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Photoproduction of π^0 Mesons from Hydrogen in the Region 900 to 1200 Mev*

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The reaction $\gamma+p\rightarrow\pi^0+p$ has been studied in three adjacent 100-Mev energy intervals between 900 and 1200 Mev and at pion center-of-mass angles of 47°, 90°, and 125°. The reaction was observed as a coincidence between the recoil proton and one of the photons from the meson's decay. The kinematics were determined by the energy of the incident photon and the angle of the recoil proton. The differential cross sections at the forward and backward angles show pronounced maxima near 1050 Mev, while the 90° cross sections decrease slowly with energy. The estimated total cross sections suggest a narrow maximum near 1050 Mev. These features are consistent with the previously proposed existence of a resonant state in the pion-nucleon system of total angular momentum 5/2.

INTRODUCTION

Investigation of the photoproduction of π mesons from hydrogen[1–6] led to the suggestion by Wilson[7] that the broad maximum in the π^-, p total cross section, observed by Cool, Piccioni, and Clark,[8] was due to an unresolved pair of resonance states of the proton. He suggested that the lower state at a laboratory photon energy of 750 Mev, corresponding to a pion laboratory kinetic energy of 600 Mev in π, p scattering, could be characterized by isotopic spin and angular momentum quantum numbers of $\frac{1}{2}$ and $\frac{3}{2}$, respectively, in order to satisfy the experimental data on photoproduction. Further theoretical work[9,10] and the measurement of the polarization of the recoil proton in photoproduction of neutral pions[11] have given support to Wilson's proposal.

Recent measurements of the π^-, p total cross section[12–14] have resolved the two maxima, one of which appears to fall at an energy corresponding to the 750-Mev photoresonance. The higher energy maximum suggests that a resonance in photomeson production should occur near 1050 Mev. Evidence supporting this prediction already exists from observations of the photoproduction of positive pions.[5] We have obtained some additional evidence by extending the measurements on photoproduction of single neutral pions to 1200 Mev. Data have been taken at meson center-of-mass angles of 47°, 90°, and 125° and for photon energy intervals of 100 Mev, centered at approximately 950, 1050, and 1150 Mev.

EXPERIMENTAL METHOD

The external bremsstrahlung beam of the Cornell synchrotron was used to produce neutral pions through the reaction $\gamma+p\rightarrow\pi^0+p$. In order to completely determine the reaction two kinematic variables must be measured. In previous experiments at Cornell,[1,2] the angles and energies of the recoil protons were selected, the energies being determined by their ranges in copper absorbers. However, in the energy range of the present experiment, the nuclear absorption correction for the range telescope would be prohibitively large for protons emitted in the forward hemisphere in the center-of-mass system. Because of the uncertainty in the value of the absorption cross section and in multiple scattering corrections, range measurements were not attempted in this experiment.

Instead, the reaction was identified by determining the energy of the incident photon and the angle of the recoil proton. In order to measure recoil protons resulting predominantly from single production of π^0 mesons, we required a coincidence between the recoil proton and one of the mesonic decay photons, observed in the direction corresponding to the emission of the meson. The incident photon energy was measured by taking a difference between experimental yields with peak bremsstrahlung energies which differ by 100 Mev. Under these conditions, the results represent differential cross sections averaged over 100-Mev intervals.

Bremsstrahlung Subtraction

In order to check the validity of the subtraction technique, a separate measurement was made to study the properties of the difference spectrum. Figure 1 shows the theoretical thin target bremsstrahlung energy spectra for peak synchrotron energies of 900 Mev and 1000 Mev, and the photon spectrum of the difference.

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1 J. W. DeWire, H. E. Jackson, and R. Littauer, Phys. Rev. 110, 1208 (1958).
2 P. C. Stein and K. C. Rogers, Phys. Rev. 110, 1209 (1958).
3 M. Heinberg, W. M. McClelland, F. Turkot, R. R. Wilson, W. M. Woodward, and D. M. Zipoy, Phys. Rev. 110, 1211 (1958).
4 J. I. Vette, Phys. Rev. 111, 622 (1958).
5 F. P. Dixon and R. L. Walker, Phys. Rev. Letters 1, 458 (1958).
6 R. M. Worlock, Phys. Rev. 117, 537 (1960).
7 R. R. Wilson, Phys. Rev. 110, 1212 (1958).
8 R. Cool, O. Piccioni, and D. Clark, Phys. Rev. 103, 1082 (1956).
9 R. F. Peierls, Phys. Rev. Letters 1, 174 (1958).
10 J. J. Sakurai, Phys. Rev. Letters 1, 258 (1958).
11 P. C. Stein, Phys. Rev. Letters 2, 473 (1959).
12 H. C. Burrowes, D. O. Caldwell, D. H. Frisch, D. A. Hill, D. M. Ritson, R. A. Schuter, and M. A. Wahlig, Phys. Rev. Letters 2, 119 (1959).
13 J. C. Brisson, J. Detoef, P. Falk-Vairant, L. van Rossum, G. Valladas, and L. C. L. Yuan, Phys. Rev. Letters 3, 561 (1959).
14 T. J. Devlin, B. C. Barish, W. N. Hess, V. Perez-Mendez, and J. Solomon, Phys. Rev. Letters 4, 242 (1960).

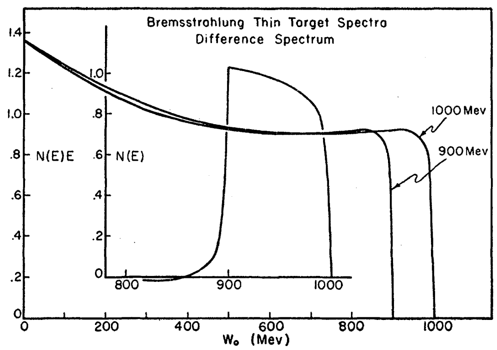

FIG. 1. Calculated thin target bremsstrahlung energy spectra for electron energies of 900 and 1000 Mev. The curves are normalized to same number of equivalent quanta. The photon difference spectrum is shown in the insert.

The energy spectra are normalized to give areas under them (the total beam energy) proportional to the peak energy. Since the photon beam is monitored by a quantameter,[15] which measures the total beam energy, the normalization becomes simple in practice.

The actual beam spectrum differs somewhat from the thin target spectrum used in Fig. 1. An analysis of some results on the actual spectrum[16] showed that while the shape of the difference spectrum is somewhat altered, the total number of photons is not changed and the average energy of the difference photons is shifted by less than 15 Mev.

It was possible to partially check the shape of the difference spectrum by looking at the beam spectra directly with a lead glass photon total absorption counter. The beam was passed through a 3/64 inch diameter hole in a 6-inch lead wall located 5 meters from the synchrotron target, then through a sweeping magnet and into the photon counter. Even with such stringent collimation it was necessary to operate the synchrotron at such a low intensity, to avoid overloading the counter, that it was not possible to use an ion chamber to normalize the integrated beam intensities at the two energies, 1072 and 975 Mev. Instead the normalization was arbitrarily chosen to give complete cancellation at 300 Mev. The resulting difference spectrum is shown in Fig. 2. The solid curve represents the expected shape using a thin target spectrum and assuming a 15% resolution width for the photon counter. From an independent calibration of the photon counter with monoenergetic electrons, channel 40 in the pulse-height analyzer was known to correspond to 1000 Mev. The agreement provides support for the use of the subtraction technique.

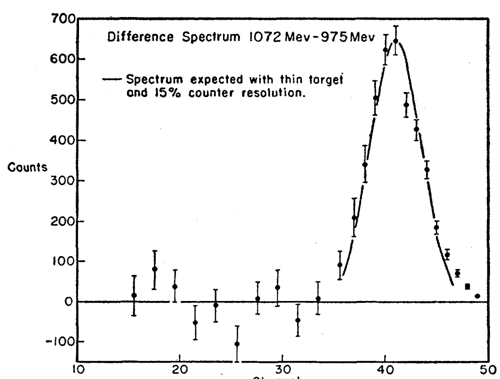

FIG. 2. Experimental difference spectrum resulting from the subtraction of two bremsstrahlung spectra of peak energies 1072 and 975 Mev. The difference spectrum is arbitrarily made zero at 300 Mev. Channel 40 corresponds to 1000 Mev.

[15] R. R. Wilson, Nuclear Inst. **1**, 101 (1957).
[16] E. Malamud (private communication).

Apparatus

The experimental arrangement for measuring the production of neutral pions is shown in Fig. 3. A 3-inch thick liquid hydrogen target was used for the measurements at the 90° and 47° center-of-mass angles; a 2-inch target at 125°. The proton telescope is shown at the left. It consisted of two $\frac{1}{4}$-inch plastic scintillators, the first being the defining counter 2 inches wide and 4 inches high, the second 6 inches square. The first counter was placed 30 inches from the target center. In order to decrease the number of events due to low-energy photons, a copper absorber was added to the telescope. At each angle the copper thickness was adjusted to eliminate recoil protons from single neutral pions produced by incident photons of energies less than 800 Mev. At successively increasing proton angles the thicknesses were 107, 51.4, and 5.64 g/cm^2.

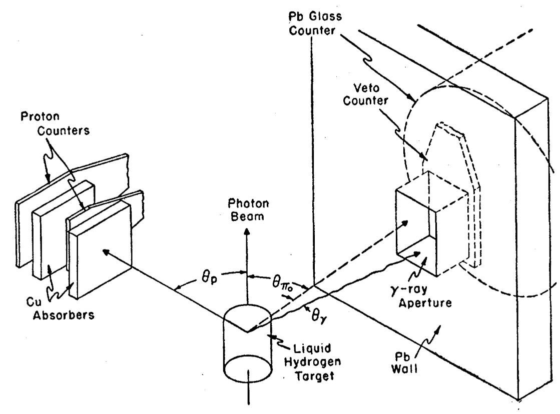

FIG. 3. Arrangement of equipment for detecting the photoproduction of π^0 mesons from hydrogen.

The pion decay photon aperture was defined by a 4-inch by 3-inch rectangular hole in a 6-inch lead wall. Behind the aperture a veto scintillation counter, sensitive to minimum ionizing particles, was used to eliminate counts in the photon counter initiated by charged particles. Varying amounts of carbon were placed in the aperture to reduce the single count rate in the veto counter. The photon counter was a lead glass cylinder

15 radiation lengths long and 13 radiation lengths in diameter. The Čerenkov light from the photon showers was detected by four 5-inch photomultiplier tubes. Coincident pulses in the photon counter and the two proton counters with no pulse in the veto counter constituted an event. With this arrangement the counting rate with no hydrogen in the target was less than 10% of the rate with hydrogen.

The veto counter also served to make the limits of the photon aperture sharp. Without it, there would be the possibility that photons which graze the edge of the aperture would materialize and lose some energy, but retain a sufficient energy to be observed in the glass counter.

It was necessary to compute the efficiency for detecting the decay photon. The expression

$$\epsilon(\theta)=\frac{1}{2\pi\gamma^2(1-\beta\cos\theta)^2}$$

gives the probability per steradian per π^0 for observing a decay photon at an angle θ with respect to the initial direction of the π^0. The terms γ and β are the usual kinematic quantities for the π^0. This probability must be averaged over the target dimensions, the proton counter solid angle, and the photon aperture. Since this quantity varied rapidly over the geometry, it was necessary to average over many sample points. This was carried out with an electronic computer.

TABLE I. Differential cross section for the photoproduction of single π^0 mesons from hydrogen.

Photon Energy (Mev)	$\bar{\theta}$[a]	$(d\sigma/d\Omega)$ (μb/sr)
905–1000	47°	1.27±0.11
	90°	1.62±0.17
900–1000	125°	2.19±0.18
1000–1100	47°	1.95±0.11
	90°	1.40±0.18
	125°	2.92±0.27
1100–1180	47°	1.13±0.20
	90°	0.87±0.21
1100–1188	125°	1.64±0.33

[a] $\bar{\theta}$ is the angle of emission of the meson in the center-of-mass system.

Several internal experimental checks were made to test whether the recorded events were actually caused by the reaction under study. The pulse-height spectra from the second proton counter and from the photon counter were observed throughout the experiment on a 30-channel pulse-height analyzer. The pulses from the proton counter appeared as a single group whose mean height varied as expected for the recoil protons as the kinematic parameters were changed. The number of pulses having heights significantly different from the single group was negligible.

The pulse-height spectra from the photon counter provided a check on the presence of events due to the double production of mesons by the process

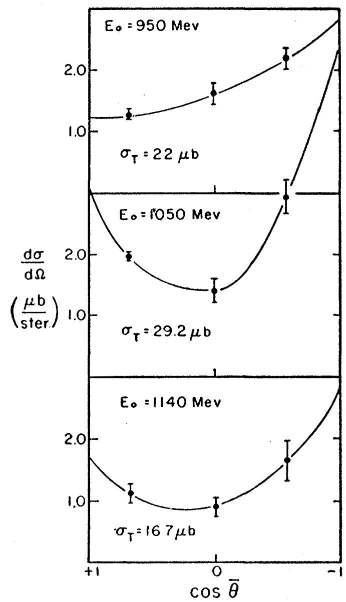

FIG. 4. Differential cross sections for single π^0 photoproduction from hydrogen, plotted against the cosine of the pion angle in the center-of-mass system. The curves are parabolas determined by the points. They are used to estimate the total cross sections.

$\gamma+p\rightarrow\pi^0+\pi^0+p$. The requirement that there be a coincidence between the recoil proton and a decay photon in the direction of the singly-produced meson greatly favors the single production process, since the high-energy meson decay has a strong forward bias in the laboratory reference frame. However, one might expect that the double production process could produce events in the system, but these should include many photons of less energy than the minimum energy defined by the well-defined kinematics of the single production process. The pulse-height spectra showed well-defined low-energy cutoffs, which were located at the values predicted from the single production kinematics.

No attempt was made to exclude events due to the elastic scattering of photons by protons (proton Compton effect). However, the present experimental results on elastic scattering[17] indicate that this effect is small.

Results

The values of the differential cross section were computed from the following formula:

$$\frac{d\sigma}{d\bar{\Omega}}=\frac{C(d\Omega/d\bar{\Omega})}{a_n a_\gamma(\Delta\Omega)Nn\epsilon},$$

where $d\sigma/d\bar{\Omega}$ is the differential cross section in the center-of-mass system, C is the number of counts per unit of beam, $d\Omega/d\bar{\Omega}$ is the ratio of differential solid angles in the laboratory and center-of-mass systems, a_n is the correction factor for nuclear absorption of protons, a_γ is the correction factor for conversion of the mesonic

[17] J. W. DeWire, M. Feldman, and R. Littauer, Proceedings of the 1959 Kiev Conference on High-Energy Physics (to be published).

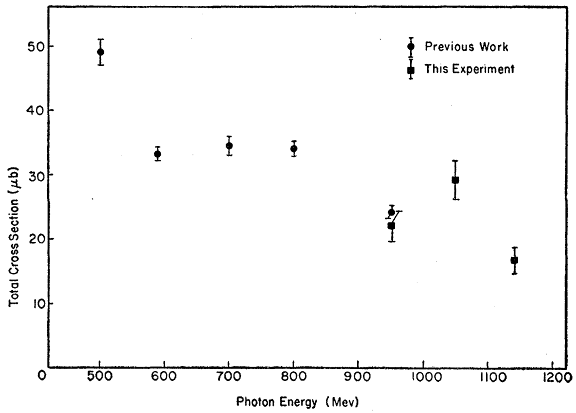

FIG. 5. Total cross sections for the photoproduction of single neutral pions from hydrogen. The data from previous work is obtained from Berkelman and Waggoner (reference 19).

decay photons in the material preceding the veto counter, $\Delta\Omega$ is the solid angle subtended by the proton counter, N is the number of protons per unit target area, $n=\int_{K_1}^{K_2} n(K)dK$ is the number of incident photons in the subtracted spectrum per unit of beam, and ϵ is the average probability that a meson decay photon is emitted in the direction of the photon counter. The correction factor a_γ varied between 0.62 and 0.93 for the several runs. The factor a_n was computed on the basis of a nuclear absorption cross section of 700 mb for protons in copper,[18] and varied between 0.49 and 0.95.

The experimental results are given in Table I. The quoted errors are the standard statistical errors. Other experimental errors are estimated to be small compared with these, the most significant being the error in the correction for nuclear absorption which is 7% at 125° and smaller at other angles. The results are plotted against $\cos\bar{\theta}$ in Fig. 4.

Estimates of the total cross section have been obtained from the areas under the parabolas determined by the points. The results are listed on Fig. 4 and are plotted on Fig. 5, together with values for lower energies, determined by Berkelman and Waggoner from all the available data.[19] The estimates from this work are of limited accuracy, since the presence of a $\cos^4\bar{\theta}$ term in the angular distribution can influence the total cross section. To estimate this uncertainty, the total cross section at 1050 Mev was computed by fitting to the experimental points an angular distribution containing a $\cos^4\bar{\theta}$ term of comparable magnitude but of opposite sign to the $\cos^2\bar{\theta}$ term. The resulting total cross section was 9% lower than the value obtained from the parabolic fit and is within the error indicated on Fig. 5.

DISCUSSION

Walker and Dixon[5] have pointed out that their results suggest a resonance due to a state of angular momentum 5/2 at a photon energy of 1050–1100 Mev. Such a pure state obtained by either magnetic or electric quadrupole absorption would be characterized by an angular distribution of the form $1+6\cos^2\bar{\theta}-5\cos^4\bar{\theta}$, which shows up as a major component in the results on π^+ production at 1000 Mev.

Two aspects of the data reported here support this interpretation, although the limited scope of the data leaves some uncertainty in this support. The sudden rise in the total cross section at 1050 Mev suggests that the resonance may be quite narrow and points out the necessity of getting data with high-energy resolution. The parabolic fits to our data also give a rapid rise in the $\cos^2\bar{\theta}$ term relative to the isotropic term, which would be also expected from the appearance of a dominance of a 5/2 resonance state.

ACKNOWLEDGMENT

We wish to thank Martin Feldman for his assistance in taking the data.

[18] F. F. Chen, C. P. Leavitt, and A. M. Shapiro, Phys. Rev. **99**, 857 (1955). (References to other measurements are given in this paper.)

[19] K. Berkelman and J. Waggoner, Phys. Rev. **117**, 1364 (1960).