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A Strong QCD Enhancement of CP Violation in Charmed Meson Decays?

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Abstract

The mass difference of c and u quarks is similar to the energy needed to excite gluonic degrees of freedom in strong QCD. This underpins the degeneracy of D and a recently observed candidate hybrid excitation of the π at$\sim$ 1.8GeV and may generate a strong analogue of Penguin mixing together with a measurable CP-violation in D and D_s decays.

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The asymmetric decays of K-mesons and, possibly, our existence (via the baryon antibaryon asymmetry of the universe) are to date the only direct evidence for CP-violation. The confirmation of three generations of quarks and leptons encourages the suspicion that CP violation may be intimately related to the presence of a phase in the CKM matrix and be large in the third generation B-system. In this standard model the charm sector is not expected to show significant CP violation effects, the asymmetry for the $D^0 \to K^+K^-$ mode being at most a few 10^{-3}[1].

We point out here that the recent confirmation of a nonstrange 0^{-+} meson resonance with the quantum numbers of a pion[2, 3, 4, 5] and, at 1.8GeV mass, in the vicinity of the D-mass, raises the possibility that D decay branching ratios may be influenced by the presence of this resonance. Furthermore, hints that this resonance is a hybrid[6, 7, 8] (where the gluon degrees of freedom are excited in the presence of ground state $q\bar{q}$) degenerate with the D may enhance the gluonic penguin diagrams in D-decays and lead to observable CP violating effects in channels such as $\pi\pi\pi$, $\pi K\bar{K}$, $\pi\eta\eta$ in S-wave which D and $\pi(1.8)$ share in common. Such an eventuality would have far reaching implications: it would provide a new window into CP violation, and also help to shed light on the dynamics of strong QCD which remains one of the least understood parts of the standard model.

The large number of open channels available for Cabibbo-suppressed D-decays into nonstrange final states enable conclusive experimental investigations. The first step is to examine the relative branching ratios of the D and this $\pi(1.8)$ resonance to see if there are any common unexpected systematics. There are not yet enough data for any reliable conclusions, but it is interesting that in both cases the 3π decay mode shows no signal for $\rho\pi$ and may be dominated by final states in which two of the pions are in S-wave. The dominant decay modes observed for the $\pi(1.8)$ resonance are in $\pi\pi\pi$ and $(\pi K\bar{K})_s$ with significant contribution from $\pi f_0(1300)$ and $\pi f_0(980)$ (where $f_0(1300)$ is the broad $\pi\pi$ S-wave structure discussed in ref.[5]). So far $D^+ \to \pi^+\pi^+\pi^-$ has been measured, but its small branching ratio $\approx 3 \times 10^{-3}$ and limited statistics means that there has not yet been a conclusive Dalitz plot analysis; (we are informed that this analysis is now in progress and hopefully data will be available soon[9]). The $\pi\eta\eta$ and $\pi\eta\eta'$ decay modes for the $\pi(1.8)$ resonance have been seen[10, 11][1], the $\eta\eta\pi^-$ decays occurring at a level of $50 \pm 10\%$ of $\pi^+\pi^-\pi^-$[11]. This mode has not yet been looked for in D decay. If it is there also at a level of $\sim 50\%$ of 3π, it could be sought at CLEO and provide further information on the relation between D decays and the $\pi(1.8)$ meson resonance.

From the hadron spectroscopy point of view, the possible existence of socalled "exotic" hadrons like glueballs and hybrids is still an exciting open question [12, 14, 13]. Radiative J/ψ decays have been suggested as a good channel for glueball searches because they produce hadrons via a gluonic intermediate state. Similarly heavy quark meson decays via penguin diagrams could provide a good channel for hybrid (quark-antiquark-gluon) mesons because they produce hadrons via a quark-antiquark-gluon intermediate state. The penguin contributions have generally been considered to be negligibly small in charm decays. However, if the penguin contribution is enhanced by the presence of a hybrid resonance near the D mass, there may be an appreciable penguin-tree interference contribution which might also have a CP-violating relative phase. Using the relative strengths of penguin and tree contributions predicted by the CKM matrix elements, a very large enhancement of the penguin would be needed to give observable CP-violating effects. However, the relative strength predictions have not yet been confirmed by experiment, and there may be

[1]This state is listed in the Particle Data Tables as $X(1830)$ with $J^{PC} = 2^{-+}$ preferred. However, it is now established as 0^{-+}[2, 11] and identical to the $\pi(1770)$ of refs[4, 5]

additional enhancements resulting from physics beyond the standard model. Thus at this stage we keep all options open and concentrate on ways of using available data to search for evidence for influence of the resonance on D decays.

We now examine in detail the contributions of the Cabibbo-suppressed tree and penguin diagrams to 3π and $K\bar{K}\pi$ final states. For the 3π final state the tree diagrams give

$$D(c\bar{q}_s) \to d + W^+ + \bar{q}_s \to (du\bar{d})\bar{q}_s \to 3\pi \tag{1}$$

where the relevant weak vertex is $c \to d + W^+ \to (du\bar{d})$ and $\bar{q}_s$ denotes a spectator $\bar{u}$ or $\bar{d}$. The penguin diagrams give

$$D(c\bar{q}_s) \to b + W^+ + \bar{q}_s \to u\bar{q}_s G \to 3\pi \tag{2}$$

where the relevant weak vertex is $c \to b + W^+ \to u\bar{q}_s G$ and G denotes a gluon. The relevant weak vertices for the Cabibbo suppressed tree transition and the penguin transition are seen to involve two different combinations of CKM matrix elements. Thus the tree-penguin interference term can exhibit CP violation in the standard model.

For the $K\bar{K}\pi$ final state the tree diagrams give

$$D(c\bar{q}_s) \to s + W^+ + \bar{q}_s \to (su\bar{s})\bar{q}_s \to K\bar{K}\pi \tag{3}$$

where the relevant weak vertex is $c \to s + W^+ \to (su\bar{s})$. The penguin diagrams give

$$D(c\bar{q}_s) \to b + W^+ + \bar{q}_s \to u\bar{q}_s G \to K\bar{K}\pi \tag{4}$$

where the relevant weak vertex is $c \to b + W^+ \to u\bar{q}_s G$. Here again two different combinations of CKM matrix elements arise and the interference term can exhibit CP violation. The penguin contributions to both 3π and $K\bar{K}\pi$ final states are seen to arise from the same relevant weak vertices, while the tree contributions to 3π and $K\bar{K}\pi$ can arise from different relevant weak vertices. Thus the possibly CP-violating interference can be different in the two cases and provide two different independent possibilities for finding a CP-violating charge asymmetry.

The presence of a 0^{-+} hadron degenerate with the D mesons requires a reassessment of the CP studies for the D in any event. In the quark model there are three possible sources for a 0^{-+} state at such a mass:

(i) A $3S$ radial excitation of the π, predicted at 1.88 GeV[15]

(ii) A "hybrid" state where the gluonic fields or "flux tubes" are excited in the presence of coloured quark sources, predicted at $1.8 - 1.9$ GeV[8, 16]

(iii) A $qq\bar{q}\bar{q}$ state[17, 18]

The effects of the presence of this resonance can be described in two equivalent ways, since only effects of first order in the weak interaction need be considered. One can consider the initial state as an unperturbed charmed meson, calculate its decay as a first order perturbation in the weak interaction using the weak interaction diagrams of the standard model, and introduce the resonance as a strong final state rescattering. One can instead examine the mixing of the π resonance into the initial state via the weak interaction. Using the latter picture we note that although mixing with a nearby π resonance is expected whatever the dynamical structure of the latter may be, the effect on the penguin amplitude may be more dramatic for a hybrid. Mixing between $D(c\bar{d}; 1S)$ and $\pi(u\bar{d}; 3S)$ via the penguin is likely to be suppressed by the orthogonality of $1S$ and $3S$ wavefunctions to the extent that the gluon transfers little momentum; by contrast the essential transition in the penguin diagram is $c \to u + G$ and hence excitation of gluonic modes, leading to hybrid final states (π_H) may be expected. Indeed, given that gluonic excitations are believed to require about $1GeV$[14, 16] and that there is also a $\sim O(1GeV)$ energy gap between c and u, d flavours, resonance with excited gluonic modes may be significant and the degeneracy between D and π_H natural.

In ref.[7] the relative sizes of the quasi two-body branching ratios for a hybrid π_H at $\sim$ 2GeV were predicted to be (after summing over all charge combinations)

$$\pi f_0(1300) \sim 16; \pi f_2 \sim 2; KK_0^* \sim 18; \pi\rho \sim 2; KK^* \sim 1 \tag{5}$$

which are consistent with the data on $\pi(1.8)$[2] where the KK_0^* channel is threshold forbidden and manifested as $(KK\pi)_S$. A prominent KK_0^* is observed and the experimentally known strong affinity of $K\bar{K} \to f_0(980)$ also probably is responsible for the coupling to $\pi f_0(980)$ with a strength comparable to the channel $\pi f_0(1300)$. The latter will also feed $\pi\eta\eta$. Thus the overall expectations for hybrid 0^{-+} are in line with the data of ref.[2].

The branching ratios anticipated for a $3S$ state at this mass are not like these. The presence of nodes in the $3S$ wavefunction enable one to suppress the $\pi\rho$ and KK^* channels, thereby "imitating" the hybrid signature, but the presence of a dominant $\pi f_0(1300)$ and $\pi f_0(980)$ appear to be unique to the hybrid configuration.

It is interesting that there appear to be anomalies in the D-decays which may be direct manifestations of the $\pi(1.8)$.

The Cabibbo favoured decays into three particle final states such as $D \to K\pi\pi$ are dominated by quasi two body vector-pseudoscalar production [20]. If spectator diagrams dominated the $D \to \pi\pi\pi$ and $D \to K\bar{K}\pi$ channels, one would expect a similar phenomenon here; however the data are very different[5] favouring "non-resonant" modes

$$D^{\pm} \to (\pi\pi\pi)_{non-res} = (2.5 \pm 0.7) \times 10^{-3}; D^{\pm} \to (\rho\pi) < 1.4 \times 10^{-3} \tag{6}$$

The situation is more complicated in the $K\bar{K}\pi$ channels

$$D^+ \to (K^+K^-\pi^+)_{non-res} = (4.6 \pm 0.9) \times 10^{-3}; \tag{7}$$

$$D^+ \to (\bar{K}^{*o}K^+) \to (K^+K^-\pi^+) = (3.4 \pm 0.7) \times 10^{-3} \tag{8}$$

$$D^+ \to (\phi\pi^+) \to (K^+K^-\pi^+) = (3.3 \pm 0.4) \times 10^{-3} \tag{9}$$

If "non-resonant" means "S-wave" then these modes may be the πf_0 and KK_0^* channels of the $\pi_H(1.8)$ driving the Dalitz plot. To test this we urge a search for other modes of the $\pi(1.8)$ among the D decays driven by πf_0 such as $\pi\eta\eta$ and $\pi(\pi\pi)_s(\pi\pi)_s$ in the 5π final state together with $\pi f_0(980)$.

There are similar anomalies in the D^0 decays. The $\pi^+\pi^-\pi^0$ channel is large: ref.[21] reports $1.6 \pm 1.1\%$ while ref.[22] in $\pi A \to (3\pi)A$ detected D by its decay vertices and find 3.9% which they acknowledge to be far in excess of that expected for a mode that is conventionally expected to be Cabibbo disfavoured. The strong direct excitation of $\pi(1.8)$ is unlikely to be a major contaminant here though it merits further study as does the possible contribution of missing π^0. The ratio of $\rho\pi/(\pi\pi\pi)_s$ needs quantifying.

In view of these qualitative hints we urge that the possibility of measurable CP-violation in these channels be considered. Thus decays of D^+ and D^- separately should be studied e.g. to test if the branching ratios $D^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}$ or of $D^{\pm} \to \pi^{\pm}K_SK_S$ are identical. Similarly $D^0 \to K^0K^-\pi^+$ and $\bar{K}^0K^+\pi^-$ non-resonant channels are superficially different[5] though with large errors.

The ratio of 5π relative to 3π rates is also interesting. The $D \to 5\pi$ come from ref.[22] which is technically only an upper limit due to the possible contamination from extra π^0. Thus it is necessary to quantify the ratio $\frac{D\to 5\pi}{D\to 3\pi}$ and compare with that for the $\pi(1.8)$. Preliminary data from VES suggest that this ratio is significantly less than unity[23].

The $K\bar{K}\pi$ channels are of particular interest for both charged and neutral D because the $\phi\pi$ decay is forbidden by the OZI rule for an ordinary $q\bar{q}$ meson. It is allowed for D decays via the tree diagram. Since both $\phi\pi$ and $\rho\pi$ are vector-pseudoscalar states, presumably related by SU(3) symmetry, the difference between the D decays into these two final states may offer interesting clues. Additional information can be obtained from the $K_S K_S \pi$ decay mode, since the p-wave decay modes including $\phi\pi$ are forbidden and only even partial waves are allowed. Here the $K\bar{K} \to f_0(980)$ may show up as an enhancement near threshold, without being masked by $\phi\pi$ which may well dominate the charged $K\bar{K}\pi$ modes.

Note that for the quasi-two-body neutral decays $D^o \to K^* \bar{K}$ the tree diagram produces only a $u\bar{u}$ pair and not a $d\bar{d}$. This diagram can give only the charged mode $D^o \to K^{*+}K^-$; the neutral mode $D^o \to K^{*o}\bar{K}^o$ is forbidden. Both modes are allowed for the penguin. However, the $\pi(1.8) \to KK^*$ is suppressed[2, 7] and so we expect $K^{*o}K^o$ to remain small.

Our arguments may also apply to the D_s decays. It has been a long standing puzzle that $D_s \to \pi^+\rho^0$ is suppressed relative to non-resonant $(3\pi)^+$. Ref.[17] has suggested that this is due to $qq\bar{q}\bar{q}$ and Terazaki[18] has also considered the influence of 0^{-+} mesons in this region. The annihilation diagram could occur in the sequence $c\bar{s} \to c\bar{s}gg \to u\bar{d}gg$ and mix the D_s into π_H; in such a case we would again expect further channels in common with $\pi(1.8)$. By analogy with the foregoing discussion, and to the extent that we anticipate the mass difference $K_H(0^{-+}) - \pi_H(0^{-+}) \sim D_s - D_d$ there will be D_s mixing with K_H via penguins that will distort D_s decays. The analysis of hybrid decays in ref.[7] when extended to K_H leads one to expect suppression of πK^* and ρK relative to $K f_0$ and πK_0^* which both feed the $(K\pi\pi)_s$ "non-resonant". If $K f_0(1500)$ is produced (analogous to $\pi f_0(1500)$ for π_H) then $K + 4\pi$ and $K\eta\eta$ may be present.

Verification of a consistent pattern in the Cabibbo disfavored modes of D and D_s that parallels those of π_H and its anticipated partner K_H would both support the idea that gluonic fields are excited in these π and K resonances and open the way to CP-violation in these resonance enhanced modes. We urge that searches be made for these channels together with partial wave analyses of the 3 and 5-body channels and that quantitative comparison be made between D^0 and $\bar{D}^0$ and between D^+ and D^- as new windows into CP-violation.

Note that no such effects are expected in the B system as the necessary 0^{-+} hybrids are far displaced in mass. Consequently B decays should behave canonically. Verification of the expected B decay phenomenology together with anomalous D (and D_s) decays in channels common to π_H (and K_H) would be a rather direct proof of the presence of strong gluonic excitation at around 1.8 - 2GeV mass.

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