CP violation in charm decays

Alexey A. Petrov

Department of Physics and Astronomy Johns Hopkins University Baltimore MD 21218

We address several topics relevant to CP violating phenomena in charm meson decays. The influence of nearby resonances on the generation CP violating asymmetries in D decays is studied, and a new mechanism for generating direct CP-violating asymmetries is discussed.

I. INTRODUCTION

Non-perturbative hadron dynamics plays an important role in the physics of non-leptonic D decay. The existence of the light quark resonances in the neighborhood of the charmed meson mass is a proof that hadron dynamics is active in this energy region and might affect weak decays of charmed particles. Similar effects, like final state hadron rescattering, can completely obscure a naive quark model interpretation of the observed processes [1]. One has to be extremely careful in trying to extract the signals of the New Physics from the charm decay data since rare decays or charmed meson mixing signals are usually mocked by the hadronic backgrounds. For instance, due to the fact that the Standard Model amplitude for $D^0 - \bar{D}^0$ mixing is tiny [2,3], this signal is usually thought of as being one of the best candidates for the observation of the virtual effects of New Physics particles. However, long distance hadronic effects can generate Δm_D at the level of one or two orders of magnitude larger than that of the short distance [4,5]. For instance, a substantial enhancement of both the Δm_d and $\Delta ,_D$ is possible due to the resonances having mass nearby the D^0 mass [6].

Hadron dynamics can also have implications for CP violating signals. Many signals of direct CP violation require two different amplitudes having non-trivial weak and strong phase difference to reach a given final state. Final state hadron dynamics is a vital part of this proposal providing non-zero strong phase shifts. Unfortunately, the impact of the final state hadronic rescattering cannot be described in perturbative QCD and therefore calls for a model-dependent description.

All of the observed nonleptonic D decays are dominated by the tree-level amplitudes in which a W-boson, emitted in the $c \to (s, d)$ transition, converts to the pair $\bar{q}_1 q_2$. It, however, involves quarks only of the first two generations in the initial, final and intermediate states. In order for the CP violating processes to occur, quarks of the third generation must somehow affect the decay amplitude. While trivially realized in the decays of B mesons, this poses a serious problem in the search of CP violation in charm decays. Normally, the solution is found in the virtual (and therefore suppressed) effects associated with the intermediate state b-quarks, the so-called penguin amplitudes. This mechanism indeed provides two distinct amplitudes with nontrivial weak and strong phase difference. The penguin amplitude in charm decays is however too small to provide significant CP violating effects. This complicates the extraction of relevant CP violating asymmetries.

Here we shall study the importance of another possibility, that the initial D meson converts weakly to a nearby resonance which then decays nonleptonically. As will be explained later, the presence of strong phases, as well as the possibility of having different weak phases, makes the interference of the tree and nearby-resonance amplitudes an interesting candidate for generating direct CP violating asymmetries [7].

II. NEARBY RESONANCES AND CP VIOLATION IN CHARM

Many signals of direct CP violation in D mesons often involves the asymmetry

$$a_{\rm CP} \equiv \frac{,_{D\to f} - ,_{\bar{D}\to\bar{f}}}{,_{D\to f} + ,_{\bar{D}\to\bar{f}}} \quad . \tag{1}$$

For the theoretical studies of direct CP violation, one selects final states that can be reached from at least two different routes. That is, one identifies final states reachable by weak decay amplitudes bearing different weak phases which can be connected by non-trivial strong rescattering. In charmless B-decays the two different weak amplitudes are typically associated with the tree and penguin transitions. Despite the years of effort and sizable branching ratios, attempts to measure CP violating asymmetries in D decays have yielded only null results. Whether or not direct CP violation will be seen for B mesons could depend on the strength of final state interaction effects. While the proof that these are not *necessarily* small [8] has been buttressed by evidence for FSI's in $B \to D^* \rho$ transitions [9], whether or not they are appreciable in any given mode remains problematic. In charm decays, final state rescattering effects are expected to be appreciably large due to the fact that the D meson mass lies in the region populated by the light quark resonances and have been observed experimentally. Therefore, final state phase does not pose a problem for the observation of direct CP violating effects in charmed meson decays. As will be discussed below, it is the fact that the Cabibbo part of the CKM matrix is "almost" unitary (i.e. weak phase effects in charmed decays are tiny) that makes the observation of CP violating effects problematic.

In the Standard Model, weak decays of charm quarks are mediated by the local $\Delta C = 1$ effective Hamiltonian

$$\mathcal{H}_W^{\Delta C=1} = \frac{G_F}{\sqrt{2}} \left[C_1(\mu) \bar{u}_j ,^{\rm L}_\mu \psi_k^{(u)} \bar{\psi}_k^{(c)} ,^\mu_{\rm L} c_j + C_2(\mu) \bar{u}_j ,^{\rm L}_\mu \psi_j \bar{\psi}_k ,^\mu_{\rm L} c_k - V_{ub} V_{cb}^* \sum_{i=3}^{6} C_i O_i \right] + \text{H.c.} \ , \tag{2}$$

with

$$O_{\substack{3\\5}} = \bar{u}_i ,^L_\mu c^i \sum_q \bar{q}_k ,^{\substack{L\\R}}_\mu q^k \ , \qquad O_{\substack{4\\6}} = \bar{u}_i ,^L_\mu c^k \sum_q \bar{q}_k ,^{\substack{L\\R}}_\mu q^i \ , \tag{3}$$

and where the subscripts are color labels, $,^{\rm L}_\mu \equiv \gamma_\mu (1 + \gamma_5)$, and we define

$$\psi^{(u)} \equiv V_{us}\ s + V_{ud}\ d \ , \qquad \bar{\psi}^{(c)} \equiv V_{cs}^*\ \bar{s} + V_{ud}^*\ \bar{d} \ . \tag{4}$$

The $C_i(\mu)$ are scale-dependent Wilson coefficients, $C_1(m_c) \simeq -0.514$ and $C_2(m_c) \simeq 1.270$, in a 'scheme-independent' NLO prescription [10].

If nearby resonances turn out to be a significant source of $D^0 - \bar{D}^0$ mixing, then they could potentially impact on CP violating signals like asymmetries. In particular, they might be a vital part of the following mechanism for generating CP-violating asymmetry of Eq.(1). Let us for definetness consider the decay mode $D^+ \to K^+ \bar{K}^0$. The decay amplitude can be decomposed as

$$\mathcal{A}(D^+ \to K^+ \bar{K}^0) = \mathcal{A}_T + \mathcal{A}_P + \mathcal{A}_A \tag{5}$$

which basically indicates that there are contributions form the tree-level $\mathcal{A}_T$, penguin $\mathcal{A}_P$, and weak annihilation $\mathcal{A}_A$ amplitudes. In general, all these amplitudes are represented by complex numbers.

In order to clarify our point it is worth recalling similar situation occurring in B decays. There, the celebrated penguin-tree amplitude interference assures that the CP-violating asymmetry, similar to the one defined in (1), is non-zero: the part of CKM matrix relevant to the third quark generation is directly probed by the tree-level transition $b \to u\bar{u}d(s)$ (this part provides a nontrivial weak phase), whereas a one-loop penguin amplitude generates part of the amplitude with trivial weak phase ($b \to d(s)u\bar{u}$ with top quark running in the penguin loop). This weak phase difference, supplemented with, for example, Bander-Silverman-Soni mechanism [11] (see, however, [8,12,13]) for the generation of strong phase difference provides all necessary conditions for the non-zero CP violating asymmetry. This asymmetry might be appreciably large if these two amplitudes are comparable in size. This is indeed the case in B decays where the size of the large tree-level amplitude is attenuated by the small value of the weak CKM factor $V_{ub} V_{ud(s)}^*$ whereas small value of the loop-induced penguin diagram[1] is almost unchanged by the corresponding weak CKM factor $V_{tb} V_{td(s)}^*$. The interference of the tree and penguin amplitudes is proportional to

[1]This information is directly encoded in the values of the Wilson coefficients of the weak effective Hamiltonian.

$$V_{tb}V_{ts}^* V_{ub}V_{us}^* \bar{A}_T \bar{A}_P \sim \lambda^6 \bar{A}_T \bar{A}_P \tag{6}$$

where the superbars in $\{\bar{A}_i\}$ indicate that CKM factors have been extracted. If compared to the branching ratio, it is suppressed by a factor of λ^2 in the Wolfenstein parameterization of CKM.

Implementing similar mechanism in charm decays one immediately makes the following observation. The weak decays of the charmed quarks involve only the quarks of the first two generations in the initial and final state. Therefore, the only way to include quarks of the third generation is via the virtual effects in the penguin loop. Clearly, in charm quark decays the non-trivial phase is suppressed by both loop factors of the penguin amplitude *and* a small combination of the CKM matrix elements, so CP asymmetry is guaranteed to be small for moderate values of the decay branching ratio. Indeed, for the decay $D^+ \to K^+\bar{K}^0$ the effect of the tree-penguin interference naively scales as

$$V_{us}V_{cs}^* V_{ub}V_{cb}^* \bar{A}_T \bar{A}_P \sim \lambda^6 \bar{A}_T \bar{A}_P. \tag{7}$$

More importantly, if compared to the branching ratio, this amplitude is suppressed by a factor of λ^4 in the Wolfenstein parameterization of CKM.

An interesting effect can be observed if we accept the fact that CP violating effect in D decays is in fact suppressed by λ^4 (i.e. exclude for a moment a possibility of the phases associated with the New Physics contributions) and try to search for other Standard Model effects that might enhance or suppress a_{CP} of Eq. (1). Let us build an asymmetry Eq. (1) from the amplitude Eq. (5). If we assume that all three components of Eq. (5) are some complex numbers we find

$$a_{CP}(D^+ \to K^+\bar{K}^0) = 4\lambda_f \frac{Im\xi_b^*\xi_s \; Im\left(\bar{A}_T\bar{A}_P^*\right) + Im\xi_s^*\xi_d \; Im\left(\bar{A}_T\bar{A}_A^*\right) + Im\xi_b^*\xi_d \; Im\left(\bar{A}_P\bar{A}_A^*\right)}{,\,(D^+ \to K^+\bar{K}^0) + ,\,(D^- \to K^-K^0)} \tag{8}$$

where λ_f represents a two-body phase space of KK and ξ_i are the combinations of the CKM matrix elements defined as $\xi_i = V_{ui}V_{ci}^*$. The first term of Eq. (8) is the familiar tree-penguin interference. Note however, that more interesting information can be extracted from the second term, the tree-annihilation interference. For this term to be non-zero, both nontrivial weak and strong phase difference must be present. Below we show that this is exactly the case.

First of all we notice that tree and weak annihilation amplitudes contribute with the different CKM matrix element combinations, $\mathcal{A}_T(D^+ \to K^+\bar{K}^0) = \xi_s\bar{A}_T$, whereas $\mathcal{A}_A(D^+ \to K^+\bar{K}^0) = \xi_d\bar{A}_A$. Since the Cabibbo part of the CKM matrix is not unitary, i.e.

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0, \text{ or } \xi_d + \xi_s + \xi_b = 0, \tag{9}$$

the weak phase is induced, $Im\xi_s^*\xi_d = -Im(|\xi_s|^2 + \xi_s^*\xi_b) = -Im\xi_s^*\xi_b \neq 0$. In fact, it is exactly the same as in the case of the tree-penguin interference of Eq. (7). Therefore, *no* additional weak suppression exists for the tree-annihilation interference. This situation is unique for the charm weak decays.

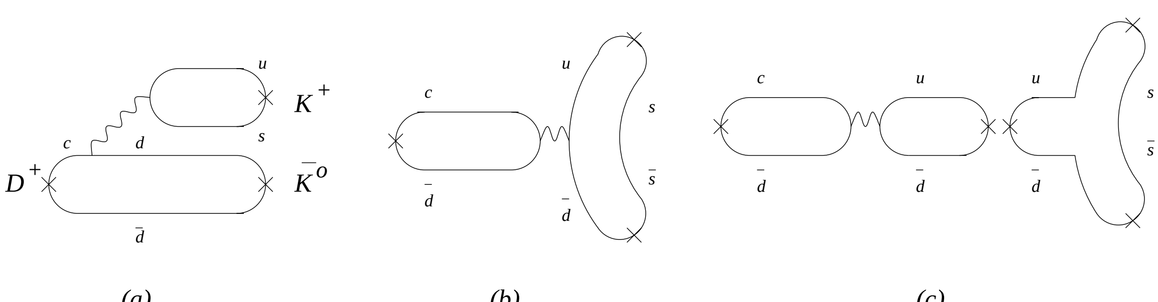

FIG. 1. Leading order diagrams ($\mathcal{O}(N_c^{1/2})$): (a) tree, (b) weak annihilation, (c) weak annihilation and final state rescattering via D – light quark resonance mixing mechanism.

Strong phases of $\bar{A}_T$ and $\bar{A}_A$ are different as well. This strong phase difference, however, cannot be generated in perturbative QCD. But the fact that this phase difference exists can be readily illustrated. At the very least, a part of the annihilation amplitude can be viewed as a mixing of the D mesons with the nearby resonance with subsequent strong resonance decay into the final state (see, for example, Fig. (1)). The strong phase is generated by the non-zero resonance width (for the nearby resonance it is *not* suppressed by $1/m_c^2$). This effect is absent in the tree amplitude which shows the existence of the nontrivial strong phase difference. Indeed, the above explanation should be taken only as indication of the existence of this phase difference. Any realistic value for the strong phase shift should be calculated by taking into account all possible nonperturbative effects. In fact, even though the diagrams of Fig. (1) provide leading contribution to the amplitude of $D \to KK$ decay, they do not generate strong phase at leading order in $1/N_c$. This is due to the fact that the resonance width, which provides CP concerving phase, is itself of the order $1/N_c$. Therefore, subleading diagrams must also be taken into account to generate strong phase difference [7]. While model-independent calculation is not possible at the time [14], model calculations should hint the size of the expected phase. Calculating the asymmetry one arrives at the bound, $a_{CP} < 10^{-3}$. We would like to emphasize that the considered effect implies non-zero value for the CP violating asymmetry even in the penguin amplitude is *absent* or suppressed. The third term of Eq. (8) involves penguin-annihilation interference and, in spite of the fact that it scales with λ as the previous two terms, can be discarded.

III. CONCLUSIONS

We have studied CP violation in charm decays. In particular we assesed the impact of the final state hadron dynamics on the patterns of CP violation in D decays, the main source of uncertainty in the predictions of CP violating asymmetries. In particular, we suggested a new interference mechanism for generating non-zero value for the CP violating asymmetry. Due to the fact that the energy scale associated with charmed mesons is uniquely located in the region of the QCD spectrum populated by the hadronic resonances, it is possible to generate CP violating asymmetry via the so-called "tree-annihilation" mechanism.

Clearly, with the new data coming from the running and completed FNAL experiments and CLEO, as well as upcoming data from B factories, new and exciting results should be expected in the area of charm decays and CP violation.

[1] J.F. Donoghue, Phys. Rev. **D33**, 1516 (1986).
[2] A. Datta and M.Khambakhar, Zeit. Phys., **C27**, 515 (1985).
[3] A.A. Petrov, Phys. Rev. **D56**, 1685 (1997).
[4] J. Donoghue, E. Golowich, B. Holstein and J. Trampetic, Phys. Rev., **D33**, 179 (1986).
[5] L. Wolfenstein, Phys. Lett., **B164**, 170 (1985).
[6] E. Golowich and A.A. Petrov, Phys. Lett. **B 427**, 172 (1998).
[7] E. Golowich and A.A. Petrov, Preprint JHU-TIPAC-98014, in preparation.
[8] J.F. Donoghue, E. Golowich, A.A. Petrov and J.M. Soares, Phys. Rev. Lett. **77**, 2178 (1996).
[9] See e.g. C. Rodrigues, talk given at "Heavy Quarks 98".
[10] F. Buccella, M. Lusignoli and A. Pugliese, Phys. Lett., **B 379**, 249 (1996).
[11] M. Bander, D. Silverman, A. Soni, Phys. Rev. Lett. **43**, 242 (1979).
[12] A.F. Falk, A.L. Kagan, Y. Nir, and A.A. Petrov, Phys. Rev. **D57**, 4290 (1998).
[13] D. Atwood and A. Soni, Phys. Rev. **D57**, 036005 (1998).
[14] A.J. Buras, J.-M. Gerard and R. Ruckl, Nucl. Phys., **B268**, 16 (1986).