Measurement of the Asymmetry Parameter in the Hyperon Radiative Decay $\Sigma^+ \to p\gamma$

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We have measured the asymmetry parameter (α_γ) in the hyperon radiative decay $\Sigma^+ \to p\gamma$ with a sample of 34754 ± 212 events obtained in a polarized charged hyperon beam experiment at Fermilab. We find $\alpha_\gamma = -0.720 \pm 0.086 \pm 0.045$, where the quoted errors are statistical and systematic, respectively.

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Hyperon radiative decays represent a class of baryon decays which require contributions from both the weak and electromagnetic interactions. Hara proved in 1964 [1] that the asymmetries in radiative hyperon decay vanish in the SU(3) limit, assuming only *CP* invariance and left-handed currents in the weak interaction. Contrary to this prediction, the first measurements of the asymmetry parameter in the decay $\Sigma^+ \to p\gamma$ revealed some evidence for large negative asymmetries ($\alpha_\gamma = -1.03^{+0.52}_{-0.42}$ [2], -0.53 ± 0.36 [3]). These were bubble chamber experiments where polarized Σ^+ were produced from the low-energy $K^- p \to \Sigma^+ \pi^-$ reaction. The average Σ^+ polarization was about 40%.

The main difficulty in such experiments is separation of the $\Sigma^+ \to p\gamma$ radiative decay from the 400 times more abundant hadronic decay $\Sigma^+ \to p\pi^0$. Moreover, the asymmetry parameter in the hadronic decay is large and negative ($\alpha_{\pi^0} = -0.980 \pm 0.016$ [4]), which raised the concern that the observed asymmetry in the $\Sigma^+ \to p\gamma$ decay might be, in fact, due to some contamination of the background into the $p\gamma$ sample. In addition, the number of $p\gamma$ events detected in both experiments was very small (61 [2] and 46 [3], respectively).

These observations raised a wide interest among theorists [5]. Various models were investigated. None of these models could describe satisfactorily both the large negative asymmetry and the observed rate of the $\Sigma^+ \to p\gamma$ decay. This became possible only recently in the form of a QCD sum-rule model [6].

A new measurement of the $\Sigma^+ \to p\gamma$ asymmetry was performed in 1987 at KEK in a counter experiment [7] with Σ^+ produced in the reaction $\pi^+ p \to \Sigma^+ K^+$. The polarization of the Σ^+ was about 87%. From a sample of 190 events the asymmetry parameter was found to be $-0.86 \pm 0.13(\text{stat}) \pm 0.04(\text{syst})$.

This experiment (E761) [8] was designed to perform a measurement of the asymmetry parameter in the $\Sigma^+ \to p\gamma$ decay on a high statistical level and with reliable separation from the $\Sigma^+ \to p\pi^0$ mode. The high-energy hyperon beam at Fermilab provided a large flux (≈ 2000/sec) of Σ^+ with a polarization of 12%. The direction of the polarization was periodically reversed to allow the separation of the asymmetry from instrumental biases. To identify the $\Sigma^+ \to p\gamma$ decay we used charged-particle spectrometers that provided high-precision measurements of the missing neutral mass. In addition, a special photon spectrometer was constructed to determine the direction and energy of the photons.

The experiment was located in the Proton Center beam line at Fermilab. The apparatus (Fig. 1) has four parts:

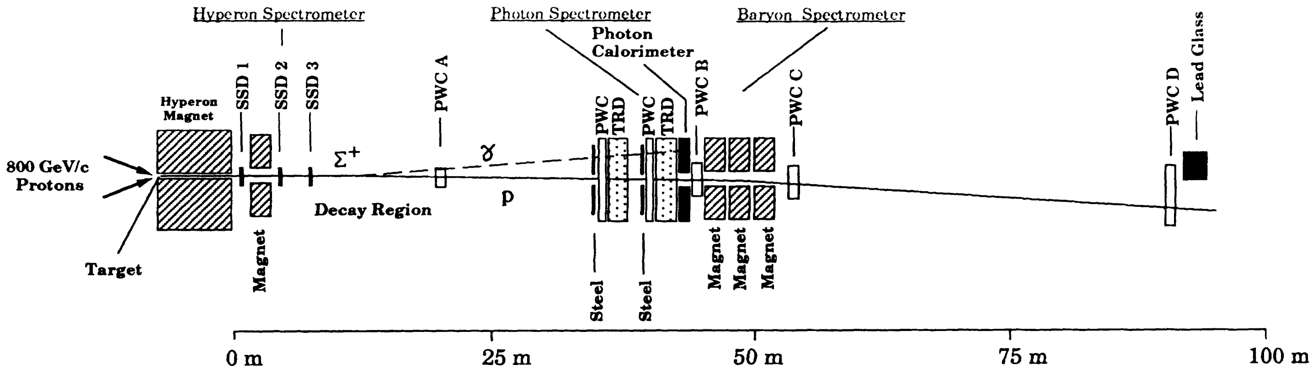

FIG. 1. Plan view of the apparatus in the Fermilab Proton Center charged hyperon beam.

the charged hyperon beam and three spectrometers, one each for the incident hyperon (Y), decay baryon (B), and photon in a generic hyperon radiative decay $Y \to B\gamma$. Protons of 800 GeV/c were steered and focused onto the hyperon production target. The targeting angle of the protons could be varied over the range ± 5 mrad. The charged hyperon beam originates from a one-interaction-length Cu target in the upstream end of a 7.3-m-long hyperon magnet which imparts a transverse momentum (ΔP_t) of -7.5 GeV/c to the 375-GeV/c hyperon beam.

The hyperon spectrometer consisted of 9 planes of 50-μm-pitch silicon strip detectors (SSD) arranged in three stations and a 2-m-long magnet with a ΔP_t of 1.4 GeV/c. Hyperons are measured with resolutions (σ) of 0.7%, 12 μrad, and 5 μrad in momentum, horizontal angle, and vertical angle, respectively. The baryon spectrometer includes 30 planes of multiwire proportional chambers (PWC) arranged in four stations. The first three stations have 8 planes each of 1-mm-pitch chambers in four views while the last station has 6 planes of 2-mm-pitch chambers. The baryon spectrometer magnet consists of three 2-m-long magnets operated in series with a combined ΔP_t of -2.5 GeV/c. Baryons are measured with resolutions (σ) of 0.2%, 9 μrad, and 6 μrad in momentum, horizontal angle, and vertical angle, respectively.

The photon spectrometer consisted of a set of tracking transition radiation detectors (TRD) to measure the position of the photon [9] and a lead-glass–bismuth-germanate (BGO) calorimeter to measure the photon energy. Photons were converted in either of two 2.54-cm-thick steel plates (≈ 1.5 radiation lengths each). Each plate is followed by 2 planes of PWC and 2 planes of TRD. The TRDs have a threshold of ≈ 2.5 GeV/c for electrons and are sensitive to the high-energy charged component of the photon shower. These electrons retain the initial direction of the photon to within the position resolution of the TRDs. The coordinate (X or Y) and fractional energy resolutions (σ) of the photon spectrometer are 2 mm and $73\%/\sqrt{E(\mathrm{GeV})}$, respectively. There is a 76×76 mm^2 hole in the photon spectrometer to allow the undecayed beam and the baryon through. This angular region is covered by a rear lead-glass array. The hole in the front lead-glass array is lined with BGO.

The trigger consisted of scintillation counters in each of the three spectrometers. A hyperon candidate was defined as the only particle within a 400-ns time window in the 100-kHz beam and a baryon by a single scintillator signal in a region where protons from Σ^+ decay were expected. A combination of scintillators in the photon spectrometer identified a converted neutral in one of the steel plates and > 5 GeV was required in the photon calorimeter. No attempt was made at the trigger level to distinguish hadronic from radiative decays. The trigger rate was typically 0.8% of the beam rate and 24% of those triggers reconstructed as Σ^+ decays. The geometrical acceptance of the apparatus and trigger was 64% for radiative and 85% for hadronic decays.

During one month in the Fermilab 1990 fixed-target running period 221×10^6 triggers were recorded on magnetic tape. These data were taken with complementary horizontal targeting angles near 3.7 mrad giving equal subsamples with the Σ^+ polarization up and down. Our analysis does not depend upon the exact value of the polarization, only that it changes significantly between the two subsamples. These data were first analyzed for hyperon and baryon tracks. Shown in Fig. 2 is the distribution in the missing neutral mass squared $[M^2_{X^0}]$ for the hypothesis $\Sigma^+ \to pX^0$. This sample contains 48×10^6 hadronic, $\approx 67\times 10^3$ radiative, and $\approx 250\times 10^3$ $K^+ \to \pi^+\pi^0$ decays.

The photon spectrometer information is analyzed for 3.2×10^6 events in the range $-0.01 < M^2_{X^0} < 0.01$ GeV^2/c^4 which decayed in the region from SSD3 to PWC A. The algorithm tests the hypothesis that the missing neutral is a single photon. At least 70% of the energy deposited in photon calorimeter is required to be within 5 cm of the extrapolated neutral track. Events consistent with the hypothesis $K^+ \to \pi^+\pi^0$ or inconsistent with coming from the hyperon production target were also removed. A reduced TRD χ^2 is formed by summing the square of the error-normalized distances between the extrapolated neutral track and the photon posi-

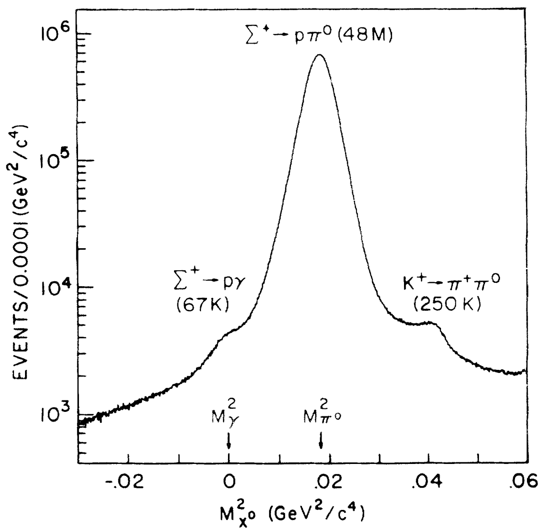

FIG. 2. Event distribution of the mass squared of the missing neutral particle (X^0) for the hypothesis $\Sigma^+ \to pX^0$ for all candidates.

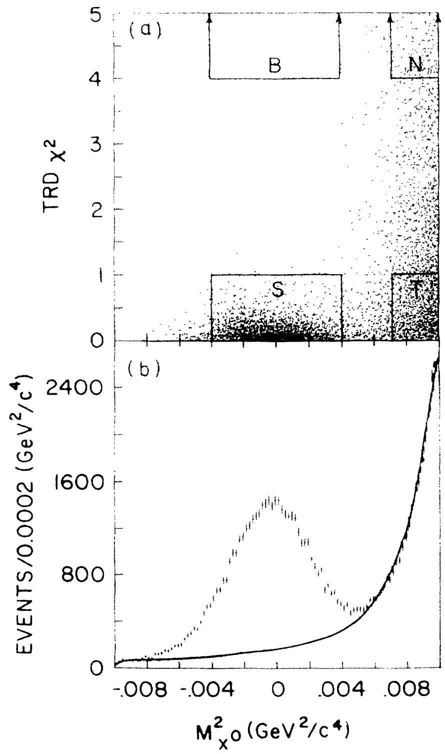

FIG. 3. (a) Scatter plot of the TRD χ^2 described in the text vs the recoiling missing mass squared [$M^2_{X^0}$] for all events in the interval $-0.01 < M^2_{X^0} < 0.01$ GeV$^2/c^4$ showing the four regions discussed in the text. (b) The missing mass squared distribution for all events with TRD $\chi^2 < 1.0$ (error bars) and the TRD $\chi^2 > 4.0$ (solid curve) normalized to equal area in the interval $0.0072 < M^2_{X^0} < 0.01$ GeV$^2/c^4$ where the distribution is dominated by hadronic decays.

tion determined by the TRDs [10].

The event distribution of $M^2_{X^0}$ vs TRD χ^2 is shown in Fig. 3(a). There is a clear excess of events near the photon mass for the region TRD $\chi^2 < 1.0$. Figure 3(b) shows the $M^2_{X^0}$ distribution for events with TRD $\chi^2 < 1.0$ and events with TRD $\chi^2 > 4.0$. The events at large TRD χ^2 model well the hadronic background under the radiative decay events. Four regions are shown in Fig. 3(a); signal (S) and background (B) in the region $|M^2_{X^0}| < 0.004$ GeV$^2/c^4$ and two corresponding normalization regions (N and T). The fraction and number of radiative decay events in the signal region are $f = 1 - N_B N_T / N_N N_S = 0.8315 \pm 0.0016$ and $fN_S = 34754 \pm 212$ events, respectively, where the N's are the number of events in the corresponding regions. The sample defined by these cuts contains 52% of all radiative decay events and has a relatively small contribution from background (17%). The asymmetry of this background is measured by analyzing events in the background region.

In order to control systematic errors in the extraction of asymmetries it is necessary to control the differences in acceptance caused by changes in the beam phase space when the targeting angle is changed. This is done by dividing the data into bins in beam-angle space, calculating the asymmetry for each, and averaging those asymmetries to achieve a final result. In the rest frame of the Σ^+ the angular distribution of the decay proton is given by

$$\frac{2}{N_{0i}} \frac{dN}{d\cos\theta_j} = \varepsilon_{ij}(\cos\theta_j, \{\theta\})(1 + A_{ij}\cos\theta_j), \qquad (1)$$

$i = \pi^0, S, B, \gamma$, $j = X, Y, Z$. The asymmetry $A_{ij} = \alpha_i P_j$ is the asymmetry parameter [11] for the sample i times the polarization component in the direction j, and $\cos\theta_j$ is the direction cosine of the proton momentum in the Σ^+ rest frame. The total number of events in sample i is N_{0i}. $\varepsilon_{ij}(\cos\theta_j, \{\theta\})$ is the acceptance of the apparatus, trigger, and analysis which depends upon both the proton direction cosine and the hyperon's laboratory angles in the decay volume ($\{\theta\} = \theta_X, \theta_Y$). These angles are the variables used to describe the change in the beam phase space when the targeting angle is reversed.

We extract the asymmetries A_{ij} for a sample i by averaging the difference over sum of Eq. (1) for spin-up and -down data. This procedure cancels biases due to the geometrical acceptance and the change in beam phase space. Since the polarization is in the vertical (Y) direction the X and Z components of A_{ij} should be zero. This technique extracts the asymmetry directly from the data by comparing spin up and down. No Monte Carlo simulation was required or used in this analysis.

Applying this procedure to the data samples in the signal and background regions produces the asymmetries shown in Table I. All the X and Z asymmetry components are consistent with zero with the exception of A_{BZ}. It is not surprising that there is a residual bias in this component [12]; its correlation with the $A_{\gamma Y}$ is small

TABLE I. Asymmetry components for each sample. The quoted errors (shown in parentheses) are statistical only. The Σ^+ polarization is in the Y direction so that A_X and A_Z should be zero.

Sample	A_X	A_Y	A_Z
Hadronic π^0	−0.0050(21)	−0.1188(21)	−0.0011(21)
Signal S	+0.0088(82)	−0.0884(83)	−0.0004(108)
Background B	+0.0121(73)	−0.0938(81)	−0.0373(64)
Radiative γ	+0.0082(100)	−0.0873(102)	+0.0070(130)

and is included in the systematic error estimate. The asymmetries of the signal and background samples are nearly as large as the hadronic sample. The asymmetry of the radiative decay events is extracted by taking the asymmetry of the events in the signal region as a linear combination of radiative and background events with relative fraction f:

$$A_{SY}=fA_{\gamma Y}+(1-f)A_{BY}\,. \tag{2}$$

The asymmetry parameter for the radiative decay is then determined from the ratio of radiative to hadronic asymmetries times the known value for the hadronic asymmetry parameter:

$$\alpha_\gamma=\frac{A_{\gamma Y}}{A_{\pi^0 Y}}\alpha_{\pi^0}=\frac{\alpha_{\pi^0}}{fA_{\pi^0 Y}}[A_{SY}-(1-f)A_{BY}]\,. \tag{3}$$

The result is $\alpha_\gamma=-0.720\pm0.086\pm0.045$ where the first error is statistical and the second systematic. The systematic error is determined by studying the variation in α_γ as a function of the cuts and parameters in the analysis and the stability of the result during the data taking (0.034), the details of the TRD algorithm (0.022), and the effect of the Z bias in the background sample (0.020). These are combined in quadrature to yield a systematic error estimate of 0.045. This result is in agreement with the previous measurements. It confirms that the asymmetry in the Σ^+ radiative decay is indeed large and negative.

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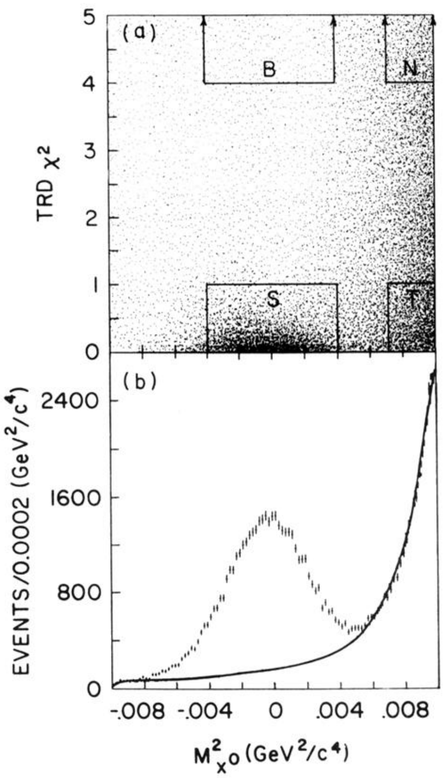
[10] Typically this χ^2 has 2 degrees of freedom.
[11] The sign convention for the alpha parameters are those of the Particle Data Group, Phys. Lett. **170B**, 154 (1986); $\alpha_{\gamma(\pi^0)}$ is the asymmetry parameter of the decay proton in the final state $\Sigma^+\to p\gamma(\pi^0)$.
[12] The background sample is dominated by incorrectly measured hadronic decays. A Z bias is caused by momentum errors while X and Y biases depend mainly on angles. The largest class of measurement errors are errors in the hyperon momentum.



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