counting rate dropped to about $\frac{1}{3}$ that found at the maximum.

ACKNOWLEDGMENTS

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Photoproduction of Neutral Pions in Hydrogen: $p-\gamma$ Coincidences*

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This paper reports measurements of the differential cross section for photoproduction of neutral pions in hydrogen at energies 300, 400, and 450 Mev, at center-of-momentum angles of 70° to 150°. One decay photon from the neutral pion is observed in coincidence with the recoil proton, whose energy and angle are measured to define the photon energy. The results obtained by this method are in good agreement with more accurate measurements obtained recently by the method of observing only the recoil proton.

INTRODUCTION

PROBABLY the most accurate method for measuring the photoproduction of neutral pions in hydrogen is to observe the recoil proton alone. Its energy and angle define uniquely the photon energy as is well known. This method has been used by Goldschmidt-Clermont, Osborne, and Scott[1] and recently in this laboratory by Oakley and Walker.[2] This method makes the assumption (for which there is good evidence) that recoil protons from hydrogen are not produced in competitive numbers by processes other than neutral pion production. In the method of Silverman and Stearns[3] the photoproduction process is identified a little more definitely, by requiring the recoil proton whose energy and angle are observed, to be in coincidence with one of the decay photons from the neutral pion. This method suffers from the disadvantages that the absolute efficiency of the photon counter enters into the cross section, and the counting rates are decreased by the photon coincidence requirement. It has an advantage if solid targets of polyethylene and carbon are used, in reducing considerably the relative background from the carbon. This reduction occurs partly because the angular correlation between neutral pion and recoil proton, which is definite for hydrogen, is destroyed to a significant extent for carbon.

The measurements here described are a continuation of earlier work[4] using the method of Silverman and Stearns. Angular distributions at 300, 400, and 450 Mev are obtained, and compared to the more recent and probably more accurate data of Oakely and Walker[2] which depend on counting the recoil proton only.

APPARATUS

The arrangement of target, counters, and absorbers is shown in Fig. 1. Recoil protons are counted by a counter telescope consisting of two scintillation counters (stilbene crystals $\frac{1}{4}$ inch thick) in coincidence followed by a third one in anticoincidence. The thickness of aluminum absorbers in the telescope determines the range, and thus the energy, of the protons, which are identified by their specific ionization, or pulse height, in the first counter.

The range, ΔT_p, of proton energies accepted by this counter is found from the range interval, ΔR, consisting of the aluminum absorber C plus a thickness of stilbene which depends on the effective biases of counters 2 and 3. This thickness is found by extrapolating the proton counting rate as a function of absorber C thickness to zero counting rate. During this measurement, when C is increased, absorber B is decreased half that amount, in order to keep the mean energy of the observed protons the same.

The photon counter consists of two liquid scintillators of dimensions 4×6×0.5 inches. The first is in

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[1] Goldschmidt-Clermont, Osborne, and Scott, Phys. Rev. **89**, 329 (1953).

[2] D. C. Oakley and R. L. Walker, following paper [Phys. Rev. **97**, 1283 (1955)].

[3] A. Silverman and M. Stearns, Phys. Rev. **88**, 1225 (1952).

[4] Walker, Oakley, and Tollestrup, Phys. Rev. **89**, 1301 (1953).

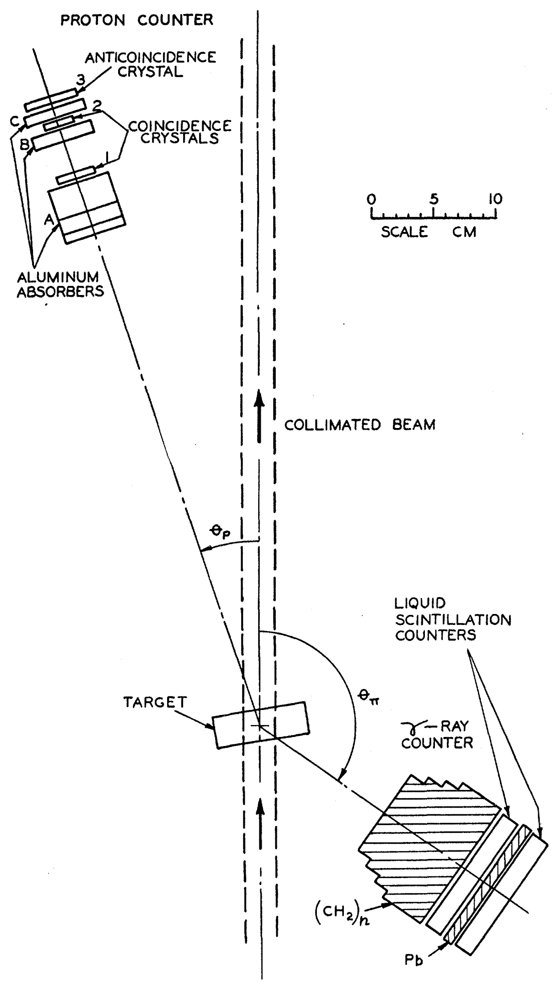

FIG. 1. Experimental apparatus. The synchrotron beam was monitored by a thick copper ionization chamber of the Cornell design, located behind the apparatus.

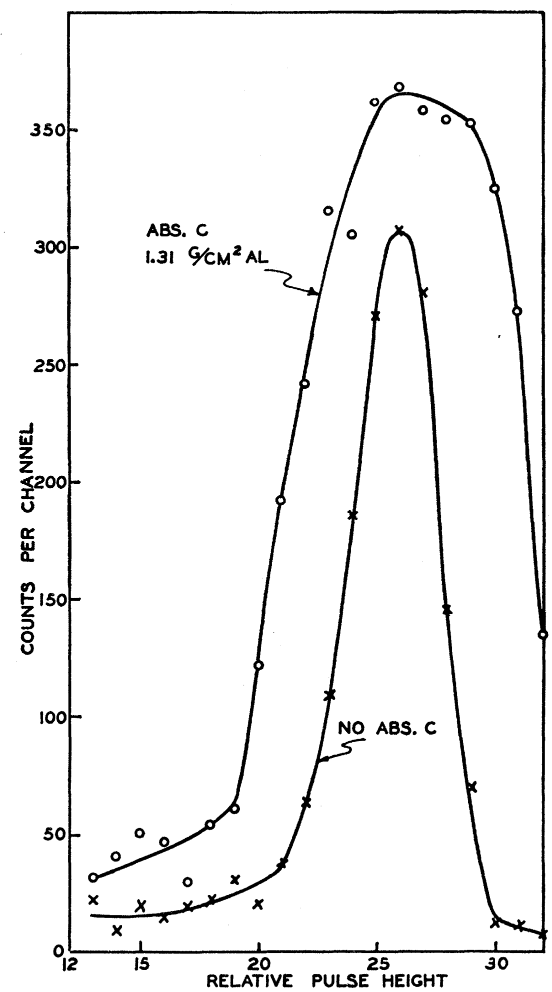

FIG. 3. Proton peaks in the pulse height spectra from proton counter number one, for two different range intervals ΔR. No photon coincidences were required in these measurements.

anticoincidence to eliminate detection of charged particles, and the second one in coincidence with the

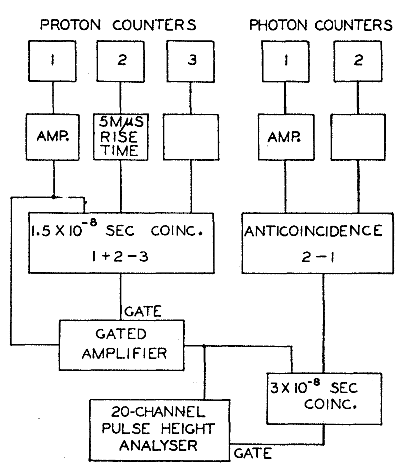

FIG. 2. Block diagram of the electronic circuits.

proton counter. A 0.64- or 0.95-cm lead converter between the counters gives an efficiency of 0.55 or 0.70, respectively, for counting a high-energy photon hitting it. A block of polyethylene was placed in front of these two counters in an attempt to reduce the large number of low-energy electrons without decreasing appreciably the photon counting efficiency.

Targets of polyethylene and carbon of the same stopping power were used, and a subtraction made to obtain the cross section in hydrogen. The carbon background varied between 13 and 40 percent, depending on the proton energy and angle, but was typically 25 percent.

For each measurement, the target thickness, range interval ΔR, and proton angular resolution (determined by the distance between target and proton counter) were adjusted to maximize the counting rate for a given resolution. The energy resolution was about the same as that shown in Fig. 2 of reference 4, having a width at half-maximum of about 40 Mev.

The x-ray beam from the synchrotron was collimated by a primary lead collimator, followed by a secondary collimator, or "scraper". Some lead shielding which is not shown in Fig. 1 was placed near the counters to shield them as much as possible from the collimators and the beam path. Despite this shielding, the individual counting rates of the counters were large, and relatively fast electronic circuits were used. The electronic circuits and their resolving times are shown in the block diagram, Fig. 2.

THE PROTON COUNTER

The extent to which the proton counter telescope distinguishes protons from other particles is indicated in Fig. 3, which shows proton peaks in the pulse-height spectrum from the first counter. The two curves show the effect of changing the range interval ΔR by different thicknesses of absorber C. A second peak in the pulse-height spectrum due to mesons is off the scale to the left. The tail at small pulse heights is omitted in finding the proton counting rate.

THE PHOTON COUNTER

The photon counter, consisting essentially of a single counter, gives many pulses which do not originate from neutral pion decay photons. Its only duty is to eliminate all proton counts not accompanied by a decay photon, and to accept those which are with a known efficiency. The neutral pion detection efficiency depends on two factors: first, the probability that one decay photon from the pion strikes the photon counter, and second, the probability that the photon is converted in the lead converter and recorded.

Since the neutral pion is associated with a recoil proton of known energy and direction, its own energy and direction are known within limits set by the size of the proton counter and the range interval ΔR. Thus the angular and energy distributions of the decay photons are known, and the calculation of the probability of one hitting the photon counter is straightforward, although somewhat tedious. The angular correlation between proton and decay photons is illustrated in Fig. 4 which shows the proton-γ coincidences as a function of the angle of the photon counter from the direction of emission of the neutral pion.

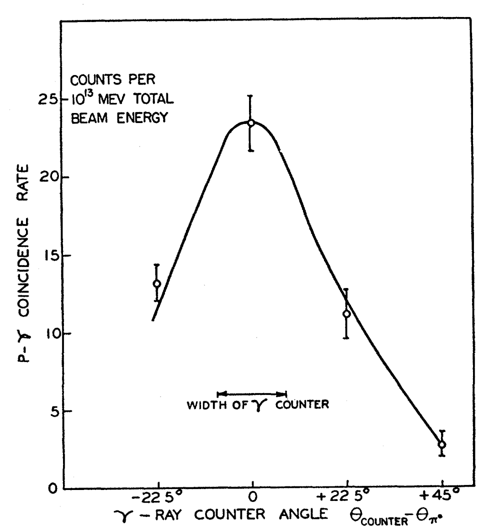

FIG. 4. Angular correlation between recoil proton and the decay photon from π^0. These measurements were made for a pion angle of 90° (lab) and incident photon energy 400 Mev.

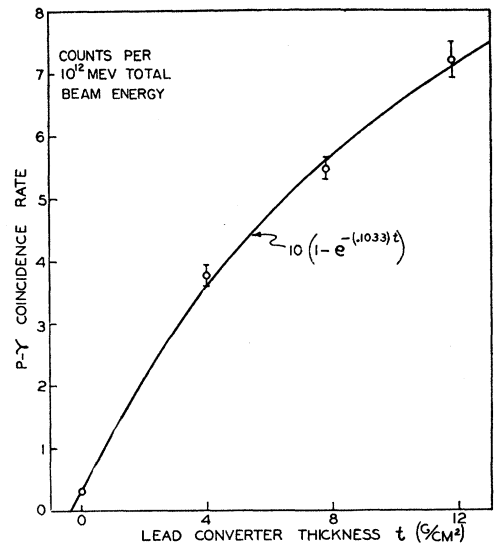

FIG. 5. Proton-γ coincidence rate as function of the lead converter thickness in the photon counter. The exponent used for the solid curve corresponds to the known absorption coefficient of lead for photons of about the average energy of the π^0 decay photons observed. These data were taken with a pion angle 90° (lab) and an incident photon energy 400 Mev.

The second factor in the pion detection efficiency, the photon conversion efficiency, is simplified by the high energy of the decay photons observed. By placing the lead converter very close to the coincidence counter to avoid scattering loss of the converted electrons, we may assume that the conversion efficiency is simply the probability of absorption of the photon in the lead. The absorption cross section, which is mainly that for pair production, is well known experimentally[5] and theoretically. The conversion efficiency is multiplied, of course, by the probability that the photon passes through the front polyethylene block and the anticoincidence counter without absorption. This is 0.90.

The above procedure for obtaining the conversion efficiency is not valid for thick converters, of course, so a check was made to see if the 0.64- and 0.95-cm plates of lead used were so thick that absorption or scattering-out is important. Figure 5 shows the proton-γ coincidence rate as a function of lead converter thickness. This is compared to a (normalized) exponential growth curve with the proper exponent for lead, and shows that

[5] J. L. Lawson, Phys. Rev. **75**, 433 (1949); DeWire, Ashkin, and Beach, Phys. Rev. **83**, 505 (1951).

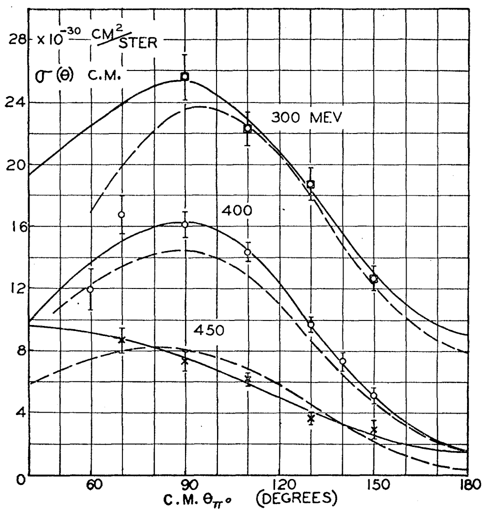

FIG. 6. Differential cross sections in the center of momentum system as a function of the c.m. pion angle. Errors are standard errors which include estimated systematic errors only to the extent that these affect the shape of the angular distribution. The solid curves are least-squares fits to the present data. The dashed curves are from the experiment of Oakley and Walker (see reference 2).

within the accuracy of the measurement, there is no correction for using too thick a converter.

THE SYNCHROTRON X-RAY BEAM

The synchrotron beam spectrum has been measured with a pair spectrometer[6] and its shape found to agree with theory within the experimental accuracy of about 3 percent. The absolute number of photons used in calculating the cross sections depends upon an absolute calibration of the beam monitor used. This was a Cornell type ionization chamber with 1-inch copper walls. The calibration used for the cross sections reported here was $Q=4.44\times10^{-18}$ Mev/coulomb. This is an average of two calibrations, one using a pair spectrometer[6] and the other the shower method of Blocher, Kenny, and Panofsky.[7] These differ unfortunately by 15 percent, and an error of about 8 percent is assigned to the beam calibration.

[6] D. H. Cooper, thesis California Institute of Technology (unpublished).

[7] Blocher, Kenny, and Panofsky, Phys. Rev. **79**, 419 (1950).

RESULTS

The differential cross sections obtained in the present experiment are shown in Fig. 6. The solid curves are least-squares fits to the form

$$\sigma(\theta)=A+B\cos\theta+C\cos^2\theta \quad \text{(c.m. system)}.$$

The values of the coefficients A, B, and C are given in Table I. The dashed curves in Fig. 6 are those obtained from the presumably more accurate values of A, B, and C reported by Oakley and Walker.[2] The present data are in reasonable agreement with these dashed curves.

The errors indicated in Fig. 6 include estimated systematic errors only to the extent that these influence the shape of the angular distributions. In addition the absolute cross sections are subject to the following errors: (1) beam calibration: 8 percent; (2) decay photon counting efficiencies: 8 percent; (3) other effects combined: 8 percent. The combined error in the absolute cross sections in thus about 14 percent.

TABLE I. Coefficients in the angular distributions, in units of 10^{-30} cm²/sterad (c.m. system).

k	300 Mev	400 Mev	450 Mev
A	25.3±1.4	16.2±0.5	7.5±0.4
B	1.6±6.1	1.4±1.2	4.2±1.2
C	−14.6±6.2	−13.4±1.7	−1.8±1.7

The absolute cross sections previously reported for 90° in the laboratory system[4] are 0 to 20 percent lower than the present values, after converting the previous cross sections to the c.m. system. The most likely source of this discrepancy is an error in the γ-ray counting efficiency assumed for the earlier experiment. The photon counter used in the present experiments is better than the earlier one in several respects, so the present cross sections are presumably the more reliable.

A comparison of the neutral pion photoproduction cross sections with the work of other laboratories and with theory is given in the accompanying paper[2] and will not be repeated here.

We are indebted to all the members of the Synchrotron Laboratory for contributions to this experiment.