Search for New Physics in $D^\pm \rightarrow K_S X^\pm$ and $D^\pm \rightarrow K_S K_S K^\pm$

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Abstract

Direct CP violation beyond the standard model can be produced in charged D decays to final states with a $K_S$ by small new physics contributions to the transitions $D^+ \rightarrow K^o X^+$, where $X^+$ denotes any positively charged hadronic state or transitions $D^+ \rightarrow K^o \bar{K}^o K^{(*)+}$, where $K^{(*)+}$ denotes any positive strange state. These transitions are doubly-Cabibbo suppressed and color suppressed in the standard model and branching ratios are experimentally observed to be suppressed by two orders of magnitude relative to the allowed $D^+ \rightarrow K^o X^+$ or $D^+ \rightarrow K^o \bar{K}^o K^{(*)+}$, branching ratio. An even smaller new physics contribution might produce an observable CP asymmetry in $D^\pm \rightarrow K_S X^\pm$ or $D^\pm \rightarrow K_S K_S K^{(*)\pm}$ decays. Since such asymmetries are easily checked in the early stages of any charm production experiment, it seems worthwhile to check them before the opportunity is lost in later stages of the analysis, even if no theoretical model predicts such an asymmetry.

Since the Standard Model predictions for CP violation in charm decays are very small, the charm sector has been cited as a good place to test the SM and to look for evidence for physics beyond the SM \cite{footnote1}. Some negative results were recently reported in a search for CP violation in certain singly Cabibbo suppressed decays.

The same experiment might have been used to look for CP violation in the interference between Cabibbo favored and doubly-Cabibbo suppressed amplitudes. This has been sug-

\footnote{Supported in part by The German-Israeli Foundation for Scientific Research and Development (GIF) and by the U.S. Department of Energy, Division of High Energy Physics, Contract W-31-109-ENG-38.}
gested by Bigi and Yamamoto [3] and the basic physics is discussed in detail in their paper. Although these lead to final states with different strangeness, interference between them can be observed in final states containing a $K_S$, as in $D^\pm \to K_S X^\pm$ decays, where $X^\pm$ denotes any charged hadronic state.

$$D^\pm \to K^o X^\pm \to K_S X^\pm \quad (1a)$$

$$D^\pm \to \bar{K}^o X^\pm \to K_S X^\pm \quad (1b)$$

The dominant standard model decay diagram is the Cabibbo favored and color favored tree diagram shown in figure 1. The standard model also has the doubly-Cabibbo suppressed and color suppressed tree diagram shown in figure 2 and the doubly-Cabibbo suppressed annihilation diagram shown in figure 3. One can wonder about new-physics diagrams like those shown in figure 4 and figure 5 which respectively resemble the SM Cabibbo-suppressed tree and annihilation diagrams of figures 1 and 2 but go via some new physics boson or more complicated diagram instead of the $W$. Such a diagram might have a different weak phase from the dominant tree diagram of figure 1 and produce a direct CP violation in the decay modes $D^\pm \to K_S X^\pm$ via interference between the two diagrams. Such interference would produce an opposite CP violation in the decay modes $D^\pm \to K_L X^\pm$ and produce no violation in the total widths as required by CPT [3].

These final states had not previously been considered in the early selection stages of the data selection process in experiments like the Fermilab charm experiment E791 whose results were cited above, and where the following observations have been made [3]:

“One can imagine reaching a sensitivity of order $10^{-3}$ in comparing $D^\pm \to K_S 3\pi$. That mode looks very interesting. It is especially nice in being a self tagging mode (by charge) and having normalization signals which are very well known ($K\pi\pi$). However, returning to these early selection stages at a later time has been estimated as requiring a large number of tapes to be mounted (say, 2000). This would be a considerable effort. Such an effort is hard to sell if there are no concrete predictions from specific models for new physics.”

It is therefore of interest both for theorists proposing new models to check whether they can provide such predictions, and for experimenters planning new experiments to be aware of these possibilities at early stages when the measurements are cheap and easy, even though no theoretical motivation exists at the time.

Similarly, one can also consider decays into final states with two $K_S$; e.g. the doubly-Cabibbo suppressed decays illustrated in figure 6,

$$D^\pm \to K^o \bar{K}^o K^{(*)\pm} \to K_SK_S K^{(*)\pm} \quad (2a)$$

and the Cabibbo allowed decays

$$D^+ \to \bar{K}^o K^o K^{(*)+} \to K_SK_S K^{(*)+} \quad (2b)$$

$$D^- \to K^o K^o K^{(*)-} \to K_SK_S K^{(*)-} \quad (2c)$$

where $K^{(*)\pm}$ denotes any positive strange state. Although there is no present model for new physics suggesting such diagrams a number of arguments support a search for this direct CP violation.
1. Branching ratios are high [4]; namely 6% for $K^o\rho^+$, 8% for $K^o\rho^+$ and 59% for $K^o + \bar{K}^o$ inclusive. Even with the loss of a factor of three in detecting $K^o$ via the decay chain $K^o \to K_\pi \to \pi^+\pi^-$ and further experimental losses, the remaining signal can be sufficiently large to see a signal. Even if nothing is found a sensible upper limit might be obtained that can shoot down some future theories.

2. The interference term is linear in the new physics and doubly-Cabibbo suppressed amplitude, while doubly-Cabibbo suppressed branching ratios are quadratic. The ratio of the experimental branching fractions for the analogous forbidden and allowed decays $D^+ \to K^+\pi^+\pi^-$ and $D^+ \to K^-\pi^+\pi^+$ is given [5] as $(7.7\pm1.7\pm0.8) \times 10^{-3} \approx (3.0\pm0.8) \tan^4 \theta_C$. This suggests that the forbidden decay is suppressed by one order of magnitude in amplitude and two orders of magnitude in branching ratio. A new physics amplitude which is two orders of magnitude below the dominant allowed amplitude and one order of magnitude below the forbidden amplitude could give an interference contribution to $D^\pm \to K_S X^\pm$ of several percent and might produce an observable direct CP violation in the one percent ball park.

3. The Cabibbo-favored amplitude leads to an exotic final state whereas the doubly-suppressed and new-physics amplitudes lead to a non-exotic final state and can be enhanced by the presence of meson resonances [6].

4. The presence of meson hadronic resonances near the $D$ mass has been pointed out and the possibility that they might influence charmed meson decays has been discussed. The nature of such resonances is still under investigation and the possibility that they might be hybrid (quark-antiquark-gluon) states opens up new possibilities of enhanced contributions to penguin and annihilation diagrams which go via a $qqG$ intermediate state [6].

5. CPT invariance requires that a final state must be a linear combination of at least two eigenstates of the strong-interaction S-matrix with different strong and weak phases in order for the observation of direct CP charge asymmetry [3]. This normally requires some nontrivial strong interaction rescattering. The present case is different because the two strong eigenstates have different strangeness and are not coupled by strong interaction scattering. Interference is achieved by the use of weak interactions in a detector that mixes $K^o$ and $\bar{K}^o$. The strong phases are expected to be very different since one state is exotic and has no resonance phase, while the other is non-exotic and is in the center of the resonance region.

6. CPT requires every CP charge asymmetry to be compensated by an opposite CP asymmetry elsewhere to give the same total widths. Here this compensation is automatic because all decays occur in pairs with $K_L$ in one mode and $K_S$ in the other or with $K_L K_L$ in one mode and $K_S K_S$ in the other. Any CP violating asymmetry in a $K_S$ mode is reversed in the $K_L$ mode, so that CPT restrictions are automatically satisfied without requiring complicated final state rescattering.

7. The search is cheap. One only needs to separate the two charge states that are observed anyway and give a result for the difference.

We now describe these effects explicitly. Let $A_f$, $A_{cs}$ and $A_{np}$ denote respectively the magnitudes of the Cabibbo-favored, the doubly-Cabibbo suppressed and new physics con-
tributions to the amplitude for a given decay $D^\pm \rightarrow K_S X^\pm$. Let $S$ and $W$ denote respectively the strong and weak phases for the dominant Cabibbo-favored amplitude for the case of the $D^+ \rightarrow K_S X^+$ decay, $S_{cs}$ denote the difference between the strong phases of the Cabibbo suppressed and Cabibbo allowed amplitudes, and $S_{np}$ and $W_{np}$ denote respectively the differences between the strong and weak phases of the new physics and the strong and weak phases of the Cabibbo allowed amplitudes. The total amplitude denoted by $A^\pm$ for a given decay $D^\pm \rightarrow K_S X^\pm$ is then

$$A^\pm = e^{i(S\pm W)} \cdot [A_f + e^{iS_{cs}} \cdot A_{cs} + e^{i(S_{np}\pm W_{np})} \cdot A_{np}]$$

(3a)

Thus

$$|A^\pm|^2 \approx A_f^2 + 2A_f A_{cs} \cdot \cos S_{cs} + 2A_f A_{np} \cdot \cos(S_{np} \pm W_{np})$$

(3b)

and

$$|A^-|^2 - |A^+|^2 \approx 4A_f A_{np} \cdot \sin S_{np} \cdot \sin W_{np}$$

(4)

The number of events counted in a given experiment can then be written

$$N^\pm = |C^\pm|^2 \cdot |A^\pm|^2 \approx |C^\pm|^2 \cdot [A_f^2 + 2A_f A_{cs} \cos S_{cs} + 2A_f A_{np} \cos(S_{np} \pm W_{np})]$$

(5a)

Where the normalization factors $C^\pm$ depend upon the conditions of the experiment, running time, acceptances, efficiencies, etc.

The statistical error is then given by

$$\delta N^\pm = \sqrt{N^\pm} \approx C^\pm A_f$$

(5b)

The observed $CP$ asymmetry is given by eq. (4), with a statistical error given by eq. (5b).

$$(A_{sym})_{CP} \equiv \frac{N^-}{|C^-|^2} - \frac{N^+}{|C^+|^2} \approx 4A_f A_{np} \cdot \sin S_{np} \sin W_{np}$$

(6a)

$$\delta(A_{sym})_{CP} \approx A_f \cdot \sqrt{|C^-|^2 + |C^+|^2} \leq A_f \cdot \sqrt{\frac{2}{C^+ + C^-}}$$

(6b)

The ratio of the $CP$ signal to the statistical error is then

$$\frac{\text{(Signal)}}{\text{Statistical Error}} = \frac{(A_{sym})_{CP}}{\delta(A_{sym})_{CP}} \approx \frac{4C^+ C^-}{\sqrt{|C^-|^2 + |C^+|^2}} \cdot A_{np} \cdot \sin S_{np} \sin W_{np}$$

(7a)

Substituting the inequality (6b) then gives

$$\frac{\text{(Signal)}}{\text{Statistical Error}} = \frac{(A_{sym})_{CP}}{\delta(A_{sym})_{CP}} \geq 2 \cdot \sqrt{2C^+ C^-} \cdot A_{np} \cdot \sin S_{np} \sin W_{np}$$

(7b)

The inequalities in eqs. (6b) and (7b) become equalities in cases where $C^\pm \approx C^- \equiv C$ as in $D^+$ and $D^-$ decays produced in $e^+e^-$ experiments. In this approximation we can write

$$\frac{(\text{Signal})_{CP}}{\text{Total Rate}} = \frac{C^2 \cdot (A_{sym})_{CP}}{N} \approx 4 \cdot \left(\frac{A_{np}}{A_f}\right) \cdot \sin S_{np} \sin W_{np}$$

(8)
Note that the ratio of the CP violation to the statistical error is independent of the dominant $A_f$ amplitude and depends only on the new-physics amplitude $A_{np}$, even though the relative strength of the CP violation is inversely proportional to $A_f$. This illustrates a general feature of searches for CP violation in a CP violating phase which occurs in an interference term between a dominant CP conserving term and a small term. One might think that the small term would be more important if its ratio to the dominant term is large. But this is not the case. The statistical significance of an observed violation is independent of the relative strengths of the dominant term and the small term.

In cases where $C^+ \neq C^-$ it is necessary to obtain the ratio of these normalization factors from another decay mode which will presumably have better statistics and a statistical error negligible in comparison with those of the decays under investigation.

It is interesting to compare the doubly-Cabibbo suppressed decays into modes with neutral kaons and the corresponding decays into modes with charged kaons. The branching ratios into the charged modes have no interference with allowed decays and therefore give a measure of the doubly-Cabibbo suppressed amplitudes. However, other factors must be taken into account in order to interpret these results.

For the quasi-two-body decays with a single kaon (1), the corresponding decays with a charged kaon are

$$D^\pm \rightarrow K^\pm X^o$$

These decays are color favored, in contrast with the doubly-Cabibbo-suppressed decays (1) into modes with neutral kaons which are also color suppressed.

For the three-kaon decays (2a) with two neutral kaons, the corresponding decays with a charged kaon pair are

$$D^\pm \rightarrow K^+ K^- K^{(*)\pm}$$

In contrast to the decay modes with neutral kaon pairs (2a) which can be produced by the dominant doubly-Cabibbo-suppressed and color-favored tree diagram shown in figure 6, the charged decay modes (10) cannot be produced by this diagram, which contains a $d\bar{d}$ pair instead of the required $u\bar{u}$ pair. The charged transition (10) can only be produced by an annihilation diagram or by an additional final state strong charge-exchange scattering; i.e. a $d\bar{d} \rightarrow u\bar{u}$ transition following the tree diagram of figure 6.

The search for CP violation in interference between Cabibbo-favored and Doubly-Cabibbo-suppressed decays has been suggested by Gronau, Wyler, Dunietz and others [7] for $B \rightarrow$ charm decays where CP effects are suggested by the standard model. In the charm decays discussed here there is no prediction from the standard model for direct CP violation, but branching ratios are much higher and there is the possibility of additional effects due to resonances which are absent at the B mass.
ACKNOWLEDGMENTS

It is a pleasure to thank Jeffrey Appel, Edmond Berger, Karl Berkelman, John Cumalat, Yuval Grossman, Yosef Nir and J. G. Smith for helpful discussions and comments. This work was partially supported by the German-Israeli Foundation for Scientific Research and Development (GIF).
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FIGURE 1.
Standard Model Cabibbo and Color favored diagram.

FIGURE 2.
SM Color and Double-Cabibbo suppressed diagram.

FIGURE 3.
SM Annihilation. $G$ denotes any number of gluons.
FIG. 4.
New Physics tree diagram.

FIG. 5.
New Physics Annihilation.

FIG. 6.
Standard Model Double-Cabibbo Suppressed $D \to 3K$ diagram.