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Search for Direct CP Violation in Ξ Hyperon Decay

CLEO Collaboration

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Abstract

Using data collected with the CLEO II detector we have performed a search for direct CP violation in the Ξ hyperon system. CP violation gives rise to an asymmetry, $\mathcal{A}$, between the parity-violating angular distributions of the decay chains $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ and $\bar{\Xi}^+ \to \bar{\Lambda}\pi^+$, $\bar{\Lambda} \to \bar{p}\pi^+$. In the Standard Model, $\mathcal{A} \approx 10^{-4}$ to 10^{-5}. If CP violation were found at a higher level it could indicate the presence of new physics. We find no evidence for CP violation: $\mathcal{A} = -0.057 \pm 0.064 \pm 0.039$. We also obtain $A_\Xi = -0.070 \pm 0.064 \pm 0.045$ and $\alpha_{\bar{\Xi}} = 0.49^{+0.06}_{-0.05} \pm 0.10$.

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To date CP violation has only been observed in the neutral kaon system [1] and its origin remains unknown. It is believed that there is insufficient CP violation in the minimal standard model (MSM) to generate the matter-antimatter asymmetry of the universe [2]. Searches for additional CP violation beyond the MSM may help reconcile this problem.

In the MSM CP violation effects are due to a single complex phase in the CKM quark mixing matrix [3]. In the standard phase convention the two matrix elements with large phases are V_{ub} and V_{td}. Because these elements have small magnitudes and involve the third generation, CP violation in kaon decays is small. In the kaon system, ϵ is a measure of CP violation due to mixing [4] and ϵ' is a measure of CP violation in the decay amplitude, called direct CP violation. Theoretical errors are too large to interptret the measured value of ϵ'/ϵ as evidence for the MSM mechanism of CP violation or for physics beyond the MSM. In the MSM, and its extensions, large CP-violating effects are anticipated in B meson decays. CP violation may also be observed by comparing $\Delta S = 1$ hyperon and antihyperon non-leptonic decays [5,6]. The latter is the subject of this Letter.

In hyperon and kaon decay gluonic penguin transitions [7] are thought to give rise to the relative weak phase difference between particle and antiparticle amplitudes. In kaon decays the interference is between the two isospin amplitudes, whereas in Ξ decay it is between the S and P wave amplitudes. Consequently, in Ξ decay the CP violation observable is not a rate difference but a difference, $\mathcal{A}$, in the degree of parity violation in charge conjugate states. MSM predictions of $\mathcal{A}$ depend on the values of ϵ, the top quark mass and the hadronic matrix element. The dominant uncertainty is due to incomplete knowledge of the hadronic matrix element. The Superweak model [8] and models with a very heavy neutral Higgs where there are no $|\Delta S| = 1$ CP-odd effects predict no CP asymmetries. Other models in which $|\Delta S| = 1$ CP nonconservation is dominant, predict asymmetries which are on the order of, or larger than those in the MSM. Theoretical predictions of A_Ξ and A_Λ range from 10^{-4} to 10^{-5} [9–11].

Parity violation occurs in hyperon $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+ 0$ decays due to the existence of two orbital angular momentum amplitudes of opposite parity. The parity violation observable is an asymmetry in the angular decay distribution due to interference between the two amplitudes. In the decay $\Xi^- \rightarrow \Lambda\pi^-$ followed by $\Lambda \rightarrow p\pi^-$, the Λ is produced with a polarization equal to

$$\mathbf{P_\Lambda} = \frac{(\alpha_\Xi + \hat{\mathbf{\Lambda}} \cdot \mathbf{P_\Xi})\hat{\mathbf{\Lambda}} - \beta_\Xi(\hat{\mathbf{\Lambda}} \times \mathbf{P_\Xi}) - \gamma_\Xi \hat{\mathbf{\Lambda}} \times (\hat{\mathbf{\Lambda}} \times \mathbf{P_\Xi})}{(1 + \alpha_\Xi \hat{\mathbf{\Lambda}} \cdot \mathbf{P_\Xi})} \tag{1}$$

where $\boldsymbol{P_\Xi}$ is the Ξ polarization, α_Ξ, β_Ξ and γ_Ξ are the Ξ asymmetry parameters, which measure the degree of parity violation in Ξ decay, and $\hat{\mathbf{\Lambda}}$ is a unit vector along the Λ momentum in the Ξ rest frame [12]. If the Ξ polarization is unobserved, or if the Ξ is not polarized, Equation 1 reduces to $\mathbf{P_\Lambda} = \alpha_\Xi \hat{\mathbf{\Lambda}}$. The angular distribution of the proton from the decay of the Λ is therefore

$$\frac{dN}{d\cos\theta_\Lambda} \propto 1 + \alpha_\Xi \alpha_\Lambda \cos\theta_\Lambda \tag{2}$$

where θ_Λ is the angle between the proton momentum vector in the Λ rest frame and $\hat{\mathbf{\Lambda}}$, and α_Λ is the Λ decay asymmetry which measures the degree of parity violation in Λ decay. If

CP is conserved in the decays $\Lambda \to p\pi$ and $\Xi \to \Lambda\pi$, $\alpha_\Lambda = -\alpha_{\bar{\Lambda}}$ and $\alpha_\Xi = -\alpha_{\bar{\Xi}}$, respectively. Therefore the CP-violating asymmetry parameters, A_Λ and A_Ξ, are defined as [6]

$$A_\Lambda = \frac{\alpha_\Lambda + \alpha_{\bar{\Lambda}}}{\alpha_\Lambda - \alpha_{\bar{\Lambda}}} \text{ and } A_\Xi = \frac{\alpha_\Xi + \alpha_{\bar{\Xi}}}{\alpha_\Xi - \alpha_{\bar{\Xi}}}. \tag{3}$$

If CP is conserved in the decay sequence $\Xi \to \Lambda\pi$, $\Lambda \to p\pi$, $\alpha_\Xi\alpha_\Lambda = \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}$. Therefore we measure the CP-violating asymmetry parameter [14]:

$$\mathcal{A} = \frac{\alpha_\Xi\alpha_\Lambda - \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}}{\alpha_\Xi\alpha_\Lambda + \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}} = A_\Xi + A_\Lambda + \mathcal{O}(\Delta\alpha_\Xi\Delta\alpha_\Lambda) \simeq A_\Xi + A_\Lambda \tag{4}$$

where $\Delta\alpha_{\Xi,\Lambda} = \alpha_{\Xi,\Lambda} + \alpha_{\bar{\Xi},\bar{\Lambda}}$.

The data sample in this study was collected with the CLEO II detector [15] at the Cornell Electron Storage Ring (CESR). The integrated luminosity consists of 4.83 fb^{-1} taken at and just below the $\Upsilon(4S)$ resonance, corresponding to approximately 5 million $e^+e^- \to c\bar{c}$ and 1.25 million $e^+e^- \to s\bar{s}$ events. The latter process is the dominant source of Ξ's in this analysis.

The Λ is reconstructed in the $p\pi^-$ decay mode[1]. We require two oppositely charged tracks to originate from a common vertex. The positive track is required to be consistent with a proton hypothesis[2]. The momentum of the Λ candidate is calculated by extrapolating the charged track momenta to the secondary vertex. The invariant mass of Λ candidates is required to be within three standard deviations (3σ = 6.0 MeV/c^2) of the known Λ mass. Track combinations which satisfy interpretation as $K_s^0 \to \pi^+\pi^-$ are rejected. Combinatoric background is reduced by requiring the momentum of the Λ candidates to be greater than 800 MeV/c. Due to this requirement B decays are not a signifcant source of Ξ's.

The Ξ^- is reconstructed in the $\Lambda\pi^-$ decay mode. Ξ^- candidates are formed by combining each Λ candidate with a negatively charged track consistent with a pion hypothesis. The Ξ^- candidate vertex is formed from the intersection of the Λ momentum vector and the negatively charged track. To obtain the Ξ^- momentum, and $\Lambda\pi$ invariant mass, the momentum of the charged track is recalculated at the new vertex. The invariant $\Lambda\pi$ mass is shown in Fig. 1 for all Ξ^- candidates satisfying the selection criteria.

The $\Lambda\pi$ mass is fit is to a double Gaussian with widths and ratio of areas fixed from a GEANT [16] based Monte Carlo (MC) simulation of the detector and a first order Chebyshev polynomial to describe the combinatorial background. The $\Xi \to \Lambda\pi$ events are generated using LUND/JETSET 7.3 [17], in the process $e^+e^- \to s\bar{s} \to \Xi X$. The MC momentum distributions and production angles of all particles in the decay chain are in good agreement with observation. We find 8434 ± 109 events consistent with $\Xi \to \Lambda\pi$. The mean of the $\Lambda\pi$ invariant mass distribution is in agreement with the MC simulation.

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[1]Charge conjugation is implied in this paper except were explicitly noted

[2]Hadronic particles are identified by requiring specific ionization energy loss measurements (dE/dx), combined with time-of-flight (TOF) information when available. The two measurements are combined into a joint probability for the particle to be a pion, a kaon or a proton. A charged track is defined to be consistent with a particle hypothesis if its probability is greater than 0.003.

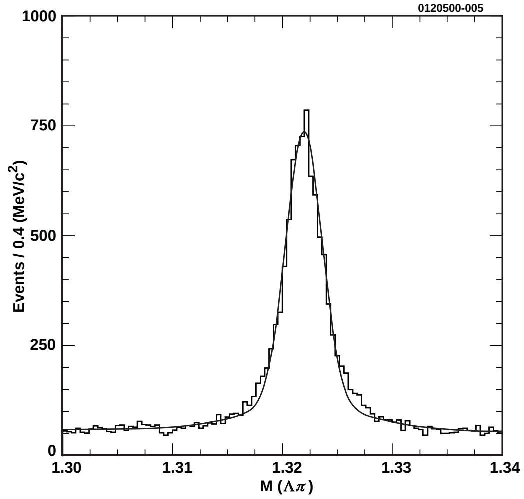

FIG. 1. $\Lambda\pi^-$ invariant mass distribution.

The $\cos\theta_\Lambda$ resolution function has both Gaussian and symmetric non-Gaussian components. The resolution in $\cos\theta_\Lambda$, σ_{av}, defined to be the average of the rms variance of the two components, weighted by their relative normalizations is $\sigma_{av} = 0.030$.

The product of the decay asymmetry parameters, $\alpha_\Xi\alpha_\Lambda$, is measured using a one dimensional unbinned maximum likelihood fit to the $\cos\theta_\Lambda$ distribution given in Equation 2, in a manner similar to [18]. This technique enables a likelihood fit to be performed to variables modified by experimental acceptance and resolution. The probability function of the signal Γ_s is determined by generating one high statistics MC sample of $\Xi^- \to \Lambda\pi^-$ at fixed $\alpha_\Xi\alpha_\Lambda$. By suitable weighting of the accepted MC events a likelihood is evaluated for each data event for trial values of $\alpha_\Lambda\alpha_\Xi$, and a fit performed. The probability for each event is determined by sampling Γ_S using an interval centered on each data point.

Background is incorporated directly into the fit by constructing the log-likelihood function: $\ln\mathcal{L} = \sum_{i=1}^{N} ln(P_S\Gamma_S + P_B\Gamma_B)$ where N is the number of events in the signal region, defined to be within 7.5 Mev/c^2 ($\pm3\sigma$) of the Ξ mass, and P_S and P_B are the probabilities that events are signal and background respectively. The probability distribution of background in the signal region, Γ_B, is determined from 15 MeV/c^2 wide ($\Lambda\pi$) mass sidebands above and below the signal region.

To ensure that there is no gross bias in the analysis technique we assume CP conservation and determine the decay asymmetry in $\Xi^- \to \Lambda\pi^-$, combining Ξ^+ and Ξ^- events. We find $\alpha_{\Xi,\bar{\Xi}}\alpha_{\Lambda,\bar{\Lambda}} = -0.291 \pm 0.021$ where the error is statistical. The result is in good agreement with the world average $\alpha_\Xi\alpha_\Lambda = -0.293 \pm 0.007$ [13].

We have considered the following sources of systematic uncertainties and give our estimate of their magnitude in parentheses. The error associated with finite MC statistics is estimated by varying the size of the MC sample used in the fit (1.6%). The uncertainty from varying the Λ selection criteria and particle identification is ($-6.3\%, +2.1\%$). The uncertainty associated with MC modeling of slow pions from Ξ and Λ decay is obtained by varying the slow pion reconstruction efficiency according to our understanding of the CLEO II detector ($-0.0\%, +0.7\%$). The error due to finite interval size is determined by varying the size of the interval for both signal and background ($-0.5\%, +4.1\%$). The uncertainty

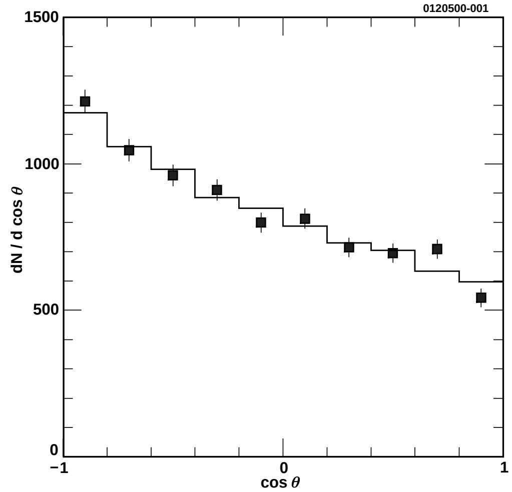

FIG. 2. The sideband subtracted angular distribution of the proton in the Λ rest frame with respect to the direction of the Λ in the Ξ^- rest frame in $\Xi^- \to \Lambda\pi^+, \Lambda \to p\pi^-$ for data (points with error bars) and projection of the fit (line). Both charge conjugate states are included.

arising from incomplete knowledge of the background shape in the sidebands is evaluated by varying the size of the mass sideband region $(-1.2\%, +0.9\%)$. A binned fit is also performed and the result is consistent with the maximum likelihood fit. This measurement is insensitive to production polarization, $\mathbf{P}_{\boldsymbol{\Xi}}$, and no systematic error has been included from this source (see below). Combining all sources of systematic errors in quadrature the total systematic error is $(-6.6\%, +5.0\%)$ and $\alpha_{\Xi,\bar{\Xi}}\alpha_{\Lambda,\bar{\Lambda}} = -0.291 \pm 0.021(\text{stat})^{+0.019}_{-0.015}(\text{syst})$.

To search for CP violation the Ξ candidates are sorted into charge conjugate states. There are 4204 ± 75 Ξ^- decays and 4200 ± 75 Ξ^+ decays. Using the same fitting procedure as above, and one MC sample for each charge conjugate state, we measure $\alpha_\Xi\alpha_\Lambda = -0.275 \pm 0.030^{+0.019}_{-0.015}$ and $\alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}} = -0.308 \pm 0.030^{+0.021}_{-0.016}$ respectively. Data and fit projections are shown in Fig. 3. From these results we calculate $\mathcal{A} = 0.057 \pm 0.064$ where the statistical error is estimated using the method in [14]. Most systematic errors associated with Ξ^- reconstruction apply equally to Ξ^+ and cancel when determining the asymmetry $\mathcal{A}$. If there is any Ξ production polarization, it is required to be normal to the production plane. The angular distribution with respect to this plane will have opposite slopes for Ξ^- and $\bar{\Xi}^+$. However both the production plane and detector acceptance are uniformly distributed in the azimuthal angle ϕ. Therefore this result is insensitive to production polarization. If there is any difference between the relative angular efficiencies of Ξ^- and Ξ^+ that is not modeled accurately by MC, this would lead to a biased value of $\mathcal{A}$. A momentum dependent asymmetry in detection efficiencies for negative and positive soft pions could, in principle, exist due to differing hadronic interaction cross sections of π^- and π^+ in the 3.5 cm radius CLEO II beryllium beam pipe. We assume this effect to be absent for two reasons. (1) In this analysis, typical decay lengths for Ξ and Λ are 6 cm and 11 cm respectively, therefore most tracks originate outside the beam pipe. (2) There is no evidence for a momentum dependent asymmetry in the CLEO II detection efficiency for tracks that originate inside the beampipe [19].

The $\Lambda\pi^-(\bar{\Lambda}\pi^+)$ mass sidebands consist mostly of real Λ's paired with random pions. The efficiency corrected angular distribution of the sidebands in each charge conjugate state will be the same if the MC accurately models the relative angular efficiency of slow π^+

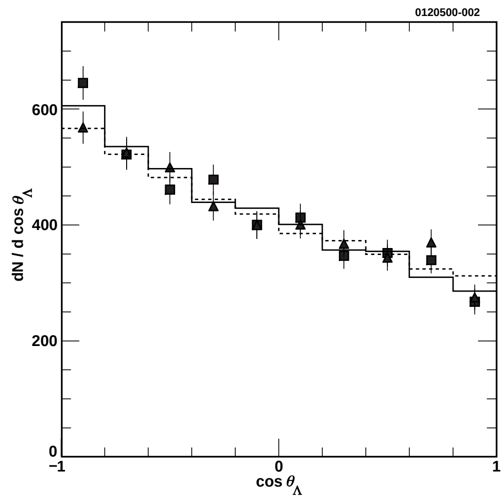

FIG. 3. The sideband subtracted angular distribution of the p in the Λ rest frame with respect to the direction of the Λ in the Ξ^- rest frame in $\Xi^- \to \Lambda\pi^+, \Lambda \to p\pi^-$ for data (triangles with error bars) and projection of the fit (dashed line). The sideband subtracted angular distribution of the $\bar{p}$ in $\bar{\Xi}^+ \to \bar{\Lambda}\pi^+, \bar{\Lambda} \to \bar{p}\pi^-$ in data (squares with error bars) and projection of the fit (solid line).

and π^-. To study this precisely, a high statistics sideband sample is obtained by relaxing the selection criteria and increasing the width of the sideband regions. The fit, performed on $12365 \pm 111(12353 \pm 111)$ events in the $\Lambda\pi^-(\bar{\Lambda}\pi^+)$ sideband regions, yields $\alpha_\Xi\alpha_\Lambda = 0.062 \pm 0.016$ in the Ξ^- sideband and $\alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}} = 0.077 \pm 0.016$ in the $\bar{\Xi}^+$ sideband. The difference between these two values -0.015 ± 0.023 indicates that there is no statistically significant discrepancy in the modeling of the Ξ^- and $\bar{\Xi}^+$ detector angular acceptance in MC compared to data. The error on the difference is taken as the systematic error on the CP asymmetry parameter measurement. The result is

$$\mathcal{A} = -0.057 \pm 0.064 \pm 0.039 \tag{5}$$

There are three measurements of A_Λ [20] [21] [22]. Using the most precise: $A_\Lambda = +0.013 \pm 0.022$ [22] we obtain $A_\Xi = -0.070 \pm 0.064 \pm 0.045$. Where the second error is systematic and includes the error on A_Λ.

It is possible to obtain a more precise value for $\mathcal{A}$ by combining our value for $\alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}$ with the PDG value of $\alpha_\Xi\alpha_\Lambda$ to obtain $\mathcal{A} = -0.025^{+0.061}_{-0.056}$ and $A_\Xi = -0.038^{+0.065}_{-0.060}$ where the statistical and systematic errors have been combined.

Finally, as this measurement of $\alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}$ is significantly more precise than the only published value [23], by combining with: $\alpha_{\bar{\Lambda}} = -0.63 \pm 0.13$ [21], we obtain $\alpha_{\bar{\Xi}} = 0.49^{+0.06}_{-0.05} \pm 0.10$, where the first error is the combined statistical and systematic error from this study and the second error is from $\alpha_{\bar{\Lambda}}$.

In conclusion, from a sample of approximately 4,000 Ξ decays and similar number of $\bar{\Xi}$, we have measured $\alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}} = -0.308 \pm 0.030^{+0.021}_{-0.016}$, and obtained $\alpha_{\bar{\Xi}} = 0.49^{+0.06}_{-0.05} \pm 0.10$. We have searched for direct CP violation by measuring the asymmetry parameter $\mathcal{A}$. We find no evidence for CP violation: $\mathcal{A} = -0.057 \pm 0.064 \pm 0.039$ and $A_{\Xi} = -0.070 \pm 0.064 \pm 0.045$[3].

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[3]As this paper was about to be submitted, we became aware of K.B. Luk *et al.* hep-ex/0007030, July 2000. This paper measures $\alpha_{\Xi}\alpha_{\bar{\Lambda}}$, $\mathcal{A}$ and A_{Ξ} with greater precision than the values reported here. The two analyses are consistent but employ different experimental techniques.

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