Hyperon CP violation

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- Situation of baryon CP violation
- Observables for hyperon CP violation
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Motivation(CP violation of baryon)

- Matter–antimatter asymmetry (Big Bang theory)
- Sakharov Conditions
  - Baryon number violation
  - C-symmetry and CP-symmetry violation
  - Interactions out of thermal equilibrium
  - A.D. Sakharov (1967)

Motivation(CP violation of baryon)

- Matter–antimatter asymmetry (Big Bang theory)
- Sakharov Conditions
  - Baryon number violation
  - C-symmetry and CP-symmetry violation
  - Interactions out of thermal equilibrium
  - A.D. Sakharov (1967)
- Standard Model CPV is still insufficient for explaining the observed matter-dominant universe.
  - Astron.Astrophys.594,A13 (2016)
- Differences in the behaviour of matter and antimatter have not yet been observed in any baryon sector.
  - Only 3.3σ significance for $\Lambda_b \to p\pi\pi\pi$
  - Triple product for multibody decay
  - LHCb, Nature Physics (2017)
- CP violation in baryon decay ? ?

Hyperon CP violation (History)

- Why hyperon CP violation in the early time

TABLE I. *CP*-nonconserving signals as calculated in the text. In the Kobayashi-Maskawa model the maximal value of the mixing angles was assumed.

	Kobayashi-Maskawa	Weinberg Higgs	Left-right	Superweak/heavy neutral Higgs
$(\alpha_\Xi+\bar{\alpha}_{\Xi})/(\alpha_\Xi-\bar{\alpha}_{\Xi})$	2×10^{-5}	1.3×10^{-4}	0.8×10^{-5}	0
$(\beta_\Xi+\bar{\beta}_{\Xi})/(\beta_\Xi-\bar{\beta}_{\Xi})$	2×10^{-3}	1.3×10^{-2}	0.8×10^{-3}	0
$\beta_{\Xi^0}/\alpha_{\Xi^0}-\beta_{\Xi^-}\alpha_{\Xi^-}$	1.6×10^{-5}	0.8×10^{-4}	0	0
$\frac{\Gamma(\Lambda\to n\pi^0)-\Gamma(\bar{\Lambda}\to\bar{N}\pi^0)}{\Gamma(\Lambda\to N\pi^0)+\Gamma(\Lambda\to N\pi^0)}$	4.5×10^{-7}	4×10^{-6}	0	0

- Hyperon CP violation is sensitive to different models
- CP violation for hyperon decay is estimated to be $\mathcal{O}(10^{-4})$.
    - John F.Donoghue, Xiao-Gang He, Sandip Pakvasa, Phys.Rev.D34 (1986) 833
    - John F.Donoghue, Sandip Pakvasa, Phys.Rev.Lett. 55 (1985) 162

Situation of experimental research

- The BESIII investigate $e^+e^- \to J/\psi \to \Lambda(\to p\pi^-)\bar{\Lambda}(\to \bar{p}\pi^+)$
- $\alpha(\Lambda \to p\pi^-)$ and $\alpha(\bar{\Lambda} \to \bar{p}\pi^+)$ are given as the most precisest value

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- CP violation for hyperon decay $\Xi^{-} \rightarrow \Lambda\pi^{-} \rightarrow p\pi\pi$, and $A_{CP}^{\alpha}(\Xi\Lambda)$ is measured.

$$A_{CP}^{\alpha}(\Xi\Lambda) = \frac{\alpha_{\Lambda\pi}^{\Xi} \times \alpha_{p\pi}^{\Lambda} - \bar{\alpha}_{\bar{\Lambda}\pi}^{\bar{\Xi}} \times \bar{\alpha}_{\bar{p}\pi}^{\bar{\Lambda}}}{\alpha_{\Lambda\pi}^{\Xi} \times \alpha_{p\pi}^{\Lambda} + \bar{\alpha}^{\bar{\Xi}_{\bar{\Lambda}\pi}} \times \bar{\alpha}_{\bar{p}\pi}^{\bar{\Lambda}}} \quad (2)$$

- The signal is consistent with CP conserved
  - BESIII Collaboration,Nature Phys.15(2019) 631-634
  - Hyper CP Collaboration,Phys.Rev.Lett. 93 (2004) 262001

Observables

- Lee-Yang parameters for $B \to B'P$

$$\alpha = \frac{2Re(S^*P)}{|S|^2+|P|^2}\,,\quad \beta = \frac{2Im(S^*P)}{|S|^2+|P|^2}\,,\quad \gamma = \frac{|S|^2-|P|^2}{|S|^2+|P|^2} \tag{3}$$

- Angular distribution for completely polarized $\Lambda \to p\pi$:

$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha cos\theta \quad (cos\theta = \hat{\sigma}\cdot\hat{p}) \tag{4}$$

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- Polarization of p from the decay $\Lambda \to p\pi^-$:

$$P_{proton} = \frac{(\alpha + cos\theta)\hat{p} + \beta\hat{p} \times \vec{\sigma} + \gamma(\hat{p} \times \vec{\sigma}) \times \vec{p}}{1 + \alpha cos\theta} \tag{5}$$

- Note that proton is polarized whether the Λ polarizes or not. If initial Λ is unpolarized then proton is polarized longitudinally by α.
  - T.D.Lee, Chen-Ning Yang,Phys.Rev. 108 (1957) 1645-1647

Observables

- β, γ can be parameterized as

$$\beta = \sqrt{1-\alpha^2} sin\Delta \quad \gamma = \sqrt{1-\alpha^2} cos\Delta \tag{6}$$

- CP asymmetry induced by Lee-Yang parameters

$$A^{\alpha}_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \quad A^{\beta}_{CP} = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}} \tag{7}$$

- A^{α}_{CP} is obtained by fitting distribution or scattering!
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- A^{α}_{CP} is obtained by fitting distribution or scattering!
- A^{β}_{CP} is measured by α and Δ indirectly such that always suffers large uncertainty
- The strong phase dependence are different

$$\begin{aligned} A^{\beta}_{CP} &\propto cos\delta sin\phi \\ A^{\alpha}_{CP} &\propto sin\delta sin\phi \end{aligned} \tag{8}$$

- Direct CP violation is also important

$$A^{dir}_{CP} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \propto sin\delta sin\phi \tag{9}$$

CP violation for Λ, Σ from Λ_c^+ decay

- Proton distribution with the cascade decay $\Lambda_c^+ \to (\Lambda/\Sigma)\pi \to p\pi\pi$

$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_{\Lambda_c} \times \alpha_{p\pi}^{\Lambda} cos\theta \tag{10}$$

- where θ is polar angle of proton relative to Λ momentum
- A CP violation observable is defined as

$$A_{CP}^{\alpha}(total) = \frac{\alpha_{\Lambda_c} \times \alpha_{p\pi}^{\Lambda} - \bar{\alpha}_{\bar{\Lambda}_c} \times \bar{\alpha}_{\bar{p}\pi}^{\bar{\Lambda}}}{\alpha_{\Lambda_c} \times \alpha_{p\pi}^{\Lambda} + \bar{\alpha}_{\bar{\Lambda}_c} \times \bar{\alpha}_{\bar{p}\pi}^{\bar{\Lambda}}} = A_{CP}^{\alpha}(\Lambda \to p\pi^-) \tag{11}$$

- The contribution from Λ_c^+ vanishes, however, first decay is essential !!

CP violation for Λ, Σ from Λ_c^+ decay

Table: $\Lambda_c \to \Lambda, \Sigma$ channels and branching ratio

$\Lambda_c^+ \to \Lambda$	BR(%)	$\Lambda_c^+ \to \Sigma^+$	BR(%)
$\Lambda_c^+ \to \Lambda\pi^+$	1.30 ± 0.07	$\Lambda_c^+ \to \Sigma^+\pi$	1.25 ± 0.10
$\Lambda_c^+ \to \Lambda\pi^+\pi^0$	7.1 ± 0.4	$\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$	4.50 ± 0.25
$\Lambda_c^+ \to \Lambda\pi^+\eta$	1.84 ± 0.26	$\Lambda_c^+ \to \Sigma^+\eta'$	1.5 ± 0.6
$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	3.64 ± 0.29	$\Lambda_c^+ \to \Sigma^+\pi^0\pi^0$	1.55 ± 0.15
$\Lambda_c^+ \to \Lambda\pi^+\omega$	1.5 ± 0.5	$\Lambda_c^+ \to \Sigma^+\omega$	1.70 ± 0.21
$\Lambda_c^+ \to \Lambda e^+\nu_e$	3.6 ± 0.4	—	—
$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$	3.5 ± 0.5	—	—

- Branching ratio of $\Lambda_c \to \Lambda/\Sigma$ is advantageous and different channel can be combined !!
- The decay asymmetry for multibody $\Lambda_c \to \Lambda/\Sigma$ is lack of research !!

Some discussions

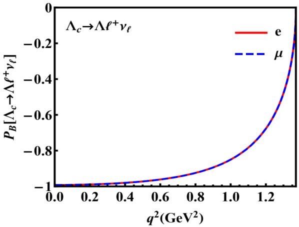
- The error induced by $\alpha_{\Lambda\pi}^{\Lambda_c}$ must be considered
- If the parameter $\alpha_{\Lambda\pi}^{\Lambda_c}$ tend to zero such that distribution tends to steady, then it is diffculit to extract A_{CP}^{α} precisely

$$\begin{aligned}\Delta A_{CP}^{\alpha} &= \sqrt{\left(\frac{2\bar{\alpha}_{\Lambda_c}\bar{\alpha}_{\Lambda}\alpha_{\Lambda}}{(\alpha_{\Lambda_c}\alpha_{\Lambda}+\bar{\alpha}_{\Lambda_c}\bar{\alpha}_{\Lambda})^2}\Delta\alpha_{\Lambda_c}\right)^2+(\alpha_{\Lambda_c}\leftrightarrow\bar{\alpha}_{\Lambda_c})} \\ &= \sqrt{\left(\frac{2}{\alpha_{\Lambda_c}}\Delta\alpha_{\Lambda_c}\right)^2+(\alpha_{\Lambda_c}\leftrightarrow\bar{\alpha}_{\Lambda_c})} \\ &(\bar{\alpha}_{\Lambda_c}\approx\alpha_{\Lambda_c},\bar{\alpha}_{\Lambda}\approx\alpha_{\Lambda})\end{aligned} \tag{12}$$

- Larger α_{Λ_c} is promising.
- The discussion about the measurement of α_{Λ_c} in multibody non-leptonic decay is necessary

Some discussions

- Decay asymmetry parameters for Semileptonic decay $\Lambda_c^+ \to \Lambda/\Sigma l\nu$
- Decay asymmetry varies with phase space



$$\frac{d\Gamma}{dcos\theta} \propto 1 + \langle \alpha_{\Lambda}^{\Lambda_c}(q^2) \rangle \times \alpha_{p\pi}^{\Lambda} cos\theta \tag{13}$$

- When redundant q^2 are intergrated out, $\langle \alpha_{\Lambda}^{\Lambda_c}(q^2) \rangle$ can be extracted out from distribution.

$$\alpha(\Lambda_c \to \Lambda l\nu) = -0.86 \pm 0.04 \quad \alpha(\Lambda_c \to \Lambda \pi) = -0.84 \pm 0.09 \tag{14}$$

Some discussions

- Decay asymmetry parameters for multibody non-leptonic $\Lambda_c \to \Lambda/\Sigma$
- Decay asymmetry varies with phase space such that it is diffculit to calculate theorectically !!
- Non-pertubative properties of low-energy QCD
- Theoretical analysis is based on fitting

Some discussions

- Decay asymmetry parameters for multibody non-leptonic $\Lambda_c \to \Lambda/\Sigma$
- Decay asymmetry varies with phase space such that it is diffculit to calculate theorectically !!
- Non-pertubative properties of low-energy QCD
- Theoretical analysis is based on fitting
- Nevertheless, what we need only is value averaged over phase space

$$\frac{d\Gamma}{dcos\theta} \propto 1 + \langle \alpha_{\Lambda}^{\Lambda_c}(q^2) \rangle \times \alpha_{p\pi}^{\Lambda} cos\theta \tag{15}$$

- When redundant angles and q^2 are intergrated out, $\langle \alpha_{\Lambda}^{\Lambda_c}(q^2) \rangle$ can also be extracted out from distribution.
- Similar to semileptonic decay, we hope asymmetry parameters are remarkabe in multibody non-leptonic decay

Some discussions

- Direct CP asymmetry must be included dut to it's similarity with A^{α}_{CP}
- A^{β}_{CP} isn't considered due to large uncertainty comparing with $\mathcal{O}(10^{-4})$
- Why we can't investigate inclusive decay $\Lambda_c^+ \to \Lambda/\Sigma^+$?

$$Br(\Lambda_c^+ \to \Lambda X) \approx Br(CF) + Br(SCS) \tag{16}$$

$$\begin{aligned} A^{\alpha}_{CP}(\Lambda_c^+ \to \Lambda X) &\approx \frac{Br(SCS)}{Br(\Lambda_c^+ \to \Lambda X)} \times A^{\alpha}_{CP}(\Lambda_c^+) \\ &\approx \lambda^2 A^{\alpha}_{CP}(\Lambda_c^+) \end{aligned} \tag{17}$$

- Why only Σ^+ is investigated

$$\Sigma^- \to n\pi^-(\approx 100\%) \quad \Sigma^0 \to \Lambda\gamma(\approx 100\%) \tag{18}$$

Some discussions(Experiment level)

- Decay asymmetry parameter α can be obtained

$$\begin{aligned} \alpha &\propto \Gamma(cos\theta > 0) - \Gamma(cos\theta < 0) \\ \bar{\alpha} &\propto \bar{\Gamma}(cos\theta > 0) - \bar{\Gamma}(cos\theta < 0) \end{aligned} \tag{19}$$

$$A_{CP}^{\alpha} = \frac{\alpha + \bar{\alpha}}{\alpha + \bar{\alpha}} \tag{20}$$

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$$A_{CP}^{\alpha} = \frac{\alpha + \bar{\alpha}}{\alpha + \bar{\alpha}} \tag{20}$$

- A_{CP}^{α} benefits from small uncertainty originated from production and detection asymemetry.
- Large statistics will be accumulated at BelIII in the future

$$\sigma_{c\bar{c}} = 1.3nb \tag{21}$$

- Multibody decay asymmetry parameters can be maesured at BESIII

Summary

- We proposed a CP violation observable induced by α
- Hyperon CP violations are anylised phenomenologically
- The experimental realization is discussed