Title
Mesons Produced in Proton-Proton Collisions

Author
Peterson, Vincent

Publication Date
1950-05-01

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

BERKELEY, CALIFORNIA

UNCLASSIFIED

UCRL 713
Unclassified Distribution

cy 2.

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

Contract No. W-7405-eng-48

MESONS PRODUCED IN PROTON-PROTON COLLISIONS

Vincent Peterson

May 22, 1950

Berkeley, California

Installation	No. of Copies
Argonne National Laboratory	8
Armed Forces Special Weapons Project	1
Atomic Energy Commission, Washington	2
Battelle Memorial Institue	1
Brush Beryllium Company	1
Brookhaven National Laboratory	8
Bureau of Medicine and Surgery	1
Bureau of Ships	1
Carbide & Carbon Chemicals Div., Union Carbide & Carbon Corp. (K-25 Plant)	4
Carbide & Carbon Chemicals Div., Union Carbide & Carbon Corp. (Y-12 Plant)	4
Chicago Operations Office	1
Cleveland Area Office, AEC	1
Columbia University (J. R. Dunning)	2
Columbia University (G. Failla)	1
Dow Chemical Company	1
H. K. Ferguson Company	1
General Electric, Richland	3
Harshaw Chemical Corporation	1
Idaho Operations Office	1
Iowa State College	2
Kansas City Operations Branch	1
Kellex Corporation	2
Knolls Atomic Power Laboratory	4
Los Alamos Scientific Laboratory	3
Mallinckrodt Chemical Works	1
Massachusetts Institute of Technology (A. Gaudin)	1
Massachusetts Institute of Technology (A. R. Kaufmann)	1
Mound Laboratory	3
National Advisory Committee for Aeronautics	2
National Bureau of Standards	2
Naval Radiological Defense Laboratory	2
New Brunswick Laboratory	1
New York Operations Office	5
North American Aviation, Inc.	1
Oak Ridge National Laboratory	8
Patent Branch (Washington)	1
Rand Corporation	1
Sandia Laboratory	1
Santa Fe Operations Office	1
Sylvania Electric Products, Inc.	1
Technical Information Division (Oak Ridge)	15
USAF, Air Surgeon (R. H. Blount)	1
USAF, Director of Armament (C. I. Browne)	1
USAF, Director of Plans and Operations (R. L. Applegate)	1
USAF, Director of Research and Development (F. W. Bruner, and R. J. Mason)	2
USAF, Eglin Air Force Base (K. K. Compton)	1

Installation	No. of Copies
USAF, Kirtland Air Force Base (H. G. Montgomery, Jr.)	1
USAF, Maxwell Air Force Base (F. N. Moyers)	1
USAF, NEPA Office	2
USAF, Office of Atomic Energy (A. A. Fickel, H. C. Donnelly)	2
USAF, Offutt Air Force Base (H. R. Sullivan, Jr.)	1
USAF, Wright-Patterson Air Force Base (Rodney Nudenberg)	1
U. S. Army, Atomic Energy Branch (A. W. Betts)	1
U. S. Army, Army Field Forces (James Kerr)	1
U. S. Army, Commanding General, Chemical Corps Technical Command (J. A. McLaughlin thru Mrs. G. Benjamin)	1
U. S. Army, Chief of Ordnance (A. R. Del Campo)	1
U. S. Army, Commanding Officer Watertown Arsenal (Carroll H. Deitrick)	1
U. S. Army, Director of Operations Research (Ellis Johnson)	1
U. S. Army, Office of Engineers (B. D. Jones	1
U. S. Army, Office of the Chief Signal Officer (Curtis T. Clayton thry George C. Hunt)	1
U. S. Army, Office of the Surgeon General (W. S. Stone)	1
U. S. Geological Survey (T. B. Nolan)	1
U. S. Public Health Service	1
University of California at Los Angeles	1
University of California Radiation Laboratory	5
University of Rochester	2
University of Washington	1
Western Reserve University	2
Westinghouse Electric Company	4
Univ. of Rochester, Physics Department (R. E. Marshak)	1
Total	143

INFORMATION DIVISION
Radiation Laboratory
Univ. of California
Berkeley, California

OUTLINE

LIST OF ILLUSTRATIONS

I. INTRODUCTION

A. Statement of problem. The particular interest in studying mesons produced in collisions of high energy protons with free protons, as compared to protons bound in nuclei, stems from the definite knowledge of the relative motion of the colliding nucleons. Mesons produced by nucleon-nucleon collisions within complex nuclei may be formed while the struck nucleon is moving toward, perpendicular, or even away from the impinging nucleon. Interpretation of the energy spectrum of mesons produced in such collisions must take account of the lack of exact knowledge of the dynamics of the collision process, and therefore the ability of the experimental data to discriminate between variations in theoretical predictions is reduced.

If, however, an assemblage of free nucleons is used as a target for nucleons of a known high energy, the energetics of the collision may be calculated with little uncertainty. The case of high energy protons on hydrogen is nearly ideal. The hydrogen molecule provides two protons "free" as far as high energy nuclear interactions are concerned. Protons are also ideal bombarding nucleons since they are capable of acceleration to high energy with a very narrow energy spread. The availability of a well-collimated beam of 340 Mev protons from the Berkeley 184-inch cyclotron makes this experiment possible.

Experiments concerning the production of mesons may be expected to indicate which features of present meson theories are qualitatively correct, and furnish quantitative checks with which any future meson theory must agree. It is always to be hoped that the experimental results will contain striking features from which properties of the meson or meson-nucleon interaction may be deduced directly without recourse to detailed calculations.

The study of mesons produced from hydrogen is a logical culmination of the knowledge and techniques gained from earlier experiments on simpler targets. Gardner and Lattes[1] made the first estimate of the meson production from carbon, using the photographic plate technique with the internal circulating cyclotron beam. Later Peterson[2] measured the differential cross-section for production of mesons from carbon in the forward direction at low meson energies for both 380 Mev alphas and 350 Mev protons inside the cyclotron. The external deflected proton beam was first used for meson production experiments by Richman and Wilcox[3] and Weissbluth[4] to study mesons produced from carbon and lead. This method offers the advantages of a well-collimated beam and a field-free region to study angular and energy distributions over the full range of meson energies. These experiments measured the energy distribution of positive and negative mesons produced in nucleon-nucleon collisions within nuclei. The results provide the first extensive experimental check on meson production calculations, although their implications are somewhat obscured by the effects of internal nuclear motion. Production from free protons is an obvious experiment to provide a more severe test of the theory.

B. Energy considerations in proton-proton collisions. In order to produce a mass 276 π meson from a stationary proton, the incident proton must have at least 292 Mev of kinetic energy. This high threshold energy means that the mesons created by collisions of 340 Mev protons with hydrogen will have, in the proton-proton center-of-mass system, kinetic energies of 20 Mev or less. The motion of the center of mass system is given by a β of 0.39, while the β of

[1] E. Gardner and C.M.G. Lattes, Science, 107, 270 (1948).
[2] V. Z. Peterson, Phys. Rev. 75, 1469(A) (1948).
[3] C. Richman and H. A. Wilcox, UCRL-592.
[4] M. Weissbluth, Thesis, UCRL-568.

a 20 Mev π meson is 0.48. Thus upon transformation to the laboratory system, we will expect to find that a large fraction of the mesons will emerge in a generally forward direction.

Presumably the only two reactions leading to the formation of a positive π meson in proton-proton collisions are:

(a) $p + p \rightarrow p + n + \pi^+$

(b) $p + p \rightarrow d + \pi^+$

In case (a) the maximum value of the continuous distribution of possible meson energies can be readily calculated and represents a definite upper limit beyond which no mesons should be observed. In case (b), whose possible existence was first pointed out by Barkas[5], the collision process is a two-body problem and the mesons formed in the center of mass system will all possess a single energy. This energy is very nearly 2.2 Mev higher than the maximum energy calculated in case (a). Upon transforming these results to the laboratory system (making the energy a function of laboratory angle), we obtain the variation shown in Fig. 1. The solid line represents the maximum energy of the continuous distribution, while the dotted line shows the variation of the unique center of mass energy of mesons corresponding to the deuteron formation. The example is calculated for the case of 340 Mev protons incident. The process of transformation increases the separation between the two energies to nearly 4 Mev in the forward direction and reduces it in the region of 90°. In principle the existence of reaction (b) could be confirmed or denied by either a precise determination of the upper energy limit of the meson energy spectrum, or by

[5] W. Barkas, Phys. Rev. 75, 1109 (1949).

showing the existence of a single energy "line" beyond the continuous distribution at any one observation angle.

C. Direct production vs. subtraction techniques. A target of free protons may be obtained either by using pure hydrogen or by obtaining it in molecular combination with other elements. In the latter case the effects of hydrogen must be obtained by measuring separately and subtracting the effects of its companion elements. In spite of this added complication, the subtraction technique may be less difficult than the construction of a special target to contain hydrogen in liquid or gaseous form. The small cross-section for meson production requires that if hydrogen gas be used it must be confined at high pressures, while the use of liquid hydrogen necessitates cryogenic techniques.

In this experiment the direct production technique was chosen, using a liquid hydrogen target. The experiments of Richman and Wilcox showed a very high background of inelastic protons from carbon in the forward directions, with which any subtraction technique must cope. In the case of hydrogen, however, the protons are all elastically scattered so that the only background at small observation angles will come from very high energy protons whose range will be much greater than the highest energy meson to be observed. A direct experiment also has the obvious advantage of allowing one to gather statistics without subtraction, this point being of particular interest in an experiment using photographic plates. In addition, it is of great advantage to know that all of the mesons observed arise from hydrogen when analyzing such effects as the angular distribution of μ-mesons resulting from decay of the positive π's.

The subtraction technique, using C and CH_2, has been tried successfully by Cartwright, Richman, Whitehead and Wilcox[6] making use of a magnetic field

[6] Cartwright, Richman, Whitehead, and Wilcox, Phys. Rev. (to be published).

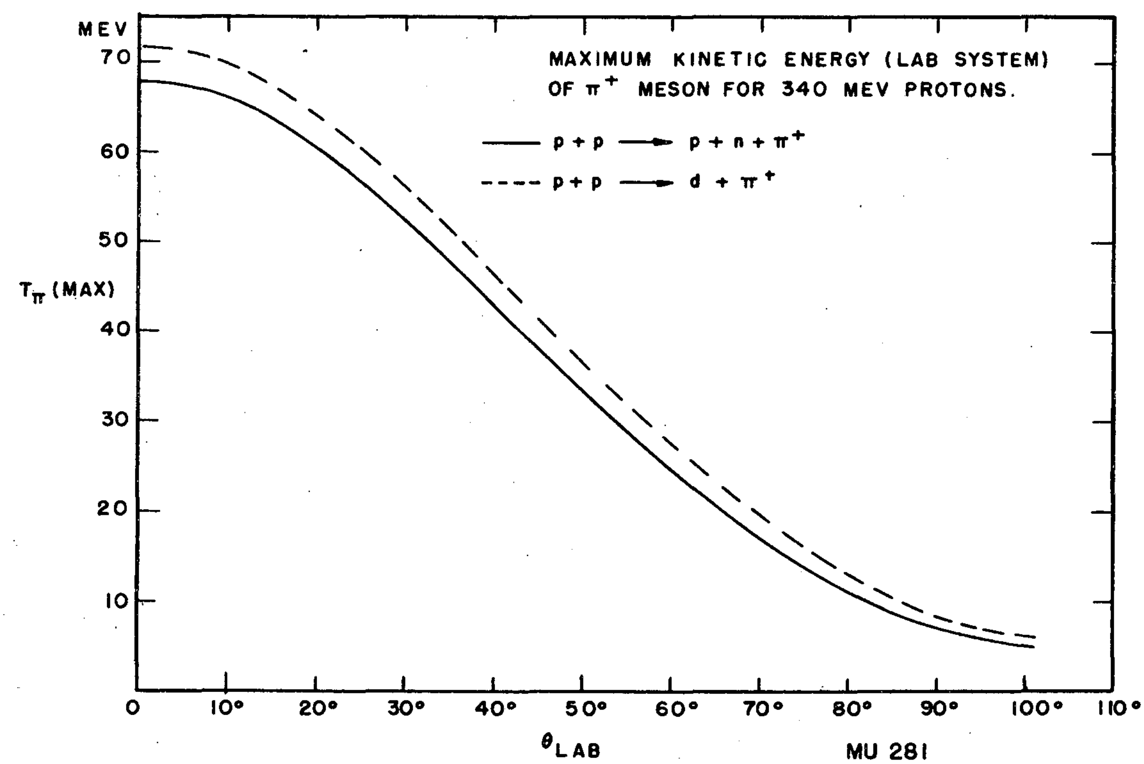

MEV
70
60
50
40
30
20
10
T_π (MAX)
MAXIMUM KINETIC ENERGY (LAB SYSTEM)
OF π+ MESON FOR 340 MEV PROTONS.
p + p → p + n + π+
p + p → d + π+
0
10°
20°
30°
40°
50°
60°
70°
80°
90°
100°
110°
θ LAB
MU 281

FIG. 1

14968-1

and channels to select narrow momentum bands of positive or negative particles for study at any one exposure. This method has succeeded in obtaining results for hydrogen without requiring prohibitive numbers of mesons, in part due to the strongly peaked energy distribution and large cross-section for hydrogen. This method is particularly well-suited to observation at 0° where the direct method cannot work, and the two methods supplement each other in this respect. Comparison of our results with those obtained by the subtraction technique will be made in Section IV.

II. EXPERIMENTAL METHOD

A. General experimental method. A sketch of the general method of bombardment by the deflected proton beam from the 184-inch cyclotron is shown in Fig. 2. Use is made of a pulsed electrostatic deflector and magnetic channel to bring a small fraction of the circulating beam outside the cyclotron. This beam is collimated by a narrow (.15 in. x .50 in.) slit just before it passes between the poles of a focusing magnet. Neutrons and low energy protons formed at the slit are lost to the beam by the time the main high energy component is bent through 10° and partially focused horizontally at the end of a 22-foot tube leading through the main cyclotron shielding to a "cave" where the deflected beam experiments are run. Final collimation of the proton beam is achieved by a long (48 in.) brass collimator mounted at the exit end ("snout") of the tube. The cross-sectional area of the beam may be limited either by the pre-magnet slit or by the snout collimator. The beam size used in these experiments was about 3/4 in. x 1-1/4 in.

A reliable beam intensity of about 10^{-10} amperes of protons can be obtained under these conditions, and the exposure times required range from 1 to 10 hours depending on the geometry involved. The total number of protons striking the target is determined by passing the beam through an ion chamber before striking the target and measuring the charge collected. The target was aligned with respect to the beam by exposing x-ray film mounted at either end of the target.

The hydrogen target will be described in more detail in the next section. Photographic plate detectors were used, and angles of observation 15°, 30°, and 60° were chosen to study the meson energy distribution. The greatest part of the plate analysis to date has been made on the 30° plates and therefore furnishes

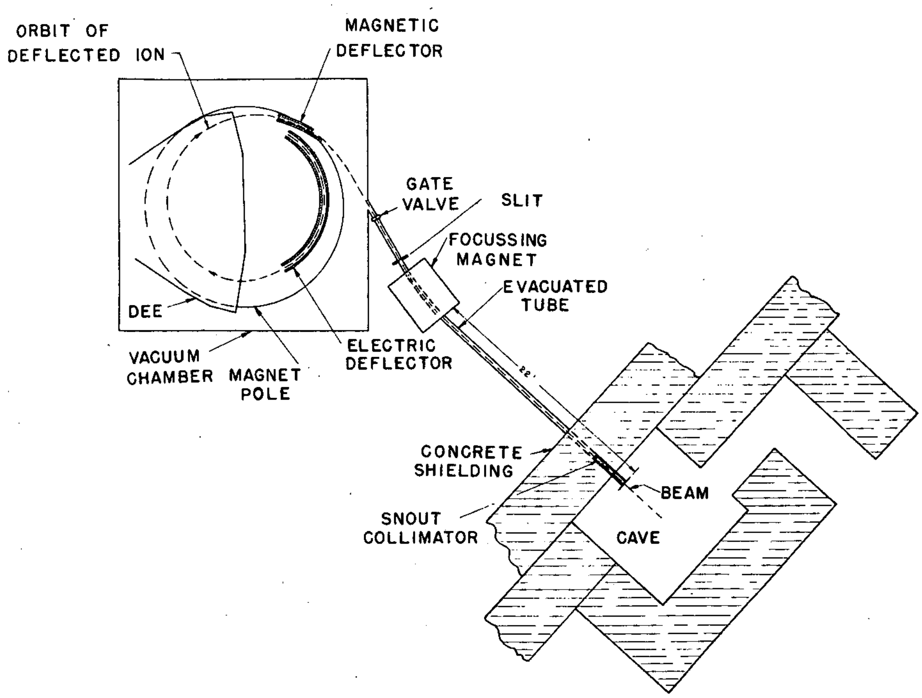


FIG. 2

MU 275

METHOD OF PRODUCING A PULSED BEAM OF DEFLECTED HIGH ENERGY PROTONS FROM THE BERKELEY 184" CYCLOTRON.

the basis of the results reported here.

Blank runs were made in connection with each series of runs, and the number of mesons detected without hydrogen in the target (but all other conditions the same) proved in all cases to be a negligible fraction of the hydrogen effect. The early runs were made with a "line" source to avoid end window effects. Later runs were made with a thin-walled "point" source after the yields proved that this could be done without reverting to a subtraction technique.

The detector geometry will be described in more detail in later sections, but in general two types were used. In the first runs the detector viewed the source directly in a region of no magnetic field and therefore registered elastically scattered protons, mesons, and neutron-induced background. Later runs employed a magnetic field interposed between source and detector in such a way as to select only positive particles having momenta below a certain maximum value. This was done to separate mesons from elastically-scattered protons.

The exposed and processed photographic plates were scanned under a microscope to detect mesons. Identifications of the mesons was made by the characteristic "wander" and change in grain density near the end of the track. The qualitative features of each event were sketched, and the orientation of the μ-meson measured and recorded. The final product of the measurements of the number and position of the mesons in the plates is a plot of the differential cross-section for meson production as a function of meson energy at a given observation angle.

B. <u>The liquid hydrogen target.</u> Although hydrogen gas at very high pressures was considered as a target in this experiment, liquid hydrogen was chosen for several reasons. One was that use of high pressures involved relatively thick end windows which would be exposed to the proton beam and therefore would produce mesons. A target of this design would be limited to a long line source with attendant difficulties in angular resolution and definition of target area. With liquid hydrogen at atmospheric pressures it seemed possible to construct a sufficiently thin-walled container so that wall effects could be ignored. Another factor in the choice of liquid hydrogen was its ready availability on the Berkeley campus from the low-temperature laboratory of Professor W. F. Giauque.

The essential requirements of a liquid hydrogen container are those of a good Dewar: That it be built as a high vacuum insulated vessel of material having low heat conductivity with highly reflecting internal surfaces. In addition this target incorporates a liquid nitrogen jacket to pre-cool the hydrogen vessel and maintain the radiative surroundings at a low temperature. The specific use of this container as a target for a charged particle beam required that the beam entrance window be reasonably thin to minimize proton scattering. Observation of low energy mesons necessitated the incorporation of thin windows in the detection direction. Finally, since hydrogen-air mixtures are potentially explosive, some safety precautions regarding the filling and venting of hydrogen had to be considered.

The size of the vacuum chamber was determined by the decision to use a line source first, and by the requirement of small observation angles. In order to observe at 15° and not "see" the end windows of the line source, the source had to be about 36 inches in length. The end windows of the vacuum chamber were displaced even further from the target area to make it easier to shield the photographic plates from scattered protons. A photograph of the main vacuum tank and associated pumping system is shown in Fig. 3. The vertical column or "stack" contains the liquid hydrogen reservoir surrounded by a double-walled

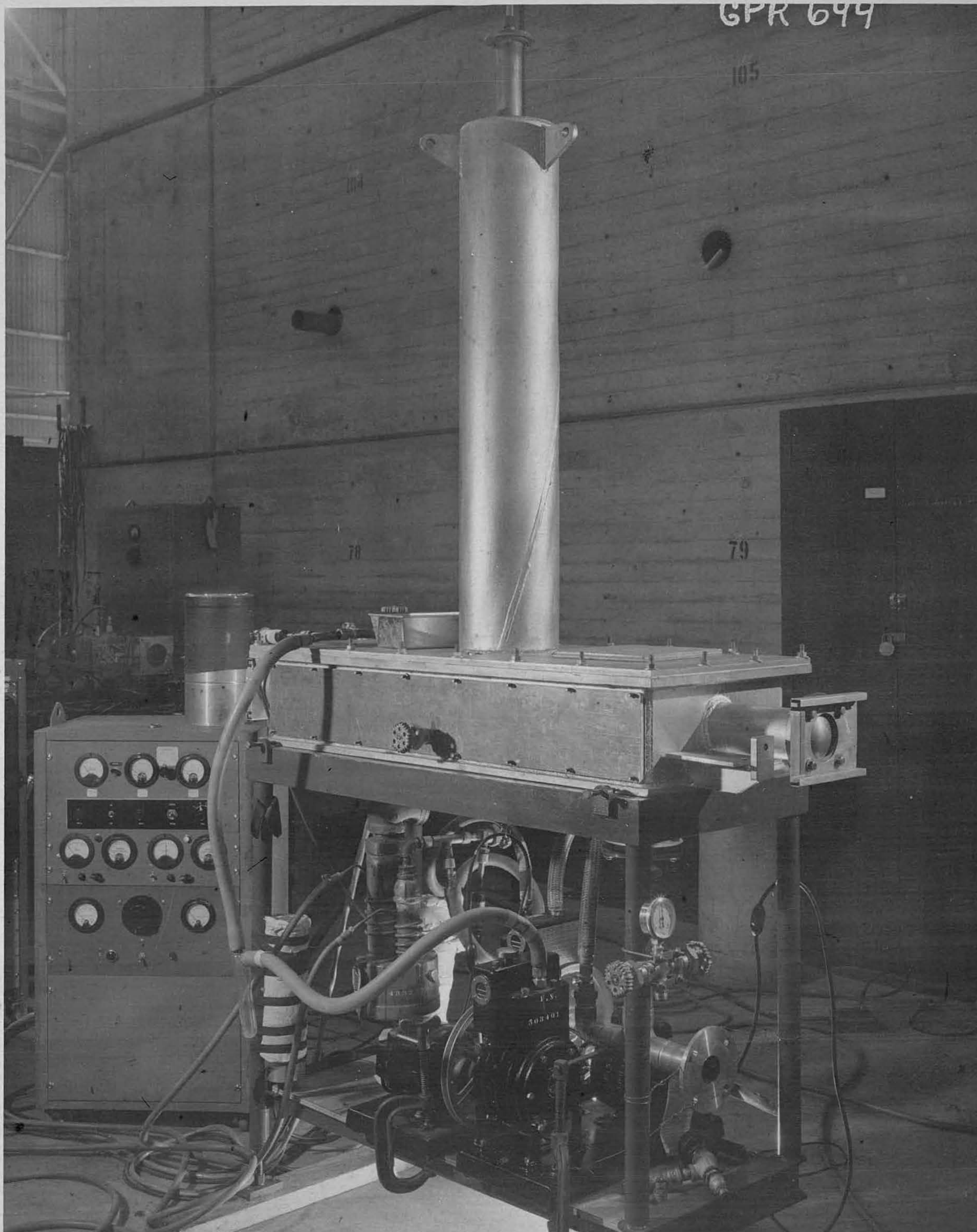


FIG. 3

LIQUID HYDROGEN TARGET WITH PUMPING SYSTEM

OZ 912

jacket of liquid nitrogen. The venting and filling apparatus is not shown.

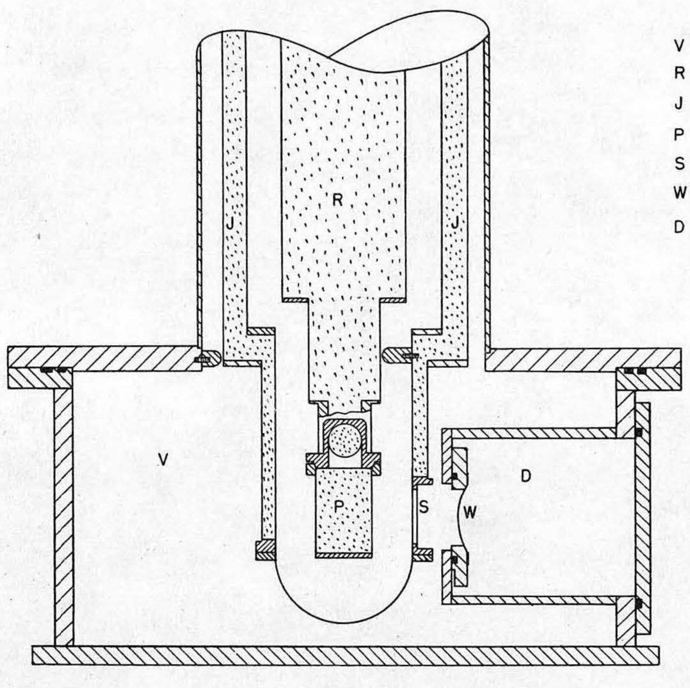
A more detailed idea of the design may be seen in Fig. 4, which is a simplified version of the assembly drawing. The view is along the beam direction. This figure shows the "point" source and reservoir surrounded by the nitrogen jacket. Reservoir and jacket are both joined to the vacuum chamber only at the top of the stack and maintain their spacings below by means of steatite standoffs. For assembly reasons the nitrogen jacket has a removable copper bottom below the source, and on one side has a long radiation shield window of two .001 inch stainless steel foils. This side is the observation side and a detection chamber fitted with a .005 inch stainless steel window intrudes into the vacuum chamber within 3-1/2 inches of the source center. This detection chamber is readily accessible from outside, although during the run it may be sealed off for safety considerations.

The line source was constructed from 3 inch diameter 1/32 inch wall stainless steel tubing and is 36 inches long. The hemispherical end caps through which the proton beam passes are made of .006 inch thick stainless steel. The entire line source and reservoir assembly is shown in Fig. 5.

The point source consists of a cylindrical cup turned from a single block of duraluminum so that the side walls are only .002 inch thick. This cup has a beveled flange at the top which is clamped tightly to a similar stainless steel flange at the bottom of the hydrogen reservoir to form a vacuum tight metal-to-metal seal. The cup can readily withstand internal pressures of 45 p.s.i. Point and line source are interchangeable, using the same reservoir.

Procedures for filling the reservoir with liquid hydrogen and venting the hydrogen gas evolved during the filling and running times were worked out, with the advice of Dr. David Lyon of Professor Giauque's laboratory. The auxiliary apparatus for these operations is shown attached to the target in Fig. 6, except that the 50-liter liquid hydrogen Dewar is not in place. The reservoir is first flushed with helium and then filled by forcing liquid hydrogen from the Dewar through a vacuum-jacketed transfer tube under a few pounds pressure of helium gas. Despite pre-cooling to liquid nitrogen temperatures, over 5 liters of liquid hydrogen are boiled off at first in cooling the reservoir to 20° K. The gas evolved is vented to the outside of the cyclotron building through 2 inch diameter tubing. A lift check valve prevents back diffusion of the air into the hydrogen system. In case the hydrogen container leaks or bursts internally and hydrogen gas is so rapidly evolved that a high internal pressure builds up, a blowout patch in the botton of the vacuum chamber is connected to the same vent. The level of the liquid hydrogen in the reservoir is determined by a series of thermocouples inside a long stainless steel tubing extending into the reservoir. In order to distinguish between hydrogen liquid and hydrogen gas, each thermocouple is surrounded by a heater coil which furnishes enough local heat to slightly raise the temperature of a gas, but not a liquid, layer just outside the tubing. A continuous record is made of the thermocouple voltages by a recording potentiometer. This record shows that the rate of hydrogen evaporation rapidly decreases as the level falls, indicating that conduction losses predominate. The volume loss rate midway in the reservoir is about 150 cc/hour.

C. Photographic plate method of detection. The method of meson detecting chosen was that of nuclear emulsions. Emulsions allow one to select mesons, both positive and negative, from relatively high backgrounds with a high degree



V - VACUUM CHAMBER
R - HYDROGEN RESERVOIR
J - LIQUID NITROGEN JACKET
P - .002" WALL POINT SOURCE
S - .001" STAINLESS STEEL HEAT SHIELDS
W - .005" STAINLESS STEEL WINDOW
D - DETECTION CHAMBER

FIG. 4
CROSS-SECTIONAL VIEW OF LIQUID HYDROGEN TARGET (BEAM DIRECTION)

MU 271

14959-

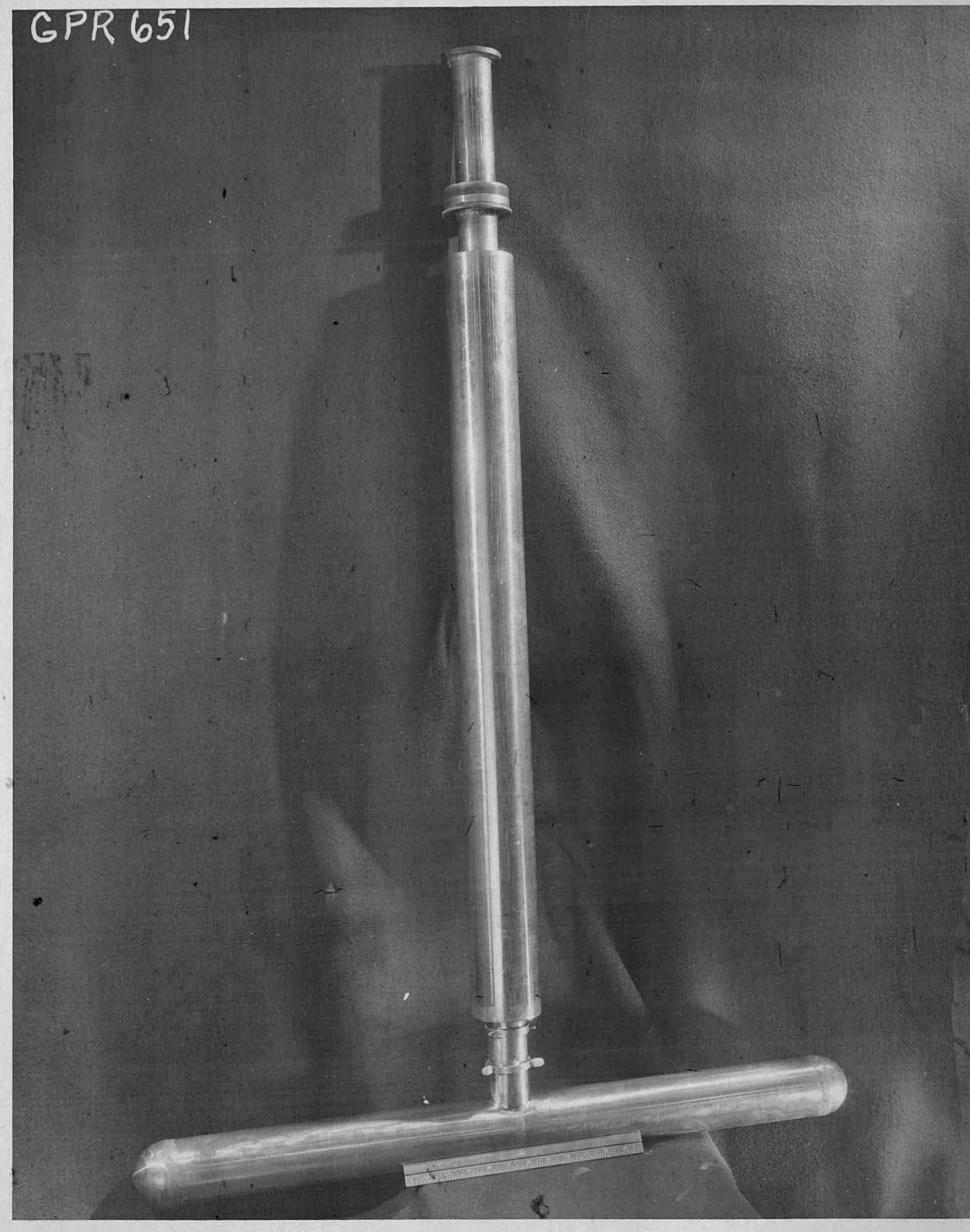


FIG. 5

LINE SOURCE CONTAINER FOR LIQUID HYDROGEN

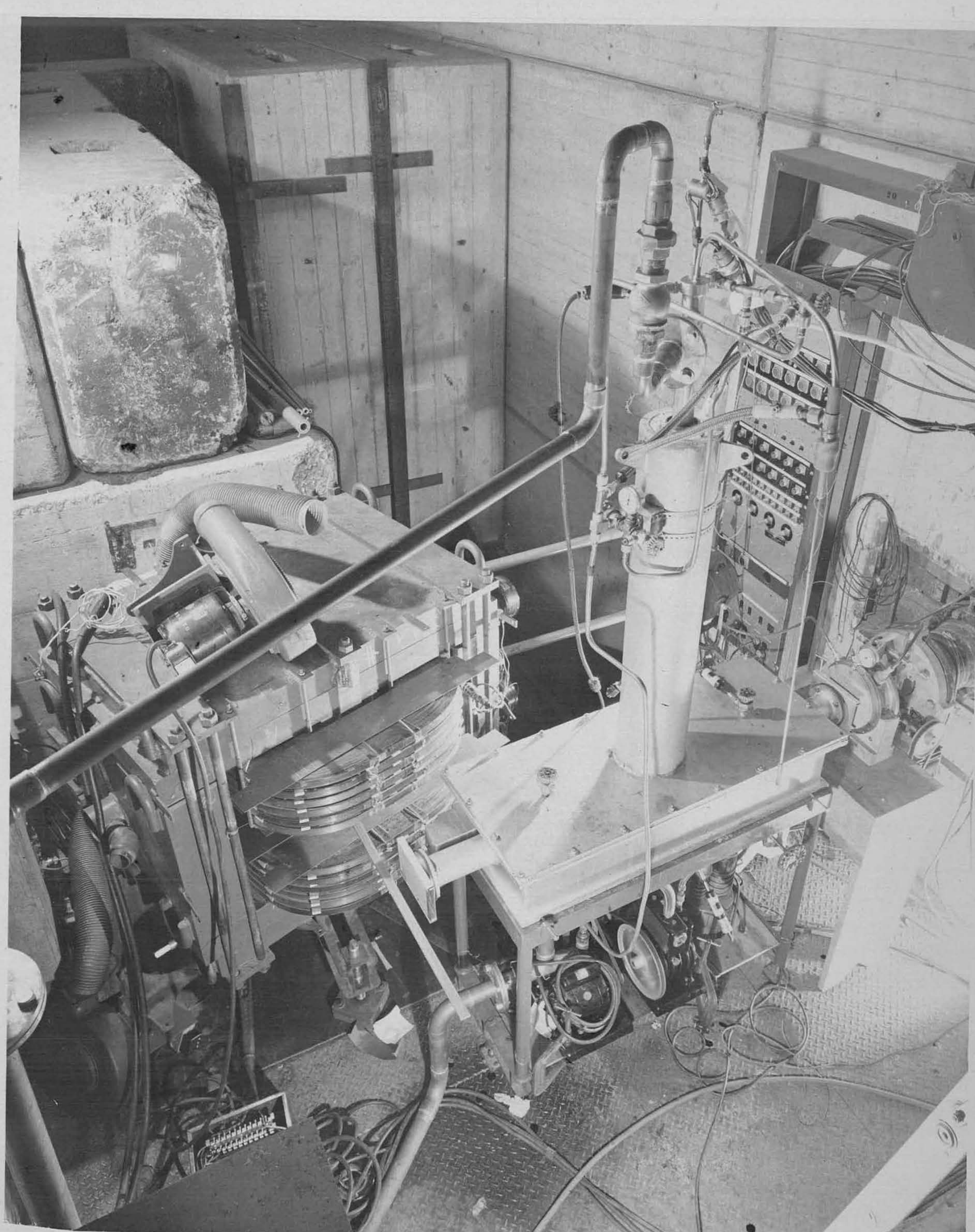


FIG. 6

TARGET IN PLACE, SHOWING FILLING AND VENTING SYSTEM of certainty. This is particularly important when, as in this experiment, the lack of negatives is a confirmation of the assumption that stray beam is not producing detectable mesons from side walls, etc. The photographic method offers excellent energy resolution when used properly in connection with absorbers. The method employed here was to imbed photographic plates in copper or aluminum absorbers, emulsion up, at a small angle of tilt with respect to incident meson flux. Mesons slowing down in the absorber will come to rest at various depths, and the inclined emulsion serves as a means of sampling the volume density of mesons ending in the absorber at various ranges. This arrangement is shown in Fig. 7, including the light-tight foil surrounding the absorber block.

The energy of the meson is determined by its position in the photographic plate, corresponding to a well-defined range in the absorber. The range-energy relations used were derived from proton range-energy curves as given by Aron, Hoffman and Williams[7]. The stopping power of the emulsion for mesons has been similarly derived from the proton range-energy relation for Ilford emulsion given by Bradner, Smith, Barkas, and Bishop[8]. By this method a complete energy spectrum of mesons can be recorded in a single photographic plate, avoiding relative errors in geometry and beam integration which may occur if the energy spectrum is determined point by point. In determining solid angle it has been assumed that the effect of multiple scattering of the mesons is negligible, since to a first approximation as many mesons scatter into the emulsion from the absorber as scatter out of the emulsion. That the correction will, in any event, be small is partially confirmed by the fact that only

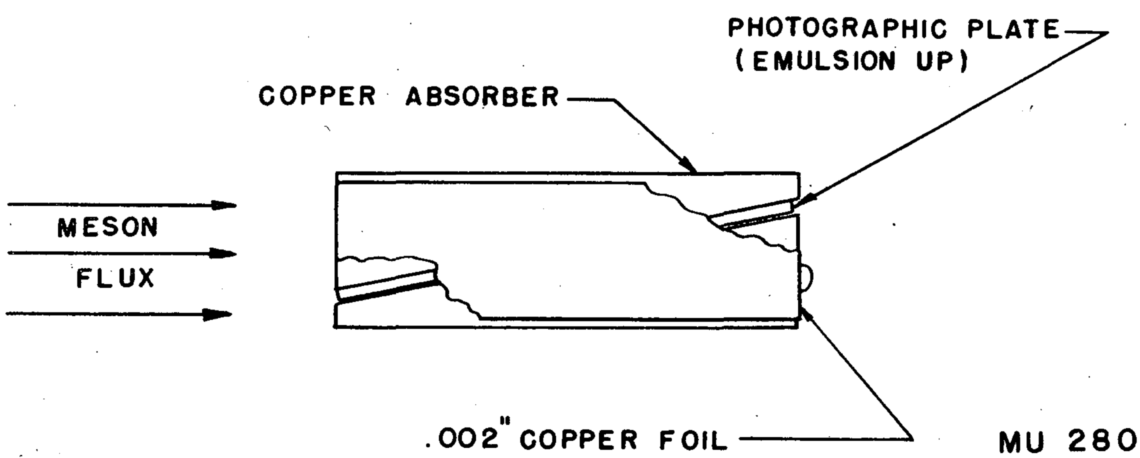
[7] W. Aron, B. Hoffman and F. Williams, UCRL-121 (Second Revision, 1949).
[8] H. Bradner, F. Smith, W. Barkas and A. Bishop, Phys Rev. **77**, 462 (1950).

ten percent of the mesons observed entered from the bottom (rather than the top) of the emulsion.

Ilford C-2 100 micron emulsions were used in this experiment, since this sensitivity of emulsion will give the lowest single-grain background from high energy protons while still recording π-u decays reliably. Elastically scattered proton tracks remain the background limitation to exposure, however, since single grains of high density eventually make identification of the u difficult. Other background arises from the interaction of these high energy scattered protons with nuclei of the emulsion, and from neutron stars.

In order to calculate the absolute differential cross-sections, the thickness of the emulsion must be determined. Since the emulsion shrinks to about 40 percent of its original thickness upon processing, one must either determine the shrinkage factor or devise some means of recording the original thickness without destroying the emulsion. A very convenient method devised by H. A. Wilcox[3] does this by irradiating unexposed plates to 380 Mev alpha particles at a known angle of incidence. After the meson exposure and normal processing have been completed, the original thickness can be calculated from the measured projected range since the emulsion shrinkage laterally is very small. Thicknesses measured in this way are probably good to 3 percent.

D. Use of auxiliary sorting magnet. The first results with the line source confirmed the expectation that only positive mesons are produced in proton-proton collisions. They also showed that the background due to elastically-scattered protons limited the exposure time and scanning rate. Therefore, although the initial exposures provided evidence of the magnitude of the cross section and of the shape of the energy spectrum with fair statistics, an attempt to reduce



MU 280

FIG. 7

METHOD OF DETECTION BY PHOTOGRAPHIC PLATES this background was made. This was done by interposing a magnetic field between source and detector so that only positive particles whose momenta are below a certain maximum value would reach the detector. Since the elastically scattered protons have roughly 5 times the momenta of the maximum energy mesons, this method sorts mesons from protons. A further separation between mesons and protons of equal momenta (resulting from secondary processes) occurs in the absorbers placed before the plates, since the proton range is only 1/50 of the meson range. The results of the experiment show that this method results in an improvement in meson-to-background ratio of about 500. The residual background is composed chiefly of neutron-induced reactions in the emulsion and calibration tracks.

The exact geometry used with the sorting magnet runs is shown in Fig. 8. Use of the magnet necessarily involves much smaller solid angles than direct exposure so that run times of the order of 10 hours are required. In these runs the point source was used, with resultant improvement in angular resolution.

E. Beam integration. The number of protons striking the liquid hydrogen target was determined by letting the proton beam pass through an argon ion chamber before entering the vacuum chamber. The ion chamber contained 99.7 percent pure argon at approximately 5 p.s.i. gage, having originally been filled to a total pressure of 100.1 cm Hg at 16.4° C. The effective chamber separation was 2.002 inches, this being the distance between the high voltage and collection electrodes of .001 inch aluminum foil. The external pressure windows of the chamber were .002 inch beryllium-copper foil.

The charge collected by the ion chamber was measured using a slide-back voltmeter electrometer circuit to determine the voltage built up on a low leakage polystyrene-insulated condenser. The multiplication factor of the ion chamber was determined in a series of separate experiments[9] by comparing the charges collected by the ion chamber and a Faraday cup placed in the same proton beam. Voltage plateau curves were taken and showed recombination effects to be negligible above 500 volts collection voltage; collection voltages of 1500 volts positive were used in the experiments. The multiplication factor of this ion chamber was found to be 1110 ± 30. Using Aron, Hoffman and Williams' range-energy curves[7] for the rate of energy loss of 340 Mev protons in argon, we calculate the e.v./ion pair to be 23.8. The value quoted by Rossi and Staub[10] for 5.3 Mev alphas in argon is 24.9 e.v./ion pair.

[9] R. L. Aamodt, V. Peterson and R. Phillips, UCRL-526.

[10] Rossi and Staub, Ionization Chambers and Counters; Experimental Techniques (McGraw-Hill, 1949) p. 227.

LIQUID HYDROGEN TARGET POINT SOURCE GEOMETRY
(FOR 345 MEV PROTONS)

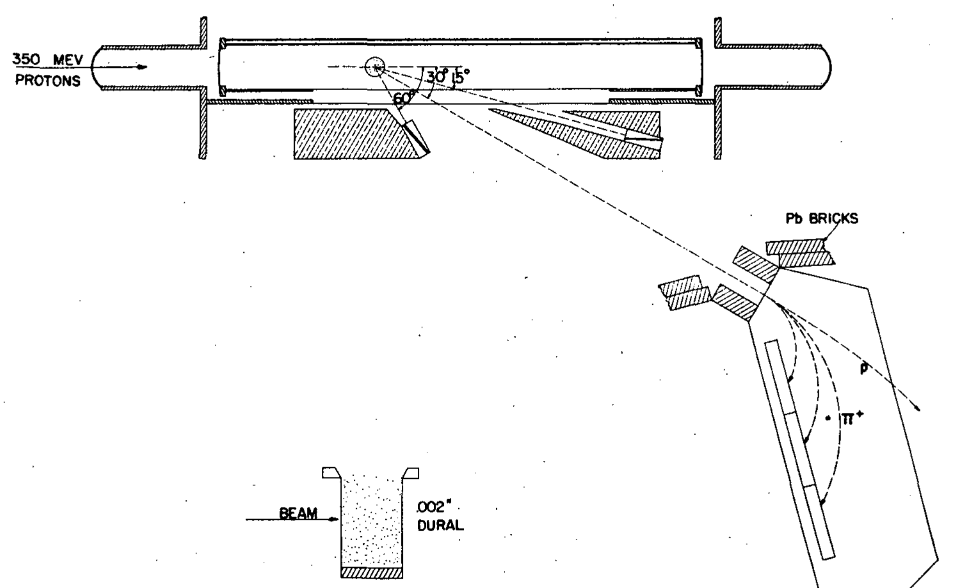


FIG. 8

MU 276

GEOMETRY OF POINT SOURCE EXPERIMENT USING SORTING MAGNET

III. EXPERIMENTAL RESULTS

A. Formula for differential cross-section. The nuclear emulsion serves as a detector by registering tracks of particles passing through it, in particular the endings of mesons. The solid angle and energy interval detected depend upon the distance from the target, area scanned, and emulsion thickness and stopping power. Within a very good approximation the detection efficiency is a volume effect and is independent of the orientation of the emulsion with respect to the incident beam. To see this, let us assume as in Fig. 9 that we have an emulsion placed in an absorber at an angle γ to the incident meson flux from a point source P at a distace D. Consider a volume element V situated in the absorber so that some mesons of energy E at the source are slowed down enough to come to rest in this region. The solid angle subtended by this volume element at the source is the product of $d\theta$ and $d\phi$, where

$$d\phi = \Delta x \sin \gamma / D \qquad d\theta = \Delta y / D$$

and Δy is the width of the scanned area perpendicular to the paper. Thus,

$$d\Omega = d\theta\, d\phi = \Delta x\, \Delta y \sin \gamma / D^2$$

The energy interval dE of mesons of initial energy E leaving the source which are stopped in the effective emulsion thickness $\Delta R = t/\sin\gamma$ depends upon the stopping power of the emulsion for mesons of initial energy E. Thus the detection efficiency of the emulsion decreases with increasing meson energy. More exactly,

$$dE = \left(\frac{dE}{dR}\right)_E \Delta R = \left(\frac{dE}{dR}\right)_E \cdot \frac{t}{\sin \gamma}$$

Finally, the product of solid angle and energy interval is independent of emulsion orientation:

$$d\Omega dE = \left(\frac{dE}{dR}\right)_E \cdot \Delta x \cdot \Delta y \cdot t \cdot \frac{1}{D^2} = \left(\frac{dE}{dR}\right)_E \frac{V}{D^2}$$

Note that $d\Omega\, dE$ is independent of the characteristics of the absorber used to slow down the mesons.

This formula may be used to express the differential cross-section in terms of the number of mesons/cm^2 found in an emulsion of uniform thickness. If L is the target thickness, Φ the total number of protons striking the target, n the volume density of target atoms, and N the number of mesons found in an area A, then

$$n L \Phi \left(\frac{d\sigma}{dE \cdot d\Omega}\right) = \frac{N}{A} \cdot \frac{D^2}{t\left(\frac{dE}{dR}\right)_E}$$

B. Line source experiment: energy distribution at 30°. The initial run was made using a line source geometry as shown in Fig. 10. This target was one built for use at the synchrotron by L. J. Cook and kindly loaned to the author before the present target was completed. Plates imbedded in duraluminum absorbers were exposed at 30° and 45° but the latter plates suffered from high background due to insufficient shielding. Parallel-sided channels 1 inch wide defined a target area of 2 inches thickness at 30° with an angular resolution of ± 3°. Additional lead brick shielding was used around the sides of the channels. Positive π-μ decays occurring in the emulsion were observed under the microscope using oil-immersion objective. Only π-μ's were included in the final statistics, but all mesons ending in the emulsion were sketched and recorded. The number of ρ mesons (mesons ending in the

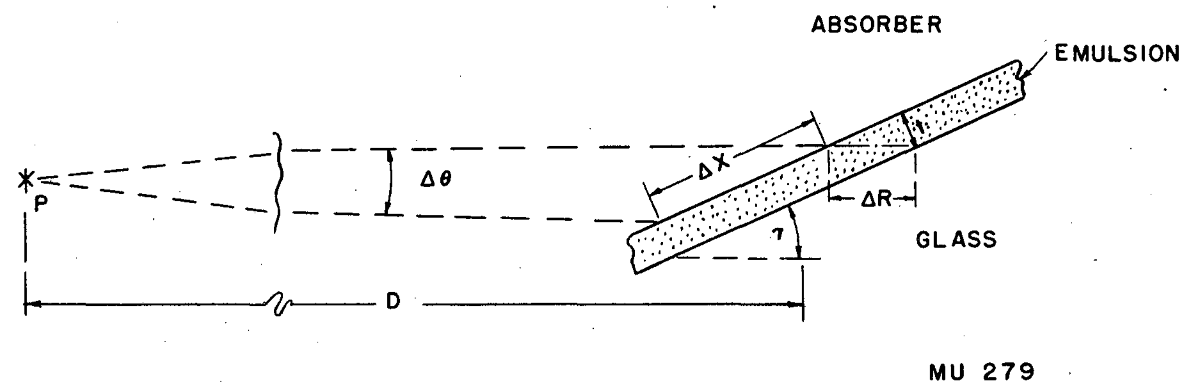
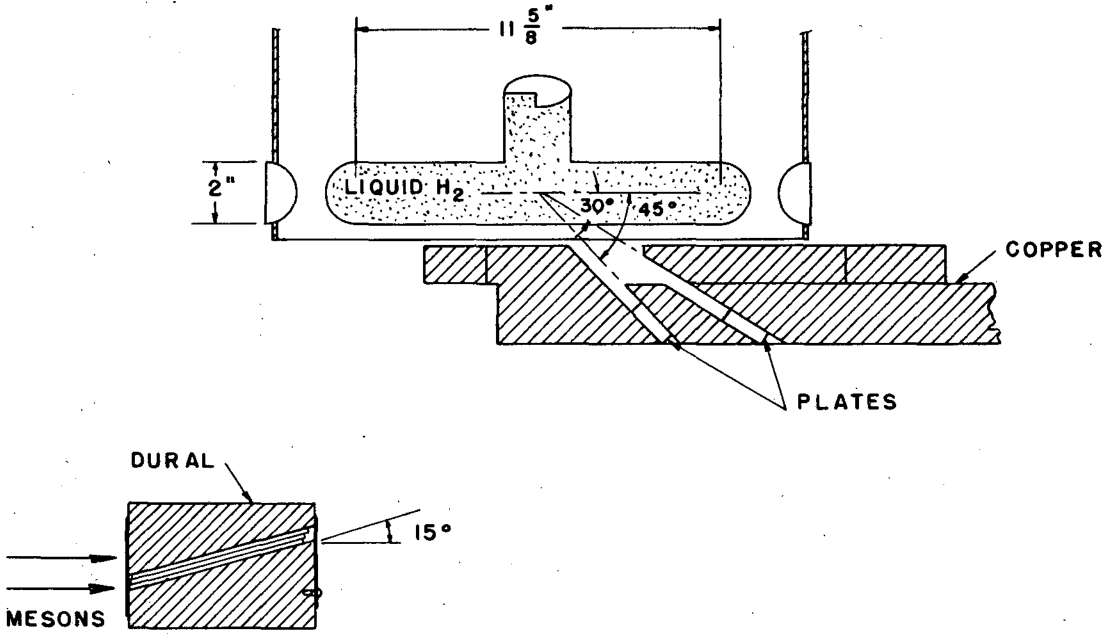


FIG. 9

GEOMETRY OF EMULSION DETECTOR



MU 278

FIG. 10

LINE SOURCE GEOMETRY

emulsion without event) in this run, and later runs, was approximately equal to the number of π-μ decays. The origin of the ρ's is undoubtedly π-u decays occurring in the adjacent absorber or glass backing.

A blank run made with the line source empty showed no mesons in a plate area and exposure comparable to the subsequent run with hydrogen in the container. The hydrogen-exposed plates yielded 115 π-μ decays in an area of 1.7 cm^2. A plot of the number of π-μ's observed per millimeter along the plate in a 1 cm wide area is shown in Fig. 11. This is the range distribution in aluminum, uncorrected for the thickness of windows, etc., which the mesons pass through between source and absorber.

In addition to the 115 positive mesons, two π^- star-forming mesons were found in the plate. These negative mesons are believed to have been formed in the absorbers by elastically scattered protons (which have an energy of 250 Mev at 30°). A rough estimate of the expected yield on this assumption can be made from known data on the p-p scattering cross-section[11], the meson production cross-section for 340 Mev protons[3,4], and the excitation curve for meson production by protons[12]. This estimate is about 1 percent of the target-produced mesons. Therefore no particular significance is attached to the discovery of a few negative mesons in this experiment. Furthermore, in view of the relatively poor statistics, no correction has been made for possible absorber-produced positive mesons.

In a large fraction (2/3) of the apparent π-μ decays, the "μ" leaves the emulsion after a relatively short distance and therefore cannot be distinguished

[11] O. Chamberlain, E. Segrè and C. Wiegand, Phys. Rev. (to be published).
[12] S. B. Jones and R. S. White, Phys. Rev. 78, 12 (1950).

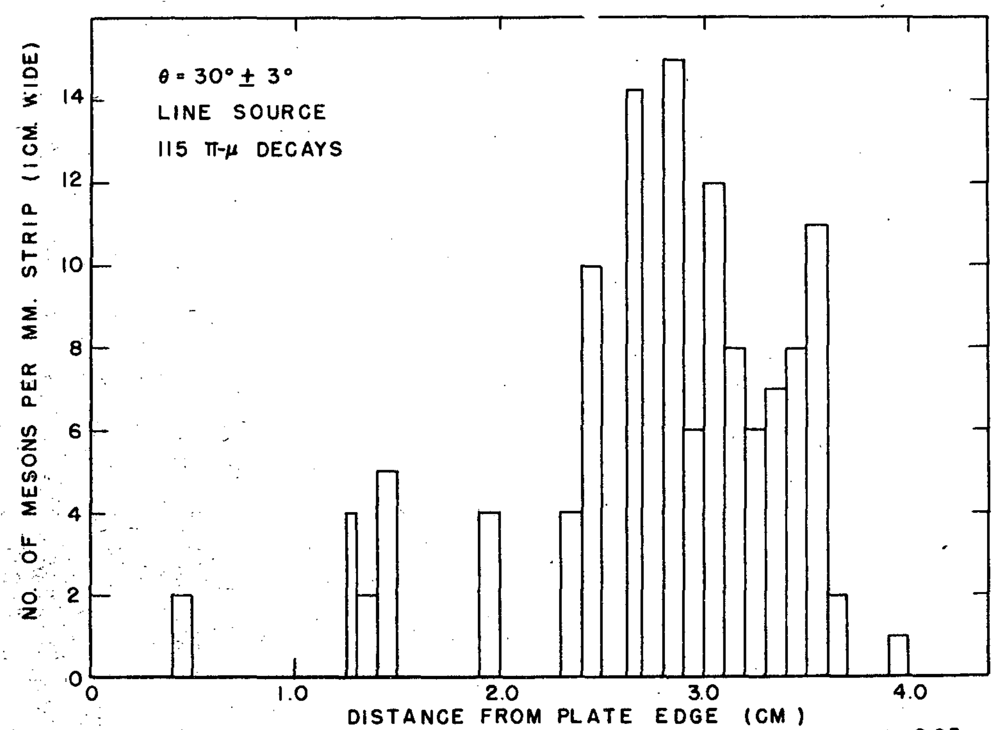
from a high-energy proton. We have counted such events as π-μ decays for two reasons. One reason is that no nuclear recoil is visible in any such case observed. The other reason is that the occurrence of only 2 identifiable π-negative stars makes the occurrence of any one-prong π-negative stars very improbable.

When the variations in solid angle and stopping power are combined with the data of Fig. 11, a plot of the differential cross-section as a function of meson energy results. This is shown in Fig. 12. The most striking feature of this spectrum is the concentration of mesons near the higher energies. This will be discussed in detail in Section IV.

The absolute values of the cross-section in Fig. 12 have been calculated using the formula developed in part (A). The density of liquid hydrogen assumed was .071 gm/cc[13]. The target area was assumed to be defined by the 1 inch channel, and no corrections have been made for possible penetration of the channel corners. The distance from target center to the near edge of the photographic plate was 27-1/2 cm. An emulsion thickness of 52 ± 3 microns was used in this first run (100 micron emulsions were used in later runs). (A shrinkage factor of 2.5 ± .1 was used in this case since calibrated plates were not available. This factor was determined later by measuring microscopically the thickness of processed emulsions containing calibration tracks).

The energy scale refers to the energy of the meson as formed at the target. An aluminum equivalent of 1.07 cm is added to the range in the absorber to take account of the half-thickness of the hydrogen, plus the stainless steel container walls and windows through which the meson must pass

[13] Dr. D. Lyon, private communication.



MU 283

FIG. 11

14972-1

RANGE DISTRIBUTION OF MESON IN LINE SOURCE RUN

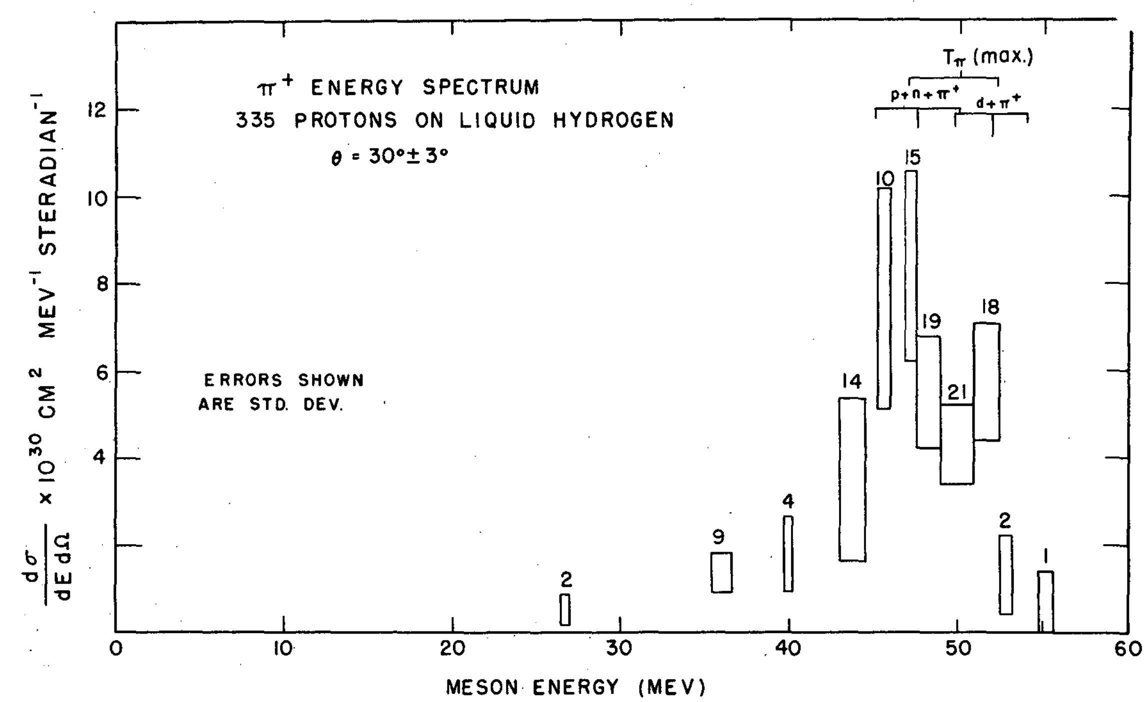


FIG. 12

CROSS SECTION vs. MESON ENERGY AT 30° (LINE SOURCE) at an angle of 30°. The minimum energy of a meson reaching the plate is therefore 22 Mev. The half-thickness of the effective target area in the detector direction is 1 inch, or 1-1/4 Mev to a 50 Mev meson. This target spread plus the estimated 1 percent uncertainty in the range-energy relation means that the energy assignment may be in error by 1 or 2 Mev.

A precise prediction of the upper energy limit on mesons observed at a given laboratory angle is limited by the inexact knowledge of the meson mass and the proton beam energy. The quoted uncertainty in the mass of the π-meson ($276 \pm 6\ m_e$)[14] amounts to ±3 Mev. The best method presently available for determination of the proton beam energy is to measure its range in absorbers. Its range in copper is about 93 gm/cm^2, as determined by exposing x-ray film at the end of the range or by measuring the Bragg curve with a pair of ion chambers. The latter method is probably good to better than 1 gm/cm^2 and gives a mean energy of 340 Mev[15]. The variation from one run to the next is of the order of 1 gm/cm^2 or 2 Mev.

The energy spread of the primary proton beam may also be inferred from range measurements. The Bragg curves show a range straggling half-width of 1-1/2 gm/cm^2. This is in agreement with the range straggling derived from comparative measurements of the $C^{12}(p,pn)C^{11}$ excitation curve[9] near the 20 Mev threshold using 32 Mev protons from the linear accelerator and 340 Mev protons slowed down in copper. The calculated range straggling to be expected if the protons were monoenergetic is .95 gm/cm^2 [16]. Therefore, assuming that the additional measured straggling is due to the energy spread of the primary

[14] F. M. Smith, et al, Bull. Amer. Phys. Soc. 24, 9 (1949).
[15] O. Chamberlain and C. Wiegand, private communication.
[16] M. Livingston and H. Bethe, Rev. Mod. Phys., 9, 283 (1937).

beam, we arrive at a value of ± 2-1/2 Mev.

Taking into consideration the uncertainty in the range-energy relations, it seems that it would be very difficult to determine the primary proton energy to better than ± 4 Mev. However, the energy spread of the beam appears to be quite small and is probably not the limiting factor in the energy resolution of the present experiment.

In the line source run the incident protons passed through a 1/16 inch stainless steel window and 14 cm of hydrogen, reducing the beam energy 8-1/2 Mev to about 332 Mev. The target thickness (2 inches of liquid hydrogen) amounts to 2-1/2 Mev for this energy proton beam. The calculated straggling in energy of 50 Mev mesons at the end of their range is equivalent to 2/3 Mev in initial energy. The angular spread of $\pm 3^{\circ}$ allowed by the geometry corresponds to a variation in the maximum kinetic energy of the mesons of about ± 2 Mev. It seems clear that the energy resolution of the experimental arrangement alone is about ± 3 Mev. Combined with the uncertainties of the proton beam energy and the meson mass, we should not look for agreement between the calculated and experimentally determined values of the upper energy meson limit within 5 Mev and should expect an energy spread of about ± 4 Mev.

C. <u>Point source experiment; energy spectrum at 30° using sorting magnet.</u> Plates directly exposed to the flux of mesons and scattered protons from the hydrogen target are limited in exposure by the proton background. In order to improve this situation and obtain better statistics, a sorting magnet was interposed between source and target (see Fig. 8). At this time the point source was also substituted for the line source in order to better define the target thickness and improve the angular resolution. Although use of the magnet requires greater source-detector distances, the improvement in meson-to-background ratio is sufficient (about 500) to allow long exposures and a larger number of mesons recorded in the plates.

As is shown in Fig. 8 the solid angle is defined in azimuth by the width of the entrance to the magnetic field, while the vertical aperature is still dependent upon the width of the scanning strip in the emulsion. The formula for the product of the energy interval and solid angle is:

$$d\Omega dE = \frac{dE}{dR}\bigg|_E t \frac{w}{D} \cdot \frac{\Delta x}{(D+S)}$$

where w = the entrance width ("gate") to the magnetic field, and $s = \frac{\pi}{2} \rho$ is the path traversed by a meson of radius of curvature ρ in the magnetic field. The plate-imbedded absorbers are placed along a line passing through the center of the gate at an angle of 45° to the incident meson flux. This line is the locus of 90° points on the circular orbits of mesons of different momenta, so that the mesons enter the absorbers at an angle of 45°. Since mesons entering the gate initially parallel will, to a first approximation, converge at the 90° position, this geometry serves to concentrate the mesons in the photographic plate. It is especially useful in this case since the angular acceptance is very small.

In this run the gate width was 2 inches at a distance of 36-1/2 inches from the source, limiting the angular acceptance at 30° to ± 1-1/2°. The photographic plates imbedded at an angle of 15° to the horizontal in copper absorbers were placed in the median plane of the 1-5/8 inch gap of the 14.81 kilogauss magnetic field shown in Fig. 8. Three 6 inch long absorber-holders, each containing two 3 inch plates, were placed along the 90°-focus position from 2 inches to 20 inches from the gate center. The mesons energies thus covered a range from 1 to 70 Mev, well above the 55 Mev meson energy limit calculated for 340 Mev protons. The minimum thickness of absorbers through which mesons must pass to be detected was 1.3 mm Cu equivalent, corresponding to an 11 Mev meson at the source.

In the ideal case of a perfectly constant magnetic field and infinitely narrow angular acceptance, the position of the meson endings in the photographic plates would be described by a line whose distance from the edge of the plate varied approximately as the fourth power of the distance from the gate. A finite angular acceptance $\Delta\theta$ tends to spread out the endings of equal momenta mesons over a distance $\rho\Delta\theta$ along this line and therefore also spreads the line into a band. Since the actual magnetic field falls off near the gate entrance to 65 percent its maximum value and persists to some extent beyond the geometrical boundary, the orbits are further perturbed from circular paths and additional spreading of the line is to be expected. An actual plot of 472 meson endings in the two plates between 11 inches and 17 inches from the gate is shown in Fig. 13, with the direction of increasing momentum indicated by the arrow. The area scanned is outlined. It can be seen that mesons are spread along the plates in a band whose distance from the plate edge increases with momentum. The variation in density of meson endings with momentum gives a rough measure of the variation of the cross-section, although because of the spreading of the orbits the energy assignment is better obtained from the range of the meson in the copper absorber. Unfortunately at an angle of incidence of 45° the calculated range is rather sensitive to variations in angle of incidence, since

$$\frac{1}{R}\frac{dR}{d\theta} = -\cot\theta$$

Thus a variation of 5° from 45° incidence will mean a 5 percent change in the meson energy as calculated from the position of the ending. The width of the band of mesons in Fig. 13 is a result of the variation of the angles of

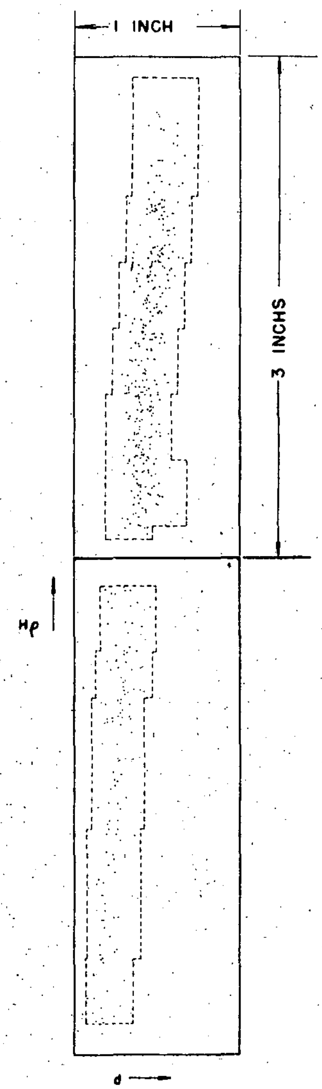


FIG. 13
POSITION DISTRIBUTION OF MESON
ENDINGS IN PHOTOGRAPHIC PLATES
(MAGNET RUN).

incidence of orbits plotted in accordance with the actual magnetic field distribution. Careful shimming of the magnetic field and orientation of the absorbers to give normal meson incidence will narrow the width of this band and therefore improve the energy resolution.

If we count the number of mesons ending in a 1 mm wide strip of constant mean distance d from the incident edge of the plate, we select mesons of a single band of energies. (The straggling in position mentioned above is about 1 mm in distance d.) Plotting the number of mesons per mm strip as a function of distance d we obtain the range distribution shown in Fig. 14. Although the energy resolution is no better than the line source experiment, because of the straggling in position of the meson endings, the statistics are very much better.

This range distribution may be converted into a plot of the differential cross section vs. meson kinetic energy, as shown in Fig. 15. Absolute values are assigned from a knowledge of the charge collected by the ion chamber, target thickness (1-1/2 inchs of liquid hydrogen or .27 gm/cm^2), and the solid angle-energy interval defined by the geometry. The correction factor for the decay of the π-mesons in flight becomes considerable due to the long path, ranging from 1.35 at 30 Mev to 1.25 at 70 Mev. A mean lifetime at rest of 2×10^{-8} sec. was assumed[17]. The emulsion thickness was nearly uniform at 110 microns as determined by the range of calibration tracks.

The effects of the fringing magnetic field in the initial portion of the orbits of the mesons has been estimated from the measured variation of the normal component of the magnetic field transverse to the orbit paths in the median plane of the magnet. Mesons above or below the plane of symmetry of

[17] E. Martinelli and W.K.H. Panofsky, Phys. Rev. 77, 465 (1950).

the magnetic field will experience a force (toward the symmetry plane in this case) approximately proportional to their distance from this plane times the gradient of the field. This focusing action is equivalent to the action of a lens in geometrical optics, and in the case that the region in which the transverse gradient exists is short a thin lens "focal length" can be calculated. In this case the gradient is about 2.3 percent per inch along 5 inches of the path, giving an equivalent thin lens focal length of 110 inches. This increases the number of mesons found in the plate by about 7 percent.

The energy spectrum shown in Fig. 15 has been corrected for the above effects. The points are shown with their standard deviations from the counting statistics. The results show the sharp peak in the spectrum at higher meson energies, in agreement with the line source run. The width of the peak at half-maximum (12 Mev) is slightly broader and the height of the peak is lower than those of the line source run. However, the cross-section integrated over energy from 32 to 70 Mev is almost identical with the integrated value for the line source run ($\sim 7\text{-}1/2 \times 10^{-29}$ cm^2 steradian^{-1}). This is reasonable in view of the greater energy straggling in the point source run.

D. <u>Angular distribution of μ-mesons.</u> Although the experimental arrangements were not designed to favor the search for possible asymmetries in the angular distribution of μ-mesons resulting from π-μ decays, it is a relatively simple job to measure the μ direction. This has been done for the runs discussed here and since the results do not show the expected isotropic distribution within statistical errors, the detailed numbers will be given.

Angular distributions for the u-mesons can be obtained under two very different conditions in this experiment. In the line source run, the plates were in a region of essentially zero magnetic field ($\sim$20 gauss). In the

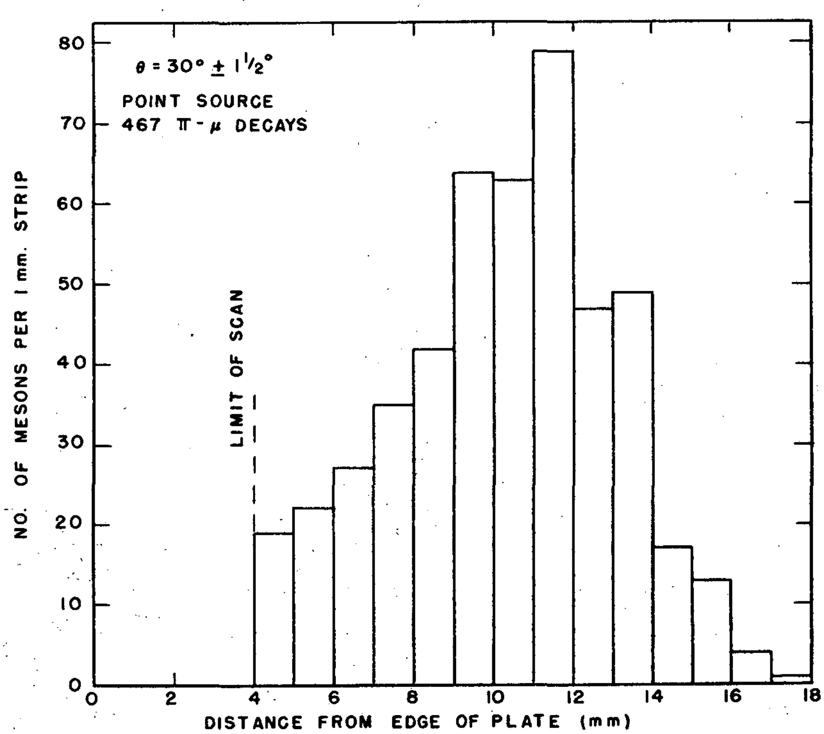


FIG. 14 14969-1

RANGE DISTRIBUTION OF MESONS (POINT SOURCE RUN)

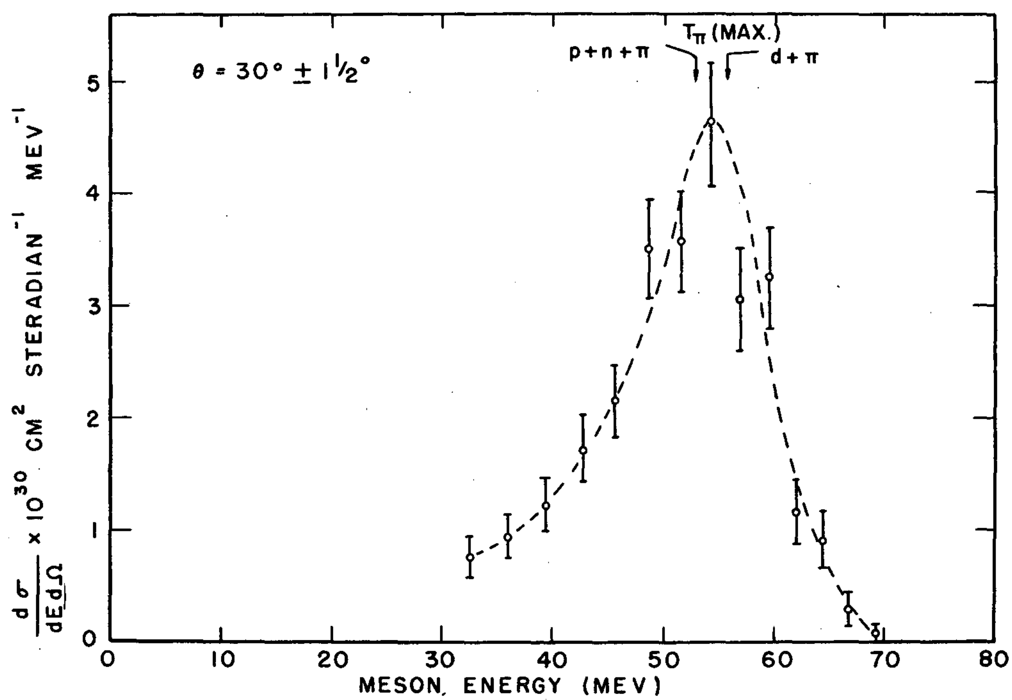


FIG. 15

CROSS SECTION vs. MESON ENERGY AT 30° (POINT SOURCE)

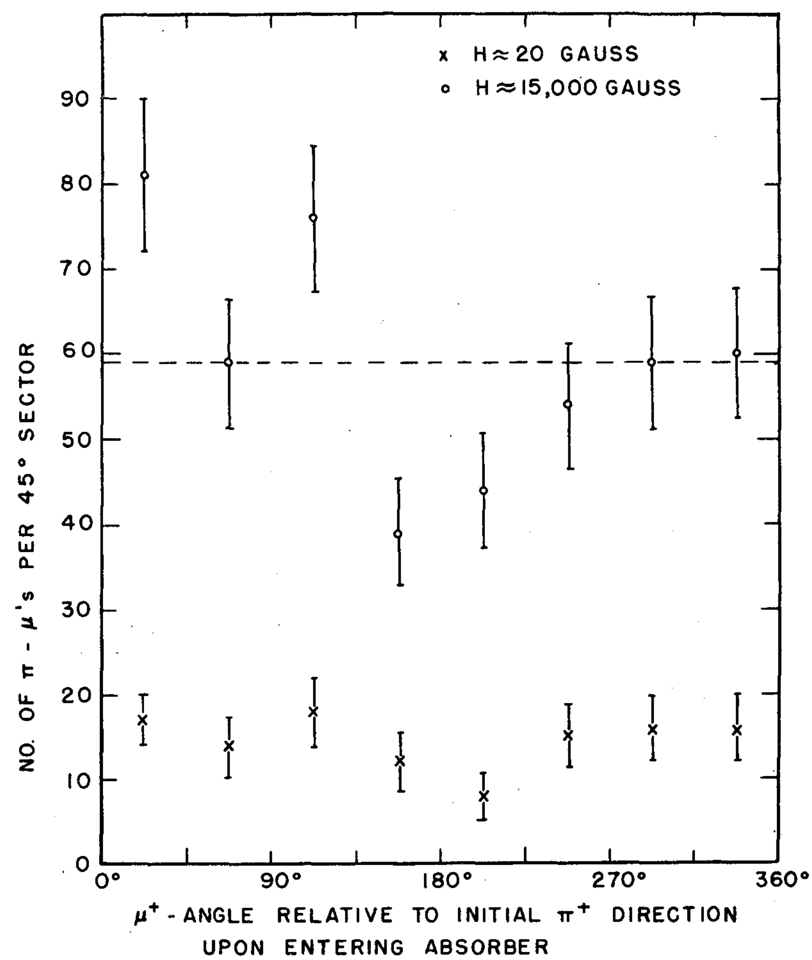
14971-1

point source run, the plates were placed between the poles of a magnet whose field was about 15,000 gauss. The geometrical arrangements of the plates with respect to the meson and proton beam directions may be obtained from Figs. 8 and 10. In both cases the plane of the emulsion intersects at an angle of 15° the plane defined by the proton beam and the line of flight of the mesons ending in the plate. Therefore asymmetries with respect to either the proton beam direction or the direction of the π-meson incident upon the absorber can be determined from the distribution of μ-mesons with plane projected angle in the emulsion.

The numbers of μ's per 45° sector have been tabulated against angle θ in Fig. 16, listing the results of the "no-field" and 15,000 gauss runs. The angle is defined with respect to the direction of the incident π-mesons as it enters the absorbers, and angles are measured clockwise as viewed in the microscope field of view. Since the optical system of the microscope preserves relative angular orientations, this is the same as viewing directly the decay process from the top of the emulsion.

The errors plotted are standard deviations based upon the number of π-μ decays observed. A total of 115 decays are included in the no-field case, and 472 decays in the 15,000 gauss case. The angles were measured with a goniometer eyepiece attachment and each measurement is good to ± 1°. The definition of the incident π-meson angle is good to ± 3° in the no-field case, and better than ± 5° in the 15,000 gauss case.

The most striking feature of Fig. 16 is the apparent minimum in the angular distribution at 180°. In the 15,000 gauss case a least squares fit assuming a flat distribution is indicated by the horizontal line. The root-mean-square deviation of the points from this fit is twice the standard deviation of the individual points, indicating that the odds against obtaining the experimental distribution (isotropic distribution assumed to be the true distribution) due to statistics alone are 21 to 1. The much poorer statistics of the no-field case do not justify such an analysis.



MU 274

FIG. 16

ANGULAR DISTRIBUTION OF μ^+ - MESONS IN $\pi^+ - \mu^+$ DECAY

14970-1

IV. DISCUSSION OF RESULTS

A. Interpretation of peaked spectrum. Calculations made by Taylor and Chew[18] of the energy spectrum of mesons produced by nucleons bombarding free nucleons on the basis of scalar interaction yielded bow-shaped curves whose mean energy was approximately half the maximum energy. Brueckner[19] has also calculated the results to be expected on the basis of pseudoscalar theory which gives a broad peak shifted slightly toward higher energies. Both of these calculations were made on the assumption that the final proton and neutron did not interact and therefore could be described by plane waves.

The experimental energy spectrum differs markedly from these theoretical predictions in that the peak is very sharp and occurs at the upper end of the spectrum. A reasonable explanation has been suggested by Chew[20] who points out that at the low final nucleon energies involved the proton and neutron cannot be treated as free particles. Indeed, since the meson takes most of the 20 Mev kinetic energy available in the center-of-mass system, the proton and neutron each have only about one Mev kinetic energy. At these energies the n-p scattering cross-section is known to be large[21] and this strong interaction at low nucleon energies increased the probability that the corresponding high energy mesons will be emitted. Calculations on this assumption by Brueckner and Noyes[22] give good agreement with the observed energy spectrum.

The energy spectrum observed by Cartwright, Richman, Whitehead and Wilcox at 0° is in good agreement with the present results and with the explanation given above. In general the 0° results show a higher and broader

[18] T. B. Taylor and G. F. Chew, Phys. Rev. 78, 86(A) (1950).
[19] K. Brueckner, UCRL-630.
[20] G. F. Chew, private communication.
[21] Bailey, Bennett, et al, Phys. Rev. 70, 583 (1946).
[22] K. Brueckner and P. Noyes, private communication.

peak and the expected shift of the maximum towards higher meson energies.

B. Existence of deuterons. If the proton and neutron in the final state are moving with low relative momenta, a deuteron may be formed as one of the resultant particles of the collision. In such events the meson has a single definite energy in the center-of-mass system which will give a "line" when observed at any laboratory angle. Since the binding energy of the deuteron provides the meson with approximately 2.2 Mev additional kinetic energy in the center-of-mass system, this line will in principle be separated from the continuous meson energy spectrum. The separation amounts to about 3 Mev at 30° observation angle in the laboratory system.

Experimentally it would be extremely difficult to determine the existences or non-existence of real deuterons by observing this gap in the meson energy spectrum, since the energy resolution would have to be significantly less than 3 Mev. The statistics would also have to be very good to prove the existence of even a dip in the distribution near the upper energy limit. Certainly these two conditions are not met by the experiments reported here. On the basis of Figs. 11 and 14 one can neither confirm nor deny the possible existence of deuterons in the production process. However, if the actual energy spread of the proton beam is less than the estimate given here it may be possible to achieve the required energy resolution.

The incentive for attempting to improve the energy resolution certainly exists, since the existence and relative magnitude of the "deuteron line" may lead to some restrictions on the choice of meson-nucleon interactions. The initial proton-proton system is limited to ^1S, ^3P, ^1D, etc., states because of the Pauli exclusion principle, and have even or odd parity depending on whether ℓ is even or odd. The bound state of the deuteron is a ^3S state. The mesons formed at these proton energies will be in an S state a large fraction of the time since the wavelength $\lambda\!\!\!^{-}$ of a 20 Mev meson is about twice as long as the range of the meson-nucleon interaction (assumed $\hbar/m_\pi c$). To this extent we may say that the parity of the final state will be even, and that the assumed interaction must be capable of conserving or changing parity depending on whether the protons collide in a singlet or triplet state. Furthermore, if the meson spin is 0 conservation of angular momentum rules out collisions in the ^1S state.

C. Total cross-section. The experimental energy spectrum of positive π-mesons at 30° when integrated over meson energy gives a value of at least 7-1/2 x 10^{-29} cm^2 steradian per proton. Due to the fact that the mesons are observed to have nearly a single energy at this angle in the laboratory system, we may readily estimate a total cross-section by assuming a spherically-symmetric angular distribution in the center-of-mass system. Then the yield may be expected to vary with laboratory angle in much the same way as S-wave p-p scattering (the upper limit on meson energies goes nearly to zero beyond 90°). Using the ratio of solid angles from p-p scattering,

$$\frac{d\Omega_{lab.}}{d\Omega_{c.m.}} = 4 \cos \theta = 3.46 \qquad \text{(at } 30^\circ\text{)}$$

and assuming spherical symmetry in the center-of-mass system, the total cross-section becomes,

$$d\sigma_{total} = 4\pi\,(7\text{-}1/2 \times 10^{-29})/\,3.46 \approx 2.7 \times 10^{-28}\ \text{cm}^2$$

D. Angular distribution of the u-mesons. It has been shown in experiments with photo-mesons[23] that neutral mesons decay into two gamma-rays and therefore

[23] J. Steinberger, W.K.H. Panofsky and J. Steller, UCRL-674.

the neutral meson must have spin zero. It seems reasonable to assume that both charged and neutral mesons are of the same type, and that photon and proton produced mesons have the same characteristics. Therefore it would be both surprising and interesting if any effect, such as an asymmetry in the direction of μ-mesons in π-u decay, were found. Previous studies by Richman and Wilcox[24] and by Weissbluth[4] of decays of positive mesons from carbon and lead showed isotropic angular distributions of the μ's. However, in these experiments only of the order of 15 mesons per 45° sector were obtained. Furthermore, whereas Wentzel[25] predicts a maximum effect near threshold these experiments were carried out 150 Mev above threshold.

The present experiment comes much closer to satisfying the conditions as laid down by Wentzel, namely that it was carried out near threshold where the final nucleon and meson momenta are small compared to those of the initial protons. In fact, as has been pointed out before, the nucleons have only about 1 Mev each in the center-of-mass system, whereas the average meson momentum is less than 1/7 of the momentum of each of the colliding protons.

The present results certainly do not prove that the π-positive meson has a non-zero spin, but they do show an asymmetry in the angular distribution of the μ-mesons which is not easily explained on the basis of statistics. If the true distribution were isotropic, then the probability that the observed distribution would occur is only 4.5 percent. Furthermore, this does not take account of the fact that the extreme points are grouped together. An arbitrary division of the angular distribution (which happens to correspond to a forward-backward separation with respect to the proton beam) at 135°

[24] C. Richman and H. Wilcox, private communication.

[25] G. Wentzel, Phys. Rev. 75, 1810 (1949).

into two hemicircles gives a ratio of 1.41 ± .13, or a probability of only 1 in 400 of being due to an isotropic distribution.

If the meson possesses a magnetic moment as large as one mesonic magneton, however, it would require a very strong asymmetry to withstand the effects of precession of the moment in a 15,000 gauss field during the lifetime for decay of the π-meson. A particle having one mesonic magneton will precess about 1 complete revolution during the half-life for meson decay. Although the angular distribution observed falls off in the rotation direction expected of a precessing positive moment, the magnitude which must be assumed for the initial asymmetry is so great that the effect should have been noticed on the no-field plates.

The results, while inconclusive, justify further experimental work with plates placed inside and outside a region of magnetic field.

V. ACKNOWLEDGEMENTS

The author wishes to acknowledge the continuous help and guidance of Professor W. K. H. Panofsky throughout the course of this problem. Many of the techniques originally used by Dr. C. Richman and Dr. H. A. Wilcox were employed in this experiment, in particular the method of calibrating emulsion thickness. Miss Dora Sherman and Mr. Edwin Iloff have been of great assistance in conducting some of the experiments and in scanning the plates. Mr. Leslie Cook aided the early progress of the experiment by kindly loaning his synchrotron liquid hydrogen target for the initial run before the target described here was completed. Mr. Al Chesterman is responsible for the mechanical design. Many helpful discussions on the original design were held with Dr. David Lyon of Professor Giauque's cryogenic laboratory, and with Drs. Richman and Wilcox, and Mr. Leslie Cook. Fruitful discussions of the theoretical implications of the results were held with Dr. G. F. Chew and Mr. K. Brueckner.

The author is indebted to Professor E. O. Lawrence for his interest in this work, and to Mr. James Vale and the cyclotron crews who furnished a reliable high intensity beam of 345 Mev deflected protons. This work was performed under the auspices of the Atomic Energy Commission.