PHYSICAL REVIEW D VOLUME 11, NUMBER 9 1 MAY 1975

Measurement of the cross section for the reaction $\pi^- p \longrightarrow$ (all neutrals) from 4.0 to 8.0 GeV/c

V. A. Polychronakos, N. M. Cason, J. M. Bishop, N. N. Biswas, V. P. Kenney, and W. D. Shephard
Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556

J. M. Watson
Argonne National Laboratory, Argonne, Illinois 60439

(Received 21 October 1974)

The cross section for the reaction $\pi^- p \longrightarrow$ (all neutrals) has been measured at 4, 5, 6, 7, and 8 GeV/c. The cross section varies with beam momentum as $p_{\text{lab}}^{-1.4}$. The analysis is based on data obtained during an experiment studying the reaction $\pi^- p \longrightarrow nK_1^0 K_1^0$ at 6 and 7 GeV/c using the Argonne National Laboratory 1.5-meter streamer chamber. An independent value for the all-neutral cross section at 8.05 GeV/c has been obtained from an exposure in the Brookhaven National Laboratory 80-in. hydrogen bubble chamber and is quite consistent with the result from the purely electronic measurement.

I. INTRODUCTION

We have measured the cross section for the reaction

$$\pi^- p \rightarrow \text{(all neutrals)} \tag{1}$$

at incident pion momenta of 4.0, 5.0, 6.0, 7.0, and 8.0 GeV/c. The measurements were carried out at the Argonne National Laboratory Zero-Gradient Synchrotron (ZGS) using an all-neutral final-state trigger designed to study the properties of neutral-strange-particle production in the 1.5-m streamer-chamber facility.

In order to correct the data for neutral-strange-particle decays which occur upstream of the veto counters, we have measured cross sections for the topologies

$$\pi^- p \rightarrow V^0 + \text{neutrals}, \tag{2}$$

and

$$\pi^- p \rightarrow V^0 + V^0 + \text{neutrals}\ , \tag{3}$$

where V^0 represents the *charged* decay of a Λ^0, $\bar{\Lambda}^0$, or K^0. Preliminary cross sections for (2) and (3) have been determined from scans of our streamer-chamber data and are presented here.

II. EXPERIMENTAL EQUIPMENT AND TRIGGER REQUIREMENTS

The liquid-hydrogen target used in the experiment was "typical" of a streamer-chamber target.[1] No electrically conducting material was used in its construction since it operated within the sensitive volume of the chamber. It consisted of a cylindrical flask 3 in. long and 2 in. in diameter with spherically shaped cups at the two ends made of 0.005 in. Mylar. The single feed line was also made from 0.005 in. Mylar. The flask and vent line were enclosed in an epoxy-coated PVC foam vacuum jacket for thermal insulation. Figure 1 shows the target flask surrounded by anti counters A_1, A_2, and A_3 discussed below.

Figure 2 shows a plan view (not to scale) of the scintillation counters used to measure the all-neutral cross section. The B counters are beam-defining counters and the A counters are anticoincidence counters. A momentum-defining hodoscope consisting of nine strip counters was placed at the momentum slit. These counters were logically fanned together to form a signal called H, and the beam was then defined to be

$$B \equiv H \cdot B_0 \cdot B_1 \cdot B_2 \cdot B_3 \cdot B_4 \cdot \bar{A}_1 \cdot \bar{A}_5 \cdot \bar{A}_6\ .$$

Counter B_4 was a 2 in. × 2 in. × 0.063 in. scintillator placed 0.25 in. upstream from A_1, a 4.75 in. × 4.75 in. × 0.25 in. anticoincidence counter with a 1.75 in. beam-defining hole as shown in Fig. 1. Counters A_5 and A_6 were large paddle counters 12 in. × 30 in. × 0.375 in. used to eliminate beam halo. Counter A_6 had a 2 in. hole to allow beam particles through. An event trigger T with only neutral particles in the final state was defined by

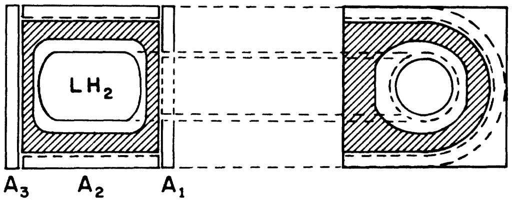

FIG. 1. (a) Side and (b) front (beam's eye) views of the liquid-hydrogen target surrounded by anti counters A_1, A_2, and A_3. Counters A_1 and A_3 are square counters with A_1 having a beam-entrance hole. Counter A_2 is a U-shaped counter.

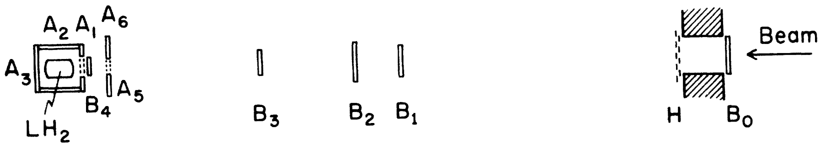

FIG. 2. Plan view (not to scale) of the scintillation counters used to determine the all-neutral cross section. The B counters are in coincidence and the A counters are in anticoincidence. H is a hodoscope (at the momentum focus) of nine strip counters, at least one of which must register a count to give a trigger.

a beam into the hydrogen target and no coincident signal from counters A_2 or A_3: $T \equiv B\cdot \bar{A}_{2+3}$.

Counter A_3 was a 4.75 in. × 4.75 in. × 0.375 in. NE110 plastic scintillator located approximately 0.75 in. downstream from the LH_2 target. Its light was viewed by an RCA 8850 photomultiplier tube through adiabatic light pipes. Counter A_2 was a U-shaped counter 0.375 in. thick following the contour of the target foam vacuum jacket. Adiabatic light pipes from both ends of the U converged to a single RCA 8850 photomultiplier tube. Special care was taken in the design and construction of these counters because of their importance in reducing the background in the $\pi^- p \to n K_1^0 K_1^0$ experiment. Furthermore, both of them (as well as A_1 and B_4) were located in the streamer-chamber sensitive volume and could therefore not be wrapped with aluminum foil in the usual manner because of the pulsed high electric field present. Instead, the target assembly and these counters were enclosed in a polyurethane foam box with 0.125 in. thick walls covered with a sheet of 0.005 in. black polyethylene which provided both the gas seal for the chambers and the light seal for the counters. The efficiency of counters A_2 and A_3 for beam tracks was measured by including two more beam-defining counters downstream from A_3 (B_5 and B_6) and measuring the ratio

$$\frac{B'\cdot \bar{A}_{2+3}}{B'},$$

where $B' \equiv B\cdot B_5\cdot B_6$. In this mode of operation, no $B'\cdot \bar{A}_{2+3}$ counts were observed for $B' = 6\times 10^6$ beam particles. This leads to a calculated efficiency better than 3 parts in 10^7 at the 90% confidence level. We also measured the ratio

$$\frac{B'\cdot (A_2 + A_3)}{B'}$$

and observed no misses of the $(A_2 + A_3)$ system for 2×10^6 beam particles.

III. TRIGGER-RATE MEASUREMENTS AND CORRECTIONS

The beam was tuned for 4.0, 5.0, 6.0, 7.0, and 8.0 GeV/c incident pion momenta and scaled values of B (beam) and T (trigger) were recorded for each run. The hydrogen target was then emptied, and B and T were again scaled and recorded for each energy. The individual runs were terminated when scaled B exceeded 10^7 incident particles.[2] These raw target-full and target-empty trigger rates (normalized to 10^6 incident particles) are shown as a function of incident beam momentum in Table I. The remainder of this section discusses corrections to these rates, which are also

TABLE I. Trigger rates and correction factors.

Incident momentum (GeV/c)	4.0	5.0	6.0	7.0	8.0
Neutrals/10^6 incident π^- (full)	679 ± 6	544 ± 6	493 ± 2	376 ± 5	332 ± 3
Neutrals/10^6 incident π^- (empty)	253 ± 4	204 ± 3	182 ± 3	150 ± 4	142 ± 2
e and μ contamination	1.08 ± 0.01	1.09 ± 0.01	1.07 ± 0.01	1.06 ± 0.01	1.04 ± 0.01
σ_{raw} (mb)	1.45 ± 0.03	1.15 ± 0.03	0.83 ± 0.02	0.73 ± 0.02	0.62 ± 0.04
Converted photons (π^0 decay) $\equiv F_1$	1.03 ± 0.01	1.03 ± 0.01	1.03 ± 0.01	1.03 ± 0.01	1.03 ± 0.01
δ rays $\equiv F_2$	1.02 ± 0.01	1.02 ± 0.01	1.02 ± 0.01	1.02 ± 0.01	1.02 ± 0.01
Neutron scatters $\equiv F_3$	1.01 ± 0.01	1.01 ± 0.01	1.01 ± 0.01	1.01 ± 0.01	1.01 ± 0.01
Light interference $\equiv F_4$	0.95 ± 0.05	0.95 ± 0.05	0.95 ± 0.05	0.95 ± 0.05	0.95 ± 0.05
Strange particles $\equiv \sigma_{\text{sp}}$ (mb)	0.233 ± 0.05	0.136 ± 0.03	0.05 ± 0.05	0.045 ± 0.05	0.033 ± 0.03
σ (mb) [a]	1.70 ± 0.09	1.30 ± 0.07	0.89 ± 0.05	0.79 ± 0.04	0.66 ± 0.04

[a] $\sigma = \sigma_{\text{raw}} \times F_1 F_2 F_3 F_4 + \sigma_{\text{sp}}$.

shown in Table I.

Most zero-prong events contain one or more π^0's. These events are missed if one of the photons from π^0 decay is converted to an electron-positron pair early enough to give a pulse in one of the anti counters. The correction for this effect was obtained using a mean π^0 multiplicity estimated from the literature.[3]

Some zero-prong events were missed because knock-on electrons (δ rays) were produced by the incident pion before production of the zero-prong event. This correction was estimated using Bhabha's formula.[4]

Neutron scatters in the anticoincidence counters or in the material before these counters can also veto a true zero-prong event. This correction was estimated using the known neutron cross sections, the material present, and an estimated average neutron energy.

Since the anticounters inside the streamer chamber were not optically isolated from one another, but were inside a common light-tight box, scintillation in one counter could conceivably be observed by a second counter. If A_1 detected any light from A_2 or A_3, it vetoed a beam count and effectively increased the cross section. To reduce this effect, while Mylar tape was placed on A_1 (the beam-defining hole counter) where it was adjacent to A_2 (the U counter). An upper limit of 10% was measured for this effect by taking A_1 out of the B requirement, and measuring the ratio $B \cdot A_1/B$. It is not known how much of the 10% was due to this effect and how much was due to beam halo which would not affect the cross section. Therefore, a correction factor of 0.95 ± 0.05 is used. This 5% uncertainty is the largest one in the experiment and is the limiting factor in the cross section measurement.

The production of an all-neutral final state involving K^0's or Λ^0's can be vetoed if the strange particle decays before the anti counters. We have determined preliminary values for the cross sections for single V^0 and double V^0 production [reactions (2) and (3)] using our streamer-chamber film, and corrected the all-neutral cross section for this effect. The cross sections are preliminary in the sense that corrections have been calculated assuming that the V^0's are all K^0's—accurate cross sections for reactions (2) and (3) will be published later after detailed analysis of the data. However, since the corrections are small, preliminary values are adequate for calculation of the correction factors. The preliminary V^0 cross sections are given in Table II and the correction factors used are shown in Table I.

Finally, there was a small solid angle not covered by the anti counters. This region, at the side of the target, was the open side of the U-shaped counter A_2 through which the feed line entered the hydrogen target. An event including charged particles in the final state can be counted as an all-neutral event if *all* the produced charged particles exited through this region. In order for this to occur, all charged particles would have to be produced at a large laboratory angle (e.g., greater than 48° for production at the center of the target). In addition, all charged tracks have to be produced within an azimuthal range of ±43.5°. By studying the inclusive production of negative pions at 8.05 GeV/c, we find that less than 3% of the negative particles produced satisfy these requirements. Thus, less than 0.1% of the *events* would have been misidentified and no correction has been made.[5] At lower energies, this upper limit increases, but is always less than 1% and no correction was made.

IV. CROSS SECTIONS AND CONCLUSIONS

The pion track length in hydrogen was determined using the geometry of the hydrogen target (including the spherical end caps) and the beam contamination. The nonpion beam contamination[6] (muon plus electron) varied from 4% at 8 GeV/c to 8% at 4 GeV/c. The pion track length was also corrected for attenuation in the target, a 1% correction for the 3 in. target. The vapor pressure of the hydrogen was monitored during the run, and was constant at 6 psia. This vapor pressure corresponds to a temperature of 17.55 °K and a corresponding density of 0.074 g/cm^3. Using the pion track length, the liquid-hydrogen density, and the corrected target-empty and target-full trigger rates, the all-neutral cross sections have been

TABLE II. Measured cross sections as a function of beam momentum.

Incident momentum (GeV/c)	4.0	5.0	6.0	7.0	8.0
$\sigma(\pi^- p \rightarrow \text{all neutrals})$ (mb)	1.70 ± 0.09	1.30 ± 0.07	0.89 ± 0.05	0.79 ± 0.04	0.66 ± 0.04
$\sigma(\pi^- p \rightarrow 1V^0)$ (mb)	0.362 ± 0.07	0.251 ± 0.05	0.099 ± 0.02	0.091 ± 0.02	0.074 ± 0.01
$\sigma(\pi^- p \rightarrow 2V^0)$ (mb)	0.056 ± 0.01	0.037 ± 0.01	0.020 ± 0.01	0.025 ± 0.01	0.021 ± 0.01

calculated and are given in Table II.

The measured cross sections are plotted in Fig. 3. Cross section measurements from previous experiments, shown for comparison, show wide variation and considerable experimental uncertainty, particularly as regards data taken above 3 GeV/c. Our results are, however, quite consistent with the recent measurements of Apel *et al.*,[7] which show comparably small errors, although the geometric corrections involved in the experiments are quite different.

As a further check on our experimental results, we have determined the all-neutral cross section at 8.05 GeV/c using data obtained in the BNL 80-in. hydrogen bubble chamber. Ten thousand frames of film were double-scanned for zero-prong and four-prong events occurring in a restricted fiducial volume. We have, in previous work,[8] determined the four-prong topological cross section. Thus, the desired cross section was obtained from the ratio of the number of zero-prong events to the number of four-prong events after determining the scanning efficiencies. The double-scan zero-prong and four-prong efficiencies were 88.9% and 99.9%, respectively. The cross section thus obtained was 0.666 ± 0.054 mb, in excellent agreement with the measurement based on our electronic experiment.

We have fitted the energy dependence of our data with the function $\sigma = a p_{\text{lab}}^{-b}$. The resulting least-squares fit is shown in Fig. 1. The fit yields values $a = 11.70 \pm 0.39$ mb and $b = 1.39 \pm 0.10$ with a χ^2 of 2.76 for 3 degrees of freedom.

The surprisingly rapid variation with energy of the all-neutral cross section contrasts with the relatively slow variation of other topological cross sections.[9] This is probably due to the fact that $I = 0$ exchanges are forbidden for the reaction, i.e., exchange of the Pomeron trajectory in the t channel, which is rather energy independent, cannot contribute to the all-neutral cross section, while this contribution to other topological cross sections can be significant. Thus, the all-neutral reaction is dominated by such exchanges as π, ρ, K, and K^* trajectories, all of which have significant energy dependence. The phenomenology of exchange processes has been considered extensively in the literature.[10]

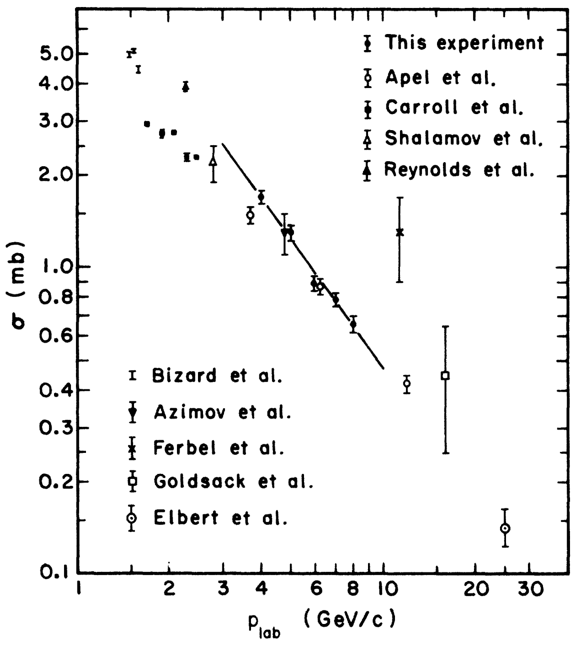

FIG. 3. The all-neutral cross section as a function of beam momentum as measured in this experiment. Previous measurements are also shown. The straight line is the best fit to our data of the form $\sigma = a p_{\text{lab}}^{-b}$ with $a = 11.70 \pm 0.39$ mb and $b = 1.39 \pm 0.10$.

ACKNOWLEDGMENTS

We would like to express our gratitude to the operating crew of the ZGS streamer chamber for their invaluable assistance during the experiment. The experiment would not have been possible without the technical contributions of W. Rickhoff, R. Erichsen, and J. Sweitzer. Graduate students M. Lawson, R. Bolduc, P. Higgins, and M. Sherlock all worked hard on the experiment and their help is gratefully acknowledged.

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[1] *Proceedings of the First International Conference on Streamer Chamber Technology, 1972,* Argonne National Laboratory, Argonne Report No. ANL-8055 (unpublished).

[2] This resulted in statistical errors on the cross sections ≤2.6%. The final error, including uncertainties from all known effects, is about 6%, so the accuracy of the experimental results are not limited by statistics.

[3] N. N. Biswas, E. D. Fokitis, J. M. Bishop, N. M. Cason, V. P. Kenney, and W. D. Shephard, Phys. Rev. D 10, 3579 (1974).

[4] H. J. Bhabha, Proc. R. Soc. A164, 257 (1938).

[5] This upper limit is based on the fact that an event involving charged secondary particles must include at least two charged particles. It also assumes they are uncorrelated, which is a rather poor assumption. On

the other hand, the average charged multiplicity is greater than two, which lowers the upper limit considerably. Thus, we feel confident that our estimates are quite conservative.

[6] E. Colton, private communication.

[7] W. D. Apel *et al.*, Phys. Lett. 46B, 460 (1973); A. S. Carroll *et al.*, Phys. Rev. 177, 2047 (1968); B. G. Reynolds *et al.*, *ibid.* 184, 1424 (1969); Ya. Ya. Shalamov and V. A. Shebanov, Zh. Eksp. Teor. Fiz. 39, 1232 (1960) [Sov. Phys.—JETP 12, 859 (1961)]; G. Bizard *et al.*, Phys. Lett. 31B, 481 (1970); M. A. Azimov *et al.*, Zh. Eksp. Teor. Fiz. Pis'ma Red. 3, 336 (1966) [JETP Lett. 3, 216 (1966); T. Ferbel *et al.*, Nuovo Cimento 28, 1214 (1963); S. J. Goldsack *et al.*, Nuovo Cimento 23, 941 (1962); J. W. Elbert *et al.*, Nucl. Phys. B19, 85 (1970).

[8] J. T. Powers, *et al.*, Phys. Rev. D 8, 1947 (1973).

[9] E. Bracci *et al.*, CERN Report No. CERN/HERA 72-1 (unpublished).

[10] See G. L. Kane, in *Particles and Fields—1973*, proceedings of the Berkeley Meeting of the Division of Particles and Fields of the APS, edited by H. H. Bingham, M. Davier, and G. R. Lynch (A.I.P., New York, 1973), p. 230 for references to recent literature on the subject.