PROTON POLARIZATION IN $\Sigma^+ \to p\pi^0$ †*

F. Harris and O. E. Overseth
University of Michigan, Ann Arbor, Michigan 48104

and

L. Pondrom and E. Dettmann
University of Wisconsin, Madison, Wisconsin 53706
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The polarization of protons from the decay of polarized Σ^+ hyperons has been measured by scattering the protons in a carbon-plate spark chamber. A sample of 1335 useful scatters gave $\alpha_0 = -0.98 \pm 0.05$ and $\varphi_0 = 22° \pm 90°$, where $\tan\varphi_0 = \beta_0/\gamma_0$. Using the data on $\Sigma^+ \to n\pi^+$ and $\Sigma^- \to n\pi^-$ and fitting to the $|\Delta\vec{I}| = \frac{1}{2}$ rule gave $\chi^2 = 0.3$ for 2 degrees of freedom.

The test of the $|\Delta\vec{I}| = \frac{1}{2}$ selection rule for nonleptonic decays of $\Sigma^\pm$ hyperons has been limited by experimental uncertainty in the asymmetry parameter α_0 for the decay $\Sigma^+ \to p\pi^0$. Two measurements of α_0 have been reported. The first was performed by Beall et al.,[1] who measured the decay proton helicity by scattering the protons in carbon and obtained $\alpha_0 = -0.80 \pm 0.18$. The second was performed by Bangerter et al.,[2] who observed a proton asymmetry of the form $(1 + \alpha_0 P_\Sigma \cos\omega)$ relative to the hyperon spin direction, and then deduced α_0 from a phase-shift analysis of the 1520-MeV Y_0^* which predicted P_Σ. Their result was $\alpha_0 = -0.986 \pm 0.072$, in good agreement with the $|\Delta\vec{I}| = \frac{1}{2}$ rule, which requires $\alpha_0 \approx -1$. It seemed desirable to repeat with greater statistical accuracy a direct measurement of the proton spin following the technique of Ref. 1 in order to avoid possible uncertainties in the Y_0^* phase-shift analysis, and to measure the decay parameter γ_0, observable if the Σ^+ hyperons are highly polarized in production.

The objective of this experiment was the measurement of the spin vector $\langle\vec{\sigma}\rangle$ for protons from the decay of polarized Σ^+ hyperons. This spin vector is given in terms of α_0, β_0, γ_0 by

$$\langle\vec{\sigma}\rangle = (1 + \alpha_0 \vec{P}_\Sigma \cdot \hat{p})^{-1}[(\alpha_0 + \vec{P}_\Sigma \cdot \hat{p})\hat{p} + \beta_0 \vec{P}_\Sigma \times \hat{p} + \gamma_0 \hat{p} \times (\vec{P}_\Sigma \times \hat{p})], \tag{1}$$

where $\vec{P}_\Sigma$ is the Σ polarization vector, $|\vec{P}_\Sigma| \equiv \overline{P}$, and $\hat{p}$ is the proton-momentum unit vector in the hyperon rest frame. The spin parameters α_0, β_0, γ_0 are not all independent, but satisfy the constraint $\alpha_0^2 + \beta_0^2 + \gamma_0^2 = 1$. The parameter β_0 vanishes if time reversal invariance is valid and final-state $\pi^0 p$ interactions are ignored.[3] The constraint can be expressed by defining $\beta_0 = (1 - \alpha_0^2)^{1/2} \sin\varphi_0$, and $\gamma_0 = (1 - \alpha_0^2)^{1/2} \cos\varphi_0$. Equation (1) then has three unknowns, α_0, φ_0, and $\overline{P}$. The product $\alpha_0 \overline{P}$ can be measured independently by observing the asymmetry distribution of protons relative to the hyperon spin direction $N(\omega) = (1 + \alpha_0 \overline{P} \cos\omega) \equiv (1 + \alpha_0 \vec{P}_\Sigma \cdot \hat{p})$. The spin vector $\langle\vec{\sigma}\rangle$ can be measured by scattering the protons in the laboratory off carbon nuclei. If $\hat{k}_i$ and $\hat{k}_f$ are the initial and final laboratory momentum unit vectors of the proton scattered by carbon, and $\hat{n} = \hat{k}_i \times \hat{k}_f / |\hat{k}_i \times \hat{k}_f|$, then the likelihood function

$$L(\alpha_0 \varphi_0) = \prod_{j=1}^{n} [1 + A_j(\theta_j, E_j) \langle\vec{\sigma}_j(\alpha_0, \varphi_0)\rangle \cdot \hat{n}_j] \tag{2}$$

can be formed for the $j = 1 \to n$ events of the sample. Here the coefficient $A_j(\theta_j, E_j)$ is the carbon-analyzing power for a p-carbon scatter at polar angle θ and energy E.[4] The unknown parameters α_0, φ_0 can be calculated by maximizing $L(\alpha_0 \varphi_0)$.

Positive pions at 1.12 GeV/c from the Princeton-Pennsylvania accelerator produced Σ^+ hyperons by the reaction $\pi^+ p \to \Sigma^+ K^+$ in a liquid-hydrogen target. The experimental arrangement is shown in Fig. 1. The beam contained protons in the ratio $p/\pi^+ = 3/1$; these protons were easily eliminated by time of flight using the time-bunching feature of the accelerator. Velocity and range were used to identify the K^+ mesons electronically. The time between the K^+ stop and the decay μ^+ was recorded on film for each event. The K^+ track was recorded in a foil spark chamber. Protons from Σ^+ decay entered a carbon-plate spark chamber with 32 plates each 2.2 gm/cm^2 thick. A scatter from carbon was not required in the trigger. The trigger rate was about 15/min. One quarter of the triggers was associated production and the remainder was background. Of a total data sample of 400 000 pictures, about 5% had proton scatters which appeared satisfactory on the film. The film was scanned for events with

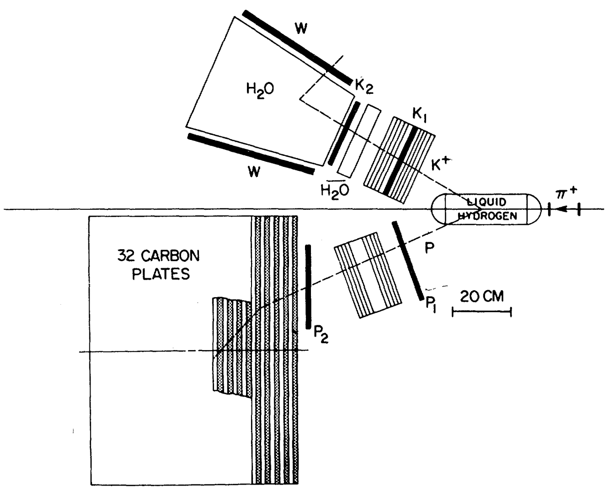

FIG. 1. Plan view of the apparatus. A positive-pion beam of 10^5/sec entered from the right at 1.12 GeV/c mean momentum and $\pm 3\%$ bite. The first two counters were timed relative to a master time signal to identify pions by time of flight (π). K^+'s produced to the right of the hydrogen target satisfied $K_1K_2\overline{H_2O}$ and stopped in the large water counter. Ten wrap counters W surrounding the large water counter used to count the decay μ^+. Decay protons were counted in P_1P_2 and entered the carbon-plate spark chamber. The trigger was $(\pi K_1K_2\overline{H_2O}P_1P_2)\times(H_2OW)$, the second H_2O in parentheses being the large water tank.

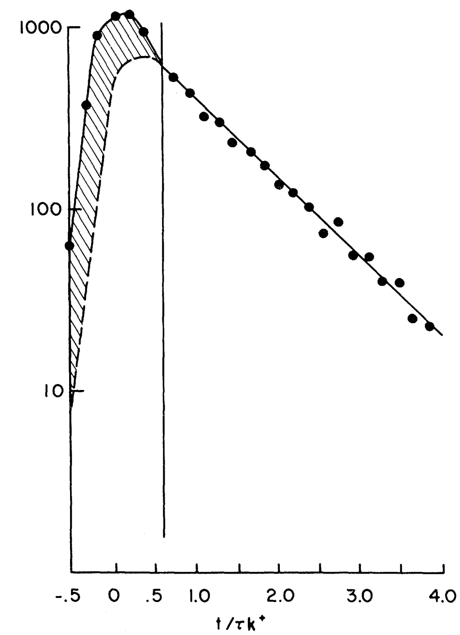

FIG. 2. Plot of the time difference between K_2 and W for 8550 events. The dashed line is the curve expected for a pure K^+ decay sample, normalized to $t > 0.6\tau_{K^+}$. The 2600 events in the shaded area were "prompt" events, not caused by $K^+\Sigma^+$ production. The data to the right of the vertical line at $t = 0.6\tau_{K^+}$ were selected to be free of the prompt background. Because of the sharp bunching of the Princeton-Pennsylvania Accelerator beam (1-nsec pulse every 66 nsec) there was no continuous accidental background under this curve.

a single K^+ track and a single decay-proton track which scattered in the carbon and stopped in the chamber volume. The K^+ direction, the initial and final proton directions, and both the total proton range and the residual range after the scatter were measured. The data contained about 40% background at this stage. Since elastic πp scattering could not satisfy the counter geometry, this background was caused by multiple pion production in the hydrogen or in the target walls. The background was reduced by requiring a vertex in the liquid hydrogen and by requiring the K^+ and proton angles to be consistent with associated production and Σ^+ decay kinematics. A total of 8550 events remained in the sample.

Figure 2 shows the distribution in delay time between the stopping K^+ and the decay μ^+ for these 8550 events. An excess of 2600 events at prompt delay times is apparent in this curve. To eliminate this prompt background only those events with delay times $t \geq 0.6\tau_{K^+}$ were accepted for further analysis. For these 3304 events, two laboratory proton energies could be calculated assuming the sequence $\pi^+p \to \Sigma^+K^+$, $\Sigma^+ \to p\pi^0$. The lower proton energy was usually insufficient to give a useful carbon scatter. The upper energy could be compared with the energy inferred from the observed proton range in carbon. Figure 3 shows the result of this comparison; $\delta \equiv$ observed-minus-predicted range in sparks. One spark corresponded to 8 MeV for a typical event. A satisfactory fit to this histogram was obtained by combining the spark-chamber resolution with the proton energy spread due to geometrical uncertainties. The data sample at this stage was consistent with a pure $\Sigma^+ \to p\pi^0$ signal, but to eliminate possible remaining background, the observed range was required to agree with the predicted range to within ± 3 sparks, corresponding to the full width at half-maximum of the curve in Fig. 3. There were 2000 events in this peak.

Each of these 2000 events had a proton scatter in carbon with no visible recoil tracks at the scatter vertex. To avoid obvious geometrical bias each scatter was required to satisfy a "cone test." 86 events were eliminated because the scattered proton track could be forced to leave the spark-chamber fiducial volume by rotating it

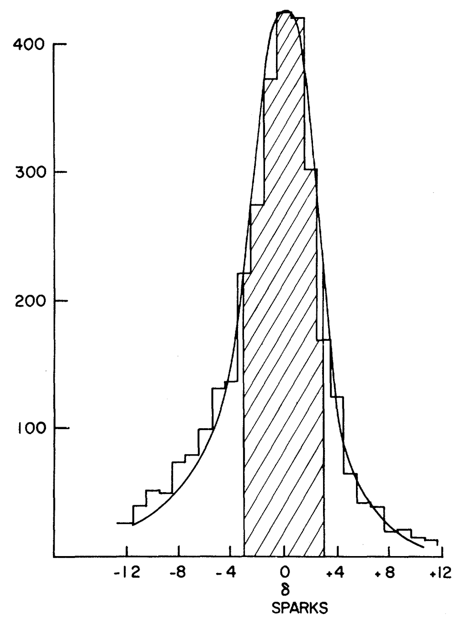

FIG. 3. Observed-minus-predicted range curve (δ curve) for the 3300 events with $t \geq 0.6\tau_{K^+}$ in Fig. 2. The Monte Carlo fit to this histogram is consistent with no background.

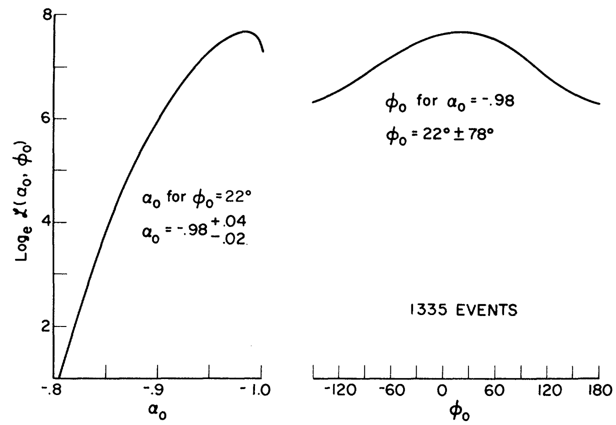

FIG. 4. Likelihood curves for the final data sample. Likelihood contours in α_0, φ_0 space show that the two parameters are essentially uncorrelated, although φ_0 is poorly determined because α_0 is very close to -1.

about the incident-proton track. No other geometrical distortions were found despite the fact that the carbon-plate spark chamber was not symmetrical with respect to the incident protons. The spatial asymmetry for the decays was calculated using $N(\omega) = (1 + \alpha_0 \overline{P} \cos\omega)$ and defining P parallel to $\vec{P}_{\pi_{in}} \times \vec{P}_{K_{out}}$ as positive. The result averaged over center-of-mass production angles $-0.6 \leq \cos\theta^* \leq +0.3$ was $\alpha_0 \overline{P} = 0.59 \pm 0.04$ for the 1914 events in the sample. Requiring the p-carbon analyzing power to be greater than 0.1 eliminated 579 events.

In summary, the final data sample was subjected to the kinematic and vertex requirements, the decay-time requirement $t \geq 0.6\tau_{K^+}$, and the range-agreement requirement $|\delta| \leq 3$ sparks. The scatters had to pass the cone test, and had to have an analyzing power greater than 10%. The average carbon analyzing power for these events was 0.41. The center-of-mass $\cos\theta^*$ region was divided into three equal bins and an $\alpha\overline{P}$ was determined for each bin for use in the likelihood function. The likelihood function defined in Eq. (2) was calculated in terms of α_0 and φ_0. Solutions for the maximum value of L were

$$\alpha_0 = -0.98^{+0.04}_{-0.02}, \quad \varphi_0 = 22° \pm 78°. \tag{3}$$

The relativistic spin transformation from center of mass to laboratory has been included in the analysis. The errors were variations in α_0, φ_0 which changed $\ln(L)$ by $\frac{1}{2}$. These likelihood curves are shown in Fig. 4. Variations in the $|\delta|$ cut produced no change in the result. Relaxing the delay time requirement $t \geq 0.6\tau_{K^+}$ and admitting all delay times increased the data sample to 2300 events, but also introduced 20% prompt background. For this enlarged sample the results were $\alpha_0 \overline{P} = 0.54 \pm 0.03$, $\alpha_0 = -0.86 \pm 0.04$, and $\varphi_0 = 25° \pm 20°$,[5] consistent with Monte Carlo calculations of the expected effects of an unpolarized background on the experimental result.

The sensitivity of the results to various systematic effects has been investigated. A ±2% uncertainty in α_0 has been ascribed to possible remnant unpolarized background in the final data sample. The dependence of α_0 on the p-carbon analyzing power was slight.[4] Nonlinear distortions in the carbon-plate–chamber optics were studied with grid pictures and straight beam tracks. Uncertainties in these corrections led to an additional error of ±2% in α_0 and ±45° in φ_0, giving the final results

$$\alpha_0 = -0.98^{+0.05}_{-0.02}, \quad \varphi_0 = 22° \pm 90°. \tag{4}$$

These values can be converted into values for α_0, β_0, and γ_0, giving

$$\alpha_0 = -0.98^{+0.05}_{-0.02}, \quad \beta_0 = +0.08^{+0.16}_{-0.28}, \quad \gamma_0 = +0.19^{+0.23}_{-0.35}. \tag{5}$$

Final-state $\pi^0 p$ interactions predict $\beta_0 = -0.03$ if the $|\Delta \vec{I}| = \frac{1}{2}$ rule is assumed. Using the latest data on $\Sigma^\pm$ lifetimes,[6] the $\alpha_\pm$ data compiled by

N. Barash-Schmidt et al.,[3] and Eq. (4), a $\chi^2=0.3$ for two degrees of freedom was obtained for the hypothesis $|\Delta\vec{I}|=\frac{1}{2}$ with no violation of time-reversal invariance. Possible $|\Delta\vec{I}|=\frac{3}{2}$ amplitudes were computed from the formula

$$\sqrt{2}A_0+A_+-A_-=-3(\tfrac{2}{5})^{1/2}B_3, \qquad (6)$$

where B_3 is the $|\Delta\vec{I}|=\frac{3}{2}$ term. Assuming all amplitudes to be real, B_3 was found to have S-wave and P-wave components

$$S_3/S_-=-0.04\pm0.05,$$

$$P_3/P_+=-0.04\pm0.05. \qquad (7)$$

Here $S_-\approx A(\Sigma^-\to n\pi^-)$, $P_+\approx A(\Sigma^+\to n\pi^+)$, and $S_-\approx P_+$ in magnitude.

This experiment is consistent with the $|\Delta\vec{I}|=\frac{1}{2}$ rule, with time-reversal invariance, and confirms the validity of the $Y_0{}^*$ phase-shift analysis used in Ref. 2.

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[1]E. F. Beall, B. Cork, D. Keefe, W. C. Murphy, and W. A. Wenzel, Phys. Rev. Letters 8, 75 (1962). The value of α_0 quoted in the text comes from a reanalysis of this experiment by D. Keefe; see N. P. Samios, Argonne National Laboratory Report No. ANL-7130, 1967 (unpublished).

[2]R. O. Bangerter, A. Barbaro-Galtieri, J. P. Berge, J. J. Murray, F. T. Solmitz, M. H. Stevenson, and R. D. Tripp, Phys. Rev. Letters 17, 495 (1966).

[3]The spin parameters are defined in agreement with N. Barash-Schmidt et al., Rev. Mod. Phys. 41, 109 (1969).

[4]V. Peterson, University of California Lawrence Radiation Laboratory Report No. UCRL-10622 (unpublished). The $\Delta E=30$-MeV curves were used in the final calculations, but the results were not sensitive to this choice. Thus if $|\alpha_0|=0.98$, $|\Delta\alpha_0|=\pm0.01$ for $|\Delta A|=\mp0.10$, where A is the analyzing power.

[5]These values were reported as a preliminary result by the authors, Bull. Am. Phys. Soc. 14, 519 (1969) and are now considered erroneous.

[6]R. Barloutaud et al., Nucl. Phys. B14, 153 (1969). These authors report $\tau^-=(1.472\pm0.016)\times10^{-10}$ sec which is lower than that of the previous high-statistics determination by C. Y. Chang, $\tau^-=(1.666\pm0.026)\times10^{-10}$ sec, Phys. Rev. 151, 1081 (1966). Preliminary data from other experiments support the lower value: See compilation by R. Bangerter, University of California Lawrence Radiation Laboratory Report No. UCRL-19244 (unpublished). The value from Barloutaud et al. was used in our fit.

DOES THE SLOPE OF THE HIGH-ENERGY ELASTIC PROTON-PROTON SCATTERING CROSS SECTION INCREASE AT SMALL MOMENTUM TRANSFER?*

R. A. Carrigan, Jr.
National Accelerator Laboratory, Batavia, Illinois 60510
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Experimental information relating to the slope of the elastic proton-proton scattering cross section in the region of $-t=0.15$ (BeV/c)^2 is reviewed. For proton energies greater than 18 BeV, most of the available data indicate that the slope changes from less than 9.0 (BeV/c)$^{-2}$ for $-t>0.2$ (BeV/c)^2 to a value greater than 10.0 (BeV/c)$^{-2}$ for $-t<0.15$ (BeV/c)^2.

Over the past several years a number of experiments have shown that proton-proton elastic scattering has several distinct regions of momentum-transfer dependence. The experiments of Akerlof et al.[1] and Allaby et al.[2] exhibit a change in the character of the slope of the cross section near $-t=6.0$ (BeV/c)^2. A distinct break in the cross section at $-t=1.2$ (BeV/c)^2 appears in measurements taken in a Brookhaven isobar run[3] and the experiment of Allaby et al.[2]

Krisch[4] has emphasized this structure by separating the cross section into three exponential regions. There are a number of theoretical models which can explain the qualitative features of a three-region structure. In particular, some optical models[5] predict a cross section in which there should be an even number of breaks[6] and consequently an odd number of regions. Regge-pole models[7] and hybrid models[8] do not have this constraint. In this note it will be shown that there is experimental evidence indicating the existence of a fourth region below $-t=0.15$ (BeV/c)^2.

It is useful to discuss cross-section parametri-