π^0 Photoproduction from Neutrons*

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We have measured the ratio of the cross section for $\gamma+n\rightarrow\pi^0+n$ to the cross section for $\gamma+p\rightarrow\pi^0+p$ at 4.7 and 8.2 GeV. The measurements were made by detecting the recoil nucleons in coincidence with the decay γ rays of the π^0's produced from a deuterium target. At 4.7 GeV the cross-section ratio, $R\equiv\sigma(\gamma+n\rightarrow\pi^0+n)/\sigma(\gamma+p\rightarrow\pi^0+p)$, is less than 1.0 at low t, with an indication of a dip at about $t=-0.7$ (GeV/c)^2, and rises to 1.0 at high t. The ratios at the higher energy have less structure and are uniformly closer to 1.0.

We report here an experiment which measured the ratio of π^0 photoproduction from neutrons to π^0 photoproduction from protons, $R\equiv\sigma(\gamma+n\rightarrow\pi^0+n)/\sigma(\gamma+p\rightarrow\pi^0+p)$, at 4.7 and 8.2 GeV, using a deuterium target. The range of t covered was from -0.2 to -1.2 (GeV/c)^2. Data were also taken for free protons, using a hydrogen target. The reactions were measured by detecting coincidences between the two decay photons of the π^0 and the recoil nucleons.

In the experiment, photons from a bremsstrahlung beam produced by the Cornell electron synchrotron struck a liquid-deuterium target. Photoproduced π^0's were detected by two lead-glass γ-ray hodoscopes, and the recoil nucleons were observed in a scintillation hodoscope. There were scintillation counters and absorbers in front of the hodoscopes to aid in particle identification.

The trigger was a coincidence between the three hodoscopes. When a trigger occurred, pulse-height and time-of-flight information was read from each hodoscope and the scintillation counters to a computer and written on magnetic tape. The desired events were selected in later analysis by placing appropriate cuts on the data.

The two γ-ray hodoscopes have been previously described.[1] The total pulse height of each hodoscope measured the photon energy, and the distribution of pulse height in the hodoscopes determines the location of the photons. From a knowledge of the two photon momenta, the invariant mass of the two-photon system may be reconstructed. The mass spectra for those events with $E_{\gamma\gamma}>0.75k_0$ and with a coincident recoil nucleon consisted of a pion peak ($\Delta m/m\simeq20\%$) with almost no background.

The recoil nucleons were detected in a 24-element, 25.4-cm-thick scintillation hodoscope (n/p counter). The thresholds of the hodoscope elements were monitored using cosmic-ray μ mesons whose average energy loss of 11 MeV was close to the (15 ± 1)-MeV cut used in the final data analysis. Two 1.3-cm-thick scintillation counters (DE_1 and DE_2) mounted in front of the hodoscope were used to identify protons and neutrons. A 2.54-cm-thick sheet of Lucite and a sweeping magnet were used to reduce the counting rate in the front scintillator. The sweeping magnet displaced the protons 0.6 cm at the nucleon hodoscope for $t=-0.2$ (GeV/c)^2.

In addition to protons and neutrons there were γ rays and charged pions incident on the nucleon hodoscope in coincidence with π^0's. Protons were identified by a triple coincidence between DE_1, DE_2, and the n/p hodoscope, and by their pulse heights in DE_1 and DE_2. For $|t|\leq0.5$ (GeV/c)^2, minimum-ionizing particles were identified by their pulse height and time of flight in DE_1 and DE_2. At large t values the ratio of protons to minimums was determined by extrapolating the low-t information. Neutrons were identified by a pulse in the n/p counter but none in DE_1 or DE_2. A 0.5-radiation-length-thick lead sheet situated between the scintillation counters enabled us to measure the photon flux. At low t, runs were taken with the lead and Lucite removed in order to measure the loss of particles due to absorption. Photons which converted in the lead radiator were counted by DE_2 and n/p but not by DE_1. The time-of-flight data from the counters were used to reject accidental events and, at the lowest-t

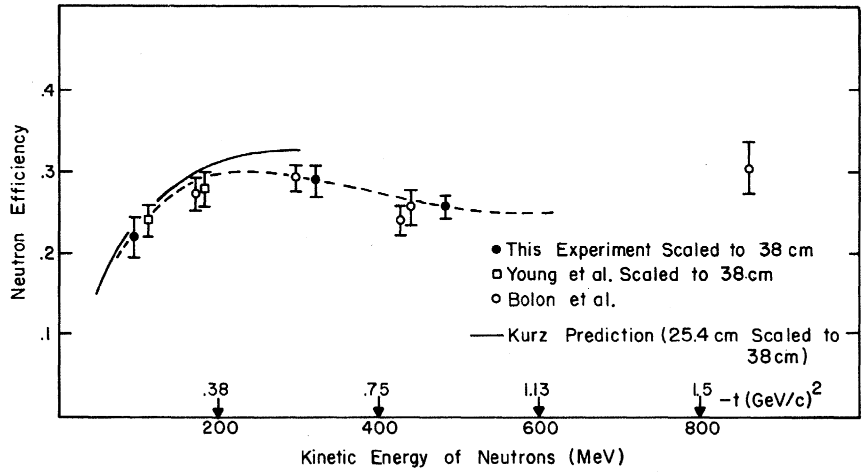

FIG. 1. Absolute neutron efficiency as compared to existing data. Dashed line interpolates between data points.

points, supplied verification that the identifications were made correctly. Two-dimensional plots of the pulse-height correlation between DE_1 and DE_2 for those events coincident with high-energy π^0's enabled relatively clean separation of neutrons, photons, protons, and minimum-ionizing particles.

The ratio of neutron to proton detection efficiency of the n/p hodoscope was measured in a subsidiary experiment in which electron-neutron and electron-proton coincidences were detected from quasielastic electron-deuteron scattering. The ratio of the e-n to e-p coincidences was then divided by the known cross-section ratio to give the ratio of detection efficiencies. Since the neutron/proton calibration data and the π^0 data were taken with similar geometries, the ratio of detection efficiencies, as determined above, was used in the calculation of $R=\sigma(\gamma+n\to\pi^0+n)/\sigma(\gamma+p\to\pi^0+p)$. By making several small geometrical and t-dependent corrections, we determined the absolute neutron efficiency. Figure 1 shows the efficiency, scaled to an effective counter length of 38 cm, as compared to the data from Bolon *et al.*,[2] scaled data of Young *et al.*,[3] and the prediction from a computer program by Kurz *et al.*[4] The dashed curve was used to interpolate between the measured points and was chosen to be consistent with other measurements.

Since the energy resolution of the photon hodoscopes was not sufficiently good to separate elastic from inelastic events, the only indication of the inelasticity of an event available to us was the coplanarity. The narrow-peaked hydrogen coplanarity distributions agreed well with Monte Carlo predictions and indicated small (~4%) inelastic contaminations. For the deuterium data, whose coplanarity peaks were smeared out by the Fermi motion in the deuteron, the inelastic contamination of each t point was determined by fitting the observed coplanarity distributions to those predicted for elastic π^0 production plus a

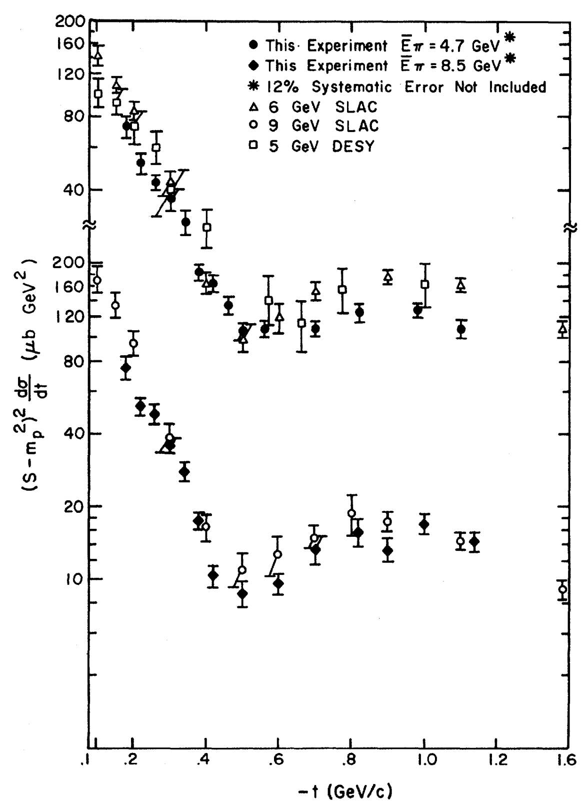

FIG. 2. $(S-m_p^2)^2 d\sigma(\gamma+p\to\pi^0+p)/dt$ from hydrogen at mean energies of 4.7 and 8.5 GeV, as compared to SLAC (Ref. 5) and DESY (Ref. 6) data.

background contribution spread uniformly over the aperture of the detectors. The resulting contaminations were found to be similar for neutrons and protons and were an average of 8% at 4.7 GeV and 17% at 8.2 GeV. The quoted errors in the final results include estimates of the errors in determining the inelastic contaminations.

The results for $d\sigma(\gamma+p\rightarrow\pi^0+p)/dt$ from hydrogen at mean pion energies of 4.7 and 8.5 GeV are shown in Fig. 2 together with data from the Stanford Linear Accelerator Center[5] (SLAC) and DESY.[6] The errors shown do not include an estimated 12% systematic error in the overall normalization of the absolute cross section. At both energies the differential cross section is characterized by an exponential decrease at low t, a dip at $-t\simeq\sim 0.5$ $(\mathrm{GeV}/c)^2$, followed by a broad maximum near $-t=\sim 1.0$ $(\mathrm{GeV}/c)^2$.

The results for the cross-section ratios at both energies are plotted in Fig. 3. At the lower energy our data are compared with data from DESY[7] and the Cambridge Electron Accelerator (CEA).[2] The ratio at 4.7 GeV shows a slight dip near $t=-0.7$ $(\mathrm{GeV}/c)^2$ rising to 0.85 at low t and to 1.0 at $t=-1.0$ $(\mathrm{GeV}/c)^2$. At 8.2 GeV the ratio has less structure and is closer to 1.0. The ratios plotted are corrected for inelastic contamination and included a 6–9% point-to-point systematic error due to uncertainties in the neutron efficiency. A 10% overall normalization error, again due to uncertainties in the neutron efficiency, has not been included in the ratios. The data have been corrected for accidental π^0-neutron coincidences (~10%), photon contamination (~10%), accidental vetoing of real neutrons (~15%), and contamination of the proton data by minimum-ionizing particles (<9%).

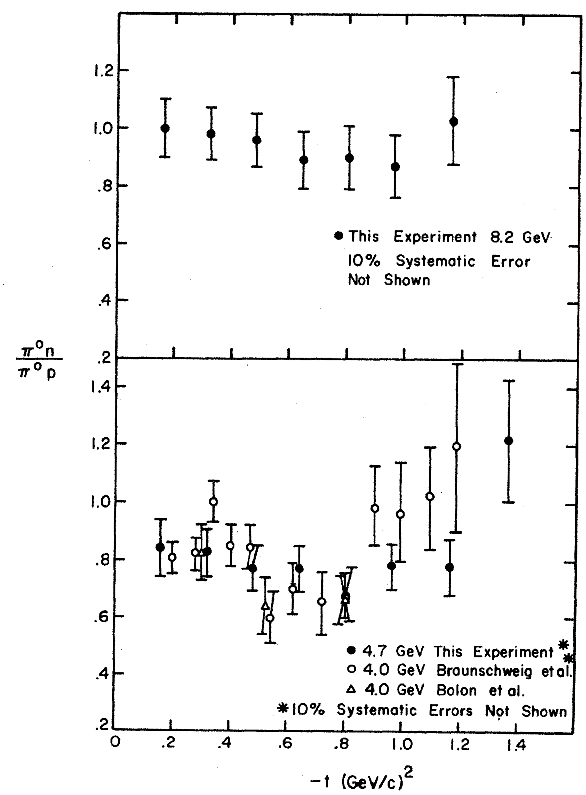

FIG. 3. Cross-section ratio $\sigma(\gamma+n\rightarrow\pi^0+n)/\sigma(\gamma+p\rightarrow\pi^0+p)$ for $\overline{E}_\pi=4.7$ and 8.2 GeV. Also plotted are 4-GeV data from CEA (Bolon *et al.*, Ref. 2) and DESY (Braunschweig *et al.*, Ref. 7).

Simple isospin relations indicate that

$$R\equiv\frac{\sigma(\gamma+n\rightarrow\pi^0+n)}{\sigma(\gamma+p\rightarrow\pi^0+p)}=\left|\frac{I_v-I_s e^{i\varphi}}{I_v+I_s e^{i\varphi}}\right|^2,$$

where I_s and I_v are the isoscalar and isovector photon production amplitudes and φ is their relative phase. Thus we conclude that there is interference between the isovector and isoscalar parts at 4.7 GeV. It appears that this interference is smaller at 8.2 GeV.

The predictions of the various Regge models are seen in Fig. 4 as compared to the 4.7-GeV data. We see clear disagreement with the parametric cut model of Froyland.[8] The strong-ab-

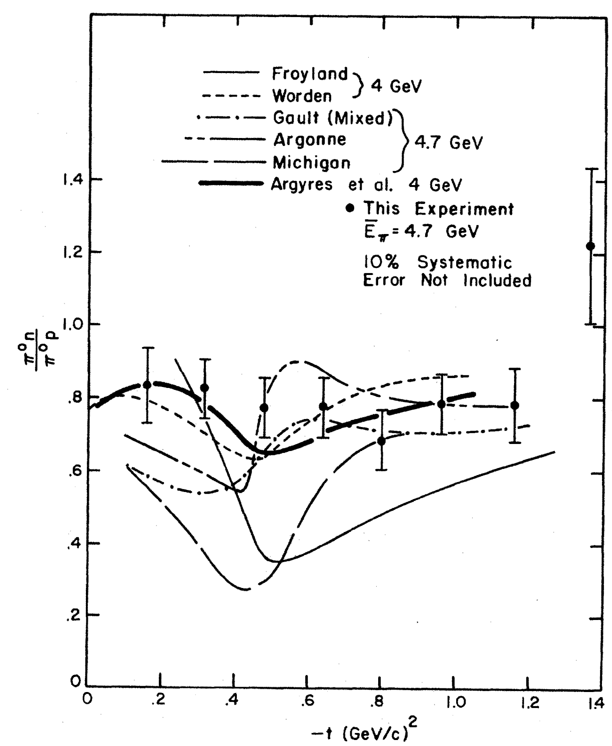

FIG. 4. Comparison between Regge models and data for cross-section ratio $R=\sigma(\gamma+n\rightarrow\pi^0+n)/\sigma(\gamma+p\rightarrow\pi^0+p)$ for $\overline{E}_\pi=4.7$ GeV.

sorption model (Michigan[9]) prediction lies well below the data, and both the Argonne[10] and mixed model of Gault[11] predict more structure than is seen experimentally. The models of Argyres[12] (dual absorptive model) and Worden[13] (nonsense zeros and strong cuts) are in best agreement with the data. There is very little energy dependence in the prediction of any of the models mentioned above (at least between 4.7 and 8.2 GeV).

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Evidence for the Onset of Semi-inclusive Scaling in Proton-Proton Collisions in the 50–300-GeV/c Momentum Range*

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Evidence is presented to support the onset, in the 50–300-GeV/c region of incident momentum, of the asymptotic prediction of Koba, Nielsen, and Olesen regarding the scaling behavior of the charged-prong multiplicity distribution in proton-proton collisions. Lower-energy data, typified by data at 19 GeV/c, are found not to demonstrate this limiting behavior.

One of the simplest and most direct measurements which can be made with a bubble chamber is the determination of charged-particle multiplicities. The present availability of bubble-chamber facilities at Serpukhov, U. S. S. R., and at Batavia, U. S. A., has consequently made available for the first time accurate measurements of topological cross sections for very high-energy proton-proton collisions (50–300 GeV/c). In this note we wish to examine the energy variation of these partial cross sections, and to point out how this variation supports the onset, in this unexpectedly low-energy domain, of the asymptotic prediction of Koba, Nielsen, and Olesen (KNO) regarding semi-inclusive scaling.[1]

The semi-inclusive scaling prediction for the asymptotic behavior of topological cross sections may be summarized in terms of the following limit:

$$\sigma_n/\sigma_{\text{inel}} \xrightarrow[s\to\infty]{} \langle n\rangle^{-1}\psi(n/\langle n\rangle). \tag{1}$$

Here, σ_n is the partial cross section for the reaction $pp \to n$ charged particles, σ_{inel} is the total inelastic pp cross section (throughout this Letter σ_2 does not include the elastic channel), $\langle n\rangle$ is the average number of charged particles produced at a particular value of squared center-of-mass energy s, and ψ is an energy-independent function.

In Fig. 1 we examine this prediction in the 50–300-GeV/c range of incident momenta by plotting $\langle n\rangle(\sigma_n/\sigma_{\text{inel}})$ versus $n/\langle n\rangle$ for experimental data consisting of topological cross sections measured at the following incident momenta: 50 and 69

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π^0 PHOTOPRODUCTION FROM NEUTRONS. A. M. Osborne, A. Browman, K. Hanson, W. T. Meyer, A. Silverman, F. E. Taylor, and N. Horwitz [Phys. Rev. Lett. 29, 1621 (1972)].

Reference 12 should read as follows: E. N. Argyres, A. P. Contogouris, S. Ray, and M. Svec, Nucl. Phys. B45, 267 (1972).

PHOTOMAGNETIC POSITRONIUM-SPIN CONVERSION IN SOLIDS. Werner Brandt and Paul Kliauga [Phys. Rev. Lett. 30, 354 (1973)].

The sentence preceding Eq. (3) should read as follows: "As a result, p-Ps contributes to the o-Ps concentration in the sample at the conversion rate $\kappa_p(x)$, and o-Ps to the p-Ps concentration at the conversion rate $\kappa_0(x)$, where $\cdots$."

The text at the beginning of the second column on p. 357 should read, "$\cdots$ these values indicate relatively large Ps diffusion constants for open molecular solids, ranging from 10^{-2} cm^2/sec in the polar glasses to 10^{-1}–1 cm^2/sec in the Van der Waals solids benzene and cyclohexane."

MOLECULAR DYNAMICS BY LIGHT SCATTERING IN THE CONDENSED PHASES OF Ar, Kr, AND Xe. P. A. Fleury, J. M. Worlock, and H. L. Carter [Phys. Rev. Lett. 30, 591 (1973)].

A textual reference to Ref. (7) following Eq. (1) was inadvertently omitted. Also, Ref. (7) is correctly given as P. A. Fleury, W. B. Daniels, and J. M. Worlock, Phys. Rev. Lett. 27, 1493 (1971).