Search for \( CP \) Violation in Hyperon Decays with the \textit{HyperCP} Spectrometer at Fermilab

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\textit{for the HyperCP collaboration}

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Why Search for \( CP \) Violation in Hyperon Decays?

- After 40 years of intense experimental effort — and many beautiful experiments — we still know little about \( CP \) violation: the origin of \( CP \) violation remains unknown.
- Although \( CP \) is expected to be ubiquitous in weak interactions — albeit often vanishingly small — the experimental evidence is still meager.
- Although \( CP \) violation is accommodated quite nicely in the standard model, there is little hard evidence that it is the sole province of the standard model.
- Many beyond-the-standard-model theories can produce large new sources of \( CP \) violation, none of which have yet been seen.

> “We are willing to stake our reputation on the prediction that dedicated and comprehensive studies of \( CP \) violation will reveal the presence of New Physics.”

*Bigi and Sanda, CP Violation*

- Hyperons are sensitive to sources of \( CP \) violation that are not probed in other systems.
- These sources are experimentally accessible.
- The cost is small:
  - No new accelerators needed.
  - Apparatus is modest in scope and cost.
How to Search for \( CP \) Violation in \( \Lambda \) Decays

Due to parity violation the proton likes to go in the direction of the \( \Lambda \) spin:

\[
\Lambda \rightarrow p\pi^- : \quad \frac{dN(p)}{d\cos \theta} = \frac{N_0}{2} (1 + \alpha_\Lambda P_\Lambda \cos \theta) \quad \alpha = \frac{2\text{Re}(S^*P)}{|S|^2 + |P|^2} = 0.642
\]

Under \( CP \) the antiproton likes to go in the direction opposite to the \( \bar{\Lambda} \) spin:

\[
\alpha_\Lambda \xrightarrow{\text{CP}} \alpha_{\bar{\Lambda}} = -\alpha_\Lambda
\]

Problem: The \( \Lambda/\bar{\Lambda} \) polarizations have to be precisely known to extract \( \alpha_\Lambda/\alpha_{\bar{\Lambda}} \)
Producing Polarized $\Lambda/\bar{\Lambda}$'s: unpolarized $\Xi$ Decays

In this technique, pioneered by HyperCP, $\Lambda/\bar{\Lambda}$'s of known polarization are produced from unpolarized $\Xi^-/\Xi^+$'s:

$$\Xi^- \rightarrow \Lambda \pi^- \quad \Xi^+ \rightarrow \bar{\Lambda} \pi^+$$

If the $\Xi$ is produced unpolarized — which can simply be done by targeting at 0 degrees — then the $\Lambda$ is found in a helicity state, with a large polarization ($\alpha_\Xi = -0.458$):

$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda \quad \vec{P}_\bar{\Lambda} = \bar{\alpha}_\Xi \hat{p}_\bar{\Lambda}$$

$$\frac{dN(p)}{d \cos \theta} = \frac{N_0}{2} (1 + \alpha_\Lambda \alpha_\Xi \cos \theta) \quad \frac{dN(\bar{p})}{d \cos \theta} = \frac{N_0}{2} (1 + \bar{\alpha}_\Lambda \bar{\alpha}_\Xi \cos \theta)$$

If $CP$ is good, the slopes of the proton and antiproton $\cos \theta$ distributions are identical, and:

$$\alpha_\Xi \alpha_\Lambda = \bar{\alpha}_\Xi \bar{\alpha}_\Lambda$$

$$\Xi^- \rightarrow \Lambda \pi^- \rightarrow p \pi^- \pi^- \quad \Xi^+ \rightarrow \bar{\Lambda} \pi^+ \rightarrow \bar{p} \pi^+ \pi^+$$

slope = $\alpha_\Lambda \alpha_\Xi$  

slope = $\bar{\alpha}_\Lambda \bar{\alpha}_\Xi$
HyperCP technique is sensitive to both $\Xi$ and $\Lambda$ CP violation

\[ \frac{\alpha_\Xi \alpha_\Lambda - \bar{\alpha}_\Xi \bar{\alpha}_\Lambda}{\alpha_\Xi \alpha_\Lambda + \bar{\alpha}_\Xi \bar{\alpha}_\Lambda} \approx A_\Xi + A_\Lambda \]

where:

\[ A_\Xi = \frac{\alpha_\Xi + \bar{\alpha}_\Xi}{\alpha_\Xi - \bar{\alpha}_\Xi} \quad \text{and} \quad A_\Lambda = \frac{\alpha_\Lambda + \bar{\alpha}_\Lambda}{\alpha_\Lambda - \bar{\alpha}_\Lambda} \]

What HyperCP experimentally measures ⇒

Important: polar axis changes from event to event.
Phenomenology of $CP$ Violation in $\Xi$ and $\Lambda$ Decay

- $CP$ violation in $\Xi$ and $\Lambda$ decays is manifestly direct with $\Delta S = 1$.
- Three ingredients are needed to get a non-zero asymmetry:
  1. At least two channels in the final state: the $S$-and $P$-wave amplitudes.
  2. The $CP$ violating weak phases must be different in the two channels.
  3. There must be unequal final-state scattering phase shifts in the two channels.

\[ A_\Lambda = \frac{\alpha_\Lambda + \alpha_{\bar{\Lambda}}}{\alpha_\Lambda - \alpha_{\bar{\Lambda}}} \cong - \tan(\delta_P - \delta_S) \sin(\phi_P - \phi_S), \]
\[ A_\Xi = \frac{\alpha_\Xi + \alpha_{\bar{\Xi}}}{\alpha_\Xi - \alpha_{\bar{\Xi}}} \cong - \tan(\delta_P - \delta_S) \sin(\phi_P - \phi_S). \]

- Asymmetry greatly reduced by the small strong phase shifts.
  - The $p\pi$ phase shifts have been measured to a precision of about one degree:
    \[
    \Lambda \left\{ \begin{array}{l}
    \delta_P = -1.1 \pm 1.0^\circ \\
    \delta_S = 6.0 \pm 1.0^\circ
    \end{array} \right.
    \]
  - The $\Lambda\pi$ phase shifts can’t be directly measured, theoretical predictions disagree:

\[
\Xi^- \left\{ \begin{array}{l}
\delta_P = -2.7^\circ \\
\delta_S = -18.7^\circ
\end{array} \right\} 1965 \quad = -1^\circ \quad = 0^\circ \quad \text{recent \chi PT}
\]

$HyperCP$ has measured the $\Lambda\pi$ phase shift: $(4.6 \pm 1.8)^\circ$
Bad News: Standard Model Theory Predictions Small

- Much enthusiasm a decade ago as Standard Model predictions were relatively large.

- At the same time there was concern that accidental cancellation in the kaon system would lead to $\epsilon'/\epsilon \approx 0$.

- Standard Model predictions have slowly fallen to:

$$-0.5 \times 10^{-4} < A_{\Xi} < +0.5 \times 10^{-4}$$

(Tandean & Valencia, 2003)

- The expected SM asymmetry is out of reach for any experiment, planned or otherwise.

Important: no unambiguous connection between: $\delta_{\text{CKM}} \Leftrightarrow A_{\Xi}, A_{\Lambda}$
Good News: Standard Model Theory Predictions Small

- Beyond-the-standard-model predictions larger, and not well constrained by kaon CP measurements: hyperon CP violation probes both parity conserving and parity violating amplitudes.
- Recent paper by Tandean (2004) shows that the upper bound on $A_{\Xi\Lambda}$ from $\epsilon'/\epsilon$ and $\epsilon$ measurements is $\sim 100 \times 10^{-4}$.
- For example, some supersymmetric models that do not generate $\epsilon'/\epsilon$ can lead to $A_{\Lambda}$ of $O(10^{-3})$.
- Other BSM theories, such as Left-Right mixing models, (Chang, He, Pakvasa (1994)), also have enhanced asymmetries.

Any CP-violation signal will almost certainly come from New Physics.
What is the experimental situation?

- To date there are only upper limits on the asymmetries.
- $A_\Lambda$ has been measured to $2 \times 10^{-2}$:

<table>
<thead>
<tr>
<th>Exp</th>
<th>Mode</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>R608</td>
<td>$A_\Lambda$</td>
<td>$p\bar{p} \to \Lambda X, p\bar{p} \to \bar{\Lambda}X$</td>
</tr>
<tr>
<td>DM2</td>
<td>$A_\Lambda$</td>
<td>$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$</td>
</tr>
<tr>
<td>PS185</td>
<td>$A_\Lambda$</td>
<td>$p\bar{p} \to \Lambda\bar{\Lambda}$</td>
</tr>
</tbody>
</table>

- There is a recent measurement of $A_{\Xi\Lambda}$, based on the $HyperCP$ technique:

<table>
<thead>
<tr>
<th>Exp</th>
<th>Mode</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>E756</td>
<td>$A_{\Xi\Lambda}$</td>
<td>$pN \to \Xi^\pm X \to \Lambda\pi^\pm$</td>
</tr>
</tbody>
</table>

- This measurement of $A_{\Xi\Lambda}$ can be used with measurements of $A_\Lambda$ to infer a limit on $A_{\Xi}$.

- None of these measurements is in the regime of testing theory.
- $HyperCP$ is pushing two orders of magnitude beyond the best limit, to $\sim 10^{-4}$. 
The **HyperCP** Spectrometer

- Alternate $+$ and $-$ running.
- 800 GeV/c incident proton beam.
- 10–15 MHz, 167 GeV/c charged beam.
- High-rate, narrow-pitch wire chambers.
- Muon system for rare/forbidden hyperon and kaon decays.

- Very high-rate DAQ:
  - $50-80$ KHz evts/spill-s to tape.
  - $27$ MB/s on 27 Exabyte 8705 tape drives.
- Simple, low-bias trigger using hodoscopes and calorimeter.
  $SS(\geq 1 \text{ hit}) \cdot OS(\geq 1 \text{ hit}) \cdot Cal(\geq 40 \text{ G eV})$
HyperCP Yields

- In 12 months of data taking HyperCP recorded one the largest data samples ever by a particle physics experiment: 231 billion events, 29,401 tapes, and 119.5 TB data.

Entire WWW on 9/11/01 was 5 TB!

Reconstructed Events

<table>
<thead>
<tr>
<th>Type</th>
<th>Channeled beam polarity</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi \rightarrow \Lambda \pi$</td>
<td>$+ \times 10^6$</td>
<td>$- \times 10^6$</td>
</tr>
<tr>
<td>$K \rightarrow \pi \pi \pi$</td>
<td>$+ \times 10^6$</td>
<td>$- \times 10^6$</td>
</tr>
<tr>
<td>$\Omega \rightarrow \Lambda \Lambda$</td>
<td>$+ \times 10^6$</td>
<td>$- \times 10^6$</td>
</tr>
</tbody>
</table>
Care Taken to Minimize Differences in + and – Running

- Targets changed to equalize secondary-beam rates.
  - + polarity: 2.0 cm Cu
  - – polarity: 6.0 cm Cu
- When flipping polarity, field magnitude kept within $\sim 2 \times 10^{-4}$.
- This corresponds to a $\sim 0.3$ mm deflection difference at 10 m for the lowest momentum ($\sim 10$ GeV/c pions).
- About a 1% difference in rates.

![Graph showing Beam Hodoscope Rate vs. Spills for + and – polarities.]

<table>
<thead>
<tr>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>58871</td>
<td>2.4812</td>
<td>0.00065</td>
</tr>
<tr>
<td>23185</td>
<td>2.4817</td>
<td>0.00066</td>
</tr>
</tbody>
</table>
Little Difference in PWC Efficiencies from $+$ and $-$ Running

- $-$ data: solid line
- $+$ data: dashed line
- 32 total planes $\Rightarrow$ good redundancy
Little Difference in Hodo Efficiencies from + and – Running

- data: solid line.
- + data: dashed line.
  - Differences where it matters <0.1%.
  - Redundant counters make real inefficiencies vanishingly small.
- Two rows on OS side.
- Two particles on SS side.
Two Different $CP$ Analyses Attempted

**Hybrid Monte Carlo Method:**
- Compare corrected cos $\theta$ distributions.
- Take a real $\Xi \rightarrow \Lambda\pi$, $\Lambda \rightarrow p\pi$ event, discard proton and pion, generate 10 new unpolarized $\Lambda$ decays.
- **Advantage:** Absolute measurement of $\alpha_\Lambda \alpha_\Xi$.
- **Disadvantage:** Monte Carlo must be very, very good, and fast: $\sim 20$ billion events needed.

**Weighting Method:**
- Compare uncorrected cos $\theta$ distributions.
- Force the $\Xi^-$ and $\Xi^+$ events to have similar momentum and spatial distributions by appropriate weighting.
- **Advantage:** No Monte Carlo needed to measure apparatus acceptance, smaller statistical error.
- **Disadvantage:** inflexible, event-size dependent analysis.

*Large data set, $\sim 1$ billion events, in both cases makes the analysis difficult.*
Weighting Technique

- **Problem:** Geometrical acceptance identical for $\Xi^-$ and $\Xi^+$ decay products only if parent $\Xi^-$ and $\Xi^+$ have same momentum and inhabit the same phase space exiting the collimator.
- **Solution:** Weight the $\Xi^-$ and $\Xi^+$ events to force the two distributions to be identical.
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- **Solution:** Weight the $\Xi^-$ and $\Xi^+$ events to force the two distributions to be identical.

- They are not the same due to different production dynamics.
- Momentum-dependent parameters of $\Xi$ at collimator exit matched.
- $100 \times 100 \times 100 = 1 \times 10^6$ bins used.
\[ \Xi^- \text{ and } \Xi^+ \text{ x Slopes and Positions not Weighted} \]

- Not momentum dependent \( \Rightarrow \) distributions almost identical
- Cut out regions where they are not.
- \( \Xi^- \): Solid lines
- \( \Xi^+ \): Dashed lines
Proton, \(\Lambda\)-pion, \(\Xi\)-pion Momenta Before/After Weighting

- Solid lines
- Dashed lines

![Graphs showing proton, \(\Lambda\)-pion, and \(\Xi\)-pion momenta before and after weighting.](image)
Extracting the \( CP \) Asymmetry

- Determine weighted proton and weighted antiproton \( \cos \theta \) distributions.

\[
\frac{dN_-}{d \cos \theta_-} = A_- \frac{N_-}{2} (1 + \alpha \overline{\alpha} \cos \theta_-)
\]

\[
\frac{dN_+}{d \cos \theta_+} = A_+ \frac{N_+}{2} (1 + \alpha \overline{\alpha} \cos \theta_+)
\]

- Assume the acceptances \( A_- \) and \( A_+ \) have the same \( \cos \theta \) dependence.

- Take the ratio of proton and antiproton \( \cos \theta \) distributions: a nonzero slope is evidence of \( CP \) violation.

- Fit ratios to:

\[
R(\theta, \delta) = C \frac{1 + \alpha \overline{\alpha} \cos \theta}{1 + (\alpha \overline{\alpha} - \delta) \cos \theta}
\]

to extract asymmetry \( \delta \):

\[
\delta = \alpha \overline{\alpha} - \overline{\alpha} \alpha
\]

\[
A_{\Xi \Lambda} = \frac{\delta}{\alpha \overline{\alpha} + \overline{\alpha} \alpha} = \frac{\delta}{2\alpha \overline{\alpha}}
\]

\[
= 1.71 \delta
\]

Proton \( \cos \theta \) ratio before before (**) and after (\( \triangle \)) weighting.
Monte Carlo Tests

Important! Monte Carlo only used to:
- Verify code and algorithm.
- Study a few systematics.

Problem: How do you generate ~1 billion MC events?
Solution:

We get the input asymmetry back $\Rightarrow$

$$\delta = (-0.73\pm0.64) \times 10^{-4}$$
$$A_{\Xi\Lambda} = (1.24\pm1.09) \times 10^{-4}$$
The $CP$ Asymmetry $A_{\Xi\Lambda}$ from Weighting Method

- Data broken up into 18 sets, each with positive and negative events.
- No acceptance corrections.
- No efficiency corrections.
- No background subtraction.

Weighted average of all 18 data sets:

$\delta = (-1.3 \pm 3.0) \times 10^{-4}$

$A_{\Xi\Lambda} = (2.2 \pm 5.1) \times 10^{-4}$

$\chi^2 = 24$

Proton $\cos \theta$ ratio before (●) after (△) weighting, from Analysis Set 1
Background Subtraction Has Little Effect

- Triple Gaussian fit with fourth-order polynomial for background.
- Background fraction:
  \( \Xi^- : 0.43\% \) (lines)
  \( \Xi^+ : 0.41\% \) (circles)

Low mass: \( \delta = (-2.2\pm0.5) \times 10^{-2} \)
High mass: \( \delta = (-3.8\pm0.7) \times 10^{-2} \)

- Weighted background asymmetry:
  \[ A_{\Xi \Lambda}(bs) = (0.0\pm5.1) \times 10^{-4} \]
The helicity frame axes changes from event to event since we always define the polar axis to be the direction of the $\Lambda$ momentum in the $\Xi$ rest frame.

Acceptance differences localized in a particular part of the apparatus do not map into a particular part of the proton (antiproton) $\cos \theta$ distribution.

Important! Overall acceptance differences do not cause any biases.
### Weighted Analysis Bias Error Summary

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Method</th>
<th>$\delta A_{\Sigma\Lambda} \times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyzing Magnets field uncertainties</td>
<td>Data</td>
<td>2.4</td>
</tr>
<tr>
<td>Calorimeter inefficiency uncertainty</td>
<td>Data</td>
<td>2.1</td>
</tr>
<tr>
<td>Validation of analysis code</td>
<td>CHMC</td>
<td>1.9</td>
</tr>
<tr>
<td>Collimator exit $x$ slope cut</td>
<td>Data</td>
<td>1.4</td>
</tr>
<tr>
<td>Collimator exit $x$ position cut</td>
<td>Data</td>
<td>1.2</td>
</tr>
<tr>
<td>PWC inefficiency uncertainty</td>
<td>CHMC</td>
<td>1.0</td>
</tr>
<tr>
<td>Hodoscope inefficiency uncertainty</td>
<td>Data</td>
<td>0.3</td>
</tr>
<tr>
<td>Particle/antiparticle interaction differences</td>
<td>MC</td>
<td>0.9</td>
</tr>
<tr>
<td>Momentum weights bin size</td>
<td>Data</td>
<td>0.4</td>
</tr>
<tr>
<td>Background subtraction uncertainty</td>
<td>Data</td>
<td>0.3</td>
</tr>
<tr>
<td>Error on $\alpha\alpha_{PDG}$</td>
<td>Data</td>
<td>0.03</td>
</tr>
<tr>
<td>Polarization</td>
<td>MC</td>
<td>negligible</td>
</tr>
<tr>
<td>Earth’s magnetic field</td>
<td>CHMC</td>
<td>negligible</td>
</tr>
<tr>
<td>Total systematic error</td>
<td></td>
<td>4.4</td>
</tr>
</tbody>
</table>
Results from \textit{CP} Violation Search

\textbf{Weighting Technique:}
- \( \sim 10\% \) total data sample
- selected from end of 1999 run
- 118.6 million \( \Xi^- \)
- 41.9 million \( \Xi^+ \)
- no acceptance or efficiency corrections

\[ A_{\Xi\Lambda} = [0.0 \pm 5.1\text{(stat)} \pm 4.4\text{(syst)}] \times 10^{-4} \]

\textbf{Check with HMC Technique:}
- \( \sim 5\% \) of the total data sample
- prescaled selection of 1997 and 1999
- 15 million \( \Xi^- \)
- 30 million \( \Xi^+ \)

\[ A_{\Xi\Lambda} = [-7 \pm 12\text{(stat)} \pm 6.2\text{(syst)}] \times 10^{-4} \]

\( \Rightarrow 20\times \) improvement on previous result.
Conclusions and Outlook

- Hyperon $CP$ violation measurements probing limits not constrained by Kaon, B, or EDM measurements.

  “...we can then conclude that the available preliminary measurement by HyperCP has already begun to probe the parity-even contributions better than $\epsilon$ does.”

  Tandean (2004)

- HyperCP, in particular, the first dedicated hyperon $CP$ violation experiment, has pushed into the region where SUSY models allow an effect.

- HyperCP finds no evidence of $CP$ violation in $\Xi^\pm$ and $\Lambda$ decays:

  $$\delta A_{\Xi\Lambda} = (0.0 \pm 5.1 \pm 4.4) \times 10^{-4}$$

- Shortly we should push our statistical limit to:

  $$\delta A_{\Xi\Lambda} \approx 2 \times 10^{-4}$$

two orders of magnitude better than the present limit.
Backup Slides
Measurement of the $\Lambda$-$\pi$ Phase Shift

- This is done by analyzing the $\Lambda$ decay distribution from 144 million polarized $\Xi^-$'s.
- $\Lambda$ has three components of polarization:
  
  $$\vec{P}_{\Lambda} = \frac{(\alpha_{\Xi} + \vec{P}_{\Xi} \cdot \hat{p}_\Lambda) \hat{p}_\Lambda + \beta_{\Xi} (\vec{P}_{\Xi} \times \hat{p}_\Lambda) + \gamma_{\Xi} (\hat{p}_\Lambda \times (\vec{P}_{\Xi} \times \hat{p}_\Lambda))}{(1 + \alpha_{\Xi} \vec{P}_{\Xi} \cdot \hat{p}_\Lambda)}$$

  \[\beta_{\Xi} = -0.037 \pm 0.011 \text{(stat)} \pm 0.010 \text{(syst)}\]

  \[\gamma_{\Xi} = 0.888 \pm 0.0004 \text{(stat)} \pm 0.006 \text{(syst)}\]

- Using the known value of $\alpha_{\Xi}$:
  \[\delta_P - \delta_S = \tan^{-1}\left(\frac{\beta_{\Xi}}{\alpha_{\Xi}}\right) = (4.6 \pm 1.4 \pm 1.2)^\circ\]

- First non-zero measurement of phaseshift.
- This is about the same magnitude as the $p$-$\pi$ phase shift:
  \[\Rightarrow \text{CP equally likely in } \Xi \text{ and } \Lambda \text{ decays.}\]
  \[\Rightarrow \text{CP predictions underestimated,}\]
  \[\Rightarrow \chi\text{PT calculations off.}\]
Search for Parity Violation in $\Omega^- \rightarrow \Lambda K^-$ Decays

$\Omega^- \rightarrow \Lambda K^-$ \quad $\Lambda \rightarrow p\pi^-$

- Although spin-$3/2$, $\Omega^- \rightarrow \Lambda K^-$ decay goes much like the other hyperon two-body decays:

$$\frac{dP}{d\cos\theta} = \frac{1}{2}(1 + \alpha_\Omega P_\Omega \cos\theta)$$

- Here:

$$\alpha_\Omega = \frac{2\text{Re}(P^*D)}{|P|^2 + |D|^2}$$

- A non-zero $\alpha_\Omega$ indicates parity violation.
- All other hyperons have non-zero $\alpha$ parameters; only the $\Omega^-$ has resisted efforts to find an asymmetrical decay distribution.
- $\text{HyperCP}$ is measuring $\alpha_\Omega$ using unpolarized $\Omega^-$'s through the polarization given to the daughter $\Lambda$, which is $\alpha_\Omega$:

$$\frac{dP}{d\cos\theta} = \frac{1}{2}(1 + \alpha_\Omega \alpha_\Lambda \cos\theta)$$

- Large data sample, little background.
Preliminary Measurement of $\alpha_\Omega$ and $\bar{\alpha}_\Omega$ in $\Omega^- \rightarrow \Lambda K^-$ Decays

1999: $\alpha_\Omega = [1.78\pm0.19{\text{(stat)}}\pm0.10{\text{(syst)}}] \times 10^{-2}$
1999: $\bar{\alpha}_\Omega = [-1.81\pm0.28{\text{(stat)}}] \times 10^{-2}$

- First evidence of parity violation in $\Omega^-$ decays.
- Can search for $CP$ violation in $\Omega^-/\Omega^+$ decays.