PHOTOPRODUCTION OF NEGATIVE AND POSITIVE PIONS FROM CARBON AT FORWARD ANGLES*

W. A. Blanpied, J. S. Greenberg, V. W. Hughes, D. C. Lu, and R. C. Minehart
Yale University, New Haven, Connecticut
(Received 30 September 1963)

The use of a "peripheral collision model" by Drell[1] in an investigation of the photoproduction of high-energy pions predicts a substantial enhancement of the differential cross section in the forward angular cone $\theta_{1/2} \lesssim m_\pi/\omega$. A check on the validity of this "pole analysis" is of some interest theoretically, as is the practical application of its predictions in the production of collimated high-energy secondary beams by electron machines. Measurements[2] performed at a photon energy of 1.23 BeV agree qualitatively with the Drell model, although the absolute cross sections are, in general, considerably higher than those predicted on the basis that the pole term is the sole contributor. It is anticipated that at higher energies the pole term would more completely dominate the cross section for forward angles.[1] This Letter reports on some preliminary results from measurements performed on the photoproduction of positive and negative pions on carbon using the nominally 3-, 4-, and 5-BeV bremsstrahlung beams from the Cambridge Electron Accelerator.

The process studied can be represented in Drell's[1] notation as

$$\gamma + \mathrm{C} \rightarrow \pi^{\mp} + (n), \tag{1}$$

where $\pi^{\mp}$ is the single pion detected, and (n) denotes all possible final states of two or more particles. Considering only the contribution from the one-pion exchange amplitude, the differential cross section for the photoproduction of charged pions with an energy $\omega \sim k$ at forward angles θ along with all final states (n) is given by

$$\frac{d^2\sigma_{\pm}}{d\Omega d\omega} = \frac{\alpha}{8\pi^2}\frac{\sin^2\theta}{(1-\beta\cos\theta)^2}\frac{\omega(k-\omega)}{k^3}\sigma_{\pi^{\mp}+\mathrm{C}}(k-\omega). \tag{2}$$

$\sigma_{\pi^{\mp}+\mathrm{C}}(k-\omega)$ is the experimentally determined charged π-carbon total cross section evaluated at an energy of $(k-\omega)$. Its use here assumes that the pion-nucleon vertex can be treated by considering that the intermediate pion is on the mass shell. Both this approximation and the emphasis on one-pion exchange will be favored by small four-momentum transfers at the nuclear vertex, and best agreement with experiment is expected under these conditions. Other characteristics of this process are the sharp forward peaking of the angular distribution, which is given by $\theta^2/[1+\theta^2(m_\pi/\omega)^{-2}]^2$, and the strongly peaked energy dependence produced by the 3-3 resonance in the π-carbon cross section.

Measurements are reported here for a laboratory production angle of $2.70^{+0.15}_{-0.05}$ deg. The mean solid angle was 1.63×10^{-4} steradian. Bremsstrahlung beams with maximum energies of 2.91, 3.88, and 4.85 BeV were used, and the laboratory momenta selected for the photoproduced pions and positrons ranged from 1.22 to 2.60 BeV/c. Positrons at each chosen momentum were measured simultaneously with the charged pions.

A momentum and velocity analysis system, consisting of magnets, a differential gas Cherenkov counter, and scintillation counters, was used to identify unambiguously electrons, muons, and pions. Figure 1 illustrates the response of the

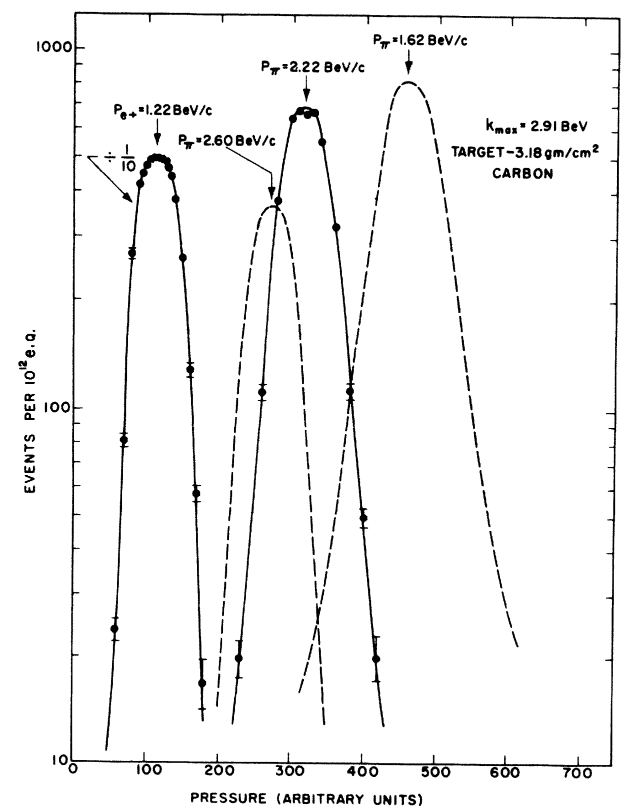

FIG. 1. Representative Cherenkov counter pressure curves for positive pions and positrons. Data points for $P_\pi = 2.60$ and 1.62 BeV/c are omitted for clarity. Maximum energy of the bremsstrahlung spectrum was 2.91 BeV.

Cherenkov counter to positrons and pions of various momenta selected by the magnet and scintillation counter system. Target-independent backgrounds have been subtracted. For pions they were never greater than 2%, and for positrons approximately 10%. These data were corrected for target-dependent backgrounds, loss of pions because of decay in flight, absorption by components in the counter system, and secondary inscattering effects. The photon beam was integrated by a Quantameter whose absolute calibration is presently known to 10%. Reproducibility was checked several times during the data-taking period.

The data for positive pion production are summarized in Figs. 2(a) and 2(b). The error bars represent statistical counting errors only. The theoretically expected rates were calculated by integrating the Drell equation for pions [Eq. (2)] over the Schiff bremsstrahlung distribution.[3] Pion-carbon total cross-section data used in Eq. (2) were obtained from the literature to 1.4 BeV,[4] and calculated from pion-nucleon cross-section data above this energy.[5] The dashed line in Fig. 2(a) shows the results of this integration for a maximum photon energy of 2.91 BeV.

The relative behavior of the measured cross sections as a function of the pion momentum agrees reasonably well with the prediction of Eq. (2). Absolute normalization of the data is presently uncertain because of incomplete information on the bremsstrahlung spectrum used. Other systematic errors are presently estimated to be approximately 15%. If the Schiff distribution is assumed, these preliminary data indicate that the experimental cross sections are larger by a factor of 1.2 to 2.5 than those calculated by assuming that the pole term is the sole contributor to the cross section at forward angles. Agreement is best for pion momenta approaching the maximum energy of the bremsstrahlung spectrum. In Fig. 2(b), the deviations from the expected theoretical rates have been plotted as a function of the average four-momentum transfer after a "synchrotron subtraction" for the 3.88- and 2.91-BeV data, suitably normalized, had been performed to limit the range of the four-

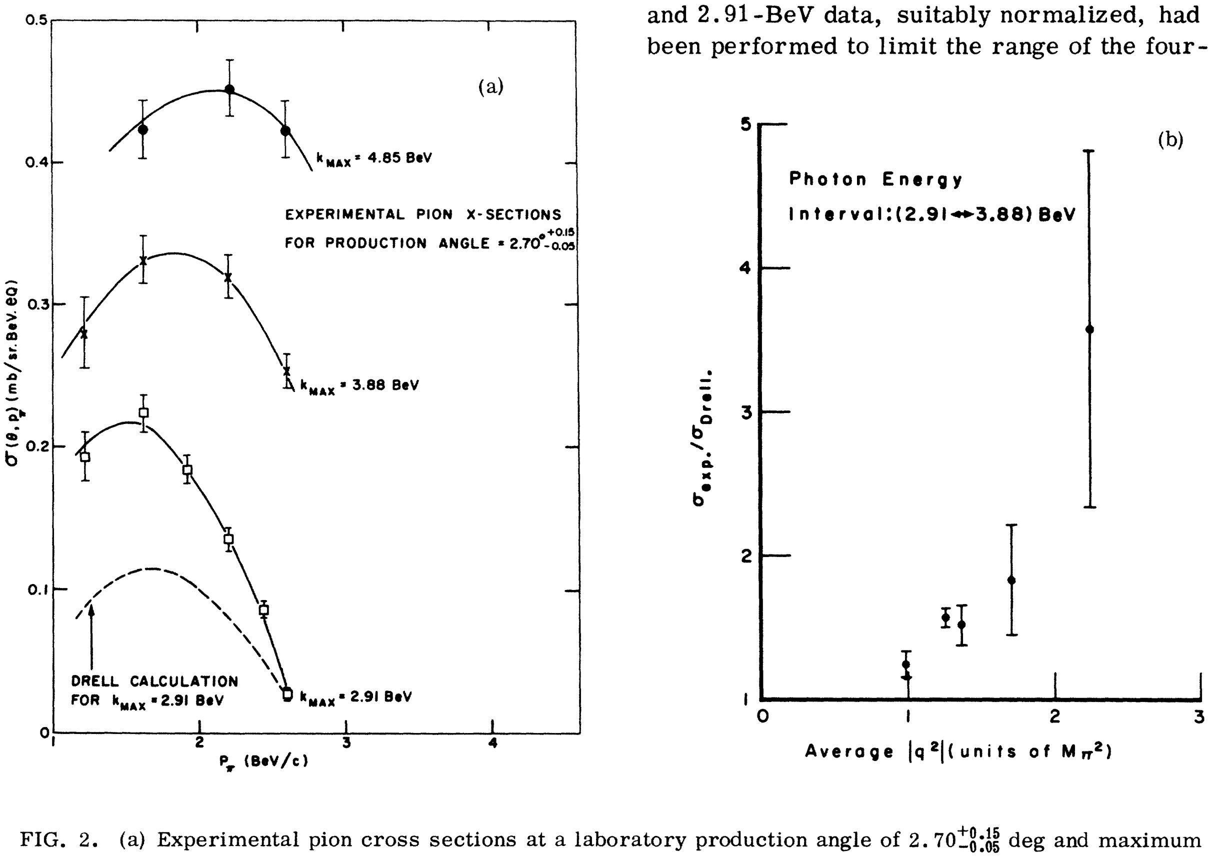

FIG. 2. (a) Experimental pion cross sections at a laboratory production angle of $2.70^{+0.15}_{-0.05}$ deg and maximum bremsstrahlung photon energies of 2.91, 3.88, and 4.85 BeV. The theoretical curve for $k_{max} = 2.91$ BeV was obtained by integrating Eq. (2) over a Schiff (see reference 3) bremsstrahlung distribution. (b) Measured deviations from the predictions of the integrated Drell equation as a function of the four-momentum transfer, after a "synchrotron subtraction" had been performed for the $k_{max} = 3.88$- and 2.91-BeV data.

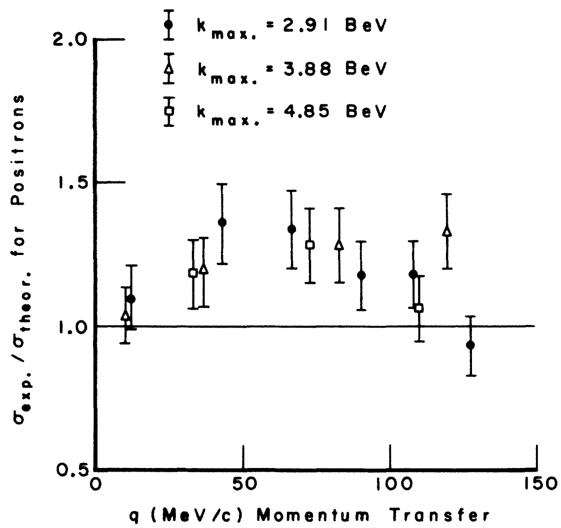

FIG. 3. Deviations from theoretical predictions for positron production (calculated as outlined in text) plotted as a function of three-momentum transfer.

momentum transfers. Agreement with theory is approached for small momentum transfers as would be expected from the initial assumptions of the calculations. The negative pion production data that were obtained show that the yields for negative and positive pions are essentially equal within the accuracy of the experiment.

The positron production rates may be used as a check on the normalization of the pion data by assuming that the cross section for pair production is given by the Bethe-Heitler equation. Figure 3 summarizes the positron data. The deviations from the theoretically predicted rates[6] are plotted as a function of the three-momentum transfer to the nucleus. Not included in this comparison are the contributions from elastic and inelastic secondary in-scattering in the target of the large number of small-angle produced positrons, and the contributions from multiple in-scattering. Also to be considered are the uncertainties in the treatment of the form factor, and the possible contributions from diagrams other than Bethe-Heitler. The net effect of these contributions would decrease the ratio plotted in Fig. 3. Although these corrections can only be estimated at present, it appears from the positron data that the error in the absolute normalization is probably not greater than 25%. Hence the data presented in Fig. 2 seem to indicate that a major contribution to the cross section for the forward production of pions with energies close to the photon energy can be understood in terms of the peripheral model, and the pion production rates at forward angles can be predicted by this model to within a factor of two. A detailed comparison with the theory will require further measurements, especially at small angles of production, and also further analysis to determine the absolute normalization with higher precision.

We wish to thank Professor Stanley Livingston and Professor Curry Street, and the Cambridge Electron Accelerator operations and technical staff for their hospitality, technical assistance, and cooperation in the preparation and performance of this experiment.

---

*This work was supported in part by the U. S. Atomic Energy Commission.

[1]S. D. Drell, Phys. Rev. Letters 5, 278 (1960); Rev. Mod. Phys. 33, 458 (1961).

[2]J. R. Kilner, R. E. Diebold, and R. L. Walker, Phys. Rev. Letters 5, 518 (1960).

[3]L. I. Schiff, Phys. Rev. 83, 252 (1951).

[4]H. Byfield, J. Kessler, and L. Lederman, Phys. Rev. 85, 718(A) (1952); P. Isaacs, A. Sachs, and J. Steinberger, ibid.; R. L. Martin, H. L. Anderson, and G. Yodh, ibid. 85, 486(L) (1952); R. L. Martin, ibid. 87, 1052 (1952); D. H. Stork, ibid. 93, 868 (1954); J. O. Kessler and L. N. Lederman, ibid. 94, 689 (1954); J. Cronin, R. Cool, and A. Abashian, ibid. 107, 1121 (1957); R. M. Edelstein, W. F. Baker, and J. Rainwater, ibid. 122, 252 (1961).

[5]J. C. Brisson, J. Detoef, P. Falk-Vairant, L. van Rossum, G. Valladas, and L. Yuan, Phys. Rev. Letters 3, 561 (1959); T. J. Devlin, B. C. Barish, W. N. Hess, V. Perez-Mendez, and J. Solomon, ibid. 4, 242 (1960); P. Falk-Vairant and G. Valladas, Proceedings of the Tenth Annual International Rochester Conference on High-Energy Physics, 1960 (Interscience Publishers, Inc., New York, 1960); and data reviewed by L. W. Jones, Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 591.

[6]The theoretical rates were calculated by using the Hough [P. V. C. Hough, Phys. Rev. 74, 80 (1948)] integration of the Bethe-Heitler equation corrected for finite nuclear size by the carbon form factors [A. Alberigi-Quaranta, A. M. DePretis, G. Marini, A. Odian, G. Stoppini, and L. Tau, Phys. Rev. Letters 9, 226 (1962); R. Hofstadter, Ann. Rev. Nucl. Sci. 7, 231 (1957)] obtained from electron-scattering experiments.