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HUNTING FOR DIRECT CP VIOLATION IN STRANGE-BARYON DECAYS [a]

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Although CP-symmetry breaking has only been seen in neutral kaon decays, this mysterious phenomenon is expected to occur elsewhere. In this talk, how CP violation can arise in strange-baryon decays is briefly reviewed. The current status and prospects for searching for such an effect will be presented.

1 Historical Introduction

Strange baryons were first discovered in cosmic-ray experiments in the late 1940s as particles heavier than the nucleons; [1] hence, they are also known as hyperons. When Lee and Yang proposed parity (P) nonconservation in 1956 to explain the famous θ-τ puzzle, they also suggested studying decays of hyperons as further tests of their idea. [2] Explicitly, they predicted that the distribution of protons in the weak decay $\Lambda^0 \to p\pi^-$ would have a forward-backward asymmetry, quantified by the decay parameter α_Λ, with respect to the polarization of Λ^0. Just a few months after the classic ^{60}Co experiment performed by Madame C.S. Wu *et al*[3] was announced, the predicted forward-backward asymmetry in Λ^0 decay was indeed observed. [4]

With the fall of parity conservation, invariance of the other discrete symmetries, charge conjugation (C) and time reversal (T), was also questioned. As early as 1957, Lee, Oehme and Yang suggested tests that were sensitive to T violation in K^0 decays. [5] Within a year, Okubo concluded that breaking of T symmetry would lead to a difference in the partial decay rates between Σ^+ and $\overline{\Sigma}^-$, [6] followed by Pais who proposed a test of T violation by comparing the magnitude of the α decay parameters of the Λ^0 and $\overline{\Lambda}^0$ decays. [7] However,

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there were arguments suggesting that the combined symmetry of charge conjugation and parity should be conserved.[8] These speculations were resolved by the surprising discovery of CP violation in K_L^0 decays in 1964[9] that led to a new series of experimental studies and searches for CP-symmetry breaking outside of K_L^0.

The early explorations of CP asymmetry in strange-baryon decays were limited by statistics. Due to low energy, it was difficult to produce large samples of hyperons and anti-hyperons to test the proposal put forward by Okuba. Pais's idea was not realized experimentally until 1985.[10] What was done in the 60's and 70's is the determination of the β_Λ decay parameter, which is sensitive to T violation if the final-state interaction is absent, in the decays of polarized Λ^0's produced in exclusive reactions.[11] However, these attempts were not precise enough to confront any predictions.

Recently, there has been a renewal of interest in hunting for CP asymmetry in strange-baryon decays. With better instrumentation, it is now possible to collect a billion hyperon decays with a simple spectrometer in a relatively short time. This will improve the search sensitivity for the CP-odd effect in hyperon decays by at least two orders of magnitude to a level of 10^{-4} or better.

In the following, theoretical motivation, recent experimental progress and the prospects for searching for direct CP violation in the nonleptonic decays of Λ and charged-Ξ baryons are presented.

2 Phenomenology

2.1 Nonleptonic hyperon decay

All long-lived spin-1/2 strange baryons decay predominantly into a spin-1/2 baryon and a pion with a change of strangeness $\Delta S = 1$.[b] Since parity is not conserved in these weak decays, the orbital angular momentum of the final-state particles can be either 0 or 1. The corresponding S-wave amplitude is parity-violating whereas the P-wave amplitude is parity-conserving.

In general, a nonleptonic hyperon decay can be described by the decay rate Γ and the decay parameters, α_p and β_p. In terms of the S- and P-wave amplitudes, the decay rate is given by[12]

$$\Gamma = G_F^2 m_\pi^4 \frac{p_d(E_d + m_d)}{4\pi m_p}\left(|S|^2 + |P|^2\right) , \tag{1}$$

where G_F is the Fermi constant, m_π is the mass of the pion, m_p is the mass of the hyperon, m_d is the mass of the daughter baryon, p_d and E_d are the

[b] Except Σ^0 that decays into Λ^0 and γ by electromagnetic interaction with $\Delta S = 0$.

magnitude of the momentum and energy of the baryon in the hyperon rest frame respectively. The decay parameters, α_p and β_p, defined as

$$\alpha_p = \frac{2Re(S^*P)}{|S|^2+|P|^2} \; , \quad \beta_p = \frac{2Im(S^*P)}{|S|^2+|P|^2} \; , \tag{2}$$

are related to the interference of the S- and P-wave amplitudes.

In the rest frame of the hyperon, the angular distribution of the daughter baryon is

$$\frac{dn}{d\Omega} = \frac{1}{4\pi}\big(1+\alpha_p \mathbf{P}_p \cdot \hat{\mathbf{p}}_d\big) = \frac{1}{4\pi}\big(1+\alpha_p P_p \cos\theta_d\big) \; , \tag{3}$$

where θ_d is the angle between the polarization of the parent, $\mathbf{P}_p$, and the momentum unit vector of the daughter, $\hat{\mathbf{p}}_d$. In addition, the polarization of the daughter baryon, $\mathbf{P}_d$, is related to the polarization of the parent by

$$\mathbf{P}_d = \frac{(\alpha_p + \mathbf{P}_p \cdot \hat{\mathbf{p}}_d)\hat{\mathbf{p}}_d + \beta_p \mathbf{P}_p \times \hat{\mathbf{p}}_d + \gamma_p \hat{\mathbf{p}}_d \times (\mathbf{P}_p \times \hat{\mathbf{p}}_d)}{\big(1+\alpha_p \mathbf{P}_p \cdot \hat{\mathbf{p}}_d\big)} \; , \tag{4}$$

where the decay parameter, γ_p, given by

$$\gamma_p = \frac{|S|^2-|P|^2}{|S|^2+|P|^2} \; , \tag{5}$$

is not an independent quantity but is subject to the constraint $\alpha_p^2+\beta_p^2+\gamma_p^2 = 1$. The decay parameters of the corresponding anti-hyperon decay will be denoted by $\overline{\alpha}_p$, $\overline{\beta}_p$ and $\overline{\gamma}_p$.

2.2 CP violation in hyperon decay

The decay of a strange baryon can be related to that of the corresponding anti-strange baryon by CP transformation. As illustrated in Fig. 1 for $\Lambda \to p\pi$ decay, under CP operation, a daughter baryon emitted in the forward hemisphere defined by the polarization of the parent is transformed into an anti-baryon emerged in the backward hemisphere. Therefore, $\overline{\alpha}_p = -\alpha_p$ under CP transformation. In general, if CP is conserved, the decay parameters will satisfy the following conditions:

$$\overline{\alpha}_p = -\alpha_p, \quad \overline{\beta}_p = -\beta_p, \quad \overline{\gamma}_p = \gamma_p \; . \tag{6}$$

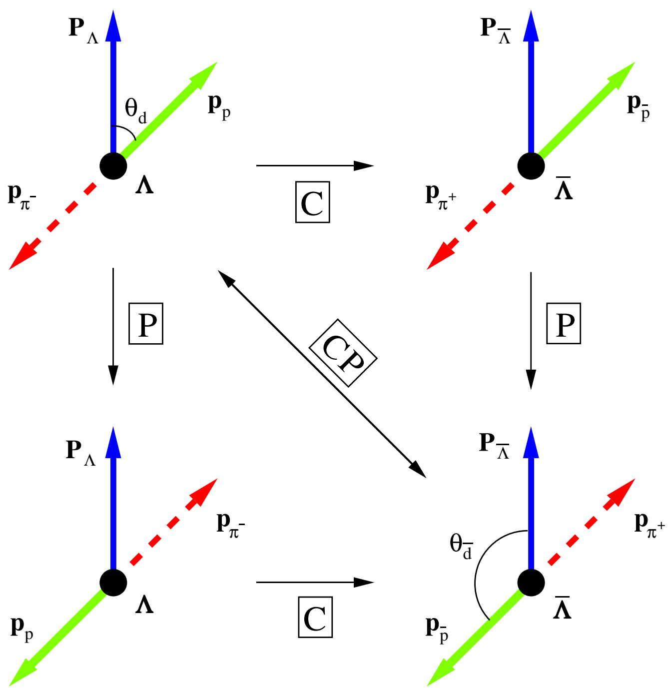

Figure 1: C- and P-operations on $\Lambda \to p\pi$ decay. Since $\theta_{\overline{d}}$ is mapped into $\pi - \theta_d$, the decay parameter $\overline{\alpha}_\Lambda$ is related to $-\alpha_\Lambda$ if CP is conserved.

These results can be obtained from Eq. (4) when we impose CP invariance to the equation.

It is then natural to look for CP-odd effects in strange baryon decays by comparing the decay parameters of the hyperon and the anti-hyperon. The comparison can be realized by defining some CP observables

$$A = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}\ , \quad B = \frac{\beta + \overline{\beta}}{\beta - \overline{\beta}}\ . \tag{7}$$

Another CP observable relies on the difference in the partial decay rates, as originally proposed by Okubo,

$$\Delta = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}} \,. \tag{8}$$

To proceed further, we can write the complex S- and P-decay amplitudes in terms of the moduli, $S_{2\Delta I,2I}$ and $P_{2\Delta I,2I}$, the CP-violating weak phases $\phi_{2\Delta I,2I}$ and the CP-conserving final-state phase shifts $\delta_{2\Delta I,2I}$, where I is the isospin of the final-state and ΔI is the change of isospin in the decay. With this parametrization, the model-independent CP observables can be expressed approximately as, for the $\Lambda \to p\pi$ decay,

$$A_\Lambda = -tan(\delta^P_{11} - \delta^S_1) sin(\phi^P_1 - \phi^S_1), \tag{9}$$
$$B_\Lambda = cot(\delta^P_{11} - \delta^S_1) sin(\phi^P_1 - \phi^S_1), \tag{10}$$
$$\Delta_\Lambda = \sqrt{2}\frac{S_{33}}{S_{11}} sin(\delta^S_3 - \delta^S_1) sin(\phi^S_3 - \phi^S_1), \tag{11}$$

where the strong phases have been measured to be $\delta^P_{11} = -1.1^\circ$, $\delta^S_1 = 6.0^\circ$, and $\delta^S_3 = -3.8^\circ$ with uncertainties of about 1°.[13] For the charged $\Xi \to \Lambda\pi$ decay,[c] we have

$$A_\Xi = -tan(\delta^P_{21} - \delta^S_2) sin(\phi^P_{12} - \phi^S_{12}), \tag{12}$$
$$B_\Xi = cot(\delta^P_{21} - \delta^S_2) sin(\phi^P_{12} - \phi^S_{12}), \tag{13}$$
$$\Delta_\Xi = 0. \tag{14}$$

The observable Δ_Ξ is zero because there is only one isospin state available in the final state. There is no measurement on the $\Lambda\pi$ re-scattering phases. Nath and Kumar calculated $\delta^S_2 = -18.7^\circ$ and $\delta^P_{21} = -2.7^\circ$ whereas Martin got $\delta^P_{21} = -1.2^\circ$.[15] However, recent calculations argue that both δ^P_{21} and δ^S_2 are very small, if not zero.[16]

It is interesting to note that we need non-zero CP-violating phase difference as well as final-state phase shifts to observe direct CP nonconservation in hyperon decays. This is a feature shared by all CP-violating processes.

2.3 Predictions of CP violation in Λ and charged Ξ decays

Predictions of the CP observables depend on the details of the models.[14,17] In the Kobayashi-Maskawa model, the weak phase is contained in the penguin diagrams that are responsible for the $\Delta S = 1$ interactions. In the Weinberg model, the CP asymmetry comes from the exchange of charged-Higgs bosons.

[c] Detailed discussion of CP violation in other strange-baryon decays can be found in Ref. 14.

Up to now, reliable predictions of CP-odd effects in strange-baryon decays have not been not available. For example, the calculated values of the $\Lambda\pi$ phases disagree by an order of magnitude, leading to an uncertainty in A_Ξ by the same amount. The situation is further complicated by the fact that exact calculation of the hadronic matrix elements cannot be implemented in evaluating the weak phases. Predictions of A, B, and Δ have been obtained by using different models to calculate the hadronic matrix elements. Some predictions of A, B, and Δ for the $\Lambda \to p\pi$ and charged $\Xi \to \Lambda\pi$ decays in the standard model, the Weinberg-Higgs model, and the isoconjugate Left-Right symmetric model are shown in Table 1. We should note that superweak models do not have $\Delta S = 1$ CP-odd effects and thus all observables in Eqs. (7) and (8) are expected to be zero.[18]

Table 1: Some predictions of Δ, A and B for $\Lambda \to p\pi$ and charged $\Xi \to \Lambda\pi$ decays.

$\Lambda \to p\pi$

	Δ_Λ	A_Λ	B_Λ
CKM	$< 10^{-6}$	$(-5 \text{ to } -1) \times 10^{-5}$	$(0.6 \text{ to } 3) \times 10^{-4}$
Weinberg	-8×10^{-6}	-2.5×10^{-5}	1.6×10^{-3}
Left-Right	0	$(-0.1 \text{ to } 6) \times 10^{-4}$	7×10^{-4}

Charged $\Xi \to \Lambda\pi$

	Δ_Ξ	A_Ξ	B_Ξ
CKM	0	$(-10 \text{ to } -1) \times 10^{-5}$	$(10 \text{ to } 1) \times 10^{-3}$
Weinberg	0	-3.2×10^{-4}	3.8×10^{-3}
Left-Right	0	$(-2.5 \text{ to } 6) \times 10^{-5}$	-3.1×10^{-4}

3 Searches

As shown in Table 1, observable B is the most sensitive probe for finding CP-symmetry breaking in the strange-baryon sector. To test the predictions of B, however, will require at least 10^8 to 10^{11} hyperons and anti-hyperons with precisely known polarization. Furthermore, the polarization of the daughter baryon must also be well measured by some means, for example by rescattering, for determining β and $\overline{\beta}$. The Δ observable requires knowing the absolute number of events and, in general, it is too small to measure. It is unlikely that a meaningful determination of Δ or B will be performed in the near future. The best observable for finding CP violation in strange-baryon decays is A. Yet, measuring A still asks for decay samples with well determined hyperon polarization.

3.1 What have been done

There were three attempts to search for CP nonconservation in Λ decay by experiments R608 at ISR, [10] DM2 at Orsay, [19] and PS185 at LEAR. [20,21] However, none of these experiments was designed specifically for studying CP symmetry in strange-baryon decays. Based on a limited number of polarized $\Lambda^0 \to p\pi^-$ and $\overline{\Lambda}^0 \to \overline{p}\pi^+$ decays, the best result for A_Λ is -0.013±0.022. [21] We will summarize below the highlights of these three measurements.

R608 at ISR

Polarized Λ^0's and $\overline{\Lambda}^0$'s were produced in the forward beam fragmentation region in the inclusive reactions $pp \to \Lambda^0 + X$ and $\overline{p}p \to \overline{\Lambda}^0 + X$, respectively. At the sensitivity of this experiment, C invariance in strong interactions is valid, and the polarization of Λ^0 produced in $pp \to \Lambda^0 + X$ is identical to that of $\overline{\Lambda}^0$ created in $\overline{p}p \to \overline{\Lambda}^0 + X$. Based on 17,028 $\Lambda^0 \to p\pi^-$ and 9,553 $\overline{\Lambda}^0 \to \overline{p}\pi^+$ events, the ratio $\alpha_\Lambda/\overline{\alpha}_\Lambda$ was measured to be -1.04 ± 0.29, which is equivalent to $A_\Lambda = -0.02 \pm 0.14$.

DM2 at Orsay

A total of 1,847 $\Lambda^0\overline{\Lambda}^0$ pairs from the decays of J/Ψ's that were produced in unpolarized e^+e^- collisions was used to study the differential cross section

$$\frac{d\sigma}{d\cos\theta_\Lambda d\Omega_p d\Omega_{\overline{p}}} \propto 2\Big(1 - \frac{p_\Lambda^2}{E_\Lambda^2}\sin^2\theta_\Lambda\Big)\left[1 - \alpha_\Lambda\overline{\alpha}_\Lambda(\mathbf{p}\cdot\mathbf{n})(\overline{\mathbf{p}}\cdot\mathbf{n})\right] + \frac{p_\Lambda^2}{E_\Lambda^2}\sin^2\theta_\Lambda\Big\{1 - \alpha_\Lambda\overline{\alpha}_\Lambda\left[\mathbf{p}\cdot\overline{\mathbf{p}} - 2(\mathbf{p}\cdot\mathbf{x})(\overline{\mathbf{p}}\cdot\mathbf{x})\right]\Big\}\ , \qquad (15)$$

where θ_Λ is the emission angle of Λ^0 with respect to the e^+ beam direction, p_Λ and E_Λ are the momentum and energy of Λ^0 in the J/Ψ decay, $\mathbf{p}$ and $\overline{\mathbf{p}}$ are the p and $\overline{p}$ momentum in the Λ^0 and $\overline{\Lambda}^0$ rest frame respectively, $\mathbf{x}$ is normal to the plane formed by the Λ^0 momentum and the beam axis, and $\mathbf{n}$ is a unit vector that suppresses the spin state of zero in the J/Ψ decay and is degenerate with the beam axis at $\theta_\Lambda = 0°$ and $90°$. By fixing the decay parameter α_Λ at the canonical value of 0.642,[22] the observed distribution for $\mathbf{p}\cdot\overline{\mathbf{p}}$ was fitted to the differential cross section in Eq. (15) by varying $\overline{\alpha}_\Lambda$. The least squares minimization yielded $\overline{\alpha}_\Lambda = -0.63 \pm 0.13$. Consequently, A_Λ was determined to be 0.01 ± 0.10.

PS185 at LEAR

In this experiment, polarized $\overline{\Lambda}^0\Lambda^0$ pairs were produced in exclusive reaction $\overline{p}p \to \overline{\Lambda}^0\Lambda^0$ at threshold. Again, conservation of charge conjugation in the production process guarantees the polarization of Λ^0 and $\overline{\Lambda}^0$ to be the same. From the ratio of $\alpha_\Lambda P_\Lambda$ to $\overline{\alpha}_\Lambda \overline{P}_\Lambda$, a value of 0.013 ± 0.022 for A_Λ was obtained recently.

3.2 Current Search: HyperCP (Experiment 871) at Fermilab

HyperCP prepares polarized Λ^0 and $\overline{\Lambda}^0$ samples from the decay of Ξ^- and $\overline{\Xi}^+$ hyperons. When an unpolarized Ξ^- decays, from Eq. (4), the daughter Λ^0 acquires longitudinal polarization which is given by

$$\mathbf{P}_\Lambda = \alpha_\Xi \hat{\mathbf{p}}_\Lambda \ . \tag{16}$$

In other words, the Λ^0 polarization is *absolutely* determined by the decay parameter α_Ξ. In this case, the angular distribution of the decay proton along $\hat{\mathbf{p}}_\Lambda$ in the helicity frame of Λ^0, as shown in Fig. 2, is

$$\frac{dn}{d\cos\theta_{p\Lambda}} = \frac{1}{2}\big(1 + \alpha_\Lambda \alpha_\Xi \cos\theta_{p\Lambda}\big) \ . \tag{17}$$

Similarly, the decay distribution of $\overline{p}$ in the $\overline{\Lambda}^0$ helicity frame has a slope of $\overline{\alpha}_\Lambda \overline{\alpha}_\Xi$. As discussed in Sec. 2, both decay parameters change sign under CP transformation. Thus, any difference in the slopes of the angular distributions between p and $\overline{p}$ will signal breaking of CP invariance in the $\Xi \to \Lambda\pi$, $\Lambda \to p\pi$ decay sequence. The degree of direct CP violation can be quantified by an observable

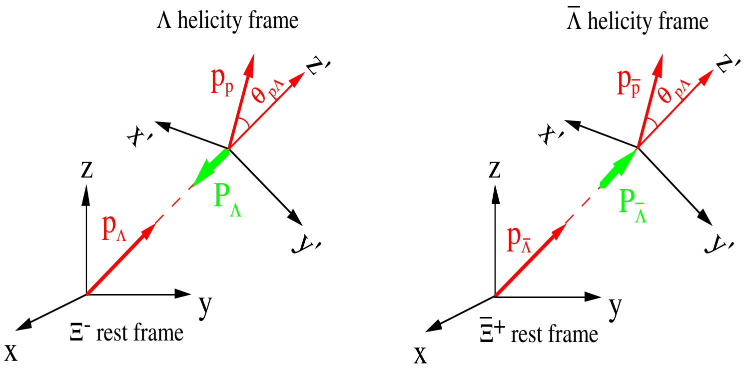

Figure 2: Helicity frame used for determining the angular distribution of the decay baryon. Since the α decay parameters change sign under CP transformation the polarizations of Λ^0 and $\overline{\Lambda}^0$ are equal and opposite. The orientation of the helicity frame is not fixed in space but changes from event to event.

$$A_{\Lambda\Xi} = \frac{\alpha_\Lambda \alpha_\Xi - \overline{\alpha}_\Lambda \overline{\alpha}_\Xi}{\alpha_\Lambda \alpha_\Xi + \overline{\alpha}_\Lambda \overline{\alpha}_\Xi} \simeq A_\Lambda + A_\Xi \ . \tag{18}$$

That is, the measurement is sensitive to any CP-odd effect in the Λ and charged Ξ decay.

A unique feature of the helicity frame defined by the polarization of Λ^0 in Eq. (16) is that its orientation varies from event to event with respect to the fixed laboratory coordinate system. As a result, any imperfection, temporal variation and systematic effects that are localized in space are mapped into a wide range of $\cos\theta_{p\Lambda}$. Hence the systematic biases are highly diluted in the helicity frame and have little impact on the determination of $A_{\Lambda\Xi}$.

The goal of HyperCP is to reach a sensitivity of 10^{-4} in $A_{\Lambda\Xi}$. The experiment is taking its first data at Fermilab. The plan and elevation views of the HYperCP spectrometer are shown in Fig. 3. The spectrometer is kept very simple to minimize any potential bias to the measurement. An 800 GeV/c proton beam, with a typical intensity of 1.5×10^{11} protons per 20 s, strikes either a 6 cm-long or a 2 cm-long copper target at a mean angle of $0°$. The longer target is used for producing Ξ^- hyperons. Two different targets are employed to ensure the singles rate in the spectrometer is comparable between the Ξ^- and the $\overline{\Xi}^+$ runs. Parity invariance in strong interactions guarantees the polarization of the produced particles to be zero. The secondary charged beam is momentum and charge selected by a curved collimator located inside a 6 m-long dipole magnet. The channel has a limited acceptance in transverse momentum, further ensuring any residual Ξ production polarization to be small. The accepted Ξ momentum is between 120 GeV/c and 240 GeV/c, with a mean value of about 167 GeV/c. Behind the collimator is a vacuum decay region where most of Ξ baryons decay. The charged particles from Ξ and Λ decays are detected with a magnetic spectrometer made up of multiwire proportional chambers with high-rate capability. After the momentum-analyzing magnet, the daughter proton is deflected toward the proton hodoscope whereas the pions from Ξ^- and Λ^0 decays go toward the pion hodoscope. These decay products are well separated from the secondary charged beam by the time they reach the trigger hodoscopes. The magnetic fields of all spectrometer magnets are monitored with high-precision Hall probes.

A simple, yet selective trigger for collecting Ξ and Λ decays is formed by requiring a time coincidence of signals from the proton and pion hodoscopes as well as the hadron calorimeter. The calorimeter is used to reduce the trigger rate which is otherwise dominated by secondary interactions of the charged beam with material in the spectrometer. In addition, events with background muons are highly suppressed by the energy requirement of the calorimeter in the trigger.

By reversing the polarities of the magnets in the spectrometer and switching to the shorter target, $\overline{\Xi}^+$ decays are collected with the identical CP-invariant trigger. To minimize bias due to temporal variation in the experiment, the Ξ^- and $\overline{\Xi}^+$ runs are cycled at least once a day.

The data acquisition system, based on multiple VME crates, is designed to handle a maximum trigger rate of $100,000$ Hz, with a maximum throughput of about 17 Mb/s.[24] At the nominal proton intensity, the total trigger rate is approximately $75,000$ Hz, with a mean event size of about 550 *bytes*.

The 1996-1997 run will end on September 5th. HyperCP will have recorded 7.5×10^9 triggers, of which 1.5×10^9 are Ξ^- triggers and 2.5×10^9 are $\overline{\Xi}^+$ triggers. Preliminary analysis indicates that this will yield approximately 9×10^8 Ξ^- and 2.5×10^8 $\overline{\Xi}^+$ decays. The anticipated statistical uncertainty in $A_{\Lambda\Xi}$ is about 2×10^{-4} in the first run. Preliminary $\Lambda\pi$ invariant-mass distributions for a small number of events from the Ξ trigger are shown in Fig. 4. An excellent mass resolution of 1.6 MeV/c^2 has already been achieved. Notice the similarity of the mass peaks, indicating that the running condition is stable between runs.

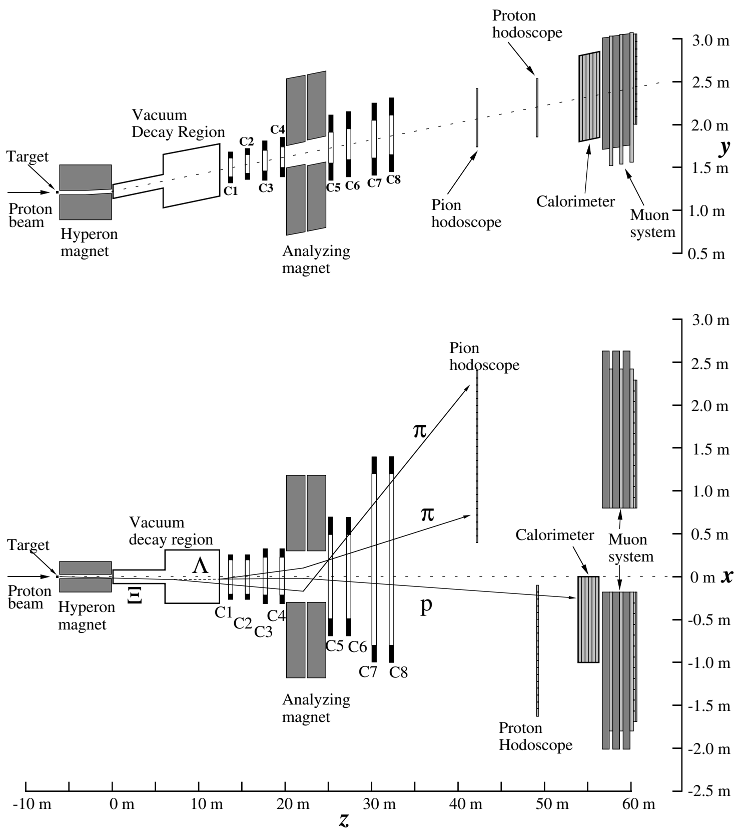

Figure 3: Schematic drawing of HyperCP spectrometer.

4 Prospects

After the commissioning of the Main Injector at Fermilab, HyperCP will have a second run in 1999. With minor improvements to the spectrometer and simple upgrades to the DAQ system, HyperCP should be able to take data at higher beam intensity. Combining the data sets of the two runs should yield an uncertainty in $A_{\Lambda\Xi}$ of 10^{-4} or better.

It has been suggested that the tau-charm factory can provide very clean and systematic free conditions for investigating CP violation in Λ and Ξ decays.[25] When a tau-charm factory is operated at the J/ψ peak, the production cross section of J/ψ strongly depends on the beam-energy spread. By using

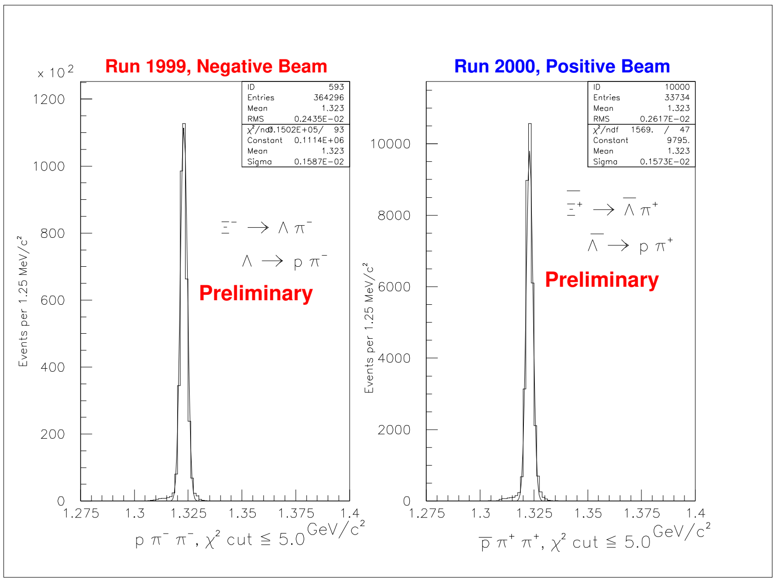

Figure 4: Λ-π invariant mass distributions from the Ξ^- and $\overline{\Xi}^+$ runs. These events pass geometric and kinematic fits. A cut on the quality of the kinematic fit has been made. The mass resolution is 1.6 MeV/c^2.

monochromators the energy spread can be reduced from 1.3 MeV to 0.1 MeV and the expected luminosity is about $4 \times 10^{32}\ cm^{-2}s^{-1}$. In $10^7 s$ of running, the number of $\Lambda^0\overline{\Lambda}^0$ and $\Xi\overline{\Xi}^+$ pairs coming from J/ψ decays is estimated to be 1.1×10^8 and 1.4×10^8 respectively.

What CP observables that the tau-charm factory can measure depends on the polarization of the colliding beam. Specifically the error in A_Λ and in A_Ξ that can be achieved in $10^7 s$ is about 10^{-3}.

5 Conclusion

Although it was proposed right after the discovery of parity nonconservation in weak interactions and almost a decade before the observation of CP violation in K_L^0 decay, the study of CP symmetry in strange baryon decays did not flourish. The current limit of testing CP invariance in hyperon decays is only at the 10^{-2} level, which is at least two orders of magnitude away from most theoretical predictions. There is no dedicated experiment with better precision in the near future except HyperCP at Fermilab that will reach a sensitivity of 2×10^{-4} in the 1997 run. The outcome of HyperCP could play an important role in defining the future program of studying CP violation in strange baryon decays.

Acknowledgments

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