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Photoproduction of Charged Pions from Deuterium†

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The photoproduction of charged pions from deuterium has been studied using a "monochromatic" gamma-ray beam of 292±8 Mev. The energy spectra of both positive and negative pions at the laboratory angle of 120° were determined and both agreed within experimental error with that predicted by the theory of Lax and Feshbach. The negative-to-positive ratio at 120° was 1.07±0.16, and within experimental error, was independent of meson energy. At an angle of 73° the ratio was 0.90±0.23 for 98.7 Mev mesons. The measured negative-to-positive ratio disagrees both with the simple classical picture of Brueckner and the phenomenological theory of Watson. Some results on the ratio using a bremsstrahlung beam are given.

I. INTRODUCTION

MANY experiments have been performed measuring the ratio of negative to positive pions produced by gamma-ray bombardment of deuterium.[1–7] In all of these experiments a continuous bremsstrahlung beam has been used, attributing the production of a particular energy meson to that gamma ray which would have produced it if a two-body reaction were involved. Previous experimental results show the following trend[1–7]: at threshold, the negative-to-positive ratio is about 1.5 and is independent of angle; away from threshold, for angles that are not well forward or well backward, the ratio decreases with increasing gamma-ray energy until a minimum is reached at a gamma-ray energy dependent upon the meson angle; away from threshold, the ratio increases with increasing angle.

In photoproduction of mesons, the photon interacts with the meson and nucleon by virtue of the meson and nucleon currents. Since the end products of negative pion production are both charged while only the meson is charged in positive pion production, there will be an asymmetry in charged meson production due to the different recoil currents (this asymmetry manifests itself in the $T=\frac{1}{2}$ state only).[8] Using a simple classical model, Brueckner[9] derived the following expression for the negative-to-positive ratio:

$$\frac{\sigma(-)}{\sigma(+)}=\left[1-\frac{q_0}{Mc^2}[1-(v/c)\cos\theta]\right]^{-2},$$

where q_0 = total pion energy, M = mass of the nucleon, v = pion velocity, and θ = angle between pion and photon velocities. This predicts that the negative-to-positive ratio will increase with both increasing angle and energy for angles greater than about 45°.

Watson *et al.*[7] have analyzed photoproduction of pions in terms of S and P waves of the final pion-nucleon system. They attribute the difference in negative and positive pion production to the nucleon recoil and obtain fairly good agreement with their quoted experimental values of the negative to positive ratio.

The negative-to-positive ratio from deuterium is important since it sheds light upon the reaction

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

which can be investigated only roughly through the inverse reaction.

In this experiment, a "monochromatic" gamma-ray beam of 292±8 Mev obtained by the subtraction of meson yields is employed, eliminating errors involved in using a bremsstrahlung beam.

II. EXPERIMENTAL METHOD

A. General Description

The experimental arrangement is shown in Fig. 1 and a block diagram of the electronics is given in Fig. 2. Charged pions produced in the target by gamma rays from the MIT synchrotron were selected in sign and bent into the six counter telescope by the magnet. Mesons of the desired energy were selected by their range and pulse heights in counters 1 and 4 (1+4+5−6 was the counting scheme used). The pion yields were measured with bremsstrahlung spectra of $E_{\max}$ of 307 Mev and 292 Mev, respectively, and these numbers, properly normalized, were subtracted to obtain the yields for "monochromatic" gamma rays. The pulse heights of the first five counters were photographed to study background in the meson counting rates.

B. The Equipment

The counter telescope was enclosed in a one-half inch thick iron box for magnetic shielding. The counters

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[1] R. M. Littauer and D. Walker, Phys. Rev. **86**, 838 (1952).
[2] Lebow, Feld, Frisch, and Osborne, Phys. Rev. **85**, 681 (1952).
[3] White, Jakobson, and Schulz, Phys. Rev. **88**, 836 (1952).
[4] Jenkins, Luckey, Palfrey, and Wilson, Phys. Rev. **95**, 179 (1954).
[5] Sands, Teasdale, and Walker, Phys. Rev. **95**, 592 (1954).
[6] Beneventano, Carlson-Lee, Stoppini, Bernardini, and Goldwasser, Nuovo cimento **12**, 156 (1954).
[7] Watson, Keck, Tollestrup, and Walker, Phys. Rev. **101**, 1159 (1956).
[8] K. Watson, Phys. Rev. **95**, 228 (1954).
[9] K. A. Brueckner, Phys. Rev. **79**, 641 (1950).

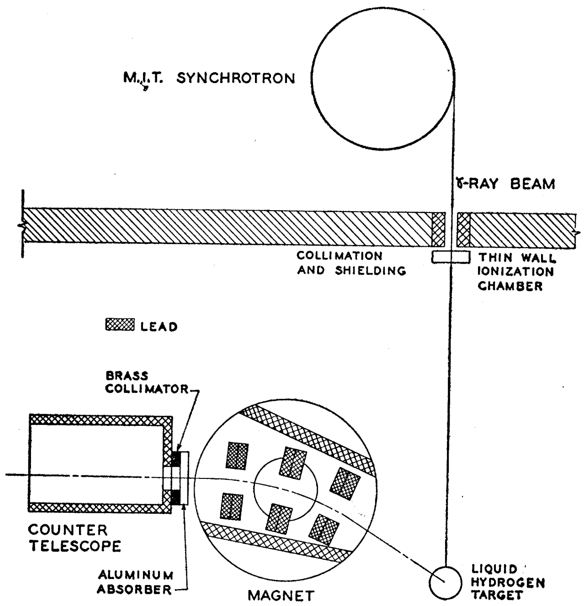

FIG. 1. The experimental arrangement.

themselves were scintillation counters employing Pilot B plastic scintillators and 6199 photomultiplier tubes. The first counter was 6 inches from the edge of the magnetic coil. The distance between the counters were: $3\frac{1}{2}$ inches for the first three counters, $6\frac{1}{2}$ inches between counters 4 and 5, and $4\frac{1}{2}$ inches between counters 5 and 6, the latter two distances were large to minimize prompt pulses from π^- star particles emanating from counters 4 and 5. In order to minimize the effects of pion scattering in counter 5, counter 6 was $5\frac{5}{8}$ inches in diameter as compared to 5 inches for the other counters. By measuring the counting rate as a function of the separation between counters 5 and 6, it was found that a distance of $4\frac{1}{2}$ inches between counters 5 and 6 was the maximum we could use and still neglect this scattering. Appropriate aluminum absorbers were placed in front of the counter telescope so that mesons of the desired energy would stop in crystal number 5.

The magnet had a coil diameter of 40 inches and the polefaces were 13 inches in diameter. Its maximum field was in excess of 12 kilogauss and it showed no signs of saturating. The magnet was calibrated by the hot wire technique. During a run, the magnet was set so that with the absorber being used, the central trajectory would be that of mesons whose energy equalled that necessary to stop halfway through counter 5. The magnet was employed principally as a sign separator and had a momentum resolution of -30%, $+40\%$.

A target constructed to liquify either hydrogen or deuterium was employed.[10] Liquid hydrogen was used as a target to measure the gamma-ray energy (by virtue of the meson energy and angle in a two-body reaction) as well as to determine the energy spread of the mesons due to the finite resolution of the equipment and to the spread in energy of the gamma ray beam. The integrated beam intensity was determined by use of a thin-walled ionization chamber standardized against a thick-walled chamber for each of the various $E_{\max}$ involved.

C. The Photographic Method

Particles from negative pion stars in counters 4 and 5 may yield false counts in counters 5 and 6, respectively. To circumvent the effects of these stars, the experiment originally employed four thin counters ($\frac{1}{4}$ inch thick scintillators) in which the detected particle would not be required to stop in a crystal. The particle identity and its energy were to be determined by photographing the pulses of these counters and determining the distribution of these pulse heights in the four counters—i.e., identify the particle and its energy by looking at the low-energy end of the Bragg curve. This system was calibrated by temporarily placing a fifth and a sixth counter into the telescope, setting the magnet for positive particles, and requiring a $1+4+5-6$ counting scheme. The positive pions stopping in the fifth crystal were identified photographically by $\mu^+ \rightarrow e^+$ decays, the e^+ pulses being identified by the requirement that the time intervals between the μ^+ and e^+ pulses have the distribution characteristic of μ-e decays. Due to the fluctuation in pulse heights and the ambiguity whether the particle did or did not stop in the fourth counter (certain pulse heights could correspond to

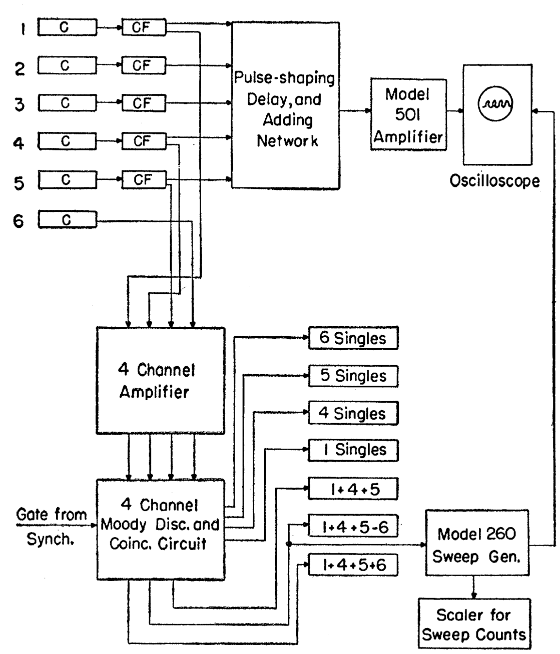

FIG. 2. Block diagram of the electronics. C = counter; CF = cathode follower.

[10] Janes, Hyman, and Strumski, Rev. Sci. Instr. 27, 527 (1956).

either case), the photographic method as described above proved to be inadequate and counters 5 (a ½-inch thick counter) and 6 (a very thick counter) were permanently added to the telescope. With a definite range now required the photographic method proved to be adequate. In Fig. 3, reproductions of the oscilloscope traces due to a positive pion, a negative pion, a proton and an electron are given. As will be discussed later, the photographic method proved unnecessary.

D. Negative Pion Stars

The problem of negative pion stars was solved by the use of good geometry. The following test was applied to see if the effect of stars was appreciable. The negative-to-positive ratio was measured with both $1+4+5$ and $1+4+5-6$ counting schemes at 120°, and 1.07 ± 0.10 and 1.07 ± 0.16 were obtained respectively. Stars produced in counter 4 with secondaries entering counter 5 should make the value of the former greater than the true value; stars produced in counter 5 with secondaries entering counter 6 (which should outweigh stars from counter 4 entering counter 5 because of the larger solid angle) should make the value of the latter less than the true value of the negative to positive ratio. Thus $1+4+5$ is an upper limit and $1+4+5-6$ is a lower limit. These agreed within experimental error, but because of this experimental error this test is not conclusive, but is indicative of the smallness of the effect of the stars. From solid angle considerations alone, about 3% of the star particles originating in counter 4 enter counter 5 and about 8% of those originating in counter 5 enter counter 6. Many of the stars involve neutral particles only (in photographic plates, for example, 28% of the negative pion captures do not involve charged particles).[11] Most charged star particles do not have sufficient energy to leave the crystal in which they were formed. This is concluded from the following: 9.5% of stars in photographic emulsions are accompanied by protons of energy greater than 30 Mev and the average energy of star particles of energy less than 30 Mev is 9.6 Mev.[11] 15% of stars in carbon are accompanied by protons of energy greater than 30 Mev,[12] for light nuclei a large portion of the stars involve alpha particles.[11] The false counts in counter 6 due to stars counteract those in 5. Taking this all into account, it is estimated that about 0.5% of the negative pion counts were lost due to stars. This loss would have been made vanishingly small by a better choice of the ratio of distances between counters 4 and 5 and counters 5 and 6.

E. Background

The most convincing evidence that pions were being counted was the following: With liquid hydrogen as a

[11] Menon, Muirhead, and Rochat, Phil. Mag. **41**, 583 (1950).
[12] L. M. Lederman, Columbia University (private communication).

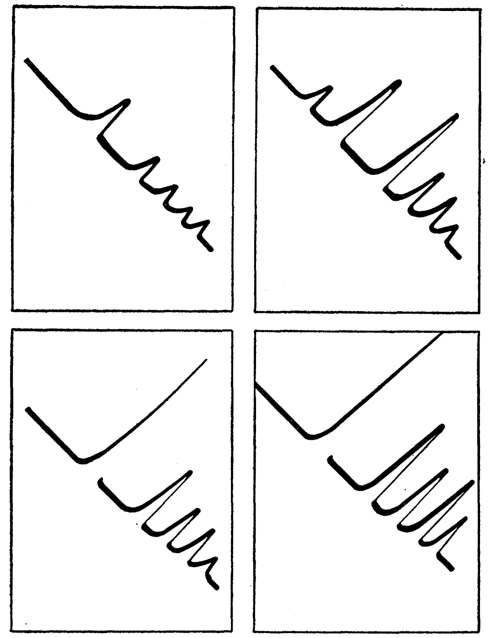

FIG. 3. Drawings of photographs of pulse-height distributions. The pulses are in order from counter number 1 to counter number 5, number 1 being in the lower right-hand corner. The upper left-hand distribution is that of an electron; the upper right, a positive pion followed by a $\mu-e$ decay in counter 5; lower left, a negative pion ending with a star in counter 5; lower right, a proton.

target, 171 counts were obtained when the magnet was set for positive pions; no counts were obtained for negative particles with the same integrated beam intensity. It was verified that the lack of counts was not due to equipment failure. With the mesons positively identified and with the effect of negative pion stars being small, the photographic method proved unnecessary and was used only to measure the amount of background in the meson counting rates.

Electrons were discriminated against by setting the discriminator bias high in counter 4. Protons were discriminated against by the simultaneous range requirements of the counter telescope and the momentum requirements of the magnet—mesons and protons of the required range differing by a factor of 3 in momentum. The biases of counters 1, 5, and 6 were set low. The biases were set photographically and were standardized against a Co^{60} source and were constantly monitored.

III. EXPERIMENTAL RESULTS

A. Corrections to Data

1. Background

The following results were obtained from scanning. The proton background was negligible—not surprising when one considers that protons and mesons of the ranges involved have momenta that differ by a factor

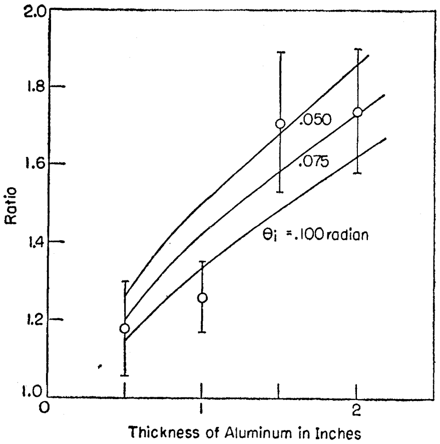

FIG. 4. The ratio of counting rates with the absorber in front of counter 4 to that with absorber in front of counter telescope. The solid lines represent calculated ratios for different initial angular spreads incident upon the absorber, assuming multiple scattering and single elastic scattering are involved.

of 3. The electron background was about 3% at 120° and 8% at 73°, and was independent of energy and sign. No correction was made for background as we are interested in the shape of the spectra and the ratio of negative-to-positive counting rates.

2. *Multiple Scattering and Single Elastic Nuclear and Coulomb Scattering*

In order to determine the effect of scattering by the absorbers, the ratio of counting rates obtained by placing various thicknesses of absorber first in front of counter 4 (the absorbers could not be placed in front of counter 5 as this would upset the biasing scheme) and secondly the same thickness of absorber in front of the telescope. Figure 4 shows the ratios thus obtained. A sharp increase with thickness such as this cannot be explained by multiple scattering only. Pevsner *et al.*[13] have measured the differential cross section for the elastic scattering of 80-Mev positive and negative pions by aluminum. Their results show a tremendous rise in the forward direction. Because of the large distance between the front of the telescope and counter 5, the solid angle subtended by counter 5 at the absorber will be small. Therefore single elastic scattering cannot be neglected. The energy dependence used for the cross section was that obtained by Stork[14] who measured single elastic scattering with a ring counter.

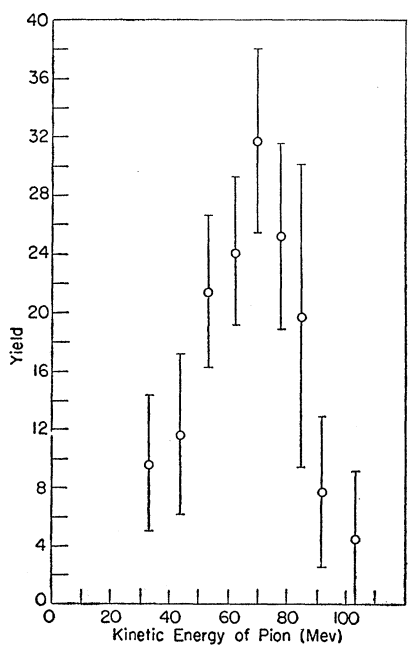

FIG. 5. Yield of negative pions from deuterium at lab angle of 120°, in arbitrary units. $E_\gamma = 292$ Mev.

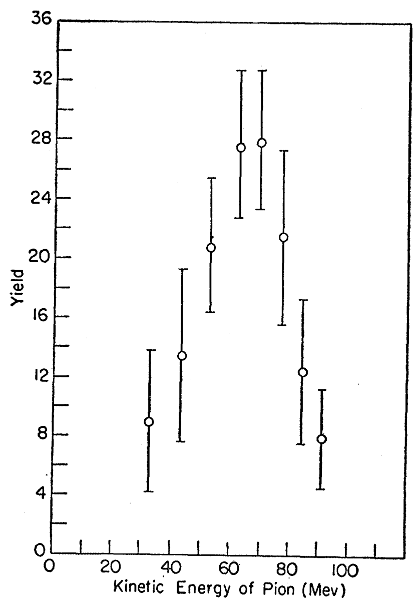

FIG. 6. Yield of positive pions from deuterium at lab angle of 120°, in arbitrary units. $E_\gamma = 292$ Mev.

The multiple scattering corrections were obtained by integrating the formula[15]

$$d\langle\theta_s{}^2\rangle_{\text{Av}} = \left(\frac{E_s}{\beta c p}\right)^2 dx$$

across the thickness of the absorber and counters doing the scattering, using the range energy relationship $x = kE^\alpha$. The scatterer was then broken into concentric annular meson source zones each having a Gaussian distribution in angle, the mean square angle being determined by the integration of $d\langle\theta_s{}^2\rangle_{\text{Av}}$. The fraction of mesons intercepted by counter 5 was obtained by numerical integration. An initial angular spread due to

[13] Pevsner, Rainwater, Williams, and Lindenbaum, Phys. Rev. **100**, 1419 (1955).
[14] D. H. Stork, thesis, University of California Radiation Laboratory Report UCRL-2288, 1953 (unpublished).
[15] B. Rossi, *High-Energy Particles* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1952), p. 68.

the finite target size and the finite spread in energy of the mesons entering the magnet was assumed. In Fig. 4, the solid lines show the calculated ratio of counting rates with the absorber in front of counter 4 to that with the absorber in front of the telescope for the multiple scattering and single elastic scattering corrections combined with assumed initial spreads of 0.050, 0.075, and 0.100 radian. An initial spread of 0.075 was assumed in making the multiple scattering and single elastic scattering corrections.

3. Discussion of Corrections

The data was also corrected for decay in flight from the target to the absorber and nuclear absorption. Since we are only interested in the shape of the spectra,

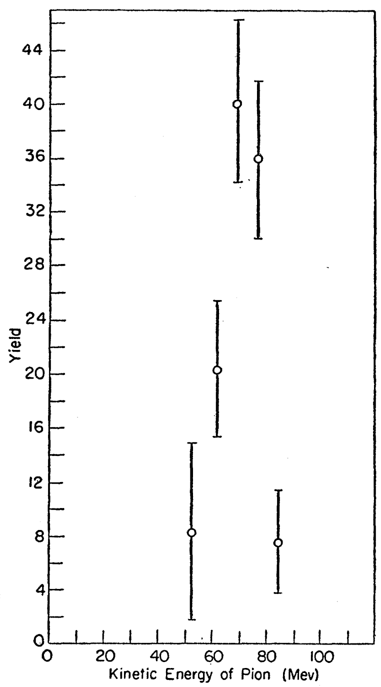

FIG. 7. Yield of positive pions from hydrogen at lab angle of 120°, in arbitrary units. $E_\gamma = 292$ Mev.

all corrections were made relative to the no absorber correction. This means that the decay in flight correction is less than 1 as faster mesons have a lower probability of decaying. To give an idea of the magnitude of the corrections, for 60-Mev mesons they were as follows:

Multiple scattering		1.22
Single elastic scattering	(negative)	1.25
	(positive)	1.21
Nuclear absorption	(negative)	1.05
	(positive)	1.04
Decay in flight		0.91

The only corrections applied to the data of the negative-to-positive ratio were small corrections for asymmetry in sign in the nuclear absorption and single elastic scattering corrections. The size of many of these corrections could have been greatly reduced by use of a 3- or 4-counter telescope, which would permit less separation between the first and last counters.

TABLE I. Energy behavior of photopions.

	Av pion energy (Mev)	rms deviation from the mean (Mev)
−Pions from D_2 (Fig. 5)	66.0±2.4	15.4±4.4
+Pions from D_2 (Fig. 6)	64.5±2.4	15.2±4.6
+Pions from H_2 (Fig. 7)	70.2±1.3	8.0±1.2

B. Pion Spectra

Figures 5, 6, and 7 show the energy distribution at 120° in the laboratory of negative pions from deuterium, positive pions from deuterium, and positive pions from hydrogen respectively. The mean pion energy and the deviation from the mean pion energy for these distributions are given in Table I.

C. The Negative-to-Positive Ratio

The results obtained for the negative-to-positive ratio are summarized in Table II.

IV. DISCUSSION

Figure 8 shows the positive pion energy spectrum from deuterium as predicted by the theory of Lax and Feshbach.[16] The average value of the pion energy is 67.3 Mev compared with the experimental values of 66.0±2.4 and 64.5±2.4 for negative and positive pions from deuterium respectively. The rms deviation from the mean is 12.4 Mev or, if we compound this with the spread in the hydrogen spectrum (which takes into account the spread due to the finite energy width of the monochromatic gamma-ray beam and the finite resolution of the instruments), we obtain 14.8 Mev compared with the experimental values of 15.4±4.4 and 15.2±4.6 for negative pions and positive pions from deuterium, respectively. The average value of the energy of the positive pions from hydrogen is 70.2±1.3, which is significantly higher than that for deuterium. This is due to the binding energy of the deuteron and

TABLE II. Negative-to-positive ratio for photopions.

Type of beam[a]	Lab angle in degrees	E_γ or E_{max} (Mev)	Kinetic energy of pion (Mev)	Negative to positive ratio
M	120	292	Averaged (30–90 Mev)	1.07±0.16
B	120	307	Averaged (30–90 Mev)	1.29±0.03
B	120	292	Averaged (30–90 Mev)	1.36±0.04
B	120	223	32.9	1.65±0.17
M	73	292	98.7	0.90±0.23
B	73	307	98.7	1.06±0.09
B	73	292	98.7	1.19±0.12

[a] *M* = monochromatic; *B* = bremsstrahlung.

[16] M. Lax and H. Feshbach, Phys. Rev. 88, 509 (1952).

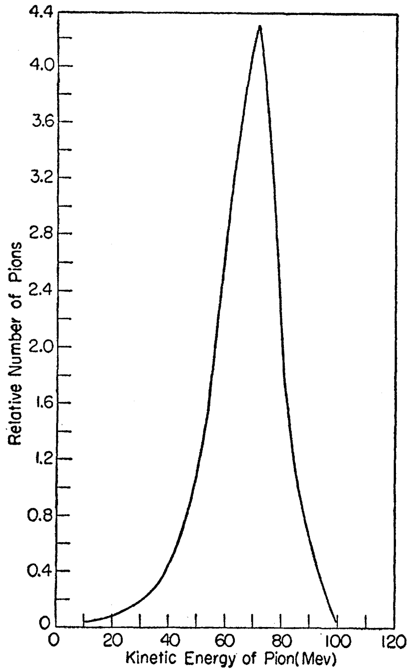

FIG. 8. Predicted positive pion energy distribution from deuterium at lab angle of 120° for $E_\gamma = 292$ Mev, in arbitrary units, using results of Lax and Feshbach.

to the scattering of the meson by the second nucleon. Kinematic calculations show that the deuteron binding energy would decrease the meson energy about 1.4 Mev below the unbound case. Rough calculations based upon the amount of meson wave at the second nucleon show that 8% of the mesons would scatter and lose energy. This would reduce the mean meson energy by about 1 Mev. The energy spread in the pion spectrum from deuterium over and above that of hydrogen is due to the internal momentum of the nucleons and the limited availability of final states due to the operation of the Pauli exclusion principle.

An experimental point was obtained at the high end of the negative pion spectrum to see if there was any spin flip of one of the nucleons involved with a quasi-bound di-nucleon formed. Kinematical considerations say that the di-proton corresponds to a 105-Mev pion at 120° in the lab for a 292-Mev photon. Because of the Pauli principle the di-proton cannot exist in a triplet state, meaning that one of the nucleons must flip its spin. Figure 5 shows no appreciable peak near 105 Mev, which indicates that the protons coming off together is not a favored mode of production.

The results for the negative-to-positive ratio given in Table II are consistent with the results of other experiments[1–7] which show the following: the ratio increases as one goes to backward angles and is high near threshold, approaching a minimum with increasing gamma-ray energy for angles that are not well forward or well backward. The negative-to-positive ratio shows a rise near threshold not predicted by the simple classical arguments of Brueckner.[9] Elsewhere where measured, it is lower than that predicted by Brueckner. Our value of the negative-to-positive ratio is higher near threshold than the value of 1.34 predicted by the phenomenological theory of Watson *et al.*[7] and lower than the values 1.14 and 1.25 predicted by Watson for the laboratory angles of 73° and 120°, respectively. The high value of the negative-to-positive ratio near threshold which disagrees with the above two theories is consistent with the experimental results of Beneventano *et al.*,[6] who obtained a ratio of 1.62 ± 0.24 for an E_γ of 176 Mev.

Looking at the results in Table II, one can see that it is probable that for 120° the negative-to-positive ratio is higher using a bremsstrahlung beam of $E_{max} = 307$ Mev than the ratio using an E_{max} of 292 Mev. This would suggest that there is a minimum in the energy variation of the negative-to-positive ratio in the vicinity of $E_\gamma = 292$ Mev. This minimum is consistent with the results of Watson.[7] Better statistical accuracy would be needed to definitely establish this minimum.

The "monochromatic" measurement of the ratio for 292 Mev is significantly lower than either the 292- or 307-Mev bremsstrahlung result. This is undoubtedly due to the fact that with a bremsstrahlung beam, mesons produced by γ rays other than the 292 ± 8 Mev band are being counted. As we decrease E_γ below 292 Mev, the value of the ratio rises and when mesons due to these lower energy γ rays in addition to the 292 ± 8 Mev γ rays are counted, the ratio will be greater than the 292-Mev "monochromatic" value.

V. ACKNOWLEDGMENTS

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