0.1%. The currents in all quadrupole magnets were set at the values determined by the computer program. The currents in the first stage bending magnets SE1, SE2, and B1 were then varied to optimize particle transmission. Finally, the position and size of the beam near the final focus was measured by exposing photographic film to the beam. In some cases slight adjustments of the first stage bending magnets were made in order to bring the spot to the surveyed center of the beam.

In order to determine the number of pions which reach the hydrogen target, it is necessary to determine the contamination of the beam due to other particles. To accomplish this a gas threshold Čerenkov counter was placed in the beam directly downstream of the momentum collimator. By observing the relative counting rates in this detector as a function of pressure of the contained Freon, the constituents of the beam were determined. At 2.4 GeV/c the following particles were found to be present in the approximate indicated percentages: pions (87.3%), electrons (10.2%), muons (1.0%), kaons and anti-protons (1.5%). In addition to this, 15.1%

of the pions present at the Čerenkov counter decayed to muons before they reached the target. A fraction of these were transported by the beam to the final focus. This fraction is calculated to be $0.5 \pm 0.5\%$, bringing the total muon component to approximately 1.5%.

The beam travelled through vacuum pipe from the production target to the first focus and again from the downstream end of the momentum collimator to 2 m upstream of the liquid hydrogen target. To reduce interactions downstream of the target, the beam travelled through helium-filled bags to a point 3 m downstream of the neutron detectors. Typical beam rates at 2.4 GeV/c were between 3 and 4×10^5 particles per 700 ms pulse.

Liquid Hydrogen Target

The liquid hydrogen target used throughout the running was a 25.4 cm long, 5.1 cm diameter cylinder oriented along the beam line. The walls of the flask containing the hydrogen were 0.127 mm thick mylar surrounded by twenty layers of "super insulation". The super insulation consisted of 0.006 mm thick mylar with a deposit of aluminum on one side about 200 Å thick. The hydrogen target flask was surrounded by a vacuum. This vacuum was contained by a cylindrical vessel, 10.2 cm in diameter, with walls of 0.89 mm aluminum and a 0.254 mm coating of mylar. The beam passed through mylar windows which were 0.14 mm thick at the upstream end and 0.254 mm thick at the downstream end. The amount of material surrounding the target was limited in order to minimize interaction of charged secondaries and conversion of gamma rays before they entered

surrounding scintillation detectors. These scintillation detectors completely surrounded the target, except for a 10.2 cm opening for the beam at the upstream end.

Beam Detectors and Electronic Logic

The beam was defined by a series of plastic scintillation detectors which are shown in Figures 1 and 2. The first of these detectors, the momentum hodoscope H and beam detector S_1 were located at the first focus just in front of the momentum collimator. The momentum hodoscope was a seven element array of scintillators with each element 0.95 cm wide by 7.60 cm high by 0.64 cm thick. The width of each element was chosen to be approximately the size of the production target image when magnified by the first stage magnets (31,32). The detector S_1 was a 6.35 cm wide by 7.60 cm high by 0.32 cm thick scintillator located just downstream of the hodoscope at the entrance to the momentum collimator. At 2.4 GeV/c the momentum defining collimator was set for a width of 5.08 cm for approximately 40% of the running and 4.45 cm for the rest. These openings correspond to a total momentum acceptance of 3.8% and 3.3% respectively. Detectors S_2 and S_3 were 3.8 cm and 2.54 cm diameter by 0.16 cm thick circular beam detectors located about 1 m upstream of the center of the target and separated by about 25 cm as shown in the detail of the target region of Figure 2. Detectors A_1 and A_2 were 23 cm diameter by 0.64 cm thick scintillators with a 3.8 cm diameter hole in the center of each. They were located just upstream of the target as shown in Figure 2.

Figure 2. Plan view of the apparatus

The primary purpose of these detectors was to veto beam particles which may have interacted in S_2 or S_3 .

Neutrons produced in the target and arriving in the appropriate time interval were detected 8.5 m downstream by an array of 20 plastic scintillators each 29 cm by 29 cm by 15.4 cm deep. A signal in one of these detectors was denoted N . The entire array subtended a laboratory solid angle of 2.34×10^{-2} sr. On the upstream face of the neutron counters, a slightly over-matched array of eleven 1.27 cm thick scintillators were used in anti-coincidence to veto charged particle interactions in the neutron counters. A signal from one of these detectors was denoted NA .

Detector S_4 was a 33 cm square by 0.32 cm thick scintillator located 750 cm downstream of the centers of the target. It subtended a solid angle of 1.3° by 1.3° with respect to the hydrogen target. Absence of a signal in S_4 indicated that a beam particle had interacted in the target.

The signature of an event then consisted of $H \cdot S_1 \cdot S_2 \cdot S_3 \cdot \bar{A}_1 \cdot \bar{A}_2 \cdot \bar{S}_4 \cdot \bar{NA} \cdot N$; that is, beam particle into the hydrogen, no beam particle out within 1.3° and a neutral signal in the neutron counters in the appropriate time window.

A simplified block diagram of the detector electronics is shown in Figure 3. 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" are fast logic coincidence units and the "VETO" signifies a signal which is in anti-coincidence. Note that in order to have a "START" or "STOP" signal sent to the time to

Figure 3. Simplified block diagram of the electronic fast logic

amplitude converter (TAC) both a beam particle and a neutron are required by the logic. This insures that every acceptable event satisfying the signature described above had both a "START" and a "STOP" signal sent to the TAC. Many of the modules have been left out of the figure or greatly simplified for clarity. There are critical timing relationships between the various pulses entering a module and these relationships have been unspecified for the same reason. Also, there are many detectors and electronic signals which "tag" various types of events that have not been shown. These are not a part of the event signature but enter the computer in coincidence with a "good event" signal.

Neutron Detectors

Neutrons are detected in plastic scintillator by their nuclear interaction with protons and carbon nuclei which provide the detectable ionization when they recoil. The thickness of the scintillator is chosen to balance two factors. It must be thick enough so that the neutron has an appreciable probability of nuclear interaction, while at the same time be thin enough to provide adequate timing resolution to see narrow mesons.

Since the neutral particles which give rise to signals in the neutron detectors can not be kinematically analyzed in order to be absolutely identified, the question may be asked, "How does one know that these are in fact neutrons?" The only neutral particles which can give rise to signals in the detectors are gamma rays, neutral kaons, and neutrons. Gamma rays from beam interactions in the target may be eliminated by virtue of their velocity. The flux of slow neutral kaons is known to be less than one percent of the neutron flux and is therefore negligible.

Further evidence that neutrons are being detected is given by the shape of the mass spectrum which is discussed in Section IV.

The efficiency of the neutron detectors is somewhat dependent on threshold level, that is, the minimum voltage pulse height accepted by the discriminators. To establish production cross sections, some knowledge of the neutron detector threshold is therefore required. In addition, accurate timing information is necessary for the reasons stated above. In order to satisfy both of these requirements both a dynode and the anode signal were used from each detector. Pulse height discrimination was accomplished with the next to last dynode signal while timing information was given by the anode. The photo tubes used were five inch diameter Amperex 58AVP's. High voltages of the photo tubes were set so that the 2.75 MeV gamma ray from a Na^{24} source gave a maximum pulse height from the Compton spectrum of approximately 200 mv on the dynode output. The discriminator thresholds were all fixed at 100 mv. 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 (33). Because of small drifts in the gain of the photo tubes and the discriminator levels, the variable attenuations were adjusted daily when necessary using Na^{24} sources. Typical daily adjustments were of the order of ± 0.5 db or $\pm 5.9\%$. The twenty neutron anode signals were timed with respect to each other to an accuracy of ± 0.2 ns using scattered beam particles. Using this system, the time of flight spectrum for charged particles and gamma rays

in the beam showed a peak at $\beta = 1$ of 1.27 ns full width at half maximum (FWHM) for all 20 detectors.

A certain percentage of the neutrons are absorbed in the material between the hydrogen target and the neutron detector. For example, the scintillator in the front array and the charged particle antis as well as the borax, helium, and the hydrogen target itself all contribute to this absorption. These effects have been calculated using known neutron cross sections (34) and the results as a function of neutron kinetic energy are shown in Figure 4. The absorption is used to correct the total number of events in the cross section calculations given in Section IV.

Target Detector Arrays

Arrays of scintillators were located around the target in order to detect particles recoiling against the neutron. This information was not used in triggering the apparatus but was central to the analysis because it provided a way to subdivide the mass spectra into different final state categories. For example, selections could be made on the number of charged particles detected and/or their approximate directions.

A cylindrical array with 16 elements 7.6 cm wide by 1.27 cm thick by 76 cm long surrounded the hydrogen target as shown in Figure 2. At the downstream end of the cylinder was another array of 16 denoted "front array" arranged to form an 8 by 8 grid as shown in Figure 5. The scintillators were all 0.64 cm thick. Their increasing width at larger distances from the beam were chosen because the target image no longer

Figure 4. Calculated neutron attenuation as a function of neutron kinetic energy for the apparatus

Figure 5. Detail of the front array

appears as a disk but becomes elongated as one moves off the beam axis.

With such an array the position of a single particle, that is, $1x$ count and $1y$ count can be located unambiguously. However, when two or more particles strike the front array an ambiguous situation may arise. This happens, for example, when there are two or more x counts and two or more y counts. To partially remove this ambiguity for the case where two charged particles strike the front array, an additional detector was placed over exactly one quadrant of the array. This resulted in 50% of the two - charged front events at 2.4 GeV/c having their ambiguities resolved. Calculations show that in cases where the ambiguity remained unresolved, the azimuthal angle of each particle could be incorrect by roughly $\pi/2$ if the wrong combination is assumed. However, the difference in azimuthal angles of two particles is found to be essentially independent of which combination is chosen. Similar results hold for the rough polar angle determination given by the array. Thus broad cuts on the azimuthal angle difference of two particles, or on polar angles, are not incorrectly applied when ambiguities remain.

The center square of the front array was 0.8 mm thick scintillator designed to detect particles going directly forward and yet minimize interaction with beam particles. The upstream end of the cylinder was covered by two semicircular 1.27 cm thick scintillators with a 10.2 cm diameter hole for the beam. Thus, except for this small opening at the upstream end of the cylinder, scintillation detectors completely surrounded the target.

In addition to these charged particle detectors, there were also three separate gamma ray detectors, one of which consisted of the neutron counters themselves. A sheet of lead 1.1 radiation lengths thick was placed between the neutron antis and the neutron detectors. The gamma signature consisted of detection of a $\beta = 1$ particle in the neutron counters and no count in the antis. The location of the other two gamma detectors is shown in Figure 2. One of these was a simple scintillator-lead-scintillator sandwich located downstream of the front array. The other was a large scintillator covered by lead and located on one side of the cylinder array. It was operated in anti-coincidence with three cylinder counters which overmatched its solid angle and thus was effectively another scintillator-lead-scintillator combination. The three gamma detectors subtended a combined laboratory solid angle of 1.24 sr.

Other Detectors and Tags

In addition to the detectors discussed thus far, there were several miscellaneous counters and counter combinations used for "tagging" events. An event may be tagged by forming an electronic signal which specifies some experimental condition. This signal can then be sent to a recording device which, in the case of this experiment, was a computer.

Events having two or more neutron dynode signals were automatically thrown away in the off-line analysis. However, it was possible for events to have only one dynode signal and yet have two anode signals. To tag these events one output from each anode discriminator was fed into a DC mixer circuit which triggered a discriminator if the combined pulse

height corresponded to two anodes having given signals. Twenty-five per cent of the final sample of usable events at 2.4 GeV/c had this tag set.

Another type of event which was tagged occurred when a charged particle recoiling against the neutron went nearly forward and preceded it into the neutron counters. This tag was set by requiring a signal from NA to be in coincidence with a prompt signal in the neutron counters.

In order to insure that only one beam particle entered the apparatus at a time, a "beam halo" and "pile up" tag were designed. The detector for these tags was 30.5 cm square by 0.32 cm thick and was located at the downstream end of the last quadrupole magnet. A dynode signal from the detector was fed into a discriminator with its threshold set so that it only fired when the dynode pulse height corresponded to more than one particle having passed through the detector within an interval of approximately 8 ns. A signal from this discriminator then vetoed the beam particle. This was called the beam halo veto because it removed events having two or more beam particles within an interval of approximately 8 ns. The anode signal from this detector was fed into a commercial pile-up gate module. This module supplies an output signal only if two input pulses are received with pulse separation times in the range 8 to 210 ns. Beam particles spaced further in time than this were of no concern since the neutron detectors were not sensitive to time of flights longer than this. In the case where two beam particles were spaced closer than 210 ns, this signal killed the event provided that the neutron had not already been detected. If the neutron had already been

detected, the event was simply tagged to provide information for beam normalization.

It was found in tune-up runs that a large number of events were accumulated at time of flights near $\beta = 1$. Since this region of the spectrum was not of interest, a signal from the halo detector was used to cut off the spectrum for neutrons which came sooner than 13 ns after $\beta = 1$.

Shielding

The shielding for this experiment was an integral part of the apparatus. The experimental areas of the ZGS are a virtual sea of neutrons. The intensity of these neutrons must be reduced by the experimenter wishing to detect neutrons from a given reaction. These unwanted background neutrons enter the apparatus and increase the probability of an accidental event. These are events in which a beam particle entered the hydrogen and a neutron from some other source was detected in the neutron detectors. Clearly it is desirable to have a low ratio of accidental events to real events.

One way in which background neutrons are detected is from neutron capture processes. For example, when the hydrogen of the plastic scintillator captures a thermal neutron a gamma ray of 2.22 MeV is emitted which may be detected. This process has a 332 mb capture cross section (34). Similar captures with cross sections in the 2-3 barn range take place in iron, which was used to house each detector, resulting in a variety of gamma rays from 5.93 MeV to 7.64 MeV. Copper, aluminum

and other materials in the vicinity of the neutron detectors all have thermal neutron capture processes giving gamma rays above the detector threshold as do Nitrogen and Oxygen in the air.

Rather than set higher thresholds on the detectors and thus lose efficiency, it was decided to solve the problem with shielding. Two types of shielding were used. First, large amounts of concrete were placed around the entire apparatus as shown in Figure 2. The purpose of this was to absorb much of the thermal component and to thermalize the higher energy component. Second, 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. Ninety-three per cent of the time this leads to a 477 MeV excited state of Lithium and an alpha particle. The absorption length for this process is 1.3 mm. Thus by placing a borax enclosure of roughly 10 absorption lengths thick around the neutron counters, most of the thermal neutrons surviving the concrete were eliminated.

The neutral singles rate in one of the detectors in an unshielded condition was approximately 6000 counts/pulse (35). After shielding, this was reduced to about 64 counts/pulse. This reduction in singles rate brought the accidental event level to 10.4% of the total events. This was measured during the experiment by delaying a signal from the neutron detector and measuring accidental coincidences with beam particles. It should be noted, however, that this is an average and therefore at a particular time of flight the accidental rate as a fraction of the real event rate could be considerably higher or lower.

On-Line Data System

Information from the 72 detectors and tags as well as neutron time of flight information from the time to amplitude converter (TAC) were fed into a PDP - 15/10 computer with an 8192 word memory. Coupling to the computer was achieved with an interface built and designed by the Ames Laboratory electronics group. Figure 6 shows a block diagram of the interface. Standard -700 mv logic signals from the 72 detectors and tags were fed into Schmidt triggers. The outputs from these triggers were put in coincidence with a strobe signal appropriate to the detector and the output of this coincidence unit set the 72 electronic latches. MECL II logic was used before the latches and thereafter signals were converted to TTL/DTL to be compatible with the PDP hardware. Variable voltage level signals from the TAC were fed into a 12 bit analog to digital converter (ADC) through a sample and hold unit. A logic signal indicating that a "good event" was ready to be accepted caused a program interrupt flag to be set and also inhibited the electronics from accepting any more data. In response to the program interrupt the computer executed a skip request which accepted the contents of the latches 18 bits at a time and then cleared and reset all latches and flags.

Each event constituted five 18 bit computer words. The 72 detectors and tags went into the first four words and the 12 bits of time of flight information went into the first 12 bits of the fifth word. The software was written so that when 50 events had filled a buffer, the octal sum of all the bits set was totalled and stored along with a record identifier in the first two words of the output buffer. This bit sum or check sum

Figure 6. Block diagram of the computer interface

was re-calculated and checked against the original in all subsequent off-line analysis, providing a convenient check that all the data had been recorded. When a buffer was full, 252 18 bit words were written on magnetic tape while a second buffer was being filled. With this procedure maximum data taking rates were about 200 events per ZGS pulse; however, the average rate for normal target full runs was only 50 events per pulse. On-line programs provided diagnostics showing detector rates and gave time of flight histograms. These rates were used to continuously monitor the scintillation detectors for any failures and to make sure that everything looked "normal".

In order to monitor the stability of the TAC - ADC combination, a system of calibration pulses was used. These pulses had a fixed time difference and corresponded to very short and very long time of flights outside the region of physical neutrons. To measure this fixed time difference absolutely the pulses were referenced to a measurement of the flight time of the $\beta = 1$ particles in the beam over a known distance. The pulses were fed into the time of flight logic just like an ordinary event only with a tag that distinguished them. On the average, a calibration event was fed in once every 28 ZGS pulses. At 2.4 GeV/c these pulses showed that the system was stable to less than 0.05 ns over the entire time of flight range and corrections of this order were made when needed. Along with a knowledge of the nanoseconds per ADC channel that such a calibration system provides, one also needs to reference this scale to some absolute time of flight as measured by the apparatus.

To accomplish this, special runs were made where the logic was set up to accept charged particles and gamma rays in the beam. The resulting spectrum gave a narrow, 1.27 ns (FWHM), peak corresponding to $\beta = 1$ time of flights. At 2.4 GeV/c four such $\beta = 1$ runs were made in the two days of running. During this time the absolute position of the $\beta = 1$ peak was stable to less than 0.17 ns. Corrections of this order were made when necessary. Linearity of the TAC-ADC system was tested with a crystal controlled oscillator accurate to a few parts in 10^6 . The system was found to deviate from linearity by less than 0.3 ns over the region corresponding to a mass range 900 to 1300 MeV. Possible bias due to this factor was considered in assigning uncertainties to the mass values given in Section IV.

Typical Running Procedures

To give the reader a feeling for the procedures which were followed while data was being taken, typical running procedures are described below. Target full runs normally consisted of approximately 50,000 events or about one hour. After each run a picture was taken of the scalars and the computer buffers printed out. After a new run had been started, scalar ratios were computed and checked against previous runs for any changes. Detector rates were also compared in this manner. Once during each run the power supplies were monitored, the magnet settings checked, and the target refrigeration apparatus inspected. Helium bag pressures were also checked. Once each day the neutron detector thresholds were monitored with a Na^{24} source and adjusted if necessary.

Typically the target was emptied for one-hour runs without hydrogen once a day. Calibration runs with beam particles were done on each shift or about three times a day. About 75% of the data were briefly analyzed off-line within a few days after being taken.

SECTION III. DATA ANALYSIS

Kinematics

Before a detailed description of the analysis system is given, several topics need to be presented which provide an essential background to the data analysis. The first of these is the subject of the kinematics of the reaction. In general, when a single particle is detected in the final state of a given reaction, the effective mass of the other particles in that final state may be calculated with a knowledge of the momentum and direction of the detected particle. Two special kinematic cases arise where one of these quantities need not be known precisely. The first is at the so called Jacobian peak angle where only the direction and not the momentum need be accurately determined (36). The second case arises at a production angle near zero degrees where only the momentum and not the angle need be determined very well.

Detecting the recoil particle near zero degrees, as was done in this experiment, allowed the following experimental features: 1. A mass range of at least 550 MeV can be covered at a single incident momentum of 2.4 GeV/c. At 7 GeV/c the mass range covered is over 1,200 MeV. 2. All data can be taken with the apparatus in one fixed location. 3. Having the neutron detectors at nearly zero degrees fixes the production angle of the particles recoiling against it to typically less than 1° with respect to the beam. This allows advantage to be taken of the cylindrical symmetry which results from production along the beam

line. A disadvantage of detecting recoil particles near zero degrees is that one must be extremely careful that the beam does not interfere with the apparatus after passing through the target region. A second disadvantage is that for a given laboratory solid angle, the center of mass solid angle subtended at zero degrees is much less than at the Jacobian peak. However this is partially off-set by the fact that typical production cross sections generally fall exponentially with the square of the scattering angle, θ , at small values of θ . Although the missing mass calculation is nearly angle independent in the zero degree region, in this experiment the actual angles of the individual neutron detectors were used in determining the missing mass.

Figure 7 shows a plot of missing mass versus time of flight for a 2.4 GeV/c incident pion and a neutron flight path of 853 cm centered on the beam line. The two values of mass at a given time of flight correspond to the neutron going forward or backward in the center of mass system. Since the time of flight spectrum at 2.4 GeV/c was cut off at a value of 45 ns, only those neutrons emitted near 180° in the center of mass system were detected. Thus in the case of two-body processes, these neutrons corresponded to meson production 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. Figure 8 shows a plot of $|t - t_{\min}|$ versus missing mass for the two extreme angles of the neutron detectors. The lower curve corresponds to a laboratory angle of 1.0° and the upper curve to an

Figure 7. Missing mass versus neutron time of flight for a 2.4 GeV/c pion beam

Figure 8. $|t - t_{\min}|$ in the reaction $\pi^- p \rightarrow M^0 n$ for laboratory angles corresponding to the inner and outer edges of the neutron detectors.

Figure 9. $|t_{\min}|$ versus missing mass for the reaction $\pi^- p \rightarrow M^0 n$

angle of 5.9° . A plot of $|t_{\min}|$ as a function of missing mass is shown in Figure 9. The essential point of these two figures is that the data are taken at t values very nearly equal to $t_{\min}$ but that the t values do vary as a function of missing mass.

Mass Resolution and Mass Uncertainty

Experimental mass resolution and mass uncertainty are both quantities which enter into the data analysis. Mass uncertainty arises because of two independent effects, the absolute uncertainty in the time of flight measurements and the absolute uncertainty of the beam momentum. These are estimated to be ± 0.3 ns and $\pm 0.4\%$ respectively. The total mass uncertainty, obtained by taking the square root of the sum of the squares of the contributing effects, is shown along with the individual contributions in Figure 10.

The mass resolution depends on three independent effects. The first is the fact that it is not known at what point in the 25.4 cm long liquid hydrogen target the interaction occurred, nor at what point in the 15.4 cm deep scintillator the neutron interacted. Thus the exact flight path of the neutron is uncertain. For neutrons near $\beta = 1$ (high mass events) this effect is of little consequence. For slower neutrons the effect is dominant. The second effect contributing to the mass resolution is the momentum resolution of a single beam hodoscope element. This is due to both the physical size of the element and the finite extent of the beam spot. The effect is 0.68% full width at half maximum (FWHM). The third effect is the time resolution of the twenty neutron detectors.

Figure 10. Total mass uncertainty and its components as a function of missing mass

This is 1.27 ns (FWHM) as determined from the width of the peak in the time of flight spectrum from charged particles and gamma rays in the beam. This contribution becomes dominant at high values of missing mass. These three effects and the resulting total effect obtained by taking the square root of the sum of the squares of the individual effects, are shown as a function of missing mass in Figure 11. The results are in agreement with Monte Carlo calculations (32).

Kinematic Reflections

Another area pertinent to the data analysis is the question of kinematic reflections. Can processes such as $\pi^- p \rightarrow \pi N^*$ or $\pi^- p \rightarrow \Lambda K$ give a narrow peak in the neutron time of flight spectrum? To answer this question Monte Carlo calculations were made to study the following reactions:

$$\pi^- p \rightarrow \pi N^* \quad (1)$$

$$\pi^- p \rightarrow \omega N^* \quad (2)$$

$$\pi^- p \rightarrow \Lambda K \quad (3)$$

$$\pi^- p \rightarrow \Lambda K^*(890) \quad (4)$$

$$\pi^- p \rightarrow \Sigma^- K^+ \quad (5)$$

$$\pi^- p \rightarrow \Sigma K^*(890) \quad (6)$$

In reactions 1 and 2 several values of the mass of the N^* were used. The events were weighted according to a Breit-Wigner shape with a Γ of 120 MeV. A production distribution of e^{-10t} was used (N^* going backward in the center of mass frame), and the N^* decayed to a neutron and a pion with an angular distribution of $1 + 3 \cos^2 \theta$. This distribution was

Figure 11. Total mass resolution and its components as a function of missing mass

chosen because aligned distributions are more likely to produce narrow structure in time of flight spectra from these reactions. In reactions 3 through 6 a production distribution of $e^{-7}t$ was used and the Λ or Σ decayed isotropically to a neutron and a pion. In the reactions 4 and 6 a Breit-Wigner shape with the standard parameters was assumed for the $K^*(890)$. In all reactions, events were subject to the trigger constraints of the apparatus, that is a neutron at less than 5.9° and no charged particles at less than 1.3° . Because of these restrictions only a few percent of the events generated give rise to acceptable events.

Monte Carlo results from a 100,000 event sample of the reaction $\pi^- p \rightarrow \pi N^*(1236)$ and a 50,000 event sample from the reaction $\pi^- p \rightarrow \omega N^*(1236)$ are shown in Figure 12. Events per 2 ns bin are plotted as a function of time of flight and mass values corresponding to the time of flights have been indicated for reference. In the case where the final state is πN^* only broad structure is indicated. For the ωN^* final state a somewhat narrower peak is seen but it lies very near to the 45 ns time of flight cut off and so is not of interest to the study of mesons below 1300 MeV. As the mass of the N^* is increased the Monte Carlo spectra become more peaked but are shifted to time of flights of less than 45 ns and so are not a problem. If one considers forward center of mass N^* production the neutrons transform into the lab system at even shorter time of flights and so again are beyond the time of flight cut off of the apparatus. The associated production reactions 3 through 6 behave qualitatively in the same manner. Only broad structure is indicated in reaction 3. Reactions 4 through 6 give structure very similar to that

Figure 12. Monte Carlo results for N^* production in the apparatus

shown from reaction 2 in Figure 12. In these cases, however, the total cross sections are less than $60 \mu\text{b}$. Using the Monte Carlo results and the known cross sections, the number of events expected in the data can be determined. In each case it is a number which is small compared to the events per mass bin in the appropriate spectrum and so cannot give rise to any significant structure.

Analysis Program

The bulk of the analysis of the $2.4 \text{ GeV}/c$ data was done at Iowa State University on an IBM 360/65 computer. The program consisted of a main routine which decoded the information from the data magnetic tapes generated by the PDP-15 computer. Before data were accepted the bits in each record were summed and compared to the check sum for that record which had been written at the beginning of each record when the data were taken. In the rare case where there was disagreement, the 50 events in that record were discarded. The main routine handled the bookkeeping to insure the proper runs were being processed and decoded the detector information for each event. A subroutine converted the ADC information to time of flight using the results from the calibration procedures outlined in Section II. Another subroutine determined the missing mass from the time of flight using the detector information indicating which hodoscope element and which neutron detector had been struck. Other subroutines used the information from the detectors surrounding the target to determine roughly the angles of the charged particles recoiling against the neutron.

Several categories of events were summed in a "failure" subroutine to eliminate them from further processing and thus increase the program efficiency. Included in this category were events with time of flight less than 45 ns, approximately 21% of the 1.83 million raw events at this momentum. This sample was removed to eliminate the possibility of instrumental bias in the high mass end of the spectrum due to any smearing in the edge of the electronic timing pulse which cut off the spectrum. Another large category which was removed by the failure subroutine consisted of events with only a single count in the center square of the front array. This category contained 16.7% of the raw events. It was found that this class of events had a target empty to target full event rate ratio of nearly 1.0; therefore these events did not originate primarily in the hydrogen but instead were due presumably to beam particles interacting in that detector. Other categories of events removed by this routine were events with two or more hodoscope elements firing (4.4%), more than one neutron dynode signal (2.7%), events with one horizontal and no vertical count in the front array (2.2%), and correspondingly those with one vertical and no horizontal count (2.7%). These latter two classes of events were probably due to gamma rays interacting in the front array. A final sample of 903,127 events survived all failure cuts.

After the events were processed and all interesting quantities were determined, a histogramming subroutine was called which typically accumulated missing mass or time of flight histograms with desired cuts on

any of the variables such as number of charges, angles of particles, etc. The events were examined in some 400 such histograms for evidence of structure above smooth polynomial backgrounds.

General Data Features

The histogramming subroutine also gave detector array distributions, charge particle distributions, and other diagnostic histograms which provided understanding of the apparatus. For example, Figure 13 shows the charged particle distribution at each of 4 incident pion momenta. The higher momenta data have been included for comparison. As is expected, the percent of neutral and two-charged events is decreasing at higher momenta while the percent of four-charged, six-charged, and higher multiplicity events is increasing. The events with an odd number of charged particles detected arise in several ways. The largest contribution is due to conversion of neutral particles and gamma rays. Calculations show that approximately 13% of all gamma rays entering the cylinder array and 4% of those entering the front array are converted by pair production and thus are counted as a charged particle. This means that up to 42% of the events in a $\pi^+ \pi^- \pi^0 \pi^0$ final state, for example, will appear as a three-charged event. A second contribution to the odd-charged multiplicities is due to delta rays from a charged particle in one detector causing a count in a neighboring detector. Evidence from the cylinder array distributions shows that this could account for roughly 5% of the three-charged events. A third source of odd-charged final states occurs when two charged particles enter the same detector.

Figure 13. Charged particle distributions at four incident momenta

As the number of charges increases, the probability that this can happen becomes appreciable. Monte Carlo studies of a four-charged pion final state show that approximately 9% of the time these will appear as three charges in the apparatus. Similar studies show that approximately 32% of the time, six charged pions will be detected as only five. A final effect which also works in this same direction is due to inefficiencies from cracks and spaces between the detectors. These spaces are estimated to subtend about 5% of the total solid angle and their effect depends on the particle distributions. These facts suggest that this effect could make roughly 5% of the two-charged events appear as one-charged, 10% of the four-charged events appear as three-charged, and 20% of the six-charged events appear as five-charged.

In addition to the mechanisms already mentioned, the events having only one charge detected have two other sources. Earlier it was stated that events having only one charge in the center square had a target empty to target full event rate ratio of nearly 1.0. These are thought to be due to interactions in that detector and were thus removed from the analysis. Of the remaining one-charged events which were analyzed at 2.4 GeV/c, 89% had the charged particle in the front array while only 11% had the particle detected in the cylinder array. Figure 14 shows the target empty to target full event rate ratios for several of the final state categories at 2.4 GeV/c. Note that the ratio for the one-charged, one front category is considerably higher than the two-charged category or the one-charged, one cylinder category. Furthermore, the time of flight spectrum of these events does not have the same general shape as the other distributions but is weighted more heavily to the

TARGET EMPTY/TARGET FULL EVENT RATE RATIOS AT 2.4 GeV/C	
FINAL STATE CATEGORY	EVENTS EMPTY/EVENTS FULL x BEAM FULL/BEAM EMPTY
0 CHARGES	0.27
1 CHARGE	0.39
1 CHARGE (FRONT ONLY)	0.41
1 CHARGE (CYLINDER ONLY)	0.14
2 CHARGES	0.10
3 CHARGES	0.13
4 CHARGES	0.15
5 CHARGES	0.22
6 CHARGES	0.32
TOTAL	0.19

Figure 14. Target empty/target full event rate ratios

shorter time of flight region. It appears then, that at least 40% of these events are due to interactions in the front array scintillator and not in the hydrogen. Elastic scattering events where the proton did not escape the hydrogen target and an accidental neutron was accepted will also appear in this one-charged category. This effect is more likely to contribute at lower momenta because of the kinematics of elastic scattering. The one-charged data in Figure 13 seem to indicate this trend.

In addition to categorizing events by the number of charged particles in the final state, it is also possible to separate to a degree the pure two-charged (plus neutron) events from the two-charged plus neutrals (plus neutron) events. One way to do this is by using the gamma detector information. Another way is to consider the azimuthal angles of the charged particles as measured by the charged particle detector. Since the missing mass is produced nearly along the beam line, a pure two-body decay (e.g., $\pi^+ \pi^-$) gives two particles whose azimuthal angles about the beam axis must differ by 180° . However, for a three-body decay (e.g., $\pi^+ \pi^- \pi^0$) the difference in the azimuthal angles of the two charged particles will not be uniquely 180° , but will be distributed from 0° to 180° .

To illustrate this point, Figure 15 (a) shows events where one charged particle is in the front array and the other is in the cylinder. This is the largest two-charged category, and contains roughly 62% of all two-charged events. These events are plotted as a function of the difference in their azimuthal angles. The detectors in the cylinder

Figure 15. Azimuthal angle distributions for two-charged events at 2.4 GeV/c. (a) Data events. (b), (c), (d) Monte Carlo events

measure the azimuthal angle of each particle, φ_i , to an accuracy of about $\pm \pi/16$ so that the natural unit for binning is 11.25° . Note the large increase of events in the region 146° to 180° . Figure 15 (b) shows results from a Monte Carlo simulation of the $\pi^+\pi^-\eta$ final state. These calculations which are relatively insensitive to the spin, parity and mass of the $\pi\pi$ system yield events which cluster about an azimuthal angle difference of 180° leading to the conclusion that the increase in this region of Figure 15 (a) is due principally to this final state. Further Monte Carlo studies also indicate that mesons which decay to two charged particles with one or more unobserved neutrals preferentially populate various azimuthal difference regions depending on their spin, parity and density matrix elements. Figure 15 (c) shows the azimuthal angle difference distribution for a $\pi^+\pi^-\pi^0$ final state with $J^P = 1^-$, $l = 0$ and $\rho_{00} = \text{maximum value}$. The same plot with the assumptions $J^P = 0^-$, $l = 0$ is shown in Figure 15 (d). In computing these distributions, the simplest form of matrix element has been assumed. These distributions show that simple cuts on the azimuthal angle difference variable are potentially beneficial in increasing meson signal to background ratios. Since these preferentially populated regions tend to be rather broad, covering at least 40° , the missing mass spectra are typically examined in five or six separate azimuthal difference regions. The Monte Carlo studies indicate further that for a given spin-parity of the meson a particular final state gives the same distribution in the difference of azimuthal angle variable independent of the mass of

the meson. Thus, cuts on this variable are incapable of generating artificial narrow enhancements.

In addition to azimuthal angle information, the detectors also provide a rough determination of the polar angles of particles. The events accumulate naturally into samples where, for example in the case of two-charge events, the particles were recorded by two detectors in the cylinder array, or one detector in the cylinder array and one pair of front detectors, or two pairs of front detectors. Since these samples define rough cuts in the polar angle direction of both charged particles, it is well to ask if these cuts bias mass spectra. Monte Carlo simulation of various final states in the apparatus show that no narrow enhancements are generated in mass spectra by such polar angle restrictions. Polar angle cuts are discussed further in Section IV with regard to the evidence for a meson near 1033 MeV.

SECTION IV. MASS SPECTRA

Total Mass Spectrum

As was discussed in Section I, the presence of a meson in the data is established by an excess of events above a background which, among other things, corresponds to three or more body production. Before looking at the evidence for mesons, a few words are in order to define more clearly this background and to understand the overall shape of the spectrum.

The total mass spectrum in 4 MeV bins is shown in Figure 16. It is characterized by an increase of events at higher values of missing mass which reflects qualitatively the form of the acceptance of the apparatus. This figure contains 78% of the 903,127 good events; 17.4% lie above the mass region shown, and the rest are below. The limits of the figure are arbitrary and have been chosen to display the bulk of the data. The solid curve in the figure is a third order polynomial whose coefficients have been determined by the method of least squares. The fit is over the region 850 to 1338 MeV and has a total chi-square of 307 for 118 degrees of freedom. Higher order polynomials do not significantly improve the confidence level of the fit.

Although the solid curve appears to the eye to follow the data quite well, the confidence level indicated by the fit is extremely low. The reason for this is as follows. Because of the large number of counts per bin, the statistical errors are much less than the systematic errors and the calculation of chi-square does not take into account this

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Figure 16. Total mass spectrum at 2.4 GeV/c. Solid curve is a least squares fit to the data. Dashed curve represents the apparatus acceptance

effect. At least part of this systematic error is due to the fact that the time of flight values come quantized in approximately $1/16$ ns bins corresponding to the least count of the ADC bits. For 4 MeV binning this gives only about 9 ADC bits per mass bin at a mass of 1250 MeV for example. The fact that mass bins are not exactly commensurate with ADC bits means that some mass bins have one more or less bit contributing than their neighbors. This effect is somewhat lessened because of the momentum spread of the beam. The six different hodoscope elements correspond to slightly different beam momentum values and therefore, for a given neutron time of flight, there are potentially six mass values which differ slightly from one another. Typically identical ADC channels populate three different 4 MeV mass bins due to these different momentum values. Therefore something like 27 ADC bits would contribute to a mass bin at 1250 MeV. The difference between 27 and 28 bits going into a neighboring bin at 1250 MeV amounts to an effect of one in 28 or approximately 4%. This effect is much larger than the statistical error on the counts in a bin and accounts for the poor value of chi-square. For low statistics histograms, or larger bin sizes, this effect is negligible.

Except for the bin to bin fluctuations just discussed the data are generally smooth indicating that there are no sizable systematic biases affecting a narrow mass region. Therefore artificial structure due for example to rf beam structure or instrumental effects are excluded to the level of a few percent.

The dashed curve under the data in Figure 16 represents the shape of the acceptance of the apparatus for the reaction $\pi^- p \rightarrow M^0 n$, normalized

to the events in the highest mass bin shown. The fact that the data follow roughly the shape of the acceptance is an indication that the bulk of the events are indeed from this reaction. The reason that the acceptance curve does not lie exactly along the data may be due to several factors. In order to investigate these effects, the data have been divided by the acceptance and are plotted in 8 MeV bins as shown in Figure 17. The vertical axis is a logarithmic scale in arbitrary units. If the detection efficiency for neutrons was a constant over this entire range the scale would be proportional to the double differential cross section $\frac{d^2\sigma}{dm dt}$. The neutron detection efficiency is not energy independent, but it does vary relatively slowly as discussed in Section II. In the central mass region the variation of the data with mass is similar to the variation of the acceptance as indicated by the fact that the spectrum is nearly flat. At higher and lower masses, deviations occur.

The curve below the data in Figure 17 shows how a constant number of events per unit time of flight interval appear when divided by the acceptance and plotted versus missing mass. The normalization of this curve is such that the number of events which it represents is 10.4% of the total number of events. This percentage is the accidental level as measured by the procedure discussed in Section II. The slope of the curve is approximately the same as the data exhibit in the low mass region. This similarity in slope indicates that most of the rise in the data at low mass is in fact due to accidental events which are constant in time of flight.

Figure 17. Logarithmic plot of the total mass spectrum divided by the apparatus acceptance. The curve represents an accidental spectrum which is constant in time of flight

In Figure 18 the curve representing the accidentals has been subtracted from the data and the resulting spectrum now shows a nearly constant value except for a gradual decrease at high missing mass. This decrease may be due to the physics of the reaction $\pi^- p \rightarrow n + \text{anything}$ at higher values of momentum transfer. The fact that subtracting an accidental level which is constant in time of flight produces a relatively flat spectrum is not intended to say that all background has been removed. An additional source of background is due to processes where a pion interacts in the target without producing a neutron in the final state. Charged particles in the final state may then interact in the shielding or other material in the vicinity of the neutron detectors and produce neutrons which give rise to spurious events. The magnitude of this contribution and shape of the spectrum is not easily estimated or measured. In general it would be expected that these accidental events would contribute most significantly at shorter time of flights, that is, at higher values of the missing mass. Thus the events which have been detected in this experiment fall basically into four categories: those corresponding to the reaction $\pi^- p \rightarrow n + \text{meson}$, those from the reaction $\pi^- p \rightarrow n + \text{multi-bodies}$, those corresponding to accidental background neutrons, and those from neutrons which have been made by charged particles originating from interaction of a beam particle. Since the effect of all accidental contributions can not be completely determined it would be incorrect to use the total events in any spectrum to calculate reaction cross sections for the process $\pi^- p \rightarrow n + \text{anything}$.

Figure 18. Logarithmic plot of the total mass spectrum divided by the apparatus acceptance minus the accidental spectrum shown in Figure 17

In many experiments it is possible to construct curves which fit the data using a priori physical considerations such as the shape of phase space and other simple kinematical factors. This is not possible in the present experiment because the number and spectral distribution of spurious events is uncertain as mentioned above. Furthermore the non-resonant contribution to the spectrum from multi-body final states is difficult to characterize since the relative contributions of various final states are not known precisely. However, it is clear from the discussion of Figure 16 that the data contain no appreciable narrow systematic biases. From Figure 18 it can be seen that although there are portions of the spectrum which are not entirely understood, the behavior is generally smooth and that therefore any uncalculated systematic or accidental effects have structure which is broad. Thus, mesons having widths on the order of 100 to 200 MeV would be difficult to uncover in these data. However, to search for narrow mesons, only smooth curves need to be drawn for the backgrounds. It has been found that generally, polynomials of second or third order give good chi-square fits to the data, and that narrow structure is easily seen above or below these curves.

One exception to the above statements concerning the ability of the apparatus to find broad mesons is the data obtained on the ρ^0 meson which is presented later in this section. In this particular case, the ρ^0 mass region is centered at a favorable region of the acceptance. This fact, coupled with the large cross section of the ρ^0 and its known decay mode, provide data which give unmistakable evidence for the meson.

The question may be asked, "Are there better variables than missing mass to employ in plotting the data in order to search for enhancements?" The time of flight variable has the advantage that the accidental events are approximately constant over such a plot. However, when the data are plotted this way they rise over two orders of magnitude in the same range that they rise only a factor of ten when plotted against mass. Plots against mass squared rather than mass are common, but the difference is a matter of personal taste. Dividing out the acceptance in order to obtain a flatter mass spectrum is inconvenient because the statistical errors are no longer simply the square root of the number of counts. For these reasons it was found that for the purpose of searching for narrow enhancements, histograms of missing mass were the most convenient way to view the data.

Figure 19 shows the mass spectrum for events with no charged particles detected in the final state. Similar spectra for events with two and four charged particles in the final state are shown in Figures 20 and 21. These spectra are shown in 4 MeV bins over the mass range 902 to 1302 MeV. The range has been somewhat narrowed to remove events at low mass where the percentage of accidental events is large, and to remove events at high mass where the spectrum becomes steep. All three spectra are fit reasonably well over the region shown by third order polynomials with the following chi-square confidence levels: zero-charged 24.7%, two-charged 0.4%, and four-charged 7.3%. These figures give an overview of the mass spectra. Although no gross indications of meson structure are apparent in these spectra, subsets of these data

Figure 19. Mass spectrum of zero-charged events. Curve is a least squares fit to the data

Figure 20. Mass spectrum of two-charged events. Curve is a least squares fit to the data

Figure 21. Mass spectrum of four-charged events. Curve is a least squares fit to the data

reveal evidence for mesons as will be discussed shortly. The spectra are also useful for determining overall branching ratios to these three final states for the enhancements found.

η^0 and ρ^0 Mesons

In order to test the apparatus, several calibration runs were made to detect established mesons. In these calibration runs the η^0 was observed at an incident beam momentum of 0.83 GeV/c, the ω^0 at 1.5 GeV/c, and the ρ^0 at 1.35 and 1.6 GeV/c. Some of these results have been published in References 27 and 30. Figure 22 shows the η^0 meson in a sample of events corresponding to zero charged particles in the final state. The mass value of 548.8 (± 0.4 , ± 1.3) MeV (37) obtained from the data agrees with the world average of 548.8 ± 0.6 MeV (1). The differential cross section $\frac{d\sigma}{dt}$ at $\tilde{t} = t_{\min}$ is found to be 8.3 ± 2.1 mb/(GeV/c)² in agreement with published data (22, 38).

Figure 23 shows data pertaining to the ρ^0 meson at a beam momentum of 1.6 GeV/c. The upper part of the figure indicates the variation of center of mass solid angle for the fixed laboratory solid angle. In the center portion of the figure are shown the two-charged events having an azimuthal angle difference within $11\frac{1}{4}^\circ$ of 180° (39). These events are labelled "coplanar" because the directions of the two charges are nearly coplanar with the beam line. The smooth background shown below the data is derived from the total missing mass spectrum at this momentum without the coplanar events, and is normalized such that a Breit-Wigner with the ρ^0 mass and width and this background gives the best least

$\pi^- p \rightarrow M^0 n$
0.83 GeV/c
NEUTRAL EVENTS ONLY

Figure 22. η^0 signal in the zero-charged mass spectrum from data at 0.83 GeV/c

Figure 23. Data pertaining to the ρ^0 meson at 1.6 GeV/c

squares fit to the coplanar events. The bottom portion of the figure shows the ρ^0 signal after this background has been subtracted and the angular acceptance is divided into this difference. The curve is a Breit-Wigner with the standard ρ^0 parameters. From the discussion of the azimuthal difference cuts and the Monte Carlo results at the end of Section III it should be clear that the coplanar selection of events was based on the known decay of the ρ^0 meson to $\pi^+\pi^-$. The procedure of subtracting a background and then dividing out the angular acceptance was used in this case because the ρ^0 is rather broad with respect to the mass region covered at this momentum. As was stated earlier, this procedure is not used in order to search for narrow enhancements.

950 MeV Region

In this section evidence is presented pertaining to three mesons in the 950 MeV region. One of these is the well known η' (958), the other two have been designated the $M^0(940)$ (40) and the $\delta^0(963)$. The information on these objects given here has been published previously in References 27 and 30.

Figure 24 shows the data pertaining to the η' (958) at 2.4 GeV/c. In the shaded sample are shown two-charged events with $3^\circ \lesssim \theta_{lab} \lesssim 17^\circ$ which is the front array region of the target detectors. The unshaded sample contains events with four charged particles all having $\theta_{lab} \lesssim 17^\circ$, events with no charged particles for which at least one gamma ray was detected, and the events in the shaded sample. These cuts were motivated by the known branching ratios of the η' . The selection of forward going

Figure 24. η' signal at 2.4 GeV/c. The curve is a least squares fit to the data as described in the text

charged particles presumably corresponds to the $\eta\pi\pi$ decay of the η' which should preferentially populate those spectra for which θ_{lab} is small because of the low kinetic energy available for the decay. The observed signals in the neutral, two-charged, and four-charged spectra are consistent with the known branching ratios of the η' . The mass and width (41) of the η' determined from these data are $957.1 (\pm 0.8, \pm 2.2)$ (37) and $6.6^{+2.8}_{-2.0}$ MeV.

Figure 25 shows events having two charged particles in the final state, one with $3^\circ \lesssim \theta_{lab} \lesssim 17^\circ$ and the other with $17^\circ \lesssim \theta_{lab} \lesssim 130^\circ$. These are two-charged events having one charge in the front array and the other in the cylinder. This sample corresponds to 62% of the total two-charged events. Two enhancements are evident, one at a mass of approximately 940 MeV and the other at approximately 963 MeV. The statistical significance of these effects are 4.5σ and 5.0σ respectively, above a quadratic fit over the range 890 to 1030 MeV, excluding the regions 934-946 MeV and 958-970 MeV. This fit, which is shown in the figure, has a confidence level of 22%. There are 182 ± 43 and 210 ± 44 events, respectively, in the enhancements. A quadratic fit over the same interval, 890 to 1030 MeV, including the regions of the enhancements, has a confidence level of 0.15%.

In order to gain more information about these enhancements several subsets of Figure 25 have been examined. It is found that the enhancement at 940 MeV preferentially populates several regions which cannot be populated by pure two-charged decays of the missing mass. The shaded spectrum of Figure 26 corresponds to those events of Figure 25 for which

Figure 25. $M^0(940)$ and $\delta^0(963)$ signals. The curve is a least squares fit to the data as described in the text

Figure 26. $M^0(940)$ signal in a subset of Figure 25 which can not be populated by pure two-charged final states. The curve is a least squares fit to the data as described in the text

the difference in azimuthal angles of the two charges is in the interval $147-180^\circ$ and, in addition, a gamma ray was detected in the neutron detectors. The unshaded spectrum of Figure 26 is the sum of this shaded sample plus those events of Figure 25 for which the difference in the azimuthal angles of the two charges lies in the interval $0-33^\circ$. The enhancement in the interval 934-946 MeV has a statistical significance of 5.6σ above a quadratic background which was determined by excluding the regions 934-946 MeV and 958-970 MeV and fitting over the region 890 to 1030 MeV. This fit, shown in Figure 26, has a confidence level of 84%. A similar fit over the same interval including the regions of the enhancements, has a confidence level of 4.6%. Although the fit which excludes the regions of the enhancements has a much higher confidence level than the fit which includes those points, the latter still has a confidence level which is acceptable. This is often the case when a comparison of this type is made. The chi-square test fails to clearly distinguish between the two hypotheses. A better comparison can be made by using the method of likelihood ratios (42). For binned data this is just the ratio of the probabilities that the data in the i^{th} bin was derived from hypothesis A over the probability that it was derived from hypothesis B. The final ratio is then the product of the individual ratios for each bin. A more familiar way to state this is that it is just the betting odds for hypothesis A over hypothesis B. In the present case this test has been used to compare enhancement versus no enhancement hypotheses. Hypothesis A assumes two Gaussian enhancements centered at 940 and 960 MeV respectively and a quadratic polynomial

background as a description of the events. Hypothesis B assumes only a quadratic polynomial as a description of the events. The fits to the data under each hypothesis cover the same mass interval with no bins excluded. The no bump hypothesis has a confidence level of 4.6% as was stated previously. The double bump hypothesis has a confidence level of 86%. The likelihood ratio for these two fits indicates that the quadratic plus Gaussian form is 6.7×10^5 times more probable than a simple quadratic fit.

The enhancement at 940 MeV in Figure 26 contains 55 ± 12 events. The mass of the $M^0(940)$ as determined from these data is $940.4 (\pm 1.3, \pm 2.2)$ MeV and the observed width is $10.5^{+3.1}_{-2.4}$ MeV (FWHM). From examination of the other charge topologies at 940 MeV, the branching fractions of the $M^0(940)$ to neutral, two-charged, and four-charged final states are estimated to be 0.21 ± 0.11 , 0.86 ± 0.17 , and 0.02 ± 0.15 (43).

The data of Figure 26 which are the strongest evidence for the $M^0(940)$ justify the procedure of excluding the interval 934-946 MeV in the fit of Figure 25 which was used to evaluate the significance of the enhancement at 963 MeV. This latter effect, which we have designated the δ^0 , has a mass of $962.4 (\pm 1.1, \pm 2.2)$ MeV and an observed width of $9.4^{+2.4}_{-2.0}$ MeV (FWHM). The branching fractions of the δ^0 to neutral, two-charged, and four-charged final states are estimated to be 0.10 ± 0.10 , 0.82 ± 0.15 , and 0.08 ± 0.14 (43).

The observed mass differences between the δ^0 and η' enhancements is 5.28 ± 1.34 MeV. The hypothesis that these mass values are equal has a confidence level of 8×10^{-5} .

To obtain a final mass value for the δ^0 , an estimated contamination of 41 ± 29 events due to the $\pi^+\pi^-\gamma$ decay of the η' have been subtracted from Figure 25 (44). Using these corrected data, a mass of $963.1 (\pm 1.1, \pm 2.2)$ MeV and a width of $9.2^{+2.3}_{-1.9}$ MeV (FWHM) are obtained. The systematic uncertainty in the mass values of both the $M^0(940)$ and the $\delta^0(963)$ can be reduced by comparing the value for the η' obtained in this experiment, $957.1 (\pm 0.8, \pm 2.2)$ MeV, and the world average of 957.1 ± 0.6 MeV (1). Since both values agree, the systematic uncertainty of ± 2.2 MeV can be reduced to the level of the statistical uncertainty on the η' mass from this experiment plus the uncertainty on the η' world average, taken in quadrature. This is ± 1.0 MeV. Final mass values and total uncertainties for the $M^0(940)$, $\eta'(958)$, and $\delta^0(963)$ are then 940.4 ± 1.5 , 957.1 ± 2.3 , and 963.1 ± 1.5 MeV. Within the uncertainty limits the η' width is consistent with the experimental resolution of 8.9 MeV (FWHM). The physical width implied by these data is consistent with the accepted upper limit on the η' width of less than 4 MeV (1). Unfolding the experimental resolution with its estimated uncertainty of $\pm 5\%$ yields physical widths of $5.8^{+4.6}_{-9.2}$ MeV (FWHM) for the $M^0(940)$ and $2.1^{+5.4}_{-7.3}$ MeV (FWHM) for the $\delta^0(963)$. The observed differential cross sections for two-body production of the $M^0(940)$, η' , and δ^0 at $t \approx t_{\min}$ are 0.55, 0.31, and 0.51 $\text{mb}/(\text{GeV}/c)^2$ respectively, with an overall uncertainty of $\pm 30\%$. From Reference 45 the cross section at $t = t_{\min}$ for η' production at 2.4 GeV/c can be estimated to be $0.4 \pm 0.2 \text{ mb}/(\text{GeV}/c)^2$ in agreement with the value reported above.

The reports of mesons (1) in the region 950 to 1000 MeV can be categorized as follows: $\eta\pi^\pm$ enhancements, $\pi^+\pi^-\pi^0$ enhancements (H meson), missing mass searches for charged mesons, and the $M^0(953)$ (46, 47). Neither the $M^0(940)$ nor the $\delta^0(963)$ reported here is predominantly an $\eta\pi$ effect. An $\eta\pi^0$ final state would have 72% of its signal in the neutral spectrum, yet only 27 ± 16 and 27 ± 16 events above background are observed in the neutral spectrum for the $M^0(940)$ and the $\delta^0(963)$ while 481 ± 111 and 553 ± 113 are expected based on the observed enhancements in the two-charged spectrum. It should be noted however, that the neutral member of an isospin multiplet whose charged member decays predominantly via $\eta\pi^\pm$ need not decay predominantly via $\eta\pi^0$. For example, if the $\eta\pi^\pm$ decay is electromagnetic, then the $\eta\pi^0$ decay may be forbidden by C conservation.

Regarding $\pi^+\pi^-\pi^0$ effects, it should be noted that at least part of the $M^0(940)$ enhancement is found in final states involving two charged particles and at least one neutral and is therefore consistent with $\pi^+\pi^-\pi^0$ or $\pi^+\pi^-\gamma$ final states.

The original CERN missing mass experiment reported a mass and width of 962 ± 5 MeV and $\Gamma \lesssim 5$ MeV for an enhancement referred to as the δ^- (48). We suggest that the $\delta^0(963)$ observed in the present experiment is the neutral member of an isotopic multiplet of which the δ^- is the singly-charged negative member.

1030 MeV Region

In this section evidence is presented for a meson near 1033 MeV denoted the $M^0(1033)$ (40). Much of the information in this section has

been published in Reference 29.

Polar angle cuts were briefly introduced near the end of Section III where it was stated that polar angle separations of the data were possible, and that in general they did not produce narrow enhancements. The motivation for making polar angle cuts is to improve meson signal to background ratios. Certain laboratory polar angle regions may be preferentially populated, or de-populated, by the particles from a decaying state because of the kinetic energy available to them. Thus the limits of the laboratory polar angle region which are accessible to these particles are dictated by the decay kinematics of the meson. The usefulness of cutting on polar angles has already been demonstrated in choosing the data samples which showed the η' meson.

In searching for evidence of a meson, the data were divided into typically six polar angle regions and the separate spectra examined. These polar angle regions corresponded to the center detector in the front array, four annular regions of the front array, and the cylinder array. Figure 27(a) shows the polar angle region which provides the strongest evidence for a meson at 1033 MeV. The cut selects those two charged events having one charge strike in the shaded region of the figure and the other strike anywhere in the front array. This cut removes events corresponding to the K^+K^-n final state which have missing mass values just above the K^+K^- threshold.

Since the liquid hydrogen target had a length of 25.4 cm, and since the front array was 63 cm from the target center, cuts on detector geometry are not precise polar angle cuts. Figure 27(b) shows the

Figure 27. Description of the cut which shows evidence of the $M^0(1033)$. (a) The events must have two-charged particles in the front array with at least one in the shaded region. (b) Polar angle acceptance of the shaded region in (a). (c) Monte Carlo results for various two-charged final states showing the fraction of events which satisfy the cuts in (a)

results of a Monte Carlo calculation of the polar angle acceptance for the cut corresponding to the shaded region of Figure 27(a). Note that the acceptance is smooth, and that it is rather broad, 6.2° (FWHM).

To examine quantitatively the mass bias that such a polar angle restriction creates, a Monte Carlo program was used. The probability for various two-charged final states to produce one charged particle which strikes the shaded area of Figure 27(a) and the second particle which hits anywhere in the front array is shown in Figure 27(c). In all cases the decay products of the missing mass were assumed to be distributed according to phase space. These results indicate that in general the acceptance does not generate enhancements except in the case of the K^+K^- final state where structure greater than 100 MeV in width is indicated. Note that the efficiency for detecting this final state at a mass of about 1030 MeV is less than 10%. It can also be seen that the acceptance for the described cut increases substantially with the number of pions in the final state.

Figure 28(a) and 28(b) show actual data corresponding to the selection described above, that is, two charged particles in the front array with at least one in the shaded region. The events in Figure 28(a) fall naturally into two subsets. The first has events with one charged particle in the central detector and the other in the shaded region. For this subset no azimuthal information is available. The second subset has events where the center detector has not fired and two pairs of crossed detectors in the front array locate the two charged particles.

Figure 28. Spectra pertinent to the $M^0(1033)$. (a) Events corresponding to the cut described in Figure 27(a). (b) Events corresponding to a cut which is complementary to the one in (a). (c) $M^0(1033)$ signal in an additional two-charged such category. The curves are least squares fits to the data as described in the text

For this second subset where azimuthal angle information is available, only those events for which the difference in azimuthal angles is between 79° and 180° have been included. The enhancement near 1033 MeV contains 63 ± 13 events above a third order polynomial curve. The curve fits the spectrum from 854 to 1206 MeV excluding the region 1022 to 1042 MeV with a confidence level of 97%. The statistical significance of the effect above this background is 5.9σ . Using the method of likelihood ratios (42) a fit to a third order polynomial plus Gaussian form is found to be 6×10^5 times more probable than a simple third order fit, when both fits are over the entire interval 854-1206 MeV. The preferred hypothesis has a confidence level of 91%. These data are evidence for a meson which we have designated the $M^0(1033)$ with a mass of $1030.9^{+2.9}_{-2.3} \pm 2.5$ MeV (37) and an observed width of $20.2^{+8.6}_{-5.8}$ MeV (FWHM) (41).

Figure 29(b) contains those two-charged events which have the same polar angle restrictions as Figure 28(a), but for which the azimuthal angle difference is between 0° and 79° . This complementary set of data shows no enhancement at 1033 MeV.

Other two-charged categories have been examined for evidence of a meson at 1033 MeV. Figure 28(c) is an independent data sample of two-charged events having one-charge in the cylindrical array ($17^\circ \lesssim \theta_{lab} \lesssim 130^\circ$) and the other in the outer two-thirds of the front array ($6.5^\circ \lesssim \theta_{lab} \lesssim 17^\circ$). In addition, the azimuthal angles of the two charged particles differ by $169 - 180^\circ$. This azimuthal region which corresponds to two charged particles coplanar with the beam is heavily

populated by the $\pi^+\pi^-n$ final state. The enhancement in the interval 1022-1042 MeV contains 174 ± 36 events above a second order polynomial curve. The curve fits the spectrum from 934 to 1134 MeV excluding the region 1022 to 1042 MeV with a confidence level of 58%. The statistical significance of the effect above this background is 5.2σ . Using the method of maximum likelihood ratios, a fit to a second order polynomial plus gaussian form is found to be 1.2×10^4 times more probable than a simple quadratic fit. The preferred hypothesis has a confidence level of 55%. The mass and observed width of the $M^0(1033)$ as determined from these data are $1034.3^{+2.3}_{-2.4} \pm 2.5$ MeV and $18.3^{+4.9}_{-4.6}$ MeV respectively. Note that the data of Figures 28(a) and 28(c) are independent samples.

The mass values as determined from these two samples differ by 3.4 ± 3.7 MeV and hence are consistent. The weighted average of the two mass values is $1032.7 (\pm 1.8, \pm 2.5)$ MeV. The systematic uncertainty in the mass may be reduced by comparing the value of the η' as determined by this experiment, $957.1 (\pm 0.8, \pm 2.2)$ MeV, and the world average of 957.1 ± 0.6 MeV. This yields a final value for the mass of the $M^0(1033)$ of 1032.7 ± 2.1 . The observed widths determined from the data of Figures 28(a) and 28(c) are also consistent. Using the larger of the asymmetric statistical errors in each case, the weighted average for the observed width is 18.7 ± 4.3 MeV. By unfolding the calculated resolution of 9.4 MeV (FWHM) with its estimated uncertainty of $\pm 5\%$, the physical width of the $M^0(1033)$ is found to be $16.2^{+4.8}_{-7.5}$ MeV (FWHM).

The sum of the events in the enhancements of Figures 28(a) and 28(c), 237 ± 38 events, yields a differential cross section for the two-

body process $\pi^- p \rightarrow M^0(1033) n$ of $\frac{d\sigma}{dt} (t \approx t_{min}) = 0.27 \text{ mb}/(\text{GeV}/c)^2$ with an overall uncertainty of $\pm 30\%$. No additional statistically significant evidence for the $M^0(1033)$ has been found in other two-charged categories. In the overall neutral and four-charged spectra there are 20 ± 25 and 9 ± 36 events respectively above background in the interval 1022 to 1042 MeV.

It is difficult in the present experiment to determine the particular final states which are contributing to the $M^0(1033)$. While it is kinematically most favorable for the $\pi^+ \pi^- n$ final state to populate two-charged samples which have their azimuthal difference in the range 169° to 180° (as in Figure 28(c)), other final states with one or more neutral pions can also populate this region as was shown in Figure 15(d). Monte Carlo results show that the enhancement of Figure 28(a) cannot be associated with either a $\pi^+ \pi^- n$ or a $K^+ K^- n$ final state because of the polar angle restrictions. These results suggest that the enhancements of Figures 28(a) and 28(c) may be due to two distinct decay modes of the $M^0(1033)$.

Previous reports (1) of mesons in the mass region 1000 to 1100 MeV can be categorized briefly as follows: the well-established $\phi(1019)$, the $\pi_N(1016)$ which is a charged KK effect, the $S^{**}(1070)$ which has been reported principally in the $K_S K_S$ channel, the $\eta_N(1080)$ which is a $\pi\pi$ effect and which may be related to the S^{**} , and the $A_1(1070)$ which is a 3π effect.

As was stated above, Monte Carlo calculations indicate that the 1033 MeV region of Figures 28(a) 28(b) and 28(c) cannot be significantly

populated by a K^+K^-n final state. In order to study the K^+K^-n channel near threshold, the spectrum containing events which have two charged particles both with $\theta_{lab} \lesssim 11.5^\circ$ and for which the azimuthal angles differ by 147° to 180° was examined. Since near K^+K^- threshold the K^+ and K^- make small angles with respect to the beam, and since they must also be nearly coplanar with the beam to conserve momentum, the acceptance of these cuts for the K^+K^- channel is large. For the $\pi^+\pi^-n$ channel the acceptance of these cuts is zero due to the large kinetic energy available to the $\pi\pi$ system and consequent large opening angles of the pions. The spectrum with these restrictive cuts shows an excess of events centered near 1060 MeV which is consistent with the calculated acceptance for the K^+K^- channel and published KK spectra. In the 1033 MeV region calculations show that at least 41% of K^+K^- events would satisfy these cuts if the spin of the K^+K^- system is assumed to be less than three. However, in the interval 1022 to 1042 MeV only 2.0 ± 3.7 events above a background of about 4 events/8 MeV can be observed in the data. Hence there is no evidence for a K^+K^- decay of the $M^0(1033)$ and thus it can not be associated with the previously reported $\pi_N(1016)$ or the S^* . In addition, since the difference between the world average for the mass of the $\phi(1019)$ of 1019.5 ± 0.6 MeV and the mass of the $M^0(1033)$ is 13.2 ± 2.2 MeV, the $M^0(1033)$ is distinct from the $\phi(1019)$ on the basis of mass as well as decay modes.

Regarding the $\eta_N(1080)$, Reference 1 gives 1083 ± 10 MeV and 98 ± 13 MeV for the average values of the mass and width of this meson. These values are inconsistent with those of the $M^0(1033)$ reported here.

Likewise, most 3π enhancements in the literature in this mass region have a higher mass and/or a larger width than the $M^0(1033)$. Thus the $M^0(1033)$ cannot be convincingly associated with any previously established meson state.

1150 MeV Region

In this section evidence is presented for a meson near 1150 MeV denoted the $M^0(1150)$ (40). Much of the information presented in this section has been published in Reference 28.

This enhancement, like the $M^0(940)$, $\delta^0(963)$, and $M^0(1033)$ is seen in a subset of the two-charged category. Figure 29(a) shows the missing mass distribution in 8 MeV bins for all events with two charged particles in the final state. The curve is a quadratic fit to the data over the range 1042 to 1242 MeV and has a confidence level of 80%. These are the same data which are shown in Figure 20 in 4 MeV bins over a wider range. They are shown again here in 8 MeV bins to provide a reference for the other parts of the figure. Figure 29(b) shows a subset of Figure 29(a) in which both of the charged particles struck pairs of detectors in the front array and their azimuthal angles differed by 79° to 146° . These events populate a part of the azimuthal region which can not be populated by pure two-charged plus neutron final states. The enhancement at 1150 MeV contains 65 ± 16 events above a quadratic polynomial curve. The curve fits the data from 1042 to 1242 MeV excluding the region 1138 to 1170 MeV with a confidence level of 85%. The statistical significance of the effect above this background is

Figure 29. Spectra pertinent to the $M^0(1150)$. (a) Total spectrum of two-charged events. (b) $M^0(1150)$ signal in a subset of (a) described in the text. (c) Events from a subset complementary to the one in (b). The curves are least squares fits to the data as described in the text.

4.7 σ . Using the method of likelihood ratios (42) a fit to a quadratic plus gaussian form is found to be 5.5×10^3 times more probable than a simple quadratic fit, when both fits are over the entire interval 1042 to 1242 MeV. The preferred hypothesis has a confidence level of 67%. These data are evidence for a meson which we have designated the $M^0(1150)$ with a mass of $1148.9 (\pm 3.0, \pm 3.0)$ MeV (37) and an observed width of $18.9^{+7.2}_{-6.7}$ MeV (FWHM) (41). Using the calculated resolution of 10.3 MeV (FWHM) with its estimated uncertainty of $\pm 5\%$, the physical width of the $M^0(1150)$ is estimated to be $15.0^{+9.0}_{-11.7}$ MeV (FWHM). The systematic uncertainty in the mass of the $M^0(1150)$ may be reduced by comparing the mass of the η' as determined by this experiment, $957.1 (\pm 0.8, \pm 2.2)$ MeV, and the world average of 957.1 ± 0.6 MeV (1). The final mass of the $M^0(1150)$ then becomes 1148.9 ± 3.2 MeV (49).

Figure 29(c) contains events with the same restrictions as Figure 29(b) except that the azimuthal angles of the two charged particles in the front array differ by 0° to 79° . The curve is a quadratic fit to the data and has a confidence level of 75%. There are -4 ± 11 events above background in the interval 1138 to 1170 MeV. Finally, the analogous distribution (not shown) in which the difference of the azimuthal angles lies between 146° and 180° shows 23 ± 13 events above background in the 1150 MeV region. In the neutral and four-charged spectra there are an estimated -42 ± 41 and 53 ± 60 events above background respectively in the interval 1138 to 1170 MeV. Thus there is no additional evidence for this effect in the data.

The enhancement in Figure 29(b) containing 56 ± 16 events corresponds to a differential cross section of $\frac{d\sigma}{dt} (\tilde{t}=t_{\min}) = 28 \mu\text{b}/(\text{GeV}/c)^2$ with an overall uncertainty of $\pm 30\%$. From this, an estimate of the total cross section can be made by assuming the differential cross section has the form $\frac{d\sigma}{dt} = Ae^{bt}$. If one assumes $b = 8 (\text{GeV}/c)^2$, this gives a total cross section of about $3 \mu\text{b}$.

Numerous enhancements near this mass in the charged meson spectra corresponding to a three pion or rho-pi final state have been reported in the literature and grouped under the heading $A_{1.5}$ (1). All groups reporting an enhancement from πp interactions cite masses in the region 1170 to 1230 MeV. The $\pi^+\pi^-\pi^0$ effect of Reference 50, in which a relatively low mass of 1177 ± 8 MeV was reported for the $A_{1.5}$ differs in mass from this enhancement by 28.1 ± 8.6 MeV. A Monte Carlo simulation of the decay of the $M^0(1150)$ to three pions distributed according to phase space shows that only 4.2% of these decays satisfy the polar angle restrictions requiring that both charges strike the front array. Spin-parity 0^- and 1^- three pion decays using the simplest forms for the density matrix elements change this result by at most a factor of two. Thus, using the observed signal of Figure 29(b) and the fact that this would correspond to at most 8.4% of a $\pi^+\pi^-\pi^0$ effect, at least 770 events are expected in the total two-charged spectrum in the region 1138 to 1170 MeV while only an estimated 180 ± 145 are found there. Thus, although a sizeable three pion decay of the $M^0(1150)$ cannot be ruled out, it is unlikely on the basis of these Monte Carlo results that the signal of Figure 29(b) is a three-pion effect. It should be noted that the

CERN missing mass experiment reported a narrow effect at 1150 MeV (51) in the reaction $\pi^- p \rightarrow M^- p$ which may be evidence that the $M^0(1150)$ is an isotriplet. However, if the $M^0(1150)$ is an isosinglet it is unlikely to have been seen in any published bubble-chamber experiment studying the reaction $\pi^+ D \rightarrow p p + \text{neutral meson}$ because of the small cross section of this object. For example, typical $\pi^+ D$ exposures in this momentum region have approximately 3 events per μb or less. There are as yet no other counter experiments reporting data on neutral mesons from the reaction $\pi^- p \rightarrow M^0 n$ in this mass region.

Summary and Conclusions

Analysis of the data taken at 2.4 GeV/c has yielded evidence for four new mesons which is summarized in Figure 30. Although all facets of the analysis are not entirely completed, there is no evidence at this time for any other effects larger than five standard deviations. Certain of the histograms that have been examined show evidence of further structure at four or five different masses which although intriguing, is not statistically convincing. The problem of interpreting effects of lower statistical significance is as follows. The probability of occurrence of an enhancement of a given magnitude, purely on the basis of statistical fluctuations, increases as the number of samples increases. For example, a one-bin four standard deviation effect should occur on the average about once in every 16,000 independent bins on statistical grounds alone. The question then arises as to how many enhancements are to be expected entirely on the basis of such statistical fluctuations. This is a

OBJECT	MASS (MeV)	PHYSICAL WIDTH	STANDARD DEVIATIONS	$\frac{d\sigma}{dt} _{t \approx t_{\min}}$
$M^{\circ}(940)$	940.4 ± 1.5	$5.8^{+4.6}_{-9.2}$	5.6σ	$0.55 \frac{\text{mb}}{(\text{GeV}/C)^2}$
$\delta^{\circ}(963)$	963.1 ± 1.5	$2.1^{+5.2}_{-7.3}$	4.5σ	$0.51 \frac{\text{mb}}{(\text{GeV}/C)^2}$
$M^{\circ}(1033)$	1032.7 ± 2.1	$16.2^{+4.8}_{-7.5}$	5.9σ	$0.27 \frac{\text{mb}}{(\text{GeV}/C)^2}$
$M^{\circ}(1150)$	1148.9 ± 3.2	$15.0^{+9.0}_{-11.7}$	4.7σ	$28 \frac{\mu\text{b}}{(\text{GeV}/C)^2}$

Figure 30. Summary of the enhancements

difficult question to answer. Although some 260 of the data samples that have been examined are statistically independent, there are an almost equal number of combinations of these that have been examined also. Therefore it is not a simple calculation to determine how many effects of a given deviation one should expect on statistical grounds.

In choosing the cuts for the spectra we have examined, by hand, categories which make physical sense in terms of the detector geometries and particle decay kinematics. Currently work is underway in which spectra from all these categories, plus others, are being systematically searched by a computer program for evidence of enhancements. By using the computer to do the search we are no longer limited to the number of spectra that can be examined and fitted by hand. In addition, the statistical questions referred to above get answered automatically because enhancements of all standard deviations are tabulated. A histogram of the number of enhancements at each standard deviation level can be accumulated and the results compared against a normal distribution.

In addition to this further analysis of the present data, the group is in the process of preparing an experiment to examine in detail the 1000 MeV region of the neutral meson spectrum with the ability to determine angles and momenta of final state charged particles. This experiment should be able to clarify the status of three of the enhancements presented here.

In order to place the findings of this experiment in an over view of the field of meson spectroscopy it is helpful to refer to a tabulation

of existing states. Reference 1 gives this tabulation and classifies the mesons within the framework of the simple quark model. This model places mesons into groups of nine particles (nonets) which have common spin and parity, J^P . All of the well established mesons occupy positions in the nonets, however, there are several nonets which have missing members. For example the spin-parity 1^+ nonet which contains the B -meson has both its isospin zero states undetermined. Similarly, the 1^+ nonet containing the A_1 meson has at least one and possibly both isospin zero positions unfilled. The status of the A_1 itself is not entirely without doubt. The point here is that within the framework of the model there is room for three or four isospin zero states and possibly an isospin one state. Whether or not any of the enhancements described here correspond to the missing states is an open question which can only be answered by future experiments.

REFERENCES

1. Review of Particle Properties, Particle Data Group, Phys. Letters 39B, 1 (1972).
2. G. Chikovani, L. Dubal, M. Focacci, W. Kienzle, B. Levrat, B. Maglic, M. Martin, C. Nef, P. Schübelin, J. Seguinot, Phys. Letters 22, 233 (1966).
3. R. Baud, H. Benz, B. Bosnjakovic, D. Botterill, G. Damgaard, M. Focacci, W. Kienzle, R. Klanner, C. Lechanoine, M. Martin, C. Nef, P. Schubelin, A. Weitsch, Phys. Letters 30B, 129 (1969).
4. Y. Antipov, R. Baud, R. Busnello, G. Damgaard, M. Kienzle-Focacci, W. Kienzle, R. Klanner, L. Landsberg, A. Lebedev, C. Lechanoine, P. Lecomte, M. Martin, V. Roinishvili, R. Sard, F. Yotch, A. Weitsch, Phys. Letters 40B, 147 (1972).
5. G. Grayer, B. Hyams, C. Jones, P. Schlein, W. Blum, H. Dietl, W. Hoch, H. Lippmann, E. Lorenz, G. Lütjens, W. Männer, J. Meissburger, U. Stierlin, P. Weilhammer, Phys. Letters 34B, 333 (1971).
6. G. Grayer, B. Hyams, C. Jones, P. Schlein, W. Blum, H. Dietl, W. Hoch, B. Lorenz, G. Lütjens, W. Männer, J. Meissburger, W. Ochs, U. Stierlin, P. Weilhammer, Phys. Letters 35B, 610 (1971).
7. K. Foley, W. Love, S. Ozaki, E. Platner, A. Saulys, E. Willen, S. Lindenbaum, Phys. Rev. Letters 26, 413 (1971).
8. L. Holloway, B. Huld, M. Jordan, D. Mortara, E. Rosenberg, H. Russell, S. Bornstein, M. Garrell, S. Margulies, D. McLeod, Phys. Rev. Letters 27, 1671 (1971).
9. H. Blieden, D. Freytag, J. Geibel, A. Hassan, W. Kienzle, F. Lefebveres, B. Levrat, B. Maglic, J. Seguinot, A. Smith, Phys. Letters 19, 444 (1965).
10. M. Feldman, W. Frati, J. Halpern, A. Kanofsky, M. Nussbaum, S. Richert, P. Yamin, A. Choudry, S. Devons, J. Grunhaus, Phys. Rev. Letters 14, 869 (1965).
11. E. Anderson, E. Bleser, H. Blieden, G. Collins, D. Garelick, J. Menes, F. Turkot, D. Birnbaum, R. Edelstein, N. Hien, T. McMahon, J. Mucci, J. Russ, Phys. Rev. Letters 22, 1390 (1969).
12. O. Baloshin, V. Vladimirovskiy, I. Dukhovskoy, V. Kishkurno, A. Krutenkova, V. Kulikov, E. Nikolaevskiy, V. Petrukhin, I. Radhevick, V. Fedorets, Soviet Journal of Nuclear Physics 14, 74 (1972).

13. A. Blagorodov, V. Luzin, L. Murza, A. Panov, I. Radhevich, T. Smolyankina, V. Sokolovskii, Y. Tomashchuk, Y. Shkurenko, ITEF-808 (1970) unpublished.
14. J. Oostens, P. Chavanon, M. Crozon, J. Tocqueville, Phys. Letters 22, 708 (1966).
15. M. Banner, J. Cheze, J. Hamel, G. Marel, J. Teiger, J. Zsebery, P. Chavanon, M. Crozon, L. Rangan, Phys. Letters 25B, 569 (1967).
16. M. Abolins, R. Graven, R. McCarthy, G. Smith, L. Smith, A. Wicklund, R. Lander, D. Pellett, Phys. Rev. Letters 25, 469 (1970).
17. J. Allaby, F. Binon, A. Diddens, P. Dutell, A. Klovning, R. Meunier, J. Peigneux, E. Sacharidis, K. Schlupmann, M. Spighe, J. Stroot, A. Thorndike, A. Wetherell, Phys. Letters 29B, 198 (1969).
18. H. Anderson, M. Dixit, H. Evans, K. Klare, D. Larson, M. Sherbrook, R. Martin, D. Kessler, D. Nagle, H. Thiessen, C. Hargrove, E. Hinks, S. Fukui, Phys. Rev. Letters 26, 108 (1971).
19. M. Feldman, W. Frati, R. Gleeson, J. Halpern, M. Nussbaum, S. Richert, Phys. Rev. 159, 1219 (1967).
20. J. Duffey, B. Gobbi, M. Pouchon, A. Cnops, G. Finocchiaro, J. Lassalle, P. Mittner, A. Müller, Phys. Letters 26B, 410 (1968).
21. A. Zichichi, Annals of Physics 66, 405 (1971)
22. E. Hyman, W. Lee, J. Peoples, J. Schiff, C. Schulz, S. Stein, Phys. Rev. 165, 1437 (1968).
23. D. Binnie, L. Camilleri, A. Duane, D. Garbutt, J. Holmes, W. Jones, J. Keyne, M. Lewis, I. Slotis, P. Upadhyay, Phys. Letters 39B, 275 (1972).
24. R. Thun, H. Blieden, G. Finocchiaro, J. Kirtz, C. Nef, D. Bowen, D. Earles, W. Fiassler, D. Garelick, M. Gettner, M. Glaubman, B. Gottschalk, G. Lutz, J. Moromisato, E. Shibata, Y. Tang, E. von Goeler, Phys. Rev. Letters 28, 1733 (1972).
25. B. Maglich, J. Oostens, M. Silverman, H. Brody, G. Featherston, E. Groves, R. Van Berg, W. Wales, G. Cvijanovich, D. Hartman, Phys. Rev. Letters 27, 1479 (1971).
26. J. Banaigs, J. Berger, J. Duflo, L. Goldzahl, M. Cottureau, F. Lefebvres, Nuclear Physics B28, 509 (1971).

27. D. L. Cheshire, R. W. Jacobel, R. C. Lamb, F. C. Peterson, A. F. Garfinkel, E. W. Hoffman, Phys. Rev. Letters 28, 520 (1972).
28. R. W. Jacobel, D. L. Cheshire, R. C. Lamb, F. C. Peterson, A. F. Garfinkel, E. W. Hoffman, Phys. Rev. Letters 29, 671 (1972).
29. A. F. Garfinkel, E. W. Hoffman, R. W. Jacobel, D. L. Cheshire, R. C. Lamb, F. C. Peterson, Phys. Rev. Letters 29, 1477 (1972).
30. D. L. Cheshire, R. W. Jacobel, R. C. Lamb, F. C. Peterson, E. W. Hoffman, A. F. Garfinkel, in Experimental Meson Spectroscopy - 1972, AIP Conference Proceedings No. 8, edited by K. W. Lai and A. H. Resenfeld (American Institute of Physics, New York, 1972), p. 124.
31. Monte Carlo calculations show that the resolution of each element was 0.68% (FWHM) and that the difference between elements was 0.713%. These calculations are in agreement with similar computations done by hand.
32. The term "Monte Carlo calculations" used throughout this thesis refers to computer simulations of a given set of experimental conditions as they relate to the apparatus. Several such programs were used in the analysis to provide information about quantities which could not be determined by closed mathematical calculations.
33. M. Elfield, E. Miller, N. Reay, N. Stranton, M. Abolins, M. Lin, H. Edwards, Nuclear Instruments and Methods 100, 237 (1972).
34. Neutron Cross Sections, BNL 325, 2nd Edition (1958).
35. Threshold level was 2.5 MeV electron equivalent energy and the room radiation level was 1 mr.
36. B. Maglic, G. Costa, Phys. Letters 18, 185 (1965).
37. When two errors are given the first is statistical, the second is systematic. In determining statistical errors on mass and width parameters a procedure has been employed whereby the desired parameter is varied until chi-square has changed by one unit after the rest of the parameters in the fit have been reoptimized.
38. W. B. Richards, C. B. Chiu, R. D. Eandi, A. C. Hemholz, R. W. Kenney, B. J. Moyer, J. A. Poirier, R. J. Cence, V. Z. Peterson, N. K. Sehgal, V. J. Stenger, Phys. Rev. D1, 10 (1970).
39. 11.25° bins have been chosen for investigating the azimuthal angle differences of two charge events because the geometry of the cylinder array gives natural breaks at $2\pi/16$ or 22.5° .

40. The practice of designating enhancements by a generic label and a mass value in parenthesis has been followed here in parallel with the procedure common in baryon spectroscopy. The generic label M has been used for non-strange mesons.
41. To minimize binning effects, all masses and widths have been determined from the data in 1 MeV bins using polynomial backgrounds and Gaussian forms for the enhancements.
42. J. Orear, UCRL-8417 (1958) unpublished.
43. The statistical errors on the branching ratios have been arbitrarily increased by 50% to account for systematic effects.
44. Events from the $\pi^+\pi^-\gamma$ decay mode are expected to populate the spectrum of Figure 25 because of the larger amount of kinetic energy available for the decay products. The 41 + 29 events have been chosen in accordance with the known η' branching ratios and the observed η' signal.
45. See for example, Robert K. Rader, UCRL-19431 (1969) unpublished.
46. M. Aguilar-Benitez, D. Bassano, R. Eisner, J. Kinson, D. Pandoulas, N. Samios, Phys. Rev. Letters 25, 1635 (1970).
47. B. Maglic, J. Oostens, M. Silverman, H. Brody, G. Featherston, E. Groves, R. VanBerg, W. Wales, G. Cvijanovich, D. Hartman, Phys. Rev. Letters 27, 1479 (1971).
48. W. Kienzle, B. Maglic, B. Levrat, F. Lefebvres, D. Freytag, H. Blieden, Phys. Letters 19, 438 (1965).
49. The reduced systematic uncertainty in the mass value of the $M^0(1150)$ is somewhat larger than those associated with the lower mass enhancements discussed previously. This is due principally to additional uncertainties in setting the mass scale at an interval of approximately 200 MeV away from the $\eta'(958)$.
50. B. Junkmann, E. Keppel, G. Kraus, R. Schulte, R. Steinberg, G. Grote, S. Nowak, E. Ryseck, H. Schreiber, K. Böckmann, H. Prevermann, N. Stief, K. Sternberger, B. Wagini, K. Barnham, V. Cocconi, J. Hansen, G. Kellner, W. Kittel, D. Morrison, H. Tøfte, A. Mihul, M. Bardadin-Otwinowski, T. Hofmohl, L. Michejda, S. Otwinowski, R. Sosnowski, M. Szeptycka, W. Wojcik, A. Wroblewski, Nucl. Phys. B8, 471 (1968).
51. F. Lefebvres, B. Levrat, H. Blieden, L. Dubal, M. Focacci, D. Freytag, J. Geibel, W. Kienzle, B. Maglic, M. Martin, J. Orear, Phys. Letters 19, 434 (1965).