Measurement of the Asymmetry in the Decay $\overline{\Omega}^+ \to \overline{\Lambda} K^+ \to \bar{p}\pi^+ K^+$

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The asymmetry in the $\bar{p}$ angular distribution in the sequential decay $\overline{\Omega}^+ \to \overline{\Lambda} K^+ \to \bar{p}\pi^+ K^+$ has been measured to be $\overline{\alpha}_\Omega \overline{\alpha}_\Lambda = [+1.16 \pm 0.18(\mathrm{stat}) \pm 0.17(\mathrm{syst})] \times 10^{-2}$ using 1.89×10^6 unpolarized $\overline{\Omega}^+$ decays recorded by the HyperCP (E871) experiment at Fermilab. Using the known value of α_Λ, and assuming that $\overline{\alpha}_\Lambda = -\alpha_\Lambda$, $\overline{\alpha}_\Omega = [-1.81 \pm 0.28(\mathrm{stat}) \pm 0.26(\mathrm{syst})] \times 10^{-2}$. A comparison between this measurement of $\overline{\alpha}_\Omega \overline{\alpha}_\Lambda$ and recent measurements of $\alpha_\Omega \alpha_\Lambda$ made by HyperCP shows no evidence of a violation of *CP* symmetry.

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It has long been known that the comparison of the α decay parameters in hyperon and antihyperon decays provides a test of *CP* symmetry [1]. If *CP* is good, $\overline{\alpha} = -\alpha$. It is important to pursue such tests as they are sensitive to sources of *CP* violation that are not probed in other systems [2]. In a previous Letter we reported results from a high-precision search for *CP* violation in charged-Ξ and Λ decays [3]. We report here a precise measurement of the product of the α decay parameters in $\overline{\Omega}^+ \to \overline{\Lambda} K^+ \to \bar{p}\pi^+ K^+$ and extract the α parameter in $\overline{\Omega}^+ \to \overline{\Lambda} K^+$. Using two previous measurements of the $\Omega^- \to \Lambda K^-$ α decay parameter made by the HyperCP collaboration [4,5] we test for *CP* conservation.

We assume that the $\overline{\Omega}^+$ is spin $\frac{3}{2}$ [6]. Hence, the α parameter is given by the interference of the *P*- and *D*-wave amplitudes: $\overline{\alpha}_\Omega = 2\,\mathrm{Re}(P^* D)/(|P|^2 + |D|^2)$. (In this Letter $\overline{\alpha}_\Omega$ refers only to the $\overline{\Lambda} K^+$ decay mode of the $\overline{\Omega}^+$.) HyperCP has made two measurements of the α parameter in the Ω^- decay: $\alpha_\Omega = (2.07 \pm 0.96) \times 10^{-2}$ from 0.96×10^6 events taken in the 1997 Fermilab fixed-target running period [4] and $(1.78 \pm 0.25) \times 10^{-2}$ from 4.50×10^6 events taken in the 1999 Fermilab fixed-target running period [5]. As expected, α_Ω is small [7]. The only measurement of $\overline{\alpha}_\Omega$ $(=0.017 \pm 0.077)$ is from an analysis of 1823 decays [8]; we report a measurement based on 1.89×10^6 events.

The experiment was mounted at Fermilab using a high-rate spectrometer described in Ref. [9]. A positively charged secondary beam with an average momentum of 160 GeV/c was produced by an 800 GeV/c proton beam impacting a $2 \times 2 \times 20$ mm^3 Cu target, the target followed by a curved collimator channel embedded in a dipole magnet. The entrance axis of the collimator was collinear with the incident proton beam so that the Ω's were produced at an average angle of 0°, which assured that their mean polarization was zero. A 13 m long evacuated pipe (vacuum decay region) immediately followed the collimator exit. After the vacuum decay region were multiwire proportional chambers, four in front of a pair of dipole magnets (analyzing magnets) and five behind. The trigger required the coincidence of at least one hit counter in each of two hodoscopes situated on either side of the secondary beam, along with a minimum energy deposit of ≈ 40 GeV in the hadronic calorimeter, an energy well below that of the lowest-energy $\bar{p}$ that impacted the calorimeter. Events that satisfied the trigger were written to magnetic tape by a high-rate data acquisition system [10].

This analysis used event-selection criteria and analysis code identical to those used in the analysis of the 1999 run negative-polarity data [5]. The 61×10^9 recorded events were initially reconstructed and separated according to event type, and loose event-selection cuts were applied.

The raw event information was preserved at this and every subsequent stage. Events with at least three charged tracks that fit the $\overline{\Omega}^+ \to \overline{\Lambda} K^+ \to \bar{p}\pi^+ K^+$ separated-vertex topology well and that had $\bar{p}\pi^+$ and $\bar{p}\pi^+ K^+$ invariant masses within $\pm 8.6\ \mathrm{MeV}/c^2$ (9.0σ) of the known value for the $\overline{\Lambda}$ and $\pm 16.4\ \mathrm{MeV}/c^2$ (10.3σ) of the known value for the $\overline{\Omega}^+$ mass were retained. This left a total of 40×10^6 candidate events. Final event-selection criteria were applied after careful study, and were tuned to maximize the signal-to-background ratio. The most important requirements were that: (1) the extrapolated $\overline{\Omega}^+$ trajectory point back to within 2.1 mm of the target center; (2) both the $\overline{\Omega}^+$ and the $\overline{\Lambda}$ decay vertices lie at least 0.28 m (0.32 m) downstream (upstream) of the entrance (exit) of the vacuum decay region; (3) the $\bar{p}\pi^+\pi^+$ ($\pi^-\pi^+\pi^+$) invariant mass be greater than $1.355\ \mathrm{GeV}/c^2$ ($0.520\ \mathrm{GeV}/c^2$), in order to eliminate $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+ \to \bar{p}\pi^+\pi^+$ ($K^+ \to \pi^-\pi^+\pi^+$) decays; (4) the $\bar{p}\pi^+$ and $\bar{p}\pi^+ K^+$ invariant masses be, respectively, within $\pm 4.0\ \mathrm{MeV}/c^2$ (4.2σ) and $\pm 8.0\ \mathrm{MeV}/c^2$ (5.0σ) of the $\overline{\Lambda}$ and $\overline{\Omega}$ masses; (5) no particle have momentum less than $12\ \mathrm{GeV}/c$; (6) the χ^2 per degree of freedom of a geometric fit to the decay topology be less than 2.5; and (7) the distance-of-closest-approach for the tracks forming the $\overline{\Lambda}$ and $\overline{\Omega}^+$ decay vertices be less than 4 mm. After all these cuts the number of events left was 1.890×10^6.

Figure 1 shows the $\bar{p}\pi^+ K^+$ and $\bar{p}\pi^+$ invariant-mass distributions after all event-selection cuts, except the respective mass cuts. The background-to-signal ratio, determined using a double-Gaussian plus second-degree polynomial fit to the invariant-mass distribution, is 0.34% in the region within $\pm 5.0\sigma$ of the $\overline{\Omega}^+$ mass. The background under the $\bar{p}\pi^+$ mass peak is less than half this.

The $\overline{\Omega}^+$ α parameter was measured through the asymmetry in the $\overline{\Lambda} \to \bar{p}\pi^+$ decay distribution. In the decay of an unpolarized $\overline{\Omega}^+$ to $\overline{\Lambda} K^+$ the $\overline{\Lambda}$ is produced in a helicity state, with its helicity given by $\overline{\alpha}_\Omega$ [11]. Hence the decay distribution of the $\bar{p}$ in that $\overline{\Lambda}$ rest frame in which the $\overline{\Lambda}$ direction in the $\overline{\Omega}^+$ rest frame defines the polar axis—the lambda helicity frame—is given by

$$\frac{dN}{d\cos\theta} = \frac{N_0}{2}(1 + \overline{\alpha}_\Omega \overline{\alpha}_\Lambda \cos\theta), \tag{1}$$

where θ is the polar angle of the $\bar{p}$ and $\overline{\alpha}_\Lambda$ is the α decay parameter in $\overline{\Lambda} \to \bar{p}\pi^+$.

The $\cos\theta$ acceptance of the $\bar{p}$ was measured and corrected for using a hybrid Monte Carlo (HMC) technique [12]. Monte Carlo events were generated by taking all parameters from real events, except for the $\bar{p}$ and π^+ directions in the rest frame of the $\overline{\Lambda}$. Isotropic $\overline{\Lambda} \to \bar{p}\pi^+$ decays were generated, and the $\bar{p}$ and π^+ were boosted back into the laboratory frame using the real $\overline{\Lambda}$ momentum. Their trajectories were then traced through the apparatus, simulating the detector responses where appropriate. The HMC $\bar{p}$ and π^+ tracks, in conjunction with the real K^+ track, were required to satisfy the trigger requirements, and were reconstructed by the standard track-finding program, with the same cuts applied as for the real events. Ten accepted HMC events for each real event were used; if over 300 generated HMC events were required to get those ten, then both the real and associated HMC events were thrown out. The result was completely insensitive to the upper limit on the number of generated HMC events per real event.

Since the HMC events were generated with a uniform $\cos\theta$ distribution of the $\bar{p}$, each accepted HMC event was weighted by

$$\begin{aligned} W &= \frac{1 + S\cos\theta_{\mathrm{mc}}}{1 + S\cos\theta_r}, \\ &\approx (1 + S\cos\theta_{\mathrm{mc}})[1 - S\cos\theta_r + (S\cos\theta_r)^2 - \cdots], \end{aligned} \tag{2}$$

where S is the (unknown) slope of the $\cos\theta$ distribution of

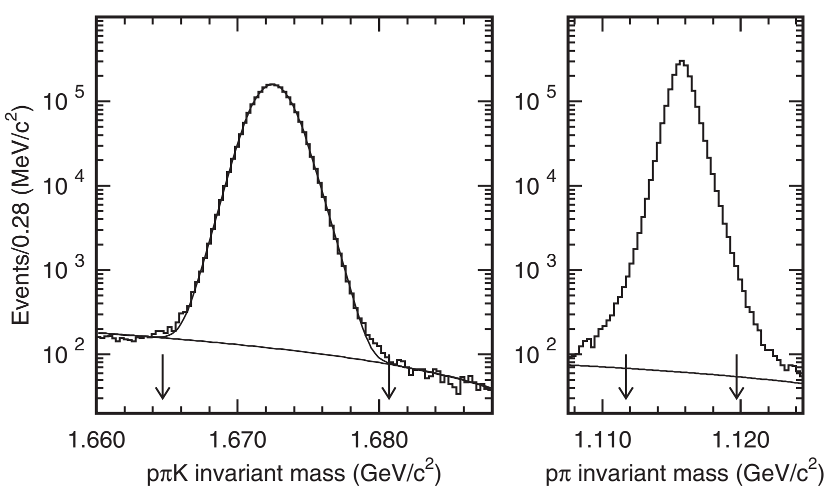

FIG. 1. The $\bar{p}\pi^+ K^+$ and $\bar{p}\pi^+$ invariant-mass distributions, after all cuts, with fits to signal and background. Arrows delimit the extent of the good event sample.

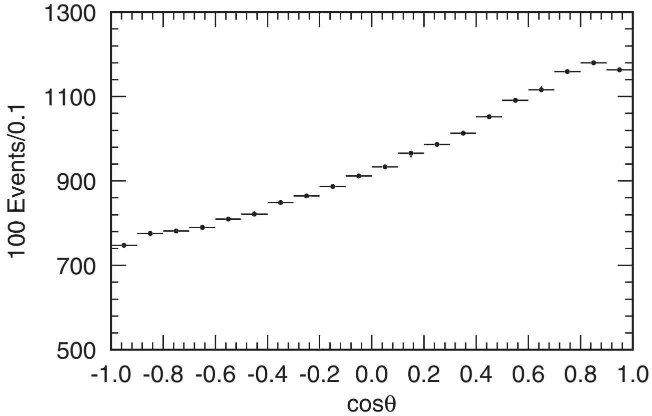

FIG. 2. The real (lines) and weighted HMC (points) $\cos\theta$ distributions of the $\bar{p}$. The total number of HMC events has been reduced by a factor of 10 to equal the number of real events.

the $\bar{p}$, and θ_{mc} and θ_r are, respectively, the HMC and real $\bar{p}$ polar angles in the lambda helicity frame. Note that in the absence of a background correction, $S = \overline{\alpha}_\Omega \overline{\alpha}_\Lambda$. The numerator in Eq. (2) effectively polarizes the HMC sample, while the denominator removes the polarization bias accrued from using parameters from real polarized $\overline{\Lambda}$ decays. The weights, binned in $\cos\theta_{\mathrm{mc}}$, were approximated by a polynomial series expansion of Eq. (2) of order 10 in S, and S was extracted by minimizing the χ^2 between the real and weighted HMC $\cos\theta$ distributions of the $\bar{p}$. The uncertainty in the extracted value of S was determined by finding the variation in S needed to increase the χ^2 by one, and it includes the uncertainty in the acceptance as determined by the HMC events.

The analysis procedure was validated by Monte Carlo simulation. Monte Carlo $\overline{\Omega}^+ \to \overline{\Lambda} K^+ \to \bar{p}\pi^+ K^+$ events, simulated with the measured hodoscope, wire chamber, and calorimeter efficiencies, were required to pass the same cuts as the real data and analyzed by the HMC analysis code. Over a wide range of $\overline{\alpha}_\Omega$ input values, the input and extracted values of $\overline{\alpha}_\Omega \overline{\alpha}_\Lambda$ were found to be consistent, the average difference being $(0.017 \pm 0.042) \times 10^{-2}$.

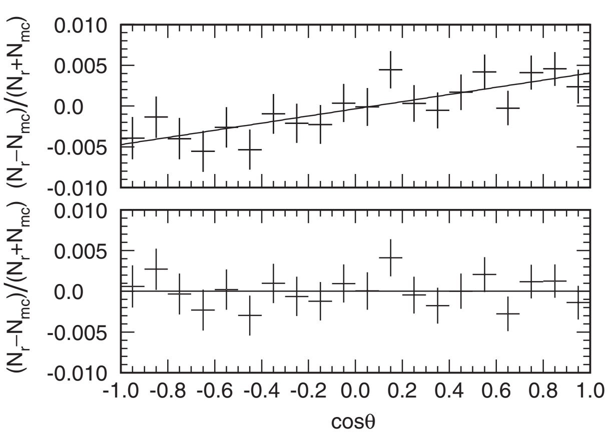

FIG. 3. The differences between the real (N_r) and HMC (N_{mc}) $\cos\theta$ distributions of the $\bar{p}$, for unweighted (top) and weighted (bottom) HMC events. The total number of HMC events has been reduced by a factor of 10 to equal the number of real events.

The extracted slope of the $\cos\theta$ distribution of the $\bar{p}$ from 1 889 608 real events was found to be $S = (1.21 \pm 0.18) \times 10^{-2}$ with $\chi^2/\mathrm{d.o.f} = 22/19$. The uncertainty is statistical. The real and weighted HMC $\cos\theta$ distributions of the $\bar{p}$ are shown in Fig. 2; differences between the real and HMC $\cos\theta$ distributions, unweighted and weighted, are shown in Fig. 3. The nonisotropic nature of the real $\cos\theta$ distribution in the top plot of Fig. 3 is unambiguous evidence of a nonzero α decay parameter.

To extract $\overline{\alpha}_\Omega \overline{\alpha}_\Lambda$ from the $\cos\theta$ slope of the $\bar{p}$, the background contribution to S was subtracted. To estimate the $\cos\theta$ slope from the background events the same analysis procedure was performed on five sideband regions, three below and two above the $\overline{\Omega}^+$ mass region. The average sideband $\cos\theta$ slope for the lower region was $S^l_{\mathrm{sb}} = (9.1 \pm 5.6) \times 10^{-2}$, that of the upper region was $S^u_{\mathrm{sb}} = (32.1 \pm 7.6) \times 10^{-2}$. No statistically significant dependence of the sideband $\cos\theta$ slopes on bin width was found. The weighted mean of all five measurements, $S_{\mathrm{b}} = 17.1 \times 10^{-2}$, was used as the estimate of the contribution of the background events under the mass peak to the $\cos\theta$ distribution of the $\bar{p}$. Using it, the background-subtracted $\cos\theta$ slope was determined; and at $\overline{\alpha}_\Omega \overline{\alpha}_\Lambda = [1.16 \pm 0.18(\mathrm{stat})] \times 10^{-2}$ it is only 4% (0.28σ) less than the uncorrected slope.

The extracted value of $\overline{\alpha}_\Omega \overline{\alpha}_\Lambda$ was found to be independent of the z location of the $\overline{\Omega}^+$ decay vertex. The non-background-subtracted slope, S, was measured on a run-by-run basis for all 450 runs in the data set. No temporal dependence of S was evident.

Systematic uncertainties are listed in Table I. The effects of detector inefficiencies—wire chambers, trigger hodoscopes, and hadronic calorimeter—on $\overline{\alpha}_\Omega \overline{\alpha}_\Lambda$ were found to be negligible: no statistically significant difference in S was found between using perfect and measured detector efficiencies when simulating the HMC $\bar{p}$ and π^+. The effect of the uncertainties in the fields of the analyzing magnets, ± 5.5 G, was also negligible. A small fraction of the daughter pions (0.7%) and kaons decayed before exiting the apparatus. The effect of such decays on S was studied using Monte Carlo events and data and found to

TABLE I. Systematic uncertainties.

Source	Error (10^{-2})
Event-selection cut variations	0.14
Validation of analysis code	0.04
Background subtraction uncertainty	0.06
Detector inefficiency uncertainties	0.06
Analyzing magnets field uncertainties	0.006

be negligible. To estimate the uncertainty due to the background subtraction an uncertainty of 25% was used for the background-to-signal ratio and the full size of the background $\cos\theta$ slope, $S_b = 17.1 \times 10^{-2}$, was used as the uncertainty in the background slope.

The largest source of systematic uncertainty was the sensitivity of the measurement to the values of the cuts used to define the data sample. The effect of small changes in these cut values was 0.14×10^{-2}. The total systematic uncertainty, including the upper limit on the uncertainty of the MC validation of the analysis program (0.04×10^{-2}), is estimated to be 0.17×10^{-2}.

To conclude, from a sample of 1.890×10^6 $\overline{\Omega}^+ \to \overline{\Lambda}K^+ \to \bar{p}\pi^+K^+$ decays, we find $\overline{\alpha}_\Omega\overline{\alpha}_\Lambda = [+1.16 \pm 0.18(\mathrm{stat}) \pm 0.17(\mathrm{syst})] \times 10^{-2}$. This is the first evidence of a nonzero value for $\overline{\alpha}_\Omega$, and hence of parity violation in $\overline{\Omega}^+ \to \overline{\Lambda}K^+$ decays. The total uncertainty in this measurement is a factor of 20 less than that of the previous measurement [8], and the result is 4.7σ from zero. This result is the most precise measurement of the α decay parameter or product of α decay parameters of any antihyperon.

Assuming that CP is conserved in Λ decays, $\overline{\alpha}_\Lambda = -\alpha_\Lambda = -0.642 \pm 0.013$ [13], and hence $\overline{\alpha}_\Omega = [-1.81 \pm 0.28(\mathrm{stat}) \pm 0.26(\mathrm{syst})] \times 10^{-2}$, where the uncertainty in α_Λ has been included in the systematic uncertainty. The α parameter in $\overline{\Lambda} \to \bar{p}\pi^+$ decays has not been directly measured. However, $A_\Lambda = (\alpha_\Lambda + \overline{\alpha}_\Lambda)/(\alpha_\Lambda - \overline{\alpha}_\Lambda)$ has been: the present world average, $(1.2 \pm 2.1) \times 10^{-2}$ [13], is dominated by the measurement of PS185 [14]. This along with α_Λ can be used to extract $\overline{\alpha}_\Lambda$, which is found to be -0.627 ± 0.029. Using this value of $\overline{\alpha}_\Lambda$ we find $\overline{\alpha}_\Omega = [-1.85 \pm 0.29(\mathrm{stat}) \pm 0.27(\mathrm{syst}) \pm 0.09] \times 10^{-2}$, where the last uncertainty is that due to the uncertainty in $\overline{\alpha}_\Lambda$. (Note that the combined asymmetry $A_{\Xi\Lambda} \equiv (\alpha_\Xi\alpha_\Lambda - \overline{\alpha}_\Xi\overline{\alpha}_\Lambda)/(\alpha_\Xi\alpha_\Lambda + \overline{\alpha}_\Xi\overline{\alpha}_\Lambda) \simeq A_\Xi + A_\Lambda$ has been measured by HyperCP to be $[0.0 \pm 5.1(\mathrm{stat}) \pm 4.4(\mathrm{syst})] \times 10^{-4}$ [3]. Hence it is very likely that $\overline{\alpha}_\Lambda = -\alpha_\Lambda$ to the precision of the uncertainty in the α_Λ measurement.)

To test CP invariance in charged-Ω and Λ decays we compare the measurements reported here with the weighted averages of $\alpha_\Omega\alpha_\Lambda$ and α_Ω reported by HyperCP from analyses of data taken in the 1997 [4] and 1999 [5] running periods: $\alpha_\Omega\alpha_\Lambda = [1.15 \pm 0.11(\mathrm{stat}) \pm 0.10(\mathrm{syst})] \times 10^{-2}$ and $\alpha_\Omega = [1.79 \pm 0.17(\mathrm{stat}) \pm 0.16(\mathrm{syst}) \pm 0.04] \times 10^{-2}$, where the last uncertainty is that due to the uncertainty in α_Λ. We find $\alpha_\Omega\alpha_\Lambda - \overline{\alpha}_\Omega\overline{\alpha}_\Lambda = [-0.01 \pm 0.21(\mathrm{stat}) \pm 0.20(\mathrm{syst})] \times 10^{-2}$, and $A_{\Omega\Lambda} \equiv (\alpha_\Omega\alpha_\Lambda - \overline{\alpha}_\Omega\overline{\alpha}_\Lambda)/(\alpha_\Omega\alpha_\Lambda + \overline{\alpha}_\Omega\overline{\alpha}_\Lambda) = [-0.4 \pm 9.1(\mathrm{stat}) \pm 8.5(\mathrm{syst})] \times 10^{-2}$. Using the value of $\overline{\alpha}_\Omega$ derived from the measurements of A_Λ and α_Λ (which does not assume CP invariance in $\Lambda \to p\pi^-$ decays), $A_\Omega \equiv (\alpha_\Omega + \overline{\alpha}_\Omega)/(\alpha_\Omega - \overline{\alpha}_\Omega) = [-1.6 \pm 9.2(\mathrm{stat}) \pm 8.6(\mathrm{syst}) \pm 2.2] \times 10^{-2}$, where the last uncertainty comes from the contribution of the uncertainty in A_Λ in extracting $\overline{\alpha}_\Omega$.

The most recent standard-model calculation of $A_{\Omega\Lambda}$ [15], which includes important final-state interactions due to $\Omega \to \Xi\pi \to \Lambda\overline{K}$, gives $|A_{\Omega\Lambda}| \leq 4 \times 10^{-5}$. New physics can greatly increase $A_{\Omega\Lambda}$ through enhanced chromomagnetic-penguin operators. Kaon measurements constrain these enhancements, and limit the asymmetry to be $|A_{\Omega\Lambda}| \leq 8 \times 10^{-3}$ [15].

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