Production of positive pions by 800 MeV protons on carbon

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The double differential cross section for the reaction $p + \mathrm{C} \rightarrow \pi^+ + X$ has been measured at laboratory angles of 7°, 15°, 20°, and 30°.

[NUCLEAR REACTIONS $E = 800$ MeV, $p + {}^{12}\mathrm{C} \rightarrow \pi^+ + X$; measured $d\sigma/dE_\pi$ for $\theta_\pi = 7°, 15°, 20°, 30°$.]

For the design of a high intensity Los Alamos Neutrino Source[1] it is necessary to know the cross section for the production of positive pions in the interaction of 800 MeV protons with carbon. Inclusive pion production cross sections have been measured for a variety of targets, and energies from 500 to 1000 MeV, at LAMPF, TRIUMF, SIN, and BNL.[2–7] The most complete pion yield data are at 730 MeV by Cochran *et al.*,[4] with 5–10% errors. We report here the measurement of the double differential cross section ($d^2\sigma/d\Omega\, dT$) for π^+ production from carbon at laboratory angles of 7°, 15°, 20°, and 30°. These are not only the most complete data at 800 MeV, but also contain the only small angle (<15°) measurement in this energy region. These data should also provide useful input for cascade model codes,[8] allowing a prediction of pion production at all angles. This will be useful for beam design and shielding studies, in addition to allowing tests of models of the nucleus.

The experiment was performed using the BR proton beam (unpolarized) at LAMPF. The apparatus used in this experiment is shown in Fig. 1. The ion chamber (IC) and left-right monitor (LR) were used to measure the number of protons used (approximately 10^{11} for the entire experiment). The detector was a pion spectrometer[9] consisting of a bending magnet, four proportional wire chambers, and scintillators, supplemented with a Čerenkov counter. S1 and S2 are scintillation counters, W1–W4 are proportional wire chambers each having x-y planes with 2 mm wire spacing, and Č is a 1 atm isobutane threshold Čerenkov counter. The spectrometer magnet has a 15.2 cm high gap, and determines the geometric acceptance of the spectrometer to be roughly 0.004 sr. The magnet was run at six different currents corresponding to pion momenta of 100 to 700 MeV/c. The average bending angle was 22°, and the momentum acceptance of the spectrometer was typically 400 MeV/c. The entire spectrometer was mounted on a movable platform, and rotated through the various angles from 7° to 45°.

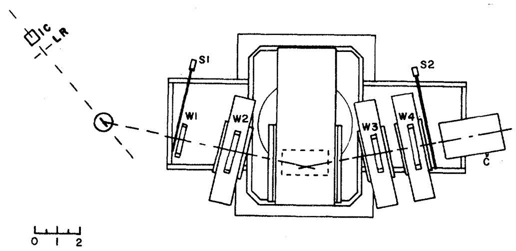

FIG. 1. Experimental apparatus.

The principal target was a graphite cylinder 2.54 cm in diameter and 2.54 cm in length. A polyethylene (CH_2) cylinder 2.54 cm in diameter and 5.000 cm in length was used in order to obtain normalization data from the reaction $p + p \rightarrow d + \pi^+$, as well as pp elastic scattering. A $2.54 \times 2.54 \times 1.27$ cm long lead target was used to enhance the number of electrons produced in order to test the Čerenkov counter. Such testing determined that the Čerenkov counter was roughly 95% efficient. Once calibrated, the Čerenkov counter was then used to tag electrons passing through the spectrometer from the graphite or polyethylene targets.

To minimize systematic errors, the trigger used for the spectrometer was kept very simple. A good event involved a signal in S1 and S2, and a majority of three out of four x planes and three out of four y planes in the wire chambers. The Čerenkov counter signal was recorded, but the signal was not used in the formation of the trigger. Since this simple trigger gave a high trigger rate, the beam flux was maintained at 1 pA or less in order to keep dead time below 10%.

The data were analyzed at the University of New Mexico on a PDP-11/60 computer. Each spectrum typically contained a few thousand pion events so that the statistical errors were approximately 10% for each of the energy bins.

Events were selected for analysis on the basis of a spectrometer fiducial volume cut. Chambers W1 and W2 were used to project the outgoing track back to the production target. The mass of the outgoing particle was calculated from its momentum through the magnet and its time of flight (TOF). The resolution of our TOF system was 1 ns full width at half maximum. A mass cut of 500 MeV/c^2 was applied to help separate protons from pions. As our mass resolution was ±50 MeV/c^2, and as there were essentially no events with a mass of 500 MeV/c^2, this cut was very clean.

The data were first analyzed for proton normalization information. Protons were selected on the basis of a mass cut and the absence of a Čerenkov pulse. A CH_2-C subtraction was then performed to extract the *pp* elastic differential cross section. The absolute normalization was taken from the Case-Western data of Ref. 10. During the analysis of pion data, a similar subtraction yielded the cross section for $p+p \rightarrow d+\pi^+$ which agreed with Ref. 11 within our statistical errors of roughly 10%. These statistical errors also made us insensitive to minor normalization errors in the references.

The data were then analyzed for pion production cross sections. Besides the standard fiducial volume cut, the pion TOF was required to be consistent with its momentum, and the calculated mass value below our cutoff of 500 MeV/c^2. Again, no Čerenkov counter signal was permitted. None of these rather simple cuts, however, were sufficient to separate muon decay contamination from the pion data. It has been shown[12] that the vertical bend angle in the spectrometer magnet, as well as the distance between the magnet's symmetry plane and the point of intersection of the reconstructed tracks going into and out of the magnet, provide an efficient means of eliminating the muonic contamination. These two quantities are uncorrelated since the separation distance is most sensitive to horizontal displacements, while the vertical bend angle is most sensitive to vertical ones. Limits on these quantities were determined from proton data, and a 3.2 standard deviation cut was applied to the two quantities added in quadrature. These tests rejected, typically, 15% of the "pion signal" as muons. Monte Carlo estimates show that muon contamination remaining after these tests is of order 5%, or less than our statistical errors, and the loss of genuine pion events was estimated to be less than 1%.[12] Having removed as much of the muonic contamination as possible, all events were then given a

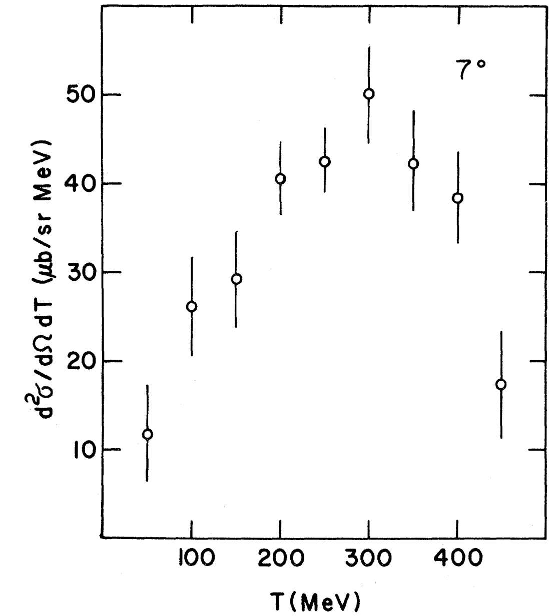

FIG. 2. Pion production cross section at 7°.

decay weight based upon the probability of a track of that length surviving the decay process.

All events, whether proton or pion, were corrected for energy loss in the production target before being binned and histogrammed. The Čerenkov counter signal indicated that less than 2% of the pion signal was electron contamination, so that no corrections

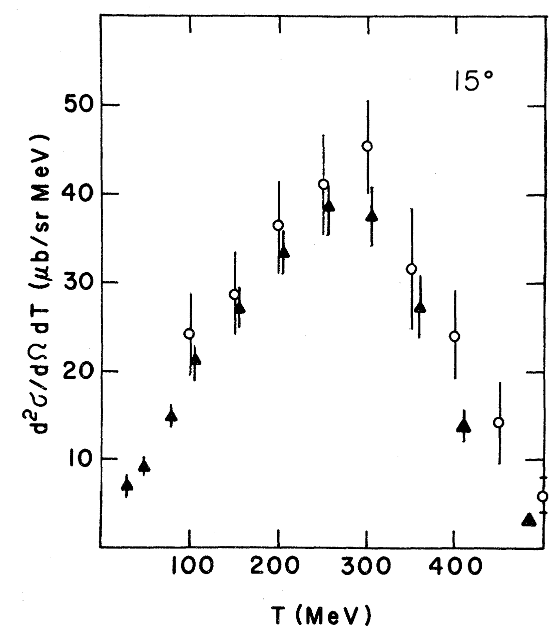

FIG. 3. Pion production cross section at 15°. Data from Ref. 4 at 730 MeV are shown in ▲ for comparison.

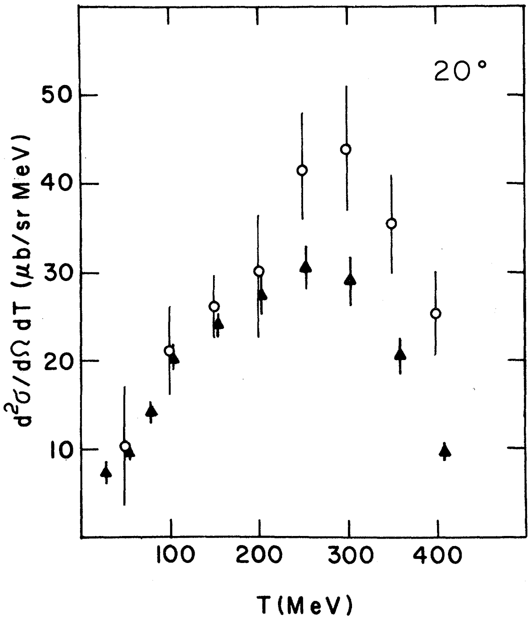

FIG. 4. Pion production cross section at 20°. Data from Ref. 4 at 730 MeV are shown in ▲ for comparison.

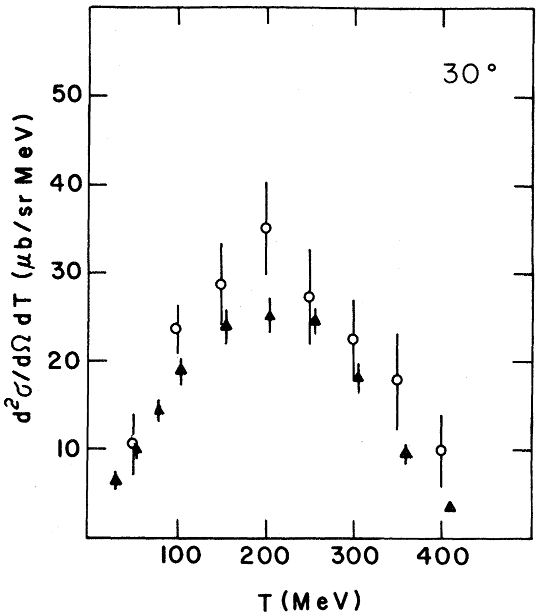

FIG. 5. Pion production cross section at 30° Data from Ref. 4 at 730 MeV are shown in ▲ for comparison.

were made.

The double differential cross section for the inclusive reaction $p+C \rightarrow \pi^+ + X$ is shown for the laboratory angles 7°, 15°, 20°, and 30° in Figs. 2–5. At 15°, 20°, and 30°, data from Cochran *et al.* at 730 MeV are shown for comparison. The differences between the two sets of data are consistent with the differences in primary proton beam energy. The statistical errors are typically 10% per bin with systematic errors judged to be smaller. The error bars shown are statistical only.

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