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Charm CP: ΔA_{CP} and Radiative decays

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Motivated by the very important discovery of CP violation in charm-decays for the first time, by the LHCb collaboration, the role of nearby resonances such as the scalar $f_0(1710)$ in accounting for the observed CP is discussed. It is suggested that the influence of such a resonance may also explain the long-standing puzzle of such a large breaking of SU(3) seen in its decays. It is also explained that intervention of such resonance(s) will render first principles calculations of ΔA_{CP} rather difficult. Instead, it is proposed that searches for CP violation in simple radiative final states, such as $D^0 \to \gamma\phi[\to K^+K^-]$, $D^0 \to l^+l^-\pi$ etc. has much better chance of theoretical precision studies and therefore theoretical and experimental investigations therein are strongly urged.

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1. Introduction and Motivation

Recently LHCb made an exciting discovery of direct CP violation in D^0 decays. Understanding CP violation is extremely important as naturalness arguments strongly suggest extensions of the SM should entail new CP-odd phases. Moreover, it seems very difficult to quantitatively understand the observed baryogenesis based on SM-CKM paradigm. To search for effects of new physics though requires comparison of SM prediction with experiment. Unfortunately, this is usually a very difficult challenge for theory as direct CP violation entails non-perturbative effects. A famous example is the direct CP violation parameter for $K \to \pi\pi$, ε' wherein after decades of effort significant progress in first principles calculation [1, 2] is being made.

For addressing $D^0 \to h^+ h^-$ ($h = K, \pi$), these established methods based on [3] are unlikely to be applicable primarily because m_D is so much larger than $2 \times m_\pi$ and in fact when D^0 decays it can and therefore will readily go to multi-particle final states.

One may be tempted to think that at m_D, SU(3) flavor symmetry [strictly speaking what is relevant is U-spin $(d - s)$ symmetry] may be valid to a good approximation and result in a cancellation between multi-particle states but we suggest that this is unikely to be the case because of intricate non-perturbative dynamics [4] as will be explained later and in fact, even more importantly, is exhibited in the experimental data [5] on D^0 decays.

In this work we make the following main points:

1) As explained in [6] scalar and pseudoscalar resonances near m_D play an important role in ΔA_{CP} [7] as well as in the decays of D-mesons.

2) Crude phenomenological estimates [6] appear to suggest that the observed size of ΔA_{CP} with the influence of a neighboring resonance is roughly consistent with expectations from the SM but more accurate and reliable calculations are highly desirable. However, the presence of these resonances is likely to complicate even further first principles calculations of Δ_{ACP} [7]

3) It is also suggested that these neighboring resonances are likely to be playing a role in significantly enhancing the SU(3) breaking seen in D^0 decays.

4) Attention is drawn to radiative decays of D^0, for example, $D^0 \to \gamma\rho^0(\to \pi^+\pi^-)$, $D^0 \to \gamma\phi(\to K^+K^-)$ [6][1]. In contrast to D^0 decays to hadronic final states, these radiative channels are more amenable to lattice calculations. The photons are quite energetic and the remaining energy in the hadron system is around a GeV or less so current techniques for tackling LD issues [8] have a good chance of being applicable.

2. LHCb observation of ΔA_{CP}

As is well known, for the past many years the LHCb collaboration has been trying to improve their search of direct CP asymmetries in $D^0 \to K^+K^-$ and in $\pi^+\pi^-$. In March 2019 at EW Moriond, they announced their important discovery [7],

$$\Delta A_{CP} \equiv [A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)]$$
$$= (-15.4 \pm 2.9) X 10^{-4} \tag{2.1}$$

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[1]Work in progress with Stefan Schacht

which represents a 5.3 σ signal of *direct* CP violation in charm decays. This result from LHCb is the first clear observation of CP violation (CPV) in the charm system and joins previous signals in K and in B-systems.

3. Back of the envelope estimate of ΔA_{CP}

A particularly important process for CP violation is the $c \to u$ penguin graph, especially wen the b-quark is in the penguin loop. Then, in the standard Wolfenstein parametrization [9] the V_{ub} vertex is a very important source for the CP-odd phase in the CKM matrix.

An extremely important point to understand is that in charm decays the penguin contribution is extremely small for several reasons. When the d and s are inside the penguin then these tend to cancel to some degree as forced by the approximate orthogonality of the 2×2 sub-matrix due to the 1st two generations and because of approximate SU(3) symmetry. The b contribution is severely CKM-suppressed by the presence of $V_{ub} \times V_{cb}^*$. For the singly Cabibbo suppressed modes such as $D^0 \to K^+ K^-$ that CKM-combination should be compared with $\sin_{\theta_{Cabibbo}} \approx 0.225 \approx \lambda$, the Wolfenstein-parameter which enters the tree decay. Since V_{ub} goes as λ^3 and V_{cb} as λ^2, the charm penguin is extremely small compared to the tree and $[penguin[P]/tree[T]] \approx \lambda^4 \approx 10^{-3}$ which is approximately the size of the expected CP-asymmetry in charm decays. However, by judiciously choosing some modes, for example, color suppressed modes [10, 11], one can get somewhat larger asymmetries by factors of order a few, $N = 3$.

Also, since partial rate asymmetry [PRA] defined as,

$$\alpha_{PRA} = (BR[I \to F] - BR[\bar{I} \to \bar{F}])/(BR[I \to F] + BR[\bar{I} \to \bar{F}]) \tag{3.1}$$

the PRA tends to go $\alpha_{PRA} \propto [1/\sqrt{(Br)}]$ because P is so small compared to T.

4. Possible role of resonances in charm decays

4.1 Large SU(3) breaking in D^0 decays

Resonances in the charm region can enter weak decays through the weak Hamiltonian and influence charm decays. Here, in particular we want to draw attention to the scalar, f_0 with mass, $m_{f_0} = 1723 MeV$ and width, $\Gamma_{f_0} = 139 MeV^2$. Note also that it has appreciable Br into $K^+ K^-$ and $\pi^+ \pi^-$, $\approx 40\%$ and $\approx 16\%$.

Now looking at Morningstar and Peardon's review [12] on glueball spectrum, it seems that f_0 at 1723 MeV is very likely rather rich in gluonia content. If this interpretation is correct, then f_0 has a very interesting consequence. It was noted long ago [4] that the low-lying scalar and pseudoscalar glueballs couple to light quarks in proportion to their (constituent) mass. The gluonic interpretation of the f_0 would then also help understand the large breaking of SU(3) in its decays,

$$Br[f_0 \to K + K^-]/[f_0 \to \pi^+ \pi^-] \approx 2.5 \tag{4.1}$$

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[2]See PDGLIVE

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In turn this breaking anticipated in [4] would help understand the large factor of ≈ 2.8 seen in D^0 decays to K^+K^- versus $\pi^+\pi^-$[3]. It has been rather difficult to understand such a large SU(3) breaking in D^0 decays for a very long time. What factorization of tree amplitudes for these decays readily gives is that the breaking should go as the ratio of decay constants, $[f_k/f_\pi]^2 \approx 1.7$ which goes in the right direction but falls considerably short of the observed 2.8. But now with the factor of 2.5 originating above in gluon dynamics strongly suggests that this long standing mystery may now be resolved through $D^0 - f_0$ mixing.

4.2 f_0 and ΔA_{CP}

It was suggested long ago [14, 15] that resonances can be used to estimate CP asymmetries. The main point is that in a channel which is dominated by a resonance, the measured width of the resonance contains the information about the rescattering phase that is needed for computing the CP-violating rate asymmetry in that channel.
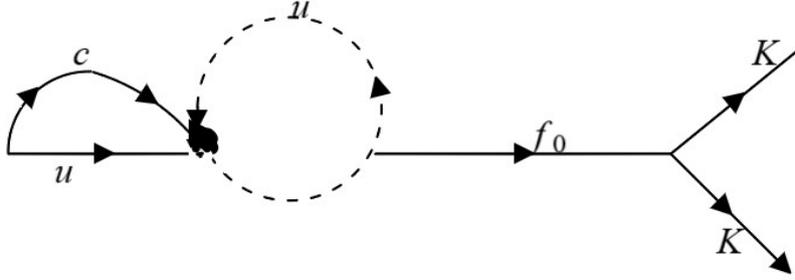
Figure 1: D^0 decay proceeding to a final state such as K^+, K^- (or $\pi^+\pi^-$) via a resonance *e.g* f_0; the weak 4-quark operator leads to the annihilation of the D^0 and the creation of a u-quark pair which forms f_0.

We can use this idea for D^0 decays to KK and $\pi\pi$ via the f_0. The key point to notice is that the 4-quark penguin operators have, in the conventional notation, Q_5 and Q_6, LXR operators which, on Fierz rearrangement contain $(S+P) \times (S-P)$ where $S = scalar$ and $P = pseudoscalar$. Thereby, for instance, PS can annihilate a D^0 and create a f_0. The f_0 then propagates and travels for a brief instant and then decays to the final state. This is depicted in fig. 1. This leads to a rough estimate [6][4],

$$\alpha_{KK} \approx 5.5 \times 10^{-4} \tag{4.2}$$

. It is important to understand that while for simplicity, only the coupling of f_0 to Q_6 is emphasized, of course in a complete calculation coupling of all the operators in H_{eff} and other neighboring scalar and pseudoscalar resonances should all be be taken into account.

Note also that there is a possibility that more nearby resonance(s) will be firmly established [17, 18][5] and then their effect may also need be included.

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[3]See also [13]

[4]See also [16]

[5]I want to thank Sheldon Stone for pointing out this higher resonance

Mode	BR (10^{-3})	Current PRA bound (10^{-2})	Predicted in resonance model (10^{-4})
K^+K^-	$3.97 \pm .07$	-0.07 ± 0.11	≈ 5.5
K_sK_s	0.17 ± 0.012	-0.4 ± 1.5	≈ 13.2
$\pi^+\pi^-$	1.407 ± 0.025	0.13 ± 0.14	≈ 5.8
$\pi^0\pi^0$	0.822 ± 0.025	0.0 ± 0.6	≈ 7.5

Table 1: Br and CP asymmetries in the resonance model

4.3 CPT restrictions

CPT theorem puts important constraint on PRAs since it requires that the total lifetime of particle and antiparticle must equal each other [19, 20, 10] Thus PRAs in certain channels have to have opposite signs for the required cancellation to take place. As a simple illustration consider the quark level processes: $c \to su\bar{u}$ versus $c \to du\bar{u}$. CPT theorem requires that the PRAs in these two channels must cancel, so they have to have an opposite sign.

As a result of this quark-level constraint we expect that the PRA for $D^0 \to \pi^+\pi^-$ must have an opposite sign to that for $D^0 \to K^+K^-$. So, as a consequence the two asymmetries entering into ΔA_{CP} add.

Another important consequence of CPT is that self-rescatterings (into the same final state) cannot generate PRAs. In other words, PRA for $c \to su\bar{u}$ arises from on-shell scattering of $c \to du\bar{u}$ and vice-versa. But that restriction is only relevant for PRA, thus in final states with 3 or more particles in there conjugate channels CP violating energy asymmeteries can arise and these can come about from self-rescattering effects.

Table 1 summarizes our expectations of PRAs in the four prominent 2-body channels.

4.4 Resonance(s) influencing ΔA_{CP} and lattice calculations

The Lellouch-Lusher [3] method for calculating finite volume correlation functions that is currently being used for $K \to \pi\pi$ [1] cannot directly be used for $D^0 \to KK(\pi\pi)$. Since m_D is about 1.86 GeV, D^0 can readily decay to multiparticle final states which are rather challenging to handle on the lattice. To the extent that LHCb experiment has positive signal for ΔA_{CP} which measures the *difference* in PRAs between K^+K^- and $\pi^+\pi^-$ final states, one may think that flavor symmetry [Uspin] may provide a basis for (approximate) cancellation between multiparticle states. But this is unlikely to hold since experimental data on D^0 decays shows large breaking of SU(3). Moreover, if the resonance hypothesis holds then there are even dynamical reasons to suggest such large breakings of SU(3).

5. Candidates for precision testing the SM

Given that D^0 decays are in the region which is highly susceptible to long-distance non-perturbative effects it prompts one to think of simpler final states where first principles methods may have a better chance of success and also where experimental signals would not be too challenging. This thinking leads us to suggest radiative decays of D^0, i.e. $D^0 \to \gamma + h_f$ where h_f stands for simple final states such as K^+K^-, $\pi^+\pi^-$ etc. It may well be that the relevant hadronic final state is being influenced by nearby resonance(s). For example $\phi \to K^+K^-$ and or $\rho \to$

$\pi^+\pi^-$. These radiative decays have attracted considerable phenomenological interest for a long time [21, 22, 23, 24, 25, 26, 27]. Study of radiative decays of D^0 may also reveal other resonances, for example, $\omega(1650)$, $\phi(1680)$, $\rho(1702)$ [5] etc. In passing, we note also that recently lattice methods are being able to address calculation of light meson scattering phases [28, 29, 30, 31, 2, 32] in the $\approx$ GeV region.

6. Summary

It is suggested that scalar and pseudoscalar resonances near m_D are playing an important role in the recently observed direct CP in charm decays by LHCb. The presence of these resonances is likely to make first principle calculations even harder. It is also suggested that these resonances are very likely playing an important role in the large observed SU(3) breaking. For first principle calculations, with an intent for precision tests of the Stndard Model, it may be better to focus on radiative decays such as $D^0 \rightarrow \gamma K^+K^-$, $\gamma\pi^+\pi^-$ or $D^0 \rightarrow K(\pi)l^+l^-$.

References

[1] RBC, UKQCD collaboration, *Standard Model Prediction for Direct CP Violation in K Decay*, *Phys. Rev. Lett.* **115** (2015) 212001 [1505.07863].

[2] C. Kelly and T. Wang, *Update on the improved lattice calculation of direct CP-violation in K decays*, in *37th International Symposium on Lattice Field Theory (Lattice 2019) Wuhan, Hubei, China, June 16-22, 2019*, 2019, 1911.04582.

[3] L. Lellouch and M. Luscher, *Weak transition matrix elements from finite volume correlation functions*, *Commun. Math. Phys.* **219** (2001) 31 [hep-lat/0003023].

[4] J. M. Cornwall and A. Soni, *COUPLINGS OF LOW LYING GLUEBALLS TO LIGHT QUARKS, GLUONS, AND HADRONS*, *Phys. Rev.* **D29** (1984) 1424.

[5] PARTICLE DATA GROUP collaboration, *Review of Particle Physics*, *Phys. Rev.* **D98** (2018) 030001.

[6] A. Soni, *Resonance enhancement of Charm CP*, 1905.00907.

[7] LHCB collaboration, *Observation of CP violation in charm decays*, 1903.08726.

[8] RBC, UKQCD collaboration, *Long distance contribution to the KL-KS mass difference*, *Phys. Rev.* **D88** (2013) 014508 [1212.5931].

[9] L. Wolfenstein, *Parametrization of the Kobayashi-Maskawa Matrix*, *Phys. Rev. Lett.* **51** (1983) 1945.

[10] D. Atwood and A. Soni, *Searching for the Origin of CP violation in Cabibbo Suppressed D-meson Decays*, *PTEP* **2013** (2013) 093B05 [1211.1026].

[11] U. Nierste and S. Schacht, *Neutral D → KK* decays as discovery channels for charm CP violation*, *Phys. Rev. Lett.* **119** (2017) 251801 [1708.03572].

[12] C. J. Morningstar and M. J. Peardon, *The Glueball spectrum from an anisotropic lattice study*, *Phys. Rev.* **D60** (1999) 034509 [hep-lat/9901004].

[13] H.-Y. Cheng and C.-W. Chiang, *SU(3) symmetry breaking and CP violation in D -> PP decays*, *Phys. Rev.* **D86** (2012) 014014 [1205.0580].

[14] G. Eilam, J. L. Hewett and A. Soni, *CP asymmetries induced by particle widths: Application to top quark decays*, *Phys. Rev. Lett.* **67** (1991) 1979.

[15] D. Atwood and A. Soni, *Influence of kaonic resonances on the CP violation in B —> K* gamma like processes*, *Z. Phys.* **C64** (1994) 241 [hep-ph/9401347].

[16] H.-n. Li, C.-D. Lu and F.-S. Yu, *Branching ratios and direct CP asymmetries in $D \to PP$ decays*, *Phys. Rev.* **D86** (2012) 036012 [1203.3120].

[17] BES collaboration, *Resonances in J / psi —> phi pi+ pi- and phi K+ K-*, *Phys. Lett.* **B607** (2005) 243 [hep-ex/0411001].

[18] LHCB collaboration, *Measurement of resonant and CP components in $\bar{B}_s^0 \to J/\psi\pi^+\pi^-$ decays*, *Phys. Rev.* **D89** (2014) 092006 [1402.6248].

[19] J.-M. Gerard and W.-S. Hou, *CP Nonconservation and CPT: A Reassessment of Loop Effects in Charmless B Decays*, *Phys. Rev. Lett.* **62** (1989) 855.

[20] D. Atwood, S. Bar-Shalom, G. Eilam and A. Soni, *CP violation in top physics*, *Phys. Rept.* **347** (2001) 1 [hep-ph/0006032].

[21] A. Khodjamirian, R. Ruckl, G. Stoll and D. Wyler, *QCD estimate of the long distance effect in B —> K* gamma*, *Phys. Lett.* **B402** (1997) 167 [hep-ph/9702318].

[22] C. W. Bernard, P. Hsieh and A. Soni, *B —> K* + gamma and B(s) —> phi + gamma on the lattice*, *Phys. Rev. Lett.* **72** (1994) 1402 [hep-lat/9311010].

[23] M. Beneke, T. Feldmann and D. Seidel, *Systematic approach to exclusive $B \to Vl^+l^-$, $V\gamma$ decays*, *Nucl. Phys.* **B612** (2001) 25 [hep-ph/0106067].

[24] G. Isidori and J. F. Kamenik, *Shedding light on CP violation in the charm system via D to V gamma decays*, *Phys. Rev. Lett.* **109** (2012) 171801 [1205.3164].

[25] S. de Boer and G. Hiller, *Rare radiative charm decays within the standard model and beyond*, *JHEP* **08** (2017) 091 [1701.06392].

[26] S. de Boer and G. Hiller, *The photon polarization in radiative D decays, phenomenologically*, *Eur. Phys. J.* **C78** (2018) 188 [1802.02769].

[27] N. Adolph, G. Hiller and A. Tayduganov, *Testing the standard model with $D_{(s)} \to K_1 (\to K\pi\pi)\gamma$ decays*, *Phys. Rev.* **D99** (2019) 075023 [1812.04679].

[28] T. Janowski, P. A. Boyle, A. Jüttner and C. Sachrajda, *K-pi scattering lengths at physical kinematics*, *PoS* **LATTICE2014** (2014) 080.

[29] R. A. Briceno, J. J. Dudek, R. G. Edwards and D. J. Wilson, *Isoscalar $\pi\pi$ scattering and the σ meson resonance from QCD*, *Phys. Rev. Lett.* **118** (2017) 022002 [1607.05900].

[30] R. A. Briceno, J. J. Dudek, R. G. Edwards and D. J. Wilson, *Isoscalar $\pi\pi, K\overline{K}, \eta\eta$ scattering and the σ, f_0, f_2 mesons from QCD*, *Phys. Rev.* **D97** (2018) 054513 [1708.06667].

[31] G. Rendon, L. Leskovec, S. Meinel, J. Negele, S. Paul, M. Petschlies et al., *$K\pi$ scattering and the $K^*(892)$ resonance in 2+1 flavor QCD*, in *36th International Symposium on Lattice Field Theory (Lattice 2018) East Lansing, MI, United States, July 22-28, 2018*, 2018, 1811.10750.

[32] D. Hoying, *Pion-pion scattering with physical quark masses*, *PoS* **LATTICE2018** (2019) 064.