PHYSICAL REVIEW D VOLUME 9, NUMBER 3 1 FEBRUARY 1974

π^0 and ρ^0 photoproduction from 6 to 18 GeV†

B. Barish, R. Gomez, D. Kreinick,* C. Peck, J. Pine, F. Sciulli,
B. Sherwood,‡ A. Tollestrup, and K. Young§
California Institute of Technology, Pasadena, California 91109

(Received 28 April 1972)

Differential cross sections for π^0 and ρ^0 photoproduction from protons have been measured at photon energies 6, 12, and 18 GeV and momentum transfers 0.5 to 3 $(\mathrm{GeV}/c)^2$.

INTRODUCTION

In this article we report the results of an experiment to measure the differential cross sections for the reactions $\gamma p \to \pi^0 p$ and $\gamma p \to \rho^0 p$ for 6-, 12-, and 18-GeV incident photon energies and for momentum transfers $-t$ to the proton between 0.5 and 3 $(\mathrm{GeV}/c)^2$.

High-energy π^0 photoproduction had been previously measured out to $-t = 1.5$ $(\mathrm{GeV}/c)^2$; the differential cross section shows a dip at $-t = 0.5$ $(\mathrm{GeV}/c)^2$, followed by a shoulder at $-t = 0.8$ $(\mathrm{GeV}/c)^2$.[1] Photoproduction of ρ^0 appears to be diffractive, with the slope parameter $A\,(d\sigma/dt \propto e^{At})$ varying smoothly from 8 $(\mathrm{GeV}/c)^{-2}$ for small $|t|$ $[< 0.6$ $(\mathrm{GeV}/c)^2]$ to ~ 6.5 $(\mathrm{GeV}/c)^{-2}$ for larger $|t|$ $[0.6\text{–}1.5$ $(\mathrm{GeV}/c)^2]$.[2]

The experimental technique used was that of detecting the recoil-proton yield at fixed momentum p as a function of production angle θ for a bremsstrahlung beam incident on a hydrogen target. A typical yield curve is shown in Fig. 1, where the yield is plotted as a function of the convenient parameter

$$\mu^2 = 2E_0 p \cos\theta + t(E_0 + M)/M,$$

which is the missing mass squared assuming that the incident photon has the bremsstrahlung endpoint energy E_0. By fitting this yield, as described later, the π^0 and ρ^0 cross sections were obtained. The observed yields for negative μ^2 are kinematically forbidden for single scatters from protons, (see, e.g., Refs. 1 and 2) (these ghost protons are usually observed in experiments in which only the recoil proton is detected). By careful design of the target and collimators the yield of these protons was decreased to the level where their rates are explained by double scattering within the target.

The experimental technique and data reduction will be discussed in more detail later in the paper.

π^0 CROSS SECTIONS

In this experiment, as in all experiments where only the recoil proton is detected, the mass resolution is insufficient to separate the contribution to the proton yields from Compton scattering and single-π^0 production; therefore this experiment measures only the *sum* of these cross sections. Recently published data on Compton scattering by Anderson *et al.*[3] were used to obtain our π^0 cross sections. However, due to uncertainty in the relative normalization of the two experiments, before subtracting the Compton cross sections we have arbitrarily renormalized our raw π^0+Compton data upwards by 20% so that for small t this sum agrees with that of Anderson *et al.*[4] We stress that we do this only because we need to use the Compton data of Anderson *et al.*, and because the Compton subtraction has a negligible effect for the large-t data, where this experiment makes a new contribution. We quote here only those cross sections where the Compton subtraction is less than 20% of the π^0 cross section. Both sets of π^0 photoproduction data are shown in Fig. 2, and our values are listed in Table I. Our corrected data are also in agreement with the 5.8-GeV data of Braunschweig *et al.*[1]

Owing to the large Compton background, we were unable to determine the π^0 cross section in the region of the dip: $-t \approx 0.5$ $(\mathrm{GeV}/c)^2$. The most important feature of the new data, which is independent of both the subtraction and normalization uncertainties, is the fast dropoff in these cross sections beyond $-t = 1.1$ $(\mathrm{GeV}/c)^2$. This imposes severe restrictions on any model for this process. For example, models that account for the dip at $-t = 0.5$ $(\mathrm{GeV}/c)^2$ by means of a "nonsense wrong-signature zero" and fill in this dip to its observed value by means of absorptive cuts have difficulties simultaneously reproducing the broad bump at $-t = 0.8$ $(\mathrm{GeV}/c)^2$ and the dropoff beyond $-t = 1.1$ $(\mathrm{GeV}/c)^2$. Furthermore, we were unable to fit the data with the model of Ball *et al.*,[5] who used a pair of complex poles to approximate the cut contributions. Kane *et al.*[6] have recently published a fit to single-π photoproduction where exchanges without "zeros" are assumed and where the dip is a result of interfering cuts associated with the exchanged poles. Their fits give a good description of our data and are

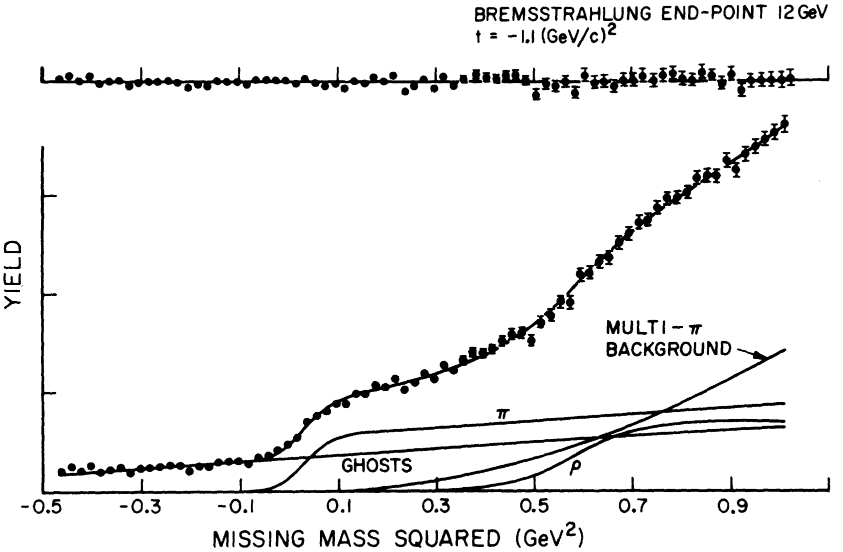

FIG. 1. Recoil proton yield as a function of the square of the missing mass, μ^2. Upper plot shows deviation from fit.

shown in Fig. 2 by the solid lines.

Our π^0 also confirms the general behavior of the cross section as measured by Anderson *et al.*[3] This confirmation is significant because our ghost background was as much as five times smaller than theirs.

ρ^0 CROSS SECTIONS

Figure 3 shows the ρ^0 cross sections together with data of Jones *et al.*[2], and our measurements are listed in Table II. Owing to the very large multipion background and the small cross section, the measurements extend only to $-t = 2$ (GeV/c)^2 and only upper limits were obtained for larger values of $|t|$. Also, since the ω and ρ were not resolved, no attempt was made to independently determine the ω cross section. We assume the SU(3) value of 1:9 for the ratio of diffractive ω to ρ photoproduction. This same assumption was made in previous measurements of ρ^0 photoproduction.[2]

Our data are consistent with no shrinking of the diffraction peak in ρ^0 photoproduction and show no major break in the slope vs t.

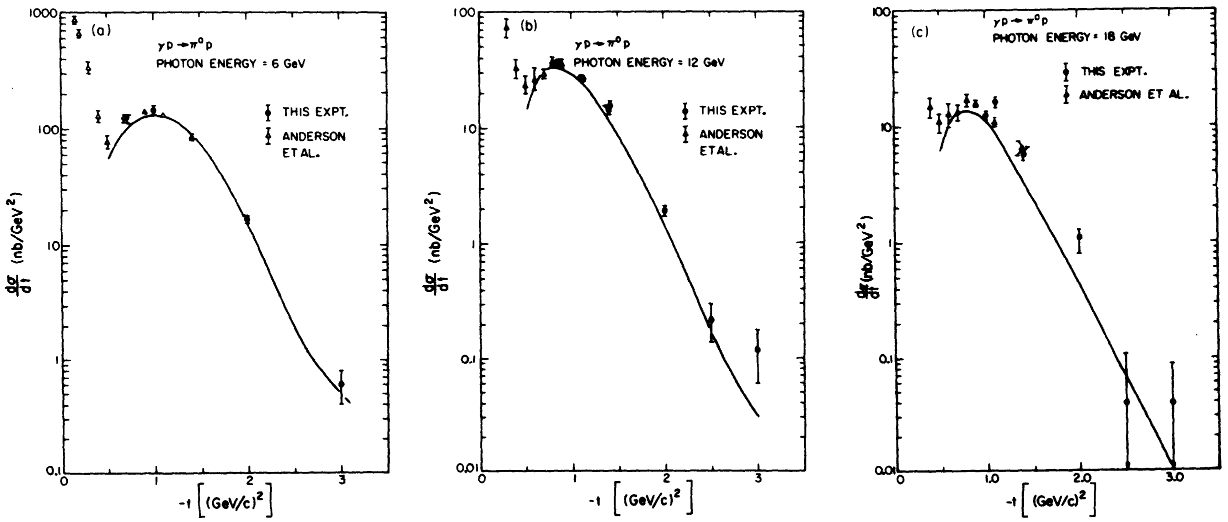

FIG. 2. Differential cross sections for $\gamma p \to \pi^0 p$ at (a) 6 GeV, (b) 12 GeV, and (c) 18 GeV photon energy. In (c) the results of Anderson *et al.* (Ref. 3) have been extrapolated from 15 GeV. The lines are the fits of Kane *et al.* (Ref. 6).

TABLE I. $d\sigma/dt$ for $\gamma p \to \pi^0 p$ in nb/GeV^2. In each case, the first column is the sum $d\sigma/dt(\gamma p \to \pi^0 p) + d\sigma/dt(\gamma p \to \gamma p)$, which is directly measured. The second column gives $d\sigma/dt(\gamma p \to \pi^0 p)$, obtained by scaling up the sum by 20% and then subtracting the Compton cross section, as described in text.

	E_γ					
$-t$ (GeV^2)	6 GeV		12 GeV		18 GeV	
0.7	120 ±10	121 ±10				
0.85			35 ±2	37 ±2		
1.0	123 ±9	146 ±9			12 ±1	12±1
1.1			23 ±1	27 ±1	14.5±1	16±2
1.4			12 ±1	14 ±1	5 ±1	6±1
2.0	13.5±1	16 ±1	1.7 ±0.2	1.9 ±0.2	1 ±0.2	1±0.2
2.5			0.18±0.07	0.22±0.08	<0.1	<0.1
3.0	0.5±0.2	0.6±0.2	0.10±0.05	0.12±0.06	<0.1	<0.1

EXPERIMENTAL METHOD

A collimated bremsstrahlung beam from the SLAC linear accelerator was passed through an 18-in.-long liquid-hydrogen target. The recoil protons were detected with the SLAC 8-GeV/c magnetic spectrometer. The spectrometer's complete detection system has been described previously.[7] In this experiment, we used only the momentum and angle (θ) hodoscopes, the two sets of trigger counters, and an additional counter to measure the trigger efficiency.

Protons were separated from π^+ mesons by means of their time-of-flight difference. For this purpose the linac beam was chopped using SLAC's BKO (Beam Knock-Out) system. Typical beam pulse length was 1 ns with a period of 12.5 ns or 25 ns. The BKO provided a reference signal and the two sets of trigger counters gave the particle time of arrival. The time difference between these signals was the target-to-counters time of flight to within an integral number of beam pulse periods.

The beam was monitored with a secondary emission quantameter and supplementarily checked with a Čerenkov monitor. The secondary emission quantameter was periodically calibrated against a silver calorimeter to provide an absolute standard.

For a given bremsstrahlung end-point energy and momentum transfer, data were accumulated over 10 to 15 runs with different angle settings of the spectrometer so as to cover a μ^2 range from -0.5 to 1.0 (GeV/c)^2. The angle settings were

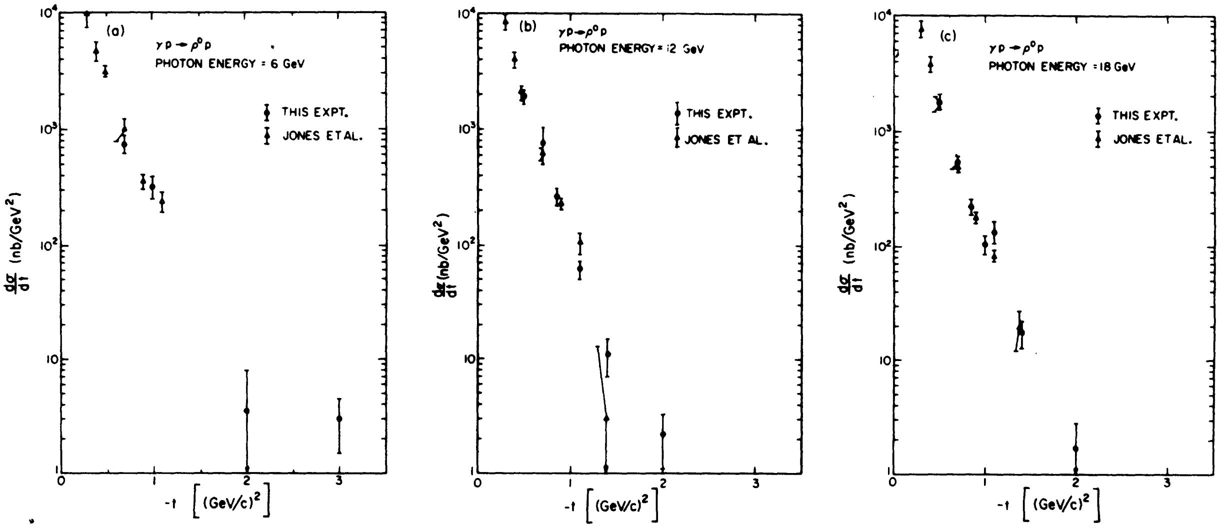

FIG. 3. Differential cross sections for $\gamma p \to \rho^0 p$ at (a) 6 GeV, (b) 12 GeV, and (c) 18 GeV photon energy (data of Jones *et al.* from Ref. 2).

TABLE II. $d\sigma/dt$ for $\gamma p \rightarrow \rho^0 p$ in μb/GeV^2.

$-t$ (GeV^2)	E_γ 6 GeV	12 GeV	18 GeV
0.5		1.9 ± 0.3	1.7 ± 0.3
0.7	0.75 ± 0.13	0.8 ± 0.3	0.5 ± 0.3
0.85		0.27 ± 0.05	0.23 ± 0.03
1.0	0.32 ± 0.07		0.11 ± 0.02
1.1		$(62 \pm 12) \times 10^{-3}$	$(135 \pm 30) \times 10^{-3}$
1.4		$(11 \pm 4) \times 10^{-3}$	$(18 \pm 5) \times 10^{-3}$
2.0	$<8 \times 10^{-3}$	$(2 \pm 1) \times 10^{-3}$	$(2 \pm 1) \times 10^{-1}$
2.5		$<0.4 \times 10^{-3}$	$<0.5 \times 10^{-3}$
3.0	$(3.0 \pm 1.5) \times 10^{-3}$	$<0.8 \times 10^{-3}$	$<0.2 \times 10^{-3}$

chosen so that the acceptance of the spectrometer would overlap by at least 50% that of the adjacent settings, thus minimizing the effect of uncertainties in the detail knowledge of the spectrometer acceptance. Typically, the resolution in μ^2 was 0.03 (GeV/c)^2. This was primarily due to the photon beam size and the multiple scattering of the recoil protons.

DATA REDUCTION

Events recorded by the computer with unambiguous counts in the momentum and angle hodoscopes and flight times appropriate for protons were accepted. For a set of runs with the same E_0 and t, μ^2 was calculated for each event from the momentum and angle measurements and histogrammed. Also, for each run a weight was calculated for every μ^2 bin from the spectrometer acceptance, the effective target length, and the number of equivalent quanta, and each bin weight was summed over all runs in the set. The ratio of the number of counts in a μ^2 bin to its total weight gave the yield, $Y(\mu^2)$.

The yield was fitted to the functional form

$$Y(\mu^2)=A_\pi Y_\pi(\mu^2)+A_\rho Y_\rho(\mu^2)+Y_{\pi\pi}(\mu^2)+Y_g(\mu^2),$$

where Y_π, Y_ρ, $Y_{\pi\pi}$, and Y_g represent proton yields associated with pion production plus Compton effect, ρ plus ω mesons, multipions, and ghosts, respectively. The functions Y_π and Y_ρ are normalized to $d\sigma/dt=1$ at the bremsstrahlung end-point energy. With this definition, A_π and A_ρ are differential cross sections.

The calculation of Y_π and Y_ρ included the effects of slowly varying kinematical parameters, the detailed shape of the bremsstrahlung spectrum, and the finite μ^2 resolution. In the calculation of Y_π, the variation of $d\sigma/dt$ with photon energy has been included. In the case of Y_ρ, the ρ shape, $P(m^2)$ was assumed to be of the form suggested by Selleri[8]:

$$P(m^2)dm^2 \propto \frac{\Gamma(m)}{(m^2-m_\rho{}^2)^2+m_\rho{}^2\Gamma(m)}\,dm^2,$$

where

$$\Gamma(m)=\Gamma_0\left(\frac{q}{q_0}\right)^3 \frac{2}{1+(q/q_0)^2},$$

with

$$q^2=(\tfrac{1}{2}m)^2-m_\pi{}^2, \text{ and } q_0{}^2=(\tfrac{1}{2}m_\rho)^2-m_\pi{}^2.$$

The values $m_\rho=765$ MeV, $\Gamma_0=125$ MeV were used in the final fitting. However, varying m_ρ and Γ_0 by up to 20 MeV or even using a simple Breit-Wigner form gave equally acceptable fits, and these shape variations caused 10–15% fluctuations in A_ρ. This uncertainty is included in the errors quoted. For Y_g we used the linear form $(b_0+b_1\mu^2)$, and for $Y_{\pi\pi}$ the quadratic form

$$c_1(\mu^2-4m_\pi{}^2)+c_2(\mu^2-4m_\pi{}^2)^2 \text{ for } \mu^2>4m_\pi{}^2.$$

Thus we have a six-parameter fit to about 100 data points. χ^2 per degree of freedon was typically 1 and never exceeded 1.5. Figure 1 shows a typical fit; the difference between the data points and the fit is also shown.

Cross sections have been corrected for counter inefficiency (1–3%), nuclear absorption in the counters (1%), loss of photon beam in the target due to pair production (3%), and inefficiency introduced by data selection in time of flight (2–4%) and in demanding correlation between trigger-counter and a hodoscope (1%).

ACKNOWLEDGMENTS

We wish to thank the members of SLAC group F, in particular R. Anderson, J. Johnson, and B. Wiik, for having always kept us informed of their results. We are grateful to the SLAC staff and operating crew. We acknowledge the contributions to various aspects of the experiment by R. Miller, L. Cottrel, D. Coward, S. Loken, A. Golde, and E. Taylor. We thank R. Worden and G. Fox for providing the various theoretical fits to our data.

---

*Now at University of Pennsylvania, Philadelphia, Pennsylvania 19104.

†Work supported in part by the U. S. Atomic Energy Commission. Prepared under Contract No. AT(11-1)-68 for the San Francisco Operations Office, U. S. Atomic Energy Commission.

‡Now at the University of Illinois, Urbana, Illinois 61801.

§Now at United College, Chinese University of Hong

Kong, Shatin, Hong Kong.

[1] M. Braunschweig, W. Braunschweig, D. Husmann, K. Lübelsmeyer, and D. Schmitz, Phys. Lett. 26B, 405 (1968).

[2] W. G. Jones, D. Kreinick, R. Anderson, D. Gustavson, J. Johnson, D. Ritson, F. Murphy, M. Gettner, and R. Weinstein, Phys. Rev. Lett. 21, 586 (1968).

[3] R. Anderson, D. Gustavson, J. Johnson, I. Overman, D. Ritson, B. Wiik, R. Talman, J. Walker, and D. Worcester, Phys. Rev. Lett. 25, 1218 (1970); R. Anderson, D. Gustavson, J. Johnson, D. M. Ritson, W. G. Jones, D. Kreinick, F. Murphy, and R. Weinstein, *ibid.* 21, 384 (1968); R. Anderson, D. Gustavson, J. Johnson, I. Overman, D. Ritson, B. Wiik, and D. Worcester, Phys. Rev. D 4, 1937 (1971).

[4] The Compton subtraction was performed in the following manner. Since the π^0 and Compton data of Anderson *et al.* (Ref. 3) were obtained using the same proton spectrometers, we assumed that the relative normalization of these experiments was correct. By comparing our raw (π^0 + Compton) data with those of Anderson *et al.* (Ref. 3), we found that our results had to be renormalized upwards by 20% so as to agree with their measurements. We have been unable to find the source of this discrepancy. After this renormalization we performed the subtraction using the measured points by Anderson *et al.*, or by extrapolating their data both on t and photon energy (for the 18-GeV points). As stated in the text, no points where the subtraction was larger than 20% were presented. In the region where this experiment makes a new contribution [$-t > 1.4$ $(\text{GeV}/c)^2$], the subtraction never amounted to more than a few percent.

[5] J. S. Ball, G. Marchesini, and F. Zachariasen, Phys. Lett. 31B, 583 (1970).

[6] G. L. Kane, F. Henyey, D. R. Richards, Marc Ross, and G. Williamson, Phys. Rev. Lett. 25, 1519 (1970).

[7] R. E. Taylor, in *Proceedings of the Third International Symposium on Electron and Photon Interactions at High Energies, Stanford Linear Accelerator Center, Stanford, California, 1967* (Clearing House of Federal Scientific and Technical Information, Washington, D. C., 1968); P. Kirk *et al.*, Phys. Rev. D 8, 63 (1973).

[8] F. Selleri, Phys. Lett. 3, 76 (1962).

PHYSICAL REVIEW D VOLUME 9, NUMBER 3 1 FEBRUARY 1974

Inelastic cross sections of *K* mesons in carbon and copper at 2.95 GeV/*c*

P. Allen, W. A. W. Mehlhop, P. Bowles, F. Marcelja, O. Piccioni,
R. W. Garland, D. Scipione, J. M. Marraffino, S. S. Murty, and W. Wheaton
University of California at San Diego, La Jolla, California 92037

(Received 4 September 1973)

The reaction cross sections for K^+ and K^- mesons in carbon and copper have been measured, at a momentum of 2.95 GeV/c, with an optical spark-chamber apparatus. In order to minimize instrumental biases, every incoming kaon triggered the system, regardless of whether or not an interaction occurred. For (K^+C), (K^-C), (K^+Cu), and (K^-Cu) we obtained, respectively, (163.2 ± 4.2), (198.6 ± 5.3), (633 ± 16), and (762 ± 23), in units of millibarns.

I. INTRODUCTION

The study of the interaction of high-energy particles with nuclei has an intrinsic interest apart from the practical consequence of furnishing numbers which are of use for other experiments, because, though the gross features of the interactions with nuclei are simply dictated by the data on the interactions with nucleons, accurate theoretical analysis of adequate experiments on nuclear parameters might still furnish important new information. In connection with our interest in the amplitude and phase of the regeneration for nuclei (Mehlhop *et al.*[1]), we undertook a study of the interactions of charged kaons of both signs with the nuclei of carbon and copper.

The experiment was done in the unseparated G-10, 4.7° beam of the AGS at Brookhaven National Laboratory, with the apparatus shown in Fig. 1. The beam of 2×10^5 particles per pulse was focused between Chamber 5 and Chamber 6, on a spot of about 2.4 cm × 1.7 cm (FWHM). The momentum was 2.95 ± 1.9% (HWHM) GeV/c. K mesons were selected electronically by means of a differential gas Čerenkov counter, operated with CO_2 at a pressure of about 500 psi. By varying the gas pressure we determined that the contamination in our beam of particles heavier than kaons was negligible, while the fraction of particles lighter than kaons was 0.89% and 0.65% for the K^+ and K^- beams, respectively. Each chamber had four sections of 0.5-in. width made of 1-mil aluminum foils. The chambers were triggered by an incoming kaon ($S_1 \cdot S_2 \cdot \bar{C}$). A total