New Measurement of the Asymmetry Parameter for the $\Sigma^+ \to p\gamma$ Decay

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The asymmetry parameter α_γ for the $\Sigma^+ \to p\gamma$ decay has been measured with counter techniques. From a sample of about 190 $\Sigma^+ \to p\gamma$ decays, the asymmetry parameter is found to be $\alpha_\gamma = -0.86 \pm 0.13 \pm 0.04$, where the quoted errors are statistical and systematic, respectively. The present result confirms with better accuracy the large and negative value for α_γ measured by two previous bubble-chamber experiments. The branching ratio is also found to be $(1.30 \pm 0.15) \times 10^{-3}$, which is consistent with previous measurements.

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The asymmetry parameter for the $\Sigma^+ \to p\gamma$ decay (α_γ) characterizes the center-of-mass (c.m.) angular distribution of the proton, $N(\vartheta_p)$, with respect to the Σ^+ spin direction:

$$dN(\vartheta_p)/d\cos\vartheta_p \propto 1 + \alpha_\gamma |P_\Sigma| \cos\vartheta_p,$$

where ϑ_p denotes the angle between the directions of the Σ^+ spin and the proton, and P_Σ is the Σ^+ polarization. The quantity α_γ was shown to vanish in the exact SU(3) limit under the assumptions of *CP* invariance and the conventional left-handed current-current form of the weak interaction.[1] On the other hand, α_γ was measured twice in the past, both by bubble-chamber experiments,[2] and the average value obtained is $\alpha_\gamma = -0.72 \pm 0.29$.[3] Hence, the naive prediction contradicts the experimental value although its error is large. Since then, a large number of theoretical models have been proposed[4] to explain this discrepancy; these include various pole-approximation models and more modern approaches based on QCD. So far, however, no convincing theoretical picture has emerged that can consistently account for both the asymmetry parameter and the rate for the $\Sigma^+ \to p\gamma$ decay. It is evident that another measurement is needed to establish or disprove the large and negative value for α_γ.

This Letter reports a new measurement for the asymmetry parameter and branching ratio. In this experiment, polarized Σ^+'s were produced in the reaction $\pi^+ p \to K^+ \Sigma^+$. The momentum of the incident π^+ beam was chosen to be 1.7 GeV/c, where the cross section is nearly maximum and the Σ^+ polarization is large ($\simeq 87\%$) for a wide range of the production angle. The experimental layout is shown in Fig. 1. A well-separated π^+ beam with an intensity of $(5-8) \times 10^5$ particles per 400-msec-long machine pulse was provided every 2.5 sec through an intermediate-energy beam line ($K2$) of the 12-GeV Proton Synchrotron at National Laboratory for High Energy Physics (KEK). Beam particles were identified and tracked by a beam-tagging system consisting of five scintillation counters, a gas Cherenkov counter, and six sets of multiwire proportional chambers[5] (MWPC's). A liquid-hydrogen target, 300 mm long and 50 mm in diam, was placed inside a C-type spectrometer magnet. The pole piece of the magnet was 1500 mm along the beam and 1200 mm wide, and the gap was 1000 mm. It provided a magnetic field of about 0.7 T at the center. The charged products, K^+ and proton, emerging from the target were detected with two nearly identical sets of detectors (referred to as left and right arms). As shown in Fig. 1, they were placed roughly symmetrically with respect to the beam direction. In each arm, the trajectories of the charged particles were recorded with four sets of MWPC's ($L1-L4$/$R1-R4$) and a set of drift chambers ($L5/R5$). A silica-aerogel Cherenkov counter[6] (ACL/ACR) was used at the trigger level to reject pions of 400 MeV/c or higher. A trigger scintillation counter (SL/SR) and a stop scintillation hodoscope[7] ($TOFL/TOFR$) for time-of-flight (TOF) measurements were also placed in each arm to tag and identify charged particles. Two sets of γ detectors were placed above and below the target to measure the conversion point of the γ rays. Each set consisted of three identical layers composed of a 5-mm-thick lead converter and two planes of MWPC's with mutually orthogonal signal wires. The efficiency for the typical γ rays from the $\Sigma^+ \to p\gamma$ decay was estimated to be about 90% by using abundant $\Sigma^+ \to p\pi^0$ events.

As the first step in the off-line analysis, the missing mass corresponding to Σ^+ was evaluated from the measured four-momentum of K^+ (and incident π^+) to identify the $\pi^+ p \to K^+ \Sigma^+$ reaction. Two clear peaks of Σ^+ and $\Sigma^{*+}(1385)$ can be seen in Fig. 2, where the arrows indicate the cut position to select the Σ^+ events. The mass of the missing neutral was also calculated; it was found that almost all the events clustered at the π^0 mass because of the dominant $\Sigma^+ \to p\pi^0$ decay. The polarization P_Σ was determined with the event samples thus obtained ($\simeq 5 \times 10^5$ events), and was found to be in good agreement with a previous measurement.[8] In this evaluation the world average of -0.980 ± 0.015 was used for the asymmetry parameter of the $\Sigma^+ \to p\pi^0$ decay.[3]

The major background against the $\Sigma^+ \to p\gamma$ events

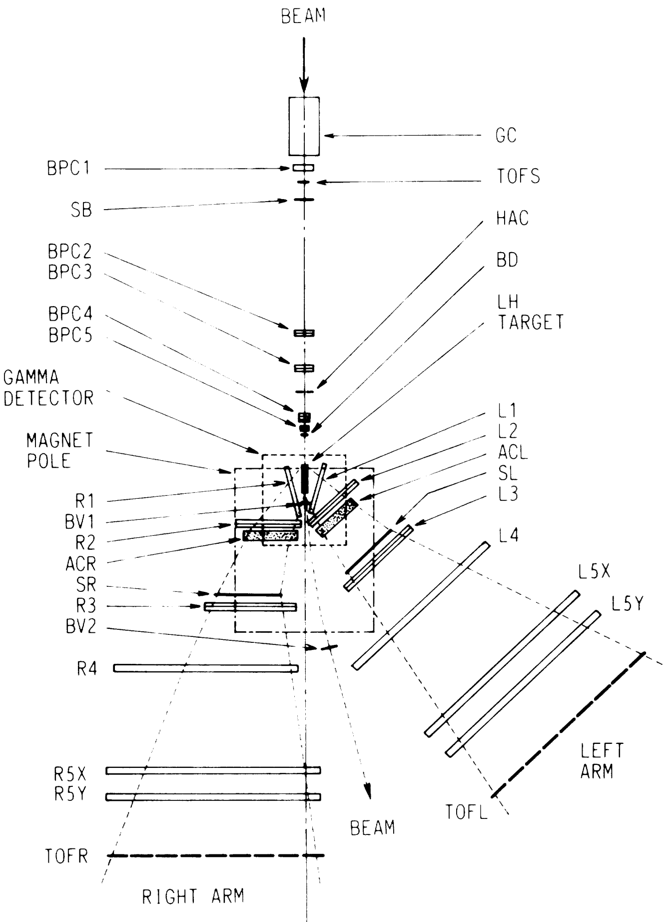

FIG. 1. Experimental layout. $S1$, *TOFS*, *SB*, *HAC*, and *BD*: beam-tagging scintillation counters. *GC*: gas Cherenkov counter which rejected positrons. $BPC0$–$BPC5$: beam-profile chambers. $BV1/BV2$: veto scintillation counters. *SL*/*SR*: trigger scintillation counters. *ACL*/*ACR*: silica-aerogel Cherenkov counters. $L1$–$L4$/$R1$–$R4$: tracking MWPC's. $L5$/$R5$: drift chambers. *TOFL*/*TOFR*: TOF scintillation hodoscopes. *GAMMA*: γ-ray detectors. *LH*: liquid-hydrogen target. $S1$ and $BPC0$, located $\simeq 11$ m upstream of the target, are not shown in the figure. *HAC* vetoed halo particles while $BV1$ and $BV2$ rejected noninteracting particles. TOF measurements between $S1$ and *TOFS* were used to reject remaining contaminations (mainly K^+) in the beam.

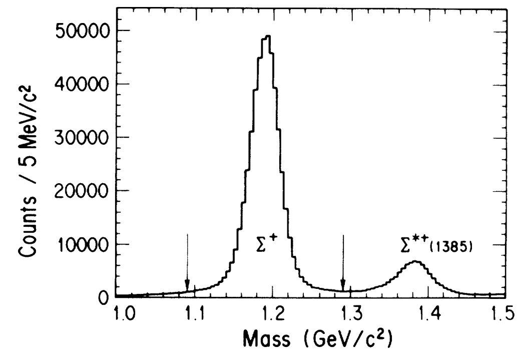

FIG. 2. Missing-mass distribution of K^+. The arrows indicate the cut position to select the Σ^+ events.

originates from the main decay $\Sigma^+ \to p\pi^0$, which has the same decay products and about a 500-times-larger branching ratio. Information available for discrimination of the signal events was the mass of missing neutrals and the direction of γ rays which was obtained from the conversion point on the γ detector and the Σ^+ decay vertex determined by the spectrometer. The direction of the γ ray is two-dimensional information and is characterized by two quantities; "acoplanarity" and "dip angle." The former is the deviation of the observed γ-ray direction from the decay plane defined by the directions of Σ^+ and proton while the latter is the angle between the observed γ-ray direction projected onto the decay plane and the direction kinematically expected for the $\Sigma^+ \to p\gamma$ decay (see Fig. 3). The strategy taken was to observe a concentration of the events at the origin of the dip-angle–acoplanarity plane after a cut on the mass of missing neutrals. In the actual analysis, however, this cut was replaced by a cut on its kinematically equivalent quantity, the proton laboratory momentum P_p. It selected the events with $-0.5\sigma_M < \Delta P_p^M < +1.5\sigma_M$, where ΔP_p^M is the deviation of the proton laboratory momentum measured by the magnetic spectrometer from that expected for the $\Sigma^+ \to p\gamma$ decay, and σ_M denotes its resolution ($\sigma_M \simeq 30$ MeV/c). In addition, the TOF system provided independent and useful measurement on P_p. Hence, a similar software cut selected the events with $-1.0\sigma_T < \Delta P_p^T < +3.0\sigma_T$, where ΔP_p^T and σ_T are the corresponding quantities determined by the TOF system ($\sigma_T \simeq 30$ MeV/c). The two requirements above (referred to as proton momentum cut) removed 98.6% of the background events while retaining 53% of the signal events. The proton momentum cut played an essential role in the discrimination of the signal events although some other minor cuts were also applied. Figure 4 shows

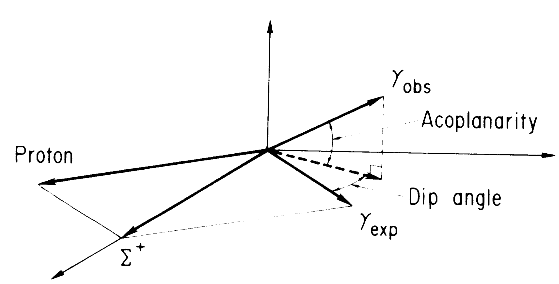

FIG. 3. Definition of acoplanarity and dip angle. γ_{obs}: direction of the observed γ ray; γ_{exp}: direction of the γ ray kinematically expected from the observed proton and Σ^+ momenta. The decay plane is defined by the directions of proton and Σ^+.

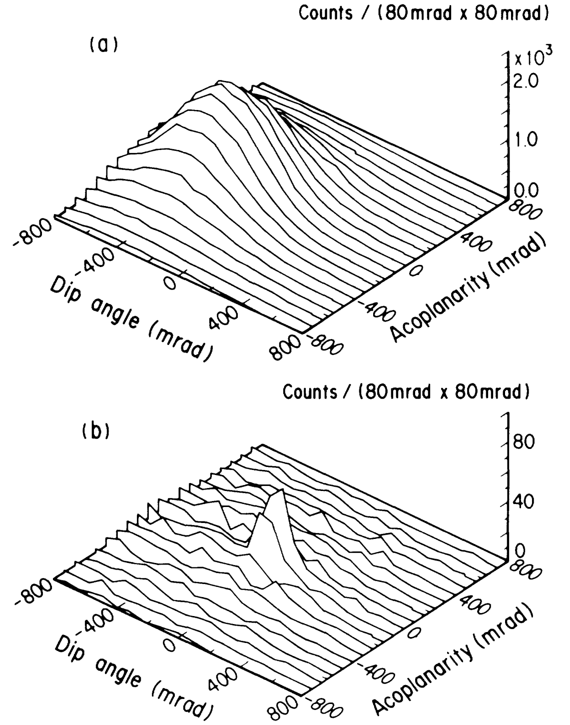

FIG. 4. Distributions of the γ rays in the dip-angle–acoplanarity plane (a) before and (b) after the proton momentum cut.

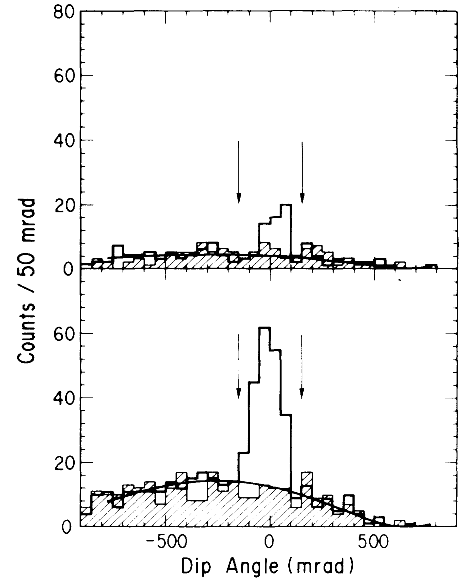

FIG. 5. Dip-angle distributions of the γ rays after the acoplanarity cut selecting the events with $|\text{acoplanarity}| < 120$ mrad. Two subsets of the data with positive $\cos\vartheta_p$ (above) and with negative $\cos\vartheta_p$ (below) are shown together with the estimated background shapes (solid lines) and the distributions of events after the "off-centered" acoplanarity cut (hatched distributions). See text for details.

the γ ray distributions in the dip-angle–acoplanarity plane before and after the proton momentum cut. A clear signal peak can be seen at the origin of Fig. 4(b) over a broad background due to the $\Sigma^+ \rightarrow p\pi^0$ events. It was confirmed by a Monte Carlo simulation that no such peak can be generated by the software cuts on pure $\Sigma^+ \rightarrow p\pi^0$ events.

The background subtraction and the determination of α_γ were done as follows. At first, the events displayed in Fig. 4(b) were divided into two subsets of the data depending on the sign of $\cos\vartheta_p$. Then the events with $|\text{acoplanarity}| \leq 120$ mrad were selected (acoplanarity cut). The dip-angle distributions of events thus obtained are shown in Fig. 5. The background shapes, shown by the solid lines in Fig. 5, were determined by fitting polynomials to the distribution outside the peak region. Here the peak region is defined by $|\text{dip angle}| \leq 150$ mrad, and is shown in Fig. 5 by the interval between the two arrows. After subtracting off the background events, the numbers of the $\Sigma^+ \rightarrow p\gamma$ events were given by counts inside the peak region. The resultant numbers are $N^+ = 35.9 \pm 9.1$ and $N^- = 154.9 \pm 17.4$, where + and − denote the sign of $\cos\vartheta_p$. The quoted errors contain uncertainty in the background subtraction as well as the statistical one. If the acoplanarity cut was displaced to the "off-centered" position defined by 120 mrad $\leq |\text{acoplanarity}| \leq 240$ mrad, the peak in the dip-angle distribution disappeared as expected (the hatched distributions in Fig. 5).

The asymmetry parameter α_γ may naively be calculated as the raw asymmetry $A = (N^+ - N^-)/(N^+ + N^-)$ divided by the product of the average polarization of Σ^+ ($\simeq 0.87$) and average $|\cos\vartheta_p|$ of the detector acceptance ($\simeq 0.80$). In the actual analysis, however, a detailed Monte Carlo simulation was carried out to take into account the geometrical acceptance of the detectors, the efficiency of the γ detectors, the effects of various software cuts, etc. This simulation provided the precise relation between A and α_γ. The asymmetry parameter thus obtained is $\alpha_\gamma = -0.86 \pm 0.13$. The systematic error was estimated to be ± 0.04. Sources of the systematic error were uncertainty in the polarization of Σ^+ (0.02), that in the property of the γ detectors (0.02), that in the influence of the software cuts (0.02), and unknown local inefficiency of the counters and/or the chambers (0.02).

The stability of α_γ was checked: Various software cuts were tried, and α_γ was determined from the acoplanarity distribution after the dip-angle cut. They all gave values consistent with the value quoted above. Purely strong-interaction events $\pi^+ p \rightarrow \pi^+ p\pi^0$ were used to check the false asymmetry; the asymmetry of the direction of the outgoing proton relative to the scattering plane was found to be consistent with zero. Various properties of the $\Sigma^+ \rightarrow p\gamma$ events were examined and found to be consistent with the expectations. These included the mass and lifetime of the decaying Σ^+ and the c.m. angular distribution of the proton. The width of the signal peak in the dip-angle–acoplanarity plane was confirmed to be consistent with that obtained by the Monte Carlo simulation. Finally, the branching ratio was also determined in this experiment and was found to be

$$\Gamma(\Sigma^+ \rightarrow p\gamma)/\Gamma(\Sigma^+ \rightarrow \text{all}) = (1.30 \pm 0.15) \times 10^{-3}.$$

This value is consistent with previous measurements.[2,9]

In summary, the first counter experiment to measure the asymmetry parameter for the $\Sigma^+ \rightarrow p\gamma$ decay has been carried out. A large number of highly polarized Σ^+'s were produced by the reaction $\pi^+ p \rightarrow K^+ \Sigma^+$. All final particles including γ rays were detected. The asymmetry parameter is found to be $\alpha_\gamma = -0.86 \pm 0.13(\text{statistical}) \pm 0.04(\text{systematic})$ from a sample of about 190 $\Sigma^+ \rightarrow p\gamma$ events. Our result has confirmed with a better accuracy the large and negative value for α_γ obtained by the two previous bubble-chamber experiments. The value of α_γ is proved to be a real challenge to the present theory. The branching ratio is also found to be $(1.30 \pm 0.15) \times 10^{-3}$.

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