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CP Asymmetry Measurements with Charmed Baryons

Thematic Area(s):

■ (RF01) Weak Decays of b and c

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Abstract:

With the massive data sets available at precision experiments over the next decade, it will be possible to explore new sectors and decay modes to make detailed studies of CP asymmetries in an effort to expose physics Beyond the Standard Model (BSM). One potential avenue that is as of yet unexploited is searching for CP violation in charmed baryon decays, wherein CP violation is expected to be small so significant CP asymmetries may indicate the BSM contributions.

One of the most significant remaining mysteries in particle physics is the possible existence of additional sources of CP violation, which is a necessary condition to explain baryogenesis. It is likely that additional sources exist, given that CP violation in the SM is insufficient to explain the matter-antimatter asymmetry of the universe[1]. While well established in the kaon[2] and beauty[3;4] sectors, CP violation was only recently established in a single measurement by the LHCb Collaboration, which measured the CP asymmetry difference between D^0 decays to K^+K^- and $\pi^+\pi^-$[5]. This measurement is consistent with, though at the upper range of, SM predictions of small CP violation in the charm sector, on the order of $10^{-4} - 10^{-3}$[6;7]. Studying CP asymmetries in additional modes will provide a greater ability to clarify the potential for BSM contributions, since any new physics may couple differently to different quarks. This is particularly true for CP studies of decays in which the dynamics involved are significantly different. Thus, a natural extension of existing CP studies is to search for CP violation in the charmed baryon sector, which remains largely unexplored and in which the decay dynamics are significantly different than for meson decays.

The recent measurement by the LHCb collaboration of CP asymmetries in beauty baryon decays[8;9] has opened a window into CP studies in baryon decays. A natural extension of these studies is to look into the charmed baryon system. Since CP violation in the charm system is expected to be much smaller than in the beauty sector, any significant CP asymmetries may indicate the presence of new sources of CP violation. The LHCb collaboration made a first study of CP asymmetries in Λ_c^+ decays to pK^-K^+ and $p\pi^+\pi^-$, finding a difference of $(0.30 \pm 0.91 \pm 0.61)\%$[10]. Additional studies of other modes are important to fully explore CP violation in the charmed baryon system.

The discovery of CP violation in the charmed meson system focused on decays of D^0 mesons that are connected by U-spin sum rules, which extends the idea of isospin to create an SU(2) subgroup of flavor SU(3) and forms a doublet of d and s quarks. Given their usefulness in CP studies of charmed meson decays, U-spin sum rules might be expected to indicate prime targets for CP studies in the charmed baryon sector. According to Grossman and Schacht[11], the Λ_c^+ decays studied by LHCb are not connected by a U-spin sum rule. However, they are related to Ξ_c decays according to

$$A_{CP}(\Lambda_c^+ \to pK^-K^+) + A_{CP}(\Xi_c^+ \to \Sigma^+\pi^-\pi^+) = 0 \tag{1}$$

$$A_{CP}(\Lambda_c^+ \to \Sigma^+\pi^-K^+) + A_{CP}(\Xi_c^+ \to pK^-\pi^+) = 0, \tag{2}$$

$$A_{CP}(\Lambda_c^+ \to p\pi^-\pi^+) + A_{CP}(\Xi_c^+ \to \Sigma^+K^-K^+) = 0. \tag{3}$$

Notably, these decays include a Σ^+ baryon, which decays almost exclusively into $\pi^0 p$ or $\pi^+ n$[12]. This makes such decays difficult to study at LHCb, which suffers from poor neutral reconstruction. However, Belle II can efficiently reconstruct neutral final state particles, giving it unique accessibility to prime candidates for BSM physics searches in charmed baryon decays. Additional Singly Cabibbo-suppressed (SCS) decays of charmed baryons can be similarly explored with the massive data sets at LHCb and Belle II.

Studies of CP asymmetries are typically complicated by detector-based effects such as reconstruction efficiencies and production asymmetries, which can skew raw asymmetries and must be carefully considered. LHCb measures differences in raw asymmetries, in order to cancel out production and detector-based effects. Belle II, which uses electron-positron collisions, enables a better disentanglement of detection and production asymmetries from the CP asymmetries than is possible at LHCb[5;13]. In particular, it will be possible at Belle II to directly measure forward-backward asymmetries, as well as reconstruction-based asymmetries, which can be used as input to determine the direct CP asymmetry in the amplitude. One of the strongest benefits for measuring CP asymmetries at e^+e^- machines is that the production asymmetry must be an odd function of the polar angle of the mother particle produced at the interaction point, which means it is possible to disentangle the production asymmetry by making measurements as a function of the absolute value of the polar angle. The offset from zero can be used to measure the CP asymmetry in the amplitude. Therefore, with Belle II data, it will be much more straightforward to measure individual CP asymmetries of Cabibbo-suppressed (CS) decays, for which theorists are eager, rather than CP asymmetry differences.

While using the total number of decays for the final states of interest to determine A_{CP} is the most straightforward means to measure CP asymmetries, resonant substructure often dominates three-body decays. CP asymmetries may be dependent on this substructure, which can be used to achieve greater precision through an amplitude analysis. This analysis method determines the amplitudes for resonant decays, which can be used to determine the number of events across the Dalitz plot and measure A_{CP} as a function of the phase space for the decay[14–16].

Another type of measurement to study CP violation is through triple product asymmetries[18–20]. One constructs asymmetries involving products of the type $T.P = \vec{v_1} \cdot (\vec{v}_2 \times \vec{v}_3)$, where the $\vec{v}_{1,2,3}$ are momenta or polarizations of the final state particles. One can construct an asymmetry as $A_T \sim N(T.P > 0) - N(T.P < 0)$ where $N(T.P < (>)0)$ are the number of events with $T.P$ less than or greater than 0. To construct a true CP asymmetry one has to compare the triple product asymmetries for the particle and antiparticle decays. This true CP asymmetry can be non-zero even with vanishing strong phases unlike the direct CP violating asymmetry. The triple product asymmetries can also be extracted from the angular distribution of the final particles[21].

Though the first charmed baryon was discovered about 40 years ago[17], detailed studies of charmed baryons remain relatively scarce. Many modes are missing or poorly measured and resonant substructure in charmed baryon decays is largely unexplored, particularly for CS decays[12]. This relative dearth of knowledge makes detailed studies of CP violation in charmed baryon decays quite challenging, as differences across phase space must be ignored, thereby potentially weakening the evidence for CP asymmetries. This highlights the importance of investigations of resonant substructure in charmed baryon decays, which is a rich source of interesting physics in itself. The lowest lying excited baryon system is expected to contain several exotic candidate states with degrees of freedom beyond that accessible in a traditional three quark state. These spectra also contain many missing and poorly measured states, with few quantum number determinations. Thus, studies of resonant substructure in charmed baryon decays provide a fertile source of early physics results, while also creating a foundation for detailed studies of CP violation in the charmed baryon system.

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