Measurement of Polarization in $\pi^- p \rightarrow \pi^0 n$ at 3.5 and 5.0 GeV/c

D. Hill, P. Koehler, T. Novey, P. Rynes, B. Sandler, H. Spinka, and A. Yokosawa
*Argonne National Laboratory, Argonne, Illinois 60439**

and

D. Eartly and K. Pretzl
*National Accelerator Laboratory, Batavia, Illinois 60510**

and

G. Burleson,† G. Hicks, and C. Wilson
Northwestern University, Evanston, Illinois 60201‡

and

W. Risk§
University of Maryland, College Park, Maryland 20742
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The polarization parameter $P(t)$ for the reaction $\pi^- p \rightarrow \pi^0 n$ has been measured at 3.5 and 5.0 GeV/c over the range $0.2 \leq -t \leq 1.8$ (GeV/c)^2. The two γ rays from the π^0 decay were detected in a large lead-glass hodoscope. The results agree with the positive polarization values found in earlier Argonne National Laboratory data at $-t < 0.35$ (GeV/c)^2. $P(t)$ drops to a small value near $t = -0.6$ (GeV/c)^2 and remains the same out to $t = -1.8$ (GeV/c)^2.

The differential cross-section data for the reaction $\pi^- p \rightarrow \pi^0 n$ in the forward region have been explained by a simple ρ-exchange model; however, the nonzero polarization[1,2] in the region $0 < -t < 0.2$ (GeV/c)^2 made theorists think seriously about Regge cuts,[3] absorption models,[3] or extra poles besides the dominating ρ pole.[4] As a result of recent polarization measurements[5] at 4.90 and 7.85 GeV/c covering the region $0.1 < -t$ 2.0 (GeV/c)^2 which indicated a large polarization near $t = -0.4$ (GeV/c)^2, theorists concluded that the above-mentioned models are incompatible with the data. Consequently, a number of efforts have been made to modify Regge-pole models.[6]

We have carried out a measurement of the polarization in the charge-exchange reaction $\pi^- p \rightarrow \pi^0 n$ at 3.5 and 5.0 GeV/c in the range $0.2 \leq -t \leq 1.8$ (GeV/c)^2. Our results are of higher precision than those of Ref. 5, and they disagree with recent theoretical models.

The experimental setup is shown in Fig. 1. The 17° beam of the Argonne zero-gradient synchrotron furnished π^- with an intensity of 5×10^5/pulse, a momentum bite of ±1%, and a divergence of ±10 mrad. A threshold Cherenkov counter (e) was used to reject the small electron component in the beam. An incident pion was defined by the coincidence $S_0 S_1 S_2 \bar{A}_B \bar{e}$.

A new polarized proton target was used, consisting of ethylene glycol (87.8% $C_2H_6O_2$, 12.2%

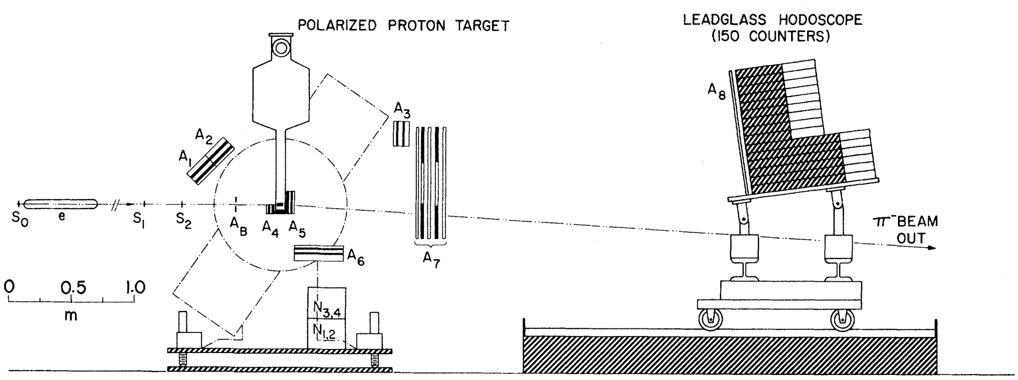

FIG. 1. Elevation view of the apparatus. The dark areas in the anticoincidence counters A_1–A_7 represent lead converters.

$K_2Cr_2O_7$ by weight) immersed in liquid ^{3}He at 0.4°K. The target polarization P_T averaged 0.66 during the 5.0-GeV/c data taking, and 0.73 during the 3.5-GeV/c run; the absolute calibration uncertainty in P_T is estimated to be ±0.05. Events due to bound nucleons were measured separately with a liquid carbon monoxide target. This subtraction method is similar to that of Ref. 5.

The target was surrounded by beam- and shower-anticoincidence counters A_1 to A_8. Neutron counters N_1 to N_4 were placed in the angular region appropriate for recoil neutrons from elastic charge-exchange events at small $|t|$.

The π^0 detector was a lead-glass hodoscope [built jointly by Argonne National Laboratory (ANL) and the National Accelerator Laboratory (NAL)] consisting of 150 counters. The dimensions of the ANL counters are $6.4\times6.4\times34.3$ cm^3, and the NAL counters are $6.4\times6.4\times76.2$ cm^3 (1 radiation length = 2.6 cm). The distance from the target to the front face of the lead-glass hodoscope was large enough to ensure a clean separation of the two showers from π^0 decays. The gains of the counters were initially adjusted and periodically monitored by observing Cherenkov light from high-energy muons traversing the full length of the lead glass.

The trigger for a charge-exchange event was defined as the coincidence between (a) an incident π^-, (b) a neutral shower with total energy ≥ 1 GeV/c in the lead-glass hodoscope, and (c) no signals from A_5 and A_7. The trigger was used to strobe the analog signals from all of the lead-glass counters into gated integrators which stored the pulse heights until they could be processed through an analog-to-digital convertor. The status of every anticoincidence and neutron counter was strobed into gated latches. All the information was then transferred to an on-line computer which stored the raw data on magnetic tape and analyzed them for monitoring purposes.

To obtain the absolute calibration of the lead-glass counters we assumed that each counter i (i = 1, . . ., 150) registering a pulse height p had absorbed a shower of energy $E = k(A_i + B_i p)$; k is a common scale factor for all counters. The calibration parameters A_i and B_i are obtained from a program which analyzes a large sample of 2γ events. It minimizes the second moment of the $M_{\gamma\gamma}^2$ (the square of the 2γ invariant mass) distribution about the known $M_{\pi^0}^2$ value. Starting with the nominal values $A_i = 0.0$ and $B_i = 1.0$, the program converged after a few iterations. Very loose cuts were imposed on the $M_{\gamma\gamma}^2$ distribution during this procedure. The resulting resolution in $M_{\gamma\gamma}$ was 17% (full width at half-maximum), reflecting roughly equal contributions from the spatial and energy resolutions of the hodoscope.

Figure 2(a) shows a distribution of the calculated missing-mass squared [$(MM)^2$]. We believe that the peak channel corresponds to M_n^2. Events with a signal in any of the neutron counters N_1 to N_4 are kinematically constrained to be elastic charge exchange; they exhibit a $(MM)^2$ distribution which peaks in the same channel as the distribution in Fig. 2(a) but falls off more rapidly as $(MM)^2$ increases. Figure 2(b) shows the asymmetry $\epsilon = (N^+ - N^-)/(N^+ + N^-)$ as a function of $(MM)^2$; N^+ and N^- are the normalized events obtained for the two directions of proton spin summed over $(MM)^2$ slices. This asymmetry remains at a constant positive value until just beyond the peak channel in Fig. 2(a), after which it drops to zero.

Charge-exchange events were obtained by applying the following criteria: (a) no signal in any of the counters A_1 through A_7; (b) the hodoscope registered only two showers, both sufficiently far from the hodoscope perimeter to avoid energy loss; (c) $0.45 M_{\pi^0}^2 < M_{\gamma\gamma}^2 < 1.56 M_{\pi^0}^2$; (d) $(MM)^2 < C_{\max}$, where $C_{\max}$ was chosen just below the break in ϵ in Fig. 2(b). The cut on the $(MM)^2$ distribution removed background due to inelastic processes such as $\pi^- p \to \pi^0 N^* \to \pi^0 \pi^0 n$ which could still be present because of inefficiency in the anticoincidence counters.

The distribution of the opening angle between the two γ rays for charge-exchange events agrees

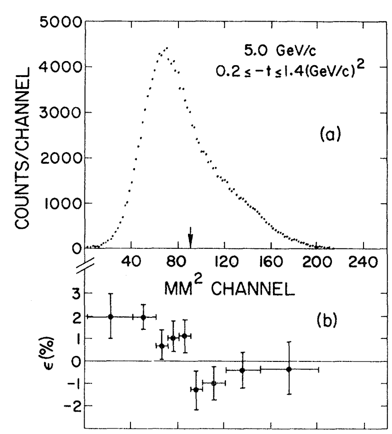

FIG. 2. (a) $(MM)^2$ distribution for the 5.0-GeV/c data. The arrow marks $C_{\max}$. (b) Asymmetry ϵ for the 5.0-GeV/c data versus $(MM)^2$ region as indicated by the horizontal bars.

very well with the $\theta_{\gamma\gamma}$ distribution generated by a Monte Carlo program. We have also computed the relative differential cross sections from our final data samples at 3.5 and 5.0 GeV/c. Both exhibit the same t dependence as existing cross-section data,[7] but they are lower by approximately 1.5 standard deviations.

We measured the background due to events involving the bound nucleons in the polarized target as follows: Ethylene glycol is $C_2H_6O_2$, and by using the cross-section data as well as Glauber calculations[8] one can show that $K_2Cr_2O_7 \approx C_7O_7$. Thus we used liquified carbon monoxide for background measurements. The polarization $P(t)$ was calculated by

$$P(t)=\frac{1}{P_T}\,\frac{N^+(t)-N^-(t)}{N^+(t)+N^-(t)-2N_{\rm CO}(t)-2N_E(t)}, \qquad (1)$$

where P_T is the average polarization of the unbound protons; $N_{\rm CO}$ and N_E are the normalized events for the carbon monoxide and empty targets, respectively. As a check the polarization was also calculated from the formula

$$P(t)=\frac{1}{P_T^{\rm eff}(t)}\,\frac{N^+(t)-N^-(t)}{N^+(t)+N^-(t)-2N_E(t)}, \qquad (2)$$

where $P_T^{\rm eff}$ is an effective target polarization calculated using Glauber corrections for carbon and oxygen cross sections.[8] The results obtained by using Eqs. (1) and (2) agree.

The results presented here are based on 48 000 and 80 000 glycol events at 3.5 and 5.0 GeV/c, respectively. Our data analysis is still being refined and we expect to recover more events.

Our results using Eq. (1) at 5.0 GeV/c are shown in Fig. 3. They are consistent with the old ANL[1] and CERN[2] data but indicate a different t structure from that of Ref. 5. Values of polarization in the region of $0.6 < -t < 1.8$ (GeV/c)^2 are small and consistent with zero. Figure 3 also shows the results at 3.5 GeV/c together with the old ANL[1] data. We observe higher polarization at 3.5 than at 5.0 GeV/c with no appreciable change in the t structure. The errors shown in Fig. 3 are only due to counting statistics, and an absolute error in our knowledge of target polarization is not included. The normalization error in $N_{\rm CO}$ in Eq. (2) is approximately 5%.

The new data are not in agreement with most of the modified Regge-pole models[6] discussed earlier. We note that πN scattering amplitudes extracted from experimental data are sensitive to the charge-exchange polarization and previous amplitude analyses[9] need to be updated.

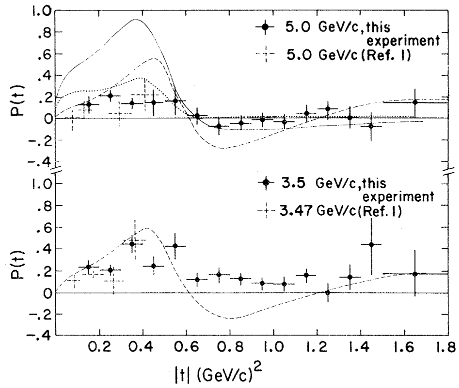

FIG. 3. πp charge-exchange polarization $P(t)$ at 5.0 and 3.5 GeV/c. The errors shown do not include the calibration uncertainty in P_T. The curves represent theoretical predictions by Kogitz and Logan (dashed), Anderson *et al.* (dotted), and Anderson and Moriarty (solid) (see Ref. 6).

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†Present address: New Mexico State University, Las Cruces, N. Mex. 88003.

‡Research supported by a grant from Northwestern University.

§Present address: School of Medicine, American University, Beirut, Lebanon.

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New Charge-Exchange Polarization Data and πN-Amplitude Analyses at 3.6 and 6.0 GeV/c*

P. Johnson
Illinois Institute of Technology, Chicago, Illinois 60616

and

K. E. Lassila
Department of Physics and Ames Laboratory, Iowa State University, Ames, Iowa 50010, and Argonne National Laboratory, Argonne, Illinois 60439

and

P. Koehler, R. Miller, and A. Yokosawa
Argonne National Laboratory, Argonne, Illinois 60439

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Using the results of recent πN charge-exchange polarization measurements at Argonne National Laboratory we have determined the amplitudes for πN scattering 3.6 and 6.0 GeV/c. Two different methods, individual t-by-t analysis and t-dependent analysis, have been adopted, and uncertainties of these amplitudes are discussed.

After the parameters R and A for πN scattering were measured at 6 GeV/c, a number of authors[1-3] attempted to extract the πN scattering amplitudes using various methods. We have determined the amplitudes to within an overall t-dependent phase. We have performed the analyses using new charge-exchange polarization data,[4] and have employed two new methods; the uncertainties of the amplitudes are realistically determined by the second method. We only show 6.0-GeV/c results of the analyses I but present both 3.6- and 6.0-GeV/c results of the analyses II.

Amplitude analysis I (individual t analysis).—In this individual t-by-t analysis two features were incorporated to improve upon the early Halzen-Michael work.[1] First we determined the seven amplitudes algebraically from seven measurements [$d\sigma(\pi^+p\to\pi^+p)/dt$, $d\sigma(\pi^-p\to\pi^-p)/dt$, $d\sigma(\pi^-p\to\pi^0n)/dt$, $P(\pi^+p\to\pi^+p)$, $P(\pi^-p\to\pi^-p)$, $P(\pi^-p\to\pi^0n)$, and $R(\pi^-p\to\pi^-p)$, denoted by σ^+, σ^-, σ^0, P^+, P^-, P^0, and R^-, respectively], obtaining the eight solutions at each momentum transfer. These solutions were used as the starting point in a gradient search, including the additional measurements[5] of $R(\pi^+p\to\pi^+p)$ and $A(\pi^-p\to\pi^-p)$, denoted by R^+ and A^-, respectively, in the data-fitting program. The fits of seven amplitudes to nine measurements incorporate more experimental information; the gradient search here was appropriate to find final amplitudes of the same character as the initial algebraic solutions from seven measurements.

The other new feature incorporated was the use of a "shortest-path" approach to determine the smoothest solution passing through each of the eight solutions at individual t. At a given momentum transfer t_2 the distances of each solution from each of the eight at the previous momentum transfer t_1 are calculated from differences in the corresponding amplitudes at t_2 and t_1 with an appropriate metric. We define the distance between solutions as follows: Let $H_1, \dots, H_7$ be real or imaginary parts of the various helicity amplitudes; $M_{ij}=\partial^2\chi^2/\partial H_i\,\partial H_j$ is the error matrix evaluated at a solution. Then the distance is defined to be

$$d_{12}=\sum_{i=j}^{7}\sum_{j=1}^{7}[H_i(t_2)-H_i(t_1)]M_{ij}[H_j(t_2)-H_j(t_1)].$$