PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Brief Reports

Precise measurement of the pion charge-exchange forward differential cross section at 522 MeV/*c*

F. C. Gaille,[*] V. L. Highland, L. B. Auerbach, and W. K. McFarlane
Physics Department, Temple University, Philadelphia, Pennsylvania 19122

G. E. Hogan,[†] C. M. Hoffman, R. J. Macek, R. E. Morgado,
J. C. Pratt, and R. D. Werbeck
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 6 February 1984; revised manuscript received 25 May 1984)

A precise measurement of the differential cross section at zero degrees for the pion charge-exchange reaction $\pi^- p \rightarrow \pi^0 n$ at $p_\pi = 522$ MeV/*c* has been made. The result is $d\sigma/d\Omega\,(0°) = 4.32 \pm 0.11$ mb/sr.

The fundamental nature of the pion-nucleon interaction makes it a topic of continuing importance. The theoretical and experimental status of the subject has been comprehensively reviewed recently by Höhler.[1] As one of the calibration procedures in a recent pion-β-decay experiment,[2] we obtained data on the reaction $\pi^- p \rightarrow \pi^0 n$. Because considerable effort went into controlling systematic errors in the β-decay experiment, the charge-exchange data is also quite accurate. We have extracted from our data the forward differential charge-exchange cross section at an incident pion momentum of 522 MeV/*c*, with an estimated accuracy of 2.6%.

The apparatus, described in more detail elsewhere,[2,3] is shown schematically in Fig. 1. The hydrogen target is probably unique: a 2-m-diam-by-3-m-long vacuum tank filled with hydrogen gas at one (Los Alamos) atmosphere. The π^0's produced near the forward direction were detected by a fast coincidence of two γ-ray detectors on either side of the beam. The detectors, a modification of the LAMPF π^0 spectrometer,[4] had three layers of active lead-glass converters, each followed by a set of scintillation counters for accurate definition of the fiducial areas and the particle arrival times. The rear of each detector consisted of a set of lead-glass blocks to absorb the total energy of the showers.

The experiment was done in the P^3 East beam line at the Clinton P. Anderson Meson Physics Facility (LAMPF). The central beam momentum was 522.1 ± 0.5 MeV/*c*, as determined by time-of-flight measurements upon an extensive set of beam-particle types: e, π, p, d, t, α, and $^3\mathrm{He}^{++}$. The momentum width of the beam was $\Delta p/p = 5\%$ (full width at half maximum). Seven data runs were made with beam intensities of 0.7, 1.4, and 3.3×10^7 pions/sec at 5.8% duty factor. Because counters could not be used directly in such an intense beam, the beam intensity was monitored by two independent ion chambers and a pair of scintillation detectors for muons from $\pi \rightarrow \mu\nu$ decays. After suitable correction of the ion chambers for beam contamination, the three monitors gave measurements of the pion flux which were consistent with each other to within 0.5%. The systematic errors in the monitor calibration at a lower, countable beam intensity lead to an overall accuracy of 1.0% for the integrated pion flux.

An absolute measurement of the arrival time of each γ

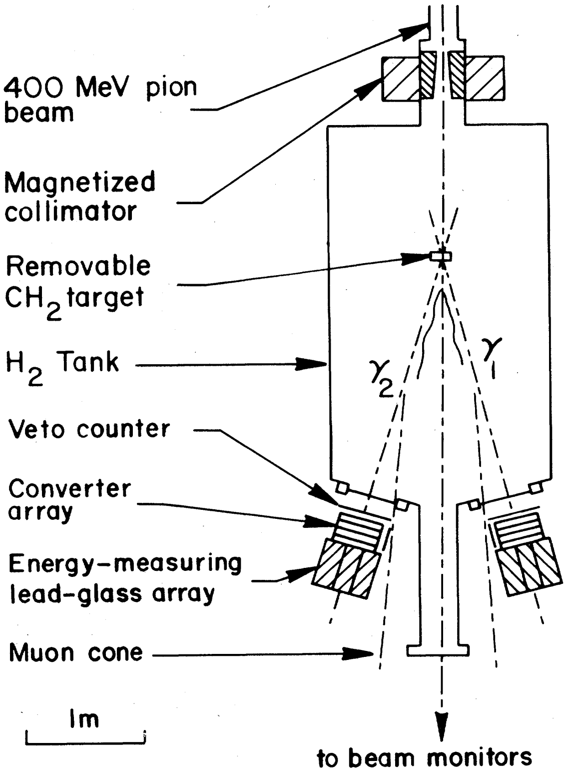

FIG. 1. Schematic diagram of the apparatus.

ray with respect to the beam pions was made by using an accelerator-derived signal correlated with the time structure of the beam; a standard deviation of 280 psec was achieved. After events are selected in the off-line analysis for prompt coincidence with the beam time and for satisfying the fiducial criteria, the summed energy spectrum is as shown in Fig. 2. The lower peak is due to $\pi^- p \rightarrow \pi^0\pi^0 n$ and $\pi^-\pi^0 p$ reactions. The total cross section for these reactions is about[5] 2 mb as opposed to[6] 12 mb for $\pi^- p \rightarrow \pi^0 n$. Because of kinematic constraints, the double-pion reactions have much lower detection probability than the single-pion reaction, except for decays very close to the detectors where the detection efficiency for $\pi^- p \rightarrow \pi^0 n$ has fallen to zero but the γ's from the double pions enjoy a large solid angle. Because of the longer joint path taken by the incident pion and decay γ rays, such downstream interactions have measured times (with respect to the accelerator signal) that are slightly later than those from events which originate in the center of the tank. By exploiting this difference, the nature and shape of the $\pi\pi$ peak can be studied.

The large peak is due to the charge-exchange π^0's. The energy-response function of the system is independently known from the production of single π^0's from a CH_2 target inserted at the center of the tank. The double-pion detection efficiency from this target is insignificant, so there is a clean single peak after the effects of charge exchange on carbon are subtracted out. (The data for this subtraction were obtained by switching to positive beam and producing π^0's from π^+C interactions.) Knowing the shape of the energy-response function, the number of events lost in the tail can be estimated. The contamination of the peak by $\pi\pi$ events is estimated by studying the shape of the lower peak for events with late times.

The $\gamma\gamma$ coincidence yields per incident pion, Y, are corrected for the following rate-dependent effects: (i) dead time in the lead-glass counters and in the data-acquisition system, (ii) accidental counts in the veto counters and in the guard-ring scintillators which defined the fiducial regions, and (iii) loss of events caused by extra particles in the detector. The corrected yields for each run are shown in Table I. The yield is evidently independent of the intensity; nevertheless, we make a conservation estimate of the accuracy of the true yield by extrapolating to zero intensity, obtaining $Y = (4.836 \pm 0.071) \times 10^{-8}$. The 1% uncertainty in the integrated π^- flux has been added in quadrature to obtain the total uncertainty in the extrapolated yield.

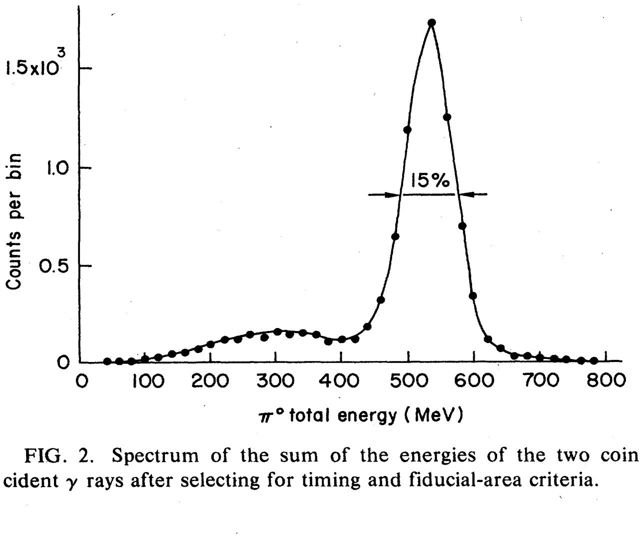

FIG. 2. Spectrum of the sum of the energies of the two coincident γ rays after selecting for timing and fiducial-area criteria.

TABLE I. Two-γ coincidence yield Y per incident π^- for runs of different intensities, after dead-time corrections.

Run No.	Intensity (10^7 π/sec)	γ yield (per 10^8 π^-)
328	0.7	4.795 ± 0.062
329	0.7	4.970 ± 0.087
327	1.4	4.740 ± 0.052
333	1.4	4.892 ± 0.064
330	3.3	4.764 ± 0.081
331	3.3	4.770 ± 0.076
332	3.3	4.899 ± 0.078
	Average:	4.818 ± 0.026
	Extrapolated to zero intensity:	4.836 ± 0.052

An internal determination of the γ conversion efficiency P of each detector is made possible by the modular nature of the detectors. Coincident γ's from π^0's produced from the CH_2 target and from the H_2 gas are analyzed, selecting events only on total energy and fiducial area. In the latter case, the trigger was modified so that in one arm no conversion was required in the modules but only registration in a central region of the total absorption blocks. In this case, the interpretation of the data is straightforward, but care is required in making the energy cut that selects the π^0 sample and the resulting sample is of limited size. The averaged results of three runs each on the left and right sides are $P_L = 0.7180 \pm 0.0116$ and $P_R = 0.7086 \pm 0.0111$.

In the former case the π^0 sample is extremely clean. The relative number of events converting in each succeeding plane conveys information about the elementary conversion efficiency in an individual plane. A simple model of the detector takes into account the slightly different solid angles (occurring only as ratios) of the three planes with respect to the target as well as a small chance of conversion in scintillator dead layers. This model gives good χ^2 fits to the data from four different runs, and from the elementary conversion efficiency the overall detection efficiency is computed. The averaged results are $P_L = 0.7198 \pm 0.0052$ and $P_R = 0.7191 \pm 0.0053$. There is good agreement between left and right sides and between the two different types of data. Averaging left and right, making a small systematic correction for average angle of incidence in the H_2 case, averaging the two types of data, and folding in some systematic uncertainties, we have $P = 0.7178 \pm 0.0043$. The Monte Carlo simulation includes the model estimates for the relative conversion probability in each plane.

The $\gamma\gamma$ yield is related to the forward cross section by

$$Y = C_1 C_2 C_3 P^2 nF \, d\sigma/d\Omega(0°) \quad . \tag{1}$$

$C_1 = 0.9423 \pm 0.0050$ is the probability of the π^0 not vetoing itself, either through Dalitz decay or through a γ converting in the hydrogen, the tank window, or the veto counter. $C_2 = 0.9923 \pm 0.0010$ is the probability that neither γ-ray shower will veto itself by leaking out into the veto counters located along the beam sides of the detectors. $C_3 = 0.9963 \pm 0.0023$ is a combined correction for the hardware coincidence inefficiency and for an inefficiency in identifying the correct pion beam time.

The average pressure in the tank, as measured by an accurate absolute pressure gauge,[7] was 11.00 ± 0.03 psia, while the ambient temperature was 20 ± 1 °C. Thus the number density of protons in the tank was $n = (3.745 \pm 0.016) \times 10^{19}$ cm^{-3}. The factor F has the dimensions of a length and represents the detection efficiency integrated over the length of the target, as evaluated by a Monte Carlo calculation. The calculation takes into account the detailed dimensions of the detectors, the beam phase space, an energy cut in each arm, the timing cut, and the lifetime of the π^-. We have used the phase-shift solution E85 of Arndt and Roper[8] at 400 MeV to provide the shape of the angular distribution in the Monte Carlo calculation, but the solution of Höhler[1,8] is essentially identical for our purposes. Since the π^0 detection efficiency is sharply peaked at 0^0, falling by half as $\cos\theta$ goes from 1.0 to 0.985, the results are insensitive to this shape. The Monte Carlo result is $F = 0.623 \pm 0.010$ cm.

From Eq. (1) we then obtain a value for the $\pi^- p \rightarrow \pi^0 n$ forward differential cross section at $p_\pi = 522$ MeV/c: $d\sigma/d\Omega(0°) = 4.32 \pm 0.11$ mb/sr.[9] There is very little forward-angle charge-exchange data in this (or any other) energy region, but at 400 MeV (521 MeV/c) there is a result due to Kravtsov *et al.*,[10] who found 4.02 ± 0.22 mb/sr, consistent with our result. Our value is in excellent agreement with that predicted by either the phase-shift solution of Arndt and Roper[11] (4.26 mb/sr) or that of Höhler[12] (4.26 mb/sr at 520 MeV/c).

We gratefully acknowledge the assistance of J. D. Bowman, M. D. Cooper, and F. H. Cverna in adapting the π^0 spectrometer to this experiment. We also acknowledge the assistance of S. Datta, E. Jastrzembski, R. Sands, G. Hart, M. Dugan, and E. Iverson, as well as the engineering effort of C. F. Hansen and the support of the staff of LAMPF. This experiment was supported in part by the Fonds National Suisse de la Recherche Scientifique and by the U.S. Department of Energy.

---

[*] Present address: EP Division, CERN, 1211 Geneva 23, Switzerland.

[†] Present address: Physics Department, Temple University, Philadelphia, Pennsylvania 19122.

[1] G. Von Höhler, in *Pion Proton Scattering, Pt. 1: Tables of Data, Pt. 2: Analyses, Tables of Amplitudes,* edited by H. Schopper, Landolt-Börnstein, New Series, Group 1, Vol. 9, Pt. b (Springer-Verlag, New York, 1982).

[2] W. K. McFarlane, L. B. Auerbach, F. C. Gaille, V. L. Highland, E. Jastrzembski, R. J. Macek, F. H. Cverna, C. M. Hoffman, G. E. Hogan, R. E. Morgado, J. C. Pratt, and R. D. Werbeck, Phys. Rev. Lett. **51**, 249 (1983). A fuller account is in preparation.

[3] F. C. Gaille, Ph.D. thesis, Temple University, 1983.

[4] H. W. Baer, R. D. Bolton, J. D. Bowman, M. D. Cooper, F. H. Cverna, R. H. Heffner, C. M. Hoffman, N. S. P. King, J. Piffaretti, J. Alster, A. Doron, S. Gilad, M. A. Moinester, P. R. Bevington, and E. Winklemann, Nucl. Instrum. Methods **180**, 445 (1981).

[5] B. C. Barish, R. J. Kurz, V. Perez-Mendez, and J. Solomon, Phys. Rev. **135**, B416 (1964).

[6] D. L. Lind, B. C. Barish, R. J. Kurz, P. M. Ogden, and V. Perez-Mendez, Phys. Rev. **138**, B1509 (1965).

[7] Series 1000 pressure gauge, Wallace-Tiernan Division of PennWalt Corporation, Belleville, New Jersey.

[8] R. A. Arndt and L. D. Roper, scattering analysis interactive dial-in (SAID) computing facility, 707-961-7311, Virginia Polytechnic Institute and State University, Blacksburg, Virginia. Dr. Arndt kindly evaluated several different phase-shift solutions (including Höhler's "Karlsrühe" solution) for our incident energy.

[9] Accurate cross-section data is not obtainable from the CH_2 target, because it was not large enough nor sufficiently precisely located to be certain of intercepting more than 99% of the beam.

[10] A. V. Kravtsov, L. A. Kuzmin, O. N. Nemozhenko, D. L. Nikolaev, T. S. Serebrova, V. A. Shchegelsky, and A. I. Shchetkovsky, Nucl. Phys. **B140**, 279 (1978).

[11] Phase-shift solution E100 of Ref. 8, which is more recent than E85.

[12] Ref. 1, p. 45. Using the SAID program (Ref. 8) with its current version (KRLH) of Höhler's phase shifts leads to a value of 4.30 mb/sr at 522 MeV/c.