

Testing discrete symmetries at a super τ -charm factory

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Tests of discrete symmetry violation have played an important role in understanding the structure of weak interactions in the Standard Model of particle physics. Historically, these measurements have been extensively performed in experiments with large samples of K and B mesons. A high luminosity τ -charm facility presents physicists with the opportunity to comprehensively explore discrete symmetry violation and test the Standard Model using τ leptons, charm mesons, and charmed baryons. This paper discusses several possible measurements for a future τ -charm factory.

Keywords discrete symmetries, P , C , T , CP , CPT violation

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[2]. Following these discoveries, there was an interest in trying to validate T independently of CPT . Although it was recognized that CPT conservation was desirable given the prior evidence available, it was noted that testing T independently of CPT was important [3]. It is possible to test the full set of discrete symmetries using triple-product asymmetries and entangled pairs of neutral mesons. This paper discusses the potential for a super τ -charm facility for testing discrete symmetries using τ leptons, charm mesons, and charm baryons produced near threshold. A number of routes toward CP violation measurements in charm decays are under study in the literature and have been discussed at length elsewhere, for example, in Refs. [4–6]; here we review additional possibilities for probing discrete symmetries that complement the traditional routes.

The remainder of this paper discusses the use of triple-product asymmetries with four-body decays to test C , P , and CP (Section 2) and the use of entangled pairs of D mesons produced in the decay of $\psi(3770)$ mesons to test CP , T , and CPT (Section 3). Finally, Section 4 summarizes this paper. The data sample assumed for a super τ -charm facility is 1 ab^{-1} , which corresponds to $10^9 \psi(3770)$ [$10^8 \psi(4040)$] mesons for $D^{0,\pm}$ (D_s^\pm) pair production. Facilities capable of producing these sample sizes are under investigation, for example, the proposed High Intensity Electron Positron Accelerator in China.

1 Introduction

The Standard Model (SM) of particle physics describes weak, strong, and electromagnetic interactions. The weak interaction is known to violate the discrete symmetries C , P , and T and the combination CP . The combination CPT is observed to be conserved. Strong and electromagnetic interactions conserve these symmetries. Parity violation was discovered in 1957 [1], and CP violation was discovered a few years later in 1964

2 Triple-product asymmetry measurements

If one considers the decay of some particle M to a four-

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body final state $abcd$ and the CP conjugate process $\overline{M} \rightarrow \overline{abcd}$, the decay planes defined by the four vectors (or spins) of pairs of final-state particles can be used to construct a scalar triple product that allows us to probe the symmetry-violating nature of the decay; for example, see Refs. [7, 8]. The scalar triple product can be written as $\psi = \vec{p}_c \cdot (\vec{p}_a \times \vec{p}_b)$, where \vec{p}_i , $i = a, b, c$ are particle momentum vectors computed in the rest frame of M . We can study data in terms of the sign of ψ or as a function of the angle ϕ between the decay planes formed by ab and cd in the reference frame of the decaying particle. The angle ϕ is used when the underlying amplitudes in the decay are known sufficiently well to allow experimenters to understand whether the interesting asymmetries are functions of $\sin \phi$ or $\sin 2\phi$. A number of measurements have been made in terms of the sign of the triple product. Following this generic approach, we define Γ_{\pm} as the rate at which M decays to a state with $\psi > 0$ (+) or < 0 (-). The corresponding rates for antiparticles are given by $\overline{\Gamma}_{\pm}$.

Twelve asymmetries can be constructed by considering Γ_{\pm} and $\overline{\Gamma}_{\pm}$ [8]. The first six are derived by considering the P , C , and CP operators acting on the four types of Γ . These yield

$$A_P = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}, \quad \overline{A}_P = \frac{\overline{\Gamma}_+ - \overline{\Gamma}_-}{\overline{\Gamma}_+ + \overline{\Gamma}_-}, \quad (1)$$

$$A_C = \frac{\overline{\Gamma}_- - \Gamma_-}{\overline{\Gamma}_- + \Gamma_-}, \quad \overline{A}_C = \frac{\overline{\Gamma}_+ - \Gamma_+}{\overline{\Gamma}_+ + \Gamma_+}, \quad (2)$$

$$A_{CP} = \frac{\overline{\Gamma}_+ - \Gamma_-}{\overline{\Gamma}_+ + \Gamma_-}, \quad \overline{A}_{CP} = \frac{\overline{\Gamma}_- - \Gamma_+}{\overline{\Gamma}_- + \Gamma_+}. \quad (3)$$

Here the subscript indicates the symmetry being tested. One can construct an additional six asymmetries considering the remaining permutations, where the superscript denotes the original symmetry considered, and the subscript denotes the subsequent permutation:

$$\begin{aligned} a_C^P &= \frac{1}{2} (A_P - \overline{A}_P), \\ a_{CP}^P &= \frac{1}{2} (A_P + \overline{A}_P), \\ a_P^C &= \frac{1}{2} (A_C - \overline{A}_C), \\ a_{CP}^C &= \frac{1}{2} (A_C + \overline{A}_C), \\ a_P^{CP} &= \frac{1}{2} (A_{CP} - \overline{A}_{CP}), \\ a_C^{CP} &= \frac{1}{2} (A_{CP} + \overline{A}_{CP}). \end{aligned} \quad (4)$$

The symmetry being tested by these last six asymmetries can be determined by multiplying the sub- and super-

scripts together. There are three types of decay that we can consider measuring; the most general case has been considered to date, but we can consider a simplification when $abcd = \overline{abcd}$. In this limit, the 12 asymmetries remain nontrivial. If we further simplify to also require that $M = \overline{M}$, we obtain only a single unique and nontrivial asymmetry, which is given by

$$A_{P,CP} = \frac{\langle \Gamma \rangle_+ - \langle \Gamma \rangle_-}{\langle \Gamma \rangle_+ + \langle \Gamma \rangle_-}, \quad (5)$$

where the average rates are indicated to highlight that M is indistinguishable from \overline{M} . Before discussing charm mesons, it is useful to proceed via an interlude (Section 2.1) that reviews triple-product asymmetry measurements in neutral kaon decays. Following this, we discuss applications to charm mesons and baryons (Section 2.2) and τ leptons (Section 2.3). We discuss a model-based interpretation of these asymmetries in Section 2.4.

2.1 $K_{L,S} \rightarrow \pi^+ \pi^- e^+ e^-$

The decay $K_L \rightarrow \pi^+ \pi^- e^+ e^-$ has been studied both theoretically and experimentally. These results provide useful insight into how to address measurements of triple-product asymmetries in the charm sector. Heiliger and Sehgal noted that this mode proceeds via four amplitudes: $K_L \rightarrow \pi^+ \pi^- \gamma$ photon conversion, bremsstrahlung from the CP -violating decay $K_L \rightarrow \pi^+ \pi^-$, a CP -conserving magnetic dipole component, and finally a short distance component related to $s\overline{d} \rightarrow e^+ e^-$. The radiative decay of $K_L \rightarrow \pi^+ \pi^-$ is CP violating, and it is the interference between this amplitude and the remaining CP -conserving ones that gives rise to a nonzero CP asymmetry. Heiliger and Sehgal predicted that the level of CP violation manifest in this decay is on the order of 14% [9]. Shortly after this prediction was made, the KTeV experiment at the Fermi National Accelerator Laboratory measured this triple-product asymmetry and confirmed the existence of a large effect [10, 11]. Subsequently, the NA48 experiment measured the triple-product asymmetry of both the K_L and K_S mesons decaying into $\pi^+ \pi^- e^+ e^-$ [12]. These results were found to be consistent with those of KTeV for the K_L mode and consistent with CP conservation for the K_S decay, as expected (given that $K_S \rightarrow \pi^+ \pi^-$ is CP conserving). This highlights an important issue with regard to CP asymmetries; first, one needs to identify a CP -violating amplitude, and only then may the interference of that amplitude with other contributions demonstrate effects that will be nonzero. This is a well-known statement of fact and is far from profound. This factor should be considered during the following discussion with regard to

existing and possible measurements. Thus far, the D decays to four-body final states that have been studied require amplitude analyses for a complete interpretation of the results. These analyses are complicated and have not yet been attempted; it is not clear a priori from inclusive measurements whether nonzero triple-product asymmetries are driven (in part) by a nonzero weak phase difference between pairs of amplitudes. One has to understand the dominant amplitude contributions to the decay model, and from that model one can evaluate what the expected outcome might be. At the time of writing, model-dependent analyses have not been performed; however, a simple example is discussed below in Section 2.4. It is hoped that measurement (and theoretical considerations) will evolve to permit model-dependent studies of these decays over the coming decade.

2.2 Testing charm mesons and baryons

In section 2.2.1, we start by considering tests using charm mesons and briefly summarize the current state of the art in terms of measurements; we then move on to discuss possible future measurements. In doing so, we look back to reflect on the work done in kaon decays to draw analogies and highlight several modes that have been ignored thus far. Having discussed measurements with mesons, we then consider baryon (Section 2.2.2) and τ lepton (Section 2.3) decays.

2.2.1 Charm meson decays

The most-studied triple-product asymmetries for four-body D decays are for the channel $D^0 \rightarrow K^+K^-\pi^+\pi^-$. This has been studied by FOCUS, BaBar, and LHCb and provides an interesting window of opportunity given a relatively large branching ratio of $(2.43 \pm 0.12) \times 10^{-3}$. Experimentally, the symmetry in the final state results in cancellation of a number of systematic uncertainties. The FOCUS measurements were insufficient to establish any nonzero triple-product asymmetry but laid the foundation for subsequent work by BaBar; this B factory initially repeated the FOCUS measurement but with a larger data sample. BaBar found nonzero values for A_P and \bar{A}_P , but the CP asymmetry A_C^P was consistent with zero. BaBar has recently measured all 12 asymmetries [13, 14]. LHCb, with its large data sample, has provided an interesting insight into these decays, as they have been studied in bins of K^+K^- and $\pi^+\pi^-$ invariant masses as well as examined by phase-space-integrated measurements [15]. The distributions for these invariant mass distributions indicate a rich resonant structure in the final state. In addition to the K^+K^- and $\pi^+\pi^-$ combinations

studied, one should investigate the $K^\pm\pi^\mp$ combinations to facilitate construction of a robust amplitude model for further study of the data. Interpretation of these results is complicated by the lack of a detailed amplitude model; however, the results of the simple model discussed below indicate that there is no evidence for a nonzero weak phase difference in this decay. All of the nonzero asymmetries measured by BaBar and LHCb can be driven by strong phase differences (see Section 2.4).

The channel $D^+ \rightarrow K_S K^+ \pi^+ \pi^-$ has been studied by BaBar, where all the measured asymmetries were found to be consistent with zero (integrating over phase space) [16]. The branching fraction for this channel is $(1.75 \pm 0.18) \times 10^{-3}$. It remains to be seen if there is a more complex picture that averages out to this null result when integrating over phase space. The corresponding D_s^+ decay has a branching fraction of $(1.03 \pm 0.10) \times 10^{-3}$ and has also been studied [16]. Here the pattern observed for $D^0 \rightarrow K^+K^-\pi^+\pi^-$ is repeated; the asymmetries driven by a nonzero weak phase difference are all zero, but those that can be driven by strong phase differences are not. The decays $D_{(s)}^+ \rightarrow K_L K^+ \pi^+ \pi^-$ have not been studied by LHCb or the B factories. Given the presence of K_L in the final state, one would expect a small residual level of CP violation from kaon decays to be present. These modes would have significant amounts of background at a B factory, and it would be difficult to attempt to reconstruct them in a hadronic environment such as the LHC. A significant virtue of a τ -charm factory is the ability to infer the missing energy and effectively reconstruct the K_L four-momentum. With 1 ab^{-1} of data, one could make precision measurements of triple-product asymmetries in $D^+ \rightarrow K_{S,L} K^+ \pi^+ \pi^-$. A data sample of 100 fb^{-1} collected at the D_s threshold would provide about $32 \times 10^6 D_s^\pm$ to perform similar measurements. This would be sufficient to provide several tens of thousands of $D_s^+ \rightarrow K_{S,L} K^+ \pi^+ \pi^-$ decays to study. Such a sample would enable a statistical precision of better than 1% for triple-product asymmetries.

A τ -charm factory is well placed to perform precision measurements of these and many other decay channels. For final states with one or more neutral mesons, there are obvious advantages in using data from an e^+e^- environment rather than pp collisions at the LHC. Kang and Li studied the prospects for a variety of D decays to VV final states [17] (here V is a vector particle with $J^P = 1^-$). Sub-percent-level precisions are attainable with modest data samples ($\sim 20 \text{ fb}^{-1}$) from BES II for the modes studied: neutral D meson decays to $\rho^0\rho^0$, $\bar{K}^{*0}\rho^0$, $\rho^0\phi$, $\rho^+\rho^-$, $K^{*+}K^{*-}$, and $K^{*0}\bar{K}^{*0}$, and charged D decays to $\bar{K}^{*0}\rho^+$. The statistical precision of

the charged D decay is at the per mille level with this sample size. A super τ -charm factory would be expected to accumulate significantly larger samples of data than this. For example, a factory accumulating 1 ab^{-1} of data at charm threshold could achieve statistical uncertainties at or below the per mille level in triple-product asymmetry measurements of all of these decays.

If we consider the kaon measurements discussed in Section 2.1, these are triple-product asymmetries from four-body decays derived from CP -violating and CP -conserving two-body decays of the kaon. The equivalent possibility for investigation of charm has been ignored thus far, i.e., the search for CP violation in D decays to $h^+h^-\ell^+\ell^-$ final states, where $h = K, \pi$ and $\ell = e, \mu$. Assuming that $D \rightarrow K^+K^+$ and/or $\pi^+\pi^+$ would exhibit CP violation at some level, one could use the interference between amplitudes generated in an analogous way to generate an asymmetry in these decays. The PDG reports upper limits on these modes ranging between 3.1×10^{-4} and 3.0×10^{-5} [18]. Some of these limits are just above naive expectations of the branching fractions based on the known two-body final-state branching fractions. The first step would be to search for these data at a B or τ -charm factory or the LHC and subsequently explore the triple-product asymmetry structure of the decays to search for symmetry violation. Note that an advantage of these modes is that they are unambiguous; the hadronic and dilepton systems can be treated as ab and cd , respectively, unlike the case in current measurements, where there are two possible pairing combinations to consider when probing amplitudes. The corresponding set of measurements for $D_{(s)}^+$ decays would involve $h^+h'^0\ell^+\ell^-$ final states, where $h = \pi, K$. The Cabibbo-suppressed decays would allow us to search for CP violation, and the Cabibbo-favored states would provide useful control samples; however, $K_{L,S}\pi^+\ell^+\ell^-$ states would ultimately have a small CP -violating effect resulting from the kaon CP violation intrinsic to the final state. A number of four-body D^0 and $D_{(s)}^\pm$ decays remain to be studied; note that the modes measured to date all have large branching fractions. Rare decays are more suitable for searches for physics beyond the SM, as small SM amplitudes can generate large effects when beating against any hypothetical new physics amplitude of a comparable size. The one thing that we do know about new physics amplitudes is that they are at best small for the energy scale being probed. Thus, multibody rare charm decays may provide an interesting test bed for CP violation; in addition to obtaining a more complete understanding of the abundant decays, experimentalists should study the available data for the rarer processes. It remains to be seen if one can generate large effects in the SM in analogy with the

$K_L \rightarrow \pi^+\pi^-e^+e^-$ case.

2.2.2 Charm baryon decays

Although measurements to date have focused on mesons, there is also a rich area of study in the decay of charm baryons. These systems are accessible using data from Belle II, BES III, the LHC, and a super τ -charm facility. The prospects for Λ_c decays to final states including baryons, pseudoscalars, and vector particles were studied in Ref. [19]. This paper assumes one year of data acquisition corresponding to an integrated luminosity of 5 fb^{-1} at the $X(4630)$ peak with BES-III. This data sample corresponds to $2.5 \times 10^6 \Lambda_c^+\Lambda_c^-$ pairs. The estimated precisions attainable for triple-product asymmetries with such a data sample are typically at the level of a few percent. A high-luminosity τ -charm facility would provide the opportunity to reach the sub-percent level in all modes studied with a data sample of about 80 fb^{-1} . For the mode $\Lambda_c \rightarrow \Lambda(p\pi^-)\rho^+(\pi^+\pi^0)$, a per mille level statistical precision for the triple-product asymmetries can be reached with data samples as small as 100 fb^{-1} . As CP violation is expected to be small in the charm sector, these decays provide an excellent set of laboratories to search for physics beyond the SM. In 100 fb^{-1} of data, one would have about $5 \times 10^7 \Lambda_c^+\Lambda_c^-$ pairs, which would enable searches for rare decays of the Λ_c^+ .

2.3 τ decays

Searches for CP violation in τ decay have concentrated on the channel $\tau \rightarrow K_S\pi\nu$ [20, 21]. The level of experimental sensitivity is approaching that of the intrinsic effect of CP violation in neutral kaons, which is an SM background to the search for new physics. One of the problems with performing a triple-product asymmetry measurement for a tau decay such as $\tau \rightarrow hh'h''\nu$, where $h^{(i)} = K, \pi, \eta$, is that the center-of-mass frame needs to be determined. Here a τ -charm factory has an advantage over other experimental facilities; while it runs on the $\tau^+\tau^-$ threshold, the leptons are created at rest in the laboratory frame, so the kinematics are fully constrained by the observed four-momenta of the reconstructed particles. Energy-momentum conservation allows one to infer the neutrino and hence fully reconstruct the event. This makes it possible to compute the full set of triple-product asymmetries outlined at the start of this section in the search for new physics. Decays with odd numbers of charged kaons in the final state suffer from detection asymmetry effects that are well known but provide additional systematic uncertainties. Those with neutral kaons suffer from regeneration and interference effects,

which again provide additional uncertainties that come into play when the results are interpreted. Higher-energy systems may be able to perform triple-product asymmetry measurements; however, in those systems, it is not possible to fully reconstruct the decay for energies above threshold. The decays $\tau \rightarrow \pi^- \pi^0 K^0 \nu$, $K^- \pi^0 K^0 \nu$, and $\pi^- K^0 \eta \nu$ are all expected to display CP violation as a result of the neutral kaon in the final state and provide an interesting complement to the $\tau \rightarrow K_S \pi \nu$ mode already studied. Any large CP violation effect observed in τ decay would be a clear sign of new physics. This is a largely unexplored experimental area that can be studied extensively at a τ -charm facility such as BES III or at a super τ -charm factory.

2.4 A simple model

We can increase our understanding of the 12 triple-product asymmetries introduced in Ref. [8] by considering a simple model of two interfering scalar amplitudes divided into + and - components according to the sign of the scalar triple product:

$$A_+ = a_1 e^{i(\phi_1 + \delta_{1,+})} + a_2 e^{i(\phi_2 + \delta_{2,+})}, \quad (6)$$

$$A_- = a_1 e^{i(\phi_1 + \delta_{1,-})} + a_2 e^{i(\phi_2 + \delta_{2,-})}, \quad (7)$$

$$\bar{A}_+ = a_1 e^{i(-\phi_1 + \delta_{1,+})} + a_2 e^{i(-\phi_2 + \delta_{2,+})}, \quad (8)$$

$$\bar{A}_- = a_1 e^{i(-\phi_1 + \delta_{1,-})} + a_2 e^{i(-\phi_2 + \delta_{2,-})}, \quad (9)$$

where δ represents a strong phase, and ϕ represents a weak phase. Here the coefficients a_1 and a_2 are just the magnitudes of the interfering amplitudes. In this case, as shown in Ref. [8], the six asymmetries A_C^P , A_C , \bar{A}_C , A_{CP}^C , A_{CP} , and A_{CP}^C can be nonzero only if the difference between the weak phases is nonzero. The remaining asymmetries can be nonzero even if $\phi_1 - \phi_2 = 0$. This simple model can be extended from the interfering (pseudo)scalar amplitude case to a more general scenario of amplitudes with higher spins following the procedure outlined in Ref. [22].

3 Tests using entangled states

John Bell resolved the Einstein–Podolsky–Rosen conundrum in 1961, and in doing so invented the concept of entangled quantum states [23]. e^+e^- collisions at a center-of-mass energy of 3770 MeV, corresponding to the $\psi(3770)$, allow us to prepare quantum-correlated pairs of neutral D mesons. In analogy with the Stern–Gerlach experiment, any pair of orthonormal states can be used to describe the system. It is convenient to use the quark flavor $\{D^0, \bar{D}^0\} \equiv \{\ell^+ X, \ell^- X\}$ and CP eigen-

states $\{D_+, D_-\} \equiv \{+1, -1\}$ to write the wave function:

$$\Psi = \frac{1}{\sqrt{2}} \left(D_1^0 \bar{D}_2^0 - \bar{D}_1^0 D_2^0 \right) \quad (10)$$

$$= \frac{1}{\sqrt{2}} (D_{1,+} D_{2,-} - D_{1,-} D_{2,+}). \quad (11)$$

The subscript + or - denotes the CP eigenvalue of the D decay as even or odd, respectively. The Arabic numeral subscripts refer to the time ordering of decaying mesons; i.e., they indicate either the first (i) or second (ii) meson to decay. The second set written indicates the final state reconstructed (for the flavor basis) or the CP eigenvalue (for the CP basis). The filter decays to a lepton $+X$ are an accurate way to determine the quark flavor in a charm decay, and the mistag probability at an e^+e^- machine running at charm threshold is small. The set of CP filter decays to complement these include $\eta_{CP} = +1$ (-1) $D \rightarrow h^+ h^-$, where $h = \pi, K$, and $D \rightarrow K_L \omega (\rightarrow \pi^+ \pi^- \pi^0)$ and $K_L \phi (\rightarrow K^+ K^-)$ [$D \rightarrow K_S \omega (\rightarrow \pi^+ \pi^- \pi^0)$ and $K_S \phi (\rightarrow K^+ K^-)$].

We can consider the possible combinations of decays that occur via either the flavor or CP filters described above, which give rise to three possible measurements of interest. However, it is useful to note that in addition to filtering using only flavor or only CP states, we can also filter using a combination of flavor then CP filters or CP then flavor filters. This results in a total of 15 distinct asymmetries [24], as listed in Table 1. The two flavor-filter-only asymmetries have been studied for many decades. The CP -filter-only asymmetry has not been studied for any neutral meson system. The remaining 12 asymmetries are derived using the approach described in Refs. [25, 26] and were measured by BaBar for neutral B decays [27]. Note that when only a single filter basis pair is used, it is not possible to construct an unambiguous test of a single symmetry; however, the constructed asymmetry can be used to simultaneously test a pair of symmetries. When two filter basis pairs are used, it is possible to resolve the remaining ambiguity to obtain a set of tests of only one symmetry.

One should generally perform these measurements as a function of the proper time difference between the first and second D meson decays in the event (usually denoted as Δt in the literature; for example, see Refs. [4, 5] for details on the time-dependent analyses). However, the mixing frequency and lifetime difference between D^0 and \bar{D}^0 are small in the charm system: $x = \Delta m / \Gamma \sim 0.5\%$, and $y = \Delta \Gamma / 2\Gamma \sim 0.7\%$. Hence, time-integrated measurements of the asymmetries outlined below would initially be of direct interest, and a small correction would be required when precision measurements are interpreted to take into account the fact that x and y are nonzero.

Table 1 The fifteen possible pairings of reference and symmetry conjugated transitions used to study CP , T and CPT for pairs of neutral D mesons.

Symmetry	Reference	Conjugate
CP and T	$D^0 \rightarrow \bar{D}^0$	$\bar{D}^0 \rightarrow D^0$
CP and CPT	$D^0 \rightarrow D^0$	$\bar{D}^0 \rightarrow \bar{D}^0$
T and CPT	$D_+ \rightarrow D_-$	$D_- \rightarrow D_+$
CP	$\bar{D}^0 \rightarrow D_-$	$D^0 \rightarrow D_-$
	$D_+ \rightarrow D^0$	$D_+ \rightarrow \bar{D}^0$
	$\bar{D}^0 \rightarrow D_+$	$D^0 \rightarrow D_+$
	$D_- \rightarrow D^0$	$D_- \rightarrow \bar{D}^0$
T	$\bar{D}^0 \rightarrow D_-$	$D_- \rightarrow \bar{D}^0$
	$D_+ \rightarrow D^0$	$D^0 \rightarrow D_+$
	$\bar{D}^0 \rightarrow D_+$	$D_+ \rightarrow \bar{D}^0$
	$D_- \rightarrow D^0$	$D^0 \rightarrow D_-$
CPT	$\bar{D}^0 \rightarrow D_-$	$D_- \rightarrow D^0$
	$D_+ \rightarrow D^0$	$\bar{D}^0 \rightarrow D_+$
	$D^0 \rightarrow D_-$	$D_- \rightarrow \bar{D}^0$
	$D_+ \rightarrow \bar{D}^0$	$D^0 \rightarrow D_+$

Section 3.1 discusses measurements of asymmetries constructed from the flavor filter basis pair, Section 3.2 discusses possible measurements of the asymmetry constructed from CP filter basis pairs, and Section 3.3 discusses the remaining measurements using a combination of CP and flavor filter basis pairs.

3.1 Using flavor filters

It is possible to construct tests of CP and T and of CP and CPT using flavor filter states. These measurements require studies as a function of the lifetime difference between opposite-sign and same-sign tagged final states. The asymmetries that one measures are

$$A_{CP,T} = \frac{\Gamma(D^0 \rightarrow \bar{D}^0) - \Gamma(\bar{D}^0 \rightarrow D^0)}{\Gamma(D^0 \rightarrow \bar{D}^0) + \Gamma(\bar{D}^0 \rightarrow D^0)}, \quad (12)$$

$$A_{CP,CPT} = \frac{\Gamma(D^0 \rightarrow D^0) - \Gamma(\bar{D}^0 \rightarrow \bar{D}^0)}{\Gamma(D^0 \rightarrow D^0) + \Gamma(\bar{D}^0 \rightarrow \bar{D}^0)}. \quad (13)$$

The former measurement is usually referred to as a measurement of CP in mixing; note, however, that it also simultaneously tests T , c.f. the Kabir asymmetry measured by CPLEAR in kaon decays [28]. Experimentally, one would typically reconstruct both D mesons via a semileptonic (SL) decay and search for same-sign dileptons, one of which would come from each decay. A nonzero value of the resulting asymmetry $A_{CP,T}$ as a function of the proper time difference between the decaying D mesons would indicate violation of both CP and T . The corresponding test for $A_{CP,CPT}$ requires an opposite-sign dilepton final state, and a nonzero value of this asymmetry would indicate a violation of both CP

and CPT . This could only appear as a result of physics beyond the SM.

Note that while these tests are performed using an entangled state prepared in the decay of a $\psi(3770)$, it is also possible to use a hadronic production environment with associated production of charm to flavor-tag the neutral D meson at the point of production and reconstruct the SL decay at a later time. A second route, which is viable at the LHCb experiment, is to use SL B decays to tag the flavor of the decaying neutral D meson at the point of production and the leptonic charge at the point of decay to provide the required rates to compute $A_{CP,T}$ and $A_{CP,CPT}$.

Over the past few years, there has been considerable interest in the like-sign SL asymmetry measurement made by the D0 experiment for B_s mesons [29]. This is a measurement of $A_{CP,T}$ using B_s decays. The reported D0 result is $A_{CP,T} = -0.787 \pm 0.172 \pm 0.093$, which deviates from the SM expectation of zero by 3.9σ . All corresponding measurements made by the B factories for this asymmetry in B_d mesons are consistent with zero (see Ref. [4] and references therein). If the anomalous like-sign dimuon asymmetry in D0 is the result of some type of new physics, then that may also appear in the charm sector. Hence, it is important to study charm decays in order to search for evidence of CP and T violation. As noted in Ref. [30], systems with $\Delta\Gamma \simeq 0$ can yield a zero asymmetry measurement for $A_{CP,T}$ even when the symmetry is violated. For neutral charm (such as B_s) mesons, $\Delta\Gamma \neq 0$; hence, such a measurement for D^0 mesons is an important test to complement the studies performed thus far.

A recent review of SL decays by Liu outlines experimental issues related to reconstructing these states [31]. The branching fraction of SL decays is large, so precision measurements of $A_{CP,T}$ and $A_{CP,CPT}$ are in principle achievable, assuming that systematic uncertainties may be controlled.

3.2 Using CP filters

The asymmetry

$$A_{T,CPT} = \frac{\Gamma(D_+ \rightarrow D_-) - \Gamma(D_- \rightarrow D_+)}{\Gamma(D_+ \rightarrow D_-) + \Gamma(D_- \rightarrow D_+)}, \quad (14)$$

constructed using only CP filter states, allows us to simultaneously test both T and CPT . To perform this test, we need to identify D meson decays into CP -even and CP -odd final states. For example, one can measure the asymmetry between $D \rightarrow K_S(\omega, \phi, \rho^0)$ followed by $D \rightarrow h^+h^-$ [or $D \rightarrow K_L(\omega, \phi, \rho^0)$] and $D \rightarrow h^+h^-$ [or $D \rightarrow K_L(\omega, \phi, \rho^0)$] followed by $D \rightarrow K_S(\omega, \phi, \rho^0)$ final

states. Any combination of +1 and -1 states can be used to test T using this method. The SM expectation is that $A_{T,CPT} = 0$. Any nonzero value for any of these combinations would indicate violation of both T and CPT , and physics beyond the SM. This type of test complements the flavor filter tests of $A_{CP,T}$ and $A_{CP,CPT}$ described above. The initial CP filter state can be tagged via the decay of a $\psi(3770)$. As a result, incoherent production of charm at a hadron collider or B factory does not permit an obvious route to performing this type of asymmetry measurement via other means.

Experimentally, double $D \rightarrow K_{S,L}\omega^0$ decays should proceed at a rate on the order of 1.2×10^{-4} . Allowing for the ability to reconstruct these decays with a modest efficiency, a single event sensitivity would be at the level of $O(\text{few } 10^{-5})$. A super τ -charm factory would be able to accumulate about 10,000 events in 1 ab^{-1} to perform a measurement of this type. Double decays to $D \rightarrow K_{S,L}\rho^0$ and $D \rightarrow K_{S,L}\phi$ have product branching fractions of 3.6×10^{-5} and 4×10^{-6} , respectively. Samples of about 1000 and 100 events, respectively, could be recorded to permit a measurement of $A_{T,CPT}$ for these decays.

It is possible to measure CP violation by searching for CP eigenstate decays with different lifetime ratios. A detailed description of how to use quantum correlations to do this in charm decays is given in Ref. [32]. Time-integrated measurements can be made given that CP violation in mixing can be neglected in charm decays. These are often referred to as measurements of y_{CP} ; for example Chapter 19.2 of Ref. [4] discusses the available B Factory measurements of this quantity. However reference [32] also describes how one can revert to time dependent measurements if this condition is relaxed. A more recent discussion of this issue is given in Ref. [33]. Here there is also a discussion of the direct CP asymmetry different between D decays to $\pi^+\pi^-$ and K^+K^- , however given the inconclusive nature of recent deliberations on the this difference (that follow trivially from the available measurements vs the number of free parameters in the problem) while being an interesting subject, it is not discussed further here. Similarly, CP tagging of $B_{s,d}$ decays can be used to constrain the Unitarity triangle angle γ as outlined in Ref. [34].

3.3 Using both flavor and CP filters

The remaining 12 asymmetries can be constructed from Table 1, and these constitute four tests each of CP , T , and CPT . These tests complement the $A_{CP,T}$, $A_{CP,CPT}$, and $A_{T,CPT}$ asymmetries discussed above, as they each unambiguously identify one symmetry to test. These

asymmetries have been measured thus far only for neutral B mesons [27], where results consistent with the SM were obtained, namely, that CP and T are violated, whereas CPT remains conserved. These measurements provide an important cross-check of our understanding of symmetry violation and complement existing routes to search for symmetry violation. The magnitudes of the asymmetries determined in these decays are related to the unitarity triangle angles in the charm sector (just as the asymmetries measured in Ref. [27] are related to $\sin 2\beta$ from the B_d “unitarity triangle”). As CP violation is expected to be small in the charm sector, the angles measurable in the CP and T asymmetries are also expected to be small (i.e., compatible with zero within the uncertainties). The CPT asymmetries are expected to be zero in the SM to signify that this symmetry is conserved. Significant deviations from this pattern would indicate physics beyond the SM. A discussion of how to relate the angles of the charm unitarity triangle to decays in the charm system can be found in Ref. [5].

Table 2 summarizes the 15 asymmetries in terms of the final states that must be reconstructed for reference and conjugated processes. These clearly highlight the symmetries being tested by same-sign and opposite-sign asymmetry measurements, as well as allowing one to clearly identify the combinations for testing the remaining 13 quantities.

Table 2 Final states reconstructed for the first and second D mesons in an event, along with the conjugate processes to test the symmetries CP , T and CPT . The ℓ^+X (ℓ^-X) state is the flavor filter for a D^0 (\bar{D}^0), and +1 and -1 indicate the CP filter decays listed in the text.

Symmetry	Reference	Conjugate
CP and T	(ℓ^-X, ℓ^-X)	(ℓ^+X, ℓ^+X)
CP and CPT	(ℓ^-X, ℓ^+X)	(ℓ^+X, ℓ^-X)
T and CPT	$(-1, -1)$	$(+1, +1)$
CP	$(\ell^-X, -1)$	$(\ell^+X, -1)$
	$(+1, \ell^+X)$	$(+1, \ell^-X)$
	$(\ell^-X, +1)$	$(\ell^+X, +1)$
	$(-1, \ell^+X)$	$(-1, \ell^-X)$
T	$(\ell^-X, -1)$	$(-1, \ell^-X)$
	$(+1, \ell^+X)$	$(\ell^+X, +1)$
	$(\ell^-X, +1)$	$(+1, \ell^-X)$
	$(-1, \ell^+X)$	$(\ell^+X, -1)$
CPT	$(\ell^-X, -1)$	$(-1, \ell^+X)$
	$(+1, \ell^+X)$	$(\ell^-X, +1)$
	$(\ell^+X, -1)$	$(-1, \ell^-X)$
	$(+1, \ell^-X)$	$(\ell^+X, +1)$

3.4 Tests of quantum mechanics

A natural question to ask about an entangled system is “can one test Bell’s inequality using entangled neu-

tral mesons?” The Belle experiment has attempted to address this issue in the context of $B_d^0\bar{B}_d^0$ mesons [4]; however, that approach has limitations that prohibit this possibility. Those limitations also preclude the possibility of a test of quantum mechanics using neutral D mesons [35], given that x is small. However, it may be possible to test for decoherence effects in the entangled wave function, in analogy with measurements performed by the B factories. The neutral charm system provides several experimental advantages over B mesons for this type of test; for example, flavor tagging can be performed with essentially no degradation of the precision (and hence minimal systematic uncertainty) of the flavor assignment. The small magnitude of mixing for charm may also prove to be advantageous for such a test. For a discussion of decoherence tests, see, for example, Ref. [36].

4 Summary

A high luminosity τ -charm factory would allow a number of interesting measurements to be performed. It will be possible to explore discrete symmetry (non-)conservation in charm meson decays using entangled neutral D mesons created via decays of the $\psi(3770)$ resonance and to explore C , P , and CP violation in τ lepton, charm meson, and baryon decays. An e^+e^- collider has advantages over other facilities for performing such measurements; in particular, tests of the full set of possible T and CPT asymmetries require the use of entangled pairs of neutral D mesons, which are unique to a τ -charm factory. A number of triple-product asymmetry measurements are discussed in the context of a search for discrete symmetry violation. Half of these measurements are tests of a nonzero weak phase difference (related to the phase of the CKM matrix). One can also use entangled states to study CP , T , and CPT symmetries. The best way to discover CP violation in the charm sector is not yet clear; as a result, one should perform all possible measurements that may lead to an effect. At the same time, it is important to perform tests of the other discrete symmetries in the hope of further elucidating our understanding of the SM of particle physics. Although it is not possible to test Bell’s inequalities with charm mesons, it will be possible to search for decoherence of the wave function for entangled pairs of neutral D mesons.

Note in proof: shortly after submitting this paper, work describing a possible model dependent analysis of $D^0 \rightarrow K^+K^-\pi^+\pi^-$ decays was released [37].

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References

1. C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, Experimental test of parity conservation in beta decay, *Phys. Rev.* 105, 1413 (1957)
2. J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Evidence for the 2π decay of the $k(2)^0$ meson, *Phys. Rev. Lett.* 13, 138 (1964)
3. For example, see: P. K. Kabir, *The CP Puzzle*, Academic Press, 1968, and R. G. Sachs, *The Physics of Time Reversal*, University of Chicago Press, 1987
4. A. J. Bevan, et al. (BaBar and Belle Collaborations), The physics of the B factories, *Eur. Phys. J. C* 74, 3026 (2014) [arXiv: 1406.6311 [hep-ex]]
5. A. J. Bevan, G. Inguglia, and B. Meadows, Time-dependent CP asymmetries in D and B decays, *Phys. Rev. D* 87(3), 039905 (2013) [arXiv: 1106.5075 [hep-ph]]
6. M. Gersabeck, Introduction to charm physics, *PoS FWNP* 001 (2015) [arXiv: 1503.00032 [hep-ex]]
7. M. Gronau and J. L. Rosner, Triple product asymmetries in K , $D_{(s)}$ and $B_{(s)}$ decays, *Phys. Rev. D* 84, 096013 (2011) [arXiv: 1107.1232 [hep-ph]]
8. A. J. Bevan, C , P , and CP asymmetry observables based on triple product asymmetries, arXiv: 1408.3813 [hep-ph]
9. P. Heiliger and L. M. Sehgal, Direct and indirect CP violation in the decay $K_L \rightarrow \pi^+\pi^-e^+e^-$, *Phys. Rev. D* 48, 4146 (1993) [*Phys. Rev. D* 60, 079902 (1999)]
10. A. Alavi-Harati, et al. (KTeV Collaboration), Observation of CP violation in $K_L \rightarrow \pi^+\pi^-e^+e^-$ decays, *Phys. Rev. Lett.* 84, 408 (2000) [arXiv: hep-ex/9908020]
11. E. Abouzaid, et al. (KTeV Collaboration), A measurement of the K^0 charge radius and a CP violating asymmetry together with a search for CP violating e1 direct photon emission in the rare decay $K_L \rightarrow \pi^+\pi^-e^+e^-$, *Phys. Rev. Lett.* 96, 101801 (2006) [arXiv: hep-ex/0508010]
12. A. Lai, et al. (NA48 Collaboration), Investigation of $K_{L,S} \rightarrow \pi^+\pi^-e^+e^-$ decays, *Eur. Phys. J. C* 30, 33 (2003)
13. J. P. Lees, et al. (BaBar Collaboration), Search for CP violation using T -odd correlations in $D^+ \rightarrow K^+K_S^0\pi^+\pi^-$ and $D_s^+ \rightarrow K^+K_S^0\pi^+\pi^-$ decays, *Phys. Rev. D* 84, 031103 (2011) [arXiv: 1105.4410 [hep-ex]]
14. M. Martinelli, Contribution to the 8th International Workshop on the CKM Unitarity Triangle, Vienna, 2014
15. R. Aaij, et al. (LHCb Collaboration), Search for CP violation using T -odd correlations in $D^0 \rightarrow K^+K^-\pi^+\pi^-$ decays, *J. High Energy Phys.* 1410, 005 (2014) [arXiv: 1408.1299 [hep-ex]]
16. J. P. Lees, et al. (BaBar Collaboration), Search for CP violation using T -odd correlations in $D^+ \rightarrow K^+K_S^0\pi^+\pi^-$ and $D_s^+ \rightarrow K^+K_S^0\pi^+\pi^-$ decays, *Phys. Rev. D* 84, 031103 (2011) [arXiv: 1105.4410 [hep-ex]]

17. X. W. Kang and H. B. Li, Study of CP violation in $D \rightarrow VV$ decay at BESIII, *Phys. Lett. B* 684, 137 (2010) [arXiv: 0912.3068 [hep-ph]]
18. K. A. Olive, et al. (Particle Data Group), The review of particle physics, *Chin. Phys. C*, 38, 090001 (2014)
19. X. W. Kang, H. B. Li, G. R. Lu, and A. Datta, Study of CP violation in Λ_c^+ decay, *Int. J. Mod. Phys. A* 26, 2523 (2011) [arXiv: 1003.5494 [hep-ph]]
20. M. Bischofberger, et al. (Belle Collaboration), Search for CP violation in $\tau \rightarrow K_S^0 \pi \nu_\tau$ decays at Belle, *Phys. Rev. Lett.* 107, 131801 (2011) [arXiv: 1101.0349 [hep-ex]]
21. J. P. Lees, et al. (BaBar Collaboration), Search for CP violation in the decay $\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau$, *Phys. Rev. D* 85, 031102 (2012) [*Phys. Rev. D* 85, 099904 (2012)] [arXiv: 1109.1527 [hep-ex]]
22. G. Valencia, Angular correlations in the decay $B \rightarrow VV$ and CP violation, *Phys. Rev. D* 39, 3339 (1989)
23. J. S. Bell, On the Einstein–Podolsky–Rosen paradox, *Physics* 1, 195 (1964)
24. A. Bevan, Experimental prospects for C , P , T , CP , and CPT tests, arXiv: 1505.06943 [hep-ex]
25. M. C. Banuls and J. Bernabeu, Studying indirect violation of CP , T and CPT in a B factory, *Nucl. Phys. B* 590, 19 (2000) [arXiv: hep-ph/0005323]
26. J. Bernabeu, F. Martinez-Vidal, and P. Villanueva-Perez, Time Reversal Violation from the entangled $B^0-\bar{B}^0$ system, *J. High Energy Phys.* 1208, 064 (2012) [arXiv: 1203.0171 [hep-ph]]
27. J. P. Lees, et al. (BaBar Collaboration), Observation of time reversal violation in the B^0 meson system, *Phys. Rev. Lett.* 109, 211801 (2012) [arXiv: 1207.5832 [hep-ex]]
28. A. Angelopoulos, et al. (CPLEAR Collaboration), First direct observation of time-reversal non-invariance in the neutral-kaon universe, *Phys. Lett. B* 444, 43–51 (1998)
29. V. M. Abazov, et al. (D0 Collaboration), Evidence for an anomalous like-sign dimuon charge asymmetry, *Phys. Rev. D* 82, 032001 (2010) [arXiv: 1005.2757 [hep-ex]]
30. E. Alvarez and A. Szykman, Direct test of time reversal invariance violation in B mesons, *Mod. Phys. Lett. A* 23, 2085 (2008) [arXiv: hep-ph/0611370]
31. C. Liu, Semileptonic charm decays: Mini review, arXiv: 1302.0227 [hep-ex]
32. D. Atwood and A. A. Petrov, Lifetime differences in heavy mesons with time independent measurements, *Phys. Rev. D* 71 (2005) 054032 [arXiv: hep-ph/0207165]
33. D. Atwood and A. Soni, Searching for the origin of CP violation in Cabibbo suppressed D meson decays, *PTEP* 2013 (9), 0903B05 (2013) [arXiv: 1211.1026 [hep-ph]]
34. A. F. Falk and A. A. Petrov, Measuring γ cleanly with CP tagged B_s and B_d decays, *Phys. Rev. Lett.* 85, 252 (2000) [hep-ph/0003321]
35. R. A. Bertlmann, A. Bramon, G. Garbarino, and B. C. Hiesmayr, Violation of a Bell inequality in particle physics experimentally verified, *Phys. Lett. A* 332, 355 (2004) [arXiv: quant-ph/0409051]
36. R. A. Bertlmann, W. Grimus, and B. C. Hiesmayr, Quantum mechanics, Furry’s hypothesis and a measure of decoherence in the $K^0\bar{K}^0$ system, *Phys. Rev. D* 60, 114032 (1999) [arXiv: hep-ph/9902427]
37. G. Durieux and Y. Grossman, Probing CP violation systematically in differential distributions, arXiv: 1508.03054 [hep-ph]