Polarization of Recoil Protons in $\pi^{\pm}p$ Elastic Scattering at 864, 981, and 1301 MeV*

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Angular distributions of recoil-proton polarization in elastic $\pi^{\pm}p$ scattering were measured at 864-, 981-, and 1301-MeV incident pion kinetic energy. Polarization measurements were made by observing the azimuthal asymmetry in the subsequent scattering of recoil protons in large carbon-plate spark chambers. The spark chambers proved to be very suitable polarization analyzer detectors. Strong variation of the polarization with backward pion scattering angle was observed.

I. INTRODUCTION

IN this paper we report the polarization of recoil protons scattered by π^+ and π^- beams of 864-, 981-, and 1301-MeV incident kinetic energy. The data reported herein were taken as part of a general survey experiment to investigate the spin dependence of the πN interaction. Polarization results for pion energies near 600 MeV are given in Ref. 1. The reader is referred to that work for a more detailed description of the experimental method and data analysis procedures. The data reduction of these higher energies had to await a calibration experiment to measure the effective analyzing power of carbon for polarized protons with energies above 425 MeV.[2]

II. EXPERIMENTAL METHOD

The polarization measurements were made with the same apparatus used in Ref. 1. A pion beam from the Bevatron was incident upon a liquid-hydrogen target. The aximuthal asymmetry in the subsequent scattering of the recoil protons was observed in two large carbon spark chambers. The spark chambers were triggered by an array of scintillation and Čerenkov counters which identified the particles entering the chambers as recoil protons from elastic pion-proton scattering.

III. DATA REDUCTION

The calculation of the polarization of recoil protons scattering into a given angular interval was performed in a manner described in Ref. 1. First, the spark chamber film was scanned and each selected scatter was geometrically and kinematically reconstructed. Second, the polarization was estimated by grouping events into given angular intervals and applying the maximum likelihood method, which demands that the correct value of P is that value which maximizes the expression,

$$L(P)=\prod_{i}^{\text{events}}\left[1+PA(\theta_i,T_i)\cos\phi_i\right],$$

where $A(\theta_i,T_i)$ is the analyzing power of the carbon scatterer for collisions in which protons of energy T are deflected through an angle θ; ϕ is the azimuthal angle between planes of the π-p and p-C scatters. The statistical error is arbitrarily defined as that increment of P which makes $L/L_{\max}$ equal to $e^{-1/2}$.

The determination of $A(T,\theta)$ for protons ranging in energy from 100 to 900 MeV was a major task in itself. Protons of energy less than 500 MeV stopped in the carbon chambers. The momentum spread of the pion beam transport system ($\Delta P/P\approx\pm 3\%$) combined with the range resolution of the 1-in. thick carbon plates gave an average uncertainty in proton energy of 30 MeV. This limited our ability to determine the elasticity of a given p-C scatter. To compensate for this broad resolution, a modified analyzability was used for this case[1,3] which included the effects of inelastic scatters with energy losses up to 30 MeV.

The higher energy recoil protons completely traversed the spark chamber after a typical scattering, and thus the proton energy was unknown. All means were lost for determining the elasticity of p-C scattering on energetic grounds, or, for that matter, of determining whether the scattered particle was still a proton. To find the effective analyzability of scatters of unknown inelastic contamination, we performed a calibration experiment, exposing the carbon spark chamber to a high-energy proton beam of known polarization. In this calibration experiment the residual trajectory following the first distinct scatter was ignored, thereby including in the measured carbon analyzability the effects of all inelastic channels which can simulate a proton-carbon scatter. The resulting effective analyzing power of carbon as a function of angle and energy is shown in Fig. 1. Thus, by using the modified analyzing power given in Ref. 3 for protons below 425 MeV and the effective analyzing power shown in Fig. 1 for protons whose energies lie between 425 and 730 MeV, we obtain

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[1] Richard D. Eandi, Thomas J. Devlin, Robert W. Kenney, Paul G. McManigal, and Burton J. Moyer, Phys. Rev. **136**, B536 (1964).

[2] Richard D. Eandi, Robert W. Kenney and Vincent Z. Peterson, Nucl. Instr. Methods (to be published).

[3] Vincent Z. Peterson, Lawrence Radiation Laboratory Report UCRL-10622 (unpublished).

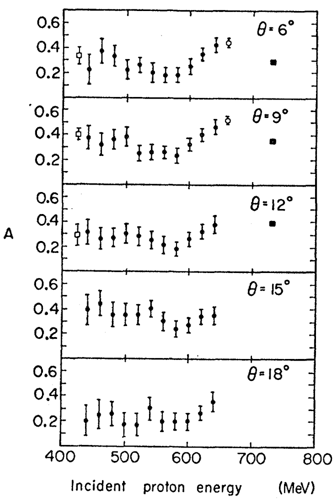

FIG. 1. The effective analyzing power of carbon as a function of incident proton kinetic energy. □—Ref. 4, ○—Ref. 5, ■—Ref. 6, and ●—Ref. 2.

the recoil proton polarization $P(\cos\theta_\pi^*)$ for 864- and 981-MeV incident pion energy (listed in Table I). Our sign convention gives positive polarization in the direction $(\mathbf{k}_i \times \mathbf{k}_f)$, where $\mathbf{k}_i$ and $\mathbf{k}_f$ are the initial and final pion momenta, respectively.

Scattering of 1301-MeV pions into the backward hemisphere gives recoil protons with energies greater than 730 MeV. The effective analyzing power of carbon for protons in this energy range is needed to determine $P(\cos\theta_\pi^*)$ for the extreme backward scattered π^+'s. Column (a) of Table II gives values for $P(\cos\theta_\pi^*)$ estimated by using the known effective analyzing power for recoil protons with energies below 730 MeV (Ref. 3 and Fig. 1); column (b) gives the polarization if we arbitrarily assume the analyzing power at 730 MeV in Fig. 1 to remain the same up to 900 MeV.

The same bias checks and systematic error investigation performed for the data in Ref. 1 apply to the data reported in this paper. There was no evidence of significant scanning bias either by the scanning apparatus or by the scanners, taken as a group or individually. If a bias does exist, it is small and has little effect in light of the existing large statistical uncertainty of the polarization. To confirm this conclusion at these higher energies, the 981-MeV π^- film was scanned twice, the second scan being performed with the film reversed, so that the right hand appeared left to the scanners, and vice versa. The average scanning efficiency estimated from double scanning this portion of the data was ~75%. The recoil proton polarization estimated from this rescan agreed well within statistics with that obtained from the first scan.

TABLE I. Recoil-proton polarization for πN elastic scattering as a function of the cosine of c.m. pion scattering angle. The polarization values quoted were derived by using the effective analyzing power given in Ref. 1 and Fig. 1. The errors quoted do not include the error in polarization resulting from uncertainty in analyzing power and systematic errors. (See Sec. III.) Only the statistical uncertainty is shown, the other uncertainties being relatively negligible.

	Polarization			
	864 MeV		981 MeV	
$\cos\theta_\pi^*$	π^+p	π^-p	π^+p	π^-p
+0.50±0.05	+0.22±0.18	+0.02±0.28	+0.24±0.18	+0.08±0.34
+0.40±0.05	+0.10±0.15	−0.20±0.22	−0.02±0.16	+0.28±0.38
+0.30±0.05	+0.22±0.14	+0.34±0.22	−0.18±0.15	−0.52±0.30
+0.20±0.05	+0.04±0.14	−0.08±0.22	−0.06±0.16	−0.70±0.18
+0.10±0.05	+0.34±0.17	−0.60±0.16	−0.14±0.22	−1.02±0.14
0.00±0.05	+0.10±0.20	−0.34±0.18	+0.02±0.22	−0.84±0.16
−0.10±0.05	+0.28±0.20	−0.28±0.18	+0.10±0.28	−1.00±0.20
−0.20±0.05	+0.22±0.26	+0.26±0.16	+0.06±0.26	−0.80±0.20
−0.30±0.05	+0.84±0.20	+0.14±0.18	+0.42±0.26	−0.02±0.30
−0.40±0.05	+0.66±0.20	+0.08±0.14	+0.62±0.20	−0.48±0.24
−0.50±0.05	+0.22±0.20	−0.06±0.12	+0.20±0.26	−0.08±0.24
−0.60±0.05	+0.70±0.20	+0.14±0.12	+0.56±0.26	−0.14±0.22
−0.70±0.05	+0.76±0.20	−0.36±0.26	+0.36±0.26	−0.12±0.18
−0.80±0.05	+0.34±0.50	···	+0.26±0.40	−0.20±0.30

IV. DISCUSSION OF RESULTS

The π^+p data show that the recoil proton for all three of the energies in which it was measured is large and positive for backward scattered π^+'s. The behavior of the 864-MeV π^- data is not very revealing; the most interesting result is the large negative value of the polarization at 981 MeV for π^- scattering at 90 deg c.m. This is in agreement with the value −0.77±0.33 obtained by Beall *et al.*,[7] and which indicates the possibility of a strong interference between angular momentum states of opposite parity.[8,9] This is consistent with the large $D_{5/2}F_{5/2}$ interference at 900 MeV observed in elastic and charge exchange scattering.[10,11]

TABLE II. Recoil-proton polarization for π^+p elastic scattering at 1301 MeV as a function of cosine of c.m. pion scattering angle. Column (a) gives the polarization values obtained by using the carbon analyzing power given in Ref. 1 and Fig. 1. Column (b) gives the values obtained by assuming the carbon data at 730 MeV in Fig. 1 to remain the same up to 900 MeV.

	Polarization	
$\cos\theta_\pi^*$	(a)	(b)
+0.10±0.05	−0.34±0.45	−0.34±0.45
0.00±0.05	+0.26±0.38	+0.26±0.38
−0.10±0.05	−0.52±0.40	−0.52±0.40
−0.20±0.05	−0.32±0.36	−0.32±0.36
−0.30±0.05	−0.10±0.26	−0.10±0.25
−0.40±0.05	−0.26±0.22	−0.28±0.20
−0.50±0.05	+0.06±0.28	+0.18±0.24
−0.60±0.05	+0.28±0.34	+0.50±0.18
−0.70±0.05	···	+0.28±0.30
−0.80±0.05	···	−0.04±0.50

[4] Edvard Heiberg, Phys. Rev. **102**, 1659 (1956).

[5] L. S. Azhgirey, Yu. P. Kumekin, M. G. Mescheriakov, S. B. Nurushev, G. D. Stoletov, and Huang De-Tsang, Nucl. Phys. **43**, 213 (1963).

[6] Paul G. McManigal, Lawrence Radiation Laboratory Report UCRL-10637, March 1963 (unpublished).

[7] E. F. Beall, B. Cork, P. G. Murphy, W. A. Wenzel, C. M. P. Johnson, and L. J. Koester, Jr., Phys. Rev. **126**, 1554 (1962).

[8] Peter B. Shaw, Phys. Rev. **124**, 1971 (1961).

[9] Michael J. Moravcsik, Phys. Rev. **118**, 1615 (1960).

[10] Jerome A. Helland, Calvin D. Wood, Thomas J. Devlin, Donald E. Hagge, Michael J. Longo, Burton J. Moyer, and Victor Perez-Mendez, Phys. Rev. **134**, B1079 (1964).

[11] Robert W. Kenney, Charles B. Chiu, Richard D. Eandi, Burton J. Moyer, John A. Poirier *et al.*, Bull. Am. Phys. Soc. **9**, 409 (1964).

It is well known[9] that the produce of the polarization and the differential cross section at a given energy can be written as

$$P(\theta_\pi{}^*)\frac{d\sigma}{d\Omega}(\theta_\pi{}^*)/\sin\theta_\pi{}^* = \sum_{n=0}^{2l_{\max}-1} b_n \cos^n\theta_\pi{}^*,$$

where the b's are real linear combinations of products between pure angular momentum amplitudes, and $l_{\max}$ is the state of maximum angular momentum involved in the scattering. A least-squares fit was made of this cosine power series to the polarization data. The series was terminated by applying standard statistical tests. The lowest order of fit consistent with the statistics and the angular resolution of the data was found, and the coefficients for these "fits of minimum complexity"

TABLE III. (a) Coefficients, b_n, in the expansion

$$P(\theta_\pi{}^*)\frac{d\sigma}{d\Omega}(\theta_\pi{}^*) = \sin\theta_\pi{}^* \sum_{n=0}^{N} b_n \cos^n\theta_\pi{}^*$$

obtained by least-squares fitting of the polarization data.

	Incident pion energy (MeV)	b_0 (mb)	b_1 (mb)	b_2 (mb)
π^+p	864	0.03±0.02	0.10±0.10	0.77±0.20
	981	0.00±0.03	−0.25±0.13	0.39±0.29
π^-p	864	−0.08±0.03	0.05±0.10	0.60±0.35
	981	−0.26±0.02	0.32±0.09	0.93±0.27

TABLE III. (b) Values of χ^2 and number of data points used for order of fit chosen.

	Incident pion energy (MeV)	Number of data points	Order of fit, N	χ^2
π^+p	864	14	2	8.4
	981	14	2	7.5
π^-p	864	13	2	19.4
	981	14	2	8.0

are given in Table III (a). Their statistical parameters are given in Table III (b). The polarization curves obtained from these fits are plotted in Fig. 2 along with the data.

These tables show that the statistical accuracy of the data of this experiment prevents the resolution of higher angular momentum amplitudes which would manifest themselves in the coefficients b_3 and beyond, although the known behavior of elastic scattering[10] implies the importance of "l" values through 3, and hence of b values up to b_5. The coefficients b_0, b_1, and b_2, we believe, are reliably determined because they deviate little in magnitude or sign if the order of fit is increased; the errors, however, become larger with increased order of fit. The higher order coefficients

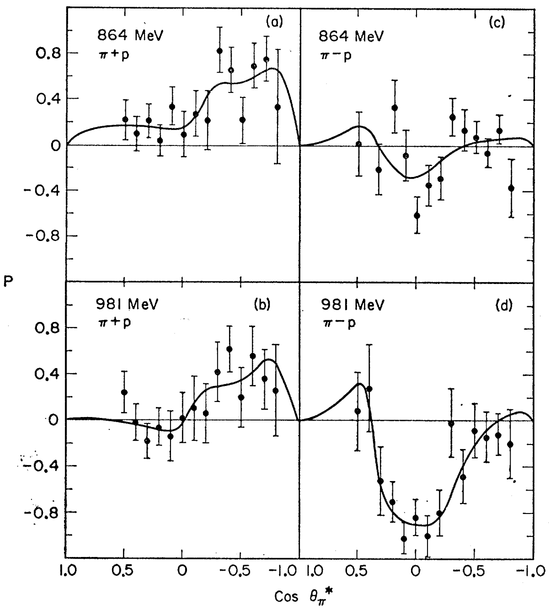

FIG. 2. Polarization of recoil protons as a function of the cosine of the c.m. pion-scattering angle. The curves were obtained by least-squares fitting the data to the form

$$P(\theta_\pi{}^*)\frac{d\sigma}{d\Omega}(\theta_\pi{}^*) = \sin\theta_\pi{}^* \sum_{n=0}^{N} \cos^n\theta_\pi{}^*$$

and choosing the lowest order fit consistent with the statistics and angular resolution of the data (see Sec. IV).

(b_3,b_4,b_5) depend significantly upon the order of fit, and possess errors large enough to make them meaningless. This was especially true for the 1301-MeV π^+ data, and made least-squares fitting of the data quite pointless.

Thus, in conclusion, the results of this experiment give only a crude survey of the behavior of the πN polarization as a function of angle in the region of the third maximum in the total cross section, and therefore do not bear strongly upon implication of the nature of this 900-MeV maximum. However, since polarization involves the interference between the spin-flip and nonspin-flip amplitudes (for which only the incoherent sum is involved in elastic scattering angular distribution measurements),[8,9] it is hoped that these polarization data may be useful in phase-shift analysis[12] and in providing some additional information that any model of the pion-nucleon interaction must satisfy.

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[12] L. David Roper, Phys. Rev. Letters 12, 340 (1964).