Photoproduction of Neutral Pions from Hydrogen in the Region of the First Pion-Nucleon Resonance

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The cross section for single π^0 photoproduction from hydrogen has been measured at nominal angles of 70°, 90°, 130°, and 180° for photon energies 220–400 MeV by detecting the recoil protons. The 180° measurements, taken with a new setup, avoid big corrections present in some of the previously published results. These new data allow a direct comparison with the experiment presented by the Bonn group and with the most recent theoretical predictions.

I. INTRODUCTION

RECENTLY there have been considerable efforts to improve the understanding of single π^0 photoproduction from hydrogen in the vicinity of the first resonance $\Delta(1236)$. Experimentally the differential cross section without polarization information has been studied extensively, with results usually given as a function of θ^* and k, where θ^* is the angle of the pion in the c.m. system, and k is the laboratory photon energy. These efforts have resulted in the publication of numerous angular distributions with k fixed[1] and excitation curves for fixed θ^*.[2–4] Theoretical attempts[5–7] to explain these data have become increasingly refined and complicated. The introduction of a certain number of adjustable parameters permits a reasonable fit to the data, but absolute theoretical predictions seem relatively unsatisfactory.

However, the task of the theoretician would be considerably clarified if the experimental results from different laboratories were free from ambiguities. In particular the recent Orsay measurements[2] for $\theta^*=180°$ were about 15% (several standard deviations) lower than the values obtained by extrapolation of the extensive angular distributions reported by the Bonn group.[1] This situation led us to measure excitation curves for $\theta^*\neq 180°$, thereby allowing direct comparison of the results of our technique with those of other laboratories, and to scrutinize the $\theta^*=180°$ measurements reported in Ref. 2 for possible errors.

We report here the results of this study comprising measurements of excitation curves at nominal angles of $\theta^*=70°$, 90°, and 130°, and five new measurements at $\theta^*=180°$ (see Sec. IV A 2 for the definition of the true measured angles). These data are combined with the previous Orsay measurements and the ensemble compared with the most recent analysis of the Bonn data,[1] and with previous results from other laboratories.

In Secs. II and III, the experimental methods and the apparatus are described. For further technical details the reader is directed to Ref. 2. In Sec. IV, we indicate the data-reduction procedure; in Sec. V, the errors are discussed, and in Sec. VI, experimental results are presented. Conclusions and discussion are given in Sec. VII.

II. EXPERIMENTAL METHOD

We have measured the differential cross section for the process

$$\gamma+p\to p+\pi^0 \tag{1}$$

without determination of any of the particle polarizations. The γ rays are produced in a thin aluminum radiator by the bremsstrahlung of electrons from the Orsay linear accelerator. The electron beam is swept aside by the field from a bending magnet downstream from the radiator, and the photon beam continues forward to strike a liquid-hydrogen target beyond the magnet (Fig. 1). Protons recoiling from the target were analyzed in momentum and angle by the triple-focusing spectrometer. The vector momentum of the detected recoil proton determines the kinematics of the reaction (1).

In fact, however, reaction (1) is accompanied by a certain number of parasite reactions induced in the target and its support. Those induced in the target support were accounted for by measuring the counting rate from an empty target cell, which was identical to the cell containing the hydrogen. The full and empty target cells are mounted on a translating mechanism which permitted alternate full and empty target measurements.

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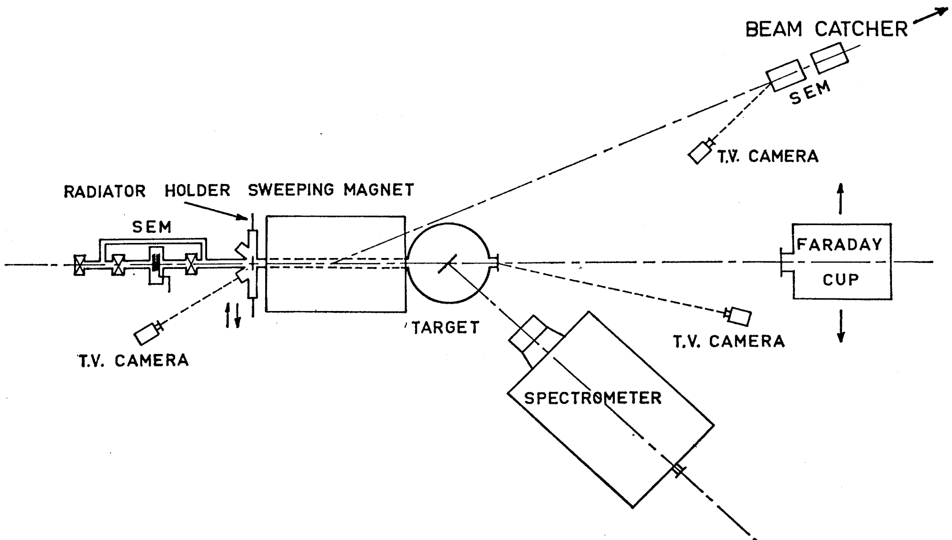

FIG. 1. Experimental setup for measurements at $\theta^* \neq 180°$

Parasite reactions induced in the target hydrogen were accounted for as follows: Double-pion photoproduction was eliminated by choice of kinematics. The proton Compton effect, although poorly known, was estimated to be negligible ($\leqslant 1\%$) for these new data ($\theta^* = 70°$, 90°, and 130° in the whole energy range and $\theta^* = 180°$ for $k \leqslant 300$ MeV). Ghost protons were shown not to contribute for points where the proton momentum was less than 500 MeV/c by detecting protons whose momentum was greater than $P_{\max}$, which is the proton momentum corresponding to photoproduction by photons having the electron beam energy; for momenta greater than 500 MeV/c, we assumed no contribution from ghost protons. The transmission by the spectrometer of initially high-momentum photoprotons, which scatter from the spectrometer's pole faces and slits, was assumed negligible because of the data of Ref. 8.

To obtain the absolute acceptance of the detection system, we measured elastic electron-proton scattering, which was accomplished by turning off the bending magnet, removing the radiator, and adjusting the electron beam energy so that the recoil proton momentum corresponded to that measured in photoproduction. These elastic scattering measurements were then compared to the values predicted using the Rosenbluth formula and the "well-known" values for the proton form factors[9] to obtain a normalization of the experimental acceptance effective in photoproduction.

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III. APPARATUS

The experimental setup differed little from that used for the 180° measurements.[2] In what follows, we emphasize the details particular to the $\theta^* \neq 180°$ work. Figure 1 shows the general arrangement.

All these measurements were done with the electron beam deflected from the vicinity of the target by the sweeping magnet. To maintain a suitable photon beam spot size at the target, we were forced to use thin radiators (0.003, 0.006, and 0.0009 radiation length of aluminum) because of the 1.8-m distance between the radiator and the target. Measurements of the photon beam spot sizes using glass slides indicated that the photon intensity distribution was not very different from a Gaussian with a rms angular spread of $(11/E)(X/2)^{1/2}$, where X is the radiator thickness in radiation lengths. We chose the radiator thickness as a function of energy so that one standard deviation in the beam spot size was less than 0.4 cm at the target.

Unlike the arrangement for the 180° measurements, the scattering chamber vacuum was not continuous with that of the spectrometer. The recoil protons had to traverse several materials (see Table I) before entering the spectrometer vacuum.

The angular acceptance of the spectrometer was defined as in Ref. 2. The counting system, also unmodified in principle, consisted of two scintillators in coincidence. Considerable care was taken to ensure that the entire photon beam spot at the target was viewed by the counters, so that there was no effect due to a polarization of the photon beam. The range of proton momenta detected in this experiment was from 200 to 527 MeV/c, which led us to choose several combinations of scintillators and target thicknesses (see Table I).

TABLE I. Experimental conditions for the measurements of the π^0 photoproduction.

θ^* Nominal pion angle (c.m.)	p_p Proton momentum (MeV/c)	ϕ_p Spectrometer angle	Target thickness (cm)	Target angle with beam	Material traversed by the protons	Scintillator thickness (mm)
180°	350–450	0°	5.7	90°	12 μ stainless steel	$e_1=4$ $e_2=6$
130°	346–527	21°84′–22°95′	1	45°	12 μ steel	$e_1=4$
90°	245–406	37°51′–41°36′	1	43°	190 μ Mylar	$e_2=6$
70°	204–328	44°60′–50°39′	1	43°	50 cm air 125 μ Kapton	$e_1=1$ $e_2=2$

IV. TREATMENT OF DATA

The data-taking procedure was the same as described in Ref. 2, although the complications of the data taking and analysis associated with the passage of the electron beam through the target were eliminated by use of the bending magnet.

A. Photoproduction

1. Cross Section

Let N_i electrons of energy E incident on a radiator of n_r atoms/cm^2 produce $N_i n_r \phi(E,k)dk/k$ photons with energies between k and $k+dk$ collinear with the electron beam. This photon beam strikes the hydrogen target of n_v protons/cm^2 and thickness t to produce neutral pions by reaction (1) at angle θ^* with cross section $d\sigma(k,\theta^*)/d\Omega^*$ in the c.m. system. There results

$$dN_p=N_i n_r\frac{\phi(E,k)}{k}n_v t\frac{d\sigma}{d\Omega^*}(k,\theta^*)Jdpd\Omega \tag{2}$$

for the number of protons with momentum between p and $p+dp$ in solid angle element $d\Omega$ in the laboratory system. The Jacobian $J=\partial(k,\Omega^*)/\partial(p,\Omega)$ transforms the phase space from $dkd\Omega^*$ to $dpd\Omega$.

Equation (2) is valid for a thin target and infinitesimal phase space. If the protons traverse a thickness of material dx (target or window or air) in which they lose momentum, the momentum interval dp before traversal is not equal to a momentum interval dp'' at momentum p'' after traversal because of the variation of the momentum loss function $dp(p)/dx$ in the material. One can show that

$$dp=\eta dp'', \tag{3a}$$

with

$$\eta=\frac{dp}{dx}(p)\bigg/\frac{dp}{dx}(p'')<1, \tag{3b}$$

where the inequality follows since $p>p''$ and dp/dx decreases with increasing p for momenta involved here. If we detect recoil protons of momentum p' in a momentum interval dp', these protons had a momentum p in an interval dp at the center of the target. These different momentum intervals are related through an expression like (3a), with η depending upon all thicknesses of material traversed by the protons from target to spectrometer vacuum.

Similarly, the solid angle for detection $d\Omega'$ may be slightly different from $d\Omega$ because of multiple scattering, absorption, etc., in the target: say, $d\Omega=zd\Omega'$, where we expect z to vary slowly as a function of p and Ω. Then (2) becomes modified by $dpd\Omega\rightarrow\eta zdp'd\Omega'$, and there remains only the integration over the finite acceptance $\Delta p'\Delta\Omega'$ of the detection system. The integrand can be shown to vary slowly for the parameters of this experiment, however, so that the number of detected protons is

$$N_p=\epsilon\int_{\Delta p'\Delta\Omega'}dN_p=\epsilon N_i n_r\frac{\phi(E,k)}{k}\times n_v t\frac{d\sigma}{d\Omega^*}(k,\theta^*)J\eta z\gamma p'\Delta\Omega', \tag{4}$$

where ϵ is the efficiency for counting the protons and $\gamma=\Delta p'/p'$. The factor $\epsilon n_v t z\gamma\Delta\Omega'$ is obtained from comparison of our measurements of elastic electron-proton scattering with the accepted values of the cross section for this process.

2. Corrections

According to (3), the interval of momentum effective at the center of the target is a function of the thickness of material traversed by the detected particles. When energy losses are considerable in the target hydrogen, it follows that there will be an important difference in the momentum interval accepted for full and empty targets. Let N_1, N_2, and N be the number of protons detected with target full, target empty (target walls only in beam), and target out, respectively, for an equal number of electrons incident on the radiator. Then the correct number of protons is no longer $N_p=N_1-N_2$ but

$$N_p=N_1-N-\rho(N_2-N), \tag{5}$$

where ρ is the ratio given in (3b), using for p'' the momentum of the protons after they have left the target, but before they reach the window of the scattering chamber. In practice, ρ differs little from η for our experiment.

Equation (5) assumes (i) that the front and back windows of the target are identical and are viewed with the same efficiency (solid angle) by the detection system, (ii) that the momentum spectrum of protons produced by interaction of the beam in the target windows varies slowly with momentum relative to δp, the maximum momentum lost by the protons in traversing the target, (iii) that the momentum loss of the protons in the window of the target is negligible, and (iv) that dp/dx is a linear function of the momentum p over the interval δp. These assumptions are valid for our experiment.

Formula (5) shows the correction for momentum acceptance to be important when the differential momentum loss function varies appreciably in the range δp, and when $N_2 \sim N_1$ and $N_2 \neq N$. This was the case for the 180° measurements reported in Ref. 2, but these results were not corrected according to Eq. (5). For instance, for the point at "$k=220$ MeV, $\theta^*=180°$," $\rho=0.945$ and the relative values for N_1, N_2, and N are, respectively, 75.27, 66.13, and 12.84 using a target 2 cm thick. Because the correction was big (43% for the point at 220 MeV) for the low-momentum data taken with the thin target (2 cm) and without the bending magnet, we decided to retake these points using the bending magnet.

For the new experimental configuration (with a thicker target, thinner radiator, and electron beam ditched), we found $N_2 \sim 0.1 N_1$, so that the correction does not exceed 2% for the lowest momenta detected. In the same conditions as above, we had $\rho=0.83$ and the relative values of N_1, N_2, and N are, respectively, 10.37, 1.13, and 9.43 using a target 5.7 cm thick.

Corrections independent of the presence of the electrons in the photon beam are the same as before,[2] except that for these new data we have made no correction for the proton Compton effect which was estimated to be negligible.[10]

Because of the large radial aperture of the entrance slits of the spectrometer, the mean proton detection angle is slightly different from the nominal angle ϕ_p of the spectrometer. The effect is important mainly for the measurements at $\phi_p=0°$; the mean proton angle is in that case 1.6°, which corresponds to $\theta^*=175°$. In the other cases ($\theta^*_{\text{nom}}=70°$, 90°, and 130°) the effect is much smaller ($<0{,}5°$).

The experimental resolutions, Δk in the photon energy and $\Delta\theta^*$ in the c.m. angle, were calculated from knowledge of δp, the momentum loss in the target, the finite photon beam spot size, the angular acceptance of the spectrometer, and the angular divergence of the photon beam. The values which we quote are estimated standard deviations.

B. Elastic Scattering

For each photoproduction point at $\phi_p=0°$ we measured an elastic electron-proton scattering peak for normalization. For the measurements at other angles, it was not necessary to measure elastic scattering for each photoproduction point because the momenta were much lower (than for the forward protons), so there was no problem of spectrometer saturation. The photoproduction data were taken as excitation curves at fixed c.m. angle, which means that the laboratory angle varied only a few degrees for values of k covering the resonance. Thus the normalization coefficient cannot vary appreciably with spectrometer angle in the angular region of each excitation curve and, in fact, all our elastic scattering data are consistent with no angular dependence of the acceptance.

In order to avoid uncertainty associated with the resolution function of the spectrometer, we measured the recoil proton momentum distribution down into the tail, where the effects of wide-angle bremsstrahlung[11] and elastic scattering by energy-degraded electrons yield a flat spectrum.

V. ERRORS

Errors in our determination of the cross section arise from uncertainties in the quantities appearing in Eq. (4). We divide the analysis into consideration of errors which affect each point independently as random errors, and consideration of errors which influence all the data points in a systematic way as systematic errors.

A. Random Errors

We estimate standard deviations for these errors and combine them in quadrature when they apply to the same quantity. First, we examine errors arising from uncertainties in kinematical quantities.

Error in the recoil proton momentum p: 0.6%, due to uncertainty in the reproducibility of the field in the spectrometer.

Error in the detected proton angle ϕ: 0.03°, a combination of 0.02° uncertainty in the spectrometer angle, and 0.02° in the beam alignment.

Uncertainty in the incident beam energy E: 0.3%, as determined from elastic scattering kinematics and the uncertainties in p and ϕ.

The effects of these kinematical uncertainties on the determination of the cross section was estimated by considering the product $Jp'\eta\Phi(E,k)/k$ in Eq. (4) as a function of p, ϕ, and E. For this purpose we used formula 3CS (A) of Koch and Motz[12] for the shape of the bremsstrahlung spectrum. The resulting error due to kinematical uncertainties varies from 3.3 to 0.4%.

Uncertainty due to random effects in the determina-

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TABLE II. π^0 photoproduction experimental results and errors at $\theta^*=70°$. The definitions of Δk, $\Delta\theta^*$, Δs, Δm, and η are indicated in the text.

k (MeV)	Δk (MeV)	θ^* (deg)	$\Delta\theta^*$ (deg)	p (MeV/c)	$d\sigma/d\Omega^*$ (μb/sr)	Δs (μb/sr)	Δm (μb/sr)	η
240.8	3.5	70.1	0.6	204.3	5.7	0.24	0.40	0.636
260.5	3.5	70.0	0.6	221.0	9.79	0.20	0.52	0.726
280.3	3.5	70.0	0.6	237.4	16.65	0.31	0.86	0.789
300.6	3.6	70.0	0.6	253.7	22.63	0.43	1.14	0.834
320.8	3.7	69.9	0.6	268.9	26.64	0.50	1.35	0.865
340.2	3.9	69.9	0.6	284.2	26.67	0.45	1.33	0.889
360.0	4.3	69.9	0.6	299.0	22.38	0.34	1.10	0.908
380	4.6	69.0	0.6	313.7	17.36	0.33	0.88	0.922
400	4.9	69.9	0.6	328.1	12.87	0.25	0.65	0.934

tion of the photon spectrum $N_i n_r \phi(E,k)$: 0.4% due to uncertainty in the secondary-emission monitor (SEM) efficiency. Maximum uncertainty in the radiator thicknesses is 0.9%.

Error in the normalization factors $\epsilon n_v tz\gamma\Delta\Omega'$: 2.2% resulting from 1.5% kinematical uncertainty in the determination of the elastic scattering cross section, 1.5% counting statistics and uncertainty in measuring the areas of the elastic peaks, and 0.4% uncertainty in the SEM efficiency.

Counting statistics on the number of protons from photoproduction N_p vary from 2 to 5%.

B. Systematic Errors

The numbers we give here represent estimated maximum uncertainties. These errors may be classified into two categories according to their nature, i.e., those intrinsic to this experiment and those independent of this experiment.

1. Intrinsic Systematic Errors

The momentum calibration of the spectrometer is uncertain to $\pm 0.3\%$. Momentum uncertainty due to calculated energy loss is $\pm 0.15\%$. Uncertainty in the angular centering of the magnet acceptance relative to the mechanical center is $\pm 0.05°$.[8] Uncertainty in the mean proton angle due to imperfect knowledge of the acceptance function is $\pm 0.2°$ at $\phi_p=0°$ and less than $\pm 0.05°$ at other angles. Uncertainty in the beam energy is $\pm 0.5\%$. Uncertainty in the calculation of η is $\pm 0.1\%$.

2. Independent Systematic Errors

The calculation of the bremsstrahlung spectrum[12] is probably valid to $\pm 2\%$. Our calculation of the bremsstrahlung included small corrections ($\lesssim 10\%$) for thick-target effects and finite incident electron beam energy spread, but the error introduced by these corrections is considered negligible.

The systematic errors in the elastic scattering cross sections used to normalize the data are $\pm 2\%$. This is due to the differences between the values of the proton form factors found from the data of Dudelzak and coworkers[9] and those of Janssens *et al.*[9] The squared four-momentum transfers of interest here are less than 8 F^{-2}.

C. Quoted Errors

To demonstrate the internal consistency of our measurements, we defined a statistical error Δs, which includes only the counting statistics and SEM efficiencies for photoproduction and elastic scattering.

In order to compare our data with the results of other experimentalists and with theory, we quote errors Δm which result from the combination in quadrature of the statistical uncertainties Δs with all the other errors discussed above.

We also estimated the errors in k and θ^*. This was done by adding a standard deviation of random errors in p and ϕ to the corresponding maximum systematic error, and treating this sum as a standard deviation in calculating the errors in k and θ^*. The resulting uncertainty in k does not exceed $\pm 0.9\%$, and the un-

TABLE III. π^0 photoproduction experimental results and errors at $\theta^*=90°$.

k (MeV)	Δk (MeV)	θ^* (deg)	$\Delta^*\theta$ (deg)	p (MeV/c)	$d\sigma/d\Omega^*$ (μb/sr)	Δs (μb/sr)	Δm (μb/sr)	η
240.3	2.8	89.8	0.6	249.6	6.55	0.18	0.35	0.824
260.2	2.9	90.0	0.6	271.3	11.81	0.22	0.59	0.870
280.1	3.1	89.9	0.6	292.3	18.96	0.34	0.94	0.900
300.0	3.3	89.9	0.6	312.6	25.14	0.38	1.22	0.922
309.9	3.5	89.9	0.6	322.4	27.99	0.52	1.39	0.930
320.0	3.6	89.9	0.6	332.5	28.87	0.43	1.40	0.936
340.	4.0	89.9	0.6	351.7	26.28	0.40	1.28	0.949
359.9	4.4	89.9	0.6	370.5	22.09	0.30	1.07	0.957
365.7	4.5	90.6	0.6	378.3	20.18	0.36	1.01	0.960
376.3	4.7	90.7	0.6	389.0	18.10	0.27	0.89	0.964
384.8	4.9	91.0	0.6	397.4	15.89	0.31	0.80	0.967
399.2	5.2	89.9	0.6	406.4	13.84	0.23	0.69	0.969

TABLE IV. π^0 photoproduction experimental results and errors at $\theta^*=130°$.

k (MeV)	Δk (MeV)	θ^* (deg)	$\Delta\theta^*$ (deg)	p (MeV/c)	$d\sigma/d\Omega^*$ (μb/sr)	Δs (μb/sr)	Δm (μb/sr)	η
258.8	1.5	129.7	0.7	346.4	9.45	0.22	0.47	0.944
278.7	1.6	129.7	0.7	374.2	15.05	0.30	0.74	0.957
298.6	1.7	129.7	0.7	401.1	20.32	0.39	0.99	0.967
318.5	1.9	129.7	0.7	427.3	21.14	0.34	1.01	0.973
338.5	2.	129.7	0.7	452.9	19.46	0.33	0.95	0.978
358.5	2.2	129.7	0.7	478.0	14.76	0.28	0.74	0.982
378.5	2.3	129.7	0.7	502.7	11.53	0.23	0.58	0.985
398.6	2.5	129.7	0.7	527.0	8.83	0.20	0.46	0.987

certainty in θ^* is less than $\pm 0.32°$ except at $\theta^*=175°$, where it is $\pm 0.7°$.

VI. EXPERIMENTAL RESULTS

The results and associated errors are given in Tables II–V.

The new measurements at 175° are those for $220 \leqslant k \leqslant 300$ MeV. These values of the cross section are generally bigger than before,[2] the difference varying from a factor of ~ 1.5 for $k=220$ MeV to a factor of 1.02 for $k=300$ MeV. The correction (5) accounts for the difference between the new and old data. The remaining 175° data are those of Ref. 2.

Using the information in Tables II–V, the data may be renormalized to account for possible improvements in the knowledge of the bremsstrahlung spectrum and/or the proton form factors. Values of k and E would be used to calculate a new theory and the present theory[12] for the bremsstrahlung cross section for each point, and the quotient of original value divided by new value would be multiplied times the cross-section values. To minimize the relative errors, we took $k/E=0.8$ for $\theta^*=175°$ and $k/E=0.85$ for $\theta^* \neq 175°$.

Renormalization of the data to account for better determination of the proton form factors would be accomplished by calculating

$$G_{\mathrm{el}}=\frac{G_{Ep}^2+\tau G_{Mp}^2}{1+\tau}\cot^2(\tfrac{1}{2}\theta_e)+2\tau G_{Mp}^2, \qquad (6a)$$

where

$$\cot(\tfrac{1}{2}\theta_e)=\sin\phi/[\cos\phi-1/(1+1/\tau)^{1/2}], \qquad (6b)$$

both for the newer form factors and those used here.[9] In Eq. (6), $\tau=T/2M$ is the square of the four-momentum transfer, T is the proton KE, and ϕ is the recoil proton angle in the laboratory. The renormalized cross sections would be those given here multiplied by the corresponding ratios G_{el} (new)/G_{el} (Ref. 9).

VII. DISCUSSION

Figures 2–4 compare our data at $\theta^*=70°$, 90°, and 130° with other measurements. The error bars represent the errors Δm discussed above. For the Bonn data[1] we show errors of $\pm 4{,}5\%$, which are meant to include their estimated maximum systematic error ($\pm 4\%$) and their statistical errors (2%). For the other data shown we have taken the absolute errors given by each author.

Most of the data points are compatible when the errors are treated in this way. At 70° (Fig. 2) the Bonn results[1] are in good agreement with ours. The point of Oakley and Walker[13] at 360 MeV is low. At 90° (Fig. 3) the Bonn values are systematically 5–7% higher than ours, although the two sets of measurements are consistent considering the possible absolute errors. The values of Miller and Bellamy[14] and those of Oakley and Walker are smaller than—although consistent with—ours, but incompatible with the Bonn data at several energies. At $\theta^*=130°$ (Fig. 4) the data of Bonn are again systematically higher than ours, although only the values at $k=360$ MeV are incompatible. In Fig. 5

TABLE V. π^0 photoproduction experimental results and errors at $\theta^*=175°$. The spectrometer was set at $\phi_p=0°$. Because of the radial aperture of the entrance slits, the mean proton detection angle is different from 0°. For the experimental conditions, $\theta^*_{\mathrm{mean}}=175°$.

k (MeV)	Δk (MeV)	θ^* (deg)	$\Delta\theta^*$ (deg)	p (MeV/c)	$d\sigma/d\Omega^*$ (μb/sr)	Δs (μb/sr)	Δm (μb/sr)	η
220.6	5.1	175	2.2	319.9	3.07	0.08	0.15	0.83
240.5	4.2	175	2.2	353.6	4.60	0.10	0.22	0.88
260.4	3.6	175	2.2	385.7	6.50	0.12	0.31	0.91
280.4	3.3	175	2.1	416.9	8.38	0.10	0.38	0.93
300.	3.0	175	2.1	447.0	9.87	0.16	0.47	0.95
317.6	1.9	175	2.1	472.1	9.52	0.21	0.47	0.984
339.0	2.1	175	2.0	503.2	7.91	0.14	0.38	0.987
359.8	2.1	175	2.0	531.7	5.73	0.21	0.34	0.99
377.3	2.1	175	2.0	556.7	4.5	0.28	0.35	0.991

[13] D. C. Oakley and R. L. Walker, Phys. Rev. **97**, 1283 (1955).
[14] D. B. Miller and E. H. Bellamy, Proc. Phys. Soc. (London) **81**, 343 (1963).

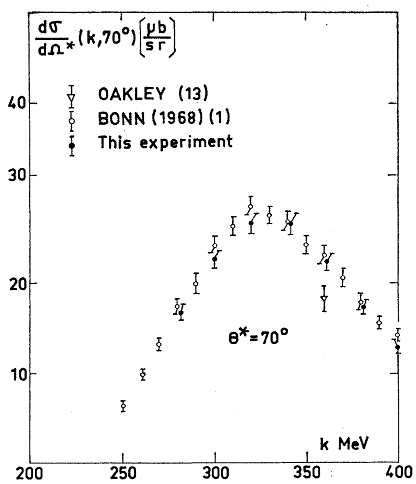

FIG. 2. Excitation curve at $\theta^*=70°$ for the photoproduction of neutral pions.

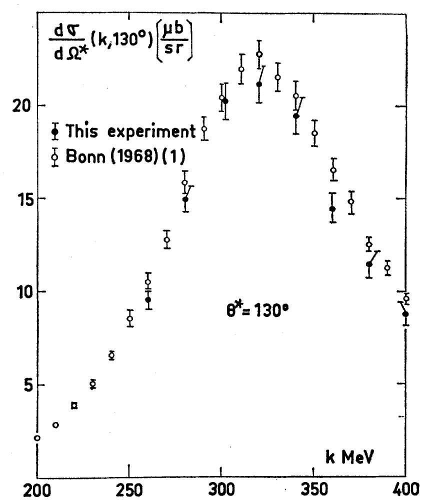

FIG. 4. Excitation curve at $\theta^*=130°$.

our 175° data are shown and compared to values extrapolated from the Bonn measurements. To do the extrapolation we assumed that the cross section could be described as a polynomial of second degree in $\cos\theta^*$, and fitted the Bonn values using their statistical errors (2%) and total errors (4 and 5%), respectively. The agreement with our data is typically better than 5%. This is comparable to the agreement found for $\theta^*\neq 175°$.

Our data alone—including the backward measurements and using only the relative error Δs—can also be consistently fitted by a polynomial of second degree in $\cos\theta^*$. Thus there is no experimental evidence for the necessity of terms in $\cos^3\theta^*$ and higher powers in fitting data. This observation rules out the argument[15] that a polynomial of the form $A+B\cos\theta^*+C\cos^2\theta^*$ would lead to errors greater than 10% for extrapolations to angles $\theta^*>140°$. The coefficients A, B, and C are tabulated in Table VI. These coefficients agree well with those calculated from the data of the Bonn magnet group. The agreement, especially for the coefficient B, with the measurements of the Bonn telescope group is less good.

Recent theoretical attempts to understand low-energy photoproduction have been made within the framework of fixed-t dispersion relations. A good summary has been given by Rollnik *et al.*[6]

Comparison of our data with the absolute theoretical predictions of Berends, Donnachie, and Weaver shows good agreement at $\theta^*=175°$, as seen in Fig. 6. However, this agreement deteriorates near $\theta^*=90°$ where their area of theoretical uncertainty (an estimated standard deviation) departs from the new experimental data (see Fig. 7). Indeed, the excitation curve at 90° (Fig. 8) shows that this theoretical prediction is shifted about 10 MeV toward higher energy relative to the experi-

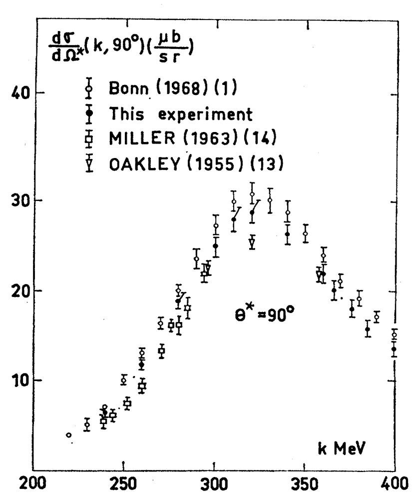

FIG. 3. Excitation curve at $\theta^*=90°$.

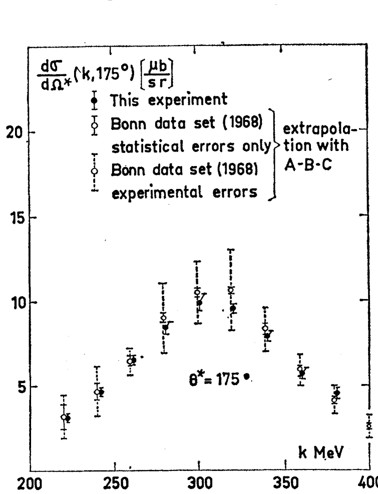

FIG. 5. Excitation curve at $\theta^*=175°$. See text for the definition of the real mean angle. The errors for the Bonn data are discussed in the text.

[15] D. Schwela, thesis, Universität, Bonn, 1968 (unpublished).

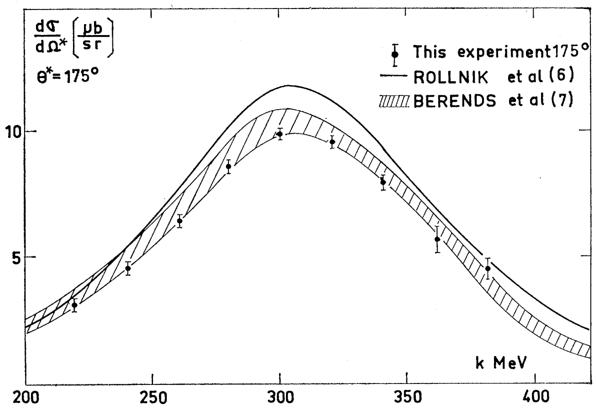

FIG. 6. Comparison between theoretical calculations by Rollnik *et al.* (Ref. 6) and Berends *et al.* (Ref. 7) at $\theta^*=180°$ and the experimental points.

mental data. A better fit might be obtained using their theory if more multipoles were included.

Engels, Müllensiefen, and Schmidt[5] try to understand photoproduction by varying parameters to fit the data. Having chosen parameters for a good fit at 90°, however, they predict an excitation curve at 180° which is displaced toward lower energies by some 10 MeV relative to the data. This feature of an energy shift in the predicted excitation curves at 90° and 180° relative to the data is thus common to the theories of Berends *et al.*[7] and Engels *et al.*,[5] and is firmly established by these new results.

It is more likely that the adjustable theory of Rollnik *et al.*[6] could be made to fit the data, since this approach seemed more flexible in fitting the Bonn data.[6,15] The same is true for the phenomenological fit made by Walker.[16] Unfortunately, all these fits have been made on the preliminary results published by the Bonn group.[17] These data are 3 or 4% higher than the definitive results now published[1]; this can explain a part of the disagreement between these fitted theories and the new experimental data from Bonn and Orsay (see Figs. 6 and 7). These new data are at present coherent within the experimental uncertainties, as can be seen in Figs. 2–5.

If the experimental situation has been somewhat improved by these data for $\theta^*>70°$, the theoretical situation has not. The satisfactory explanation of the data (at 90° and 175°) remains a challenge for the theoreti-

TABLE VI. Coefficients A, B, and C in the expansion $d\sigma/d\Omega = A+B\cos\theta^*+C\cos^2\theta^*$, are calculated from the results at $\theta^*=70°$, 90°, 130°, and 175°. The errors of A, B, and C are calculated from the errors Δm.

k (MeV)	A (μb/sr)	B (μb/sr)	C (μb/sr)
240	6.4±0.10	−1.2±0.50	−3.1±0.80
260	11.5±0.10	−1.7±0.70	−6.8±1.1
280	18.8±0.30	−1.2±1.9	−11.6±2.8
300	25.7±0.50	−2.0±3.3	−17.8±4.9
320	29.1±0.60	0.1±4.2	−19.4±5.9
340	27.3±0.50	1.9±3.8	−17.4±5.0
360	22.5±0.30	3.9±2.5	−12.9±3.1
380	17.5±0.20	2.5±1.5	−10.5±1.9
400	14.0±0.30	1.3±1.6	−10.1±9.2

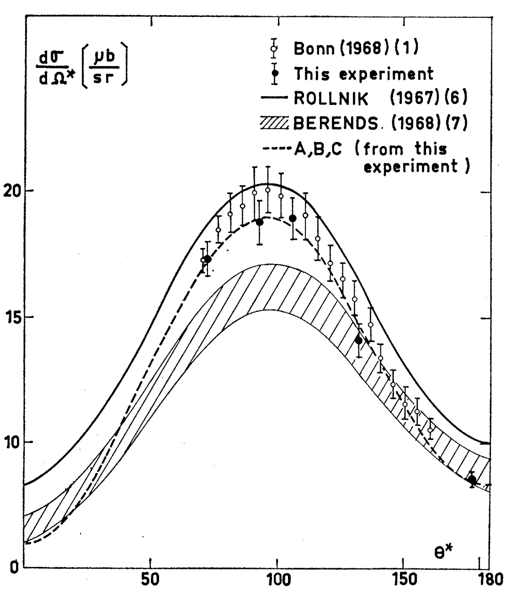

FIG. 7. Comparison of the angular distribution at $k=280$ MeV between the theoretical calculation by Rollnik (Ref. 6) and Berends *et al.* (Ref. 7) and the experimental points of this experiment and the Bonn data (Ref. 1).

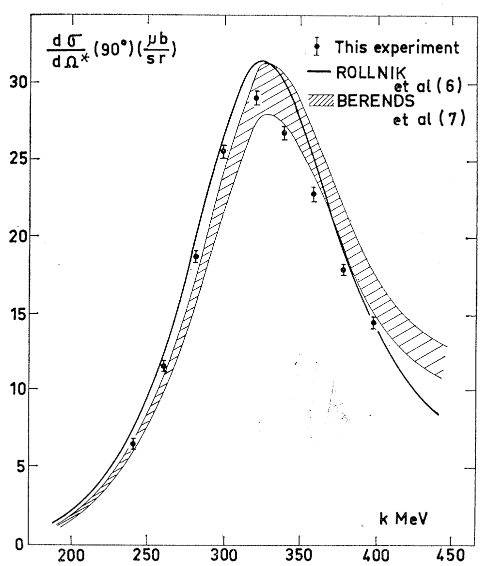

FIG. 8. Comparison between theoretical calculation by Rollnik *et al.* (Ref. 6) and Berends (Ref. 7) and experimental results at $\theta^*=90°$.

[16] R. L. Walker, California Institute of Technology Report No. Cal T. 68. 158 (to be published).

[17] G. Fischer, H. Fischer, H. J. Kämpgen, G. Knop, P. Schulz, and H. Wessels, in *Proceedings of the Thirteenth Annual International Conference on High-Energy Physics, Berkeley, 1966* (University of California Press, Berkeley, 1967).

cian. The experimental situation has also to be improved for $\theta^* < 70°$.

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Lifetimes of Light Hyperfragments. II*

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We have continued our studies of the lifetimes of light hyperfragments. Our analysis is based on a total sample of 1476 mesonic decays of hyperfragments, of which 77 decayed in flight. The values we found for the mean lives are the following: $\tau({}_\Lambda H^3) = (2.85_{-1.05}^{+1.27}) \times 10^{-10}$ sec, using both two-body and three-body decays; $\tau({}_\Lambda H^4) = (2.68_{-1.07}^{+1.66}) \times 10^{-10}$ sec, using only three-body decays; $\tau({}_\Lambda He^4) = (2.28_{-1.29}^{+2.33}) \times 10^{-10}$ sec; $\tau({}_\Lambda He^5) = (2.51_{-0.73}^{+1.90}) \times 10^{-10}$ sec; and $\tau({}_\Lambda He^{4,5}) = (2.43_{-0.43}^{+0.60}) \times 10^{-10}$ sec for the combined mean life of all the ${}_\Lambda He^4$ and ${}_\Lambda He^5$ events. The last lifetime quoted contains only a statistical error. The others, in addition, contain in their errors the effects due to uncertainties in our knowledge of the bias for two-body events and of the separation of ambiguous three-body events. All the results are in good agreement with theoretical calculations of hyperfragment lifetimes.

I. INTRODUCTION

THE data presented in this paper represent the continuation of a program to determine the lifetimes of light hyperfragments in nuclear emulsion by observing their mesonic decays, both at rest and in flight. Earlier results on ${}_\Lambda H^3$, ${}_\Lambda H^4$, ${}_\Lambda He^4$, and ${}_\Lambda He^5$ were reported in 1965 in a paper[1] which we shall hereafter refer to as I. The status of experimental and theoretical work on hyperfragment lifetimes was also reviewed in that paper. At that time, the only serious discrepancy which existed between theoretical and experimental values concerned the lifetime of ${}_\Lambda H^3$. Recently, there have been reported two new measurements of the lifetime of ${}_\Lambda H^3$, one by Keyes *et al.*[2] and one by the present authors,[3] which appear to have reconciled this discrepancy.

The new data reported here were obtained from a stack of nuclear emulsions exposed to a 1.1-GeV/c K^- beam at the Bevatron. We obtained a total of 1218 π^--mesonic decays in this stack, of which 59 were in flight. We combined these with the 258 mesonic decays reported in I, of which 18 were in flight, making a total sample of 1476 mesonic decays (77 in flight) on which we based our analysis. Although the results concerning ${}_\Lambda H^3$ have already been reported in Ref. 3, we also include them here in greater detail, with some refinements in the calculations and amplification of the discussion.

* Supported by the U. S. Atomic Energy Commission.
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[1] Y. W. Kang, N. Kwak, J. Schneps, and P. A. Smith, Phys. Rev. **139**, B401 (1965).
[2] G. Keyes, M. Derrick, T. Fields, L. G. Hyman, J. G. Fetkovich, J. McKenzie, B. Riley, and I. T. Wang, Phys. Rev. Letters **20**, 819 (1968).
[3] R. E. Phillips and J. Schneps, Phys. Rev. Letters **20**, 1383 (1968).

II. EXPERIMENTAL PROCEDURE

A. Exposure and Processing

A stack of 160 Ilford $K5$ nuclear emulsion pellicles, each 6×8 in. and of 600-μ thickness, was exposed to a 1.1-GeV/c K^- beam from the Bevatron. Approximately 3×10^6 K^- mesons were incident on the central portion of the stack, covering about 30 pellicles. The rest of the stack served to bring energetic decay particles to rest so that they could be followed to the end of their range.

After exposure, each pellicle was cut in half for ease of handling. A coordinate grid was then lightly printed on the surface of each half pellicle for the purpose of locating events. The pellicles were then mounted on glass plates and processed according to standard procedures.[4]

B. Scanning

The scanning procedure was the same as that used in I. That is, the plates were area-scanned under low magnification (100×) for stars produced by an incident K^- meson. Each grey or dark track leading from such a star was followed until it ended or left the pellicle. Any secondary star found was examined under high magnification (1000×) in order to reveal a possible light meson track which may have been missed under low power. In addition, all apparent scatterings were ex-

[4] W. H. Barkas, *Nuclear Research Emulsions* (Academic Press Inc., New York, 1963).