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TOTAL CROSS SECTION FOR POSITIVE PIONS IN HYDROGEN

Stanley L. Leonard* and Donald H. Stork

Radiation Laboratory, Department of Physics,
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I. ABSTRACT

The total cross section for positive pions in hydrogen has been measured at pion kinetic energies of 33, 44, 56, and 70 Mev. The attenuation of pions of these energies in liquid hydrogen was studied by scintillation-counter techniques. The geometry was such that pions scattered at angles greater than $\pm 35^{\circ}$ were counted as having been removed from the beam. Therefore, the term "total cross section" is taken to mean the cross section for all interactions except those in which the pion is scattered into an angle of less than $\pm 35^{\circ}$ from the pion beam direction. The results are

Pion Energy (Mev)	Cross Section (mb)
33 ± 4.5	6.4 ± 2.1
44 ± 4	9.8 ± 1.5
56 ± 4	17.6 ± 2.2
70 ± 5	19.0 ± 2.6

The energy dependence of the cross section seems to agree with the predictions of lowest order perturbation theory for pseudoscalar mesons with gradient coupling to the nucleon.

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* Now at Principia College, Elsah, Illinios.

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II. INTRODUCTION

At the time when work on this experiment was begun, the total cross section for positive pions in hydrogen had been measured for pions of energies greater than 53 Mev.[1, 2, 3] It is of theoretical interest to extend these measurements to lower energies. This paper describes a determination of this cross section for 33, 44, 56, and 70 Mev pions. This measurement provides a comparison to previous measurements and extends the cross section data to energies as low as feasible for the particular method utilized. The lower energy limit resulted from the low pion beam flux and the rapid increase, with decreasing energies, of the correction required because of pion-muon decay.

Recently cross section measurements have been reported for pions of 37,[4] 40,[5] and 43[6] Mev. Comparison of the results with those of this experiment shows that the agreement is satisfactory.

III. EXPERIMENTAL METHOD

In this experiment, the 340 Mev scattered deflected proton beam of the Berkeley 184-inch synchrocyclotron was brought out through the cyclotron shielding, through a 2 in. diameter collimator, into the so-called "cave" area (Fig. 1). There it passed through a pion-production target, of polyethylene or carbon, placed at the front edge of a strong magnetic field. Pions of the desired energy were deflected by the field, through about 90° in an 18.5 in. radius, passed through an exit slit at the rear edge of the magnet pole faces, and into a narrow hole cut through the concrete shielding that formed the side wall of the cave. In this way a beam of pions of the desired energy was produced. This beam was defined further by a thin anthracene scintillation counter placed inside the hole in the cave wall. The beam then emerged into a region outside the shielding, passed through two stilbene crystals viewed by photomultiplier tubes, and entered the liquid-hydrogen target. Upon emerging from this attenuation target, the beam passed into a large cell of liquid scintillator viewed by photomultipliers.

Pions were identified by the heights of the pulses produced in the photomultiplier tubes viewing the two stilbene crystals, in conjunction with the momentum measurement which is implicit in the magnetic selection of beam particles. By means of the electronic setup (see below), those pions that interacted with the hydrogen nuclei, and so did not reach the back counter, were counted. In addition, the total number of pions passing through both the stilbene crystals was measured. From these two numbers, plus information about the amount of hydrogen in the attenuation target, the total attenuation cross section was calculated.

Carbon targets were used to produce the beams for the 56 and 70 Mev attenuation measurements, while polyethylene was used at the other two energies. The thicknesses of the polyethylene targets were chosen so that the pions due to the reaction $p + p = \pi^+ + d$ would emerge from the target at the energy desired for the pion beam. In all cases the width of the production target was 1-7/8 in., the same width as the exit slit. These dimensions determined the momentum selection of the pions.

Counters 1 and 2 (Fig. 1) were placed at the approximate position where the magnetic lens consisting of the fringing field of the magnet formed an image (in the vertical plane) of the target. For the lower two pion energies, the magnetic field was varied and the twofold coincidence counting rate in counters 1 and 2 was maximized with respect to the field intensity, thus insuring that the beam particles were primarily due to the intense peak in production from polyethylene resulting from the $p + p = \pi^+ + d$ reaction.[7]

The energy of the particles in the beam was determined by an integral range measurement, in which the threefold coincidence counting rate for counters 1 and 2 and the back counter was obtained for various thicknesses of copper placed between counter 2 and the back counter. The percentage of the beam particles that were pions was determined by a pulse-height analysis that is described below.

The intensity of the pion beam was increased over the value obtained in preliminary runs by a factor of about two by extending to the pion-production target the evacuated tube through which the protons traveled. This expedient reduced the spreading of the beam caused by multiple coulomb scattering in the air and in the ion chamber monitor that was placed at the exit of the evacuated tube. Since the vertical dimension of the proton beam at the production target was decreased in this way, the vertical focusing of the magnet fringing field produced a smaller pion image at the counter telescope. The resulting pion beam flux through the telescope was about two particles per second.

The beam defining counter (No. 0 in Fig. 1) was placed two feet in front of counter 1 and consisted of a 1-1/2 in. x 1-1/2 in. x 1/8 in. anthracene crystal viewed from one edge through a short lucite light pipe by a single RCA 1P21 photomultiplier tube. Counter 1 was a 1-1/4 in. x 1-1/4 in. x 1/2 in. stilbene crystal viewed from opposite ends through short lucite light pipes by two RCA 5819 photomultipliers. Counter 2 was very similar, a 1-1/4 in. x 1-1/4 in. x 1/4 in. stilbene crystal viewed on opposite ends by two RCA 5819 photomultipliers, also through short light pipes. The separation between counters 1 and 2 was 2-3/4 in. The back counter consisted of a disk-shaped cell, 14 in. in diameter and 1/2 in. thick. The front face was made of 16 mil dural foil and the rear face of 1/4 in. lucite. This cell was filled with a solution of terphenyl (0.4 percent by weight) in phenylcyclohexane with about 15 mg of diphenylhexatriene per kilogram of solution, to shift the wave length of the radiated light to a region of greater sensitivity of the 5819 photomultiplier cathode. It was viewed from the rear by ten RCA 5819 photomultiplier tubes separated by a light baffle into two groups, a central core of four tubes viewing a central 8 in. circle, and an outer ring of six tubes viewing the outer 3 in. ring of the disk.*

The photomultipliers used in counters 1 and 2 were selected for good pulse-height resolution in viewing stilbene crystals. Since the pulse-height

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*This separation was not at all complete since the baffle extended only up to the rear face of the disk, but it would have permitted an estimate of the relative number of pions scattered into the outer ring as compared with those coming through the center section. This feature of the rear counter was not exploited in this experiment.

resolution also depended upon light collection efficiency, the light pipes were designed for optimum light collection consistent with the requirements of geometry. All the 5819 photomultipliers were protected from the effects of the stray magnetic fields in the cyclotron building by mumetal shields. The tubes viewing the pulse-height counters were encased in an iron box for additional shielding.

The liquid hydrogen target was placed as close to the second crystal as possible to reduce to a negligible amount the number of pions removed from the beam by multiple scattering in the crystal. While "poor" geometry was required for the multiple coulomb scattering, it was desirable to have the back counter as far from the target as possible in order to have fairly "good" geometry for the nuclear scattering, so that as much of the total attenuation cross section was measured as possible.

The angle subtended at the second crystal by the back counter was determined in part by the fact that some beam pions decayed in flight after passing through the first crystal (some of the decay muons then passing through the second crystal) or the second crystal. It was important to make the angle subtended by the back counter large enough so that a negligible number of the decay muons passed outside the rear counter. As a compromise between the conflicting "good" and "bad" geometry requirments, the back counter was placed so that it subtended a half angle of 35° at the center of the hydrogen target. This was the smallest angle which was still large enough to include all but a negligible fraction of the multiply scattered pions, and all but a negligible fraction of the largest angle pion muon decays.

It was impossible to distinguish experimentally the true attenuation events from those pion muon decay events occurring after counter 2 which yielded muons of such low energy that they reached the end of their range without entering the back counter. A discussion of the calculation of this correction appears later in this paper.

The electronic apparatus used in this experiment is shown schematically in Fig. 2. Pulses from the defining counter and counters 1 and 2 were amplified by means of standard linear amplifiers (LA) and passed through gate forming circuits (VG). The outputs of the gate forming circuits were fed into a coincidence circuit of 0.5 microsecond resolving time. A threefold coincidence caused by pulses from these counters triggered the oscilloscope sweep. From the second outputs of the linear amplifiers, pulses from counters 1 and 2 and from the two sections of the back counter passed through different amounts of RG65/U delay line and were fed into a "funnel" circuit whose output was fed into the signal input of the oscilloscope. The function of this funnel circuit was to provide independent impedance matching and voltage attenuation and to funnel the pulses into one output. In this way, the four pulses from the four counting units, separated in time by means of the delay line, were displayed on the oscilloscope trace, the sweep being triggered by the threefold coincidence. These traces were photographed on continuously moving 35 mm film. The sweep time was 5 microseconds, and the pulses were separated by about 0.8 microseconds.

In order to insure that the pulses in the two pulse-height counters were not too short for effective feedback in the linear amplifiers, the pulses were lengthened by a simple R-C network not shown in the diagram and then clipped to 0.25 microseconds in length by shorted clipping lines. The individual voltage attenuation at the input of the funnel circuit made it possible to adjust the heights of the pulses for photographic convenience at the start of any run without tampering with the gains of the amplifiers or the voltages on the phototubes. The latter two variables could thus be adjusted for optimum performance of the phototubes, amplifiers, and gates.

The oscilloscope was equipped with a gating circuit that provided a gate pulse whenever the sweep was triggered. This gate output was fed into a scaler, which therefore registered the total number of sweeps. A record was kept of the number of sweeps photographed on each section of film. An ion chamber placed in the primary proton beam served to monitor the integrated proton beam flux.

The liquid hydrogen target used in this experiment (Fig. 3) was one designed by Mr. John Garrison for experiments on proton-proton scattering. The hydrogen flask was a circular cylinder with axis perpendicular to the beam, and about 5.6 in. in diameter. The thickness of hydrogen in the beam direction was 1.00 gram/cm^2. A liquid nitrogen jacket cooled the target, several heat shields reduced radiant heat transfer, and an insulation vacuum of less than 10^{-2} microns provided good heat insulation.

For this experiment a new outer jacket was designed and constructed. This jacket is shown in Fig. 3. The beam entered the target through a 3 in. diameter hole in the jacket covered with a 7.5 mil aluminum foil. The exit window was covered with 10 mil aluminum foil and was 9 in. in diameter.

This diameter was such that when the back counter was set to subtend a half angle of 35° at the center of the hydrogen flask, the angles subtended at the second crystal by the back counter and by the exit window were the same.

The pulses from counters 1 and 2 and from both sections of the back counter were displayed on the screen of a 5XP11A cathode ray tube using a 12 kv power supply. These pulses were photographed on continuously moving Kodak Linagraph Pan 35 mm film by means of a General Radio camera with a f/1.5 lens. The speed with which the film was moved through the camera was adjusted to keep the spacing between sweeps great enough for ease in subsequent reading of the processed film. A set of small neon lamps was mounted around the rim of the cathode ray tube face and inside the light shield which enclosed the camera lens and oscilloscope face. The lights were controlled from outside the shield, and were used to mark the film to identify which portions were exposed under a given set of conditions. After processing, the film was examined with the aid of a Recordak film reader. The pulse heights and separations between pulses could then be measured on an arbitrary scale by means of a grid placed in the focal plane of the film reader. The height of the pulses could be read to an accuracy of about one part in thirty, and the separation between pulses could be determined to about one part in twenty. The latter corresponded to a time resolution of about 0.04 microsecond.

IV. DETERMINATION OF THE CROSS SECTION

In order to determine the attenuation cross section, it was necessary to know the thickness of the target in grams/cm^2, the total flux of pions through the target, and the number of pions that failed to reach the back counter. The target thickness was 1.00 gm/cm^2.

In order to find the flux of pions, it was only necessary to determine the fraction of the sweeps initiated by pions, since the total number of traces photographed on each section of film was registered on the scaler connected to the gate output of the oscilloscope. To accomplish this, pulse-height measurements were made on all traces in a group of samples of the film. These pulse heights were then plotted in the following way: A set of coordinate axes was laid out with the abscissa representing the pulse height in counter 1 and the ordinate representing the pulse height in counter 2. Each trace was represented by a dot whose coordinates indicated the pulse heights in the two counters. The distribution of the dots then represented the pulse-height distribution for the counters. A typical diagram representing the data at the lowest pion energy is given in Fig. 4. It is seen that most of the dots cluster in a rather limited region; these represent the pions. From this diagram one can set up criteria for classifying the particle responsible for a given trace on the oscilloscope. The criteria actually used are shown on the diagram, all dots inside the indicated polygon being ascribed to beam pions. From this diagram the fraction of beam particles that fulfilled the criteria was determined. From this fraction and the total number of sweeps, the number of pions traversing the target was computed. It is seen from this diagram that the pulse-height resolution in counter 1 is about 1.5 times as good as that in counter 2. This ratio is what one expects if the resolution width is due primarily to the statistics of electron emission at the photocathodes of the photomultiplier tubes, since about twice as much energy is lost in the first crystal as in the second.

The number of attenuated pions, $N_{att.}$, was determined in the following way: All the film exposed with the liquid hydrogen target in place was scanned for sweeps on which appeared pulses from counters 1 and 2 alone. The heights of the two pulses on each of these sweeps were measured. These were then plotted in the "three-dimensional" type of diagram described above. The diagram for the lowest energy measurement is shown in Fig. 5. The pulse-height criteria for pion identification were applied, and the number of such anti-coincidence events initiated by pions was determined.

It is believed that the other groups of dots in Fig. 5 may be identified as follows: Those falling along line A have the correct pulse height in counter 1, but too large a pulse height in counter 2. These are considered to be due to pions that a) decay between counters 1 and 2, giving rise to low energy muons that stop before reaching the rear counter, or b) are captured in counter 2, giving rise to a nuclear star. Those in region B have the right relative pulse heights to be considered due to the low energy muon contamination of the beam, resulting from pion decays near the backward direction in the pion center of mass, the decays occurring ahead of counter 1 and the muons stopping in the target. The dots in region C appear to represent the proton contamination of the beam. It should be mentioned that there was a group of dots for very large pulses in both counters which could not be shown on this diagram; this group also represented protons.

Then, if N_b is the total number of pions passing through the target, ρt the thickness of the target in grams/cm^2, A the atomic weight of the target hydrogen, and A_o Avogadro's number, one can write an expression for the attenuation cross section,

$$\sigma = \frac{N_{att}}{N_b \, \rho t A_o / A} = \frac{N_{att}}{5.98 \, N_b} \times 10^{-23} \text{ cm}^2$$

The last relation makes use of the fact that the target thickness was 1.00 gram/cm^2 and that the attenuation fraction was very small compared to unity.

V. CORRECTIONS

a. Pion decay giving rise to spurious events.

It is apparent that beam pions that decayed after passing through counter 1 and at least most of the way through counter 2 were indistinguishable from any other beam pions. Some of the muons from these decay events had such low energy in the laboratory that they reached the end of their range before being detected in the back counter. Such events were indistinguishable from the true attenuations of the pion beam. Therefore, it was necessary to correct for these false attenuations on a theoretical basis, using the lifetime and dynamics of the decay process. At the lowest energy (33 Mev), the correction is a very significant one, the number of false attenuations being about 0.53 percent of the total flux, and the number of true attenuations being about 0.36 percent of the total pion flux. At 44 Mev, the correction was about 0.1 percent of the total flux, and it was negligibly small at the two higher energies.

Because of the asymmetry of the liquid hydrogen target with respect to the beam direction, it was inconvenient to calculate the correction for spurious events by means of any analytic expressions. For this reason it was decided that the correction could most reliably be determined by means of a Monte Carlo calculation that simulated the actual random processes involved in the experimental situation. Such a calculation is exact within the limits determined by the statistics involved and can be carried to any desired degree of precision, the accuracy of the results being limited only by the uncertainty in the initial data used for the calculation (such as the value of $\tau = 2.54 \times 10^{-13}$ sec. used for the pion mean life[8]). Because of the relatively large statistical uncertainties caused by the low counting rate in this experiment, coupled with the large target-out subtraction (Section V. b below), it is necessary only that the muon-decay correction be known to an accuracy of 15 percent at the lowest energy. At the higher energies the required accuracy was smaller still.

To calculate this correction to 15 percent, it was necessary to consider only 600 decay events in the counter telescope. These were assumed to be isotropically distributed in the pion center of mass, and consideration had to be given only to those muons coming off at large enough center-of-mass angles to have a chance of being stopped in the target. For each of these latter muons the position and direction of decay were assigned with the aid of a table of random numbers, and its fate was then decided on the basis of knowledge of the geometry and stopping power of materials in its path. The spread in the energy of the beam pions was taken into account to first approximation and introduced only a very small uncertainty (less than 5 percent) into the correction.

It was the magnitude of this correction and its rapidly increasing importance as the pion energy was reduced that set the lower practical limit on the pion energies used in the experiment.

In addition to the above considerations, it was necessary to take into account those muons arising from decay of beam pions ahead of counter 1. Some of these muons had such low energy that they stopped before reaching the rear counter. At all energies except the lowest (33 Mev), these muons were reliably separated from the pions by pulse height. It is possible that at the lowest energy some of these muons caused pulse heights within the limits of the pion criteria, because of the width of the gaussian pulse-height distribution for these muons. However, it can be shown that this is a negligible correction even at the lowest energy, largely because of the small number of pion decays near the first counter that gave rise to muons reaching the second counter.

b. Attenuation in the walls of the target and in the second crystal.

Some of the pion beam passing through the counter telescope was attenuated by the second crystal, by the walls of the hydrogen flask, by the heat shields, and by the various beam windows. In order to correct for this, a "dummy" target was constructed that was essentially identical to the actual target except that the hydrogen was replaced by a vacuum. In the experimental run, a measurement of the total attenuation in the dummy was made in precisely the same manner as the measurement of the attenuation in the target itself. The percentage attenuated in the dummy cannot be directly subtracted from that in the hydrogen target, however. In the hydrogen target the pion beam was reduced in energy by passing through the target hydrogen, and therefore passed through the rear walls, heat shield, and window of the target at a lower energy. In the dummy, the beam passed through all the material at essentially the same energy. Since the attenuation cross section for positive pions in complex nuclei is a rather steep function of the energy, the amount of attenuation in the rear half of the dummy had to be corrected for this difference in cross section before the attenuation in the dummy was subtracted from that in the hydrogen target. The correction to the correction was relatively small, however. The total "target out" or dummy correction was greatest for the 70 Mev measurement, amounting there to 6.5 mb.

c. Accidentals.

In addition to the pulses from the counters, randomly distributed single accidental pulses appeared on many of the sweeps. These presumably were caused by the random charged particle background in the vicinity of the counter telescope. Since an attenuation event could be masked by an accidental pulse appearing at the usual position of a pulse from the rear counter, it was necessary to correct for this effect. The distribution of accidentals was determined from the film; from the portions of the sweeps between the positions of the normal counter pulses, the frequency of accidental pulses per cm of sweep could be calculated. It was found necessary to increase the observed number of attenuated pions by about 3 percent at each energy to correct for this effect. The number of pions attenuated in the dummy target was similarly corrected.

d. Muon flux correction.

The calculated cross section must also be corrected to take into account the fact that a) the pion beam contained a small fraction of muons of the same pulse height as the pions, and b) the flux of pions through the hydrogen target was reduced by pion decay after the first pulse-height counter.

Calculation of the muon flux correction for muons coming from the region ahead of counter 1 was based on reasonable assumptions as to the variation of pion intensity with distance from the production target and the portion of the total beam area "seen" by the counter telescope. The pion mean life used was $\tau = 2.54\,(10^{-8})$ sec.[8] This calculation indicated a contamination of about 0.5 percent. The contribution of muons from pion decay in the region of high pion density near the production target was estimated to be negligibly small ($<$ 1 percent) on the basis of some experimental data on the number of particles passing through large ranges of Cu. These data were obtained during the integral range measurements of the pion beam energies.

The number of pion traversals was reduced by about 2 percent at each energy by decays after counter 2. Calculation of the correction for decays between the two pulse height crystals took into account a) the fact that many of the muons resulting from these decays did not have such a pulse height as to be confused with pions, and b) the fact that many of the muons which would have had such a pulse height decayed at large enough laboratory angles to miss the second counter altogether.

This muon contamination was assumed to be noninteracting, and the total correction to the flux was between 3 and 3.5 percent at each energy.

VI. RESULTS

The measured values for the cross section and the major corrections are given in Table I. Column 1 gives the mean energy of the pions in the target. In the second and third columns appear the attenuation percentages in the liquid hydrogen target and in the dummy target, corrected for accidentals. The fourth column lists the corrections for the spurious events caused by pion decay in the counter telescope. The sixth and seventh columns list the correction factors needed to account for the noninteracting muon contamination of the beam and for the fact that the length of path in hydrogen varied for pions in different parts of the beam because of the cylindrical shape of the hydrogen flask. The last column gives the corrected values for the cross section.

Since the rear counter subtended an angle of ±35° at the center of the hydrogen target, these values for the "total cross section" refer to the cross section for all interactions except those in which a pion is scattered into an angle within ±35° of the pion beam direction.

Table I

T_π	% Pions attenuated* H_2	Dummy**	Spurious Events	Net % Attenuated	Correction factors: Muon flux correction	Unequal H_2path	Final σ
33 ± 4.5 Mev	1.207 ±0.071	0.313 ±0.062	0.530 ±0.070	0.364 ±0.118	1.034	1.009	6.4 ± 2.1 mb
44 ± 4	0.919 ±0.061	0.247 ±0.054	0.107 ±0.026	0.565 ±0.086	1.033	1.009	9.8 ± 1.5
56 ± 4	1.343 ±0.094	0.329 ±0.083	0.004 ±0.003	1.010 ±0.125	1.031	1.009	17.6 ± 2.2
70 ± 5	1.480 ±0.132	0.388 ±0.077	0	1.092 ±0.152	1.029	1.009	19.0 ± 2.6

* Corrected for accidentals

** Corrected for energy difference

VII. DISCUSSION OF RESULTS

The total cross section for positive pions in hydrogen has been measured by a number of observers at a variety of energies. The results are displayed in Fig. 6, along with those obtained in this experiment. The measurements at 110 and 135 Mev are those obtained by Anderson, Fermi, Martin, and Nagle[1] from the integration of their measured angular distribution. The measurement shown at 58 Mev is that of Bodansky, Sachs, and Steinberger.[9] This value is believed by these authors to be more reliable than their earlier value, obtained in an attenuation measurement.[2] The value shown at 53 Mev is that of Fowler, Fowler, Shutt, Thorndike, and Whittemore,[3] measured by cloud chamber techniques. The measurement at 47 Mev is a very recent one by Weaver, Lord, and Orear,[6] using nuclear emulsions. The cross section shown at 37 Mev is the most recent value obtained in an attenuation measurement reported by Angell and Perry.[4] The cross section at 40 Mev was obtained by Perry[5] by integrating his measured angular distribution. Most of these values represent the cross section for scattering of positive pions at angles larger than some limiting angle determined by the experimental apparatus used. This limiting angle is different for each of the measurements. The cross sections may be compared with little error, however, since the angular distributions of Anderson, et al,[1] Bodansky, et al,[2] and Perry[5] show that the scattering cross section at small angles is relatively small.

The curve drawn through the points represents the relation $\sigma = b\ p'^4/E'^2$ plotted as a function of the pion kinetic energy in the laboratory, T. E' is the center-of-mass total energy of the pion and p' is its center-of-mass momentum. The value of b has been adjusted for least squares best fit to all the data. The above energy dependence is obtained theoretically when the cross section is calculated from second-order perturbation theory, assuming a pseudoscalar pion field and using gradient coupling $(\sigma \cdot \nabla \phi)$ to the nucleon. Marshak[10] has performed this calculation in the lowest order perturbation theory, using a) the complete pseudovector coupling interaction and b) the pseudoscalar coupling interaction. The result for the pseudovector coupling differs only slightly from the curve shown in Fig. 6. The result for pseudoscalar coupling gives an entirely different energy dependence, the cross section decreasing slightly with energy, in disagreement with the experimental results. The results of these theoretical calculations depend very strongly on the mathematical methods used to obtain them. Recent speculations[11, 12] have lent support to the notion that pseudovector and pseudoscalar coupling may give results which are quite similar in this energy range. Nevertheless, the curve shown provides a fairly good fit over a large range of energies, and it seems plausible to infer that gradient coupling is predominant above 30 Mev.

VIII. ACKNOWLEDGMENTS

It is a pleasure to acknowledge the advice and encouragement of Professor C. Richman. Several stimulating conversations were also held with Dr. J. Lepore.

The experimental technique used in this work was first suggested by Professor H. A. Wilcox while he was at the University.

We are indebted to Mr. John Garrison for the use of his liquid hydrogen target.

Information Division
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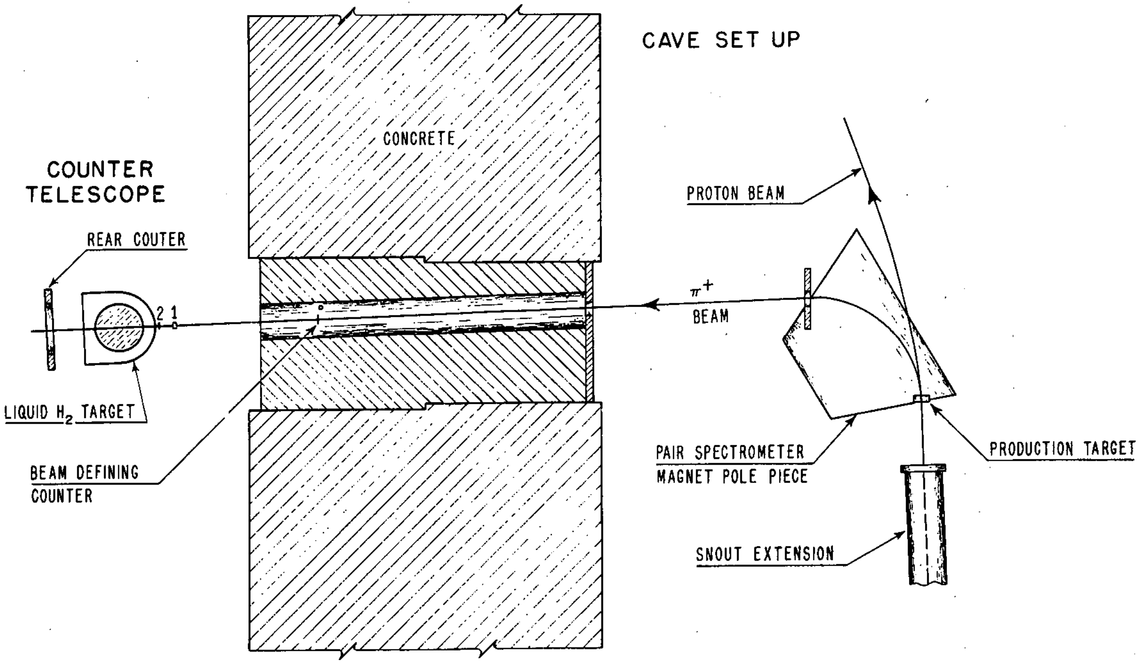

MU-5443

Fig. 1

Experimental arrangement.

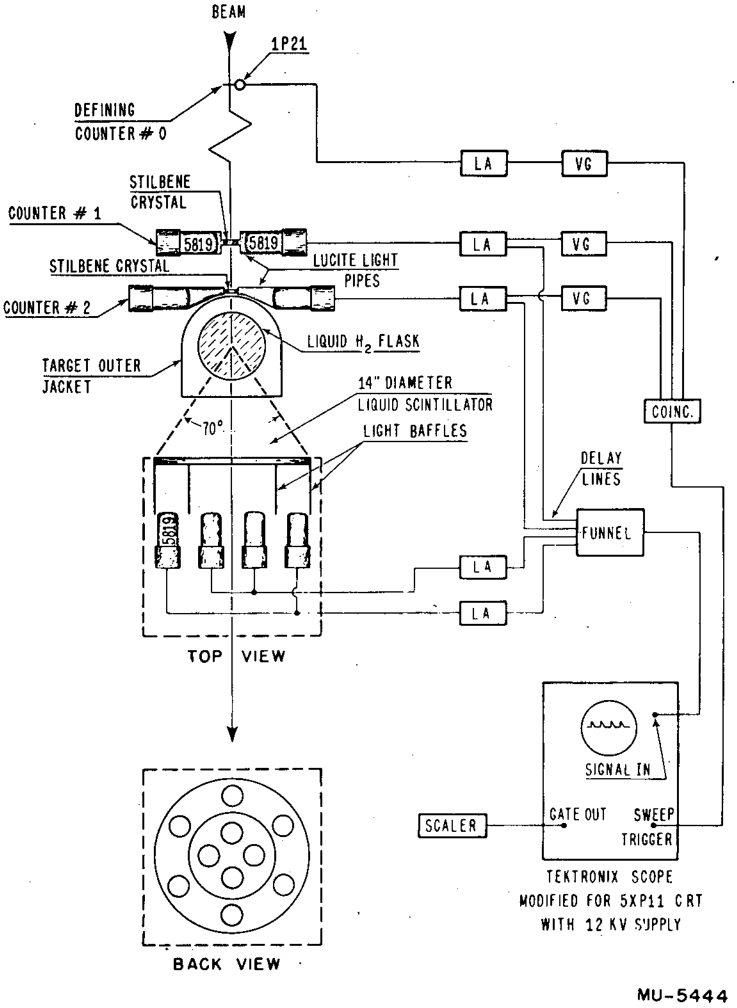

Fig. 2

Schematic diagram of electronic apparatus and counters.

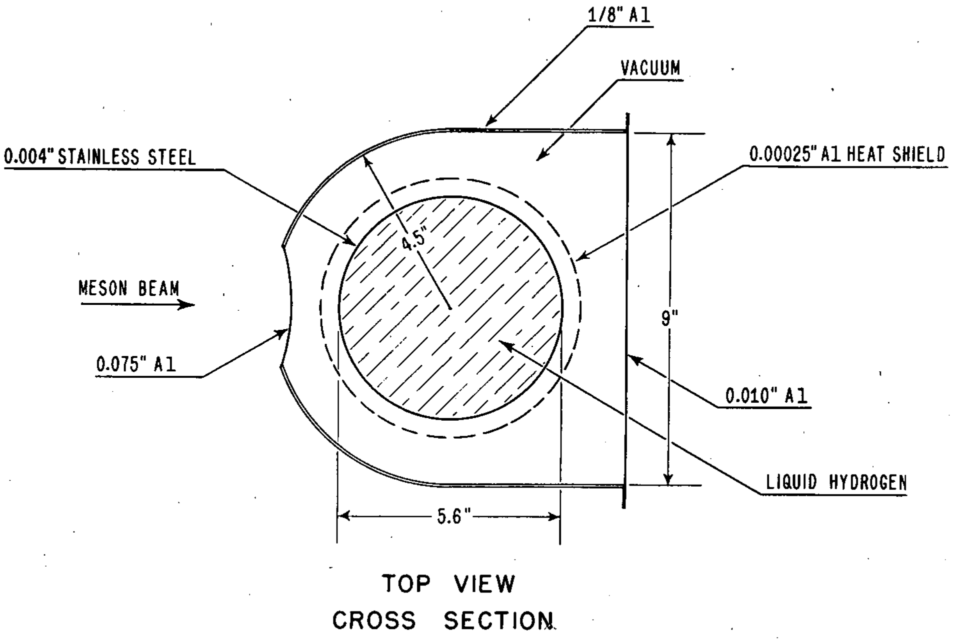

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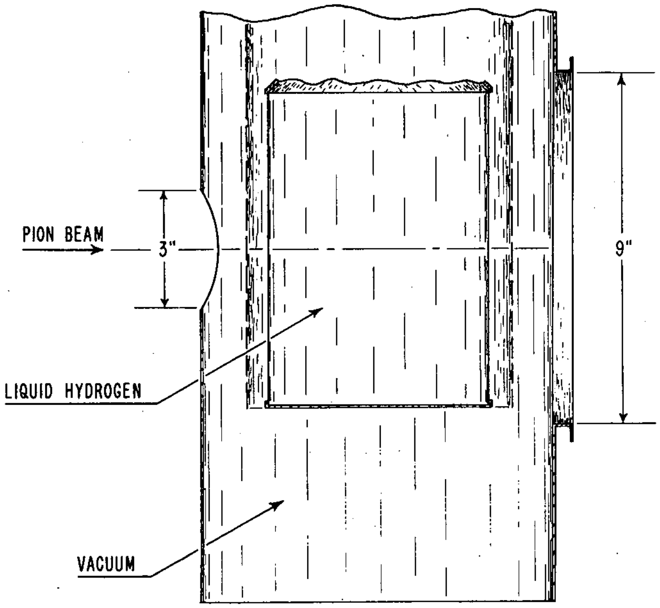
Fig. 3 (a)

Sketch of liquid hydrogen target.



SIDE VIEW CROSS SECTION

LIQUID HYDROGEN TARGET.

MU-5365

Fig. 3 (b)

Sketch of liquid hydrogen target.

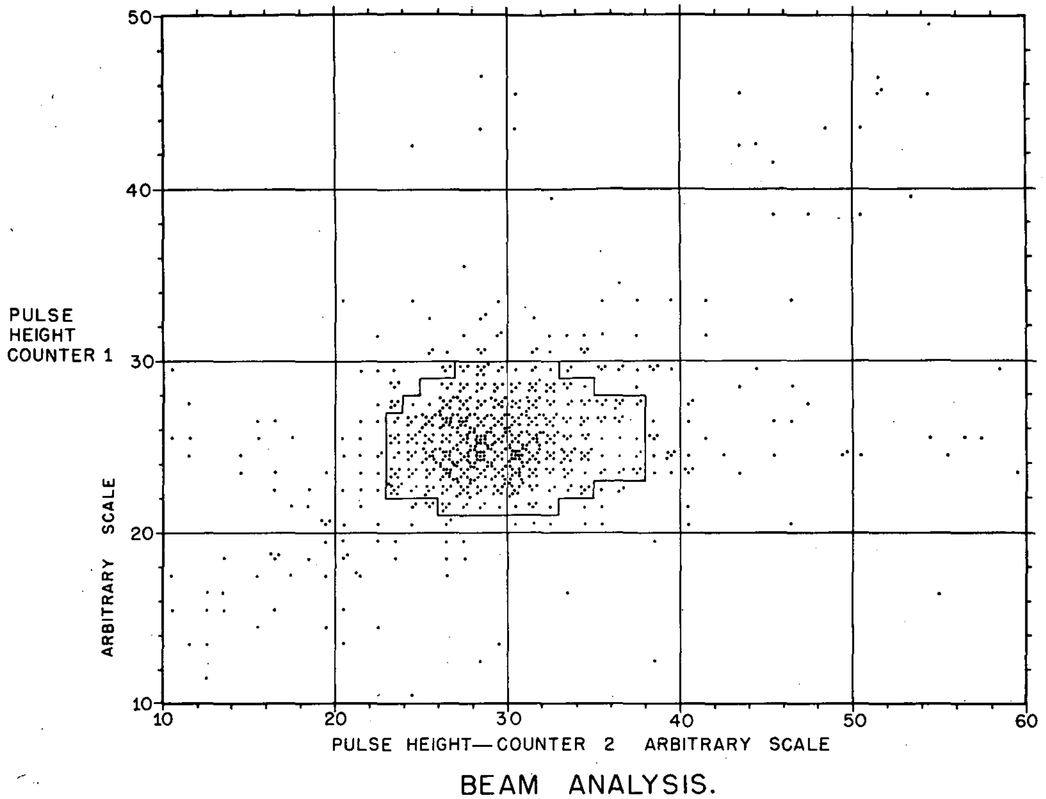


Fig. 4

"Three-dimensional" plot of pulses from counters 1 and 2 on all sweeps in a group of samples of film, for the case of 33 Mev pions. Criteria for identifying pions are shown.

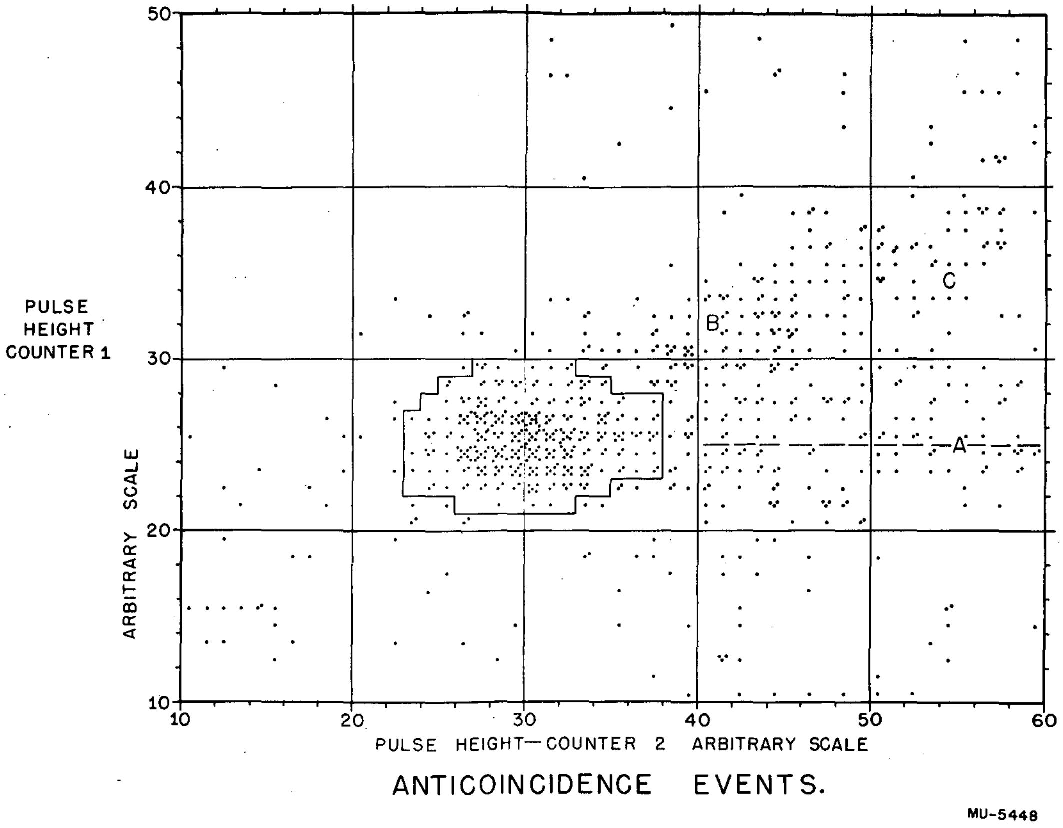


Fig. 5

"Three-dimensional" plot of pulses from counters 1 and 2 on all sweeps for which the pulses from the back counter were missing, for the case of 33 Mev pions.

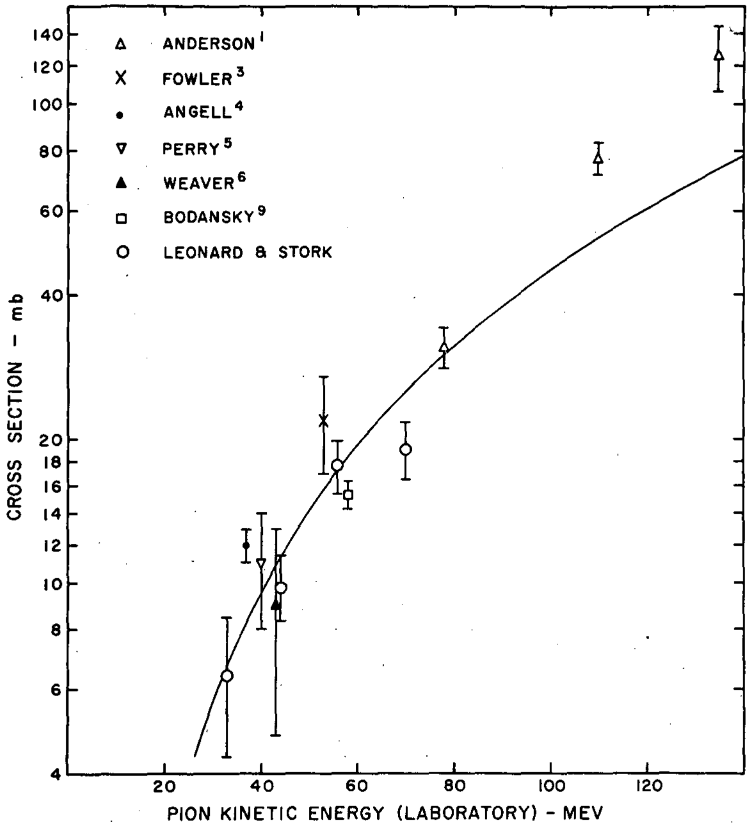


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Fig. 6

Experimental values of the total cross section for positive pions in hydrogen, as a function of pion energy.