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Photoproduction of π^0 Mesons from Hydrogen near Zero Degrees*

V. L. HIGHLAND† AND J. W. DEWIRE
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

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We report measurements of the differential cross section for photoproduction of π^0 mesons from hydrogen, with the pion emerging near 0 deg, in the photon energy range 290 to 700 MeV. The results show no unusual behavior of the cross section in the forward direction. They are consistent with the angular distribution characteristic of a magnetic-dipole transition to a $P_{3/2}$ state. The results agree reasonably well with theoretical predictions of Gourdin and Salin, but disagree with a prediction of DeTollis and Verganelakis. Least-squares fits in powers of $\cos\theta$ have been made to the available angular distributions.

INTRODUCTION

WE have measured the differential cross section for photoproduction of π^0 mesons from hydrogen, with the pion emerging near 0 deg. The photon energy varied from 290 to 700 MeV. Preliminary results have been reported earlier,[1] and the experiment is described in detail elsewhere.[2]

To a large extent this experiment was originally motivated by the suggestion of Moravcsik[3] that a spin-one pion-pion resonance (then undiscovered) could contribute to π^0 photoproduction. Moravcsik attempted unsuccessfully to extract such an effect from the then available data, and concluded that more accurate data and data at more forward angles would be necessary to see such an effect, if it existed. Also, data at extreme angles, which have been generally lacking, are useful since they provide a stringent test for all theories of photoproduction. In addition, the front-back asymmetry of the angular distribution is governed by the interference of the dominant p wave with odd-parity terms; at moderate energies this should provide information on s-wave π^0 production.

EXPERIMENTAL METHOD

The usual method of measuring π^0 photoproduction, detection of the recoil proton, is limited in the forward direction, since the energy of the proton becomes very small. This technique has been pushed to its present limit by McDonald *et al.*[4] and by Berkelman and Waggoner,[5] who reached a pion angle of 25°–30°. In order to measure π^0's at 0 deg we adopted the technique of detecting in coincidence the two gamma rays from the π^0. The original π^0 experiment of Panofsky *et al.*[6] and several experiments since then have used this technique, which, despite its low detection efficiency, has the virtue that with it one can detect, in principle, π^0's made at any angle. In the energy range of our experiment the only measurements with this method are the recent ones of Talman *et al.*[7] and of Gillespie and Williams.[8]

The experimental setup is shown in Fig. 1. The bremsstrahlung beam from the Cornell electron synchrotron produces π^0 mesons in the hydrogen target, and the subsequent gamma rays are detected by total-absorption Čerenkov counters C and D. The counting apertures are 6-in.-high by $1\frac{1}{2}$-in.-wide tapered slits in the 6-in.-thick lead shielding walls in front of the counters. Behind each aperture is an anticoincidence counter to reject charged particles. Two inches of CH_2 in each aperture prevent the large flux of low-energy electrons from reaching the anticounters.

The counters were at small angles to the beam, 28°–10°, necessitating careful collimation and shielding. In order to reduce both the singles rates and the real π^0 background, a thin hydrogen target was made whose total wall thickness was 0.014 in. of Mylar. Downstream from the target a helium bag displaced the air in the

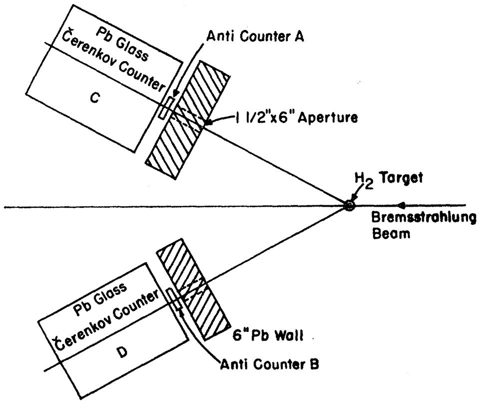

FIG. 1. Plan view of the experimental setup. The two photons from the decay of π^0's produced in the target are detected in coincidence by the Čerenkov counters.

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† Present address: Department of Physics, University of Pennsylvania, Philadelphia 4, Pennsylvania.

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[7] R. M. Talman, C. R. Clinesmith, R. Gomez, and A. V. Tollestrup, Phys. Rev. Letters **9**, 177 (1962); R. M. Talman, Ph.D. thesis, California Institute of Technology, 1963 (unpublished).

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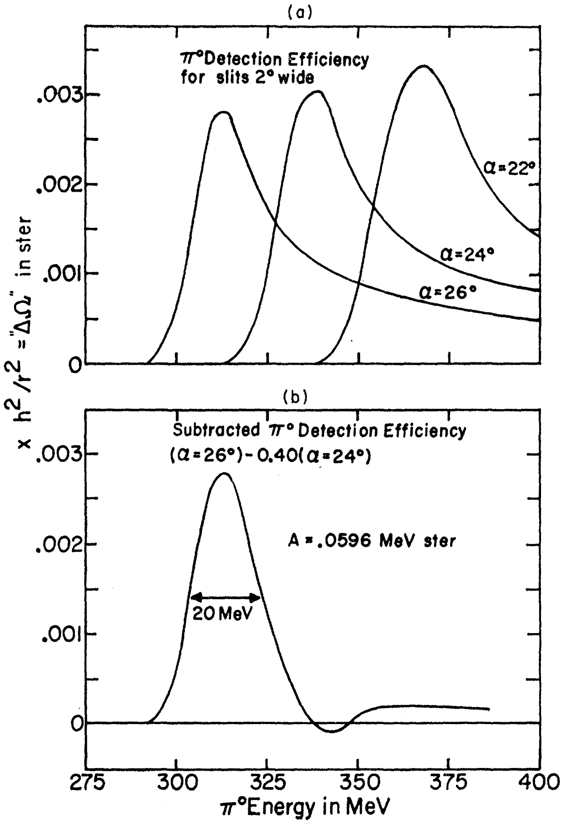

FIG. 2. (a) π^0 detection efficiency versus energy for two slits, 2° wide, which detect the two decay photons. The angle between the slits is 2α, and h and r are the slit height and distance from the target. (b) Curve resulting from subtraction of 0.40 of 24° curve from 26° curve in (a). The area under the curve A is used in the derivation of the cross section.

beam line. At the smallest angles a horizontal magnetic field just beyond the target swept low-energy electrons away from the apertures.

METHOD OF TAKING DATA

The detection efficiency for π^0's of such a two-slit system[9] can be described as follows: If 2α is the angle between the two decay photons, then it can be shown that the half-angle α has a minimum given by

$$\sin\alpha_m = 1/\gamma\,, \tag{1}$$

where $\gamma = E/\mu c^2$, E and μ being the π^0 energy and mass. One can also show that this is the most probable opening angle. So, as a function of energy, the detection efficiency is peaked at a meson energy corresponding [by Eq. (1)] to the mean angle between the apertures, having risen sharply from zero at a minimum energy corresponding to the maximum opening angle accepted by the apertures. The efficiency falls again, but more gradually, as the π^0 energy increases. The detection efficiency has been calculated exactly[9] for each data point; some examples of the results are shown in Fig. 2(a).

In order to obtain good energy resolution without resorting to using the bremsstrahlung cutoff, we adopted a method introduced by Prentice, Bellamy, and Williams.[10] One measures the counting rate with two values of the opening angle and subtracts a fraction of one rate from the other. The result corresponds to data that would be obtained with a detection efficiency curve without a high-energy tail, such as the curve in Fig. 2(b), which is obtained by subtracting 40% of the 24° curve from the 26° curve in Fig. 2(a). The subtracted curve shows quite good energy resolution. The cancellation at higher energies is, of course, not perfect, but all but a small part of the imperfections are cut off by the bremsstrahlung spectrum. The remaining imperfections are unimportant.

The shielding walls and slits in front of the counters were made so that they could be easily moved in a horizontal direction. Then for a given cross-section measurement the slits were moved several times between two positions to obtain the necessary data for the subtraction. For a given angular aperture, the width of the resolution curve increases as the square of the energy, so to maintain good resolution with slits of fixed width the distance r between the apertures and the target had to be increased for the higher energies. The distances were 43 in. for $E<340$ MeV, 57.3 in. for 393 and 460 MeV, and 86 in. for $E>455$ MeV, so that the apertures subtended 2°, $1\frac{1}{2}$°, and 1°.

The energy definition was thus essentially determined by the geometry. At the lower energies the pulse-height spectra in the Čerenkov counters were used only for monitoring purposes, but at the higher energies we made use of a multidimensional analyzer (MDA)[11] to make a pulse-height analysis of counters C and D for each event. The events clustered roughly in a hyperbolic distribution as expected according to the kinematic relation requiring the product of the pulse heights in the two counters to be equal to $\mu^2/4\sin^2\alpha$. This analysis enabled us to separate a large fraction of the accidental and cosmic-ray events from the true π^0's. This was valuable since at higher energies, where the counting rate became very small, the counts due to cosmic rays ($\sim 1/h$) were a significant background.

We had intended that the MDA would also distinguish double π^0 events, which could be counted if each π^0 emitted a photon into one of the apertures. (A single one of the π^0's would in all cases have insufficient energy to be detected.) It turned out that all the ambiguous events could be accounted for by the expected number of cosmic rays and accidentals. This may

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[9] A detailed discussion of π^0 decay kinematics, of an exact solution for the detection efficiency, and of the angular resolution of the two-gamma-detection scheme is to be found in Ref. 2.

[10] J. D. Prentice, E. H. Bellamy, and W. S. C. Williams, Proc. Phys. Soc. (London) **74**, 124 (1959); W. S. C. Williams (private communication).

[11] R. M. Littauer and L. Tepper (to be published).

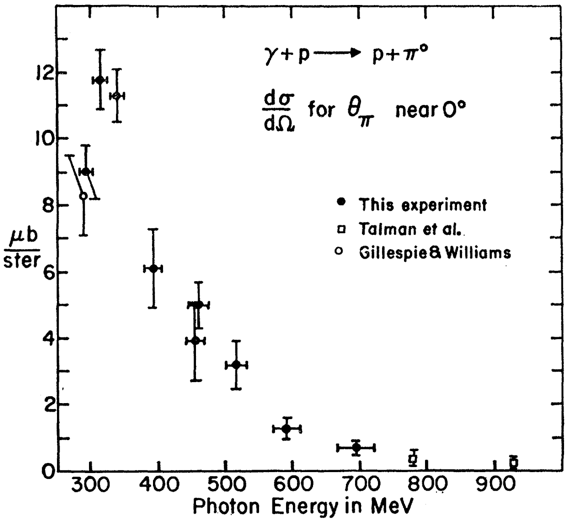

FIG. 3. Differential cross section for π^0 photoproduction near 0 deg as a function of energy.

merely mean that the detection efficiency for double π^0's was low enough that they went unnoticed. Nevertheless, this circumstance led us to the interesting observation that, according to the double-pion photoproduction theory of Cutkosky and Zachariasen,[12] double π^0 production should be essentially forbidden at moderate energies. They suppose that at these energies an s-wave pion is produced along with a recoil isobar which decays into a nucleon and a second pion. For double π^0's the s-wave pion is suppressed for the same reasons that s-wave π^0's are suppressed in single production. Since Carruthers and Wong[13] have obtained reasonable agreement with the $\pi^+\pi^-$ data up to 600–700 MeV using the above model, it should be expected that $\pi^0\pi^0$ production will be very small compared to $\pi^+\pi^-$ at these energies. This prediction seems not to have been generally noticed.[14] Our data in no way prove this hypothesis, but provided the suggestion.

RESULTS

The counting rate and the cross section are related by the following expression:

$$C=N_\gamma N_p \frac{h^2}{r^2} A \frac{d\Omega'}{d\Omega}\frac{d\sigma}{d\Omega'}.$$

N_γ is the number of incident photons per unit energy of energy E; N_p is the number of protons/cm^2 in the hydrogen target; h is the height of the apertures and r is their distance from the target; A is the area under the subtracted effective solid angle function, as in Fig. 2(b), and E is the energy of the peak of this curve; $d\Omega'/d\Omega$ is the transformation factor for the solid angle of the π^0 between the center-of-mass system (primed) and the lab.

Corrections to C for background and accidentals amounted to roughly 10% each. Other corrections were (a) conversion of the gamma rays in the CH$_2$ absorber: 17%; (b) Dalitz decay of the π^0: 1.3%; (c) penetration of the edges of the slits by the gamma rays: 8%; (d) counts lost due to accidental triggering of the anticounter: 1–4%.

The final results for the cross section are given in Table I and shown as a function of energy in Fig. 3. The figure also shows a point of Gillispie and Williams[8] and two of Talman *et al.*[7] The mean pion angle differs from 0° because of the rather wide angular resolution inherent in the two-gamma detection technique.[9] This angle decreases as the energy increases. The effect of the nonzero mean angle on the subtraction technique has been investigated and shown to be unimportant.

The estimated 6.5% systematic error is compounded from (a) error in calculation of detection efficiency: 3%; (b) error in beam energy: 1.5%; (c) uncertainty in geometrical alignment of target and counters: 1.5%; (d) uncertainty in slit width and penetration: 1.5%;

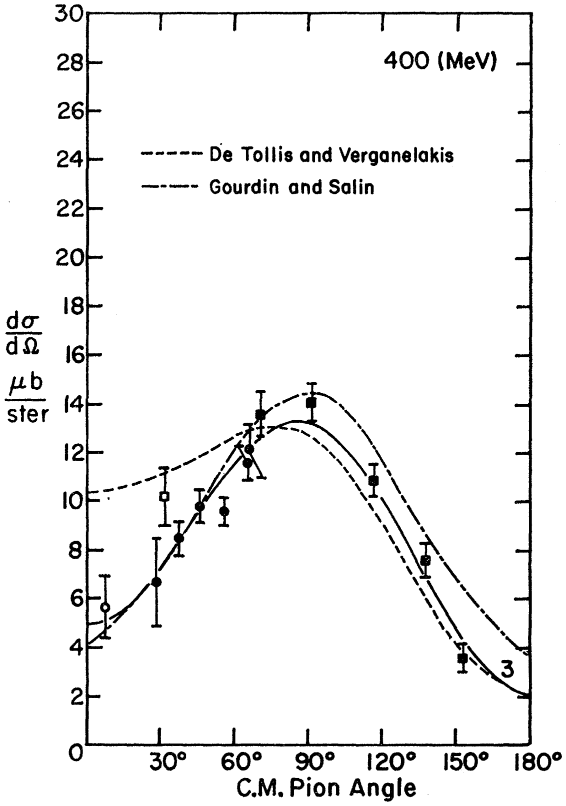

FIG. 4. π^0 photoproduction differential cross section versus angle at 400 MeV. ○ this experiments; ● Ref. 5; □ Ref. 4; ■ Ref. 15. Solid curve is 3-parameter fit to the data. Dashed curves are theoretical curves of Refs. 20 and 21.

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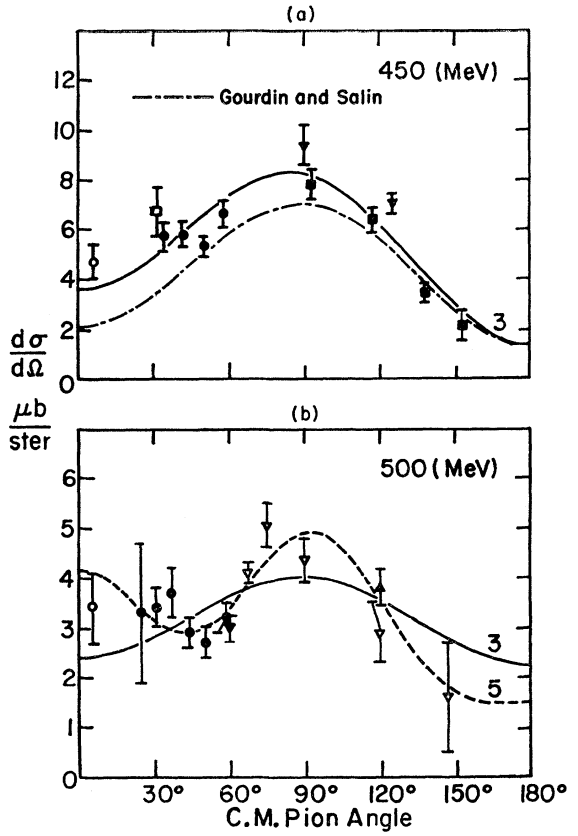

FIG. 5. π^0 photoproduction differential cross section versus angle at (a) 450 MeV and (b) 500 MeV. ○ this experiment; ▼ Ref. 16; ▽ Ref. 18; ▲ Ref. 17; other references as in Fig. 4. Solid curves are 3-parameter fits to data, and dashed curve is a 5-parameter fit. Dot-dash curve is a theoretical curve from Ref. 21.

(e) uncertainty due to conversion correction: 1%; (f) error in N_p due to uncertainty in the density of liquid hydrogen and possible bulging of Mylar target cup under pressure: 3%; (g) error due to biases: 4%. Not included is a 3% uncertainty in the absolute calibration of the beam monitor (quantameter).

TABLE I. Differential cross section $d\sigma/d\Omega$ for π^0 photoproduction from hydrogen near 0 deg.

Photon energy (MeV)	C.m. pion angle (deg)	$d\sigma/d\Omega$[a] (μb/sr)	Systematic error (μb/sr)	Total error (μb/sr)
293	10.0°	9.0±0.8	0.6	1.0
314	9.6	11.8±0.9	0.8	1.2
340	9.5	11.3±0.8	0.7	1.2
393	7.5	6.1±1.2	0.3	1.3
460	6.7	5.0±0.7	0.3	0.8
455	5.8	3.9±1.2	0.3	1.2
457[b]	6.2	4.6±0.6	0.3	0.7
514	5.6	3.2±0.7	0.2	0.7
590	4.1	1.3±0.3	0.08	0.3
693	3.9	0.7±0.2	0.05	0.2

[a] With statistical error only.
[b] Average of the 460- and 455-MeV results.

DISCUSSION

Figure 3 shows that all the small-angle π^0 cross sections are consistent. The curve reproduces the shape of the 3-3 resonance and then falls off smoothly to very small values, the second resonance having no discernible effect.

We have added our points to the angular distribution of the available data at each energy; three examples are shown in Figs. 4 and 5.[15–17] In general, our results fall smoothly onto curves characteristic of a magnetic-dipole transition to a $P_{3/2}$ state. There seems to be no unusual behavior in the forward direction. In this energy region any possible effect such as Moravcsik suggests is at most a subtle one, and the data are probably not yet good enough to allow it to be extracted. The relatively large masses found for the ω and ρ make it understandable that their effects should not show up at these energies; Talman *et al.*[7] have interpreted their data at 1140 MeV as perhaps due to such an effect of the ω.

We confirm the result of Berkelman and Waggoner,[5] as opposed to Vette,[18] that the cross section decreases in the forward direction. Only at 500 MeV is the situation still somewhat confused, probably because of inaccuracies in the data.

We have made least-squares fits to the angular distributions[19] with an equation of the form:

$$d\sigma/d\Omega = A + B\cos\theta + C\cos^2\theta + D\cos^3\theta + E\cos^4\theta.$$

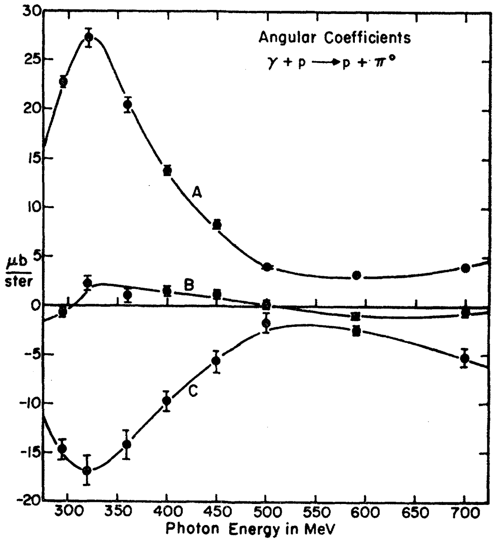

FIG. 6. Values of A, B, and C for best fits to the angular distributions of the form $d\sigma/d\Omega = A + B\cos\theta + C\cos^2\theta + D\cos^3\theta + E\cos^4\theta$. D and E are different from zero only at 590 and 700 MeV.

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[17] P. C. Stein and K. C. Rogers, Phys. Rev. **110**, 1209 (1958).
[18] J. I. Vette, Phys. Rev. **111**, 622 (1958).
[19] A survey of the available π^0 data, and least-squares fits to the angular distributions from 295 to 950 MeV, is to be found in Ref. 2.

Below 590 MeV a three-parameter curve (A,B,C) fit the data sufficiently well. At 590 and 700 MeV the 5-parameter fits seemed to make a significant improvement, but the errors in D and E are still large and great significance should not be given to these parameters. The values were $D=1.6\pm0.8$, $E=0\pm1$ and $D=-0.1\pm0.9$, $E=2.8\pm1.3$, all in μb/sr, at the two energies, respectively. The results for A, B, and C as a function of energy are shown in Fig. 6. The errors given are derived from the absolute errors in the cross sections. The adopted 3-parameter fits are indicated by the solid lines in Figs. 4 and 5; for the 500-MeV data the 5-parameter fit is also shown.

In Fig. 4 are also drawn the theoretical curves of DeTollis and Verganelakis[20] and of Gourdin and Salin.[21] DeTollis and Verganelakis supplement the dispersion theory expression of Chew *et al.* with bipion and tripion contributions. They are able to fit the data at 200 and 320 MeV reasonably well but, as seen in Fig. 4, they disagree sharply with our forward-angle data at 400 MeV. On the other hand, Gourdin and Salin attempt to fit the data using an isobar model; they find no necessity for any pion-pion terms. As seen in Fig. 4 they fit the data at 400 MeV much better than DeTollis and Verganelakis. At higher energies the agreement with the data, though not perfect, is qualitatively satisfactory; a typical example of the degree of agreement is shown in Fig. 5 for 450 MeV. Finally at 800 MeV they are in severe disagreement with the data of Talman *et al.*[7]

ACKNOWLEDGMENTS

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Intensity of Upward Muon Flux due to Cosmic-Ray Neutrinos Produced in the Atmosphere*

T. D. LEE,† H. ROBINSON, AND M. SCHWARTZ†
Columbia University, New York, New York

AND

R. COOL
Brookhaven National Laboratory, Upton, New York

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Calculations have been performed to determine the upward going muon flux leaving the earth's surface after having been produced by cosmic-ray neutrinos in the crust. Only neutrinos produced in the earth's atmosphere are considered. Rates of the order of one per 100 sq m/day might be expected if an intermediate boson exists and has a mass less than 2 BeV.

THE possibility of detecting high-energy neutrinos in cosmic rays has been discussed by many authors.[1–3] In particular, it has been pointed out[2] that an effective method is to use the earth's crust as a target and observe high-energy muons which are produced by cosmic-ray neutrinos coming from the opposite side of the earth. Such an experiment, if feasible, may well be the only means to yield direct information on very high-energy neutrino reactions. Because of the rapid decrease of cosmic-ray neutrino flux with increasing energy, the number of muons produced in this way depends sensitively on the high-energy behavior of neutrino reactions. In this letter, the expected upward muon flux at the surface of earth is calculated in some detail under certain assumptions on the nature of the weak interactions.

We first consider the case that weak interactions are transmitted by intermediate bosons, called $W^{\pm}$, of a mass m_W which is not much bigger than 1 BeV. Since we are only interested in very high-energy neutrinos (from about 10 to several hundred BeV) the dominant reactions are the coherent processes

$$\nu_\mu + Z \rightarrow \mu^- + W^+ + Z \qquad (1)$$

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† Alfred P. Sloan Fellow.

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