Search for Direct CP Violation in Non-Leptonic Decays of Charged Ξ and Λ Hyperons

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Abstract

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

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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 anti-matter in the Universe [2]. To date, CP nonconservation is only seen in $K^0_L$ 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 $\Sigma^+$ and its charge-conjugate decay [3]. Pais independently stressed that if CP symmetry is exact the slope parameter, $\alpha_\Lambda$, 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 non-leptonic hyperon decays was not available until the early 1980’s. Contrary to the CP asymmetry of $K^0_L$ 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 and is due to different dynamics in the decay of a hyperon and its antiparticle. Models other than the superweak type [5] generally predict that CP symmetry is broken in strange-baryon decays [6–11]. Recasting Pais’s proposal an asymmetry $A_\Lambda$ is defined as

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

for the $\Lambda$ 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. $A_\Lambda$ is estimated to be $(2 - 5) \times 10^{-5}$ in the standard model [12,13], but it can be as large as a few times $10^{-4}$ in the other models [12,14]. For the charged $\Xi \to \Lambda\pi$ decay, $A_\Xi$ is expected to be smaller than $A_\Lambda$ by about a factor of ten because the strong phase shifts of the $\Lambda\pi$ final state are predicted to be small [15].

There have been three experimental searches for CP violation in $\Lambda$ decay reported [16–18]. The most precise result came from PS185 at LEAR with $A_\Lambda = -0.013 \pm 0.022$. There is no measurement available for $A_\Xi$. 

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In this letter we present the result on a new search for direct CP violation in hyperon decay by determining the sum of $A_{\Lambda}$ and $A_{\Xi}$. In our experiment, E756, the search was performed with polarized $\Lambda^0(\bar{\Lambda}^0)$ obtained from the decay of polarized $\Xi^- (\Xi^+)$. According to the Lee-Yang formula, the polarization of the daughter $\Lambda$, $P_\Lambda$, in the $\Lambda$ rest frame is related to the polarization of $\Xi$, $P_\Xi$, in its rest frame by

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

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

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

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

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

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

Our experiment was carried out in the Proton Center beam line at Fermilab. Fig. 1 shows the plan view of the spectrometer. The details of the experiment can be found in [20] and references therein. An 800 GeV proton beam, with a typical intensity of $3 \times 10^{10}$ protons in 23 sec, was used to produce $\Xi^-$ by striking a $0.2 \text{ cm} \times 0.2 \text{ cm} \times 9.2 \text{ cm}$-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 $\Xi^-$ 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.
momenta of the proton and the π’s from the decays of the Ξ⁻’s and Λ⁰ 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 Ξ⁻ → Λπ⁻, Λ → pπ⁻ 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, and 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 Ξ⁺ events, the incident proton intensity was reduced to an average of about 1 × 10¹⁰ 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 Ξ⁺ runs.

In the offline 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, events that satisfied the three-track two-vertex topology were searched for. The geometric χ² 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 pπ invariant mass between 1.108 and 1.124 GeV/c². The momentum of the reconstructed Ξ candidate was required to be between 240 GeV/c 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 $3\pi$ hypothesis. The resulting $3\pi$ 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 $\Xi^-$ and $\Xi^+$ samples before the final mass selection is shown in Fig. 2. The mass resolution of the $\Xi$ and backgrounds of the samples agreed well. Only events with the $\Lambda\pi$ invariant mass between 1.309 GeV/$c^2$ and 1.333 GeV/$c^2$ were used for analysis.

Two different methods were applied to measure $A_{\Xi\Lambda}$. In the first approach, the acceptance that affected the $\cos\theta_{p\Lambda}$ distribution given in Eq. (3) was determined with the Hybrid Monte Carlo (HMC) method [21] before the value of $\alpha_{\Xi}\alpha_{\Lambda}$ was calculated for the $\Xi^-$ and the $\Xi^+$ 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 $\Lambda$ 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 and the triggers. Based on about 70,000 $\Xi^+$ decays $\alpha_{\Xi}\alpha_{\Lambda}$ was found to be $-0.2894 \pm 0.0073$. Three independent $\Xi^-$ samples, each with approximately 70,000 events, were selected from a larger pool of events in such a way that the resulting momentum distribution of each $\Xi^-$ sample was identical to that of the $\Xi^+$. In doing so the difference in the momentum-dependent acceptance between the $\Xi^-$ and $\Xi^+$ samples was reduced. The values of $\alpha_{\Xi}\alpha_{\Lambda}$ for these data sets were determined to be $-0.2955 \pm 0.0073$, $-0.3041 \pm 0.0073$, and $-0.2894 \pm 0.0073$, giving an average of $-0.2963 \pm 0.0042$. As shown in Fig. 3, these results are in good agreement with the world average [22] and were stable with respect to the momentum of the $\Xi$. This method gave a value of $0.012 \pm 0.014$ for $A_{\Xi\Lambda}$. The systematic uncertainty, estimated by varying some of the event-selection requirements, was insignificant.

In the second approach, the difference in $\alpha_{\Xi}\alpha_{\Lambda}$ between $\Xi^-$ and $\Xi^+$ was determined directly without unfolding the acceptance in $\cos\theta_{p\Lambda}$. Two data sets can be compared by defining
\[
R(\cos \theta_{p\Lambda}) = \frac{\epsilon_1(\cos \theta_{p\Lambda})}{\epsilon_2(\cos \theta_{p\Lambda})} \left[ 1 + (\alpha_\Lambda \alpha_\Xi) \cos \theta_{p\Lambda} \right] \quad (5)
\]

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

When two sets of \( \Xi^- \) events are compared, \( R \) is a measure of how well the acceptances agree. Without any corrections, detailed studies showed that the acceptance in \( \cos \theta_{p\Lambda} \) was strongly dependent on the momentum of the \( \Xi^- \), but was insensitive to the polarization of the \( \Xi^- \) or other variations in the experiment, and that \( R \) was consistent with unity and independent of \( \cos \theta_{p\Lambda} \) down to a few \( \times 10^{-3} \) level \[23\]. 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 rest frame of the \( \Xi \). Any systematic bias due to local inefficiencies of the experiment in the laboratory is mapped into a wide range of \( \cos \theta_{p\Lambda} \) and thus highly diluted.

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

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

where \( \alpha_\Lambda \alpha_\Xi \) is taken to be \(-0.2928 \[22\], and \( D = \alpha_\Lambda \alpha_\Xi - \alpha_\Xi \alpha_\Xi \) can be determined by fitting \( R' \) as a function of \( \cos \theta_{p\Lambda} \). With approximately 70,000 \( \Xi^- \) events along with equal number of \( \Xi^+ \) decays, the comparison of the momentum and \( \cos \theta_{p\Lambda} \) distributions of the \( \Xi \) samples, and the resulting \( R' \) are shown in Fig. 4. The \( \theta_{p\Lambda} \) distributions agree well, with a \( \chi^2 \) per degree of freedom of 0.45. \( D \) was found to be \(-0.011 \pm 0.009 \). This implied that \( A_{\Xi\Lambda} \) was 0.019 \( \pm 0.015 \), which was consistent with the result obtained with the HMC method. As a check, another sample of \( \Xi^- \) events was picked to repeat the measurement, which yielded a result of 0.008 \( \pm 0.015 \) for \( A_{\Xi\Lambda} \). Although this normalization method constituted a powerful
cross check for the HMC approach, it suffered from the fact that we had to rely on the measured value of $\alpha_\Lambda\alpha_\Xi$ to determine $A_{\Xi\Lambda}$. Thus, we preferred to choose the result from the HMC method as our measurement for $A_{\Xi\Lambda}$.

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

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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.
FIG. 3. Results on $\alpha_\Xi \alpha_\Lambda$ as a function of the momentum of the $\Xi$. The shaded area is a one-standard-deviation band centered at the world average.
FIG. 4. Comparison of $\Xi^+$ and $\Xi^-$ events after the momentum distributions are normalized. The momentum distributions are shown in (a). The $\cos \theta_{p\Lambda}$ distributions are shown in (b). $R'$ as a function of $\cos \theta_{p\Lambda}$ is shown in (c).