RICE UNIVERSITY

A TARGET CHAMBER FOR SMALL ANGLE SCATTERING EXPERIMENTS

by

Thomas Marion Williams

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ARTS

Thesis Director's signature:

Houston, Texas

September 1975
ABSTRACT

A Target Chamber for Small Angle Scattering Experiments

This target chamber was used in Experiment 80 at the Los Alamos Meson Physics Facility. Experiment 80 was designed to measure the total cross sections and the small angle cross sections for charged pions on C-12, Ca-40, and Pb-208. Particles can be detected from 0 to 35 degrees on one side and from 10 to 180 degrees on the other side of the beam except near 75 degrees which is parallel to the plane of the target. A scintillator can be inserted on the small angle side to detect particles that miss the target. Any one of four target positions can be selected at the remote control, either of three targets or the target out position. This chamber can accept a beam of dimensions up to 3 by 5 inches. It was helium filled to reduce multiple scattering and to protect the calcium target.

By measuring the total cross section and the small angle differential cross section, both the real and the imaginary parts of the forward scattering amplitude, $f(0^\circ)$, can be determined.

Thomas Marion Williams
TABLE OF CONTENTS

I. Introduction

II. Experimental Layout
   A. Total Cross Section
   B. Small Angle Cross Section

III. Beam

IV. Purity

V. Target Chamber
   A. General
   B. Target Holder
   C. Target Changer Control
   D. Scintillator Ports

VI. Results

VII. References

VIII. Acknowledgements
LIST OF FIGURES

1. Total Cross Section Experimental Layout
2. Small Angle Scattering Experimental Layout
3. $^3$P Secondary Beam Channel
4. Photograph of Target Chamber in Position at LAMPF
5. Decay Volume
6. Muon Decay in CM Frame (a) and Lab Frame (b)
7. Jacobiam Peak at $E_\pi = 175$ MeV
8. Target Chamber (top view)
9. Target Chamber (side view)
10. Target Holder Frame
11. Target Changer (cutaway view)
12. Photograph of Chamber showing Target Changer Section
13. Photograph of Remote Control Panel
14. Circuit Diagram
15. Beam Distribution at Target
16. Distribution of Events along Beam
17. Comparison of the Beam Trajectories Measured by the MSSCs to those Measured by the MWPCs
18. Momentum Resolution of 30D40 Magnet compared to Ames 'C' Magnet
19. Momentum Spread in 30D40 Magnet
I. INTRODUCTION

This paper describes the target chamber used in Experiment 80 at the Los Alamos Meson Physics Facility (LAMPF). Experiment 80 was designed to measure small angle (8° to 24°) elastic scattering and total cross section for both positive and negative pions on C-12, Ca-40, and Pb-208 at several pion energies. The measurements are necessary to determine the forward scattering amplitude, \( f(0^\circ) \).

The imaginary part of \( f(0^\circ) \) can be determined by measuring the total cross section. The total cross section \( \sigma \), is related to the imaginary part of \( f(0^\circ) \) through the optical theorem,

\[
\sigma = \frac{4\pi}{k} \text{Im}[f(0^\circ)]
\]

where \( \hbar k \) is the center of mass momentum. The real part of the forward scattering amplitude is obtained from the differential cross section, \( d\sigma/d\Omega \), at small angles where Coulomb-nuclear interference is important.

\[
d\sigma/d\Omega = |F_C + f_S e^{-2i\phi}|^2
\]

where \( F_C \) is the Coulomb and \( f_S \) the "nuclear" scattering amplitude. The pure Coulomb phase and the relative phase have been combined in \( 2\phi \).

\[
2\phi = -2\eta \ln(\sin \theta_{\text{cm}}/2) - \eta \int_{-4k^2_{\text{cm}}/(t'-t)}^{0} \frac{dt'}{|t'-t|} \left[ 1 - \frac{f_S(t')}{f_S(t)'} \right]
\]
where $t$ is the squared four momentum transferred.

$$t = -2k^2_{\text{cm}} (1 - \cos \theta_{\text{cm}})$$

and $\eta = Zze^2/hc\beta$. The sign of $F_c$ and $\phi$ change with the charge of the pion. [M1]

The behavior of the real part of $f(0^\circ)$ is particularly interesting at energies spanning the $T = 3/2$, $J = 3/2$ pion-nucleon resonance since the sign of $\Re f(0^\circ)$ is expected to change at the resonance energy. This conclusion results from the assumption that the pion-nuclear interaction proceeds via the pion-nucleon interaction and that the $(3/2, 3/2)$ resonance is a Breit-Wigner one level resonance with

$$f(0^\circ) \propto \frac{1}{(E_r - E) - i\Gamma/2}$$

and

$$\Re f(0^\circ) \propto \frac{E_r - E}{(E_r - E)^2 + \Gamma^2/4}$$

where $E$ is the total energy in the center of mass, $E_r$ is the total energy at resonance, and $\Gamma$ is the width of the resonance. It is obvious that $\Re f(0^\circ)$ passes through zero at $E = E_r$ for such a resonance.

For accurate results and ease of use, several things must be considered in the design of the target chamber. Multiple scattering and background scattering need to be reduced as much as possible. Events from $\pi-\mu$
decays need to be minimized. The calcium target must not be exposed to air. It should be easy and fast to remove the targets from the beam and insert different targets. The purity of the beam must be determined before any accurate cross sections can be calculated.

This target chamber was designed for Experiment 80 but includes certain additional features that should make it useful in future experiments.
II. EXPERIMENTAL LAYOUT

A. Total Cross Section

The layout for the total cross section part of the experiment is shown in Figure 1. To get a large solid angle and maximum accuracy, the Multiwire Proportional Counters (MWPC) were placed as close as possible to the target. Although not originally designed for this part of the experiment, the chamber was used very successfully here because it was built in sections. Several sections were removed leaving the chamber only ten inches by ten inches and normal height at the target position. The trajectories of the beam particles were determined by three MWPCs. The trajectories of the scattered particles were measured by two MWPCs. Scintillators were used to trigger the wire counters. Electrons were vetoed by a CO$_2$ Cerenkov counter. If a particle was detected in the back three inch diameter scintillator, it was vetoed. This greatly reduced the dead time of the computer. At those small angles, most scattering is multiple Coulomb scattering.

B. Small Angle Cross Section

The experimental layout for the small angle part of the experiment is shown in Figure 2. The electrons were detected by the Cerenkov counter and electronically
The experimental arrangement for the Total Cross Section experiment is shown here. P indicates a Multiwire Proportional Counter, C the Cerenkov counter, and S signifies a scintillator. T is the target.
Figure 2

This figure shows the experimental arrangement for the small angle elastic scattering experiment. P indicates the Multiwire Proportional Counters, S indicates a scintillator, T is the target, and V the veto scintillator. Kontiki is a large motor driven spectrometer stand. All equipment from P1 to S2 is mounted on Kontiki. The pivot point of Kontiki is directly beneath the target.
vetoed. The trajectory of each beam particle was determined by two Multistrip Scintillation Counters (MSSC). These counters gave the X and Y position of the beam at two points. The scattered pions were detected in six MWPCs and momentum analyzed through two magnets. A veto scintillator was used to electronically veto muons from pions that decayed before they hit the target.

The flight path of the pions needed to be as short as possible to increase the number of pions that made it through the system without decaying. The first MWPC (P1 in Fig. 2) needed to be as close as possible to the target to determine the vertex accurately. The minimum distance from the target to the first MWPC was limited by the need to have the counter out of the beam at small angles. The first MWPC was 3.2 by 4.8 inches. There is approximately one and one-half inches of fiberglas between the last active wire and the outside edge of the plane. With a three inch diameter beam, this requires the center of the plane to be at least 5.4 inches from beam center. At eight degrees this limits the first plane to at least forty inches from the target. Since the electronic boxes of the MWPC are toward the target, the maximum extension from the target center to the edge of the target chamber was about thirty-two inches.

A 'C' magnet was necessary to bend the scattered pions away from the beam. To do this with the spectro-
meter magnet would have meant a very long flight path (with its small solid angle and large percentage of decays) or a shorter path with the beam striking the edge of the magnet and increasing background.

All MWPCs, both magnets, and the fourteen inch diameter scintillator (S2 in Fig. 2) were mounted on Kontiki, a large movable spectrometer arm. Thus once the magnets and counters were aligned with respect to each other, they were moved as a unit.

The target chamber extended over the spectrometer with the target centered over the pivot point (see Fig. 3). Since the target chamber should remain stationary when the spectrometer was rotated, it was cantilevered over the spectrometer. This was done by building an extension on the frame that supported the MSSCs, Cerenkov counter, and collimator.
Figure 3

This photograph shows the target chamber in position in Experiment 80. The second Multistrip Scintillation Counter and the first Multiwire Proportional Counter are also visible.
III. BEAM

The layout of the $^3$P Secondary Beam Channel is shown in Figure 4. The total cross section part of the experiment required a beam of low intensity to reduce the number of double readouts in the wire planes. The small angle portion of the experiment required a much more intense beam. To get this intense beam it was necessary to have the beam jaws open at the A2 production target, to have the momentum slits open wider than might be otherwise preferred, and to have the collimator bored to three inches instead of two inches. The beam magnets were set for a focus at the target position. At the target the beam was still over two inches in diameter. The beam had a larger momentum spread than was desired and the divergence was unknown.

Because of this beam size and a desire to reduce scattering from the exit window frame as much as possible, the target chamber exit ports were made six and one-half inches high.
A diagram of the $P^3$ Secondary Beam Channel at LAMPF is shown here. A2 is the production target for the $P^3$ and Stopped Muon channels. BM indicates bending magnets, Q indicates quadrupole magnets. The MS are the momentum slits. The proton absorber is just before BM03. There are two $P^3$ caves as indicated. Experiment 80 was in $P^3$ East.
IV. PURITY

Pion beams contain particles other than pions. A \( \pi^+ \) beam contains \( \pi^+, \mu^+, p, \) and \( e^+ \). To obtain accurate cross section measurements, the purity (per cent of pions) of the beam must be accurately determined. In the \( P^3 \) area at LAMPF, the protons can be eliminated from the beam by proper use of the degrader and proton absorber (see Fig. 4). Since the protons are much heavier than the pions, for equal momenta, the \( \beta_p \ll \beta_\pi \). Thus the protons lose more energy (momenta) in a given thickness of carbon than the pions. Then the protons can be magnetically separated from the pions. In the momenta range in which we are interested (220 to 400 MeV/c), the electrons (positrons) have a velocity very close to \( c \). Thus they can be detected in a \( CO_2 \) Cerenkov counter and electronically vetoed.

The hardest problem is to determine the ratio of pions to muons. Charged pions have a mean life of \( 2.6 \times 10^{-8} \) seconds when at rest. By counting the number of decays into a given solid angle from a certain beam volume, it is possible to determine the number of pions in the beam. The accuracy of this number can be no more accurate than the accuracy of the solid angle and decay volume.

Original plans for the experiment did not call for
particle by particle tracking of beam particles. Since the decay volume varies with the cosecant of the angle, a small uncertainty in the particle position at the first or second MWPC may result in a large uncertainty in the decay volume (see Fig. 5). To increase the accuracy, a port was made on the top and bottom of the target chamber so scintillators could be inserted. With these scintillators defining an acceptance window closer to the beam (≈3 inches from beam center) than the first MWPC, the decay volume can be more accurately determined. With the use of the MSSCs, the point of decay of the pion can be determined because its trajectory before decay is known. Thus the decay volume can be determined without the use of the window scintillators.

The cross section of the decay of the pion in the Lab system is

\[ \frac{d\sigma}{d\Omega_L} = N \frac{d\Omega_{cm}}{d\Omega_L} = NJ \]

where \( N = \frac{d\sigma}{d\Omega_{cm}} \) is constant because of the isotropic decay of the pion in the CM frame, and \( J \) is the Jacobian transformation from the CM to the Lab system. The angular transformation from the CM to the Lab system is

\[ \tan \theta_L = \beta^\mu' \sin \phi' / \gamma (\beta^\mu' \cos \phi' + \beta) \]

where \( \beta^\mu' \) is the velocity of the decay muon in the center.
This figure shows the decay volume which cannot be differentiated from the target (assuming a two inch diameter beam) unless the trajectory of each beam particle is known. Using only the information from P1 and P2, a particle could come from the right side \((X = -1)\) of the target \((Z = 0)\) or anywhere back to \(Z = -26\) inches \((X = 1)\). A different trajectory yields a \(Z = 0\) at the left side \((X = 1)\) of the target or \(Z = 19\) inches \((X = -1)\). An uncertainty of a half wire \((0.05\) inch) in P1 and P2 yields an uncertainty in \(Z\) of 2.4 inches assuming \(X = 0\). The central angle between the beam and P1 is 8 degrees.
The decay of the muon is isotropic in the CM frame (a). In the Lab frame (b) the muon has a maximum decay angle of

\[ \tan \theta_L^{\text{max}} = \frac{\beta^{\mu'}}{\gamma \sqrt{\beta^2 - \beta^{\mu'2}}}. \]
of mass system in units of c, $\beta$ is the pion velocity in units of c, and $\gamma = 1/\sqrt{1 - \beta^2}$.

A sharp peak (or cusp) in the Lab cross section at the limiting value of the Lab angle is expected. The angle of this peak gives a measure of the momentum while the width of this peak (see Fig. 7) is a measure of the momentum spread of the pion beam, and the angular resolution of the detector system. Therefore an accurate measurement can give information on beam momentum and quality as well as beam purity [Cl]. The beam purity measurements were taken at this cusp.
This shows the Jacobian peak expected from pion decay. The $\Delta P/P$ is assumed to be 1% in this Monte Carlo run. The pion kinetic energy is 175 MeV.
V. TARGET CHAMBER

A. General

The chamber extends four and seven-eighths inches toward the accelerator and thirty-two inches toward the detectors from target center. It extends twelve inches to the left of the beam and twenty-four inches to the right. The chamber may be rotated such that the small angle side is on the left instead of the right. This chamber was built for possible use in a two arm experiment even though Experiment 80 was only a single arm experiment. Particles may be detected from zero to thirty-five degrees on one side of the beam and ten to one-hundred-eighty degrees on the other side of the beam except near seventy-five degrees, which is parallel to the plane of the target. The target is offset fifteen degrees from the perpendicular to the beam so that particles may be detected at ninety degrees. There is a port (see Fig. 9) about one-half inch down beam from the target on the small angle side so a veto scintillator can be inserted to within one inch of the beam center. This veto counter will intercept many decay muons that miss the target.

Most of the chamber is eight and one-quarter inches tall, but at the target the target changing apparatus extends fifty inches above the beam and thirteen inches below the beam.
Figure 8

This figure shows the top view of the Target Chamber but without all of the target changing equipment.
Figure 9

This is a side view of the Target Chamber. The rectangular slot labeled V is for the veto counter.
The entire target chamber is designed to be filled with helium. This was a compromise between air and vacuum. A vacuum would have been most desirable. Because of the area of the target chamber, the walls of the chamber would have to be very thick to withstand atmospheric pressure, creating a chamber very difficult to move, difficult to support, and expensive to build. The easiest way would be to make a small chamber to suspend the target and let the flight path be air. This would create about a one-quarter degree error in the trajectory at the first plane. Also the calcium target must not be exposed to oxygen. The entire chamber was designed to be gas tight. Helium was used to fill the chamber because of its low multiple scattering characteristics and because it would not damage the calcium target.

B. Target Holder

The target holder (Fig. 10-12) will hold three targets up to four by six inches and up to one and one-half inches thick. Using extreme care, it would be possible to insert targets up to two and one-quarter inches thick, but this is not recommended because of the possibility of target damage. The frame necessary to support thin targets would limit their dimensions to three and one-half by five and one-half inches. Thus
This is a front and side view of the Target Holder frame. The holes are tapped for #6-32 screws. This frame is also visible in the next two figures.
Figure 11

This cutaway view of the Target Changer shows the target frame in the extreme bottom position. In this position the top target is centered in the beam. The cross hatched pieces are brass guides to keep the target frame properly oriented at 15° from the perpendicular to the beam.
This photograph shows the target frame in the extreme top position. The cover plate is off so targets can be changed. A carbon target is in the center position of the target frame.
this chamber can use a beam of three inches in diameter or an ellipse three by five inches. The targets used were three and one-half inches square.

With the target holder in the extreme top position, new targets can be inserted. Figure 12 shows the cover plate off and one target installed. A glove box was made to fit over the front of the target box. Then a change can be made without letting air into the chamber. It is much easier to insert and remove targets without the glove box, but the box is necessary for installing or removing the calcium target or installing another target when the calcium target is already in place.

The target frame is moved by a three-quarter inch aluminum rod sealed by an O-ring in a brass sleeve. It is driven by a chain on a ten RPM reversible motor. Target position is sensed by micro switches tripped by a round head cap screw which is screwed into the aluminum rod.

Brass guides keep the target frame fifteen degrees from the perpendicular to the beam.

C. Target Changer Control

The original control circuit for this target chamber required the operator to hold his finger on either the up or down button until the desired position was reached. Neon lamps indicated the position of the targets. The modified control circuit has a holding circuit built in
so the motor keeps running until the desired position is reached. The operator selects a target position with the four position switch (Fig. 13). Then the operator can press the L button if going to a smaller numbered position or the R button if going to a higher numbered position. This is not a necessary step because the motor is self reversing at positions 1 and 4. The operator must then press the START button. The motor will then run until the position requested with the switch is reached. When the target and switch positions match, the lamp illuminates. Sometimes the motor overruns the desired position because of inertia. Reversing to the desired position is easy. One set of contacts on relay K1 (Fig. 14) applies voltage to contacts on K2. The other set of contacts on K1 is used to keep K1 energized until the desired position is reached. Relay K2 determines whether the motor rotates clockwise or counterclockwise. The circuit is nearly foolproof if the micro switches are properly adjusted. At the remote control it is impossible to run the target frame beyond its limits no matter what combination of buttons are pushed. The local control switch is a momentary DPDT switch (S6 Fig. 14). This switch is normally used to bring the targets all the way to the top so they can be changed.
Figure 13

This is a photograph of the control panel with the light on. This indicates there is no target in the beam since the switch is in the target out position (1). The L and R push buttons are used to change the direction of the motor. The circuit is wired to be self reversing at positions one and four, so the push buttons may speed up acquiring the proper target, but are not necessary.
This is the wiring diagram for the target chamber and remote control. S1-S5 are micro switches. S6 is a momentary-off-momentary DPDT switch for local control. K1 and K2 are DPDT relays. After the START is pushed, K1 keeps the motor on until the desired position is reached. K2 determines the direction of rotation of the motor. Both K1 and K2 are shown in the de-energized position.
D. Scintillator Ports

At small angles (less than twelve degrees) background from muons was a problem. A veto scintillator was installed about three-eights inch downstream from the target. This made it possible to electronically veto many particles that decayed before they hit the target. Many of these particles made it through all detectors and would have been put to tape without the veto counter. This reduced dead time of the computer and reduced the number of events that would have been put on magnetic tape and then discarded at analysis time.

Provisions were made for the installation of scintillators ten inches downstream and three inches from beam center. These scintillators would have been used to define an acceptance window for the particles for beam purity measurements (see PURITY section). This was not used, possibly because of the use of MSSCs to determine the X and Y of the beam particle and thus get a better definition of where the particle decayed.
VI. RESULTS

Figures 15-19 show some of the results of the experiment. The coordinate system used in the experiment was Z negative at beam origin, positive Y up, and positive X horizontal to the left of the beam (away from the veto counter). X, Y, and Z are zero at target center. These definitions make the coordinate system right-handed. Figure 15 shows the beam at the target. This was a zero degree run and the events are projected back to the target using P1 and P2. The appearance that the beam is larger in X than in Y may be caused by the detectors which are larger in X than in Y. Part of the beam may be missing the detectors.

Figure 16 shows a Z distribution of events taken at sixteen degrees. This is outside the cone of decayed muons, so they cease to be a problem. For some reason the target appears to be at $Z = +3/4$ inch. The cause of this has never been determined. There is no peak in Z other than at the target. This indicates there was nothing in the beam which scatters enough of it to be detected. The only thing that might be expected to be seen was the entrance window which was 0.001 inch Mylar.

The Multistrip Scintillation Counters were new pieces of equipment and completely untested in the system. In Figure 17, the trajectory measured by the MSSCs is
This plot of X and Y at the target position was made at 0° and used the MWPCs to project back to the target.
This shows the Z (along beam) distribution of events for $\theta = 16^\circ$. The peak is centered near $+3/4$ inch. The reason for this offset from zero has not been determined.
To determine the accuracy of the trajectory measurements, the trajectory measured by the MSSCs was compared to the trajectory measured by the MWPCs. This is a plot of the angle between the two trajectories. The width of this peak is determined by the plane wire spacing, MSSC strip width, and multiple scattering.
The momentum measured in the 30D40 spectrometer magnet was compared to the momentum measured in the Ames 'C' magnet at 250 MeV/c. The resolution of the system was 1.6% FWHM.
This is a plot of the beam momentum measured by the 30D40 magnet at 250 MeV/c. It has a width of 2.2% FWHM.
compared to the trajectory measured by the MWPCs. This was a target out run at zero degrees and 145 MeV. The difference in trajectories is a measure of the accuracy of the measured trajectories. The full width at half maximum of this peak is about 1.2°. This is caused by the resolution of the MSSCs, the resolution of the MWPCs, and multiple scattering. The table below lists the contributions of each cause.

<table>
<thead>
<tr>
<th>$T_\pi$ (MeV)</th>
<th>$R_{\text{MSSC}}$ (deg.)</th>
<th>$R_{\text{MWPC}}$ (deg.)</th>
<th>M.S. (deg.)</th>
<th>Total (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>0.63</td>
<td>0.18</td>
<td>0.63</td>
<td>1.12</td>
</tr>
<tr>
<td>145</td>
<td>0.63</td>
<td>0.18</td>
<td>0.53</td>
<td>1.07</td>
</tr>
<tr>
<td>175</td>
<td>0.63</td>
<td>0.18</td>
<td>0.46</td>
<td>1.03</td>
</tr>
<tr>
<td>205</td>
<td>0.63</td>
<td>0.18</td>
<td>0.42</td>
<td>1.02</td>
</tr>
</tbody>
</table>

The resolution of the wire planes and the strip counters are in each dimension so a factor of $\sqrt{2}$ must be inserted to obtain the total. The difference between measured width and calculated width can be accounted for by considering multiple scattering before MSSC2 or after P1. A peak offset from zero would indicate misalignment of either the wire planes or the MSSCs or both.

Figures 18 and 19 show the momentum resolution of the system. Figure 18 shows the momentum resolution of the 30D40 spectrometer magnet compared to the Ames 'C' magnet. The resulting curve has a spread of 1.6% full
width at half maximum. Figure 19 shows the momentum of the beam measured by the 30D40 magnet. This curve has a width of 2.2\%FWHM. Both of these were taken at zero degrees and 250 MeV/c.
VII. REFERENCES


VIII. ACKNOWLEDGEMENTS

The author wishes to express his gratitude to his research advisor, Professor G. C. Phillips, for his guidance, encouragement, and active participation in the work involved in this thesis.

I wish to thank all those in the Rice-University of Houston Medium Energy Physics group for their suggestions as to what capabilities this chamber should have. Special thanks are extended to W. P. Madigan and Pierson DeVries for their suggestions in materials and design, to Ed Hungerford for his preliminary drawings, and to Alex Renzetti and Ray Terhune for their machine work.

I also wish to thank Michael Warneke for several of the drawings used in this thesis and Gary Pfeufer for taking the photographs used in this paper.