using the same bubble chamber. The muon exposure and event measurement were done at the Enrico Fermi Institute for Nuclear Studies, and the scanning and analysis at Argonne National Laboratory.

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LOW-ENERGY CHARGED MESON PHOTOPRODUCTION

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Recently the discrepancies which still exist in the study of low-energy π-meson photoproduction have been discussed.[1] It was emphasized that a new and rather precise experiment by Adamovich *et al.*[2] on the reaction $\gamma + p \rightarrow \pi^+ + n$ at a gamma-ray energy of 185 Mev was in sharp disagreement with the old results of Beneventano *et al.*[3] Both these experiments were performed using nuclear emulsions to detect the positive pions and it seemed strange that such a wide disagreement should have been found. In particular, the disagreement was not in the form of absolute normalization (which has usually been the source of greatest error in photon-induced experiments), but rather it seemed to exist as an energy or angular dependence.

In an attempt to resolve this discrepancy, we have measured the angular distribution of π^+ mesons from hydrogen at 185-Mev gamma-ray energy using a bremsstrahlung beam of maximum energy of 220 Mev produced by the electron linear accelerator of the Ecole Normale Supérieure.

In this reaction, pions produced at backward angles have energies of the order of 12 Mev, whereas at forward angles energies of 40 Mev are reached. Due to the long path length (2.6 meters) from source to image of the double-focusing magnetic spectrometer which was used, the percentage of mesons which decay varies from 60% to 40% between the above two energies. If a detection system at the focal plane of the spectrometer can distinguish pions from muons of the same momentum, then this large energy-dependent correction can be made to the data. However, as the experiment depended critically on the fact that there should be no systematic energy-dependent error present, we adopted an alternative approach which required no energy-dependent correction at all, but relied on the analysis of several experimental sets of data at fixed momentum transfer. This analysis was reported elsewhere[1] and it was shown that there exists agreement, within the quoted experimental errors which in some cases were as small as 5%, of the five available sets of experimental data with the predictions[4] of the Chew-Goldberger-Low-Nambu (CGLN) fixed-momentum dispersion relation theory. Our method, therefore, is to calibrate the meson counting rate at a given meson energy under the above kinematical conditions where the cross section is known and properly described by the CGLN theory.

The experiment measures (1) the yield N_1 of mesons produced by absorption of a photon of energy k_1 corresponding to a fixed meson energy at angle θ_1 and (2) the yield N_2 of mesons produced by absorption of photons of energy k_2 corresponding to the same fixed meson energy at angle θ_2.

If $\sigma(k)$ is the differential pion photoproduction cross section in the center-of-mass system, and $N(k)dk=[\alpha(k)/k]dk$ is the number of photons between k and $k+dk$, then

$$N_1=N_0\Omega\Delta E_\pi\left[\sigma(k_1)\frac{d\cos\theta_1{}^*}{d\cos\theta_1}\frac{\alpha(k_1)}{k_1}\frac{dk_1}{dE_\pi}\right]F(E_\pi), \quad (1)$$

where N_0 is the number of protons per unit area of the target, Ω is the effective solid angle of the spectrometer for mesons of energy E_π, and ΔE_π is the fixed energy interval of mesons which are detected at the focal plane of the spectrometer. $F(E_\pi)$ is an energy-dependent function which takes into account effects such as decay in flight and nuclear absorption of the pions between the target and the counter telescope. We can then write:

$$\sigma(k_1)=\sigma(k_2)\frac{N_1}{N_2}\left\{\frac{d\cos\theta_2{}^*}{d\cos\theta_2}\frac{dk_2}{dE_\pi}\alpha(k_2)k_1\Big/\frac{d\cos\theta_1{}^*}{d\cos\theta_1}\frac{dk_1}{dE_\pi}\alpha(k_1)k_2\right\}. \quad (2)$$

The first and second terms within the brackets are kinematic factors, whereas the third term $\alpha(k)$ requires knowledge of the shape of the bremsstrahlung spectrum.

The electron beam translation system and general experimental layout of this accelerator has been described previously.[5] The intensity of the electron beam was monitored continuously by means of a secondary emission monitor, of standard design,[6] which was calibrated frequently against a Faraday cup.[7] Random variations of the monitor were found to be less than 0.5% during the course of the experiment. Although the deviation of the accelerator has been calibrated to a nominal 0.25%, the energy of the beam at any time is uncertain to about 0.8% when an energy interval of 0.8% of the direct accelerator beam is

Table I. A list of the kinematic factors and observed counting rates.[a]

θ_B (lab)	E_γ (Mev)	E_π (Mev)	$d\cos\theta^*/d\cos\theta$	dk/dE_π	$\alpha(k)$	A	B	C	$d\sigma/d\Omega$
43.53°	187.4	37.2	1.483	1.076	0.817	676 ±27	476 ±38	452 ±39	0.693
44.97°	182.1	31.9	1.485	1.074	0.830	509 ±21	337 ±27	328 ±27	0.675
46.68°	175.9	25.7	1.494	1.067	0.842	396 ±16	255 ±22	237 ±23	0.641
48.55°	168.9	18.7	1.526	1.050	0.850	267 ± 8	173.5 ±10	151.5 ±13	0.582
49.55°	164.0	13.9	1.579	1.023	0.855	135.5 ± 4.5	94.9 ± 6.0	79.6 ± 6.7	0.520
θ (c.m.)									
45°	185	37.2	1.587	1.027	0.824	720 ±27	489 ±39	450 ±41	0.653 ±0.083
70°	185	31.9	1.356	1.140	0.824	513 ±21	358 ±26	344 ±27	0.743 ±0.085
95°	185	25.7	1.082	1.320	0.824	368 ±15	257 ±21	248 ±21	0.818 ±0.105
125°	185	18.7	0.767	1.644	0.824	234 ± 9	153.5 ±11	148.5 ±11	0.817 ±0.095
155°	185	13.9	0.548	2.033	0.824	134.5 ± 4.5	102.8 ± 6.0	94.0 ± 7.0	1.045 ±0.112

[a] Column A is the counting rate with radiator in and target full. B is A after subtraction of "radiator out and target full" counting rate. C is B after subtraction of 87% of the counting rate with radiator in and target empty; this takes into account the finite radiation length (vacuum foils, etc.) still in the electron beam even when the radiator is removed.

used. This produced a 0.8% uncertainty in the instantaneous photon flux, which, with the frequent reversals in the meson counting procedure, probably averages to less than 0.4% relative error in the final cross sections. The multiple and Møller scattering of the electron beam in the radiator produces a systematic error in beam current integration compared to those runs when the radiator is not in place. This effect has been estimated to produce less than 1% relative error in the final cross sections. The 57.5-cm radius, 180°, double-focusing spectrometer, which was used to select the pions, has been described in detail previously.[5] The absolute calibration and stability of the spectrometer are about 0.5%, and < 0.1%, respectively. The corresponding uncertainty in the final cross sections is less than 0.3%.

A 22-mm diameter cylindrical liquid hydrogen target with 30-micron thick aluminum walls was positioned with its axis vertical, and on the axis of rotation of the spectrometer, to an accuracy of about 1 mm. The electron beam before passing through the target traversed a tantalum radiator which was 8.2% of a radiation length thick. The surface of the radiator had a thin coat of fluorescent paint which allowed the position and shape of the electron beam to be controlled to an accuracy of about 1 mm. A closed circuit television system was used to observe the radiator, and under all operating conditions the diameter of the beam was ≤ 8 mm. Fluctuations of the position of the beam spot were less than 1 mm from one run to another.

Pions were detected at the focal plane of the spectrometer by means of two scintillation counters operating in coincidence. The sizes of the counters were 4 cm×4 cm×0.3 cm and 4 cm×4 cm×2.5 cm, respectively; the 4-cm height corresponded to ~2% momentum interval for the detected pions. The coincidence circuit had a resolving time of 25 mμsec and its output was used to open a 0.2-μsec gate through which the signal from either counter 1 or 2 (depending on the particular meson energy being studied) was allowed to pass. This signal was sent to another gate which was opened by a 2-μsec pulse which straddled the 1-μsec accelerator pulse. After lengthening and amplification, the resulting signal was displayed on a 100-channel pulse-height analyzer. At all meson energies studied, well-defined counting rate plateaus were obtained as a function of high voltage on each counter. The pulse-height spectra showed meson peaks with a peak height to valley ratio of typically 30:1. This ratio did not show any appreciable angular dependence.

The counting procedure adopted was to measure the counting rate: (a) at angle θ_1 with target full and radiator in, (b) at angle θ_1 with target full and radiator out, and (c) at angle θ_2 under the same two conditions.

The whole procedure was then repeated several times. The counting rate with target empty and radiator in was measured twice during the experiment. Table I shows the data. The numbers in the sixth column represent the deviation of the bremsstrahlung spectrum from a pure $N(k) \propto k^{-1}$ spectrum. This effect was calculated in the usual way by assuming the Schiff[6] gamma spectrum for a thin target, and integrating over the energy straggling of the electron beam by radiation in the 8.2% radiation thickness used. The correction due to this effect is seen to be at most 4% to which we assign an error of 1%. The counting rates of pions shown in Table I have all been corrected for dead-time losses which never exceeded 1%. Due to the finite size of the liquid target, there is a small variation of effective solid angle of the spectrometer as a function of angle. This effect was calculated and checked experimentally using a thin CH_2 target. The relative error introduced to the final cross sections due to this effect was shown to be always less than $(0.8 \pm 0.4)\%$ and was neglected.

In Table I, C represents photoproduction from hydrogen except for a $(1 \pm 1)\%$ contribution of electroproduced mesons from the aluminum target walls which has not been properly subtracted. The relative error introduced into the final cross sections is less than 1% due to this effect. The absolute uncertainty of the cross sections to which the final normalization has been made is about ±5% and we take a relative error of 3%. All systematic errors are listed in Table II. It should be noted that their quadratic sum is of the order of one-third that of the statistical error.

The differential cross sections at 185 Mev were calculated using (2) and are shown in the last column of Table I. The errors shown are purely

Table II. Systematic errors.

Photon flux	0.4%
Monitoring	1.0%
Spectrometer	0.3%
Bremsstrahlung spectrum	1.0%
Subtraction procedure	1.0%
Cross sections	3.0%
Quadratic sum	3.5%

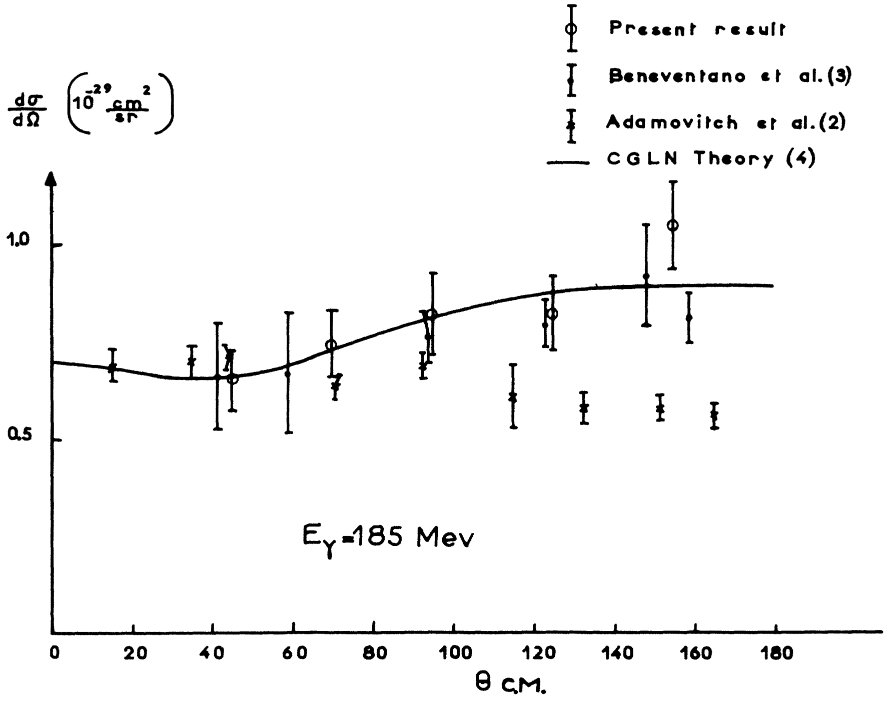

FIG. 1. The angular distribution of π^+ mesons photoproduced from hydrogen at 185-Mev gamma-ray energy.

statistical. Figure 1 shows the present results in the form of open circles. It is clear that our results are in substantial agreement with the results of Beneventano *et al.* and also with the predictions of CGLN. The result of this experiment is in disagreement with the result of Adamovich *et al.*

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