Hyperon decays and production

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On behalf of BESIII Collaboration

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CP violation

- CP violation (CPV) is essential to explain the dominance of matter than anti-matter in the universe.

- CPV has been confirmed experimentally in meson sector:
  - In Kaon sector in 1964 (BNL-E-0181 : PRL 13, 138 (1964))
  - In B meson decay in 2001 (BaBar: PRL 87, 091801 (2001), Belle: PRL 87, 091802)
  - In neutral charm meson decays in 2019 (LHCb: PRL 122, 211803 (2019))

- The amount of CPV is not enough to explain the asymmetry degree of matter and anti-matter, we need to search for new CPV evidence.

- CPV in baryon sector has never been observed, and hyperon decays provide a good lab to test CP violation.
Hyperons are quasi-stable baryons composed of s quarks, discovered in 20th century in cosmic ray.

Hyperon decays fall into three categories:
- Non-leptonic weak decays
- Radiative decay decays
- Beta decay or semi-leptonic decays

Lee and Yang’s prediction for parity violation in hyperon decays[1]

Decay asymmetry can be constructed by Parity-Conserving amplitude($A_{PC}$) and Parity-Violating amplitude($B_{PV}$) in the transition matrix.

In experiment, decay asymmetry can be determined by the angular distribution of final state particles, only if the hyperon is polarized. Decay asymmetry(-1.0~1.0) is the probe of mixing degree of $A_{PC}$ and $B_{PV}$

\[
\alpha_0 = \frac{2Re(A_{PC} \ast B_{PV})}{|A_{PC}|^2 + |A_{PV}|^2}
\]

\[
\frac{dN}{d\Omega} = \frac{N_0}{4\pi}(1 + \alpha_0 \mathbf{p}_i \cdot \hat{p})
\]

BEPCII & BESIII

- **Electromagnetic Calorimeter**
  - CsI(Tl): L=28 cm
  - Barrel $\sigma_E=2.5\%$
  - Endcap $\sigma_E=5.0\%$

- **Muon Counter**
  - RPC
  - Barrel: 9 layers
  - Endcap: 8 layers
  - $\sigma_{\text{spatial}}=1.48\,\text{cm}$

- **Time Of Flight**
  - Plastic scintillator
  - $\sigma_T(\text{barrel})=80\,\text{ps}$
  - $\sigma_T(\text{endcap})=110\,\text{ps}$
  - Update to 65 ps with MRPC

- **Main Drift Chamber**
  - Small cell, 43 layer
  - $\sigma_{xy}=130\,\mu\text{m}$
  - $\text{d}E/\text{d}x \approx 6\%$
  - $\sigma_p/p=0.5\%$ at 1 GeV

- **Peak luminosity in continuously operation**
  - $E_{cm}=2.0-4.6\,\text{GeV}$ (2.0-4.95 GeV since 2019)
  - $\approx 0.8 \times 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$
  - Collision angle: 22 mrad

- **Storage ring**
  - 237.53 m

- **Linear injector**
  - 202 m

- **Collision angle**
  - 22 mrad

- **Primary interaction vertex**
  - Vertical: 10 m
  - Horizontal: 150 m

- **Beam Interaction Region**
  - 204 m

- **Magnetic field strength**
  - 1.9 T

- **Total number of detector layers**
  - 56 layers

- **Storage ring**
  - 237.53 m

- **Beam energy range**
  - 2.0 - 4.95 GeV
Production of hyperon-antihyperon pairs at BESIII

- $e^+e^- \rightarrow J/\psi, \psi(3686) \rightarrow \Lambda\Lambda, \Sigma\Sigma, \Xi\Xi, \Omega\Omega$ at BESIII

Parity conservation in charmonium decay guarantees that the $\cos \theta$ dependent hyperon and anti-hyperon polarizations are equal and perpendicular to the production plane\[2\]

If the relative phase ($\Delta \Phi$) between hadronic form factor of $e^+e^- \rightarrow \psi \rightarrow \bar{Y}Y$ is not zero (hyperon is polarized). The decay parameters could be measured.

If CP is conserved, the decay parameters for $Y$ and $\bar{Y}$ are equal in magnitude, but opposite in sign.

The differential cross-section for events of the reaction \( e^+e^- \rightarrow J/\psi \rightarrow \Lambda(\rightarrow p\pi^-) \bar{\Lambda}(\rightarrow \bar{p}\pi^+) \) is

\[
d\sigma = \omega(\theta_\Lambda, \hat{n}_p, \hat{n}_{\bar{p}}) d\theta d\Omega_1 d\Omega_2
\]

Helicity formalism method to describe the joint angular distribution

Unpolarized

\[
\omega(\xi, \Delta \Phi, \alpha_\psi, \alpha_+, \alpha_-) = 1 + \alpha_\psi \cos^2 \theta_\Lambda + \alpha_+ \alpha_- \left[ \sin^2 \theta_\Lambda (n_{p,x}n_{\bar{p},x} - \alpha_\psi n_{p,y}n_{\bar{p},y}) + \left( \cos^2 \theta_\Lambda + \alpha_\psi \right) n_{p,z}n_{\bar{p},z} \right]
\]

\[
+ \alpha_+ \alpha_- \sqrt{1 - \alpha_\psi^2} \cos(\Delta \Phi) \sin \theta_\Lambda \cos \theta_\Lambda (n_{p,x}n_{\bar{p},z} + n_{p,z}n_{\bar{p},x})
\]

\[
+ \sqrt{1 - \alpha_\psi^2} \sin(\Delta \Phi) \sin \theta_\Lambda \cos \theta_\Lambda (n_{p,y} + \alpha_- n_{\bar{p},y})
\]

Polarized

\[ -\ln L = \sum_{i=1}^{N} \ln \frac{\omega(\xi, \Delta \Phi, \alpha_\psi, \alpha_+, \alpha_-)}{S} \]

The maximum likelihood fit to extract the decay parameters

\( S \) is the normalization factor than can be estimated by PHSP MC

Kinematic space \( \xi(\theta_\Lambda, \hat{n}_p, \hat{n}_{\bar{p}}) \):

- \( \hat{n}_p(\hat{n}_{\bar{p}}) \) : unit vector of \( \bar{p}(p) \) momentum in the rest frame of \( \bar{\Lambda}(\Lambda) \)

Parameter space:

- \( \alpha_\psi \) : angular distribution parameter
- \( \Delta \Phi \) : helicity phase of two different amplitudes
- \( \alpha_- \) : decay asymmetry of \( \Lambda \rightarrow p\pi^- \)
- \( \alpha_+ \) : decay parameter of \( \bar{\Lambda} \rightarrow \bar{p}\pi^+ / \bar{\Lambda} \rightarrow \bar{n}\pi^0 \)

Weak decay parameters and CP test in $J/\psi \rightarrow \Lambda\bar{\Lambda}$

- First measurement of hyperon polarization in $J/\psi$ decays, max polarization reaches 25% in longitudinal direction\(^4\). Charged and neutral channels are measured separately.

- Non-zero relative phase allows for individual determinations of $\Lambda$ and $\bar{\Lambda}$ decay parameters, and thus allow for CP test with charged channels, most sensitive test of CP violation for $\Lambda$ hyperon.

- The decay asymmetry of $\Lambda \rightarrow p\pi^-$: 7σ shift from PDG2018 average.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>This work</th>
<th>Previous results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_\phi$</td>
<td>$0.461 \pm 0.006 \pm 0.007$</td>
<td>$0.469 \pm 0.027$ (11)</td>
</tr>
<tr>
<td>$\Delta \phi$</td>
<td>$42.4 \pm 0.6 \pm 0.5^\circ$</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha_-$</td>
<td>$0.750 \pm 0.009 \pm 0.004$</td>
<td>$0.642 \pm 0.013$ (12)</td>
</tr>
<tr>
<td>$\alpha_+$</td>
<td>$-0.758 \pm 0.010 \pm 0.007$</td>
<td>$-0.71 \pm 0.08$ (12)</td>
</tr>
<tr>
<td>$\bar{\alpha}_0$</td>
<td>$-0.692 \pm 0.016 \pm 0.006$</td>
<td>-</td>
</tr>
<tr>
<td>$A_{CP}$</td>
<td>$0.006 \pm 0.012 \pm 0.007$</td>
<td>$0.006 \pm 0.021$ (12)</td>
</tr>
<tr>
<td>$\bar{a}<em>0/a</em>+$</td>
<td>$0.913 \pm 0.028 \pm 0.012$</td>
<td>-</td>
</tr>
</tbody>
</table>

$\Lambda \rightarrow p\pi^-$: $\alpha_- = 0.750 \pm 0.009 \pm 0.004$

\(^4\) Nat. Phys. 15, 631 (2019)
\[5\] arXiv:2204.11058
Update of $J/\psi \to \bar{\Lambda}\Lambda$ result with 10 billion $J/\psi$ data

- The measurement results are updated based on 10 billion $J/\psi$ data and the results are consistent with the previous results based on the 1.3 billion $J/\psi$ data

10 billion $J/\psi$ data is used to improve the accuracy$^5$

<table>
<thead>
<tr>
<th>Paras.</th>
<th>This work (10 billion)</th>
<th>Previous Results (1.3 billion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_\psi$</td>
<td>0.4748±0.0022±0.0024</td>
<td>0.461±0.006 ±0.007</td>
</tr>
<tr>
<td>$\Delta \Phi$</td>
<td>0.7521±0.0042±0.0080</td>
<td>0.740 ±0.009±0.004</td>
</tr>
<tr>
<td>$\alpha_-$</td>
<td>0.7519±0.0036±0.0019</td>
<td>0.750±0.009±0.004</td>
</tr>
<tr>
<td>$\alpha_+$</td>
<td>-0.7559±0.0036±0.0029</td>
<td>-0.758±0.010±0.007</td>
</tr>
<tr>
<td>$A_{CP}$</td>
<td>-0.0025±0.0046±0.0011</td>
<td>0.006±0.012±0.007</td>
</tr>
<tr>
<td>$\alpha_{avg}$</td>
<td>0.7542±0.0010±0.0020</td>
<td>-</td>
</tr>
</tbody>
</table>
CP test in $J/\psi(\psi') \rightarrow \bar{\Sigma}^+\Sigma^+$

- With the 1.3 billion $J/\psi$ and 0.4 $\psi'$ data at BESIII, the first observation of $\Sigma^+$ spin polarization in $e^+e^- \rightarrow J/\psi(\psi') \rightarrow \bar{\Sigma}^+\Sigma^+$ decays

### 1.3 billion $J/\psi$ and 0.4 $\psi'$

![Graphs showing polarized signal of $J/\psi$ and $\psi'$](image)

- Number of candidates $J/\psi$: 87,815 ; $\psi'$ : 5,327
- The non-zero value of $\Delta\Phi$ allows for a direct measurement of the decay asymmetry parameters
- Simultaneous fit to $J/\psi$ and $\psi'$ with BKG subtracted

\[
S = -\ln L_{\text{Data}} + \ln L_{\text{BKG}}
\]

\[
A_{CP,\Sigma} = \frac{\alpha_0 + \overline{\alpha}_0}{\alpha_0 - \overline{\alpha}_0} = -0.004 \pm 0.037 \pm 0.010
\]

SM prediction: $A_{CP,\Sigma} \sim 3.6 \times 10^{-6}$

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**TABLE I.** Values and uncertainties of the fit parameters extracted in this work.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{J/\psi}$</td>
<td>$-0.508 \pm 0.006 \pm 0.004$</td>
</tr>
<tr>
<td>$\Delta\Phi_{J/\psi}$</td>
<td>$-0.270 \pm 0.012 \pm 0.009$</td>
</tr>
<tr>
<td>$\alpha'_{\psi'}$</td>
<td>$0.682 \pm 0.03 \pm 0.011$</td>
</tr>
<tr>
<td>$\Delta\Phi_{\psi'}$</td>
<td>$0.379 \pm 0.07 \pm 0.014$</td>
</tr>
<tr>
<td>$\alpha_0$</td>
<td>$-0.998 \pm 0.037 \pm 0.009$</td>
</tr>
<tr>
<td>$\overline{\alpha}_0$</td>
<td>$0.990 \pm 0.037 \pm 0.011$</td>
</tr>
</tbody>
</table>
Three decay parameters in the sequential decays are accessible: Lee-Yang parameters \( \alpha, \beta \) and \( \gamma \) (decay parameters govern the decay angular distribution and Only two are independent)

\[
\tan \phi_Y = \frac{\beta_Y}{\gamma_Y}
\]

\[
\alpha_Y^2 + \beta_Y^2 + \gamma_Y^2 = 1
\]

\[
\beta_Y = \sqrt{1 - \alpha_Y^2 \sin \phi_Y}, \quad \gamma_Y = \sqrt{1 - \alpha_Y^2 \cos \phi_Y}
\]

The hyperon decay is completely described by two independent parameters \( \alpha_{\Xi^-}/\phi_{\Xi^-} \)

\( \Lambda \) is fully polarized in sequential \( \Xi^- \) decay and \( \) CP violation can be quantified in terms of the observables:

\[
A_{CP} = \frac{\alpha_Y + \bar{\alpha}_Y}{\alpha_Y - \bar{\alpha}_Y}, \quad \Delta_{CP} = \frac{\phi_Y + \bar{\phi}_Y}{\phi_Y - \bar{\phi}_Y}
\]

CP symmetry and weak phases in $J/\psi \rightarrow \Xi^- \Xi^+$

1.3 billion $J/\psi$ data

- 1.3 billion $J/\psi$ events at BESIII
- BKG level is low, ~73200 signal events
- Direct measurement of all decay parameters
- First measurement of polarization
- Measurement of weak phase difference

- Helicity formalism method to describe the joint angular distribution of final state particles

$$W(\xi; \omega) = \sum_{\mu, \nu=0}^{3} C_{\mu \nu} \sum_{\mu', \nu'=0}^{3} a_{\mu \nu}^\Xi a_{\mu' \nu'}^\Xi a_{\mu 0}^\Lambda a_{\nu 0}^\Lambda$$

$$C_{\mu \nu} = (1 + \alpha_\psi \cos^2 \theta)$$

- Kinematic space with 9 helicity angles:
  $$\xi \left( \theta_\Xi^-, \theta_\Lambda, \theta_\Lambda^-, \phi_\Lambda, \phi_\Lambda^-, \hat{n}_\Lambda, \theta_p, \theta_{\bar{p}}, \phi_p, \phi_{\bar{p}} \right)$$

- Parameter space with 8 free parameters:
  $$\omega \left( \alpha_\psi, \Delta \Phi, \alpha_\Xi^-, \phi_\Xi^-, \alpha_\Xi^+, \phi_\Xi^+, \alpha_\Lambda, \bar{\alpha}_\Lambda \right)$$

- Determined by maximum log likelihood method

CP symmetry and weak phases with $J/\psi \to \Xi^- \Xi^+$

Results based on 1.3 billion $J/\psi$ events at BESIII$^{[6]}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>This work</th>
<th>Previous result</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_\psi$</td>
<td>$0.586\pm0.012\pm0.010$</td>
<td>$0.58\pm0.04\pm0.08$</td>
<td>Ref. 40</td>
</tr>
<tr>
<td>$\Delta \Phi$</td>
<td>$1.213\pm0.046\pm0.016$ rad</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\bar{\alpha}_\Xi$</td>
<td>$-0.376\pm0.007\pm0.003$</td>
<td>$-0.401\pm0.010$</td>
<td>Ref. 26</td>
</tr>
<tr>
<td>$\phi_\Xi$</td>
<td>$0.011\pm0.019\pm0.009$ rad</td>
<td>$-0.037\pm0.014$ rad</td>
<td>Ref. 26</td>
</tr>
<tr>
<td>$\Delta \Phi_\Xi$</td>
<td>$0.371\pm0.007\pm0.002$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\phi_\Xi$</td>
<td>$-0.021\pm0.019\pm0.007$ rad</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\delta_{\Xi^-} - \delta_{\Xi^+}$</td>
<td>$(1.2\pm3.4\pm0.8)\times10^{-2}$ rad</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\phi_{\Xi^-} - \phi_{\Xi^+}$</td>
<td>$(4.0\pm3.3\pm1.7)\times10^{-2}$ rad</td>
<td>$(10.2\pm3.9)\times10^{-2}$ rad</td>
<td>Ref. 33</td>
</tr>
<tr>
<td>$A_{\xi_\Xi}^\Xi$</td>
<td>$(6\pm13\pm6)\times10^{-3}$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\Delta \phi_{\Xi_\Xi}$</td>
<td>$(-5\pm14\pm3)\times10^{-3}$ rad</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$A_{\Lambda_\Xi}^\Xi$</td>
<td>$(-4\pm12\pm9)\times10^{-3}$</td>
<td>$(-6\pm12\pm7)\times10^{-3}$</td>
<td>Ref. 44</td>
</tr>
<tr>
<td>$\langle \phi_{\Xi^-} \rangle$</td>
<td>$0.016\pm0.014\pm0.007$ rad</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

The $J/\psi \to \Xi^- \Xi^+$ angular distribution parameter $\alpha_\psi$, the hadronic form factor phase $\Delta \Phi$, the decay parameters for $\Xi^- \to \Lambda \pi^-$ ($\alpha_{\Xi}, \phi_{\Xi}$), $\Xi^+ \to \bar{\Lambda} \pi^+$ ($\alpha_{\Xi}, \phi_{\Xi}$) and $\Lambda \to p \pi^-$ ($\alpha_{\Lambda}$) and $\bar{\Lambda} \to \bar{p} \pi^+$ ($\alpha_{\bar{\Lambda}}$); the CP asymmetries $A_{\xi_\Xi}^\Xi$, $\Delta \phi_{\Xi_\Xi}$ and $A_{\Lambda_\Xi}^\Xi$ and the average $\langle \phi \rangle$. The first and second uncertainties are statistical and systematic, respectively.

- First measurement of the polarization
- Direct measurement of all decay parameters
- Independent measurement of $\Lambda$ decay parameters, good agreement with previous BESIII results
- First measurement of weak phase difference, one of the most precise tests of CP symmetry for strange baryons
- Three independent CP tests in single channel

The radiative decay provides a unique probe for strong/weak/EM interactions [7].

A long standing puzzle is “Hara’s theorem” that parity violating amplitude should vanish [8] while experiments find large negative $\alpha_\gamma$ in $\Sigma^+ \rightarrow \gamma p$ and $\Sigma^0 \rightarrow \gamma \Lambda/\Sigma^0$ [9].

It is proposed that $\Lambda \rightarrow n\gamma$ could resolve the ambiguities of various theoretical models [10].

Branching fraction (BF) of $\Lambda \rightarrow n\gamma$ measured based on fixed target, differ by 2$\sigma$.

No information of decay asymmetry $\alpha_\gamma$ obtained experimentally.

DT method to determine the branching fraction and helicity method to extract the asymmetry.

[9] (Particle Data Group), PTEP 2020, 083C01 (2020)
Hyperon radiative decay $\Lambda \rightarrow n\gamma (s \rightarrow d$ transition)

- The first study of hyperon radiative decays at electron-positron collider$^{[11]}$

- Absolute BF of $\Lambda \rightarrow n\gamma$ with improved precision $(0.832 \pm 0.038 \pm 0.054) \times 10^{-3}$, smaller than PDG value $(1.75 \pm 0.15) \times 10^{-3}$ by $5.6\sigma$

- First determination of decay asymmetry $\alpha_\gamma = -0.16 \pm 0.10 \pm 0.05$

- The results provide essential input for Hara’s theorem validation and constraining the effective models

Hyperon semi-leptonic decay $\Lambda \rightarrow p\mu^-\bar{\nu}_\mu$

- Absolute BF measurement\(^{[12]}\) of the branching fraction of $\Lambda \rightarrow p\mu^-\bar{\nu}_\mu$ with DT method

  10 billion $J/\psi$ events

- First study at a collider experiment; most precise result to date; Update measurement after ~50 years

- Test lepton flavor universality

- Search for CP violation

\[
R_{ue}^{\mu e} = \frac{\mathcal{B}(\Lambda \rightarrow p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda \rightarrow pe^-\bar{\nu}_e)_{PDG}} = 0.178 \pm 0.028 \quad \text{Consistent with SM}
\]

\[
R_{SM}^{\mu e} = 0.153 \pm 0.008
\quad \text{(PRL 114, 161802 (2015))}
\]

\[
\mathcal{A}_{CP} = \frac{\mathcal{B}_{\Lambda \rightarrow p\mu^-\bar{\nu}_\mu} - \mathcal{B}_{\bar{\Lambda} \rightarrow \bar{p}\mu^+\nu_\mu}}{\mathcal{B}_{\Lambda \rightarrow p\mu^-\bar{\nu}_\mu} + \mathcal{B}_{\bar{\Lambda} \rightarrow \bar{p}\mu^+\nu_\mu}} = 0.02 \pm 0.14 \pm 0.02 \quad \text{Consistent with CP symmetry}
\]

\(^{[12]}\) PRL 127, 121802 (2021)
Polarized hyperon-antihyperon pairs produced from charmonium decays open a new era to search for CP violation

Studies of hyperon non-leptonic weak decays, radiative decays and semi-leptonic decays are performed at BESIII

10 Billion $J/\psi$ data and 4 Billion $\psi (3686)$ data collected will bring more exciting results in the future

Summary

Thanks for your attention!