Symmetry violations at *BABAR*

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Abstract. Following a brief introduction I report the current status of symmetry violation tests from the *BABAR* experiment, including recent results on the measurement of T violation, and searches for CP and T violation in mixing.

1. Introduction

The study of the discrete symmetries C (charge conjugation), P (parity), CP, T (motion reversal), and CPT has provided many insights as to the underlying structure of the weak interaction. Noether's theorem reminds us that in general we expect that exact symmetries in nature relate to conservation laws. Hence, any conserved symmetry should lead to a corresponding conservation law that underpins some physical phenomenon. Likewise symmetry violation would lead to the consequence that the conservation law did not work exactly, but was at best a rule of thumb that may be used to make estimates with some degree of uncertainty regarding the accuracy of any conclusion inferred; for example SU(3) falls into this category of symmetry. The symmetries C and P are known to be broken, and the violation of parity discovered by Wu in 1957 [1] was the first experimental signal of how important it was to understand violation of these symmetries for weak interactions. Parity violation led inextricably to the $V - A$ structure of the weak interaction in the Standard Model of particle physics. The fact that there are weak decays to flavour specific final states also highlights the presence of C violation. However a remarkable thing at that time was that CP was found to be conserved. Hence the large violation of parity and charge conjugation was such that it balanced in the combination CP. This assertion remained true until 1964, when Cronin, Fitch, Christenson and Turlay discovered CP violation in neutral kaon decay as a consequence of trying to improve our understanding of regeneration [2]. It was quickly noted by Sakharov as to how important CP violation was for cosmology [3]. Without C and CP violation the matter and antimatter manifest in the big bang would annihilate each other and the residual Universe would have been devoid of the large imbalance that we observe today. It is interesting to note that since that discovery we have found several other manifestations of CP violation, and also tested the level of T violation. However it took 45 years from the initial discovery for direct CP violation to be found in kaons [4][5]. A few years after this, large (10% level) CP violation was found studying the longitudinal polarisation basis of a rare K^0_L decay to a four body final state [6][7]. On the theoretical side a model of CP violation was proposed by Kobayashi and Maskawa, building on earlier work concerning quark mixing by Cabibbo [8][9]. With hindsight, after several decades of detailed experimentation, it turns out that this model is the correct leading order description of CP violation in the SM. It is worth noting that just as in the case of C and P violations balancing to conserve *CP* (most of the time), that the measured levels of *CP* and *T* violation balance such that overall *CPT* is conserved. The ramifications of *CPT* conservation include Lorentz invariance, which underpins our understanding of modern physics. At some energy scale it is expected that quantum effects will become important when trying to describe space-time, and a consequence of this would be Lorentz violation, and hence *CPT* violation. Thus far however, experimental evidence continues to support both Lorentz and *CPT* invariance. The remainder of these proceedings focus on the *B* Factory tests of these discrete symmetries from the perspective of *BABAR* results, with a brief historical interlude followed by more recent results. The avid reader should refer to the Physics of the *B* Factories for more details [10].

2. *CP* violation in *B* meson decay

The *B* Factories, the *BABAR* experiment and PEP-II collider at the SLAC National Accelerator Laboratory and the Belle experiment and KEKB collider at KEK, were built to discover *CP* violation in the decay of neutral *B* mesons. This primary goal drove the teams building those experimental facilities to build in safety margins in order to be sure that the mission would be accomplished, even if *CP* violation turned out to be much smaller than expected by many theorists of the day. Nature was kind, and in 2001 *BABAR* unveiled results showing *CP* violation in the decay of a b quark to a $c\bar{c}s$ final state (modes such as $B \to J/\psi K_S^0$, and $J/\psi K_L^0$ were included in this discovery). That was quickly confirmed by Belle, firmly establishing that indeed *CP* violation was exhibited in *B* decay, and that it was large. These two results were published as back-to-back articles in Phys. Rev. Lett. [11][12]. In contrast with kaons, it only took a further two years before direct *CP* violation was established in *B* decays via the decay $B \to K^{\pm}\pi^{\mp}$. Both *CP* violation in the interference between mixing and decay amplitudes and direct *CP* violation turned out to be order one effects in *B* decays, in contrast to the $10^{-3} - 10^{-6}$ levels seen in kaons. The foresight that led to including safety margins in the design of the *B* Factories has resulted in a richer and broader physics programme than originally envisaged.

3. Other symmetry tests in *B* meson decay

Banuls and Bernabeu proposed using entangled pairs of *B* mesons to test *T*, *CP*, and *CPT* asymmetries [13] as a generalisation of the Kabir asymmetry measurement proposed in 1970 [14] that used only a flavour filter basis. Using two pairs of orthonormal states, one based on b-quark flavour and one based on *CP* eigenvalue, *BABAR* are able to measure 12 asymmetries of which there are four distinct tests of each of *T*, *CP*, and *CPT* [15]. The methodology relies on comparing some reference process with that of the symmetry conjugated one as a function of proper time between two events for the entangled pair of mesons evolving into their flavour and *CP* decay filters. The first event is marked by the collapse of the entangled wave function (at some time t_1) which coincides with the decay of one of the *B* mesons in the entangled pair, and the second event is marked by the decay of the remaining *B* (at time t_2). For example one of the four tests of *T* involves comparing the time-dependent ($t_2 - t_1 > 0$) rate of $\overline{B}^0 \to B_-$ with that of the conjugate transition $B_- \to \overline{B}^0$.[1] The standard *BABAR* flavour tagging techniques developed for the *CP* violation discovery measurement are used in order to select B^0 and $\overline{B}^0$ mesons, and the selection of *CP* even and *CP* odd filter basis pairs, for $b \to c\bar{c}s$ transitions differ by a K_L^0 vs a K_S^0 in the final state (see for example [16]). As reported in [15], the *BABAR* data are consistent with both *CP* and *T* violation, whilst *CPT* is conserved. The significance reported for the observation of *T* violation (assuming Gaussian uncertainties) exceeds 14σ. Thus the level of *CP* and *T* violation balance each other. A number of related measurements have recently been

[1] Here the $-(1)$ subscript refers to the *CP* eigenvalue of the *B* decay filter; in this case it is *CP* odd, corresponding to $J/\psi K_S^0$. The other pairings of reference and transformed transitions can be found in Refs. [13][15].

proposed [17][18] and Ref. [19] is a recent review on T violation measurements in mesons, which may be of interest to the reader.

Using only a flavour filter basis pair one can define two additional asymmetries. One of these is the Kabir asymmetry, which tests CP and T (in mixing), and the other tests CP and CPT. The corresponding asymmetry is given by

$$A_{CP,T} = \frac{\Gamma(\overline{B}^0 \to B^0) - \Gamma(B^0 \to \overline{B}^0)}{\Gamma(\overline{B}^0 \to B^0) + \Gamma(B^0 \to \overline{B}^0)} = \frac{1-|q/p|^4}{1+|q/p|^4} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}, \tag{1}$$

where q and p are parameters related to mixing and N^{++} and N^{--} are event yields. The SM expectation for $A_{CP,T}$ is $(-4.0 \pm 0.6) \times 10^{-4}$ [20][21][22], which is beyond current experimental reach, however large enhancements are possible in the presence of physics beyond the SM (c.f. the D0 measurement of this quantity for B_s mesons [23][24]). Traditional measurements searching for CP (and T) violation in mixing use semileptonic decays of B mesons (see for example Section 17.5 of [10]). The experimental signature typically used for this measurement is a pair of semi-leptonic decays reconstructed with same sign leptons, as the first meson decays to fix the initial flavour of the un-decayed B, and that meson subsequently mixes before decay. However those results are systematically limited by the size of control samples to estimate the level of wrong sign events. As a consequence it is interesting to attempt other ways of performing the same test. BABAR have recently performed a measurement using a combination of hadronic and semi-leptonic tags in order to explore an experimentally distinct final state with the hope of bypassing the traditional systematic limitations. The semi-leptonic decay $B^0 \to D^{*-}X\ell^+\nu$ with a partially reconstructed $D^{*-} \to \pi^-\overline{D}^0$ is used for this measurement where the asymmetry between ℓ^+ and ℓ^- observed in data includes the effect of B mixing, and of charge reconstruction bias in the detector, both of which have to be corrected for in order to determine $A_{CP,T}$. Hadronic B decays used in this analysis are "kaon tagged" events, where a neutral B meson decays into a final state with a charged kaon. The charge asymmetry observed in data for these events, in addition to including an overall detector bias, has a correction from the asymmetry in reconstructing the charged kaon, arising from the difference in nuclear cross sections of K^+ and K^- in detector material. The measured value of $A_{CP,T}$ is $(0.06 \pm 0.17^{+0.38}_{-0.32})\%$, which is compatible with expectations. However, the uncertainties are considerably larger than the SM level and dominated by systematic uncertainties associated with peaking background contributions and the Δt (the proper time difference between the decay of the semi-leptonic and hadronic B decays in the event) resolution function model. Hence these uncertainties can be further reduced with input from larger data samples in the future.

BABAR has also measured CP asymmetries for a number of rare decays, and the contribution by Simon Akar to these proceedings gives a review of some of those recent measurements.

4. Symmetry violation searches in charm decay

BABAR has also searched for CP violation in charm decays. The details can be found in [10], where time-integrated and time-dependent analyses have been performed. In recent years there has been a resurgence of interest in this area for two reasons (i) charm mixing is now firmly established, which sets the scale for mixing-dependent effects to be manifest and opens the door for such measurements, and (ii) in 2011 LHCb reported time-integrated CP asymmetry difference between $D \to K^+K^-$ and $\pi^+\pi^-$ modes that was non trivial. The latest results are compatible with no evidence for CP violation [25]. There is also interest in the study of triple product asymmetries that probe CP violation using the longitudinal polarisation basis of a decay (c.f. kaon decays), in particular the decay modes $D^0 \to K^+K^-\pi^+\pi^-$, $D^+ \to K^0_S K^+\pi^+\pi^-$, and $D^+_s \to K^0_S K^+\pi^+\pi^-$ have been studied [26][27]. The results are consistent with CP conservation, in line with expectations that the charm system exhibits small weak phase differences in the

SM, hence small levels of *CP* violation. A recent re-analysis of the *BABAR* data was presented at CKM '14 [28] using the methodology introduced in Ref. [29]. This shows non-trivial C and P violations for the D^0 and D_s^+ decay, but not for D^+. These results may ultimately yield deeper insights on the weak interaction and hadronisation.

5. The search for *CP* violation in τ decay

Searches for *CP* violation are not confined to quark interactions and following CLEO and Belle's lead, *BABAR* has measured the direct *CP* asymmetry of $\tau^+ \to K_S^0 \pi^+ \nu$. A non-trivial level of *CP* violation is expected as a result of the neutral kaon in the final state, as well as K_S^0-K_L^0 interference and regeneration effects. The result obtained $A_{CP} = (-0.36 \pm 0.23 \pm 0.11)\%$ is compatible with no evidence for *CP* violation, however this lies 2.8σ from the SM expectation of $+0.36\%$ [30].

6. Summary

In summary *BABAR* has performed many interesting tests of discrete symmetries for B, D, and τ decays, and has observed several symmetry violations in meson decay. While *BABAR* stopped taking data several years ago, it is still producing results that are competitive and able to teach us something new about the behaviour of the weak interaction and of these discrete symmetries.

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