

$K_S^0 - K_L^0$ asymmetries and CP violation in charmed baryon decays into neutral kaons

Di Wang, Peng-Fei Guo, Wen-Hui Long and Fu-Sheng Yu¹

*School of Nuclear Science and Technology, Lanzhou University,
Lanzhou 730000, China*

E-mail: dwang15@lzu.edu.cn, guopf15@lzu.edu.cn, longwh@lzu.edu.cn,
yufsh@lzu.edu.cn

ABSTRACT: We study the $K_S^0 - K_L^0$ asymmetries and CP violations in charm-baryon decays with neutral kaons in the final state. The $K_S^0 - K_L^0$ asymmetry can be used to search for two-body doubly Cabibbo-suppressed amplitudes of charm-baryon decays, with the one in $\Lambda_c^+ \rightarrow pK_{S,L}^0$ as a promising observable. Besides, it is studied for a new CP -violation effect in these processes, induced by the interference between the Cabibbo-favored and doubly Cabibbo-suppressed amplitudes with the neutral kaon mixing. Once the new CP -violation effect is determined by experiments, the direct CP asymmetry in neutral kaon modes can then be extracted and used to search for new physics. The numerical results based on $SU(3)$ symmetry will be tested by the experiments in the future.

KEYWORDS: Heavy Quark Physics, CP violation

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¹Corresponding author.

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1 Introduction

Charm physics plays an important role in studying the perturbative and non-perturbative QCD and searching for new physics with special structure in the up-type quark sector. Unlike the charmed meson decays with fruitful results during the past decades [1], the study of weak decays of charmed baryons has been made little progress both in theory and in experiment until a few years ago when some new measurements were performed by the Belle and BESIII experiments [2–11]. Charmed baryon physics is becoming intriguing with more data available and collected by Belle (II), BESIII and LHCb. Charmed baryon decays provide an ideal laboratory to study the heavy-to-light baryonic transitions [12–19] and test the flavor SU(3) symmetry [20–27]. They also provide the essential inputs for the decays of b -flavored hadrons decaying into charmed baryons to determine the CKM matrix element $|V_{cb}|$ [28, 29]. In this work, we will study charmed baryon decays into neutral kaons.

Under the flavor SU(3) symmetry, the ground states of Λ_c^+ , Ξ_c^+ and Ξ_c^0 form an anti-triplet, all of which decay weakly. In the Standard Model (SM), the charmed baryon weak decays are classified into three types: the Cabibbo-favored (CF) decays, the singly Cabibbo-suppressed (SCS) decays and the doubly Cabibbo suppressed (DCS) decays [30]. It can be generally expected that the branching fractions of the CF, SCS and DCS modes are of the order of 10^{-2} , 10^{-3} and 10^{-4} , respectively. Due to the small branching fractions, the DCS decays are more difficult to be observed compared to the CF and SCS decays. The first and only evidence of DCS transitions of charmed baryons is found in a three-body Λ_c^+ decay by the Belle collaboration [10],

$$BR(\Lambda_c^+ \rightarrow pK^+\pi^-)/BR(\Lambda_c^+ \rightarrow pK^-\pi^+) = (2.35 \pm 0.27 \pm 0.21) \times 10^{-3}. \quad (1.1)$$

But none of the two-body DCS processes has been observed to date. The two-body DCS decays play an essential role in understanding the dynamics of charmed hadron decays, since the multi-body decays are difficult to be studied in theory. Besides, new physics might contribute to the relatively small DCS amplitude, leading to a much larger direct CP

violation compared to the SM prediction [31–34]. Therefore, it is important to search for the two-body DCS amplitudes of charm-baryon decays. Except for the direct measurement on the DCS processes, the two-body DCS amplitudes can also be revealed by the $K_S^0 - K_L^0$ asymmetry in charmed baryon decays into neutral kaons. The $K_S^0 - K_L^0$ asymmetry is induced by the interference between the CF and DCS amplitudes, which has been studied in D meson decays [33, 35–41]. In this work, we investigate the $K_S^0 - K_L^0$ asymmetry in charmed baryon decays, and find that the one in $\Lambda_c^+ \rightarrow pK_{S,L}^0$ is the promising observable to search for two-body DCS charm-baryon decay amplitudes.

CP violation can occur in charmed baryon decays into neutral kaons. It is an essential element to interpret the matter-antimatter asymmetry in the Universe [42] and provides a window to search for new physics beyond the SM. CP asymmetries have been well established in kaon and B meson systems [30]. In the baryon sector, the only signal of CP asymmetry is found in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^+$ with 3.3σ [43]. CP violation in charmed baryon decays has not been observed up to now. In some literatures, the CP violation in charm decays into neutral kaons have been studied [31, 34, 44–48]. In ref. [49], a new measurable CP -violation effect is found existing in D meson decays into neutral kaons, except for the known indirect CP violation in $K^0 - \bar{K}^0$ mixing and direct CP asymmetry in charm decays. The new effect is induced by the interference between the CF and DCS amplitudes with the mixing of final-state mesons. In this work, we will show that the new CP -violation effect also exist in charmed baryon decays. Once the new effect was well determined in experiment, the direct CP asymmetry could be obtained and used to search for new physics.

Numerically, the dynamics of charmed baryon decays is always difficult to describe, due to the sizable non-factorizable contributions [12–27]. In order to estimate the $K_S^0 - K_L^0$ asymmetry and CP asymmetry, we analyze the decays of charm-baryon anti-triplet into light baryon octet and pseudoscalar octet based on the flavor $SU(3)$ symmetry, in which those universal parameters are extracted from the available data. Our results are well consistent with the measured data and can be tested by Belle II, BESIII and LHCb.

This paper is organized as follows. In section 2, we discuss the $K_S^0 - K_L^0$ asymmetry in charmed baryon decays into neutral kaons and its search for the DCS transitions. The corresponding time-dependent and time-integrated CP asymmetries are studied in section 3. The numerical analysis is given in section 4. And section 5 is the summary.

2 $K_S^0 - K_L^0$ asymmetry

In the charmed hadron decays into neutral kaons, the interference between the Cabibbo-favored (CF) and the doubly Cabibbo-suppressed (DCS) amplitudes leads to the $K_S^0 - K_L^0$ asymmetry, an observable to search for the DCS transitions. Specifically, the $K_S^0 - K_L^0$ asymmetry in charmed baryon (\mathcal{B}_c) decaying into light baryon (\mathcal{B}) and neutral kaons is defined as

$$R(\mathcal{B}_c \rightarrow \mathcal{B}K_{S,L}^0) \equiv \frac{\Gamma(\mathcal{B}_c \rightarrow \mathcal{B}K_S^0) - \Gamma(\mathcal{B}_c \rightarrow \mathcal{B}K_L^0)}{\Gamma(\mathcal{B}_c \rightarrow \mathcal{B}K_S^0) + \Gamma(\mathcal{B}_c \rightarrow \mathcal{B}K_L^0)}. \quad (2.1)$$

Due to the fact that the $K_S^0 - K_L^0$ asymmetry is not sensitive to the CP violating effect in the $K^0 - \bar{K}^0$ mixing [40], the K_S^0 and K_L^0 states can be referred as the CP eigenstates

$$|K_S^0\rangle = \frac{1}{\sqrt{2}} \left(|K^0\rangle - |\bar{K}^0\rangle \right), \quad |K_L^0\rangle = \frac{1}{\sqrt{2}} \left(|K^0\rangle + |\bar{K}^0\rangle \right), \quad (2.2)$$

under the convention $\mathcal{CP}|K^0\rangle = -|\bar{K}^0\rangle$.

The CF amplitude of $\mathcal{B}_c \rightarrow \mathcal{B}\bar{K}^0$ and the DCS amplitude of $\mathcal{B}_c \rightarrow \mathcal{B}K^0$ decays read as

$$\mathcal{A}(\mathcal{B}_c \rightarrow \mathcal{B}\bar{K}^0) = \mathcal{T}_{\text{CF}} e^{i(\phi_{\text{CF}} + \delta_{\text{CF}})}, \quad \mathcal{A}(\mathcal{B}_c \rightarrow \mathcal{B}K^0) = \mathcal{T}_{\text{DCS}} e^{i(\phi_{\text{DCS}} + \delta_{\text{DCS}})}, \quad (2.3)$$

where \mathcal{T}_{CF} (\mathcal{T}_{DCS}) is the magnitude of the CF (DCS) amplitude, and δ_{CF} (δ_{DCS}) and ϕ_{CF} (ϕ_{DCS}) are the relative strong and weak phases, respectively. The decay amplitudes of $\mathcal{B}_c \rightarrow \mathcal{B}K_S^0$ and $\mathcal{B}_c \rightarrow \mathcal{B}K_L^0$ are then

$$\begin{aligned} \mathcal{A}(\mathcal{B}_c \rightarrow \mathcal{B}K_S^0) &= \frac{1}{\sqrt{2}} \mathcal{T}_{\text{DCS}} e^{i(\phi_{\text{DCS}} + \delta_{\text{DCS}})} - \frac{1}{\sqrt{2}} \mathcal{T}_{\text{CF}} e^{i(\phi_{\text{CF}} + \delta_{\text{CF}})}, \\ \mathcal{A}(\mathcal{B}_c \rightarrow \mathcal{B}K_L^0) &= \frac{1}{\sqrt{2}} \mathcal{T}_{\text{DCS}} e^{i(\phi_{\text{DCS}} + \delta_{\text{DCS}})} + \frac{1}{\sqrt{2}} \mathcal{T}_{\text{CF}} e^{i(\phi_{\text{CF}} + \delta_{\text{CF}})}. \end{aligned} \quad (2.4)$$

Similar as ref. [40], the ratio between the DCS and CF amplitudes are defined as

$$\frac{\mathcal{A}(\mathcal{B}_c \rightarrow \mathcal{B}K^0)}{\mathcal{A}(\mathcal{B}_c \rightarrow \mathcal{B}\bar{K}^0)} \equiv r_f e^{i(\phi + \delta_f)}, \quad (2.5)$$

where $r_f = \mathcal{T}_{\text{DCS}}/\mathcal{T}_{\text{CF}}$, $\phi = \phi_{\text{DCS}} - \phi_{\text{CF}}$ and $\delta_f = \delta_{\text{DCS}} - \delta_{\text{CF}}$. The parameters r_f and δ_f depend on the individual processes, while ϕ is mode independent in the SM. It is found that if the DCS amplitude vanishes, $r_f = 0$. In the SM, r_f is expected to be proportional to the ratio $|V_{cd}^* V_{us}/V_{cs}^* V_{ud}| \sim \lambda^2 \sim \mathcal{O}(10^{-2})$, and the weak phase is negligibly small, i.e., $\phi \equiv \text{Arg}[-V_{cd}^* V_{us}/V_{cs}^* V_{ud}] = (-6.2 \pm 0.4) \times 10^{-4}$. The $K_S^0 - K_L^0$ asymmetry can be further reduced as [40]

$$R(\mathcal{B}_c \rightarrow \mathcal{B}K_{S,L}^0) = \frac{|1 - r_f e^{i\delta_f}|^2 - |1 + r_f e^{i\delta_f}|^2}{|1 - r_f e^{i\delta_f}|^2 + |1 + r_f e^{i\delta_f}|^2} \simeq -2r_f \cos \delta_f, \quad (2.6)$$

which is expected to be of the order of $\mathcal{O}(10^{-2})$, being measurable in experiments.

The $K_S^0 - K_L^0$ asymmetry could be used to search for the DCS decays in charmed baryon decays. If the DCS transition is absent, i.e., $r_f = 0$, the $K_S^0 - K_L^0$ asymmetry shall vanish. Thereby, a non-zero experimental result of $R(\mathcal{B}_c \rightarrow \mathcal{B}K_{S,L}^0)$, namely $r_f \neq 0$, can be taken as the evidence for the DCS transitions of charmed baryons. In fact, since the branching fraction of $\Lambda_c^+ \rightarrow pK_S^0$ is measured as [9]

$$\text{Br}(\Lambda_c^+ \rightarrow pK_S^0)_{\text{exp}} = (1.52 \pm 0.08 \pm 0.03)\%, \quad (2.7)$$

it can be expected that $\Lambda_c^+ \rightarrow pK_L^0$ has a branching fraction of the order of one percent, and thus might be measured with large data sample. Therefore, the corresponding $K_S^0 - K_L^0$ asymmetry can reveal the DCS amplitude of $\Lambda_c^+ \rightarrow pK^0$.

In the following discussions, we will see that the $K_S^0 - K_L^0$ asymmetry in the decays of $\Lambda_c^+ \rightarrow pK_{S,L}^0$ is a promising observable to search for the two-body DCS amplitude of charmed baryon decays. At BESIII, only Λ_c^+ can be produced due to the energy limit. At Belle (II) and LHCb, the productions of Ξ_c^+ and Ξ_c^0 with an additional strange quark are smaller than Λ_c^+ . For the two-body Λ_c^+ decays into the light baryon octet and a pseudoscalar meson, the only two DCS modes are $\Lambda_c^+ \rightarrow pK^0$ and $\Lambda_c^+ \rightarrow nK^+$. In the latter mode, neutron is always difficult to be detected in experiments. On the contrary, $\Lambda_c^+ \rightarrow pK^0$ can be revealed by the $K_S^0 - K_L^0$ asymmetry in $\Lambda_c^+ \rightarrow pK_{S,L}^0$ with K_L^0 detected with a high efficiency at Belle (II). In the decay modes of Λ_c^+ into the baryon octet and a vector meson, and the baryon decuplet and a pseudoscalar meson, the DCS transitions include $\Lambda_c^+ \rightarrow pK^{*0}$, nK^{*+} , Δ^+K^0 , Δ^0K^+ . Among them, the decays of $\Lambda_c^+ \rightarrow nK^{*+}(\rightarrow K^+\pi^0)$ and $\Lambda_c^+ \rightarrow K^0\Delta^+(\rightarrow p\pi^0)$ suffer from the low efficiencies of detections of neutrons or π^0 . The modes of $\Lambda_c^+ \rightarrow pK^{*0}(\rightarrow K^+\pi^-)$ and $\Lambda_c^+ \rightarrow K^+\Delta^0(\rightarrow p\pi^-)$ are actually included in the measured three-body DCS decay $\Lambda_c^+ \rightarrow pK^+\pi^-$ [10], while a partial-wave analysis requires much more data. In short, the $K_S^0 - K_L^0$ asymmetry in $\Lambda_c^+ \rightarrow pK_{S,L}^0$ decays is of a priority to investigate the two-body DCS charm-baryon-decay amplitudes in experiments, especially at Belle (II).

3 CP asymmetry

CP violation can occur in the charm decays into neutral kaons, induced by the interference between the CF and DCS amplitudes with the $K^0 - \bar{K}^0$ mixing. As pointed out in [49], there exist three CP -violation effects in charmed meson decays, i.e., the indirect CP violation in $K^0 - \bar{K}^0$ mixing, the direct CP asymmetry in charm decays, and the effect from the interference between two tree (CF and DCS) amplitudes with neutral kaon mixing. It is also worthwhile to study the CP -violation effects in the charmed baryon decays.

Unlike eq. (2.2), the indirect CP violation in $K^0 - \bar{K}^0$ mixing should be taken into account for the study of CP violation effects in charmed baryon decays. Such that the K_S^0 and K_L^0 states are

$$|K_{S,L}^0\rangle = p|K^0\rangle \mp q|\bar{K}^0\rangle, \tag{3.1}$$

where $p = (1+\epsilon)/\sqrt{2(1+|\epsilon|^2)}$, $q = (1-\epsilon)/\sqrt{2(1+|\epsilon|^2)}$, and ϵ is a small complex parameter characterizing the indirect CP asymmetry in the $K^0 - \bar{K}^0$ mixing system, with the values of $|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$ and its phase $\phi_\epsilon = 43.52^\circ \pm 0.05^\circ$ [30]. In experiments, the K_S^0 state is actually reconstructed by $\pi^+\pi^-$. The time-dependent CP asymmetry in the decay chain of $\mathcal{B}_c \rightarrow \mathcal{B}K(t)(\rightarrow \pi^+\pi^-)$ reads as

$$A_{CP}(t) \equiv \frac{\Gamma_{\pi\pi}(t) - \bar{\Gamma}_{\pi\pi}(t)}{\Gamma_{\pi\pi}(t) + \bar{\Gamma}_{\pi\pi}(t)}, \tag{3.2}$$

with $\Gamma_{\pi\pi}(t) \equiv \Gamma(\mathcal{B}_c \rightarrow \mathcal{B}K(t)(\rightarrow \pi^+\pi^-))$ and $\bar{\Gamma}_{\pi\pi}(t) \equiv \Gamma(\bar{\mathcal{B}}_c \rightarrow \bar{\mathcal{B}}K(t)(\rightarrow \pi^+\pi^-))$, where the intermediate state $K(t)$ is recognized as a time-evolved neutral kaon $K^0(t)$ or $\bar{K}^0(t)$, and t is the time difference between the charmed baryon decays and the neutral kaon

decays in the kaon rest frame [47, 49]. The amplitude of $\mathcal{A}(\mathcal{B}_c \rightarrow \mathcal{B}K(t)(\rightarrow \pi^+\pi^-))$ can be deduced as

$$\begin{aligned} \mathcal{A}(\mathcal{B}_c \rightarrow \mathcal{B}K(t)(\rightarrow \pi^+\pi^-)) &= \mathcal{A}(\mathcal{B}_c \rightarrow \mathcal{B}K^0) \left[g_+(t)\mathcal{A}(K^0 \rightarrow \pi^+\pi^-) + \frac{q}{p}g_-(t)\mathcal{A}(\bar{K}^0 \rightarrow \pi^+\pi^-) \right] \\ &+ \mathcal{A}(\mathcal{B}_c \rightarrow \mathcal{B}\bar{K}^0) \left[g_+(t)\mathcal{A}(\bar{K}^0 \rightarrow \pi^+\pi^-) + \frac{p}{q}g_-(t)\mathcal{A}(K^0 \rightarrow \pi^+\pi^-) \right], \end{aligned} \quad (3.3)$$

in which g_+ and g_- describe the flavor preserving and flavor changing time evolutions, respectively,

$$g_{\pm}(t) = \frac{1}{2}e^{-i(m_L - \frac{i}{2}\Gamma_L)t} \pm \frac{1}{2}e^{-i(m_S - \frac{i}{2}\Gamma_S)t}, \quad (3.4)$$

with the mass m_S (m_L) and the width Γ_S (Γ_L) of the K_S^0 (K_L^0) meson.

Neglecting the tiny direct CP asymmetry in $K^0 \rightarrow \pi^+\pi^-$, i.e., $\mathcal{A}(\bar{K}^0 \rightarrow \pi^+\pi^-) = -\mathcal{A}(K^0 \rightarrow \pi^+\pi^-)$, the time-dependent CP asymmetry is approximated as

$$A_{CP}(t) \simeq \left[A_{CP}^{\bar{K}^0}(t) + A_{CP}^{\text{dir}}(t) + A_{CP}^{\text{int}}(t) \right] / D(t), \quad (3.5)$$

with $D(t) = e^{-\Gamma_S t}(1 - 2r_f \cos \delta_f \cos \phi) + e^{-\Gamma_L t}|\epsilon|^2$. The first term $A_{CP}^{\bar{K}^0}(t)$ in the numerator denotes the CP violation in neutral kaon mixing [47],

$$A_{CP}^{\bar{K}^0}(t) = 2\mathcal{R}e[\epsilon]e^{-\Gamma_S t} - 2e^{-\Gamma t}(\mathcal{R}e[\epsilon] \cos(\Delta m t) + \mathcal{I}m[\epsilon] \sin(\Delta m t)), \quad (3.6)$$

with $\Gamma \equiv (\Gamma_S + \Gamma_L)/2$, $\Delta m \equiv m_L - m_S$. It is clear that $A_{CP}^{\bar{K}^0}(t)$ is independent of r_f , i.e., independent on the DCS amplitude. The second term $A_{CP}^{\text{dir}}(t)$ is the direct CP asymmetry induced by the interference between the CF and DCS amplitudes,

$$A_{CP}^{\text{dir}}(t) = 2e^{-\Gamma_S t} r_f \sin \delta_f \sin \phi. \quad (3.7)$$

The third term $A_{CP}^{\text{int}}(t)$ originates from the interference between the two tree (CF and DCS) amplitudes with the neutral kaon mixing,

$$A_{CP}^{\text{int}}(t) = -4r_f \cos \phi \sin \delta_f (\mathcal{I}m[\epsilon]e^{-\Gamma_S t} - e^{-\Gamma t}(\mathcal{I}m[\epsilon] \cos(\Delta m t) - \mathcal{R}e[\epsilon] \sin(\Delta m t))). \quad (3.8)$$

$A_{CP}^{\text{int}}(t)$ has been missed in the literature of studying D meson decays [31, 34, 46–48] in which the DCS amplitudes are assumed to be zero, and was first pointed out in [49] as a new CP -violation effect. It arises from the mother decay and the daughter mixing. Its physical meaning can be depicted in figure 1, a schematic description of the chain decay, taking $\Lambda_c^+ \rightarrow pK(t)(\rightarrow \pi^+\pi^-)$ as an example. $A_{CP}^{\text{int}}(t)$ is from the interference effect between the Cabibbo-favored amplitude of $\Lambda_c^+ \rightarrow p\bar{K}^0$ with neutral kaon mixing $\bar{K}^0 \rightarrow K^0(t) \rightarrow \pi^+\pi^-$, and the doubly Cabibbo-suppressed amplitude of $\Lambda_c^+ \rightarrow pK^0$ without kaon mixing $K^0 \rightarrow K^0(t) \rightarrow \pi^+\pi^-$. Equivalently, the new CP -violation effect is also from the interference effect between the amplitudes of $\Lambda_c^+ \rightarrow p\bar{K}^0$ without kaon mixing $\bar{K}^0 \rightarrow \bar{K}^0(t) \rightarrow \pi^+\pi^-$, and $\Lambda_c^+ \rightarrow pK^0$ with kaon mixing $K^0 \rightarrow \bar{K}^0(t) \rightarrow \pi^+\pi^-$. The weak phase of $A_{CP}^{\text{int}}(t)$ is from the (daughter) kaon mixing, ϵ , while the strong phase is from

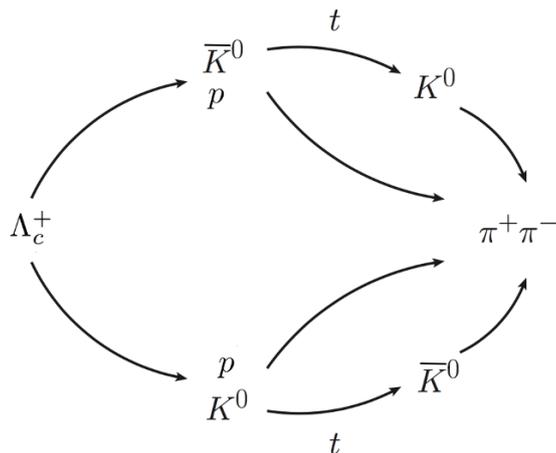


Figure 1. Schematic description of the chain decay $\Lambda_c^+ \rightarrow pK(t)(\rightarrow \pi^+\pi^-)$.

the (mother) charm decays, δ_f . Its mechanism is more complicated than for the ordinary mixing-induced CP asymmetry in, for instance, the $D^0(t) \rightarrow K^+K^-$ mode, in which both the oscillation and decay take place in the mother particle $D^0(t)$. Besides, $A_{CP}^{\text{int}}(t)$ isn't the direct CP asymmetry in charm decays, since it doesn't vanish as $\phi \rightarrow 0$. In order to investigate the direct CP violation $A_{CP}^{\text{dir}}(t)$ which is tiny in the SM due to the smallness of ϕ and thus sensitive to new physics, it is necessary to extract $A_{CP}^{\bar{K}^0}(t)$ and $A_{CP}^{\text{int}}(t)$ from the total CP violation, seen in eq. (3.5). Thus it is worthwhile to study $A_{CP}^{\text{int}}(t)$ in the relevant processes. In eq. (3.8), neglecting the weak phase in charm, i.e., setting $\phi \rightarrow 0$, only r_f and δ_f are required to predict the values of $A_{CP}^{\text{int}}(t)$, since ϵ is well determined in experiment. Fortunately, r_f and δ_f can be obtained by the data of branching fractions, which will be discussed in section 4.

From eqs. (3.6) ~ (3.8), it is found that $A_{CP}^{\bar{K}^0}(t)$ and $A_{CP}^{\text{int}}(t)$ vanish at $t = 0$ and

$$A_{CP}(t = 0) = A_{CP}^{\text{dir}}(t = 0) = 2 r_f \sin \delta_f \sin \phi. \tag{3.9}$$

In the SM, $A_{CP}(t = 0)$ is of order of 10^{-5} since $r_f \sim \mathcal{O}(10^{-2})$ and $\phi \sim \mathcal{O}(10^{-4})$. Such an order is far beyond the precision limit of the forthcoming experiments, Belle II and LHCb upgrade. However, in some new physics models, the weak phase difference can be large, which results in a larger $A_{CP}(t = 0)$. Thereby, an observation with nonvanishing $A_{CP}(t = 0)$ would be the signal of new physics [49]. Unlike the SCS processes, in which the precise measurement of the CP asymmetry cannot discriminate new physics due to the ambiguities in estimating the penguin amplitudes, the measurable direct CP asymmetry in $\mathcal{B}_c \rightarrow \mathcal{B}K(t)(\rightarrow \pi^+\pi^-)$ indicates new physics effect because of its tiny value in the SM.

The time-integrated CP asymmetry is covered by the bare asymmetry with a time-dependent function, $F(t)$, introduced to take into account relevant experimental effects,

$$A_{CP}(0, \infty) = \frac{\int_0^\infty dt F(t) \left[A_{CP}^{\bar{K}^0}(t) + A_{CP}^{\text{dir}}(t) + A_{CP}^{\text{int}}(t) \right]}{\int_0^\infty dt F(t) D(t)}. \tag{3.10}$$

In this work, we adopt the approximation in [47]

$$F(t) = \begin{cases} 1 & t_1 < t < t_2, \\ 0 & t > t_2 \text{ or } t < t_1. \end{cases} \quad (3.11)$$

Eq. (3.10) is reduced as

$$A_{CP}(t_1, t_2) \simeq \frac{2r_f \sin \delta_f \sin \phi}{1 - 2r_f \cos \delta_f \cos \phi} + \frac{2\mathcal{R}e[\epsilon] - 4\mathcal{I}m[\epsilon]r_f \cos \phi \sin \delta_f}{1 - 2r_f \cos \delta_f \cos \phi} \\ \times \left[1 - \frac{[c(t_1) - c(t_2)] + \frac{\mathcal{I}m[\epsilon] + 2\mathcal{R}e[\epsilon]r_f \cos \phi \sin \delta_f}{\mathcal{R}e[\epsilon] - 2\mathcal{I}m[\epsilon]r_f \cos \phi \sin \delta_f} [s(t_1) - s(t_2)]}{\tau_S \Gamma (1 + x^2)(e^{-t_1/\tau_S} - e^{-t_2/\tau_S})} \right], \quad (3.12)$$

in which $x \equiv \Delta m/\Gamma$, $c(t) = e^{-\Gamma t}[\cos(\Delta mt) - x \sin(\Delta mt)]$, and $s(t) = e^{-\Gamma t}[x \cos(\Delta mt) + \sin(\Delta mt)]$. The first term, being independent of $t_{1,2}$, corresponds to the direct CP asymmetry in charm decays. In the rest part of eq. (3.12), the terms proportional to r_f represent the new effect $A_{CP}^{\text{int}}(t_1, t_2)$, and those without r_f are the CP violation in the neutral kaon mixing.

In the limitation of $t_1 \ll \tau_S \ll t_2 \ll \tau_L$, $e^{-\Gamma t_1} = e^{-\Gamma s t_1} = 1$ and $e^{-\Gamma t_2} = e^{-\Gamma s t_2} = 0$. The time-integrated CP violation then reads as

$$A_{CP}(t_1 \ll \tau_S \ll t_2 \ll \tau_L) \simeq \frac{2r_f \sin \delta_f \sin \phi}{1 - 2r_f \cos \delta_f \cos \phi} + \frac{2(\mathcal{R}e[\epsilon] - 2\mathcal{I}m[\epsilon]r_f \cos \phi \sin \delta_f)}{1 - 2r_f \cos \delta_f \cos \phi} \\ \times \left[1 - \frac{2}{1 + x^2} - \frac{\mathcal{I}m[\epsilon] + 2\mathcal{R}e[\epsilon]r_f \cos \phi \sin \delta_f}{\mathcal{R}e[\epsilon] - 2\mathcal{I}m[\epsilon]r_f \cos \phi \sin \delta_f} \frac{2x}{1 + x^2} \right]. \quad (3.13)$$

Under the approximation of $\mathcal{I}m[\epsilon]/\mathcal{R}e[\epsilon] \simeq -x/y$ and $y \approx -1$ [47], we get

$$A_{CP}(t_1 \ll \tau_S \ll t_2 \ll \tau_L) \simeq \frac{-2\mathcal{R}e[\epsilon] + 2r_f \sin \delta_f \sin \phi - 4r_f \mathcal{I}m[\epsilon] \cos \phi \sin \delta_f}{1 - 2r_f \cos \phi \cos \delta_f} \\ = [A_{CP}^{\bar{K}^0} + A_{CP}^{\text{dir}} + A_{CP}^{\text{int}}]/D. \quad (3.14)$$

Considering the sizes of ϵ , r_f and ϕ , the interference between charm decays and neutral kaon mixing A_{CP}^{int} is expected to be of the order of $\mathcal{O}(10^{-4 \sim -3})$. Such an order is much larger than the direct CP violation in charm decays.

In eq. (3.14), the $2r_f \cos \phi \cos \delta_f$ term in the denominator cannot be neglected, since the new CP -violation effect, $4r_f \mathcal{I}m[\epsilon] \cos \phi \sin \delta_f$, is a sub-leading contribution which is at the same order as the term in the denominator by expansion to be $4r_f \mathcal{R}e[\epsilon] \cos \phi \cos \delta_f$. The $2r_f \cos \phi \cos \delta_f$ term can be determined by the measurement of the $K_S^0 - K_L^0$ asymmetry since the weak phase ϕ is tiny in the SM,

$$R(\mathcal{B}_c \rightarrow \mathcal{B}K_{S,L}^0) \simeq -2r_f \cos \delta_f \simeq -2r_f \cos \phi \cos \delta_f. \quad (3.15)$$

In the case of $D^+ \rightarrow \pi^+ K_S^0$ decay, the term in the denominator is one order of magnitude smaller than the new CP -violation effect and can be neglected [49], since $R(D^+ \rightarrow \pi^+ K_S^0)$ is measured to be small [41]

$$R(D^+ \rightarrow \pi^+ K_{S,L}^0) = 0.022 \pm 0.016 \pm 0.018. \quad (3.16)$$

But in the case of $\Lambda_c^+ \rightarrow pK_S^0$, the contribution from the denominator can only be determined by the measurement of the $K_S^0 - K_L^0$ asymmetry.

The time-dependent and time-integrated CP violation in $\Lambda_c^+ \rightarrow pK_S^0$ can be measured by Belle II and LHCb. In order to extract the new CP -violation effect A_{CP}^{int} , we propose an observable,

$$\begin{aligned} \Delta A_{CP}(K_S^0, p, \pi^+) &\equiv A_{CP}(\Lambda_c^+ \rightarrow pK_S^0) - A_{CP}(D^+ \rightarrow \pi^+ K_S^0) \\ &\simeq A_{CP}^{\text{int}}(\Lambda_c^+ \rightarrow pK_S^0) - A_{CP}^{\text{int}}(D^+ \rightarrow \pi^+ K_S^0) \\ &\quad - A_{CP}^{\bar{K}^0} \cdot [D(\Lambda_c^+ \rightarrow pK_S^0) - D(D^+ \rightarrow \pi^+ K_S^0)], \end{aligned} \quad (3.17)$$

where D in the last line is the denominator of eq. (3.14). The CP violation in neutral kaon mixing is mode-independent and thus cancelled between the ones in $\Lambda_c^+ \rightarrow pK_S^0$ and $D^+ \rightarrow \pi^+ K_S^0$. As discussed above, the direct CP violation is negligible. Therefore, the new CP -violation effect can be revealed in $\Delta A_{CP}(K_S^0, p, \pi^+)$. It can be measured at LHCb by combination of the raw asymmetries A_{raw} with those in CF channels, canceling the production and detection asymmetries, as

$$\begin{aligned} \Delta A_{CP}(K_S^0, p, \pi^+) &= [A_{\text{raw}}(\Lambda_c^+ \rightarrow pK_S^0) - A_{\text{raw}}(\Lambda_c^+ \rightarrow pK^- \pi^+)] \\ &\quad - [A_{\text{raw}}(D^+ \rightarrow \pi^+ K_S^0) - A_{\text{raw}}(D^+ \rightarrow K^- \pi^+ \pi^+)]. \end{aligned} \quad (3.18)$$

4 Numerical analysis

In this section, we numerically estimate the $K_S^0 - K_L^0$ asymmetries and CP asymmetries in charmed baryon decays into neutral kaons based on the flavor SU(3) symmetry. The CF and DCS processes are model-independently analyzed with the parameters extracted from experimental data. In this work, we focus on the decays of the charmed-baryon anti-triplet ($\Xi_c^0, -\Xi_c^+, \Lambda_c^+$) into light baryon octet and pseudoscalar octet.

Note that sizable flavor SU(3) breaking effect is always expected in charmed hadron decays. It is found to be very large in the SCS processes of D decays, like the difference between $D^0 \rightarrow K^+ K^-$ and $\pi^+ \pi^-$. However, the SU(3) symmetry seems to work well in the CF processes. For example, in the analysis of D meson decays using the topological diagrammatic approach under the SU(3) symmetry in ref. [39], the fitted results show that $\chi^2/d.o.f = 0.65$ for a global fit with only CF processes, while $\chi^2/d.o.f = 87$ in the case with only SCS processes. Since we focus on the charmed baryon decays into neutral kaons in the CF and DCS processes in this work, the SCS processes are not involved in the global fit. Thus large SU(3) breaking effects can be avoided. Besides, unlike the D^0 decays into neutral kaons in which the strong phase difference $\delta_f = 0$ in the flavor SU(3) limit [40, 50–54] and thus $A_{CP}^{\text{int}} \propto \sin \delta_f$ is unobservable, δ_f and A_{CP}^{int} are non-vanishing in the charged D -meson decays [49, 55, 56]. In charmed baryon decays, it will be found in the following that the CF and DCS amplitudes are different in the SU(3) decomposition, inducing non-vanishing δ_f and A_{CP}^{int} .

The nonleptonic charmed decays are induced by the operators $(\bar{s}c)(\bar{u}d)$ for the CF modes, and $(\bar{d}c)(\bar{u}s)$ for the DCS modes. These operators can be decomposed into irreducible representations of flavor SU(3) symmetry group. For example, $(\bar{s}c)(\bar{u}d) = \mathcal{O}_6 + \mathcal{O}_{\bar{15}}$,

with $\mathcal{O}_6 = \frac{1}{2}[(\bar{s}c)(\bar{u}d) - (\bar{u}c)(\bar{s}d)]$ and $\mathcal{O}_{\overline{15}} = \frac{1}{2}[(\bar{s}c)(\bar{u}d) + (\bar{u}c)(\bar{s}d)]$. The perturbative QCD corrections enhance the coefficient of \mathcal{O}_6 over $\mathcal{O}_{\overline{15}}$ by a factor of $[\alpha_s(m_b)/\alpha_s(m_W)]^{18/23} [\alpha_s(m_c)/\alpha_s(m_b)]^{18/25} \sim 2.5$ [57, 58]. In an approximation of neglecting the contributions from $\mathcal{O}_{\overline{15}}$, the effective Hamiltonian is expressed as [20, 21, 27]

$$\mathcal{H}_{\text{eff}} = e\mathcal{H}^{ab}(6)T_{ac}\bar{\mathcal{B}}_d^c M_b^d + f\mathcal{H}^{ab}(6)T_{ac}M_d^c\bar{\mathcal{B}}_b^d + g\mathcal{H}^{ab}(6)\bar{\mathcal{B}}_a^c M_b^d T_{cd}, \quad (4.1)$$

with the charmed-baryon anti-triplet

$$T_c = (\Xi_c^0, -\Xi_c^+, \Lambda_c^+), \quad T_{ab} = \epsilon_{abc}T^c, \quad (4.2)$$

the light baryon octet,

$$\mathcal{B}_b^a = \begin{pmatrix} \frac{1}{\sqrt{6}}\Lambda + \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^+ & p \\ \Sigma^- & \frac{1}{\sqrt{6}}\Lambda - \frac{1}{\sqrt{2}}\Sigma^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{2/3}\Lambda \end{pmatrix}, \quad (4.3)$$

and the pseudoscalar octet

$$M_b^a = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\sqrt{2/3}\eta_8 \end{pmatrix}. \quad (4.4)$$

The non-zero elements $\mathcal{H}^{22}(6) = 2$ for Cabibbo-allowed modes, and $\mathcal{H}^{33}(6) = 2 \tan^2 \theta_C$ for doubly Cabibbo-suppressed modes, where θ_C is the Cabibbo angle and $\tan^2 \theta_C \simeq |V_{cd}^* V_{us} / V_{cs}^* V_{ud}|$. The coefficients e, f, g are free complex parameters to be extracted from data of branching fractions.

The partial decay width of charmed baryon decays is

$$\Gamma(\mathcal{B}_c \rightarrow \mathcal{B}M) = \frac{|p_c| m_{\mathcal{B}}}{2\pi m_{\mathcal{B}_c}} |\mathcal{A}|^2, \quad (4.5)$$

where p_c is the center-of-mass momentum of the final state particles, $m_{\mathcal{B}_c}$ and $m_{\mathcal{B}}$ are the masses of charmed baryon and light baryons. The decay amplitudes are expressed by the e, f, g parameters, with the representations given in table 1. Since only the relative phases between e, f and g make sense, we take e as real. At the current stage, the available relevant data include five branching fractions of CF decays of Λ_c^+ (shown in table 1) and the ratio of branching fractions between $\Xi_c^0 \rightarrow \Lambda K_S^0$ and $\Xi_c^0 \rightarrow \Xi^- \pi^+$. So then five free parameters are fixed by six data via a global fit. Notice that f and g always occur together as $(f + g)$ in the CF amplitudes, we use $h = f + g$ in the fit to avoid large correlation, and g can be obtained through $g = h - f$. Then we find

$$e = 0.67 \pm 0.03, \quad |f| = 0.26 \pm 0.03, \quad h = f + g = (0.43 \pm 0.06) e^{i(0.97 \pm 0.06)}, \quad (4.6)$$

with $\chi^2/d.o.f = 0.17$, and the phase of f ranges from $-\pi$ to π . One can find the magnitudes of $|e|$ and $|f|$ are mostly fixed by $\Lambda_c^+ \rightarrow p K_S^0$ and $\Xi_c^0 K^+$, respectively, where the DCS contribution in the $p K_S^0$ mode is highly suppressed. The parameter h is also well determined

Modes	Representation	$BR_{\text{exp}}(\%)$	$BR_{\text{SU}(3)}(\%)$
$\Lambda_c^+ \rightarrow \Lambda\pi^+$	$\frac{1}{\sqrt{6}}(-2e - 2f - 2g)$	1.30 ± 0.07	1.30 ± 0.17
$\Lambda_c^+ \rightarrow \Sigma^0\pi^+$	$\frac{1}{\sqrt{2}}(-2e + 2f + 2g)$	1.29 ± 0.07	1.27 ± 0.17
$\Lambda_c^+ \rightarrow \Sigma^+\pi^0$	$\frac{1}{\sqrt{2}}(2e - 2f - 2g)$	1.24 ± 0.10	1.27 ± 0.17
$\Lambda_c^+ \rightarrow pK_S^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(2g) - \frac{1}{\sqrt{2}}(-2e)$	1.58 ± 0.08	$1.36 \sim 1.80$
$\Lambda_c^+ \rightarrow pK_L^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(2g) + \frac{1}{\sqrt{2}}(-2e)$		$1.24 \sim 1.67$
$\Lambda_c^+ \rightarrow \Xi^0 K^+$	$-2f$	0.50 ± 0.12	0.50 ± 0.12
$\Xi_c^0 \rightarrow \Xi^-\pi^+$	$2e$		2.24 ± 0.34
$\Xi_c^0 \rightarrow \Xi^0\pi^0$	$\frac{1}{\sqrt{2}}(-2e + 2g)$		$0.07 \sim 1.81$
$\Xi_c^0 \rightarrow \Lambda K_S^0$	$\frac{1}{\sqrt{12}}\tan^2\theta_C(-2e + 4f + 4g) - \frac{1}{\sqrt{12}}(-4e + 2f + 2g)$		0.47 ± 0.08
$\Xi_c^0 \rightarrow \Lambda K_L^0$	$\frac{1}{\sqrt{12}}\tan^2\theta_C(-2e + 4f + 4g) + \frac{1}{\sqrt{12}}(-4e + 2f + 2g)$		0.50 ± 0.09
$\Xi_c^0 \rightarrow \Sigma^+ K^-$	$2f$		0.31 ± 0.09
$\Xi_c^0 \rightarrow \Sigma^0 K_S^0$	$\frac{1}{2}\tan^2\theta_C(2e) - \frac{1}{2}(-2f - 2g)$		0.23 ± 0.07
$\Xi_c^0 \rightarrow \Sigma^0 K_L^0$	$\frac{1}{2}\tan^2\theta_C(2e) + \frac{1}{2}(-2f - 2g)$		0.20 ± 0.06
$\Xi_c^+ \rightarrow \Xi^0\pi^+$	$-2g$		$0.01 \sim 10.22$
$\Xi_c^+ \rightarrow \Sigma^+ K_S^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(-2e) - \frac{1}{\sqrt{2}}(2g)$		$0.06 \sim 4.84$
$\Xi_c^+ \rightarrow \Sigma^+ K_L^0$	$\frac{1}{\sqrt{2}}\tan^2\theta_C(-2e) + \frac{1}{\sqrt{2}}(2g)$		$0.00 \sim 4.30$

Table 1. Branching fractions and amplitude representations for the Cabibbo-favored charmed baryon decays. For the modes with neutral kaons $K_{S,L}^0$ in the final states, the associated doubly Cabibbo-suppressed amplitudes are taken into account with the factor of $\tan^2\theta_C$. The ratio of $BR(\Xi_c^0 \rightarrow \Lambda K_S^0)/BR(\Xi_c^0 \rightarrow \Xi^-\pi^+) = 0.210 \pm 0.028$ is also included in the global fit. Our results are given in the last column, compared to the experimental data [30].

by global fitting. The phase of f cannot be extracted from the available data, and thus is free in the full range between $-\pi$ and π . The numerical results of branching fractions are given in the last column in table 1, compared to the experimental data [30]. The uncertainties in our predictions include the errors from the global fit and the ones from the lifetimes of Λ_c^+ , Ξ_c^+ and Ξ_c^0 . For those modes in which g occurs without f , we only give a range due to the ambiguity of the phase of f , including the uncertainties from the other fitted parameters and from the lifetimes of charmed baryons. The exceptions in the DCS amplitudes do not affect the fitting very much. Besides, the branching fractions of $\Lambda_c^+ \rightarrow \Sigma^0\pi^+$ and $\Sigma^+\pi^0$ are identical to each other due to the isospin symmetry. From table 1, it is clear that our results are well consistent with the data. It is plausible that the CF and DCS transitions of charm baryons are well expressed by flavor SU(3) symmetry. Besides, in ref. [27], the authors studied charmed baryon decays under the SU(3) symmetry analysis similarly to our work, but including the SCS processes. Their χ^2 is much larger than ours, and their result of $\mathcal{B}(\Lambda_c^+ \rightarrow p\pi^0)$ significantly exceeds the experimental upper bound. The predictions on the branching fractions of $\Lambda_c^+ \rightarrow pK_L^0$ and those of $\Xi_c^{+,0}$ decays can be tested by experiments in the future.

$R(\Lambda_c^+ \rightarrow pK_{S,L}^0)$	$R(\Xi_c^0 \rightarrow \Lambda K_{S,L}^0)$	$R(\Xi_c^0 \rightarrow \Sigma^0 K_{S,L}^0)$	$R(\Xi_c^+ \rightarrow \Sigma^+ K_{S,L}^0)$
$-0.010 \sim 0.087$	-0.037 ± 0.004	0.091 ± 0.016	$-0.113 \sim 0.390$

Table 2. $K_S^0 - K_L^0$ asymmetries in $\mathcal{B}_c \rightarrow \mathcal{B}K_{S,L}^0$ decays.

	$A_{CP}(\Lambda_c^+ \rightarrow pK_S^0)$	$A_{CP}(\Xi_c^0 \rightarrow \Lambda K_S^0)$	$A_{CP}(\Xi_c^0 \rightarrow \Sigma^0 K_S^0)$	$A_{CP}(\Xi_c^+ \rightarrow \Sigma^+ K_S^0)$
$S1$	$-3.15 \sim -2.67$	-3.13 ± 0.05	-3.42 ± 0.05	$-4.57 \sim -2.60$
$S2$	$-3.55 \sim -3.09$	-3.58 ± 0.04	-2.50 ± 0.10	$-2.91 \sim -1.39$

Table 3. Time-integrated CP asymmetries $A_{CP}(t_1 \ll \tau_S \ll t_2 \ll \tau_L)$ in $\mathcal{B}_c \rightarrow \mathcal{B}K_S^0$ decays in the units of 10^{-3} , where the sets of $S2$ are obtained by flipping the signs of all phase parameters of $S1$.

From table 1, one can find the branching fractions of $\mathcal{B}_c \rightarrow \mathcal{B}K_S^0$ are obviously different from the $\mathcal{B}_c \rightarrow \mathcal{B}K_L^0$ ones due to the interference between the CF and DCS amplitudes, which results in measurable $K_S^0 - K_L^0$ asymmetries. The results of $K_S^0 - K_L^0$ asymmetries, $R(\mathcal{B}_c \rightarrow \mathcal{B}K_{S,L}^0)$, are given in table 2. It is found that the $K_S^0 - K_L^0$ asymmetry in $\Lambda_c^+ \rightarrow pK_{S,L}^0$ decay, the promising observable to search for two-body DCS amplitudes of charmed baryons, can reach the order of 10^{-2} or even 0.1, within the experimental capability.

The numerical results of the time-integrated CP asymmetries $A_{CP}(t_1 \ll \tau_S \ll t_2 \ll \tau_L)$ (denoted by A_{CP} for simplification) are presented in table 3. There are two solutions of the CP asymmetries for each parameter set. We label the results obtained from eq. (4.6) by $S1$, and $S2$ is obtained by flipping the signs of all phase parameters in $S1$ since the solution with opposite strong phases contributes equivalently to branching fractions that are proportional to the cosine of the strong phases. The measurements in the future, to establish the above CP asymmetries, could discriminate these solutions. In the absence of the DCS contributions, i.e., $r_f = 0$, $A_{CP}(\mathcal{B}_c \rightarrow \mathcal{B}K_S^0) = A_{CP}^{\bar{K}^0} \simeq -2\mathcal{R}e[\epsilon] \approx -3.23 \times 10^{-3}$. The new CP -violation effect A_{CP}^{int} can be revealed by the subtraction of $A_{CP}^{\bar{K}^0}$ and the $-2r_f \cos \phi \cos \delta_f$ term in denominator of eq. (3.14) from the total CP asymmetries. The signs of A_{CP}^{int} are opposite between the solutions of $S1$ and $S2$ due to its proportion to $\sin \delta_f$, while the ones of $-2r_f \cos \phi \cos \delta_f$ are the same in solutions of $S1$ and $S2$. The denominator D in eq. (3.14) could be obtained from the corresponding $K_S^0 - K_L^0$ asymmetries, seen in eq. (3.15). The new CP asymmetry effect, A_{CP}^{int} , is of the order of 10^{-4} , while the direct CP asymmetry A_{CP}^{dir} is $\mathcal{O}(10^{-5})$. For example, the range of $A_{CP}^{\text{int}}(\Lambda_c^+ \rightarrow pK_S^0)$ is $(0.16 \sim 3.37) \times 10^{-4}$ and the one for $A_{CP}^{\text{dir}}(\Lambda_c^+ \rightarrow pK_S^0)$ is $(0.3 \sim 6.8) \times 10^{-5}$ in solution $S1$. The direct CP violation are sensitive to new physics which may contribute to the DCS amplitudes with a large weak phase [49]. Thus if the new CP violating effect was determined in experiment, the direct CP violation in charmed baryon decays into neutral kaons can be obtained and used to search for new physics.

5 Summary

Charmed baryon decays are becoming more intriguing due to the new measurements by Belle and BESIII in recent years. In this work, we investigate the $K_S^0 - K_L^0$ asymmetries and CP violation in charmed baryon decays into neutral kaons. Induced by the interference between the Cabibbo-favored and the doubly Cabibbo-suppressed amplitudes, the $K_S^0 - K_L^0$ asymmetries can be used to study the DCS amplitudes. As no evidence of two-body DCS process in charmed baryon decays has been found so far, we propose to measure the $K_S^0 - K_L^0$ asymmetry in the $\Lambda_c^+ \rightarrow pK_{S,L}^0$ decay mode as a promising method to search for the two-body DCS transition. Besides, a new CP -violation effect is found in charmed baryon decays into neutral kaons, induced by the interference between the CF and DCS amplitudes with the $K^0 - \bar{K}^0$ mixing. Once it is determined in experiments, the direct CP asymmetries can be used to search for new physics beyond the Standard Model. A numerical analysis based on SU(3) symmetry is performed to estimate the values of $K_S^0 - K_L^0$ asymmetries and CP violations.

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