Search for Direct *CP* Violation in Nonleptonic Decays of Charged Ξ and Λ Hyperons

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A search for direct *CP* violation in the nonleptonic decays of hyperons has been performed. In comparing the product of the decay parameters, $\alpha_\Xi \alpha_\Lambda$, in terms of an asymmetry parameter, $A_{\Xi\Lambda}$, between hyperons and antihyperons in the charged $\Xi \to \Lambda\pi$ and $\Lambda \to p\pi$ decay sequence, we found no evidence of direct *CP* violation. The parameter $A_{\Xi\Lambda}$ was measured to be 0.012 ± 0.014.

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A few years after the discovery of charge-conjugation/parity (*CP*) violation in the neutral-kaon decay [1], Sakharov suggested that this *CP* asymmetry was one of the three conditions necessary for explaining the domination of matter over antimatter in the Universe [2]. To date, *CP* nonconservation is seen only in K_L^0 decays, and the origin of this phenomenon remains a mystery.

In 1958, Okubo pointed out that time reversal (T) invariance, or *CP* symmetry under *CPT* conservation, could be tested by establishing the equality of the partial decay rates between Σ^+ and its charge-conjugate decay [3]. Pais independently stressed that if *CP* symmetry is exact the slope parameter, α_Λ, of the $\Lambda^0 \to p\pi^-$ decay should be equal in magnitude but opposite in sign to $\alpha_{\overline{\Lambda}}$ of the $\overline{\Lambda}^0 \to \overline{p}\pi^+$ decay [4]. However, quantitative analysis on the validity of *CP* conservation in nonleptonic hyperon decays was not available until the early 1980s. Contrary to the *CP* asymmetry of K_L^0 observed in 1964, which is related to K^0-$\overline{K}^0$ mixing and is called indirect *CP* violation, *CP* nonconservation in the strange-baryon sector is classified as direct *CP* violation, recently observed in neutral-kaon decay [5], and is due to different dynamics in the decay of a hyperon and its antiparticle. Models other than the superweak type [6] generally predict that *CP* symmetry is broken in strange-baryon decays [7,8]. Recasting Pais's proposal we define an asymmetry A_Λ,

$$A_\Lambda = \frac{\alpha_\Lambda + \alpha_{\overline{\Lambda}}}{\alpha_\Lambda - \alpha_{\overline{\Lambda}}}, \tag{1}$$

for the Λ decay. The amount of *CP*-odd effect is found to depend on the strong phase shifts of the final state of the decay and the *CP* violating weak phases which are model dependent. A_Λ is estimated to be $(2\text{–}5) \times 10^{-5}$ in the standard model [8], but it can be as large as a few times 10^{-4} in the other models [9]. For the charged $\Xi \to \Lambda\pi$ decay, A_Ξ is expected to be smaller than A_Λ by about a factor of 10 because the strong phase shifts of the $\Lambda\pi$ final state are predicted to be small [10].

There have been three experimental searches for *CP* violation in Λ decay reported [11–13]. The most precise result came from PS185 with $A_\Lambda = -0.013 \pm 0.022$ [12]. There is no measurement available for A_Ξ.

In this Letter we present the result on a new search for direct *CP* violation in hyperon decay by determining the sum of A_Λ and A_Ξ. In our experiment, E756, the search was performed with polarized $\Lambda^0(\overline{\Lambda}^0)$ obtained from the decay of polarized $\Xi^-(\overline{\Xi}^+)$. According to the Lee-Yang formula, the polarization of the daughter Λ, $\mathbf{P}_\Lambda$, in the Λ rest frame is related to the polarization of Ξ, $\mathbf{P}_\Xi$, in its rest frame by [14]

$$\mathbf{P}_\Lambda = \frac{(\alpha_\Xi + \mathbf{P}_\Xi \cdot \hat{\mathbf{p}}_\Lambda)\hat{\mathbf{p}}_\Lambda + \beta_\Xi \mathbf{P}_\Xi \times \hat{\mathbf{p}}_\Lambda + \gamma_\Xi \hat{\mathbf{p}}_\Lambda \times (\mathbf{P}_\Xi \times \hat{\mathbf{p}}_\Lambda)}{(1 + \alpha_\Xi \mathbf{P}_\Xi \cdot \hat{\mathbf{p}}_\Lambda)}, \tag{2}$$

where $\hat{\mathbf{p}}_\Lambda$ is the momentum unit vector of the Λ in the Ξ rest frame, and β_Ξ and γ_Ξ are the other two decay parameters for the $\Xi \to \Lambda\pi$ decay. The distribution of the protons in the Λ helicity frame, after integrating over the solid angle of Λ in the Ξ rest frame and the azimuthal angle of the proton in the Λ helicity frame, is given by

$$\frac{dn}{d\cos\theta_{p\Lambda}} = \frac{1}{2}(1 + \alpha_\Lambda \alpha_\Xi \cos\theta_{p\Lambda}), \tag{3}$$

with $\theta_{p\Lambda}$ being the angle between the momentum of the proton and $\hat{\mathbf{p}}_\Lambda$. If *CP* is an exact symmetry, the product $\alpha_\Lambda \alpha_\Xi$ should equal $\alpha_{\overline{\Lambda}}\alpha_{\overline{\Xi}}$. By introducing an asymmetry parameter

$$A_{\Xi\Lambda} = \frac{\alpha_\Lambda \alpha_\Xi - \alpha_{\overline{\Lambda}}\alpha_{\overline{\Xi}}}{\alpha_\Lambda \alpha_\Xi + \alpha_{\overline{\Lambda}}\alpha_{\overline{\Xi}}} \simeq A_\Xi + A_\Lambda, \tag{4}$$

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CP symmetry can be studied in the $\Xi \to \Lambda\pi$, $\Lambda \to p\pi$ decay sequence. A nonzero value for $A_{\Xi\Lambda}$ will signal the breaking of CP invariance in the decay.

The goals of E756 were to measure the production polarization and magnetic moments of hyperons [15–17]. Our experiment was carried out in the Proton Center beam line at Fermilab. Figure 1 shows the plan view of the spectrometer. The details of the experiment can be found in [16] and references therein. An 800 GeV proton beam, with a typical intensity of 3×10^{10} protons in 23 sec, was used to produce Ξ^- by striking a 0.2 cm × 0.2 cm × 9.2 cm long beryllium target at an angle of 2.4 mrad in the vertical plane relative to the proton beam. The sign of the production angle was flipped regularly to minimize temporal systematic problems. The Ξ^- hyperons were momentum selected by a curved channel inside a 7.32 m long dipole magnet M1. The data presented here were collected with M1 operating at a vertical field of 2.09 T. Typically the rate of the secondary beam was on the order of 100 kHz. The momenta of the proton and the π's from the decays of the Ξ^-'s and Λ^0 were measured with eight planes of silicon strip detectors arranged in vertical and horizontal views, nine multiwire proportional chambers with wire spacing of 1 mm (C1, C2, and C3) and 2 mm (C4 to C9), and two dipole magnets, M2, which deflected charged particles in the horizontal plane with a total transverse-momentum kick of 1.5 GeV/c. The trigger for detecting the $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ decay sequence required no hit in V1 and V2, hits in both S1 and S2, an analog signal from the multiplicity counter M corresponding to at least two but less than five minimum ionizing charged particles, and a digital signal from the pion side of C8, C8R, as well as one from the proton side of C9, C9L. In some portion of the data collection, the fields of the momentum analyzing magnets were reversed, and the trigger sides of C8 and C9 were switched to C8L and C9R to improve our understanding of systematics.

To collect $\overline{\Xi}^+$ events, the incident proton intensity was reduced to an average of about 1×10^{10} protons per spill so that the secondary-beam intensity did not vary significantly from the negative mode. The production angles remained unchanged and were cycled between +2.4 and −2.4 mrad. The polarities of M1 and M2 were reversed and there was no change in the triggers. Hence the experiment was CP invariant to first order. This greatly reduced the number of potential sources of systematic bias due to changes in the spectrometer between the Ξ^- and $\overline{\Xi}^+$ runs.

In the off-line analysis, data taken with the positively and negatively charged secondary beams were processed with the same reconstruction program and subjected to identical event-selection criteria. By imposing geometric and kinematic requirements, we searched for events that satisfied the three-track two-vertex topology. The geometric χ^2 for the topological fit of the selected events was required to be less than 70 for a mean of 30 degrees of freedom. The tracks assigned to be a proton and a pion had to have a $p\pi$ invariant mass between 1.108 and 1.124 GeV/c^2. The momentum of the reconstructed Ξ candidate was required to be between 240 and 500 GeV/c, and the track had to trace back to within 0.63 cm from the center of the beryllium target in the plane normal to the length of the target. The decay vertex of Ξ was required to be within the fiducial region between the exit of the channel, $z = 0.25$ m, and $z = 23$ m. To suppress charged $K \to 3\pi$ background, the event was also reconstructed under the 3π hypothesis. The resulting 3π invariant mass was then required to be greater than 0.51 GeV/c^2. The comparison of the $\Lambda\pi$ invariant mass distributions between the Ξ^- and $\overline{\Xi}^+$ samples before the final mass selection is shown in Fig. 2. The mass resolution and backgrounds of the samples agreed well, indicating that the difference between the Ξ^- and $\overline{\Xi}^+$ runs were indeed small. Only events with the $\Lambda\pi$ invariant mass between 1.309 and 1.333 GeV/c^2 were used for analysis.

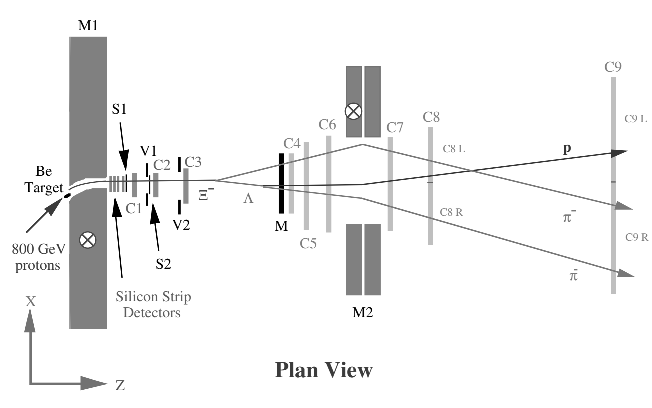

FIG. 1. Plan view of the E756 spectrometer (not to scale). The x dimensions of the silicon strip detectors and C9 are 3 cm and 1.2 m, respectively. C9 is located at 62.3 m from the exit of the collimator through M1.

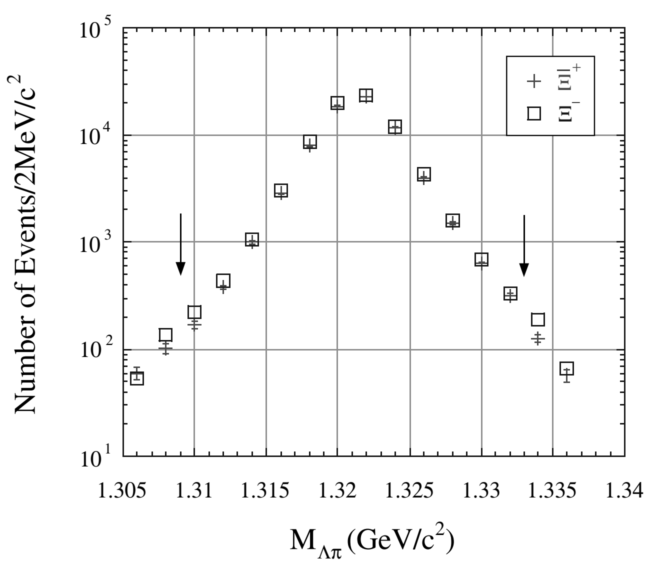

FIG. 2. Distributions of $\Lambda\pi$ invariant mass with all event-selection requirements applied except the cut on $\Lambda\pi$ invariant mass. Events between the arrows were used for analysis.

The acceptance that affected the $\cos\theta_{p\Lambda}$ distribution given in Eq. (3) was determined with the hybrid Monte Carlo (HMC) method [18] before the value of $\alpha_{\Xi}\alpha_{\Lambda}$ was calculated for the Ξ^- and the $\overline{\Xi}^+$ samples separately. For each event, up to 200 HMC events were generated with a uniform distribution in $\cos\theta_{p\Lambda}$, but the rest of the kinematic quantities such as decay vertices and the momentum of the Λ were taken from the data. The event was included in the asymmetry measurement when 10 of the generated HMC events satisfied all the requirements in the software that simulated the geometry of the spectrometer, any dead channels in the wire chambers, and the triggers.

To measure $\alpha_{\Xi}\alpha_{\Lambda}$, data taken at $+2.4$ and -2.4 mrad were combined to form effectively unpolarized Ξ^- and $\overline{\Xi}^+$ samples. Based on about 63 000 $\overline{\Xi}^+$ decays $\alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}$ was found to be -0.2894 ± 0.0073. Three independent Ξ^- samples, each with approximately 63 000 events, were selected from a larger pool of events in such a way that the resulting momentum distribution of each Ξ^- sample was identical to that of the $\overline{\Xi}^+$. In doing so the difference in the momentum-dependent acceptance between the Ξ^- and $\overline{\Xi}^+$ samples was minimized. The values of $\alpha_{\Xi}\alpha_{\Lambda}$ for these data sets were determined to be -0.2955 ± 0.0073, -0.3041 ± 0.0073, and -0.2894 ± 0.0073, giving an average of -0.2963 ± 0.0042. These results are in good agreement with the world values [19]. To study the stability of the measurement as a function of the Ξ momentum, each sample was subdivided into three momentum bins. As shown in Fig. 3, the results are stable. Another systematic study was done by changing the requirement of the upstream position of the Ξ decay vertex from 0.25 to 0.50 m, which was a one-standard-deviation variation. In this case, the values of $\alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}$ and $\alpha_{\Xi}\alpha_{\Lambda}$ for the samples were found to be -0.2876 ± 0.0075, -0.2940 ± 0.0074, -0.3044 ± 0.0074, and -0.2896 ± 0.0075, respectively, showing no significant deviation from the results obtained with the full samples. Using the value of -0.2894 ± 0.0073 for $\alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}$ and -0.2963 ± 0.0042 for $\alpha_{\Xi}\alpha_{\Lambda}$, we determined $A_{\Xi\Lambda}$ to be 0.012 ± 0.014.

At the 10^{-2} level, the major systematic effects could come from the differences in acceptances between hyperon and antihyperon decays, and the polarization of the Ξ^- and $\overline{\Xi}^+$ in the production process. To investigate these systematics, the difference in $\alpha_{\Xi}\alpha_{\Lambda}$ between two samples was determined directly without unfolding the acceptance in $\cos\theta_{p\Lambda}$. Two data sets can be compared by defining

$$R(\cos\theta_{p\Lambda}) = \frac{\epsilon_1(\cos\theta_{p\Lambda})}{\epsilon_2(\cos\theta_{p\Lambda})} \frac{[1 + (\alpha_\Lambda\alpha_\Xi)_1 \cos\theta_{p\Lambda}]}{[1 + (\alpha_\Lambda\alpha_\Xi)_2 \cos\theta_{p\Lambda}]}, \quad (5)$$

where $R(\cos\theta_{p\Lambda})$ is the ratio of the probabilities of getting $\cos\theta_{p\Lambda}$ in the two samples, and the ϵ's are the acceptance functions of the $\cos\theta_{p\Lambda}$ distributions.

When two sets of Ξ^- events are compared, R is a measure of how well the acceptances agree. Since R was uniform in $\cos\theta_{p\Lambda}$, it was parametrized as $a + b\cos\theta_{p\Lambda}$. Based on 835 000 Ξ^- events with a mean momentum of 318.7 GeV/c and an average polarization of about -10% [15], and 732 000 Ξ^- decays with a mean momentum of 319.3 GeV/c but a polarization of $+10\%$, the parameters a and b of the comparison were found to be 1.0001 ± 0.0016 and $(2.3 \pm 2.9) \times 10^{-3}$, respectively, with a reduced chi square of 0.9. With a total of over 10^7 significantly polarized Ξ^- events collected in six different run conditions, the average value of b was still consistent with zero at the 10^{-3} level [20]. This study showed that even without any corrections the acceptance in $\cos\theta_{p\Lambda}$ was momentum dependent, but was insensitive to the polarization of the Ξ^- or other systematic effects in the experiment. This unique feature is due to the fact that the unit vector $\hat{\mathbf{p}}_\Lambda$ defining the helicity frame changes from event to event over the entire phase space in the Ξ rest frame. Any systematic bias due to local inefficiencies of the experiment in the laboratory is mapped into a broad range of $\cos\theta_{p\Lambda}$ and thus highly diluted. Since the residual polarizations of the "unpolarized" Ξ^- and $\overline{\Xi}^+$ samples for measuring $A_{\Xi\Lambda}$ were known to be at most 3% [15,16], using linear interpolation, the systematic bias of this residual polarization in measuring $A_{\Xi\Lambda}$ was less than 10^{-3}.

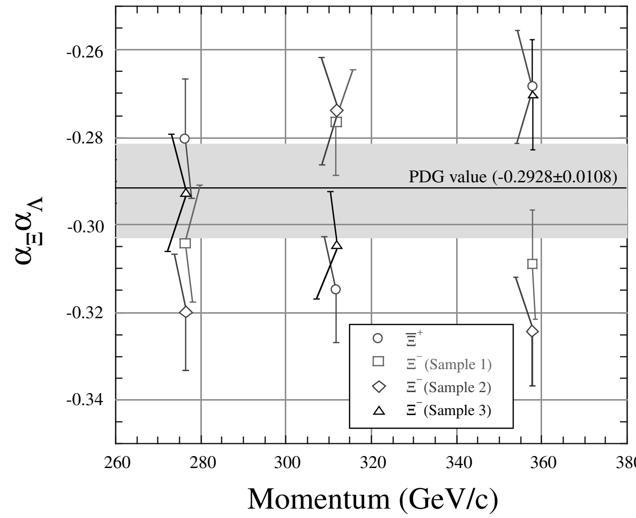

FIG. 3. Results on $\alpha_{\Xi}\alpha_{\Lambda}$ as a function of the momentum of the Ξ. The shaded area is a one-standard-deviation band centered at the world average.

Another study was done with a sample of Ξ^- events selected in such a way that the resulting Ξ^- momentum spectrum was identical to that of the $\overline{\Xi}^+$ sample. This removed any difference in the momentum spectra which are due to the different mechanisms for producing particles and antiparticles by protons, and ensured that $\epsilon(\cos\theta_{p\Lambda})$ was identical for both data sets. In this case, Eq. (5) is simply

$$R'(\cos\theta_{p\Lambda}) = \frac{1 + \alpha_\Lambda\alpha_\Xi\cos\theta_{p\Lambda}}{1 + \alpha_{\overline{\Lambda}}\alpha_{\overline{\Xi}}\cos\theta_{p\Lambda}} = \frac{1 + \alpha_\Lambda\alpha_\Xi\cos\theta_{p\Lambda}}{1 + (\alpha_\Lambda\alpha_\Xi - D)\cos\theta_{p\Lambda}}, \quad (6)$$

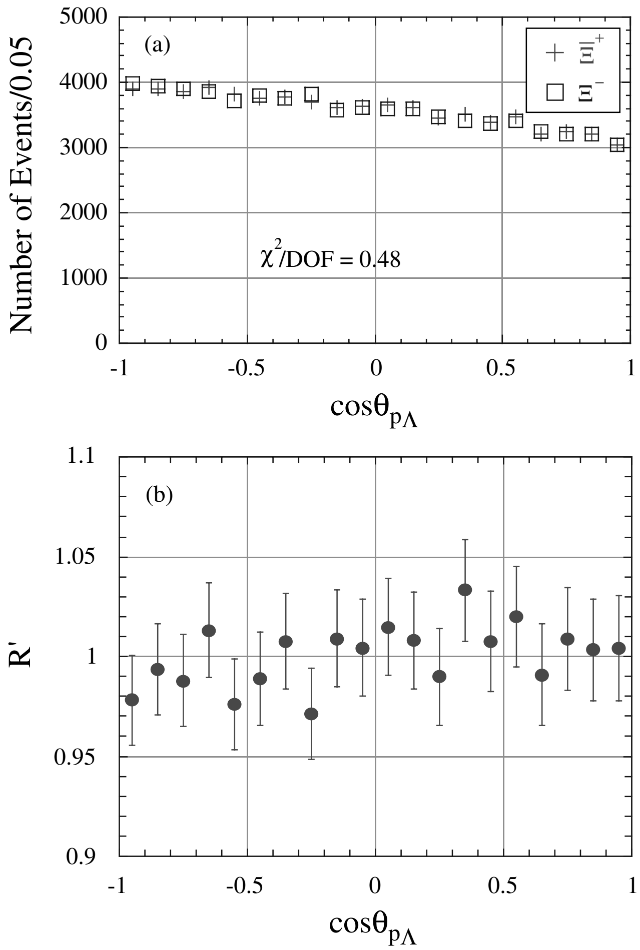

FIG. 4. Comparison of $\overline{\Xi}^+$ and Ξ^- events after the momentum distributions are normalized. The $\cos\theta_{p\Lambda}$ distributions are shown in (a). R' as a function of $\cos\theta_{p\Lambda}$ is shown in (b).

where $\alpha_\Lambda \alpha_\Xi$ is taken to be -0.2928 [19], and $D = \alpha_\Lambda \alpha_\Xi - \alpha_{\overline{\Lambda}} \alpha_{\overline{\Xi}}$ can be determined by fitting R' as a function of $\cos\theta_{p\Lambda}$. With approximately 70 000 Ξ^- events along with an equal number of $\overline{\Xi}^+$ decays, the comparison of $\cos\theta_{p\Lambda}$ distributions of the Ξ samples, and the resulting R', are shown in Fig. 4. Again, with no acceptance correction, the $\theta_{p\Lambda}$ distributions agree well. D was found to be -0.011 ± 0.009. This implied that $A_{\Xi\Lambda}$ was 0.019 ± 0.015, which was consistent with the result obtained with the HMC method. As a check, another sample of Ξ^- events was picked to repeat the measurement, which yielded a result of 0.008 ± 0.015 for $A_{\Xi\Lambda}$; again, no disagreement was observed.

In summary, we have searched for direct *CP* violation in nonleptonic decays of charged Ξ and Λ by determining the asymmetry parameter $A_{\Xi\Lambda}$. With approximately 70 000 $\overline{\Xi}^+$ and 210 000 Ξ^- decays, we obtained a result of 0.012 ± 0.014 for $A_{\Xi\Lambda}$. Based on the result of $A_\Lambda = -0.013 \pm 0.022$ from PS185, we deduced A_Ξ to be 0.025 ± 0.026. Our results are consistent with no *CP* violation at the 10^{-2} level in the nonleptonic decays of charged Ξ and Λ.

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