

Measurement of Decay Parameters for $\Xi^- \rightarrow \Lambda \pi^-$ Decay

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(Received 19 February 2003; published 15 July 2003)

Based on 1.35×10^6 polarized Ξ^- events, we measure the parameter ϕ_Ξ to be $-1.61^\circ \pm 2.66^\circ \pm 0.37^\circ$ for the $\Xi^- \rightarrow \Lambda \pi^-$ decay. New results for the parameters β_Ξ and γ_Ξ are also presented. Assuming that the CP -violating phase difference is negligible, we deduce the strong phase difference between the P -wave and S -wave amplitudes of the $\Lambda \pi$ final state to be $3.17^\circ \pm 5.28^\circ \pm 0.73^\circ$, reducing the uncertainty in estimating the level of CP violation in Ξ -hyperon decay.

DOI: 10.1103/PhysRevLett.91.031601

PACS numbers: 13.30.Eg, 11.30.Er, 14.20.Jn, 14.65.Bt

Breakdown of CP invariance is well known in the weak decays of the neutral K meson [1,2] and has been recently established for the B meson as well [3]. A deeper understanding of this effect, which is evidence of a subtle difference between the dynamics of particles and antiparticles, is one of the central issues of current-day particle physics. Complementary to CP violation in the mesons is a similar effect in the nonleptonic hyperon decays. This has been the subject of theoretical discussion [4,5] and ongoing experimental searches [6–8]. Current models generally predict the breakdown of CP symmetry in strange-baryon decays due to the different dynamics in the decay of a hyperon and its antiparticle. In general, observing such a CP -odd effect requires a strong phase-shift difference, which is the subject of this paper.

For the $\Xi^- \rightarrow \Lambda \pi^-$ decay, the orbital angular momentum of the $\Lambda \pi^-$ is either $L = 0$ (S wave) or $L = 1$ (P wave) [9] with amplitudes as [4,10]

$$S = |S| \exp[i(\delta_S + \eta_S)], \quad P = |P| \exp[i(\delta_P + \eta_P)], \quad (1)$$

where δ_S, δ_P are the strong rescattering phases and η_S, η_P are weak CP -violating phases. The CP asymmetry of the Ξ decay [4,5],

$$A_\Xi = \frac{\alpha_\Xi + \alpha_{\Xi}}{\alpha_\Xi - \alpha_{\Xi}}, \quad (2)$$

with α_Ξ (α_{Ξ}) being a Lee-Yang parameter of the hyperon (antihyperon) decay [9], is given by

$$A_\Xi \simeq -\tan(D) \sin(d_{CP}), \quad (3)$$

where $D = \delta_P - \delta_S$ and $d_{CP} = \eta_P - \eta_S$ are phase differences. Predictions of D vary between -3° and 16°

[10,11]. The model-dependent CP -violating phase shifts are typically a couple of orders of magnitude smaller than the strong phase shifts [5]. D can thus be deduced from the decay parameter β_Ξ expressed as

$$\beta_\Xi = \alpha_\Xi \tan(D + d_{CP}) \simeq \alpha_\Xi \tan(D). \quad (4)$$

The parameter β_Ξ can be determined with the phase $\phi_\Xi = \tan^{-1}(\beta_\Xi/\gamma_\Xi)$, where γ_Ξ is another decay parameter such that $\alpha_\Xi^2 + \beta_\Xi^2 + \gamma_\Xi^2 = 1$. The world average is $\phi_\Xi = 4^\circ \pm 4^\circ$, taken over several measurements with the largest sample using 20 865 events [12]. In this Letter, we report a new measurement of ϕ_Ξ based on 1.35×10^6 polarized $\Xi^- \rightarrow \Lambda \pi^-$ decays.

Our data come from Experiment 756 at Fermi National Accelerator Laboratory [13–15]. Polarized Ξ^- hyperons with transverse momenta p_T spanning 0.5 to 1.5 GeV/ c and momentum fraction x_F from 0.3 to 0.7 were produced by unpolarized 800 GeV/ c protons striking a beryllium target at an angle in the vertical plane. The secondary beam was momentum and sign selected by a curved collimator inside a dipole magnet. The magnet current was set to yield a field integral $\int B dl$ of 15.30 ± 0.15 T m, as measured with a Hall probe, for the data used in this analysis.

The momenta of the proton and the pions in the decay sequence $\Xi^- \rightarrow \Lambda \pi^-$, $\Lambda \rightarrow p \pi^-$ were measured with eight planes of silicon strip detectors, nine multiwire proportional chambers, and two dipole analyzing magnets that deflected charged particles in the horizontal plane. The polarity of these magnets could be reversed by switching the direction of the applied current. The Ξ^- triggers have been described in [6]. Data were taken for permutations of two production angles, averaging

± 2.4 mrad, and two analyzing magnet currents ± 2500 A. The Ξ^- polarization and magnetic moment from these data have been reported [14,15].

The events were analyzed with a reconstruction program that determined tracks and kinematic variables from the chamber hits. Events were required to satisfy the three-track, two-vertex topology corresponding to a Ξ^- decay-sequence hypothesis. The geometric χ^2 for the topological fit was required to be less than 100 for a mean of 30 degrees of freedom. The proton and pion from Λ decay were required to have a $p\pi$ invariant mass within 3.5 standard deviations ($8 \text{ MeV}/c^2$) of the Λ mass ($1.116 \text{ GeV}/c^2$), and the $\Lambda\pi$ invariant mass was required to be within 5 standard deviations ($14 \text{ MeV}/c^2$) of the Ξ^- mass ($1.321 \text{ GeV}/c^2$). The momenta of the reconstructed Ξ^- candidates were required to be between 240 and 450 GeV/c , and were required to trace back to within 0.63 cm of the center of the target. The Λ -decay vertex was required to be downstream of the Ξ^- -decay vertex, and both vertices were required to be in a fiducial region 0.25 m downstream of the collimator exit and 0.31 m upstream of the multiplicity counter located at 23.31 m from the collimator exit.

The decay parameters are related to the experimental observables through the polarization and angular distribution of the daughter baryon. For $\Xi^- \rightarrow \Lambda\pi^-$, we have [9]

$$P_\Lambda = \frac{(\alpha_\Xi + \vec{P}_\Xi \cdot \hat{\Lambda})\hat{\Lambda} + \beta_\Xi(\vec{P}_\Xi \times \hat{\Lambda}) + \gamma_\Xi\hat{\Lambda} \times (\vec{P}_\Xi \times \hat{\Lambda})}{1 + \alpha_\Xi\vec{P}_\Xi \cdot \hat{\Lambda}}, \quad (5)$$

where \vec{P}_Λ is the polarization of the Λ hyperon in its rest frame, $\hat{\Lambda}$ is the momentum direction of the Λ in the Ξ^- rest frame, and \vec{P}_Ξ is the Ξ^- polarization in the Ξ^- frame. The helicity-frame axes, specified event by event in the Ξ^- rest frame, are defined as

$$\hat{X} = \frac{\vec{P}_\Xi \times \hat{\Lambda}}{|\vec{P}_\Xi \times \hat{\Lambda}|}, \quad \hat{Z} = \hat{\Lambda}, \quad \hat{Y} = \hat{Z} \times \hat{X}. \quad (6)$$

Then, for the $\Lambda \rightarrow p\pi^-$ decay, the angular distribution of the proton in the Λ rest frame can be projected onto the helicity-frame axes to give [16]

$$\frac{dn}{d\cos\theta_{pZ}} = \frac{1}{2}(1 + \alpha_\Lambda\alpha_\Xi\cos\theta_{pZ}), \quad (7)$$

$$\frac{dn}{d\cos\theta_{pX}} = \frac{1}{2}\left(1 + \frac{\pi}{4}\alpha_\Lambda\beta_\Xi P_\Xi\cos\theta_{pX}\right), \quad (8)$$

$$\frac{dn}{d\cos\theta_{pY}} = \frac{1}{2}\left(1 + \frac{\pi}{4}\alpha_\Lambda\gamma_\Xi P_\Xi\cos\theta_{pY}\right), \quad (9)$$

where θ_{pi} is the angle between the proton momentum in the Λ rest frame and the i th helicity-frame axis. The ratio of the slopes of the $\cos\theta_{pX}$ and $\cos\theta_{pY}$ distributions provides a measurement of $\tan\phi_\Xi = \beta_\Xi/\gamma_\Xi$.

Conservation of parity in strong interaction dictates that any Ξ^- polarization be normal to the production plane at the target. The precession angle Φ of this polarization relative to the Ξ^- momentum at the collimator exit, after the Ξ^- hyperons pass through the vertically directed magnetic field in the collimator, is

$$\Phi = \frac{q}{\beta m_\Xi c^2} \left\{ -\frac{\mu_\Xi m_\Xi}{\mu_N m_p} - 1 \right\} \int B dl, \quad (10)$$

where q , μ_Ξ , and m_Ξ are the electric charge, magnetic moment, and mass of the Ξ^- , respectively, $\beta \approx 1$, μ_N is the nuclear magneton, and m_p is the proton mass. As reported in [14], the polarization of Ξ^- for this data set was confined in the horizontal plane and approximately 10% in magnitude. We used $\mu_\Xi = -0.6505 \pm 0.0025 \mu_N$ [17] to determine $\Phi = -16.68^\circ \pm 0.86^\circ$ and, hence, the orientation of the Ξ^- polarization in the spectrometer. The helicity-frame axes defined in Eq. (6) were calculated from the reconstructed Λ momentum.

The slopes of the $\cos\theta_{pX}$ and $\cos\theta_{pY}$ distributions in Eqs. (8) and (9) were measured using the hybrid Monte Carlo (HMC) method [18] which factored out the acceptances. Up to 200 HMC events were generated per real event for each distribution. These HMC events were uniformly distributed in $\cos\theta_{pX}$ ($\cos\theta_{pY}$), with the rest of the kinematic quantities such as decay vertices and Λ momentum taken from the associated real event. The event was included in the analysis if ten of its associated HMC events satisfied the requirements used to simulate the triggers, the geometry, and inefficiencies of the spectrometer. A χ^2 minimization based on the comparison of weighted HMC data with real events was used to determine the slope of each $\cos\theta$ distribution.

The data were analyzed separately as four streams: data taken at positive and negative production angles for each polarity of the analyzing magnets. The measured slope for a given distribution is comprised of the true slope plus a bias term [13]. The bias, arising from imperfections in the apparatus and reconstruction effects not fully simulated in the analysis, is not sensitive to the reversal of the production angle. The polarization, however, changes sign when the production angle is reversed. The helicity-frame axes in Eq. (6) transform as $\hat{X} \rightarrow -\hat{X}$, $\hat{Y} \rightarrow -\hat{Y}$, and $\hat{Z} \rightarrow \hat{Z}$ when the polarization changes sign. A bias term in the X direction (B_X) will thus reverse sign in the transformed helicity frame. If the slope measured for the positive (negative) production angle is S_+ (S_-), the true slope and bias are extracted using

$$\frac{\pi}{4}\alpha_\Lambda\beta_\Xi P_\Xi = \frac{S_+ + S_-}{2}, \quad B_X = \frac{S_+ - S_-}{2}. \quad (11)$$

Similar expressions can be written for $\alpha_\Lambda\gamma_\Xi P_\Xi$ and the Y bias (B_Y). Figure 1 shows the $\cos\theta_{pX}$ and $\cos\theta_{pY}$ distributions for each stream and the corresponding weighted HMC fit. The HMC analysis was repeated with 26 different random number seeds and the results were averaged. Table I shows the extracted slopes and bias terms of the

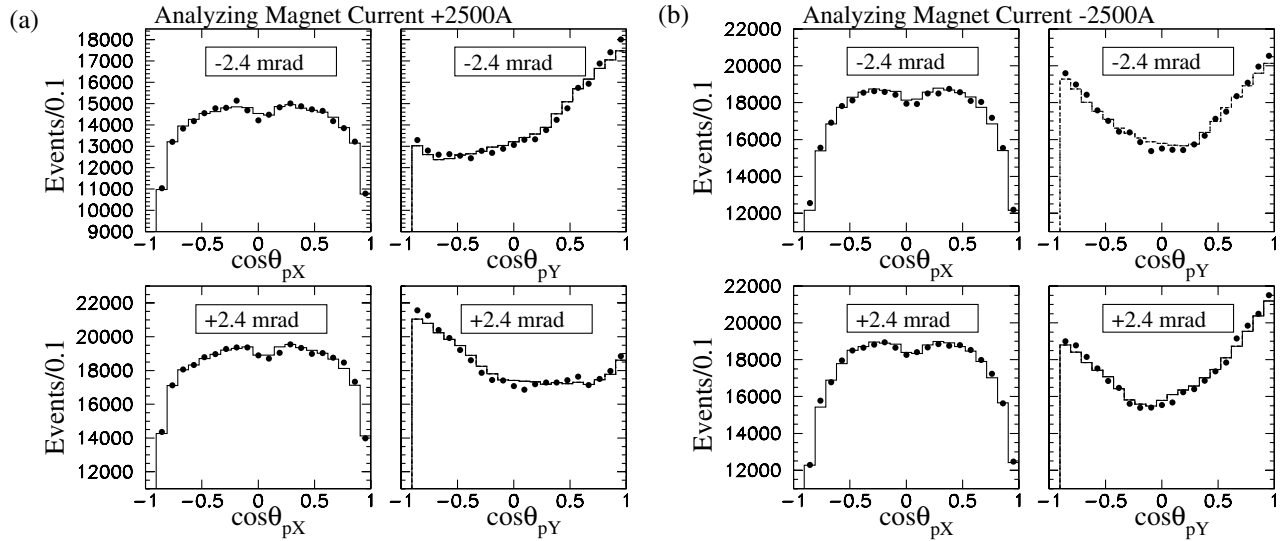


FIG. 1. $\cos\theta_{pX}$ and $\cos\theta_{pY}$ data distributions (points) with corresponding weighted HMC events (histograms) for (a) the +2500 A and (b) the -2500 A current setting of the analyzing magnets.

$\cos\theta_{pX}$ and $\cos\theta_{pY}$ distributions for each polarity of the analyzing magnet.

To show that we were able to determine the correct axes, we measured the slope $\alpha_{\Lambda}\alpha_{\Xi}$ of the distribution in Eq. (7). Our result, which does not include systematic studies, was $\alpha_{\Lambda}\alpha_{\Xi} = -0.305 \pm 0.002$, consistent with the world average [17]. As a further check, we measured the magnitude of the Ξ^- polarization by projecting the angular distribution of the proton onto the laboratory axes and summing the components (a technique discussed in [13,14]). We then calculated $\frac{\pi}{4}\alpha_{\Lambda}\gamma_{\Xi}P_{\Xi} = 0.043 \pm 0.003$, in agreement with the results in Table I and in [14].

By taking the ratio of the measured values of $\frac{\pi}{4}\alpha_{\Lambda}\beta_{\Xi}P_{\Xi}$ and $\frac{\pi}{4}\alpha_{\Lambda}\gamma_{\Xi}P_{\Xi}$, the phase ϕ_{Ξ} was determined to be $-1.28^\circ \pm 3.86^\circ$ for the +2500 A data and $-1.93^\circ \pm 3.68^\circ$ for the -2500 A data. The good agreement for two settings of the analyzing magnets provides a systematic check of the analysis method.

The measured ϕ_{Ξ} displays no significant dependence on either the Ξ^- momentum, p_{Ξ} , or the transverse momentum, p_T (Fig. 2). A study of the biases B_X and B_Y as a function of the Ξ^- momentum showed no significant

dependence [19]. Variation of some of the data-selection criteria allowed us to study systematic effects due to background, poorly measured events, goodness of the track fitting, and resolution at the target. The systematic effect of the random number seed in the HMC program was investigated. In addition, we studied the effect of changing the precession angle on the measured ϕ_{Ξ} by varying the value of Φ by one standard deviation. Table II summarizes our estimates of the systematic uncertainties.

By averaging the measurements for the two settings of the analyzing magnet, and adding the systematic errors in quadrature, we obtain our final result:

$$\phi_{\Xi} = -1.61^\circ \pm 2.66^\circ \pm 0.37^\circ,$$

where the first error is statistical and the second systematic. Our measurement is consistent with the current world average of $4^\circ \pm 4^\circ$ [17] and with zero. Using

$$\beta_{\Xi} = (1 - \alpha_{\Xi}^2)^{1/2} \sin\phi_{\Xi}, \quad (12)$$

$$\gamma_{\Xi} = (1 - \alpha_{\Xi}^2)^{1/2} \cos\phi_{\Xi}, \quad (13)$$

where $\alpha_{\Xi} = -0.458 \pm 0.012$ [17], we calculate

TABLE I. Extracted slopes and biases.

Analyzing magnet current (A)	No. of events	Mean Ξ momentum (GeV/c)	$\frac{\pi}{4}\alpha_{\Lambda}\beta_{\Xi}P_{\Xi}$	B_X
+2500	646 774	309	-0.0009 ± 0.0028	$+0.0042 \pm 0.0028$
-2500	696 337	326	-0.0014 ± 0.0026	-0.0015 ± 0.0026
			$\frac{\pi}{4}\alpha_{\Lambda}\gamma_{\Xi}P_{\Xi}$	B_Y
+2500	647 029	309	$+0.0410 \pm 0.0024$	$+0.0037 \pm 0.0024$
-2500	696 633	326	$+0.0400 \pm 0.0022$	$+0.0012 \pm 0.0022$

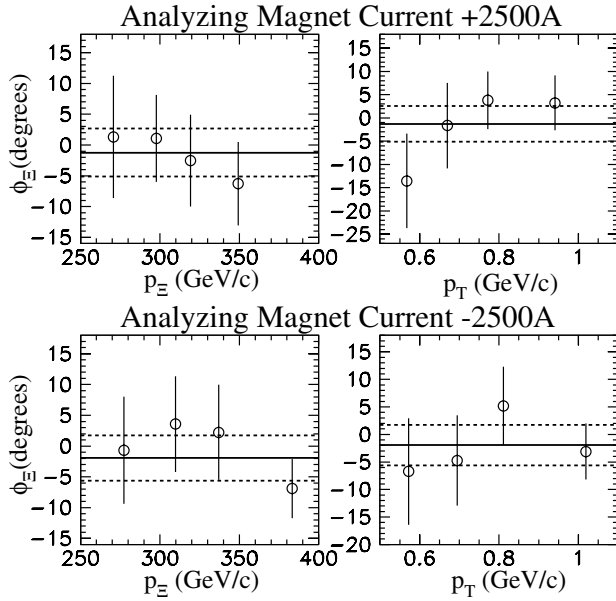


FIG. 2. ϕ_{Ξ} as a function of p_{Ξ} (left) and p_T (right) for +2500 A (top) and -2500 A (bottom) settings of the analyzing magnets. Solid and dotted lines indicate the central measurement and its statistical error.

$$\beta_{\Xi} = -0.025 \pm 0.042 \pm 0.006,$$

$$\gamma_{\Xi} = +0.889 \pm 0.001 \pm 0.007.$$

Both statistical and systematic errors on β_{Ξ} are dominated by the uncertainties in our measurement of ϕ_{Ξ} , whereas the systematic error on γ_{Ξ} is due to the uncertainty in α_{Ξ} .

Using Eq. (4), the phase-shift difference in the Ξ^- decay process is also deduced:

$$D + d_{CP} = 3.17^\circ \pm 5.28^\circ \pm 0.73^\circ.$$

This measurement is consistent with zero and indicates that the strong phase-shift difference of the final state in $\Xi^- \rightarrow \Lambda \pi^-$ decay is small, in agreement with recent calculations [10] but disagreeing with that of [11].

In conclusion, we have measured the parameter ϕ_{Ξ} using 1.35×10^6 $\Xi^- \rightarrow \Lambda \pi^-$ decays. Our result has a precision that is ≈ 1.5 times better than the world average and ≈ 3.3 times better than the previous best single

measurement [20]. With this result, we obtain new values for β_{Ξ} and γ_{Ξ} . The strong phase-shift difference deduced from this measurement is consistent with zero and thus imposes a limit on the level of CP violation in $\Xi^- \rightarrow \Lambda \pi^-$ hyperon decay.

We would like to acknowledge support by the U.S. Department of Energy. K. B. L. was also partially supported by the Miller Institute. The excellent assistance of the Fermilab staff was essential for the completion of the experiment.

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TABLE II. Systematic errors for the measurement of ϕ_{Ξ} .

Study	Estimated maximum systematic error
Momentum dependence	$<0.1^\circ$
p_T dependence	$<0.1^\circ$
Selection criteria	0.25°
Random number seed	0.25°
Precession angle	0.11°
Total	0.37°