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A Measurement of the Decay Asymmetry Parameters in $\Xi_c^0 \to \Xi^-\pi^+$ and $\Xi^- \to \Lambda\pi^-$ and a Search for Direct CP Violation in Hyperon Decays

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Abstract

Using the CLEO II detector at the Cornell Electron Storage Ring we have measured the Ξ_c^0 decay asymmetry parameter in the decay $\Xi_c^0 \to \Xi^-\pi^+$. We find $\alpha_{\Xi_c^0}\alpha_{\Xi} = 0.26 \pm 0.18^{+0.05}_{-0.04}$, using the world average value of $\alpha_{\Xi} = -0.456 \pm 0.014$ we obtain $\alpha_{\Xi_c^0} = -0.56 \pm 0.39^{+0.10}_{-0.09}$. The physically allowed range of a decay asymmetry parameter is $-1 < \alpha < +1$. Our result prefers a negative value: $\alpha_{\Xi_c^0}$ is < 0.1 at the 90% CL. The central value occupies the middle of the theoretically expected range but is not yet precise enough to choose between models. We also measure $\alpha_\Lambda\alpha_\Xi$ in the decay chain $\Xi^- \to \Lambda\pi^-,\ \Lambda \to p^+\pi^-$. We find $\alpha_\Lambda\alpha_\Xi = -0.293 \pm 0.021^{+0.019}_{-0.014}$ which is in good agreement with the current world average $\alpha_\Lambda\alpha_\Xi = -0.293 \pm 0.007$. Using our reconstructed sample of 4204 ± 75 Ξ^- and similar number of Ξ^+, we search for evidence of direct CP violation by measuring the asymmetry, $\mathcal{A}$, in the angular distribution of $\Xi \to \Lambda\pi$ charge conjugate states. In the Standard Model, direct CP violation in hyperons is expected to occur at the $10^{-4} - 10^{-5}$ level. If CP violation were found at a higher level it may indicate the presence of new physics. We find no evidence of CP violation: $\mathcal{A} \simeq A_\Xi + A_\Lambda = -0.057 \pm 0.064 \pm 0.028$. Given the world average $A_\Lambda = -0.03 \pm 0.06$, we find $A_\Xi = -0.03 \pm 0.06 \pm 0.07$ where the systematic error is dominated by the A_Λ measurement. This is the first measurement of A_Ξ.

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I. INTRODUCTION

In this paper two distinct but related physics analysis are presented. (1) Parity violation in the decays $\Xi^- \to \Lambda\pi^-$ and $\Xi^+ \to \bar{\Lambda}\pi^+$ is measured and compared to place a limit on CP violation. (2) The degree of parity violation in the decay $\Xi_c^0 \to \Xi^-\pi^+$ is measured for the first time. We will refer to (1) as the hyperon analysis and (2) as the charm analysis. Parity violation occurs in hyperon and charm baryon $\frac{1}{2}^+ \to \frac{1}{2}^+ 0$ decays due to the existence of two orbital angular momentum amplitudes of opposite parity. The experimental observable is an asymmetry in the angular decay distribution due to interference between the two amplitudes.

In the decays $\Lambda_c^+ \to \Lambda\pi^+$ and $\Xi^- \to \Lambda\pi^-$ both followed by $\Lambda \to p\pi^-$, the Λ is produced with a polarization equal to:

$$\mathbf{P_\Lambda} = \frac{(\alpha_B + \hat{\boldsymbol{\Lambda}} \cdot \mathbf{P_B})\hat{\boldsymbol{\Lambda}} - \beta_B(\hat{\boldsymbol{\Lambda}} \times \mathbf{P_B}) - \gamma_B \hat{\boldsymbol{\Lambda}} \times (\hat{\boldsymbol{\Lambda}} \times \mathbf{P_B})}{(1 + \alpha_B \hat{\boldsymbol{\Lambda}} \cdot \mathbf{P_B})} \tag{1}$$

where $\boldsymbol{P_B}$ is the parent baryon polarization, α_B, β_B and γ_B are the parent baryon asymmetry parameters and $\hat{\boldsymbol{\Lambda}}$ is a unit vector along the Λ momentum in the parent baryon frame [1]. If the parent baryon polarization is unobserved, or if the parent baryon is not polarized, Equation 1 reduces to $\mathbf{P_\Lambda} = \alpha_B \hat{\boldsymbol{\Lambda}}$. The angular distribution of the proton from the decay of the Λ is therefore:

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

where θ_Λ is the angle between the proton momentum vector in the Λ rest frame and $\hat{\boldsymbol{\Lambda}}$, and α_Λ is the Λ decay asymmetry.

Hyperon decay asymmetry parameters are already well measured. For the decay $\Xi^- \to \Lambda\pi^-$ and $\Xi^+ \to \bar{\Lambda}\pi^+$ followed by $\Lambda \to p\pi$ Equation 2 has the form

$$\frac{dN}{d\cos(\theta_\Lambda)} \propto 1 + \alpha_\Xi \alpha_\Lambda \cos\theta_\Lambda \tag{3}$$

The product $\alpha_\Xi\alpha_\Lambda$ has been measured by several experiments and the world average is $\alpha_\Xi\alpha_\Lambda = -0.293 \pm 0.007$ [2]. In the decays $\Lambda \to p\pi$ and $\Xi \to \Lambda\pi$ if CP is conserved then $\alpha_\Lambda = -\alpha_{\bar{\Lambda}}$ and $\alpha_\Xi = -\alpha_{\bar{\Xi}}$ respectively therefore the CP violating asymmetry parameters, A_Λ and A_Ξ , are defined as [3]

$$A_\Lambda = \frac{\alpha_\Lambda + \alpha_{\bar{\Lambda}}}{\alpha_\Lambda - \alpha_{\bar{\Lambda}}} \qquad A_\Xi = \frac{\alpha_\Xi + \alpha_{\bar{\Xi}}}{\alpha_\Xi - \alpha_{\bar{\Xi}}} \tag{4}$$

In the two step decay $\Xi \to \Lambda\pi$, $\Lambda \to p\pi$, the slope of the angular distribution is $\alpha_\Xi\alpha_\Lambda$, which if CP is conserved should be identical to $\alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}$, therefore we measure the CP violating asymmetry parameter $\mathcal{A}$ where [3]

$$\mathcal{A} = \frac{\alpha_\Xi\alpha_\Lambda - \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}}{\alpha_\Xi\alpha_\Lambda + \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}} \simeq A_\Xi + A_\Lambda \tag{5}$$

This is the first measurement of $\mathcal{A}$.

In the Standard Model CP violation effects are due to a single complex phase in the CKM matrix [4]. The two elements with large phases are $V_{ub} \sim e^{-i\gamma}$, $V_{td} \sim e^{-i\beta}$ hence CP asymmetries can only arise from matrix elements involving transitions to the third quark generation. In hyperon and kaon decays these are thought to be dominated by gluonic penguins [5]. Standard Model predictions depend on the values of ϵ, ϵ', the top quark mass and the hadronic matrix element. The dominant uncertainty is due to incomplete knowledge of the hadronic matrix element. Non-Standard Model predictions of the magnitude of the CP asymmetry are model dependent. The Superweak model and models with a very heavy neutral Higgs where there are no $|\Delta S| = 1$ CP-odd effects predict no CP asymmetries. Other models such as the Weinberg model in which $|\Delta S| = 1$ CP nonconservation is dominant, predict asymmetries which are on the order of those calculated by the Standard Model. Theoretical predictions of A_Ξ and A_Λ are on the order of 10^{-4} - 10^{-5} [6] [7] [8].

The weak interactions underlying hadronic charm weak decay are straightforward to describe theoretically, but complications arise because the quarks are bound inside hadrons by the strong force. These interactions, which are described by the theory of quantum chromodynamics (QCD), are very difficult to predict using perturbative methods because the strong coupling is large at the typical energies of charm decays. Compared to charm mesons, charm baryons offer new information for two reasons: firstly, non-factorizable contributions to the decay amplitude, are important: W-exchange diagrams can contribute without the helicity suppression that decreases their contribution to pseudoscalar meson decays, and internal W emission is expected to be significant. The relative importance of these effects is believed to be responsible for both the observed lifetime hierarchy of the charm baryons and the relatively shorter lifetime of charm baryons compared to charm mesons. Secondly, parity violation in charm baryon decays is readily observable because the decay of the daughter hyperon produced in the decay also violates parity. In consequence a variety of models [9] [10] [11] [12] are used to predict both the decay rate and degree of parity violation in charm baryon decays. To constrain the models it is important to provide as much experimental information as possible.

In charm baryon decays Equation 2 has been used to determine α_B. For example in $\Lambda_c^+ \to \Lambda\pi^+$, $\alpha_B = \alpha_{\Lambda_c^+}$; since α_Λ is well measured ($\alpha_\Lambda = 0.642 \pm 0.013$ [2]) α_B can be determined. In the massless fermion limit the chirality of the weak interaction corresponds to $\alpha = -1$, however, the interplay between the strong and weak interactions in the weak decay alters the value of α. The decay asymmetry in $\Lambda_c^+ \to \Lambda\pi^+$ is relatively well measured [2], [13]. CLEO found $\alpha_{\Lambda_c^+} = -0.94^{+0.21+0.12}_{-0.06-0.06}$ [13], which is remarkably close to the naive V-A expectation. This result had been predicted by Heavy Quark Effective Theory (HQET) in conjunction with the factorization hypothesis [14]. Most pole and quark models [9], [11] also predict large negative values of $\alpha_{\Lambda_c^+}$. For $\Xi_c^0 \to \Xi^-\pi^+$ theoretical predictions cover a larger range: $-1 < \alpha_{\Xi_c^0} < -0.38$ [10] [12].

The decay of Ξ_c^0 we study in this paper is a three step process where parity violation occurs at each decay stage: $\Xi_c^0 \to \Xi^-\pi^+$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$. The differential rate is therefore given by [15]:

$$\frac{dN}{d\cos\theta_\Xi d\cos\theta_\Lambda} \propto 1 + \alpha_{\Xi_c^0}\alpha_\Xi \cos\theta_\Xi + \alpha_\Lambda\alpha_\Xi \cos\theta_\Lambda + \alpha_\Lambda\alpha_{\Xi_c^0} \cos\theta_\Xi \cos\theta_\Lambda \tag{6}$$

where in addition to the terms previously defined: θ_Ξ is the angle between the Λ momentum vector in the Ξ^- rest frame and the Ξ^- direction in the Ξ_c^0 rest frame as shown in Fig. 1. Equation 6 reduces to the familiar form of Equation 2 when integrated over $\cos\theta_\Lambda$.

II. DATA SAMPLE AND EVENT SELECTION

The data sample in this study was collected with the CLEO II detector [16] at the Cornell e^+e^- Storage Ring, CESR, operating at and just below the $\Upsilon(4S)$ resonance. We used a total integrated luminosity of 4.83 fb^{-1} corresponding to approximately 5 million $e^+e^- \to c\bar{c}$ events.

Identification of hadronic particles is achieved by using time-of-flight (TOF) and specific ionization energy loss measurements (dE/dx). By itself, the dE/dx measurement provides 2σ π/K separation up to 0.7 GeV/c. Time-of-flight measurements extend the 2σ π/K separation up to 1.1GeV and 2σ p/K separation up to 1.7 GeV/c. Using the two measurements, we form 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 pion (proton) hypothesis if its probability is greater than 0.003. For both pion and protons which enter the drift chambers or the barrel TOF counters, the particle identification efficiency, corresponding to the above criteria is about 98 % and nearly independent of the track momentum.

We search for the decays $\Xi^- \to \Lambda\pi^-$ and $\Xi_c^0 \to \Xi^-\pi^+$ in $e^+e^- \to c\bar{c}$ events by reconstructing the decay chain $\Xi_c^0 \to \Xi^-\pi^+$ [1], $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$.

III. UNBINNED MAXIMUM LOGLIKELIHOOD FIT

In this paper we use a 1-D unbinned maximum likelihood fit to Equation 3 for the hyperon analysis and a 2-D unbinned maximum likelihood fit to Equation 6 for the charm analysis. In principle, given enough statistics, the maximum loglikelihood method in conjunction with the two-fold joint angular distribution of Equation 6 allows the direct measurement of all three asymmetry parameters, $\alpha_{\Xi_c^0}$, α_Ξ, and α_Λ. So far, α_Ξ has always been measured indirectly as the product of the asymmetry parameters $\alpha_\Xi\alpha_\Lambda$.

The maximum likelihood method is the most powerful technique for finding the value of unknown parameters. It is especially useful for dealing with a small number of events where it is essential to extract the maximum possible information. In the unbinned loglikelihood method the smeared distribution from a Monte Carlo (MC) simulation is compared directly with data and the asymmetry at the generator level is varied until the best agreement between data and MC is obtained. This eliminates the systematic uncertainty introduced in the MC asymmetry angle reconstruction efficiency due to the lack of knowledge of the proper decay asymmetry model to use when generating MC.

Given a theoretical distribution $\mathcal{F}(\vec{x}, \vec{a})$ of kinematic variables, $\vec{x}$, where $\vec{a}$ are the unknown parameters that are to be determined experimentally, the experimentally observed shape of the distribution Γ_S is a function of the smeared kinematic variables $\vec{x'}$ and $\vec{a}$ [17]:

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[1]Unless otherwise noted throughout this paper charge conjugate modes are implied

$$\underbrace{\Gamma_S(\vec{x'},\vec{a})}_{data} = \underbrace{A(\vec{x'})}_{acceptance} \int \underbrace{S(\vec{x'},\vec{x})}_{smearing}\underbrace{\mathcal{F}(\vec{x},\vec{a})}_{theory} \tag{7}$$

MC takes into account smearing and acceptance effects due to the selection criteria and detector resolution of kinematic variables enabling Γ_S to be determined directly without the need to model the smearing and acceptance functions $S(\vec{x'},\vec{x})$ and $A(\vec{x'})$. For $\Gamma_S(\vec{x'},\vec{a})$, the MC signal shape and $\Gamma_B(x')$, the shape of the background distribution in the signal region, the loglikelihood incorporating background, smearing and acceptance effects for N events is defined as:

$$\ln\mathcal{L} = \sum_{i=1}^{N} ln(\underbrace{P_S\Gamma_S(\vec{x'}_i,\vec{a})}_{signal} + \underbrace{P_B\Gamma_B(\vec{x'}_i)}_{bkgd}) \tag{8}$$

P_S is the probability an event is signal and P_B is the probability it is background. The values of $\vec{a}$ at the generator level are varied to maximize $\ln\mathcal{L}$.

IV. RECONSTRUCTION OF HYPERONS

The Λ is reconstructed using its decay to $p^+\pi^-$ with a branching ratio of $(63.9\pm0.5)\%$ [2]. To reconstruct the Λ, we use two oppositely charged tracks which originate from a common vertex and interpret the positive and negative charged tracks as a proton and pion respectively. The proton candidate track is required to be consistent with a proton hypothesis. The momentum of the neutral track is calculated by extrapolating the charged track momenta to the secondary vertex. The invariant mass of Λ candidates is required to be within 6.0 MeV/c^2 of the known Λ mass (3σ). We reject track combinations which satisfy interpretation as a $K_s^0 \rightarrow \pi^+\pi^-$.

The Ξ^- is reconstructed through its decay to $\Lambda\pi^-$ with a branching ratio of $(99.887 \pm 0.035)\%$ [2]. We form Ξ^- candidates 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, the momentum of the charged track is recalculated at the new vertex. To reduce background from B decays we require the Λs from Ξ candidates to have momenta > 800 MeV/c. The invariant mass of $(\Lambda\pi)$ for all Ξ^- candidates satisfying the selection criteria outlined is plotted in Fig. 2. The fit is to a a 1st order Chebyshev for the background and a double Gaussian signal shape whose parameters are fixed from MC. We find 8434 ± 109 events with an invariant mass of 1322.0 ± 0.03 Mev/c^2 and width, $\sigma_{av} = 2.5$ MeV/c^2 where σ_{av} is the weighted average width of the double Gaussian.

V. MEASUREMENT OF THE $\Xi^- \rightarrow \Lambda\pi^-$ DECAY ANGLE DISTRIBUTION AND THE CP VIOLATING ASYMMETRY PARAMETER $\mathcal{A}$

The decay asymmetry in $\Xi^- \rightarrow \Lambda\pi^-$, where Ξ^+ and Ξ^- events are combined, is measured to ensure that there is no gross bias in our techniques for determining decay asymmetries. A one dimensional unbinned maximum loglikelihood (LL) fit to Equation 3 was performed on the $\cos\theta_\Lambda$ distribution in the Ξ signal region defined as $\pm3\sigma$ around M(Ξ). In $\Xi^-\to\Lambda\pi^-$, θ_Λ is the angle between the proton momentum vector in the Λ rest frame and the Λ momentum vector in the Ξ rest frame. To obtain $\cos\theta_\Lambda$ from the reconstructed 4-momentum vectors of the Ξ, Λ and proton measured in the lab. frame, a 2 step forward Lorentz transformation from the lab frame into the Ξ rest frame and then into the Λ rest frame is performed. A GEANT [18] based Monte Carlo (MC) simulation of $\Xi^-\to\Lambda\pi^-$ production in continuum events at CLEO is generated to model the signal shape $\Gamma_S(\cos\theta_\Lambda;\alpha_\Xi\alpha_\Lambda)$ after detector smearing and acceptance effects. The signal shape is determined from the MC distribution by counting the number of MC events in a given region, $\Delta(\cos\theta_\Lambda)$, centered around a $\cos\theta_\Lambda$ point measured in data and properly normalizing. The shape of the data background in the signal region, $\Gamma_B(\cos\theta_\Lambda)$, is similarly measured using the $\cos\theta_\Lambda$ distribution in 6 σ $(\Lambda\pi)$ mass sidebands on each side of M(Ξ). The result from all Ξ candidates, shown in Fig. 3, is $\alpha_\Xi\alpha_\Lambda=-0.293\pm0.021$ which is in good agreement with the current world average $\alpha_\Lambda\alpha_\Xi=-0.293\pm0.007$. A binned fit in 10 $\cos\theta_\Lambda$ bins is also performed and the results are consistent with the 1-D LL fit. There is a 10 % improvement in the statistical error on the measurement from the 1-D LL fit as compared to the binned fit. We have considered the following sources of systematic uncertainties and give our estimate of their magnitude in parentheses. The uncertainty from varying the Λ selection criteria and particle identification are $(-6.32\%,+2.14\%)$ and $(-3.11\%,+1.9\%)$ respectively. The uncertainty associated with the MC model of continuum Ξ production is determined by varying the MC momentum spectrum until agreement with data is found $(-0.63\%,+0\%)$. 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 $(-0\%,+0.72\%)$. The size of the region, $\Delta(\cos\theta_\Lambda)$, used to model the signal and background shapes in the LL fit is varied and the change in $\alpha_\Xi\alpha_\Lambda$ measured $(-0.46\%,+4.06\%)$. The uncertainty arising from an incomplete knowledge of the background shape in the sidebands is evaluated by varying the size of the mass sideband region $(-1.20\%,+0.91\%)$. Adding all sources of systematic error in quadrature we find the total systematic error to be $(-6.53\%,+4.63\%)$ and $\alpha_\Xi\alpha_\Lambda=-0.293\pm0.021^{+0.019}_{-0.014}$.

The Ξ candidates in data and MC are divided into separate charge conjugate states. We find 4204 ± 75 Ξ^- events and the same number of Ξ^+. The product of the decay asymmetry parameters for each charge conjugate state is measured (see Fig. 4): $\alpha_\Xi\alpha_\Lambda=-0.275\pm0.030$ and $\alpha_{\bar\Xi}\alpha_{\bar\Lambda}=-0.308\pm0.030$. Using these results we calculate $\mathcal{A}\simeq A_\Xi+A_\Lambda=0.057\pm0.064$ where the statistical error is estimated using the method in [3]:

$$\delta\mathcal{A}=\frac{1}{(2\alpha_\Xi\alpha_\Lambda)}\sqrt{\frac{3}{N_{\Xi^-}}+\frac{3}{N_{\Xi^+}}}=0.064 \tag{9}$$

The systematic uncertainty associated with the measurement of $\mathcal{A}$ arises from differences between the relative angular efficiencies of Ξ^- and Ξ^+ that are not modeled accurately by the MC. The momentum dependent asymmetry in detection efficiencies for negative and positive soft pions due to the difference in hadronic interactions of π^- and π^+ in the CLEO II Beryllium beam pipe at a radius of 3.5 cm is negligible [19] especially given the long lifetimes of the hyperons - $c\tau(\Xi)=4.91$ cm and $c\tau(\Lambda)=7.89$cm. All of the remaining systematic errors associated with the Ξ^- reconstruction apply equally to Ξ^+ and cancel when determining the asymmetry $\mathcal{A}$. To estimate the overall systematic error on $\mathcal{A}$, we study the angular distribution of the right sign $\Lambda\pi^-(\bar\Lambda\pi^+)$ sidebands in each charge conjugate state.

For this study to be statistically viable a sideband sample with significantly more events than the data is needed therefore the momentum and particle identification selection criteria on the Ξ candidates are relaxed and the size of the sideband regions increased. The $\Lambda\pi^-(\bar{\Lambda}\pi^+)$ yield in the sideband region after relaxing the selection criteria was $12365\pm111(12353\pm111)$ which is 3 times larger than the number of events in the data signal region used to measure the CP asymmetry. The 1-D loglikelihood is performed on the sideband $\cos\theta_\Lambda$ distributions using the same MC used in the fit to the signal data. The result is $\alpha_\Xi\alpha_\Lambda = 0.062\pm0.016$ in the Ξ^- sideband and $\alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}} = 0.077\pm0.016$ in the Ξ^+ sidebands. The difference is -0.015 ± 0.023. The results indicate that there is no statistically significant discrepancy in the modeling of the Ξ^- and Ξ^+ detector angular acceptance in MC as compared to data. The error on the difference of the asymmetry parameter products measured in Ξ^- and Ξ^+ sidebands will thus be used as the systematic error on the CP asymmetry parameter measurement. The result is

$$\mathcal{A} = -0.057 \pm 0.064 \pm 0.028 \tag{10}$$

Given the world average $A_\Lambda = -0.03 \pm 0.06$, we find $A_\Xi = -0.03 \pm 0.06 \pm 0.07$ where the systematic error is dominated by the A_Λ measurement.

VI. Ξ_c^0 RECONSTRUCTION AND MEASUREMENT OF THE Ξ_c^0 DECAY ANGLE DISTRIBUTION

The decay asymmetry parameter in $\Xi_c^0 \to \Xi^-\pi^+$ is measured in a two dimensional unbinned loglikelihood fit to the two-fold decay angular distribution of Equation 6, where θ_Ξ and θ_Λ are defined in Fig. 1. Note that CP conservation requires $\alpha_{\Xi_c^0} = -\alpha_{\bar{\Xi}_c^0}$. Since Equation 6 depends on the the products $\alpha_{\Xi_c^0}\alpha_\Xi$, $\alpha_{\Xi_c^0}\alpha_\Lambda$ and $\alpha_\Xi\alpha_\Lambda$ which have the same sign for particle and anti-particle states, particle and anti-particle distributions can be combined for the measurement of $\alpha_{\Xi_c^0}$. With the current statistics we are not sensitive to the presence of CP violation, therefore CP is assumed to be conserved for the charm analysis.

To reconstruct Ξ_c^0 candidates all Ξ^- candidates are matched to positively charged tracks consistent with a pion hypothesis. Since charm fragmentation is a relatively hard process the Ξ_c^0 spectrum from $e^+e^- \to c\bar{c}$ is also fairly stiff. We therefore use a scaled momentum cut, $x_p > 0.5$ [2] to reduce combinatoric background. This cut also eliminates charmed baryons from decays of B mesons. Fig. 5 shows the invariant mass distribution of $\Xi^-\pi^+$ combinations, the fit is to a double Gaussian and a polynomial distribution, where the double Gaussian shape is fixed from a GEANT [18] based Monte Carlo (MC) simulation of the detector. The large hump in the right sign (RS) background below $\mathrm{M}(\Xi^-\pi^+) = 2.33$ GeV/c^2 is feedthrough from $\Xi_c^{+,0} \to \Xi^- n(\pi)$ modes where one or more pions are missing. The kinematic limit for feedthrough is $M(\Xi_c^0) - M(\pi) = 2.3304$ GeV/c^2. To simplify the fit to $\mathrm{M}(\Xi^-\pi)$ the feedthrough region is excluded. We find 138 ± 14 $\Xi_c^0 \to \Xi^-\pi^+$ candidates with a mass of 2470.6 ± 1.0 MeV/c^2 and σ_{av}, the average width of the double Gaussian, of

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[2] $x_p = p/p_{max} = p/\sqrt{E_{beam}^2 - m_{\Xi_c^0}^2}$

10 MeV/c^2. The dashed histogram is wrong sign (WS) random $\Xi^-\pi^-$ combinations. There are less WS than RS random combinations due to charge conservation. We require that the invariant mass of Ξ_c^0 candidates be within 30 MeV/c^2 (3σ) of the known Ξ_c^0 mass.

From MC, the difference between generated and reconstructed values of $\cos\theta_\Xi$ and $\cos\theta_\Lambda$ is parameterized well by a Breit Wigner and single Gaussian distribution. The resolution in $\cos\theta_\Xi$, (σ_{av}) defined to be the average of the standard deviation of the Gaussian and width of the Breit Wigner weighted by the relative area of each shape, is $\sigma_{av}(\cos\theta_\Xi) = 0.014$ and $\sigma_{av}(\cos\theta_\Lambda) = 0.030$. In the fit MC models the signal shape and the Ξ_c^0 mass sideband region is used to model the shape of the background under the signal. We find $\alpha_{\Xi_c^0}\alpha_\Xi = 0.26 \pm 0.18$, $\alpha_\Xi\alpha_\Lambda = -0.57 \pm 0.21$, $\alpha_{\Xi_c^0}\alpha_\Lambda = -0.26 \pm 0.37$. The product $\alpha_{\Xi_c^0}\alpha_\Lambda$ is second order in decay angles consequently the fit is less sensitive to this quantity than to $\alpha_{\Xi_c^0}\alpha_\Xi$ and $\alpha_\Xi\alpha_\Lambda$. We provide a value of $\alpha_{\Xi_c^0}\alpha_\Lambda$ for completeness only. Fig. 6 shows the MC fits to data in the $\cos\theta_\Xi$ and $\cos\theta_\Lambda$ projections. The value of $\alpha_\Xi\alpha_\Lambda$ found in the fit is in reasonable agreement with the result obtained from the generic $\Xi^- \to \Lambda\pi^-$ analysis and the current world average value. From $\alpha_{\Xi_c^0}\alpha_\Xi = 0.26 \pm 0.18$ using the world average value of $\alpha_\Xi = -0.456 \pm 0.014$ we obtain $\alpha_{\Xi_c^0} = -0.56 \pm 0.39$.

This measurement is insensitive to the presence of production polarization, $\mathbf{P}_{\Xi_c^0}$, of the Ξ_c^0, because parity conservation in the electromagnetic and strong interactions requires Ξ_c^0 production polarization to be normal to the production plane, and charge conjugation invariance requires the sign of the polarization to be the same for particle and anti-particle. Since $\alpha_{\Xi_c^0}$ is CP-odd, $(\alpha_{\Xi_c^0}\mathbf{P}_{\Xi_c^0})$ is CP-odd so that averaged over charge conjugate states the net polarization is zero, therefore no systematic error has been included from this source.

We have considered the following sources of systematic error and give our estimate of the percentage error on $\alpha_{\Xi_c^0}\alpha_\Xi$ in parentheses. The error associated with the uncertainty in the Ξ_c^0 fragmentation function is estimated by varying this function ($+0.97\%, -13.89\%$). To determine the effect of incomplete knowledge of the background shape and the effect of statistical fluctuations in the sidebands used to model the background under the signal, we vary the size of the lower and upper sidebands used in the loglikelihood fit and repeat the fit using the wrong sign $\Xi^-\pi^-$ events in both signal and sideband regions to model the background shape ($+16.06\%, -1.39\%$). The error associated with MC modeling of slow pions from Ξ and Λ decay is obtained by varying the efficiency according to our understanding of the CLEO II detector ($+9.37\%, -6.28\%$). Using a large sample of $\Xi_c^0 \to \Xi^-\pi^+$ MC generated with $\alpha_{\Xi_c^0} = -0.5$ and the world average values of α_Ξ and α_Λ and including a randomly generated background based on the shape of the data sideband, we measure the effect of varying the volume element used to determine $\Gamma_S(\cos\theta_\Xi, \cos\theta_\Lambda; \alpha_{\Xi_c^0}, \alpha_\Xi, \alpha_\Lambda)$ and the background shape $\Gamma_B(\cos\theta_\Xi, \cos\theta_\Lambda)$ in the 2-D LL fit ($+0.6\%, -1.9\%$). Possible background from $\Sigma_c^0(2450) \to \Lambda_c^+\pi^-_{\rm slow}$, $\Lambda_c^+ \to \Lambda\pi^+_{\rm fast}$ is determined to be negligible through a MC simulation.

Adding all sources of systematic error in quadrature ($+18.63\%, -15.42\%$) we find $\alpha_{\Xi_c^0}\alpha_\Xi = 0.26 \pm 0.18^{+0.05}_{-0.04}$. A similar study for the systematic uncertainty on the measurement of $\alpha_\Xi\alpha_\Lambda$ in $\Xi_c^0 \to \Xi^-\pi^+$ yields ($-8.08\%, +3.89\%$) and consequently $\alpha_\Xi\alpha_\Lambda = -0.57 \pm 0.21^{+0.05}_{-0.02}$.

From the measurement of $\alpha_{\Xi_c^0}\alpha_\Xi$ and the world average value of $\alpha_\Xi = -0.456 \pm 0.014$ we obtain $\alpha_{\Xi_c^0} = -0.56 \pm 0.39^{+0.10}_{-0.09}$. The physically allowed range of a decay asymmetry parameter is $-1 < \alpha < +1$. Our result prefers a negative value: $\alpha_{\Xi_c^0}$ is < 0.1 at the 90% CL. This is the first measurement of a charm strange baryon decay asymmetry parameter. This value sits in the middle of the theoretically expected range but is not yet precise enough to choose between models.

VII. SUMMARY AND CONCLUSION

In conclusion, we have measured the product of decay asymmetry parameters $\alpha_\Xi \alpha_\Lambda$ in the decay $\Xi \to \Lambda\pi$. We find $\alpha_\Xi \alpha_\Lambda = -0.293 \pm 0.021^{+0.019}_{-0.014}$ which is in good agreement with the current world average value of -0.293 ± 0.007 [2]. In the Standard Model, direct CP violation in hyperons is expected to occur at the $10^{-4} - 10^{-5}$ level. If CP violation were found at a higher level it may indicate the presence of new physics. We find no evidence of CP violation: $\mathcal{A} \simeq A_\Xi + A_\Lambda = -0.057 \pm 0.064 \pm 0.028$. Given the world average $A_\Lambda = -0.03 \pm 0.06$, we find $A_\Xi = -0.03 \pm 0.06 \pm 0.07$ where the systematic error is dominated by the A_Λ measurement. This is the first measurement of A_Ξ.

The decay asymmetry parameter of the Ξ_c^0 has been determined to be $\alpha_{\Xi_c^0} = -0.56 \pm 0.39^{+0.10}_{-0.09}$. This is the first measurement of a charm strange baryon decay asymmetry parameter. The physically allowed range of a decay asymmetry parameter is $-1 < \alpha < +1$. Our result prefers a negative value: $\alpha_{\Xi_c^0}$ is < 0.1 at the 90% CL. The central value occupies the middle of the theoretically expected range but is not yet precise enough to choose between models.

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FIGURES

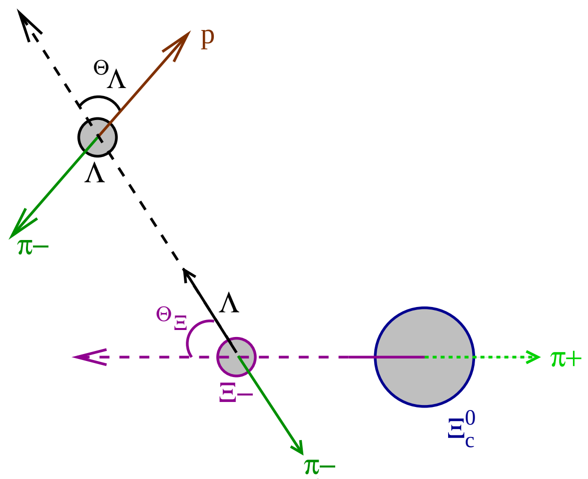

FIG. 1. Definition of the angles θ_Ξ and θ_Λ in $\Xi_c^0 \to \Xi^- \pi^+$. The decay of each particle is drawn in its own rest frame.

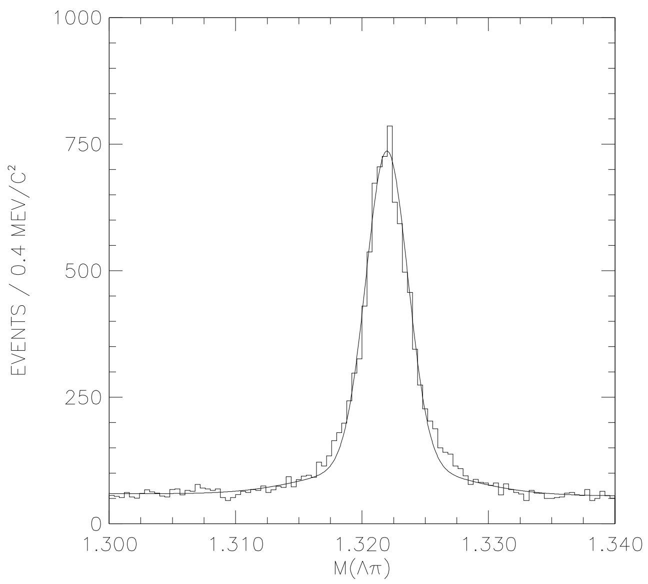

FIG. 2. M($\Lambda\pi$) distribution of generic Ξ^- candidates.

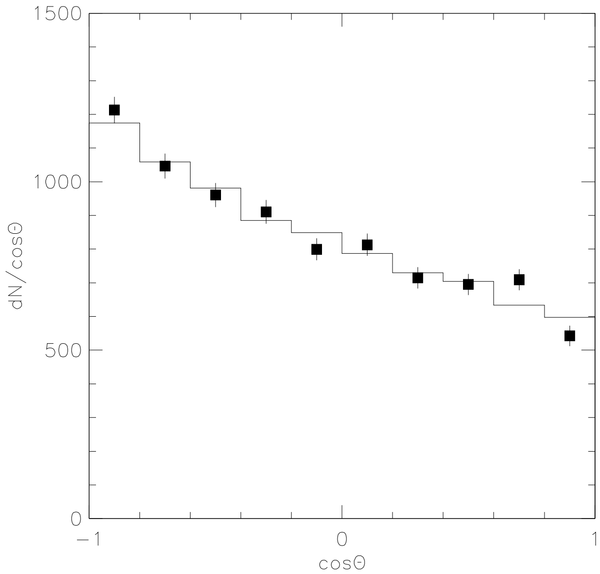

FIG. 3. Result from 1-D LL fit to $\alpha_\Xi\alpha_\Lambda$ using all $\Xi^{-,+}$ candidates. Solid histogram is the MC fit and points with error bars are sideband subtracted data.

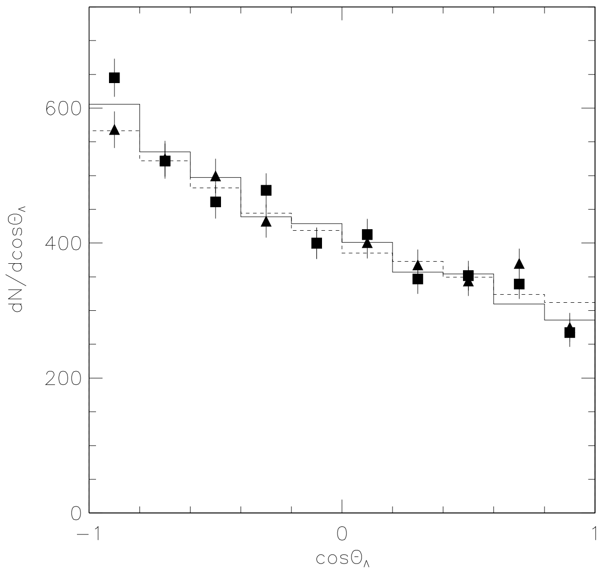

FIG. 4. 1-D LL fit to $\alpha_\Xi\alpha_\Lambda$ using Ξ^- and Ξ^+ candidates separately. Squares (triangles) with error bars and solid (dashed) line are Ξ^+ (Ξ^-) sideband subtracted raw data yields and fit.

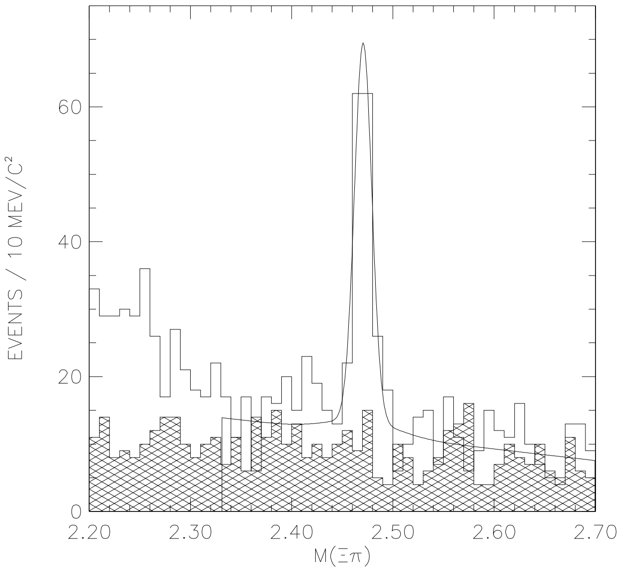

FIG. 5. $\Xi^{-}\pi^{+}$ invariant mass distribution

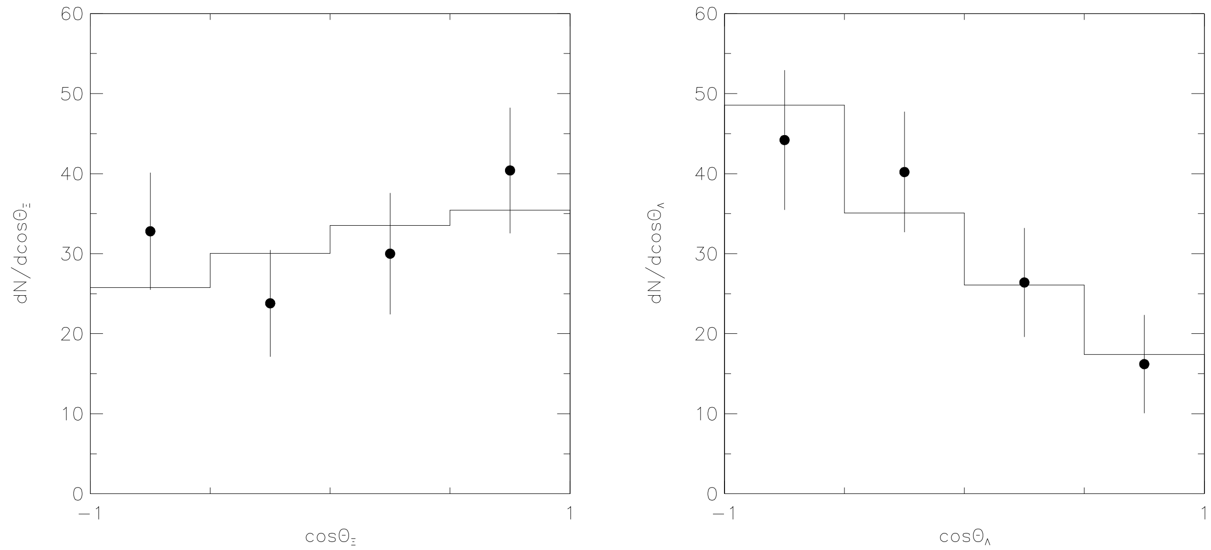

FIG. 6. Result from 2-D unbinned loglikelihood fit showing the chosen MC distribution in $\cos(\theta_{\Xi})$ (left) and $\cos(\theta_{\Lambda})$ (right). Solid histogram is MC fit and points with error bars are sideband subtracted data