Test flavor SU(3) symmetry in exclusive Λ_c decays (Postprint)

Authors: Cai-Dian Lu, Wei Wang, Fu-Sheng Yu

Date: 2016-08-30T00:00:00+00:00

Abstract

Flavor SU(3) symmetry is a powerful tool to analyze charmed baryon decays, however its applicability remains to be experimentally validated. Since there is not much data on Ξc decays, various exclusive Λc decays especially the ones into a neutron state are essential for the test of flavor symmetry. These decay modes are also helpful to investigate final state interactions in charmed baryon decays. In this work, we discuss the explicit roles of Λc decays into a neutron in testing the flavor symmetry and exploring final state interactions. The involved decay modes include semileptonic decays, two-body and three-body non-leptonic decays, but all of them have not been experimentally observed to date.

Full Text

Testing Flavor SU(3) Symmetry in Exclusive Λc Decays

Cai-Dian Lü[1], Wei Wang[2],[3], and Fu-Sheng Yu

[1] Institute of High Energy Physics, P.O. Box 918(4), Chinese Academy of Sciences, Beijing 100049, People' s Republic of China
[2] INPAC, Shanghai Key Laboratory for Particle Physics and Cosmology, Department of Physics and Astronomy, Shanghai Jiao-Tong University, Shanghai, 200240, China
[3] State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China
School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, People' s Republic of China

Introduction

Flavor SU(3) symmetry is a powerful tool for analyzing charmed baryon decays, yet its applicability remains to be experimentally validated. Since experimental data on Ξc decays are scarce, various exclusive Λc decays—particularly those involving a neutron in the final state—are essential for testing this flavor symmetry. These decay modes also provide valuable insights into final-state interactions in charmed baryon decays. In this work, we discuss the explicit roles of Λc decays into a neutron for testing flavor symmetry and exploring final-state interactions. The decay modes under consideration include semileptonic decays, two-body nonleptonic decays, and three-body nonleptonic decays, none of which have been experimentally observed to date.

Charmed baryon decays, particularly Λc and Ξc decays, are of great interest as they serve as a platform for studying strong and weak interactions in heavy-to-light baryonic transitions. They also provide essential inputs for Λb decay modes that produce a charmed baryon such as Λc. On the experimental side, most available results on Λc decays were obtained from older data until recently. In 2014, the Belle collaboration provided a measurement of the branching fraction with very small uncertainty [1]: $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)_{\text{Belle}} = (6.84 \pm 0.24^{+0.21}_{-0.27})\%$, but the central value is much larger than the previous measurement by the CLEO-c collaboration [2]: $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)_{\text{CLEO}} = (5.0 \pm 1.2)\%$.

Based on their large dataset, the Belle collaboration also began studying doubly Cabibbo-suppressed processes [3]. Using data collected in e^+e^- collisions at a center-of-mass energy of $\sqrt{s} = 4.599$ GeV and adopting the double-tag technique, the BES-III collaboration reported the first measurements of absolute hadronic branching fractions for Cabibbo-favored decay modes [4]. In total, twelve Λc decay modes were observed, with significant improvement on the $pK^-\pi^+$ branching fraction in particular: $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)_{\text{BESIII}} = (5.84 \pm 0.23)\%$. While the uncertainties are comparable to the Belle results, the central value is much smaller and closer to the CLEO result. We believe this difference will be clarified in the future, as the experimental prospects for charmed baryon decays are very promising [5, 6].

Theoretical descriptions of charmed baryon decays are mostly based on the factorization assumption together with analyses of non-factorizable contributions in nonperturbative explicit models [7-10]. However, the factorization scheme does not appear to be supported by experiments, as evidenced by the observed large branching fractions for decays such as $\Lambda_c^+ \to \Sigma^+\pi^0/\Xi^0K^+$, which are forbidden in the factorization scheme [11]. An alternative, model-independent approach is to use flavor SU(3) symmetry, which has been argued to work better in charmed baryon decays [12-17] and bottom baryon decays [18-20].

As experimental precision gradually increases, the time is ripe to validate or invalidate the applicability of SU(3) symmetry to charmed baryon decays. The SU(3) transformation connects Λc with Ξc, but at present and in the foreseeable future there are no experiments focusing on Ξc decays. Thus, Λc decays into various final states—especially those involving a neutron—are of great value, as they will be the only source for testing SU(3) symmetry in charmed-baryon decays. The motivation of this work is to discuss the roles of Λc decays into a neutron in testing SU(3) symmetry and exploring final-state interactions, including semileptonic decays, two-body nonleptonic decays, and three-body nonleptonic decays. All these exclusive decay modes have not yet been experimentally measured.

This paper is organized as follows. In Sec. III and Sec. IV, we explore the two-body and three-body nonleptonic decays of the Λc, respectively. In Sec. II, we study the semileptonic Λc decays. The final section contains our summary.

II. Semileptonic Λc Decays

We begin with semileptonic Λc decays. In the flavor SU(3) symmetry limit, charmed baryons are classified according to SU(3) irreducible representations, namely as multiplets of the light-quark system: $3 \otimes 3 \otimes \bar{3} = \bar{3} \oplus 6 \oplus \bar{15} \oplus 15$. The Λc and Ξc form the charmed-baryon anti-triplet in the initial state: $B_c = (\Xi_c^0, \Xi_c^+, \Lambda_c^+)$. For the light baryons, we focus on the SU(3) octet represented by the matrix:

$$T^a = (\Xi^0, \Xi^-, \Lambda, \Sigma^+, \Sigma^0, \Sigma^-, n, p)$$

The operator responsible for the $c \to q$ transition forms an SU(3) anti-triplet in the final state. Thus the effective Hamiltonian at the hadron level is constructed as:

$$\mathcal{H}_{\text{eff}} = aH_a^{(\bar{3})} T^b \bar{B}_c^a \bar{\nu}_e e$$

Measurements of the relevant branching fractions provide the most straightforward test of flavor SU(3) symmetry in charmed baryon decays. With the most recent data from the BES-III collaboration [21], we can obtain the following result:

$$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)_{\text{BESIII}} = (3.65 \pm 0.20)\%$$

From SU(3) symmetry, we predict:

$$\mathcal{B}(\Lambda_c^+ \to n e^+ \nu_e)_{\text{SU(3)}} = (2.93 \pm 0.34)\%$$

which might be accessible for the BES-III and Belle-II collaborations [5, 6].

In semileptonic decays, the neutron can be produced together with a light pseudoscalar meson. The lowest-lying pseudoscalar mesons can be written as:

$$M = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

In this case, the effective hadronic interaction Hamiltonian is constructed as:

$$\mathcal{H}_{\text{eff}} = a[T^a H_a^{(\bar{3})}](\bar{B}_c^b M_b^a)\bar{\nu}_e e + b[T^a \bar{B}_c^b H_c^{(\bar{3})}]\bar{\nu}_e e + c[T^a M_b^a H_c^{(\bar{3})}]\bar{\nu}_e e$$

where the singlet contribution to has been neglected. The coefficients a, b, c are nonperturbative coefficients.

The above Hamiltonian leads to the expectation:

$$\mathcal{B}(\Lambda_c^+ \to n e^+ \nu_e) = \mathcal{B}(\Lambda_c^+ \to p K^- e^+ \nu_e)$$

which is testable in the near future. In fact, this identity holds under isospin symmetry, whose breaking effect is much smaller in charm decays than that of flavor SU(3) symmetry. In the semileptonic decays of $c \to s e^+ \nu_e$, the isospins do not change, $\Delta I = 0$. It should be stressed that this identity is applicable to both resonant and non-resonant contributions.

The branching fraction for the inclusive decay of Λc into an electron has been measured as [11]:

$$\mathcal{B}(\Lambda_c^+ \to e^+ + X) = (4.5 \pm 1.7)\%$$

Combining the results for $\Lambda_c^+ \to \Lambda e^+ \nu_e$ in Eq. (8), we may expect:

$$\mathcal{B}(\Lambda_c^+ \to n e^+ \nu_e) = \mathcal{B}(\Lambda_c^+ \to p K^- e^+ \nu_e)$$

III. Two-Body Nonleptonic Λc Decays

For two-body nonleptonic decays of the Λc, there are no Cabibbo-allowed decay modes into a neutron. Two-body decays into a neutron are either singly Cabibbo-suppressed or doubly Cabibbo-suppressed:

$$\Lambda_c^+ \to n\pi^+, \quad \Lambda_c^+ \to nK^+, \quad \Lambda_c^+ \to \cdots$$

The nonleptonic Λc decays are induced by the operators $[\bar{s}c][\bar{u}d]$ for Cabibbo-allowed modes and $[\bar{d}c][\bar{u}d]$ for Cabibbo-suppressed modes. These operators can be decomposed into irreducible representations of flavor SU(3). For instance:

$$(\bar{s}c)(\bar{u}d) = O_{15} = [(\bar{s}c)(\bar{u}d) - (\bar{u}c)(\bar{s}d)], \quad [(\bar{s}c)(\bar{u}d) + (\bar{u}c)(\bar{s}d)]$$

Perturbative QCD corrections give rise to an enhancement of the coefficient for O_6 over the coefficient for O_{15} by [22, 23]:

$$\frac{c_6}{c_{15}} \sim \left(\frac{\alpha_s(m_b)}{\alpha_s(m_W)}\right)^{18/23} \left(\frac{\alpha_s(m_c)}{\alpha_s(m_b)}\right)^{18/25}$$

If this is valid, then one has:

$$\mathcal{H}_{\text{eff}} = eH^{ab(6)}T_{ac}\bar{B}^c_c + fH^{ab(6)}T_{ac}M^b_c + gH^{ab(6)}\bar{B}^b_c T_{cd}$$

with $H^{22(6)} = 1$ for Cabibbo-allowed modes, $H^{23(6)} = H^{32(6)} = 2\sin(\theta_C)$ for singly Cabibbo-suppressed modes, and $H^{33(6)} = +2\sin(\theta_C)^2$ for doubly-Cabibbo-suppressed modes, where θ_C is the Cabibbo angle, and $T_{ab} = \epsilon_{abc}T^c$. The coefficients e, f, g are nonperturbative amplitudes.

Using Eq. (19), we find that for the doubly-Cabibbo-suppressed modes:

$$\mathcal{A}(\Lambda_c^+ \to \cdots) = \cdots$$

For the singly-Cabibbo-suppressed modes, we have the decay amplitudes:

$$\mathcal{A}(\Lambda_c^+ \to nK^+) = \mathcal{A}(\Lambda_c^+ \to pK^0)$$

$$\mathcal{A}(\Lambda_c^+ \to n\pi^+) = \sqrt{2}\mathcal{A}(\Lambda_c^+ \to p\pi^0) = (2f + 2g)\sin(\theta_C)$$

which implies the relation:

$$\mathcal{B}(\Lambda_c^+ \to n\pi^+) = 2\mathcal{B}(\Lambda_c^+ \to p\pi^0)$$

Furthermore, we have the amplitudes for Cabibbo-allowed modes:

$$\mathcal{A}(\Lambda_c^+ \to n\pi^+) = 2\mathcal{A}(\Lambda_c^+ \to p\pi^0)$$

$$\mathcal{A}(\Lambda_c^+ \to \Lambda\pi^+) = \mathcal{A}(\Lambda_c^+ \to \cdots)$$

Thus we can derive the sum rule that can be experimentally examined:

$$\mathcal{B}(\Lambda_c^+ \to n\pi^+) = \sin^2(\theta_C)\left[\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+) + \mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+)\right]$$

The recent BES-III data [4] implies:

$$\mathcal{B}(\Lambda_c^+ \to n\pi^+) = \sin^2(\theta_C)[3.04\% + 1.27\%] = 0.04\%$$

Future measurements by BES-III will be able to validate or invalidate the dominance of the sextet assumption in the effective operator.

IV. Three-Body Nonleptonic Λc Decays

Compared to two-body decays, three-body Λc decays are more involved, since they can proceed via quasi-two-body processes and non-resonant decays, and secondly there are a number of independent amplitudes in SU(3) symmetry. In the following we consider the $NK\pi$ system in the isospin limit:

$$|pK^-\pi^+\rangle = \sqrt{\frac{2}{3}}|I = 1/2, I_3 = +1/2\rangle + \sqrt{\frac{1}{3}}|I = 3/2, I_3 = +1/2\rangle$$

The superscripts (1) and (2) denote isospin states from $(I_{NK}, I_{K\pi}) = (1, 0)$ and $(0, 1)$ couplings, respectively, which are independent of each other. Since the Hamiltonian of the $c \to s\bar{d}u$ transition has $\Delta I = 1$, and the isospin of Λc is zero, we can derive the decay amplitudes from the above decompositions:

$$\mathcal{A}(\Lambda_c^+ \to n\pi^0) = \frac{1}{\sqrt{2}}\mathcal{A}^{(1)} + \sqrt{2}\mathcal{A}^{(2)}$$

$$\mathcal{A}(\Lambda_c^+ \to pK^-\pi^+) = \mathcal{A}^{(1)} + \mathcal{A}^{(2)}$$

The above amplitudes lead to the sum rule:

$$\mathcal{A}(\Lambda_c^+ \to n\pi^0) + \mathcal{A}(\Lambda_c^+ \to pK^-\pi^+) + \mathcal{A}(\Lambda_c^+ \to \cdots\pi^+) = 0$$

Note that the isospin amplitudes in Eq. (32) can change if we first couple the $K\pi$ states from Eqs. (29-31), but the sum rule in Eq. (33) still holds.

Measurements of the branching ratios of the three channels can determine the two amplitudes and, in particular, investigate the relative strong phases between the two independent decay amplitudes. These phases arise from final-state interactions, since if factorization works, the two independent amplitudes are real with vanishing phases at leading order. These amplitudes, including phases, can provide essential inputs for the analysis of nonleptonic decays into other baryons like Λ.

From Eq. (32), we define the relative strong phase δ between $\mathcal{A}^{(1)}$ and $\mathcal{A}^{(2)}$:

$$\mathcal{A}^{(2)} = |\mathcal{A}^{(2)}|e^{i\delta}$$

Then the branching fractions can be expressed as:

$$\mathcal{B}(\Lambda_c^+ \to n\pi^0) = \frac{1}{2}|\mathcal{A}^{(1)}|^2 + 2|\mathcal{A}^{(2)}|^2 + \sqrt{2}|\mathcal{A}^{(1)}||\mathcal{A}^{(2)}|\cos\delta$$

$$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = |\mathcal{A}^{(1)}|^2 + |\mathcal{A}^{(2)}|^2 + 2|\mathcal{A}^{(1)}||\mathcal{A}^{(2)}|\cos\delta$$

where we consider the relative strong phase to understand the final-state interaction and neglect the phase spaces, which are actually integrated in the three-body decays. Hence:

$$\cos\delta = \frac{\mathcal{B}(pK^-\pi^+) + \mathcal{B}(\cdots) - \mathcal{B}(\cdots)}{2\sqrt{\mathcal{B}(pK^-\pi^+)\mathcal{B}(\cdots)}}$$

Defining:

$$R_p = \frac{\mathcal{B}(\Lambda_c^+ \to n\pi^0)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$

$$R_n = \frac{\mathcal{B}(\Lambda_c^+ \to \cdots\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$

we have:

$$\cos\delta = \frac{R_p(1 + R_n - \cdots)}{2\sqrt{R_p R_n}}$$

From the recent measurement by BESIII [4], $R_p = 0.64 \pm 0.017$. Then $\cos\delta$ can be obtained once R_n is measured. The relation between $\cos\delta$ and R_n is shown in Fig. 1. Since we have $0.06 \leq R_n \leq 4.54$, the branching fraction of $\Lambda_c^+ \to \cdots\pi^+$ is obtained as:

$$\mathcal{B}(\Lambda_c^+ \to \cdots\pi^+)_{\text{Belle}} \leq 0.04\%$$

$$\mathcal{B}(\Lambda_c^+ \to \cdots\pi^+)_{\text{BESIII}} \leq 0.035\%$$

As we can see, this constraint is rather loose, thus experimental measurements are urgently needed.

[Figure 1: see original paper]: Correlation between $\cos\delta$ and R_n, with δ as the strong phase difference in Eq. (34) and R_n as the ratio of branching fractions in Eq. (37).

V. Summary

Unlike bottom hadron decays where the momentum transfer is typically large enough to ensure the validity of perturbative QCD, charmed meson and baryon decays are very difficult to understand. Due to the limited energy release, the factorization scheme based on expansions in $1/m_c$ and $1/E$ is not always valid. Flavor SU(3) symmetry is a powerful tool for analyzing charmed baryon decays, which has been argued to work better than in charmed meson decays; however, its validity must be experimentally examined. Since there is limited data on Ξc decays, exclusive Λc decays into a neutron are essential for testing flavor symmetry and investigating final-state interactions in charmed baryon decays.

In this work, we have discussed the roles of exclusive Λc decays into a neutron in testing flavor symmetry and final-state interactions. We found that semileptonic decays into a neutron provide the most straightforward way to explore flavor SU(3) symmetry. Two-body nonleptonic decays can examine the assumption of sextet dominance mechanism. Three-body nonleptonic decays into a neutron are of great interest for exploring final-state interactions in Λc decays. All these decay modes have not been experimentally observed to date.

Acknowledgements: The authors are very grateful to Xiao-Gang He, Lei Li, Xiao-Rui Lyu, and Yang-Heng Zheng for enlightening discussions. This work is supported in part by the National Natural Science Foundation of China under Grant Nos. 11575110, 11521505, 11347027, 11505083, 11235005, and 11375208, the Natural Science Foundation of Shanghai under Grant Nos. 15DZ2272100 and 15ZR1423100, by the Open Project Program of State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, China (No. Y5KF111CJ1), and by the Scientific Research Foundation for Returned Overseas Chinese Scholars, State Education Ministry.

References

[1] A. Zupanc et al. [Belle Collaboration], Phys. Rev. Lett. 113, no. 4, 042002 (2014) doi: 10.1103/PhysRevLett.113.042002 [arXiv:1312.7826 [hep-ex]].

[2] D. E. Jaffe et al. [CLEO Collaboration], Phys. Rev. D 62, 072005 (2000) doi: 10.1103/PhysRevD.62.072005 [hep-ex/0004001].

[3] S. B. Yang et al. [Belle Collaboration], arXiv:1512.07366 [hep-ex].

[4] M. Ablikim et al. [BESIII Collaboration], arXiv:1511.08380 [hep-ex].

[5] D. M. Asner et al., Int. J. Mod. Phys. A 24, S1 (2009) [arXiv:0809.1869 [hep-ex]].

[6] T. Aushev et al., arXiv:1002.5012 [hep-ex].

[7] H. Y. Cheng and B. Tseng, Phys. Rev. D 46, 1042 (1992) [Phys. Rev. D 55, 1697 (1997)]. doi: 10.1103/PhysRevD.55.1697, 10.1103/PhysRevD.46.1042

[8] P. Zenczykowski, Phys. Rev. D 50, 402 (1994) doi: 10.1103/PhysRevD.50.402 [hep-ph/9309265].

[9] T. Uppal, R. C. Verma and M. P. Khanna, Phys. Rev. D 49, 3417 (1994). doi: 10.1103/PhysRevD.49.3417

[10] Fayyazuddin and Riazuddin, Phys. Rev. D 55, 255 (1997) [Phys. Rev. D 56, 531 (1997)]. doi: 10.1103/PhysRevD.55.255, 10.1103/PhysRevD.56.531

[11] K. A. Olive et al. [Particle Data Group Collaboration], Chin. Phys. C 38, 090001 (2014). doi: 10.1088/1674-1137/38/9/090001

[12] M. J. Savage and R. P. Springer, Phys. Rev. D 42, 1527 (1990). doi:10.1103/PhysRevD.42.1527

[13] Y. Kohara, Phys. Rev. D 44, 2799 (1991). doi:10.1103/PhysRevD.44.2799

[14] R. C. Verma and M. P. Khanna, Phys. Rev. D 53, 3723 (1996) doi:10.1103/PhysRevD.53.3723 [hep-ph/9506394].

[15] L. L. Chau, H. Y. Cheng and B. Tseng, Phys. Rev. D 54, 2132 (1996) doi:10.1103/PhysRevD.54.2132 [hep-ph/9508382].

[16] K. K. Sharma and R. C. Verma, Phys. Rev. D 55, 7067 (1997) doi:10.1103/PhysRevD.55.7067 [hep-ph/9704391].

[17] M. J. Savage, Phys. Lett. B 257, 414 (1991). doi:10.1016/0370-2693(91)91917-K

[18] M. Gronau and J. L. Rosner, Phys. Rev. D 89, no. 3, 037501 (2014) [Phys. Rev. D 91, no. 11, 119902 (2015)] doi:10.1103/PhysRevD.91.119902, 10.1103/PhysRevD.89.037501 [arXiv:1312.5730 [hep-ph]].

[19] X. G. He and G. N. Li, Phys. Lett. B 750, 82 (2015) doi:10.1016/j.physletb.2015.08.048 [arXiv:1501.00646 [hep-ph]].

[20] M. He, X. G. He and G. N. Li, Phys. Rev. D 92, no. 3, 036010 (2015) doi:10.1103/PhysRevD.92.036010 [arXiv:1507.07990 [hep-ph]].

[21] M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. 115, no. 22, 221805 (2015) doi: 10.1103/PhysRevLett.115.221805 [arXiv:1510.02610 [hep-ex]].

[22] M. K. Gaillard and B. W. Lee, Phys. Rev. Lett. 33, 108 (1974). doi: 10.1103/PhysRevLett.33.108

[23] G. Altarelli and L. Maiani, Phys. Lett. B 52, 351 (1974). doi:10.1016/0370-2693(74)90060-4

Note: Figure translations are in progress. See original paper for figures.