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## Ernest O. Lawrence Radiation Laboratory

# TOTAL CROSS SECTIONS FOR NEGATIVE PIONS ON PROTONS AT 230, 290, 370, 427, and 460 Mev

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## ABSTRACT

Total cross sections for negative pions on protons were measured at laboratory-system energies of 230, 290, 370, 427, and 460 Mev. The measurements were made at energies identical with those used in other $\pi^-$-p experiments on the differential elastic, charge-exchange, and inelastic processes so that comparisons could be made without introducing errors due to uncertainties in energies measured separately. The total cross sections found agree within statistical error with other measured values, and with values calculated from sums of elastic, inelastic, and charge-exchange measurements. The results are;

| Energy (Mev) | Total cross section |
|---|---|
| 230 ± 6 | 58 ± 9 |
| 290 ± 7 | 33 ± 2 |
| 370 ± 9 | 27 ± 2 |
| 427 ± 10 | 27 ± 2 |
| 460 ± 20 | 28 ± 2 |

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## I. INTRODUCTION

Many measurements of the $\pi^-$-p total cross section have been made in the energy region from 230 to 460 Mev.[1,2,3] The purpose of this experiment was to measure this cross section at pion energies identical with those used in other $\pi^-$-p differential elastic and inelastic experiments done recently at the Berkeley Synchrocyclotron.[4,5,6] This total cross section was determined by measuring the attenuation of the pions in a thick hydrogen target, using the same pion beam as was used in those other experiments.

The total cross sections measured in this experiment can be used to check the total cross sections obtained by integrating the corresponding differential cross sections. They can also be used with the differential data to check the predictions of dispersion theory. The advantage in comparing the differential data with the total cross sections found thus, is in minimizing errors that might possibly arise in these comparisons when the pion energies are separately measured.

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## II. EXPERIMENTAL METHOD

### A. Experimental Arrangement

This experiment was carried out by measuring the attenuation in hydrogen of a negative pion beam obtained from an internal Be target in the proton beam of the Berkeley 184-in. synchrocyclotron. The quadrupole magnets, analyzing magnet, and general layout of this beam in the meson cave of the cyclotron are shown in Fig. 1. The beam energies used and the muon and electron contaminations of the beam are listed in Table I. These energies and muon contaminations were determined by range measurements in copper. The electron contaminations of the beams were measured at the two lower energies by using a gas Čerenkov counter set to detect only the electrons, and were estimated at the three higher energies by calculation.[7] The method of obtaining this beam, and its various properties are discussed in detail in the reports of the other experiments performed in conjunction with this experiment.[4,5,6]

The liquid hydrogen target used was 4 ft long to provide an attenuation large enough for the total cross-section measurements.[8] A diagram of the location of this long liquid hydrogen target relative to the pion beam monitor and attenuation-measuring counters is shown in Fig. 1. The counters have been numbered for reference, and their dimensions are given in Table II.

A schematic diagram of the electronics circuit used is shown in Fig. 2. Both monitor doubles (12) and triples (123) were recorded. Accidentals rates were measured by inserting $5.4 \times 10^{-8}$-sec delay between the monitor and counter 3. The electronics arrangement is essentially the same as in previous experiments.[4,5,6]

Two separate data runs were made. The three higher beam energies (Table I) were used during the first run, and the counters used are those shown in Fig. 1. The two lower energies were measured during a second run, and Counter 2 was replaced by Counter 4, and Counter 3 was replaced by Counter 5 (Table II).

Beam-profile measurements were made with the empty target in place by using a small counter at about 1 ft from the target's downstream end. Typical horizontal and vertical profiles obtained are shown in Fig. 3.

### B. Experimental Procedure

Double (12) and triple (123) coincidences were recorded for both the conditions of liquid hydrogen target, full and empty. Accidental counts (see IIA) were also recorded for each condition. The beam intensity (about $10^3$ monitor counts/sec) was considerably reduced below the maximum obtainable, so that the accidental correction necessary was very small. Even with these low counting rates, sufficient data were obtained in a few minutes to make the statistical error resulting from the number of pions measured negligible.

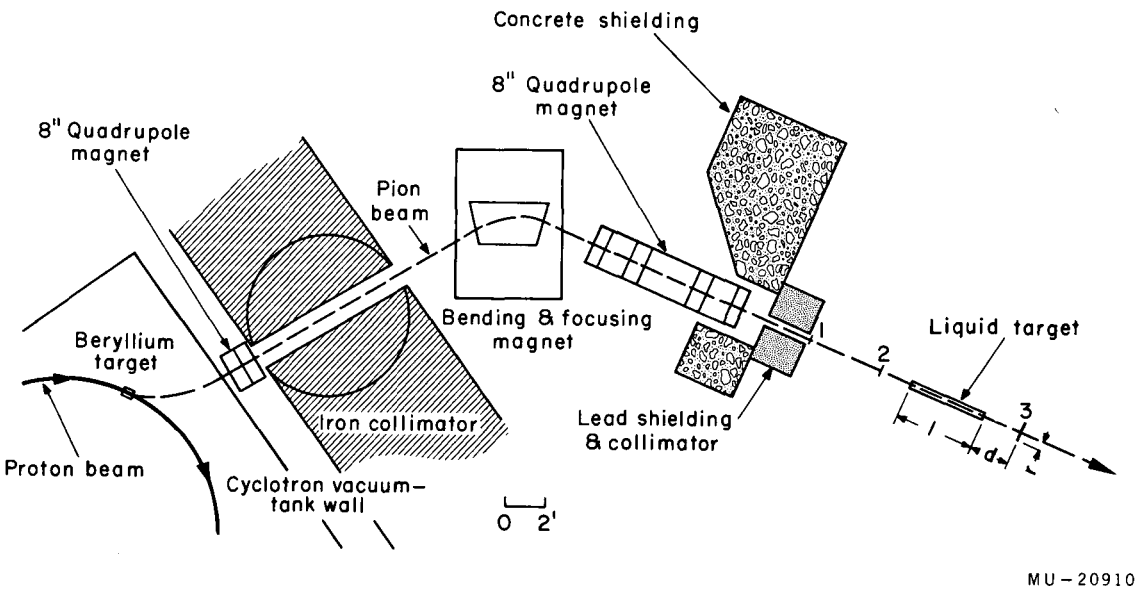


Fig. 1. Diagram of experimental arrangement.

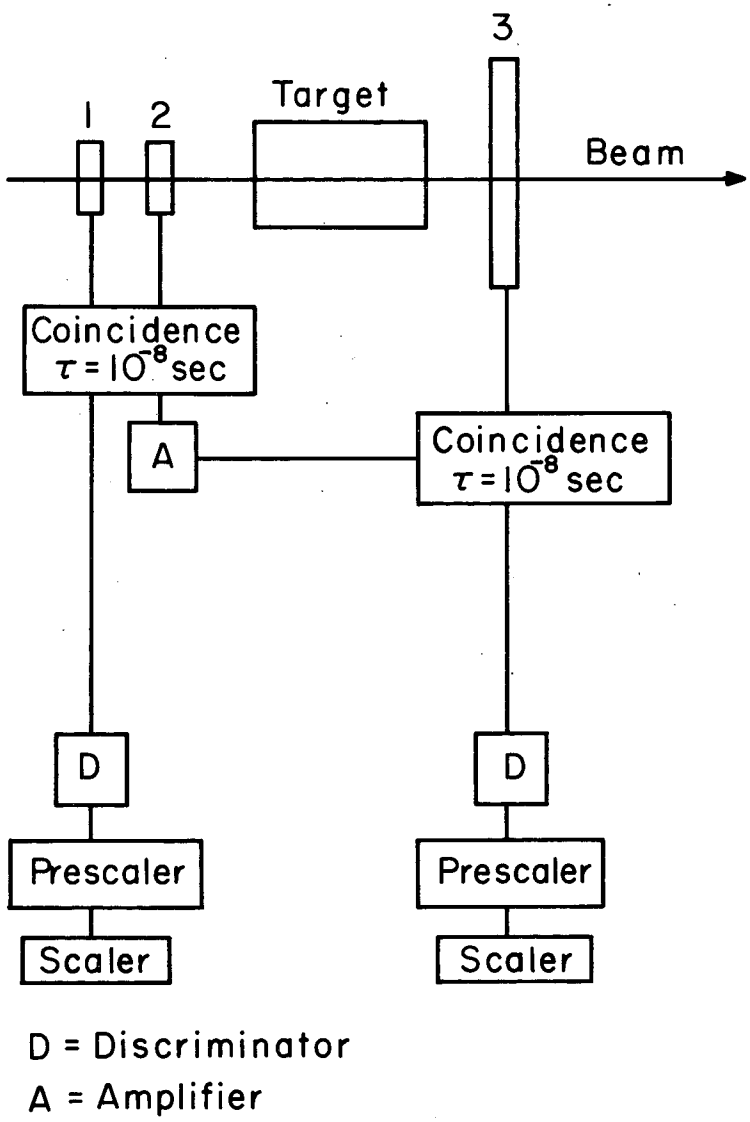


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Fig. 2. Block diagram of electronics system.

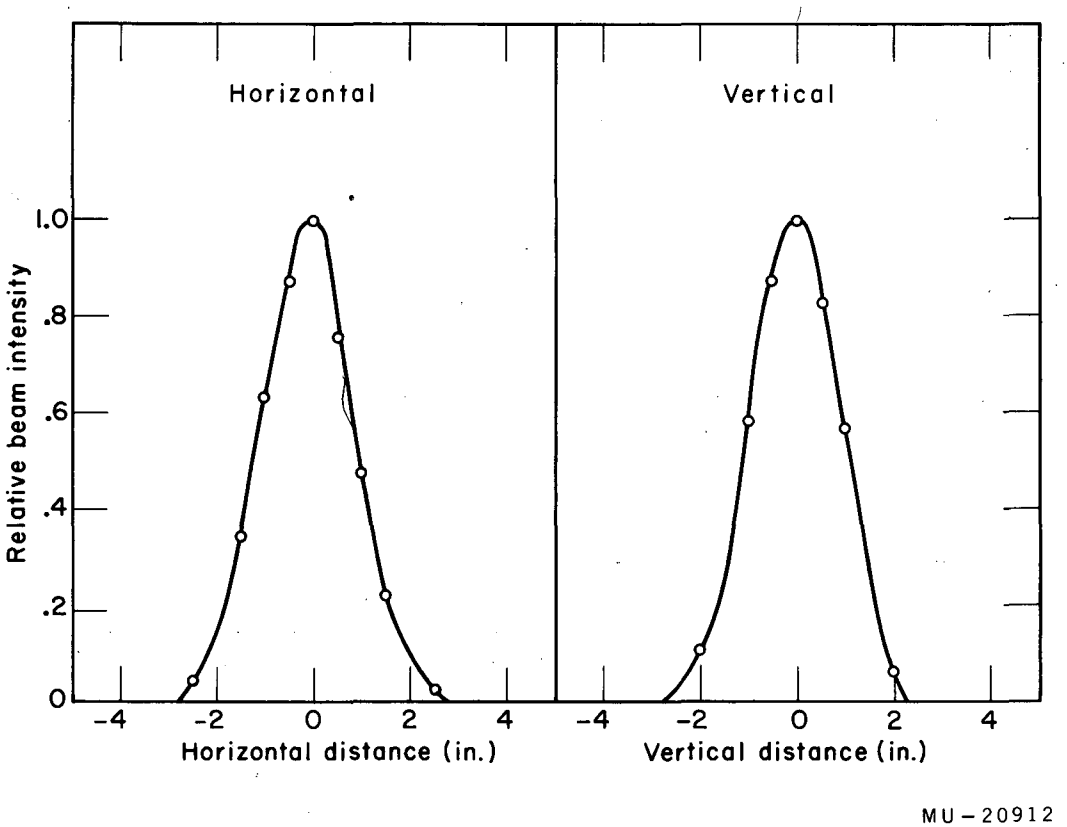


Fig. 3. Pion beam profiles.

Table I

Negative pion beam energies and contaminations

| Pion beam energy (lab) (Mev) | Muon contamination (%) | Electron contamination (%) |
|---|---|---|
| 230 ± 6 | 15 ± 1 | 5 ± 1 |
| 290 ± 7 | 8 ± 1 | 1 ± 1 |
| 370 ± 9 | 4 ± 1 | 1 ± 1 |
| 427 ± 10 | 4 ± 1 | 1 ± 1 |
| 460 ± 20 | 4 ± 1 | 1 ± 1 |

Table II

Scintillation counter dimensions

| Counter No. | Width (in.) | Height (in.) | Diameter (in.) | Thickness (in.) |
|---|---|---|---|---|
| 1 | | | 2.00 | 0.25 |
| 2 | | | 1.00 | 0.25 |
| 3 | | | 12.00 | 1.00 |
| 4 | 0.25 | 0.25 | | 0.25 |
| 5 | | | 6.00 | 0.50 |

These four types of data were taken at the five beam energies listed in Table I. The relatively large errors on the measurements at the highest energy are due to the fact that we did not have a range-energy curve at this point and had to estimate the spread in beam energy from wire-orbit measurements.

## III. RESULTS

### A. Beam Attenuation

The fraction of the beam particles transmitted through the target was determined as follows. Triple coincidences, 123, were first divided by the corresponding number of double coincidences, 12, for each energy and kind of data. For the target-full and target-empty runs separately, the real counting rate per unit monitor, C, was determined by subtracting the accidental rate A from the total rate T using the formula

$$C = T - A, \tag{1}$$

where it is assumed that the monitor rate per unit time is constant.

The fraction of the beam transmitted, F, was then obtained from the formula

$$F = C_f/C_e, \tag{2}$$

where "f" and "e" refer to the target-full and -empty conditions, respectively.

The pion attenuation R differs from the beam attenuation F because of the electron and muon contamination present in the beam. Letting the fractional muon contamination of the incident beam be K, and the fractional electron contamination be E, we express the relation between R and F by the equation

$$R = (F - K - gE)/(1 - K - E), \tag{3}$$

where it is assumed that the muons are negligibly affected by the presence or absence of the hydrogen in the target, and that when the target is full a fraction g ($0 \leq g < 1$) of the electrons is scattered enough by the hydrogen to miss Counter 3 (see Fig. 1).

### B. Target Constant

The cross section $\sigma'$ is given by the formula

$$\sigma' = K \ln(1/R), \tag{4}$$

where R is obtained from Eq. (3), and K is the target constant. The target constant for hydrogen is given by the formula

$$K = 1/(\rho_\ell N), \tag{5}$$

where $\rho$ is the density of the liquid hydrogen in the target, $\ell$ is the length of the target, and N is Avogadro's number. The density $\rho$ was actually taken as the difference between that of boiling liquid hydrogen and that of the vapor in the empty target,[4] $\rho = 69.3 \pm 0.8$ g/l. The average target length $\ell$ at liquid hydrogen temperature was found to be 48.50 in. These values give, for the target constant, $K = 193 \pm 2$ mb.

## C. Total Cross Sections

The total cross section desired is the zero-degree limit of the nuclear attenuation cross section for pions. To find this cross section it is necessary to separate out Coulomb scattering and then to extrapolate the results to zero deg forward solid angle.

To make such an extrapolation possible, a number of small forward solid angles were measured at each energy. The average solid angle subtended by Counter 3, $\Omega$, is given by the equation

$$\Omega = 2\pi \left[1 - \left(\sqrt{(d+\ell)^2 + r^2} - \sqrt{d^2 + r^2}\right)/\ell\right] , \qquad (6)$$

where r is the radius of Counter 3, which is at a distance d from the nearest end of the hydrogen target of length $\ell$ (see Fig. 1). Equation (6) is derived in Appendix A. The various distances d and the average solid angles $\Omega$ corresponding to them, which were calculated from Eq (6) are listed in Table III.

Cross sections were calculated by using Eq. (4) for the limiting values of R obtained from Eq. (3), using g = 0 and g = 1. The values of R obtained are listed in Table III. The cross sections $\sigma'$ listed in Table III are the averages of the two obtained from the limiting values of R in each instance.

The average Coulomb cross section at each point, $\sigma_c$ (mb), was calculated by using the formula

$$\sigma_c = \frac{86.73}{(\beta c p)^2} \frac{(d+\ell)^3}{\ell r^2} , \qquad (7)$$

where p is the momentum of the particle and $\beta$ is its relativistic velocity, the other quantities being the same as indicated after Eq. (6). This is an approximate formula valid for $r^2 << d^2$, derived in Appendix B. The values of $\sigma_c$ obtained from Eq. (7) are listed in Table III.

The Coulomb cross sections were subtracted from the measured cross sections by using the formula

$$\sigma = \sigma' - \sigma_c , \qquad (8)$$

where $\sigma$ is assumed to be purely nuclear, and that the interference between nuclear and Coulomb scattering can be neglected. The values of $\sigma$ obtained are given in Table III.

Table III

Forward cross sections at various solid angles

| Beam energy (Mev) | Target distance, d (in.) | Ω (sr) | F | R (g=0) | R (g=1) | $\sigma'$ (mb) | $\sigma_c$ (mb) | $\sigma$ (mb) |
|---|---|---|---|---|---|---|---|---|
| 230 | 19.44 | .021 | .7844 | .7930 | .7305 | 52.7 ± 7.9 | 0.6 | 52.1 ± 7.9 |
| | 24.44 | .015 | .7784 | .7855 | .7230 | 54.6 ± 8.0 | 0.8 | 53.8 ± 8.0 |
| | 33.44 | .010 | .7735 | .7794 | .7169 | 56.2 ± 8.1 | 1.1 | 55.1 ± 8.1 |
| | 45.44 | .007 | .7576 | .7595 | .6970 | 60.8 ± 9.0 | 1.6 | 59.2 ± 9.0 |
| 290 | 19.44 | .021 | .8620 | .8593 | .8484 | 30.5 ± 1.3 | 0.4 | 30.1 ± 1.3 |
| | 24.44 | .015 | .8593 | .8564 | .8454 | 31.2 ± 1.3 | 0.5 | 30.7 ± 1.3 |
| | 33.44 | .010 | .8471 | .8430 | .8320 | 34.3 ± 1.3 | 0.7 | 33.6 ± 1.3 |
| | 45.44 | .007 | .8524 | .8488 | .8378 | 33.0 ± 1.3 | 1.1 | 31.9 ± 1.3 |
| 370 | 20.00 | .080 | .8812 | .8855 | .8749 | 24.7 ± 1.1 | 0.1 | 24.6 ± 1.1 |
| | 25.00 | .062 | .8792 | .8834 | .8728 | 25.1 ± 1.2 | 0.1 | 25.0 ± 1.2 |
| | 32.00 | .044 | .8797 | .8839 | .8734 | 25.0 ± 1.2 | 0.1 | 24.9 ± 1.2 |
| | 44.00 | .028 | .8744 | .8783 | .8678 | 26.3 ± 1.2 | 0.2 | 26.1 ± 1.2 |
| | 56.00 | .019 | .8687 | .8723 | .8618 | 27.6 ± 1.2 | 0.3 | 27.3 ± 1.2 |
| 427 | 20.00 | .080 | .8759 | .8799 | .8694 | 25.9 ± 1.2 | 0.1 | 25.8 ± 1.2 |
| | 25.00 | .062 | .8756 | .8796 | .8691 | 25.9 ± 1.2 | 0.1 | 25.8 ± 1.2 |
| | 32.00 | .044 | .8741 | .8780 | .8675 | 26.3 ± 1.2 | 0.1 | 26.2 ± 1.2 |
| | 44.00 | .028 | .8702 | .8739 | .8634 | 27.2 ± 1.2 | 0.1 | 27.1 ± 1.2 |
| 460 | 20.00 | .080 | .8743 | .8782 | .8677 | 26.3 ± 1.2 | 0.1 | 26.2 ± 1.2 |
| | 25.00 | .062 | .8711 | .8748 | .8643 | 27.0 ± 1.1 | 0.1 | 26.9 ± 1.1 |
| | 32.00 | .044 | .8696 | .8733 | .8627 | 27.4 ± 1.2 | 0.1 | 27.3 ± 1.2 |

The cross sections obtained from Eq. (8) were extrapolated to zero solid angle at each energy by making a least-squares fit to a curve of the form

$$\sigma = A + B\,(\Omega)^2 \quad . \tag{9}$$

This parabolic extrapolation was chosen because it was a simple form having the desired property of zero slope at $\Omega = 0$. The calculations were carried out by using an IBM 650 computer program.[4] The curves obtained are shown in Fig. 4, and the total cross sections obtained from the extrapolation, $\sigma_t$, are listed in Table IV for each pion energy.

### D. Errors

The main source of errors in this experiment was the uncertainty in the fraction of electrons scattered out of the beam. The fraction of electrons scattered enough by the liquid hydrogen to miss Counter 3 is strongly dependent upon the electron energy (see Eq. (7)). The Čerenkov counter used for measuring the fraction of electrons present had an energy threshold for electrons of about 10 Mev. Electrons of this low energy are Coulomb-scattered enough so that almost 100% of them miss Counter 3. Electrons of the same energy as the pion beam, on the other hand, are scattered so little that almost none of them misses Counter 3.

Since no data were obtained on the energy distribution of the electron contamination, it is not possible to evaluate g, the fraction scattered out. Consequently, the value of R was calculated from Eq. (3) by using the limit values 0 and 1 of g. The cross sections obtained from these two limits were averaged, and the error assigned to them taken as half the difference between the limits. These errors on $\sigma'$ are given in Table III.

Errors arising from counting statistics and from Coulomb scattering of pions and muons were calculated and are included in the errors assigned to the final total cross sections, $\sigma_t$. The fraction of the beam that left the target before passing through its length was estimated from the beam profile curves (Fig. 3) and found to be negligible. The uncertainty in the target constant is also included in the final cross sections.

## IV. CONCLUSIONS

The total $\pi^-$-p cross sections found are in statistical agreement with previously measured values.[2,3] They can also be compared with cross sections calculated from $\pi^-$-p elastic, charge-exchange, and inelastic cross sections at energies where these exist. Measured values of elastic $\pi^-$-p total cross sections are available at the four lowest energies,[4] comparable data on the measured charge-exchange total cross sections is available at the three lowest energies.[5] The inelastic cross section for the interaction $\pi^- + p \rightarrow \pi^+ + \pi^- + n$ has been measured previously,[6] and information is available for the total charged inelastic cross sections at 290, 370, and 427 Mev.[4] These data are given in Table IV. The sum of these cross sections where known is also given in Table IV, and the values obtained agree within statistics with the total cross sections measured in this experiment. At 427 Mev, the available data were used to calculate a value for the charge-exchange cross section. In these calculations, the contribution from the interaction $\pi^- + p \rightarrow \pi^0 + \pi^0 + n$ is not included. From agreement obtained in these compilations it can be assumed that this cross section cannot be more than a few mb.

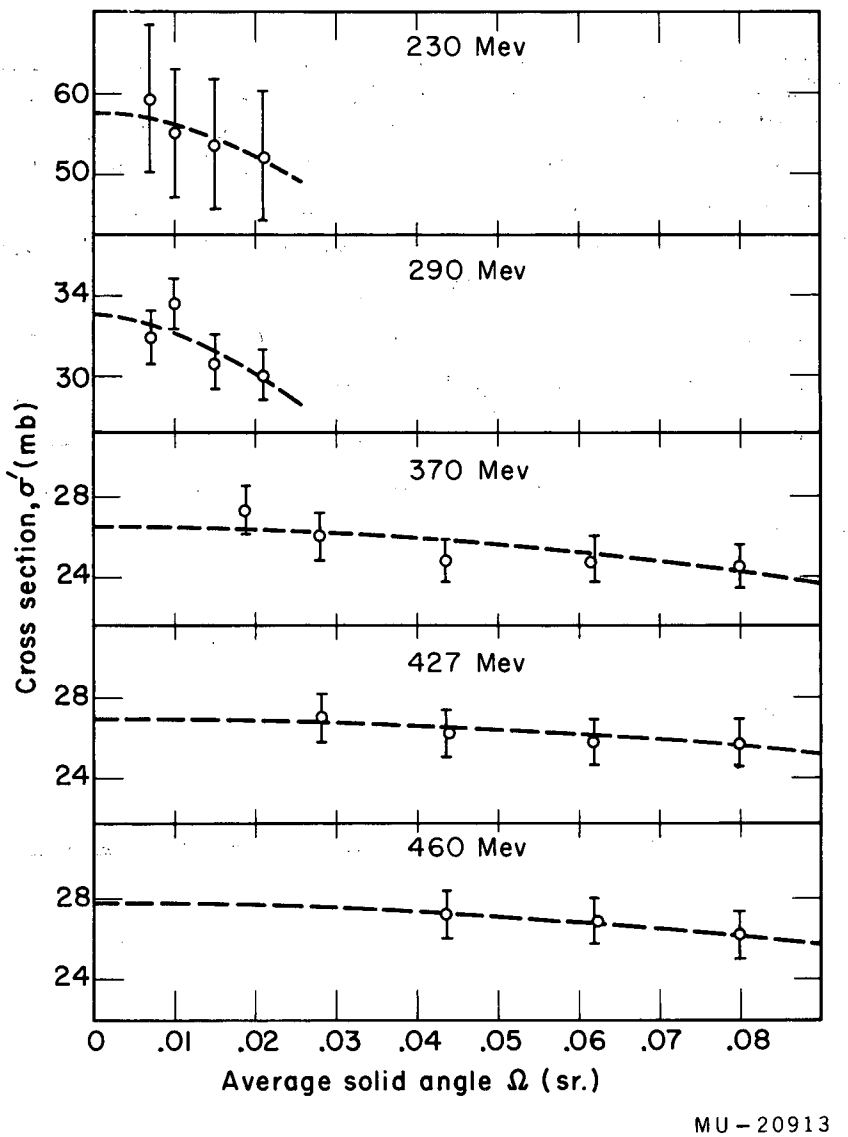


Fig. 4. Cross sections as a function of solid angle collected at various beam energies. Dashed lines are parabolic least-squares fits.

Table IV

Total $\pi^-$-p cross sections

| Beam Energy (Mev) | Total cross section $\sigma_t$ (mb) | Total elastic cross section (mb) | Total charge-exchange cross section (mb) | Total chgd. inel. cross section(mb) | $\Sigma^d$ total cross section (mb) |
|---|---|---|---|---|---|
| 230 | 58 ± 9[a] | 20.8 ± 0.4[b] | 30.4 ± 1.3[c] | 0.3 ± 0.3[d] | 51.5 ± 1.4 |
| 290 | 33 ± 2[a] | 13.8 ± 0.3[b] | 18.2 ± 0.8[c] | 2.4 ± 0.8[b] | 34.4 ± 1.2 |
| 370 | 27 ± 2[a] | 10.9 ± 0.2[b] | 13.6 ± 0.6[c] | 3.1 ± 0.8[b] | 27.6 ± 1.0 |
| 427 | 27 ± 2[a] | 13.0 ± 0.4[b] | 10.3 ± 2.3[e] | 3.7 ± 1.0[b] | ——— |
| 460 | 28 ± 2[a] | ——— | ——— | ——— | ——— |

[a]This experiment

[b]Goodwin et al.[4]

[c]Caris et al.[5]

[d]Perkins et al.[6]

[e]Calculated

Since the major source of error in this experiment results from the electron contamination in the pion beam, more precise values would be obtained either by using purer beams or measuring the electron contamination and its energy distribution more accurately.

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## APPENDIX A

### Long-Target Effective Solid Angle

If the distance from the center of Counter 3 (Fig. 1) to some point on the center line of the hydrogen target is called x, then the solid angle subtended from this point by Counter 3 is given by

$$\Omega(x) = 2\pi\,(1 - x/\sqrt{x^2 + r^2}) \quad , \tag{10}$$

where r is the radius of Counter 3.

The average solid angle $\Omega$ subtended by the target is then given by

$$\Omega = \frac{1}{\ell}\int_d^{d+1} \Omega(x)\,dx = 2\pi \left[1 - (\sqrt{(d+\ell)^2 + r^2} - \sqrt{d^2 + r^2})/\ell\right], \tag{6}$$

where d is the distance from Counter 3 to the near end of the target of length $\ell$ (Fig. 1).

The effect of points off the axis is assumed to be negligible.

# APPENDIX B

## Long-Target Average Coulomb Cross Section

The differential Coulomb scattering cross section, $d\sigma_c/d\Omega$, in the laboratory system for hydrogen in mb/sr is given by[4]

$$d\sigma_c/d\Omega = \frac{5.178}{(\beta cp)^2 \sin^4(\theta/2)} , \tag{11}$$

where p is the momentum of a particle with relativistic velocity $\beta$.

The cross section for particles scattered outside Counter 3 from a point x on the axis of the hydrogen target is given by

$$\sigma_c(x) = 2\pi \int_{\theta_x}^{\pi} d\sigma_c/d\Omega \sin\theta \, d\theta = \frac{8\pi\,(5.178)}{(\beta cp)^2} \left[ \frac{1}{(1-\cos\theta_x)} - 1/2 \right] \tag{12}$$

where $\tan\theta_x = r/x$, and r is the radius of Counter 3 (Fig.1).

Averaging $\sigma_c(x)$ from EQ. (12) over the target length gives the effective average Coulomb cross section, $\sigma_c$, as

$$\sigma_c = \frac{1}{\ell} \int_d^{d+\ell} \sigma_c(x)\, dx = \frac{8\pi\,(5.178)}{(\beta cp)^2\, \ell r^2} \left[ \left| \frac{x^3}{3} + \frac{(x^2+r^2)^{3/2}}{3} + \frac{r^2 x}{2} \right|_d^{d+\ell} \right]. \tag{13}$$

The lower limit of Eq. (13) is negligibly small for $d < \ell$, and for $r^2 << \ell^2$, Eq. (13) is well approximated for the purposes of this experiment by

$$\sigma_c = \frac{86.73\,(d+\ell)^3}{(\beta cp)^2\, r^2 \ell} , \tag{7}$$

where $\sigma_c$ is the average Coulomb cross section in mb.

Contributions from off-axis points are neglected in this derivation.

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