CP Violation in Charmed and Bottom Baryon Physics

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This is an experimentalist’s view of the recent results on, and prospects for, CP Violation in charmed and bottom baryons.

I. INTRODUCTION

The phenomenon of CP violation has been discussed in several contributions to this conference already. However, these studies have focussed on mesons. Studies of baryon decays are usually one or decades behind those of mesons, but in CP violation the situation is even more difficult. Whereas in neutral mesons there can be mixing between particle and anti-particle, and two distinct interfering amplitudes which can produce time-dependent CP violation, baryon number is a very strong constraint and the window provided by mixing is not available. This means that any CP violation in baryons needs to be direct. However, though the difficulties are many, the prize is great. If we want to understand why we are here today (and made out of matter), we need to understand CP violation in baryons.

This is an experimentalist’s review of recent results on, and prospects for, CP violation studies in charmed and bottom baryons.

II. THE EXPERIMENTS

It is no surprise to find that the two featured current experiments are LHCb (representing the “energy frontier” of pp collisions), and Belle II (representing the “intensity frontier” of $e^+e^-$ annihilation).

Table I shows the comparison between the two. The first and last rows show huge benefits of LHCb. These are partly compensated by the other entries in the table, which means that there will be a complementarity of approaches in the next few years.

<table>
<thead>
<tr>
<th>Particles produced</th>
<th>Includes b baryons</th>
<th>Only c and s</th>
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This analysis is presented in [1]. The signal is around 500 events. As CP violation is expected to be enhanced in the baryon resonance region, the analysis performs a fit to the entire Dalitz plot taking into account the six excited $\Lambda$ and $\Sigma$ resonances tabulated in the Particle Data Book [2] in the region 1.4-2.0 GeV/$c^2$, searching for a significant difference between particle and anti-particle. The results are that there is no significant CP violation in any of the six quasi-two-body decays. The statistical uncertainties are large (not surprising when several resonances are barely significant), and so will improve with more data. The systematic uncertainties will also improve.

III. LHCb SEARCH FOR CP VIOLATION IN $\Xi_b \rightarrow pK^-K^-$

Why look at this mode? Interference between two amplitudes with different weak and strong phases leads to CP violation in decay. Weak phases are associated with the complex elements of the CKM matrix. Strong phases associated with hadronic final-state effects. In general, the common decays of $b$ hadrons to charm quarks have one amplitude that dominates and so there is no useful interference between amplitudes to use for CP violation studies. This is similar to the situation in meson decays.

This is a suppressed decay mode and comes in different varieties. The one that is interesting is $\Lambda_c^0 \rightarrow [K^+\pi^-]_D pK^-$ where the kaons have different charges. Note that we do not specify whether the $K\pi$ is a $D$ or a $D^*$ as both can contribute. This decay has contributions both from $b \rightarrow c$ and $b \rightarrow u$ which are of the same order of magnitude, and an interference that depends on the CKM angle $\gamma$.

What is measured is the asymmetry:

\[ A = \frac{(B_{\text{particle}} - B_{\text{antiparticle}})}{(B_{\text{particle}} + B_{\text{antiparticle}})} \]

where $B_{\text{particle}} = B(\Lambda_b^0 \rightarrow [K^+\pi^-]_D pK^-)$ and $B_{\text{antiparticle}} = B(\bar{\Lambda}_b^0 \rightarrow [K^-\pi^+]_D pK^+)$.

Note that the interference is anticipated to be larger in regions.
of phase space that involve excited $\Lambda$ states.

The analysis is presented in [3]. The measured CP asymmetries are:

$$A_{CP} = 0.12 \pm 0.09^{+0.02}_{-0.03} (\text{stat}) - 0.03 (\text{syst.})$$

and

$$A_{CP} = 0.01 \pm 0.16 (\text{stat})^{+0.02}_{-0.03} (\text{syst.})$$

where this first is integrated over all phase-space and the second in the low-mass (resonance) $pK$ region. The conclusion is that there is no evidence of CP violation.

V. LHCb SEARCH FOR CP VIOLATION IN $\Lambda^0 \to D\pi^-\pi^+\pi^-$

There are two methods now in use to analyze this decay mode, which has the benefit of relatively high statistics [4]. The first uses “scalar triple products”, defined in [5], which involve the momentum correlation between the proton, the positive pion and the “faster” of the negative pions, and the analogs for antiparticles.

$$C = \vec{p}_p \cdot (\vec{p}_\pi^- \times \vec{p}_\pi^+)$$

$$\bar{C} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$$

The data is then divided into four pieces, each with yields N (i.e. divide by two by particle/antiparticle, and again by 2 according to the sign of the scalar triple product.

The Triple Product Asymmetry is then defined for particles and antiparticle:

$$A = \frac{N(\Lambda_T > 0) - N(\Lambda_T < 0)}{N(\Lambda_T > 0) + N(\Lambda_T < 0)}$$

$$\bar{A} = \frac{\bar{N}(\bar{\Lambda}_T > 0) - \bar{N}(\bar{\Lambda}_T < 0)}{\bar{N}(\bar{\Lambda}_T > 0) + \bar{N}(\bar{\Lambda}_T < 0)}$$

where these two would be the same if there is no CP violation. Then, the CP violating piece looked for is defined as:

$$a_{CP} = \frac{1}{2}(A - \bar{A})$$

Integrated over all phase-space they find $a_{CP} = (-0.7 \pm 0.7 \pm 0.2)$% which is clearly consistent with zero.

Once again there is the expectation that any CP violation will be in any area of phase-space dominated by resonances, and here there are two sorts of resonances - excited nucleons ($N^*$), and excited mesons (e.g. $\alpha_1$). Each of these preferred regions are then divided into bins dependent on the relative angles of the final state particles.

The biggest discrepancy from the non-CPV expectation is found in the $N^*$ enhanced sample when plotted in terms of the angle between the decay planes of the $(\pi^+\pi^-)_\text{slow}$ and $(p\pi^-)_\text{fast}$. This discrepancy is of 2.9 $\sigma$ significance. A previous version of this analysis provided some excitement as it found 3.3 $\sigma$ significance on 25% of the dataset, but the extra data has not enhanced the effect.

LHCb have also analyzed the data in a less model-dependent manner using independent unbinned tests [6]. Again, no significant evidence of CP violation has been found.

VI. CP VIOLATION SEARCHES USING CHARMED BARYONS

The charm sector has some experimental advantages over the B sector. One is the complementary datasets available in $e^+e^-$ annihilations, and the other is the comparatively low multiplicities in the final states.

The basic research thrusts comprise choosing a suitable decay mode and measuring its branching fraction, measuring the asymmetry parameter, $\alpha$ defined below, and then measuring the difference in asymmetry parameters in particles and anti-particles. Once again, no measurable CPV is expected in 2-body Cabibbo-favored decays, and singly-Cabibbo-suppressed decays are a more promising laboratory, with effects of order $10^{-3}$ to be expected.

Typical decay modes that we can hope to produce interesting results are $\Lambda^+_c \to \Lambda K^+$ and $\Lambda^+_c \to \Sigma^0 K^+$ which have measured branching fractions of $(6.1 \pm 1.2) \times 10^{-4}$ and $(5.2 \pm 0.8) \times 10^{-4}$ respectively. In $e^+e^-$ machines these (particularly the former) can be detected with good efficiency and purity.

In decays of $\Lambda^+_c$ to a baryon and pseudo-scalar meson, the $\alpha$ parameter is defined to be: $\alpha = \frac{2Re(s/p)}{|s|-|p|}$ where $s$ and $p$ are the parity-violating s-wave and the parity-conserving p-wave amplitudes. Operationally, for a decay such as $\Lambda^+_c \to \Lambda K^+$, we define an angle $\theta_\Lambda$, which is the angle between the proton momentum in the $\Lambda$ frame and the $\Lambda$ in the $\Lambda^+_c$ frame. The data is divided into bins of $cos(\theta_\Lambda)$, and then use the equation:

$$dN/dcos\theta_\Lambda \propto 1 + \alpha(\Lambda^+_c \to \Lambda K^+)\alpha(\Lambda \to p\pi^-)cos\theta_\Lambda$$

In other words, split the data into bins of $cos\theta_\Lambda$, fit the mass peak in each plot, find the slope and extract the product of the $\alpha$ parameters ($\alpha$ for a $\Lambda$ is well-known).

The $\alpha$ parameters are found separately for particles and antiparticles, and then the CP-violating parameter defined as:

$$A_{CP}^\alpha = \frac{\alpha(\Lambda^+_c) + \alpha(\Lambda^-_c)}{\alpha(\Lambda^+_c) - \alpha(\Lambda^-_c)}$$

The $\alpha$ parameters are interesting in their own right, as they are parameters, along with the partial width, that can in principle be predicted theoretically in different models of weak decays. However, until recently, neither the experimental measurements or the theoretical models were of sufficient quality for such comparisons to be meaningful. However, the situation is changing. For example, in 2001 CLEO measured $\alpha$ for $\Xi^- \to \Xi^-\pi^+$ to be $-0.56 \pm 0.39^{+0.10}_{-0.09}$, but that paper did not receive a single citation for the first eight years! Recently, BELLE [7] measured $\alpha$ for particles and anti-particles and found $A_{CP}^\alpha = 0.024 \pm 0.052 \pm 0.012$. This, of course is a Cabibbo-allowed decay and finding CP violation in such a mode would be a major surprise. However, in the Cabibbo-suppressed modes $\Lambda^+_c \to \Lambda K^+$ and $\Lambda^+_c \to \Sigma^0 K^+$ precisions of the order
of 0.1 and 0.3 would seem to be attainable for each 1 $ab^{-1}$ of data (i.e. the already taken Belle dataset). Although this may not be sufficient, the prospect of 50 $ab^{-1}$ Belle II data opens realistic possibilities for these and other similar modes.

VII. LHCb MEASUREMENTS IN $\Lambda_c^+ \to phh^-$

These, with $h = \pi$ or $K$, are two Cabibbo-suppressed decays of the $\Lambda_c^+$, and the big challenge is to understand the detection efficiency of protons and anti-protons. One way of avoiding this [9] is to use two related decays and compare them. That is, instead of

$$A_{CP}(f) = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})}$$

use

$$A_{Raw} = \frac{N(f) - N(\bar{f})}{N(f) + N(\bar{f})}$$

where $f$ refers to a specific final state and $N$ is the number detected.

Then we can say that the difference in the $A_{Raw}$ parameters will be a good approximation to the difference of the $A_{CP}$ parameters.

Although the raw asymmetries of the two modes are significantly non-zero, the difference is $\Delta_{CP} = (0.30 \pm 0.91 \pm 0.61)\%$ and therefore there is no evidence of CP violation.

VIII. LHCb MEASUREMENTS IN $\Xi_c^+ \to K^+\pi^-$

This Cabibbo-suppressed decay is a very useful one for LHCb as the statistics are very high and the background suppression good [10]. The Cabibbo-allowed decay of $\Lambda_c^+ \to pK^-\pi^+$ is used as a control. The substructure of these decays are very rich, and CP violation, if it exists in these modes, is likely to depend on where in the Dalitz plot the decay lies. Two different analysis techniques are used. One is binned into areas of the Dalitz plot, searching for localized differences in the plots for baryons and anti-baryons. The second is unbounded. However, no significant differences are found between baryons and anti-baryons, and the results are consistent with the hypothesis of no CP violation.

IX. CONCLUSIONS

I have reviewed a number of searches for CP violation in charmed baryon baryons. No significant violation has been observed. However, the sensitivity is not at the level that this is a surprise.

It is clear that more predictions for specific decay modes for CPV would be very useful. I expect in the next few years to have more measurements of the asymmetry parameter, $\alpha$, which are interesting in their own right and can lead to measurements of CP violation. I would like to point out that many of the searches involve knowledge of the excited hyperons in the substructure of the heavy baryon decays. Research in the area of excited hyperons is under-appreciated. However, clearly the biggest challenge in the next decade is to collect big enough datasets that comparatively rare decays can be studied with good statistics.

Acknowledgments

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