CP-violation study in b-baryon hadronic decays using $SU(3)$ symmetry

Shibasis Roy* and Rahul Sinha†
The Institute of Mathematical Sciences, Taramani, Chennai 600113, India and
Homi Bhabha National Institute, Training School Complex, Anushaktinagar, Mumbai 400094, India

N. G. Deshpande‡
Institute for Fundamental Science, University of Oregon, Eugene, Oregon 94703, USA

A significant effort has been made by CDF and LHCb experiments towards establishing CP violation in hadronic b-baryon decays. Future experimental runs, led by the LHCb collaboration, promise a much larger dataset of such decays paving the way for several interesting CP-asymmetry measurements. In this letter of interest, we identify some of those decay modes and discuss CP-asymmetry relations among them.

I. INTRODUCTION

The CP-asymmetry study of bottom baryons [1, 2] is of great interest as it provides a direct probe of matter-antimatter asymmetry in baryon decays. Despite of the experimental challenges, both CDF [3, 4] and LHCb [5–11] have come tantalizingly close to measuring CP-violation in b-baryon decays. So far, within the current uncertainties, CP-asymmetry studies [3, 4, 9] in $\Lambda_b \to p^+K^-$ and $\Lambda_b \to p^+\pi^-$ decays are consistent with no CP-asymmetry. The situation may change, however, when the statistical errors go down as LHCb gears up to analyze a significant number [12] of hadronic b-baryons decays in its subsequent runs [13].

One expects b-baryon CP-asymmetries [14, 15] to be of similar magnitude as observed in B-meson decays since the underlying quark level transition are the same for the two cases. Moreover, a non-vanishing CP-asymmetry is a measure of direct CP violation as baryons and antibaryons do not undergo mixing due to baryon number conservation. The two body [16–20] and multibody charmless decays [6–8, 10, 11, 21, 22] of b-baryons mediated by $b \to u\bar{u}s$ and $b \to u\bar{u}d$ transitions are ideal places to look for CP-violating effects by either measuring decay rate asymmetries directly or through T-odd asymmetry observables [23–25] between decay mode and its conjugate. Motivated by the discovery potential of CP-violation in baryons, we focus on b-baryons decaying to an octet or decuplet baryon and a pseudoscalar meson and use $SU(3)$-flavor symmetry to derive CP-relations [17, 18, 20] that can be tested in near future [26].

* shibasisr@imsc.res.in
† sinha@imsc.res.in
‡ desh@uoregon.edu

II. $SU(3)$-DECOMPOSITION OF DECAY AMPLITUDES

The number of $SU(3)$-reduced matrix elements [18, 20] pertaining to describe a $SU(3)$-flavor anti-triplet b-baryon ($\mathcal{B}_b$) decaying to a ground state baryon and a pseudoscalar meson ($\mathcal{P}$) is ten or five depending on whether the daughter baryon belongs to an octet or a decuplet of $SU(3)$. In both these cases, the total numbers of possible strangeness changing ($\Delta S = -1$) and strangeness conserving ($\Delta S = 0$) decay modes are higher than the number of independent $SU(3)$-reduced matrix elements. As a consequence, several amplitude relations exist between decay modes. CP relations can be inferred by noting that both the tree and penguin part of the decay amplitude satisfy the amplitude relations. More than one partial waves can contribute to such decays [1, 2, 27, 28] and the decay amplitude is decomposed as,

$$\mathcal{A}^l = \lambda_u^q \mathcal{A}^l_{\text{tree}} + \lambda_t^q \mathcal{A}^l_{\text{penguin}}. \quad (1)$$

where $l = 0, 1, 2$ denote contributions from particular partial waves. The δ^l_{CP} for each partial wave is given by,

$$\delta^l_{\text{CP}}(\mathcal{B}_b \to \mathcal{B}\,\mathcal{P}) = -4\mathbf{J} \times \text{Im}\Big[\mathcal{A}^{l*}_{\text{tree}}(\mathcal{B}_b \to \mathcal{B}\,\mathcal{P})\mathcal{A}^l_{\text{penguin}}(\mathcal{B}_b \to \mathcal{B}\,\mathcal{P})\Big], \quad (2)$$

$\mathbf{J}$ being the well known Jarlskog invariant and $\mathcal{B} = \mathcal{D}$ or $\mathcal{O}$ depending on whether the final state baryon belongs to a decuplet or an octet of $SU(3)$. The experimentally measured quantity, A_{CP}, is the sum of CP violating contributions from the $\delta^l_{\rm CP}$ with appropriate phase-space factor multiplied. Starting from a Λ^0_b baryon in the initial state, some of the $\delta_{\rm CP}$ relations [20] having decuplet baryon in the final state are quoted below,

$$\delta^l_{\rm CP}(\Lambda^0_b \to \Delta^+ K^-) = \delta^l_{\rm CP}(\Lambda^0_b \to \Delta^0 \overline{K^0}) \tag{3}$$

$$\begin{aligned}&\delta^l_{\rm CP}(\Lambda^0_b \to \Sigma^{'-}\pi^+) = \delta^l_{\rm CP}(\Lambda^0_b \to \Xi^{'-}K^+)\\ &= -\frac{1}{3}\delta^l_{\rm CP}(\Lambda^0_b \to \Delta^+\pi^-) = -\delta^l_{\rm CP}(\Lambda^0_b \to \Sigma^{'-}K^+)\end{aligned} \tag{4}$$

In case of octet baryons in the final state, all of the $\delta_{\rm CP}$-relations [18] can be derived from U-spin symmetry,

$$\begin{aligned}\delta^l_{\rm CP}(\Lambda^0_b \to \Sigma^- K^+) &= -\,\delta^l_{\rm CP}(\Xi^0_b \to \Xi^-\pi^+),\\ \delta^l_{\rm CP}(\Lambda^0_b \to p^+\pi^-) &= -\,\delta^l_{\rm CP}(\Xi^0_b \to \Sigma^+ K^-),\\ \delta^l_{\rm CP}(\Xi^-_b \to n K^-) &= -\,\delta^l_{\rm CP}(\Xi^-_b \to \Xi^0\pi^-),\\ \delta^l_{\rm CP}(\Xi^-_b \to \Xi^- K^0) &= -\,\delta^l_{\rm CP}(\Xi^-_b \to \Sigma^-\overline{K}^0),\\ \delta^l_{\rm CP}(\Xi^0_b \to \Xi^- K^+) &= -\,\delta^l_{\rm CP}(\Lambda^0_b \to \Sigma^-\pi^+),\\ \delta^l_{\rm CP}(\Xi^0_b \to \Sigma^-\pi^+) &= -\,\delta^l_{\rm CP}(\Lambda^0_b \to \Xi^- K^+),\\ \delta^l_{\rm CP}(\Xi^0_b \to \Sigma^+\pi^-) &= -\,\delta^l_{\rm CP}(\Lambda^0_b \to p^+ K^-),\\ \delta^l_{\rm CP}(\Xi^0_b \to n\overline{K}^0) &= -\,\delta^l_{\rm CP}(\Lambda^0_b \to \Xi^0 K^0),\\ \delta^l_{\rm CP}(\Xi^0_b \to p^+ K^-) &= -\,\delta^l_{\rm CP}(\Lambda^0_b \to \Sigma^+\pi^-),\\ \delta^l_{\rm CP}(\Xi^0_b \to \Xi^0 K^0) &= -\,\delta^l_{\rm CP}(\Lambda^0_b \to n\overline{K}^0),\end{aligned} \tag{5}$$

Since, A_{CP} depends on the masses of the initial and final baryons as well as the outgoing meson [1, 2], some approximation is needed to obtain A_{CP} relations between various modes. In the U-spin limit, CP violation relations can be experimentally verified using the relation [29],

$$\frac{A_{\rm CP}(\mathcal{B}_{b,i} \to \mathcal{B}_j \mathcal{P}_k)}{A_{\rm CP}(\mathcal{B}_{b,l} \to \mathcal{B}_m \mathcal{P}_n)} \simeq -\frac{\tau_{\mathcal{B}_{b,i}}}{\tau_{\mathcal{B}_{b,l}}}\frac{\mathcal{BR}(\mathcal{B}_{b,l} \to \mathcal{B}_m \mathcal{P}_n)}{\mathcal{BR}(\mathcal{B}_{b,i} \to \mathcal{B}_j \mathcal{P}_k)}, \tag{6}$$

where i, j, k and l, m, n are indices corresponding to the various hadrons belonging to the above mentioned δ_{CP} relations. There is a further simplification in case $i = l$, resulting in

$$\frac{A_{\rm CP}(\mathcal{B}_{b,i} \to \mathcal{B}_j \mathcal{P}_k)}{A_{\rm CP}(\mathcal{B}_{b,i} \to \mathcal{B}_m \mathcal{P}_n)} \simeq -\frac{\mathcal{BR}(\mathcal{B}_{b,i} \to \mathcal{B}_m \mathcal{P}_n)}{\mathcal{BR}(\mathcal{B}_{b,i} \to \mathcal{B}_j \mathcal{P}_k)}, \tag{7}$$

where the uncertainties due to lifetime measurement also cancel out [17, 29]. These ratios serve as an important test of flavor $SU(3)$ symmetry in beauty-baryon non-leptonic decays and one can compare these findings with the analogous decays of bottom mesons to have a better understanding of the $SU(3)$ flavor symmetry breaking pattern.

III. FUTURE DIRECTIONS

A non-zero CP asymmetry measurement in b-baryons look promising and it is being pursued alongside B-meson decays at the LHCb. Such observations may provide complimentary information about the CP violating parameter in the quark sector of the Standard Model. While we have focused on two body b-baryon decays, one can also measure CP asymmetry in the final multibody state [6–8, 10, 11] which is often dominated by quasi two-body decays of a b-baryon into another baryon and vector meson. Measurements of CP-violation in regions of phase space using T-odd observables [23–25] have already been performed and new results with updated statistics are awaited.

[1] I. Dunietz, "CP violation with beautiful baryons," Z. Phys. C **56** (1992) 129.

[2] H. Y. Cheng, "Nonleptonic weak decays of bottom baryons," Phys. Rev. D **56**, 2799-2811 (1997)

[3] T. Aaltonen *et al.* [CDF], "Measurements of Direct CP Violating Asymmetries in Charmless Decays of Strange Bottom Mesons and Bottom Baryons," Phys. Rev. Lett. **106**, 181802 (2011)

[4] T. A. Aaltonen *et al.* [CDF], "Measurements of Direct CP -Violating Asymmetries in Charmless Decays of Bottom Baryons," Phys. Rev. Lett. **113**, no.24, 242001 (2014)

[5] R. Aaij *et al.* [LHCb Collaboration], "Observation of the $\Lambda^0_b \to \Lambda\phi$ decay," Phys. Lett. B **759**, 282 (2016)

[6] R. Aaij *et al.* [LHCb Collaboration], "Measurement of matter-antimatter differences in beauty baryon decays," Nature Phys. **13** (2017) 391

[7] R. Aaij *et al.* [LHCb Collaboration], "Measurement of branching fractions of charmless four-body Λ^0_b and Ξ^0_b decays," JHEP **1802** (2018) 098

[8] R. Aaij *et al.* [LHCb Collaboration], "Search for CP violation using triple product asymmetries in $\Lambda^0_b \to pK^-\pi^+\pi^-$, $\Lambda^0_b \to pK^-K^+K^-$ and $\Xi^0_b \to pK^-K^-\pi^+$ decays," JHEP **1808** (2018) 039

[9] R. Aaij *et al.* [LHCb Collaboration], "Search for CP violation in $\Lambda^0_b \to pK^-$ and $\Lambda^0_b \to p\pi^-$ decays," Phys. Lett. B **787**, 124 (2018)

[10] R. Aaij *et al.* [LHCb], "Measurements of CP asymmetries in charmless four-body Λ^0_b and Ξ^0_b decays," Eur. Phys. J. C **79**, no.9, 745 (2019)

[11] R. Aaij *et al.* [LHCb], "Search for CP violation and observation of P violation in $\Lambda^0_b \to p\pi^-\pi^+\pi^-$ decays," [arXiv:1912.10741 [hep-ex]].

[12] R. Aaij *et al.* [LHCb Collaboration], "Measurement of b hadron fractions in 13 TeV pp collisions," Phys. Rev. D **100** (2019) no.3, 031102

[13] "Report from Working Group 4," CERN Yellow Rep. Monogr. **7**, 867-1158 (2019)

[14] C. D. Lu, Y. M. Wang, H. Zou, A. Ali and G. Kramer, "Anatomy of the pQCD Approach to the Baryonic Decays $\Lambda_b \to p\pi$, pK," Phys. Rev. D **80** (2009) 034011

[15] Y. K. Hsiao and C. Q. Geng, "Direct CP violation in Λ_b decays," Phys. Rev. D **91** (2015) no.11, 116007

[16] M. Gronau and J. L. Rosner, "Flavor SU(3) and Λ_b decays," Phys. Rev. D **89** (2014) no.3, 037501 Erratum: [Phys. Rev. D **91** (2015) no.11, 119902]

[17] X. G. He and G. N. Li, "Predictive CP violating relations for charmless two-body decays of beauty baryons $\Xi_b^{-,0}$ and Λ_b^0 with flavor SU(3) symmetry," Phys. Lett. B **750**, 82 (2015)

[18] S. Roy, R. Sinha and N. G. Deshpande, "Nonleptonic beauty baryon decays and CP asymmetries based on an SU(3) -flavor analysis," Phys. Rev. D **101**, no.3, 036018 (2020)

[19] A. Dery, M. Ghosh, Y. Grossman and S. Schacht, "SU$(3)_F$ analysis for beauty baryon decays," JHEP **03**, 165 (2020)

[20] S. Roy, R. Sinha and N. G. Deshpande, "Beauty baryon non-leptonic decays into decuplet baryons and CP-asymmetries based on $SU(3)$-Flavor analysis," [arXiv:2006.16813 [hep-ph]].

[21] R. Aaij *et al.* [LHCb], "Searches for Λ_b^0 and Ξ_b^0 decays to $K_S^0 p\pi^-$ and $K_S^0 pK^-$ final states with first observation of the $\Lambda_b^0 \to K_S^0 p\pi^-$ decay," JHEP **04**, 087 (2014)

[22] R. Aaij *et al.* [LHCb Collaboration], "Observations of $\Lambda_b^0 \to \Lambda K^+\pi^-$ and $\Lambda_b^0 \to \Lambda K^+K^-$ decays and searches for other Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+h'^-$ final states," JHEP **1605**, 081 (2016)

[23] W. Bensalem, A. Datta and D. London, "T violating triple product correlations in charmless Lambda(b) decays," Phys. Lett. B **538**, 309-320 (2002)

[24] G. Durieux and Y. Grossman, "Probing CP violation systematically in differential distributions," Phys. Rev. D **92**, no.7, 076013 (2015)

[25] G. Durieux, "CP violation in multibody decays of beauty baryons," JHEP **10**, 005 (2016)

[26] I. Bediaga and C. Gbel, "Direct CP violation in beauty and charm hadron decays," Prog. Part. Nucl. Phys. **114**, 103808 (2020)

[27] T. Brown, S. F. Tuan and S. Pakvasa, "CP Nonconservation in Hyperon Decays," Phys. Rev. Lett. **51** (1983) 1823.

[28] M. J. Savage and R. P. Springer, "SU(3) Predictions for Charmed Baryon Decays," Phys. Rev. D **42** (1990) 1527.

[29] M. Gronau, "U spin symmetry in charmless B decays," Phys. Lett. B **492** (2000), 297-302