Photoproduction of Negative and Positive Pions from Deuterium for Photon Energies 500 to 1000 Mev*

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The ratio of the yields of negative and positive pions photoproduced in deuterium has been measured at six photon energies between 500 and 1000 Mev and at seven angles between 20° and 160° in the center-of-momentum system of the photon and target nucleon. Pions were selected with a magnetic spectrometer and identified using momentum and specific ionization in a scintillation counter telescope. The spectator model of the deuteron was used to identify the photon energy. Statistical errors assigned to the π^-/π^+ ratio range between five and fifteen percent. The results of the present experiment join smoothly with the low-energy π^-/π^+ ratios obtained by Sands *et al.* At high energies the π^-/π^+ ratio varies from 0.5 at forward angles and energies near 900 Mev to 2.5 at 160° c.m. and energies 600 to 800 Mev. The cross sections for π^- photoproduction from neutrons have been derived from the π^-/π^+ ratio and the CalTech π^+ photoproduction data. The angular distributions for π^- production are considerably different from those for π^+; there is, for example, a systematic increase at the most backward angles. The energy dependence of the total cross section for π^- is similar to that for π^+, although the second resonance peak occurs at a slightly lower energy, and at 900 and 1000 Mev the π^- cross section is smaller by a factor 1.6. A comparison is made of the cross sections for π^+ photoproduction from hydrogen and deuterium, although the accuracy of this comparison is not high.

I. INTRODUCTION

An experiment designed to measure the photoproduction of negative pions from neutrons in the energy range of 500 to 1000 Mev has been completed at the CalTech Synchrotron Laboratory. The data obtained complement the recent measurements of the photoproduction of positive pions from hydrogen in the same energy range.[1,2]

Although the reaction

$$\gamma+n\rightarrow\pi^-+p$$

cannot be investigated for free neutrons, the use of neutrons bound in deuterium seems quite satisfactory, at least at high energies. Not only are the nucleons in deuterium loosely bound, but complications caused by the nuclear structure can be minimized by measuring the ratio, henceforth called the π^-/π^+ ratio, of the cross sections for the reactions

$$\gamma+d\rightarrow\pi^-+p+p,$$

and

$$\gamma+d\rightarrow\pi^++n+n.$$

This ratio is identified directly with the ratio of the cross sections for the reactions

$$\gamma+n\rightarrow\pi^-+p,$$

and

$$\gamma+p\rightarrow\pi^++n.$$

At energies near threshold, effects of Coulomb and nuclear interactions between the three particles in the final state are important, and sizeable corrections for these effects must be made in order to interpret the cross sections observed from deuterium in terms of those for free nucleons.[3] However, at high energies, these effects are unimportant, and the main complication from using deuterium is the kinematic one arising from the motion of the target nucleons in the nucleus. A possible exception to this statement is that at small angles the Pauli exclusion principle inhibits the yield from deuterium, and this effect may not be the same for π^+ and π^-. This is discussed in Sec. VI.

Extensive measurements of the π^-/π^+ ratio at low energies have been made by the University of Illinois emulsion group.[4] Careful measurements of the reaction $\gamma+d\rightarrow\pi^-+p+p$ in deuterium loaded emulsions are reported by Adamovich *et al.*[5] and analyzed in terms of Baldin's[3] calculations concerning the final state interactions. More recent low-energy work is referred to by Bernardini in his report at the Kiev conference, 1959.

The widest survey of the π^-/π^+ ratio at energies up to 500 Mev was made by a CalTech group using a magnetic spectrometer.[6] The present experiment was planned to extend these measurements to 1000 Mev.

II. EXPERIMENTAL METHOD

In the present experiment, charged pions were observed from the interaction of the bremsstrahlung

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[1] F. P. Dixon and R. L. Walker, Phys. Rev. Letters **1**, 142 (1958); **1**, 458 (1958); and to be published.

[2] M. Heinberg, W. M. McClelland, F. Turkot, W. M. Woodward, R. R. Wilson, and D. M. Zipoy, Phys. Rev. **110**, 1211 (1958).

[3] A. Baldin, Nuovo cimento **8**, 569 (1958).

[4] M. Beneventano, G. Bernardini, G. Stoppini, and L. Tau, Nuovo cimento **10**, 1109 (1958).

[5] M. I. Adamovich, G. V. Kuz'micheva, V. G. Larionova, and S. P. Kharlamov, J. Exptl. Theoret.Phys. U.S.S.R. **35**, 27 (1958) [translation: Soviet Phys.-JETP **8** (35), 21 (1959)].

[6] M. Sands, J. G. Teasdale, and R. L. Walker, Phys. Rev. **95**, 592 (1954).

beam of the CalTech Synchrotron with a liquid deuterium target. Negative or positive pions of a given laboratory momentum and angle of emission with respect to the photon beam were selected using a magnetic spectrometer. The magnet of this spectrometer provides a wedge-shaped, uniform field which deflects particles vertically and focuses those of the proper momentum at a line focus (single focusing). A system of three scintillation counters was located at the focus and, at high energies, a Čerenkov counter was added to help discriminate against protons. Some long narrow veto counters were placed against the pole faces of the magnet in such a way as to avoid particles which might scatter or otherwise originate from the pole pieces. The solid angle of acceptance was determined by these veto counters and by a thin front aperture counter located at the entrance edge of the magnet. The entire system of magnets, counters, and shielding is mounted on a rotating carriage which pivots about an axis containing the target, so that the angle may easily be changed.

The spectrometer had two different geometric configurations; in the "medium-energy" configuration momenta up to 600 Mev/c were selected, while in the "high-energy" configuration momenta from 600 to 1200 Mev/c were selected. In both configurations the momentum dispersion, $\Delta P/P$, was approximately 0.1. The solid angle of acceptance was 0.006 steradian in the medium-energy and 0.002 steradian in the high-energy configuration. The corresponding angular resolutions were 1.6° and 1.0° (full width at half maximum), respectively.

The instrumentation of the spectrometer has been described by Dixon and Walker[1] who used the same equipment to measure the positive pion photoproduction from hydrogen; reference should be made to their article for specific details. The construction of the liquid target has been described by Vette.[7]

Pions were identified as those particles which passed through the spectrometer and produced minimum ionizing pulses in the scintillation counter telescope located at the focus of the magnet. Examination of pulse-height distributions from the counters indicated that with the biases used the counting system had an efficiency greater than 98% for detecting pions. Approximately 10% of the counting rate was produced in the walls of the target container; background counting rates were measured in separate runs and subtracted from full target counting rates. The positive pion counting rates were corrected by subtracting the counting rates (calculated) of pions produced from the free hydrogen contamination of the deuterium; this correction did not exceed three percent.

Electrons, if present, would also have been identified as pions. However, from the counting rates of negative particles produced in hydrogen under similar experimental conditions it was possible to conclude that the electron contamination was less than about 2%, and this might change the π^-/π^+ ratio by less than one percent. This conclusion is based on the assumption that positive and negative electrons are produced in approximately equal numbers, and the fact that negative pions from hydrogen would not be observed under these experimental conditions.

A large number of protons were incident on the spectrometer, especially at forward angles. Protons which would have been counted when the spectrometer was used in the medium energy configuration were always more than 2.2 times minimum ionizing, and these were easily eliminated by setting an upper bias on the pulse heights from the counters. (Protons with momenta less than 475 Mev/c were absorbed before reaching the final counter in the spectrometer.) At the higher momenta investigated, protons could not be distinguished on the basis of pulse heights. A Lucite Čerenkov counter sensitive to velocities greater than $0.7c$ was, therefore, incorporated into the high momentum configuration. A small fraction (about 0.0075) of the protons traversing the Čerenkov counter were counted by it, so that a correction, which was generally less than one percent and never exceeded six percent, had to be made for this proton contribution to the positive pion counting rates. To make this correction, the above fraction was measured at several energies, and the number of protons passing through the system at each setting was measured by placing the Čerenkov counter in veto.

Data were taken so that differences in the measurement of positive and negative meson counting rates were minimized; thus, many systematic errors present in absolute cross-section measurements were reduced or eliminated by measuring a ratio. Data were taken in runs of approximately one hour during which time a few hundred mesons of one charge were counted. Runs counting pions of different charges were made sequentially; all controllable factors relating to the synchrotron operation, the experimental area, and the detecting equipment were unaltered between such runs. Thus the absolute calibration of the beam intensity was unimportant and drifts over periods of a few hours could be neglected. The geometrical factors relating the cross section to the counting rate were the same for both positive and negative mesons and cancelled in the ratio. Likewise, detailed knowledge of the deuterium density and target geometry was unnecessary. Any counting inefficiency caused by bias settings or long period drifts in gain was the same for both positive and negative pions. Furthermore, data were taken which showed that the ratio was very insensitive to the synchrotron end-point energy for a range of hundreds of Mev. At least two runs separated by several days were made at each spectrometer setting and end-point energy.

Since photomultipliers are sensitive to magnetic fields, measurements were made to determine whether a large shift in the magnetic field strength would appreciably change the counting efficiencies. Pulse-height

[7] J. I. Vette, Phys. Rev. **111**, 622 (1958).

spectra obtained with the magnetic field at its maximum positive and maximum negative values were indistinguishable. Also, field changes from zero to maximum did not appear to change the gains appreciably.

As an additional check, one point (spectrometer central momentum = 580 Mev/c, laboratory angle = 39.5°, synchrotron end-point energy = 800 Mev) was run with both the medium and the high-energy configurations. In the medium-energy configuration the central magnetic field of the spectrometer was 14.1 kilogauss; in the high-energy configuration this magnetic field was only 7.4 kilogauss. The π^-/π^+ ratios obtained were 0.794 ± 0.037 and 0.778 ± 0.050, respectively.

Corrections to the observed counting rates for scattering in the counters and for $\pi-\mu$ decays were calculated to be the same for positive and negative pions within two percent.

The π^-/π^+ ratio was measured at pion momenta and angles selected both to continue the π^-/π^+ data previously obtained by Sands *et al.*[6] and to examine the same range of angles and energies included in the π^+ photoproduction data obtained by Dixon and Walker.[1] Spectrometer settings were chosen so that if pions had been observed from free nucleons with a momentum equal to the central (not average) momentum of the spectrometer, the photon energy would have increased in steps of 100 Mev from 500 to 1000 Mev. If quite reasonable assumptions are made, it can be shown that this energy roughly equals the average energy of photons which produce pions accepted by the spectrometer with a central momentum of P_0 from a deuterium target.

The center-of-momentum angles from free nucleons associated with each of these photon energies were selected to increase in steps of either 20° or 30° from 20° to 150°. An additional series of data was taken at the largest angle possible in the laboratory, 151.5°, which corresponds to a c.m. angle[8] of ~163°.

III. KINEMATIC EFFECTS OF TARGET NUCLEON MOTION

Although the measurement of the π^-/π^+ ratio can be made very accurately, the interpretation of these data is complicated by the use of bound instead of free nucleons. Specifically, the appropriate initial photon energy, which was not measured directly, cannot be uniquely determined from a knowledge of the momentum and angle of the outgoing pion. These complications are not really very important and should not be overemphasized. Thus, although a large amount of work was done to analyze the data in terms of the spectator model described below, the final results shown in Figs. 3 through 10 would not look very different if the target nucleons had been considered free. Thus inaccuracies in the model are probably not important.

[8] The c.m. system as used here is defined to be the center-of-momentum system of the appropriate nucleon, treated as a free particle, and the incoming photon.

It is possible to calculate the energy distribution of those photons which contribute to the pion counting rate by using the following "spectator" model of the deuteron-photon interaction. In this model the photon interacts with just one of the nucleons in the deuteron, while the other nucleon remains a spectator and is not involved in the interaction. Furthermore, the spectator nucleon is assumed to have the same momentum distribution in the final state as it had while a bound particle inside the deuteron.

The validity of the spectator model has been discussed previously.[9] The assumption that the incident photon interacts with only one nucleon is obviously poor for small nucleon separations or for high nucleon momenta. However, the deuteron is loosely bound and the average nucleon separation is large so that this difficulty is not serious.

An experiment which tests this model has recently been performed at Cornell University.[10] The reaction $\gamma+d\rightarrow\pi^-+2p$ was observed in a deuterium-filled diffusion cloud chamber. Although the experiment was statistically poor, it had the advantage that the kinematics were completely defined, since all the reaction products and their momenta could be identified. The momentum distribution of the spectator nucleons as determined by this experiment was compared to the distribution derived from the Hulthén wave function and was found to be in good agreement.

Using the spectator model, it is a straightforward problem in kinematics to calculate the appropriate energy distribution of photons kinematically capable of producing pions which can be accepted by the spectrometer.[11]

For each setting of the spectrometer a resolution function $F(K,\mathbf{P}_0,E_0)$ was calculated which gives the relative probability for a photon with an energy K to produce a pion acceptable by the spectrometer.[12] The spectrometer setting is described by the central momentum P_0 and the laboratory angle θ_L; E_0 is the end-point energy of the synchrotron and for convenience K is measured in the rest system of the target nucleon. The counting rate at a given setting is proportional to the integral $\int F(K,\mathbf{P}_0,E_0)dK$. Typical resolution functions $F(K,\mathbf{P}_0,E_0)$ are shown in Fig. 1. For these calculations the Hulthén wave function for the deuteron ground state and the "thin target" bremsstrahlung spectrum were

[9] See references listed in footnote reference 4.

[10] D. H. White, B. M. Chasan, G. Cocconi, V. T. Cocconi, and R. M. Schectman, Bull. Am. Phys. Soc. 4, 273 (1959); also private communication.

[11] A fundamental ambiguity arises in that the specification of the momentum of a bound nucleon does not specify its velocity. This means that the transformation to the c.m. system of a nucleon and the incoming photon is not defined. The present calculations were made assuming each bound nucleon to have a total energy of Mc^2 where M is the free nucleon rest mass, and a velocity P/M. In practice the differences caused by this choice were negligible.

[12] The calculational method used was similar to the one outlined in R. Smythe, R. M. Worlock, and A. V. Tollestrup, Phys. Rev. **109**, 518 (1958).

used. Account was taken of the finite momentum resolution of the spectrometer and the finite size of the target.

At pion laboratory angles forward of 60° the function $F(K,\mathbf{P}_0,E_0)$ for deuterium exhibits an asymmetry which favors higher energy photons. At backward pion angles the resolution function becomes broader and the bremsstrahlung end point cuts off the high-energy tail. At any given pion angle the width at half maximum is roughly a constant fraction of the average photon energy.

The shape of the energy resolution curve for one spectrometer setting can be found experimentally by measuring the pion yield at that setting as a function of the synchrotron end-point energy E_0. Measurements were made of the π^+ yield at a laboratory angle of 64° and a central momentum of 475 Mev/c which corresponds to photons of about 700 Mev and a c.m. angle of 90°. The experimentally measured yields for this setting are shown in Fig. 2 for a sequence of synchrotron end-point energies. Corrections have been made for empty target counts, pion absorption, and pion decays; the errors shown are statistical.

In order to compare the calculations of the resolution function with the measured yields shown in Fig. 2, $F(K,\mathbf{P}_0,E_0)$ was computed for the one spectrometer setting used and for end-point energies E_0 going in 50-Mev steps from 600 to 1000 Mev. The shape of the function $F(K,\mathbf{P}_0,E_0)$ was then modified by folding in the measured positive pion cross sections from free hydrogen. Finally, the predicted relative yield for a given value of E_0 was obtained by integrating the modified resolution function over K. The absolute values of the calculated yields were then normalized by setting the measured and calculated yields equal at $E_0=850$ Mev. The predicted dependence of the pion yield on E_0 is given by the dashed curve of Fig. 2.

Figure 2 shows that the measured resolution curve is slightly wider than the calculated curve. Some factors, however, such as the finite angular resolution of the magnet, have been omitted from the calculations. These factors would, in general, broaden the range of energies

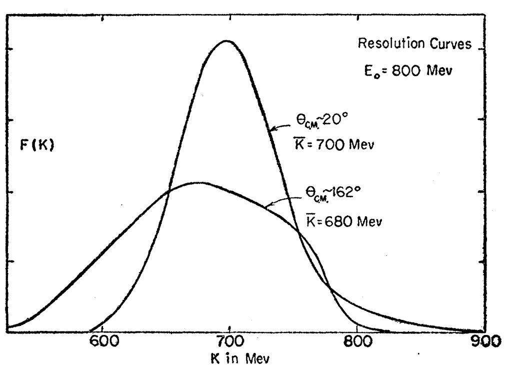

FIG. 1. Resolution functions calculated using the spectator model for two of the experimental settings. $F(K)$ is the $F(K,\mathbf{P}_0,E_0)$ of the text, and the units are arbitrary. The curve for $\theta_{c.m}\approx 162°$ shows clearly the effect of the bremsstrahlung upper limit cutting off the high-energy tail.

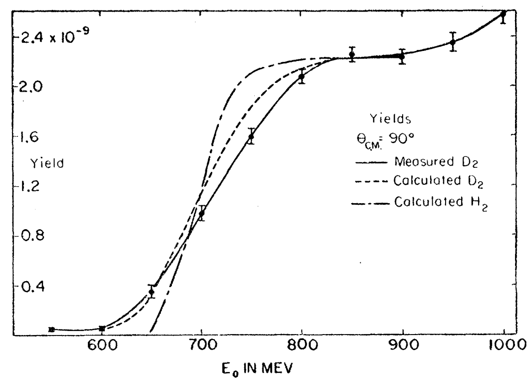

FIG. 2. The yield of π^+ from deuterium at $\theta_L=64°$ and $P_0=475$ Mev/c, corresponding to $\theta_{c.m}\approx 90°$ and a photon energy 700 Mev, as a function of the bremsstrahlung upper limit, E_0. The experimental points are compared to a curve (dashed) calculated for deuterium by the procedure explained in the text, Sec. III. The units of yield are counts per equivalent quantum, and the calculated curves have been normalized to the measured one at 850 Mev. The rise at high energy presumably results from the contribution of pions produced multiply.

of photons which produce pions which are detected experimentally. Furthermore, it can be seen that if the experimental determination of the end-point energy E_0 were in error by one percent, the agreement between the calculated and experimental yields would be considerably better. Since no special precautions were taken in measuring E_0, such an error is not impossible. Thus the check on the validity of these calculations is felt to be satisfactory.

The yields expected from a hydrogen-filled target are also shown in Fig. 2. These yields are a measure of the finite energy width caused by the equipment alone.

At each setting of the spectrometer, a range of photon energies was sampled. The weighted averages of these energies, $\bar{K}$, has been calculated for each data point using the relation:

$$\bar{K}=\int_K KF(K,\mathbf{P}_0,E_0)dK \Big/ \int_K F(K,\mathbf{P}_0,E_0)dK.$$

The production of a pion with momentum P_0 and angle θ_L corresponds to a range of pion angles in the c.m. system. Rough calculations based on the spectator model indicate that the angular width is largest at backward pion angles, but is never much larger than 8° (full angular width at half maximum). The average angle of emission was found to be within 2% of the angle expected if hydrogen had been used.

The spectator model permits calculation of the average photon energy and angle of emission assuming that the pions were produced singly. However, charged pions can also be produced through multiple production. Recent experiments at CalTech[13] and Cornell[14] show

[13] M. Bloch and M. Sands, Phys. Rev. **113**, 305 (1959).

[14] J. M. Sellen, G. Cocconi, V. T. Cocconi, and E. L. Hart, Phys. Rev. **113**, 1323 (1959).

TABLE I. Experimental conditions and results. E_0 is the bremsstrahlung end-point energy, P_0 is the spectrometer central momentum, and θ_L is the angle of the spectrometer in the laboratory. The second column gives the geometric configuration of the spectrometer, H standing for the high-energy configuration and M for the medium-energy one. $\theta_{c.m.}$ is the average pion angle in the center of momentum system of the incoming photon and the (moving) target nucleon. $\bar{K}$ is the average photon energy in the rest system of the target nucleon, and ΔK is an effective photon interval in this system defined in Sec.IV. π^-/π^+ is the ratio of yields of π^- and π^+ under the given conditions.

E_0 Mev	Con-fig.	P_0 Mev/c	θ_L deg	$\theta_{c.m.}$ deg	$\bar{K}$ Mev	ΔK Mev	π^-/π^+
600	H	468	13.7	20	510	60	1.11±0.06
600	M	447	27.8	40	510	60	0.98±0.05
600	M	414	42.8	60	510	60	0.89±0.04
600	M	349	68.0	90	510	60	1.07±0.06
600	M	284	98.5	120	500	70	1.74±0.12
600	M	232	136.1	150	500	80	2.05±0.18
600	M	222	151.5	161	500	80	2.21±0.24
700	H	569	13.1	20	600	70	1.23±0.06
700	M	542	26.7	40	610	70	0.88±0.05
700	M	498	41.1	60	610	70	0.78±0.04
700	M	414	65.7	90	610	70	1.03±0.05
700	M	328	96.0	120	600	80	1.49±0.09
700	M	262	134.5	150	590	100	2.33±0.20
700	M	247	151.5	162	590	100	2.47±0.27
800	H	669	12.6	20	700	80	1.08±0.05
800	H	633	25.6	40	700	80	0.82±0.04
800	H	580	39.5	60	710	80	0.78±0.05
800	M	580	39.5	60	710	80	0.79±0.04
800	M	475	63.6	90	700	80	0.80±0.03
800	M	370	93.7	120	700	100	1.20±0.05
800	M	288	132.6	150	680	120	2.42±0.23
800	M	268	151.5	162	680	130	2.39±0.27
900	H	769	12.2	20	810	100	0.87±0.05
900	H	725	24.6	40	800	90	0.82±0.05
900	H	660	38.1	60	800	90	0.65±0.04
900	M	534	61.6	90	800	90	0.69±0.03
900	M	407	91.5	120	790	110	0.93±0.05
900	M	310	130.9	150	770	140	1.80±0.15
900	M	286	151.5	163	770	150	2.86±0.33
1000	H	866	11.7	20	900	110	0.62±0.03
1000	H	817	23.8	40	900	110	0.55±0.04
1000	H	740	36.9	60	900	110	0.49±0.04
1000	M	592	59.8	90	900	110	0.56±0.04
1000	M	443	89.5	120	880	110	0.61±0.05
1000	M	331	129.3	150	860	160	1.51±0.14
1000	M	301	151.5	164	850	170	2.17±0.25
1080	H	648	55.0	85	950	120	0.40±0.04
1080	H	966	11.4	20	1000	120	0.72±0.04
1080	H	908	23.0	40	1000	120	0.64±0.04
1080	H	819	35.7	60	1000	120	0.48±0.03
1080	M	590	67.0	100	990	120	0.66±0.05
1080	M	478	87.5	120	970	130	0.50±0.05
1080	M	347	127.9	150	940	170	1.27±0.12
1080	M	314	151.5	164	930	200	1.73±0.16

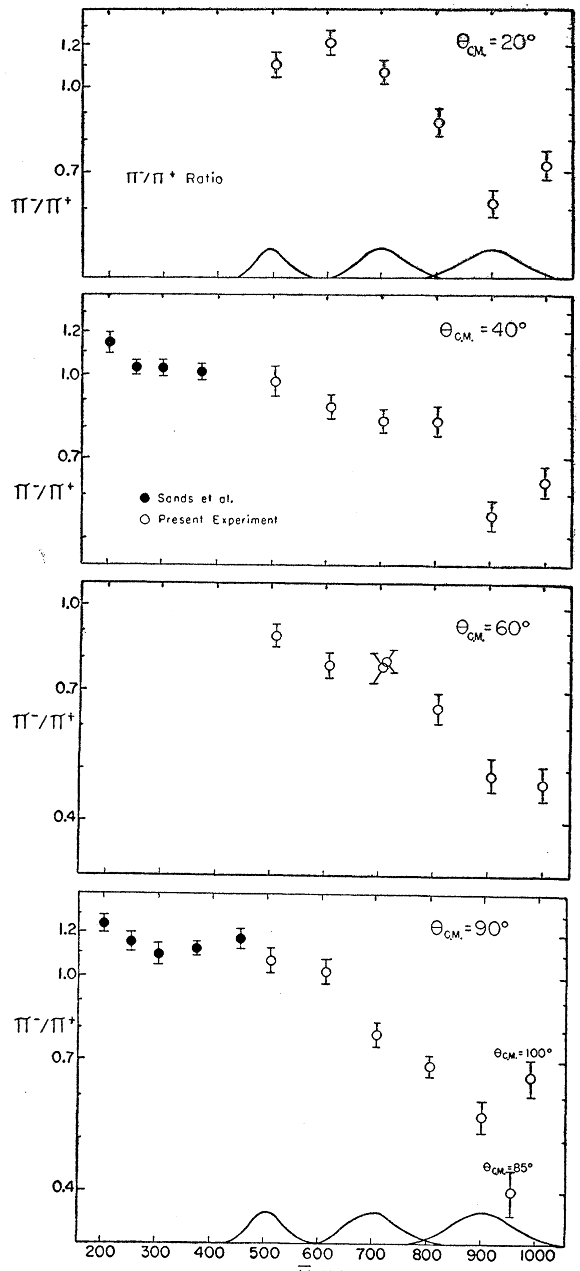

FIG. 3. The π^-/π^+ ratio from deuterium as a function of photon energy for c.m. angles 20°, 40°, 60°, and 90°. The mean photon energy, $\bar{K}$, is in the rest system of the target nucleon corresponding to the convention used in experiments with free nucleons of quoting photon energies in the laboratory system, which is also the nucleon rest system in that case. Some sample resolution curves are shown on a linear scale at the bottom of the graphs. The data shown as solid circles at low energies are taken from Sands *et al.* footnote reference 6.

that the total cross section for multiple production from hydrogen is very small for photon energies less than approximately 200 Mev above threshold. Above about 500 Mev, however, the cross section rises steeply and reaches a plateau of 40 to 60 microbarns; this value is comparable to the single pion photoproduction cross sections from hydrogen.

In the study of positive pion photoproduction from hydrogen it is feasible to eliminate multiply produced pions by adjusting the end-point energy of the synchrotron, because the threshold energy for these reactions is always at least 150 Mev greater than the photon energy required for single production. However, when deuterons are bombarded, the nucleon momentum may decrease the threshold energy required for multiple production to a value even below the average photon energy required for single production. This difficulty is most pronounced at backward angles and at high photon energies. From calculations using the CalTech and Cornell multiple pion data it is possible, however, to conclude that at the worst configuration the contamination of the singly produced pion counting rate by multiply produced pions is less than three percent. This leads to an error of less than two percent in the ratio due to multiple pion production. A check on these calculations was made by measuring the π^-/π^+ ratio as a function of the synchrotron end-point energy at two spectrometer settings. In both cases, the effect on the ratio attributable to multiple production was within the statistical errors assigned. Such a check is rather sensitive because the contribution from pions produced multiply is greatly enhanced by raising the synchrotron energy, of course.

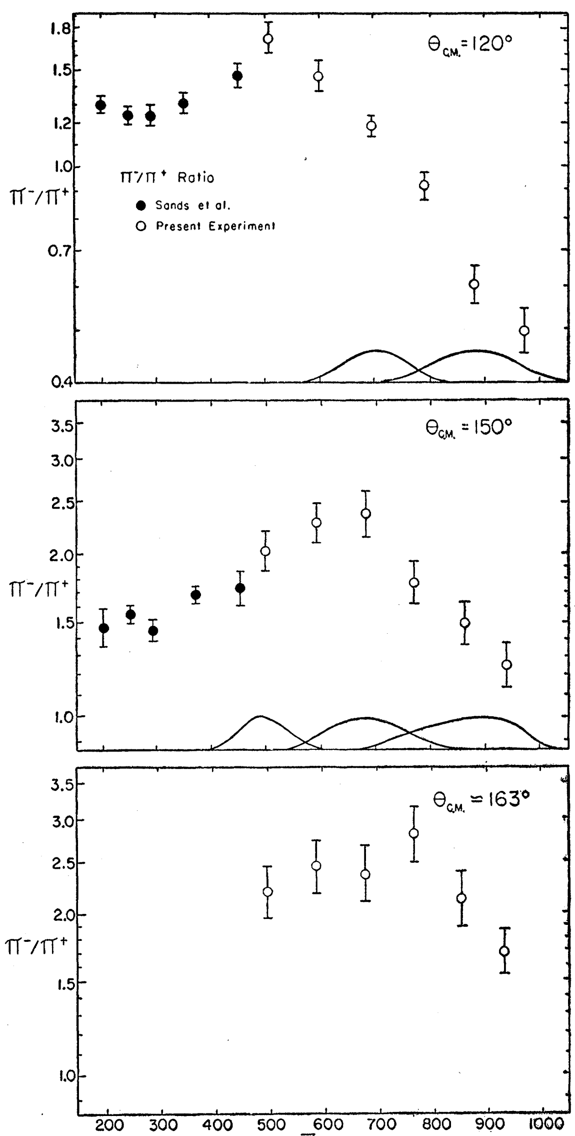

FIG. 4. The π^-/π^+ ratio at $\theta_{c.m.}=120°$, 150°, and 163°. See the caption of Fig. 3.

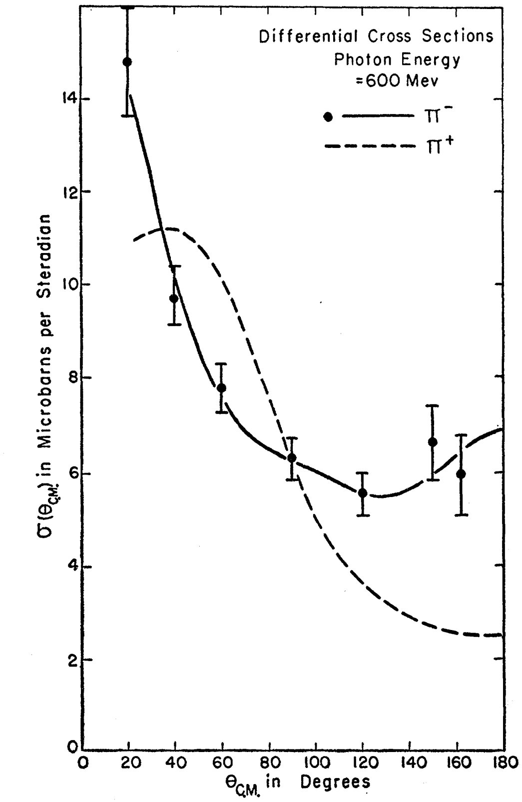

FIG. 5. The differential cross section at $\bar{K}=600$ Mev for the reaction $\gamma+n\rightarrow\pi^-+p$, derived from the π^-/π^+ ratio and the π^+ cross sections of Dixon and Walker, reference 1. For comparison, the π^+ angular distribution at the same energy is shown by the dashed curve. The cross sections are in the center of momentum system.

IV. RESULTS

The experimental settings for each data point are given in Table I. The mean photon energy $\bar{K}$ is tabulated as well as the photon energy interval $\Delta K\equiv K_2-K_1$ which is defined by the following:

$$\int_{K_1}^{K_2} F(K,\mathbf{P}_0,E_0)dK\equiv 0.68\int_0^{\infty} F(K,\mathbf{P}_0,E_0)dK,$$

$$\int_0^{K_1} F(K,\mathbf{P}_0,E_0)dK\equiv \int_{K_2}^{\infty} F(K,\mathbf{P}_0,E_0)dK.$$

The π^-/π^+ ratios obtained in this experiment are also tabulated in Table I and shown, as a function of energy, in Figs. 3 and 4 on a logarithmic scale. The earlier data of Sands *et al.*[6] are included in the figures; the agreement of the present data with the older results is seen to be excellent. The photon energy resolution

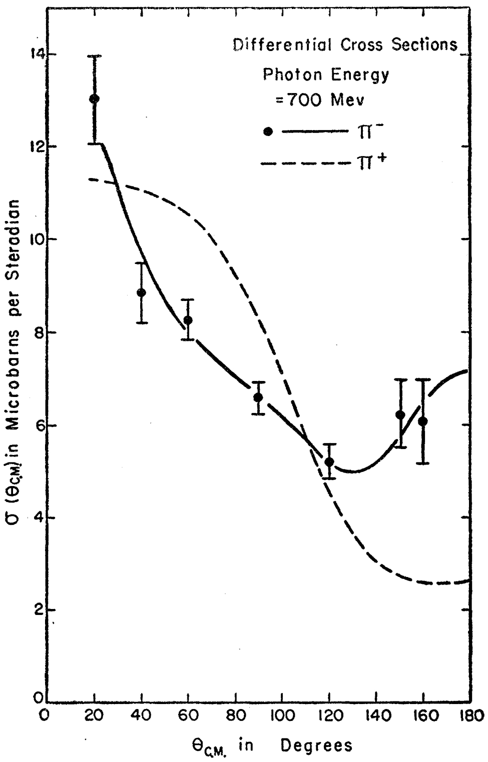

FIG. 6. π^- and π^+ angular distributions at 700 Mev. See caption of Fig. 5.

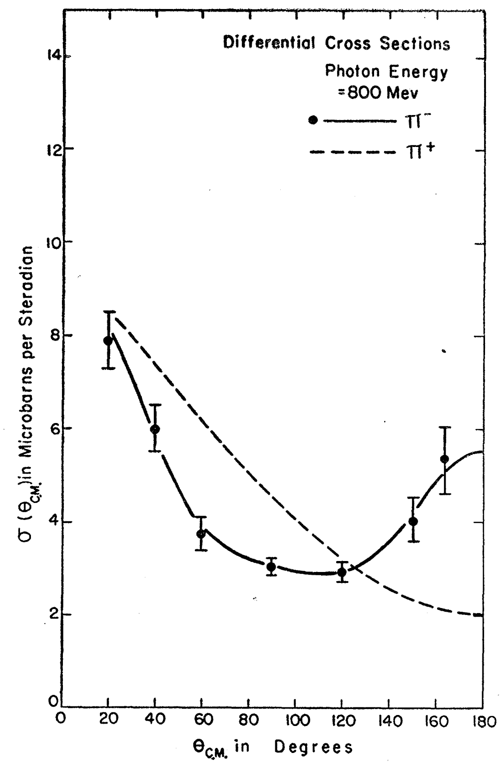

FIG. 7. π^- and π^+ angular distributions at 800 Mev. See caption of Fig. 5.

function $F(K,\mathbf{P}_0,E_0)$ is also shown at the bottom, on a linear scale, for some representative points.

The errors included with the π^-/π^+ ratio are purely statistical. In most cases the corrections applied were negligible compared to the statistical errors; in fact, the largest correction was equal to the statistical error at only one setting.

Although the kinematic model used in the reduction of the data is obviously not completely correct, it is felt that the identification of the measured ratio with the ratio of negative to positive pion photoproduction from free nucleons is valid within the accuracy of the data. The interpretation is most sensitive to the model at backward angles where the statistical errors and the energy spread are largest. The possible effects of the multiple pion production are also largest at those settings for which the least statistical accuracy was obtained.

The data at different settings are generally consistent with each other. The close agreement with the results of Sands *et al.* at the lower energies is reassuring. The data around 1000 Mev seem to be erratic; specifically, at some angles the ratio appears to reverse its downward trend while at other angles it decreases steadily with increasing energy. However, there is no reason to suspect that there are errors present in these data which would not also be present at lower energies. Furthermore, the agreement between the different runs taken on different days at a single setting is satisfactory.

The absolute cross sections for the photoproduction of negative pions from neutrons can be derived by multiplying the π^-/π^+ ratio by the cross section for producing positive pions from hydrogen. The differential cross sections obtained from such a calculation using the π^+ cross sections obtained by Dixon and Walker[1] with the same equipment are shown in Figs. 5 through 9. For $\theta_{\text{c.m.}}=120°$, 150°, and 161° the ratios were measured at energies considerably different from the energies presented which are at even 100-Mev intervals. At these angles the value of the ratio at the desired energy was found by interpolation. The "1000 Mev" cross sections at backward angles required an extrapolation of the π^-/π^+ ratio. Since the apparent slope of the data at the high-energy end is changing radically as a function of $\theta_{\text{c.m.}}$, the resulting cross sections must be viewed cautiously. The data at $\theta_{\text{c.m.}}=40°$ required an interpolation of the π^+ data.

Total cross sections for π^- photoproduction were calculated from the differential cross sections by fitting the angular distributions with a least squares fit of the form:

$$\sigma(\theta_{\text{c.m.}})=\sum_{m=0}^{M} A_m \cos^m\theta_{\text{c.m.}}.$$

For $k=600$, 700, and 800 Mev terms up to $\cos^4\theta_{\text{c.m.}}$ were included; for $k=900$ and 1000 Mev terms up to $\cos^6\theta_{c.m.}$ were included. These fits are shown in Figs. 5 through 9 for both positive and negative pion photoproduction. The total cross sections are shown in Fig. 10. The total cross sections at energies less than 600 Mev were derived from the π^-/π^+ data (interpolated) of Sands *et al.*,[6] and the π^+ cross sections from the early CalTech work.[15,16]

The fitting of the data with a simple power series in $\cos\theta_{c.m.}$ was done merely to find the total cross sections easily, and the coefficients in this fit are not given, since they have no particular significance. A "Moravcsik fit"[17] would perhaps be more significant, but this is also unreliable for extrapolation to angles smaller than those where our data exist, and would not give better values of the total cross sections. It differs from our fit only for angles less than 20°.

The cross sections reported for negative pion production obviously contain any systematic errors which may be present in the positive pion cross sections. These include errors in the beam calibration, in the spectrometer solid angle and momentum interval, and in corrections made for nuclear absorption and π-μ decay.[1] Furthermore, the negative cross sections are sensitive to uncertainties in $\bar{K}$ and to the extrapolation or interpolation of

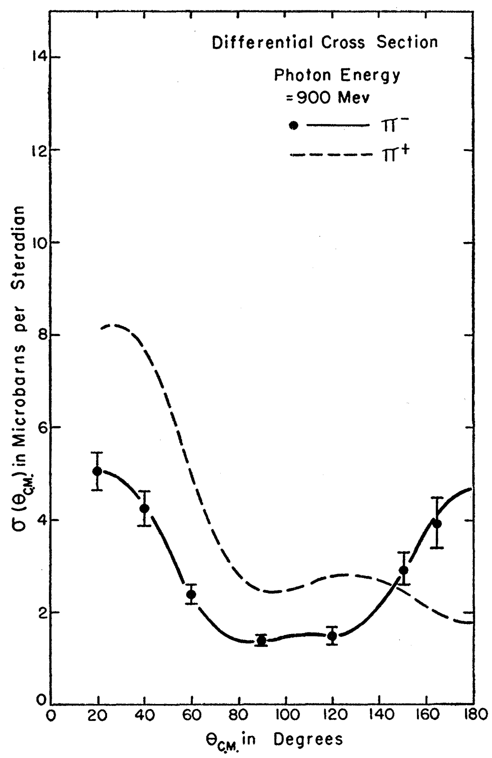

FIG. 8. π^- and π^+ angular distribution at 900 Mev. See caption of Fig. 5.

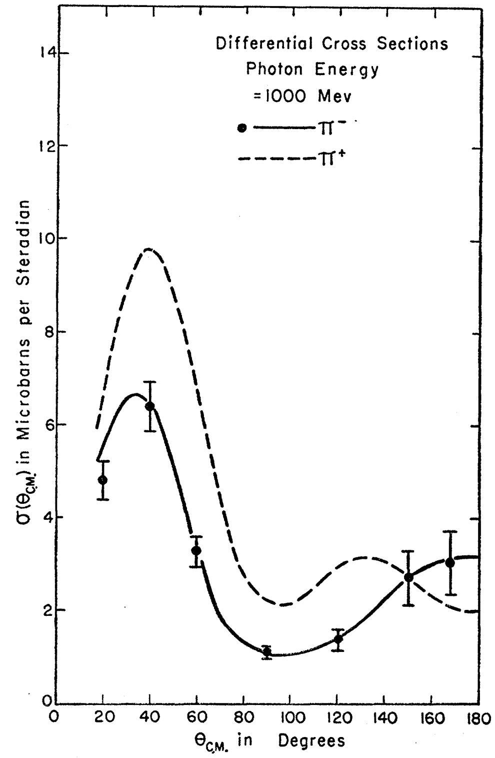

FIG. 9. π^- and π^+ angular distributions at 1000 Mev. See caption of Fig. 5.

the data, especially at the higher energies. A crude estimate of the possible uncertainties which are thus introduced is included in the quoted errors. Other than this, the errors shown are mainly statistical. The values of the π^+ cross section were taken from the thesis of Dixon, and may, be slightly changed before final publication.[1] This would, of course, also change the π^- cross sections, but this will not alter the comparison of the π^- and π^+ cross sections made in Figs. 5 to 9. It is clear from these figures that the angular distributions for π^- and π^+ are quite different, which simply reflects the fact that the π^-/π^+ ratio varies considerably with angle and energy. An interesting feature is that the π^- angular distributions rise upward at the most backward angles for all energies investigated.

The total cross section for π^- shown in Fig. 10 shows a clear second resonance peak similar to that found for π^+. The π^- peak seems to fall at a slightly lower energy than the π^+ peak. The fact that the two look quite similar is probably significant, since the shape and energy of the π^+ peak seems to be governed by interference effects[18] and these could be different for π^- and π^+. At lower energies there are not enough data to obtain accurate π^- total cross sections, but the dominance of the first resonance near 300 Mev is clear.

[15] A. V. Tollestrup, J. C. Keck, and R. M. Worlock, Phys. Rev. **99**, 220 (1955).
[16] R. L. Walker, J. G. Teasdale, V. Z. Peterson, and J. I. Vette, Phys. Rev. **99**, 210 (1955).
[17] M. J. Moravcsik, Phys. Rev. **104**, 1451 (1956).
[18] A. M. Wetherell, Phys. Rev. **115**, 1722 (1959).

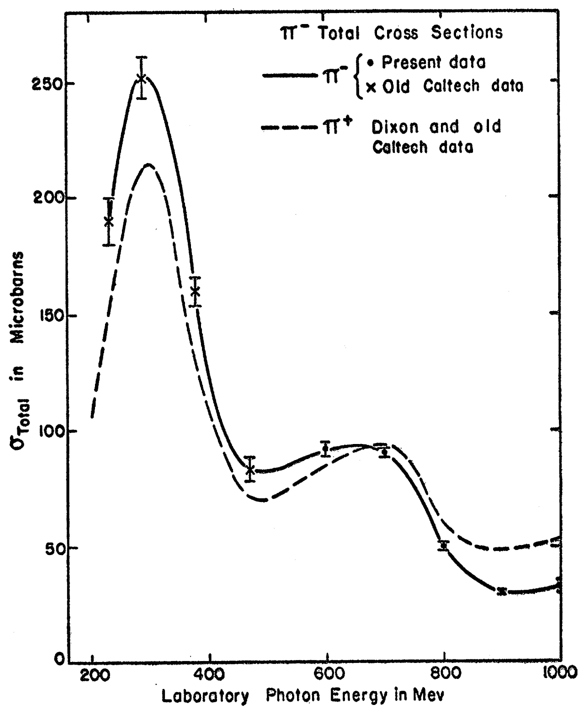

FIG. 10. The total cross section for the reaction $\gamma+n \rightarrow \pi^-+p$ as a function of photon energy, with the corresponding curve for π^+ shown for comparison. The "old CalTech data" refer to those reported in references 6, 15, and 16.

V. INTERPRETATION

At present there is no theoretical treatment applicable to photoproduction in the energy range of this experiment. A phenomenological interpretation of the data was therefore attempted using the following simple model:

(1) The pion-nucleon interaction is dominated by three resonant states; each of these is characterized by a definite total angular momentum, parity, and definite total isotopic spin. Only the characteristics of the first resonance at $k_{\text{lab}} \approx 300$ Mev were accepted as well established.

(2) Nonresonant S waves and the "retardation term," or "meson current term," were included for charged pions in the Born approximation.

The necessity of including the retardation term,[17] which is caused by the direct interaction of the photon with the meson cloud, has been shown in the phenomenological analysis of the low-energy π^+ angular distributions. Furthermore, the interference between the retardation term and the second resonance was used by Wetherell[18] to predict qualitatively the measured energy shift between the second resonance peaks in pion-nucleon scattering and positive pion photoproduction.

Predictions of the pion angular distributions expected from the above model were calculated for many choices of assignments for the upper resonances. The calculations followed in detail the method used by Wetherell in which the resonance amplitudes and phase shifts were chosen to agree with the pion-nucleon scattering data and the total photoproduction cross sections.

Unfortunately, with this simple model, we have been unsuccessful so far in reproducing even qualitatively the observed cross sections or the π^-/π^+ ratio at high energies. It is interesting to note, however, that predictions at energies below 350 Mev based on this simple model agreed qualitatively with the measured π^-/π^+ ratio. The agreement with experiment at these energies was approximately as good as that obtained by Watson *et al.*[19] using small adjustable nonresonant terms in the photoproduction amplitude in order to account for the π^-/π^+ ratio.

VI. COMPARISON OF π^+ PRODUCTION FROM HYDROGEN AND DEUTERIUM

From the yields of positive pions from deuterium measured in the present experiment, one may calculate the absolute cross sections for producing π^+ from the proton bound in deuterium, $\sigma_{\pi^+d}(\theta)$, and compare these with the corresponding cross sections for free protons,[1] $\sigma_{\pi^+p}(\theta)$. This comparison might show up effects of using target nucleons bound in deuterium. Since these effects are not large, it would require rather accurate data on the ratio of $\sigma_{\pi^+d}(\theta)$ to $\sigma_{\pi^+p}(\theta)$, (called the π^+d/π^+p ratio), to measure them. The values of this ratio obtained in this experiment have an accuracy of about ten percent, and are not sufficiently precise to lead to definite conclusions about the effects of the nuclear structure. Therefore, we will merely try to summarize the results in a general way without giving details.[20] In order to obtain the cross sections from the measured π^+ yields, corrections were made for the purely kinematic effects arising from the motion of the target nucleons in deuterium. These corrections involved the resolution functions discussed in Sec. III and shown in Figs. 1 and 2. They were calculated with the spectator model, and ranged between 0 and 20%, being largest at the backward angles. Although the π^-/π^+ ratio is practically independent of the kinematic corrections, the π^+d/π^+p ratio is not, and is subject to errors introduced by the spectator model calculations. Such errors are not included in the results quoted below, where only the statistical errors are given.

(1) The π^+d/π^+p ratio is, except possibly at photon energies of 1000 Mev, smallest at the most forward angles measured. ($\theta_{\text{c.m.}}=20°$). The ratios at 20° vary between 0.77 and 0.84 at all energies 600 to 1000 Mev, with statistical errors about ± 0.08.

(2) At angles $\theta_{\text{c.m.}} \geq 40°$ and energies 600 to 900 Mev, the values of the π^+d/π^+p ratio do not seem to show a

[19] K. M. Watson, J. C. Keck, A. V. Tollestrup, and R. L. Walker, Phys. Rev. **101**, 1159 (1956).

[20] More details are given in W. D. Wales, Ph.D. thesis, California Institute of Technology, 1959 (unpublished).

significant variation with angle for a given energy, within the errors of about 10%. Thus, the energy dependence is essentially the same as that given for the total cross sections in (3) below.

(3) The π^+d/π^+p ratios for the total cross sections from 500 to 900 Mev have an average value of 0.95$\pm$ 0.05. The energy dependence, (which may not be significant) is shown in Table II.

(4) At 1000 Mev, the π^+d/π^+p ratios found at 40° and 60° c.m. are anomalously low, 0.75 and 0.72, and since they are weighted heavily in σ_{total} because of the large cross section there, the π^+d/π^+p ratio obtained for the total cross sections is only 0.81. Because of this, and the erratic behavior of the π^-/π^+ ratio observed at 1000 Mev, it is clear that more work should be done at this energy and above.

Some of the features found for the π^+d/π^+p ratio may be understood in a qualitative way. Thus, the fact that the ratio decreases at forward angles is presumably an effect of the Pauli exclusion principle inhibiting production from deuterium. This effect will be largest when the nucleon recoil is least, namely at forward angles. It has been discussed by Chew and Lewis,[21] and their predictions agree qualitatively with the observations, although no quantitative comparison is possible without knowing the probability of spin flip in the photoproduction process. At 20°c.m. and 700 to 800 Mev, for example, the effect of the Pauli principle according to the results of Chew and Lewis is to reduce the pion yield from deuterium by about 13% if the nucleon spin flips and by about 40% if the spin is not flipped. Our data are not sufficiently accurate to determine the probability of spin flip as proposed by Chew and Lewis. At 0° the non-spin-flip part of the photoproduction amplitude vanishes, minimizing the effect of the exclusion principle in the exact forward direction.

At the larger angles the Pauli exclusion is not important, but the π^+ production from deuterium still appears less on the average, than from hydrogen. This probably results from competition with another process, namely photodisintegration of the deuteron.[22]

Neither of these effects is large enough to discredit the basic assumption made in this experiment, that the π^-/π^+ ratio observed in deuterium is essentially the same as that for free nucleons. However, since the effects of the Pauli exclusion principle are apparently noticeable at the smallest angle, and since the relative probability of spin flip may be different for π^- and π^+ production, the π^-/π^+ ratio observed at the smallest angle may differ slightly from that characteristic of free nucleons.

[21] G. F. Chew and H. W. Lewis, Phys. Rev. **84**, 779 (1951).
[22] See for example R. R. Wilson, Phys. Rev. **104**, 218 (1956).

TABLE II. Ratios of the total π^+ cross sections from deuterium and hydrogen. The statistical errors are about 5%.

Photon energy $\bar{K}$ in Mev	500	600	700	800	900
π^+d/π^+p ratio	0.95	0.89	0.88	0.99	1.00

VII. SUMMARY

The angular distribution of the π^-/π^+ ratio has been measured at photon energies between 500 and 1000 Mev to an accuracy between five and fifteen percent; the ratio varies considerably as a function of the pion angle and the photon energy.

At forward pion angles, the π^-/π^+ ratio is generally less than unity and becomes as low as 0.5 at photon energies around 900 Mev between 40 and 90 degrees (c.m. system). At backward pion angles the ratio is consistently larger than unity and exhibits a maximum at photon energies roughly corresponding to the second resonance. At c.m. angles near 150 degrees this maximum becomes as large as 2.5. The total π^- cross sections obtained in this experiment, when combined with the low-energy results, show a strong second resonance maximum at a photon energy about the same, but slightly lower than the corresponding peak in the π^+ photoproduction.

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