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CP violation in D-meson decays and the fourth generation

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LHCb collaboration measured CPV at the level of one percent in the difference of assymetries in $D^0(\bar{D}^0) \to \pi^+\pi^-, K^+K^-$ decays. If confirmed on a larger statistics and final systematics this would mean New Physics manifestation. The fourth quark-lepton generation can be responsible for the observed effect.

CP-violating (CPV) asymmetry in $D^0(\bar{D}^0) \to \pi^+\pi^-$ decays is defined as

$$A_{\rm CP}(\pi^+\pi^-) \equiv \frac{\Gamma(D^0 \to \pi^+\pi^-) - \Gamma(\bar{D}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^+\pi^-) + \Gamma(\bar{D}^0 \to \pi^+\pi^-)} \quad (1)$$

and $A_{\rm CP}(K^+K^-)$ is defined similarly. LHCb collaboration result looks like [1][1)]:

$$\Delta A_{\rm CP} = A_{\rm CP}(K^+K^-) - A_{\rm CP}(\pi^+\pi^-) = \\ = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})]\,\%. \quad (2)$$

In both decays singly Cabibbo suppressed quark tree diagram dominates, $c \to du\bar{d}$ and $c \to su\bar{s}$ correspondingly. They are proportional to $V_{cd}V_{ud}^* = -(\lambda + iA^2\lambda^5\eta)$ and $V_{cs}V_{us}^* = \lambda$, so both are almost real and have opposite signs [3] ($\lambda \approx 0.22$, $A \approx 0.81$, $\eta \approx 0.34$). CPV in both decays is proportional to the imaginary term in Cabibbo–Kobayashi–Maskava (CKM) matrix elements which occurs in the interference of tree and QCD penguin diagrams. In a penguin diagram virtual gluon decays to $d\bar{d}$ pair in case of $D \to \pi\pi$ and to $s\bar{s}$ pair in the case of $D \to KK$. Since the factor which multiplies four quarks operator is universal in the exact U-spin limit we obtain

$$A_{\rm CP}(\pi^+\pi^-) = -A_{\rm CP}(K^+K^-). \quad (3)$$

However, in charmed decays U-spin symmetry is violated considerably and equality (3) can be violated substantially as well.

Let us consider penguin amplitude in Standard Model. It is proportional to

$$V_{cd}V_{ud}^* f(m_d) + V_{cs}V_{us}^* f(m_s) + V_{cb}V_{ub}^* f(m_b) = \\ = V_{cs}V_{us}^*[f(m_s) - f(m_d)] + V_{cb}V_{ub}^*[f(m_b) - f(m_d)], \quad (4)$$

where due to unitarity of CKM matrix we subtract zero from the initial expression. For D-meson decays

$$f(m_d) \sim \ln\frac{M_W}{m_c}, \quad f(m_s) \sim \ln\frac{M_W}{m_c} + O(m_s^2/m_c^2), \\ f(m_b) \sim \ln\frac{M_W}{m_b}. \quad (5)$$

Taking into account that $V_{cs}V_{us}^*$ is real we get that the last term in (4) dominates in CPV, since V_{ub} has large phase; in the difference $f(m_b) - f(m_d)$ big log cancels and what remains is close to one:

$$[A_{\rm CP}(\pi^+\pi^-)]_{\rm SM} = -[A_{\rm CP}(K^+K^-)]_{\rm SM} \sim \\ \sim |V_{cb}V_{ub}| \ln\tfrac{m_b}{m_c} \approx 2\cdot 10^{-4}. \quad (6)$$

This small number makes $\Delta A_{\rm CP} \sim 1\,\%$ highly improbable in Standard Model. Naive estimates lead to $\Delta A_{\rm CP} = O(0.05\% - 0.1\%)$, an order of magnitude smaller than the experimental result [4]. Nevertheless it is not excluded that Standard Model explaines large CP violation in D decays [5, 6]. In order to increase $A_{\rm CP}$ in the framework of Standard Model one need to assume very big annihilation amplitudes with penguin contraction [7]. As such a scenario has very high uncertainty we do not consider it in the following.

In the case of the fourth generation the second line of (4) is substituted by:

$$V_{cs}V_{us}^*[f(m_s) - f(m_d)] + V_{cb}V_{ub}^*[f(m_b) - f(m_d)] + \\ + V_{cb'}V_{ub'}^*[f(m_{b'}) - f(m_d)]. \quad (7)$$

Let us take $m_{b'} = 500\,\text{GeV}$ in order to avoid bounds from the searches of the fourth generation quarks at Tevatron and Large Hadron Collider (LHC). For such heavy b' quark $f(m_{b'})$ is small, $f(m_{b'}) \approx 0.15$ (see for example [8], Eqs. (A.12), (A.13), where explicit dependence of penguin amplitude $F_1 \equiv 2f$ on the mass of the virtual quark is presented) and can be safely neglected

[1)] recently CDF confirmed this getting $\Delta A_{\rm CP} = [-0.62 \pm \pm 0.21\,(\text{stat.}) \pm 0.10\,(\text{syst.})]\%$ [2].

in comparison with $f(m_d)$. Assuming a large phase of the product $V_{cb'}V^*_{ub'}$ instead of SM estimate (6) we obtain:

$$[A_{\rm CP}(\pi^+\pi^-)]_{4g}{=}{-}[A_{\rm CP}(K^+K^-)]_{4g}{\sim}|V_{cb'}V^*_{ub'}|\ln\frac{M_W}{m_c}. \quad (8)$$

The value of $|V_{cb'}\cdot V^*_{ub'}|$ is bounded from above by the measurement of $D^0-\bar{D}^0$ oscillation frequency. Let us suppose that in the case of the fourth generation this frequency is dominated by the box diagram with intermediate $b'\bar{b}'$ quarks. Then according to standard formula [9]

$$\Delta m_D=\frac{G_{\rm F}^2 B_D f_D^2}{6\pi^2}m_D m_{b'}^2\cdot\eta_D|V_{cb'}V^*_{ub'}|^2 I\left(\frac{m_{b'}^2}{M_W^2}\right). \quad (9)$$

Substituting $\eta_D=0.5$, $f_D=200$ MeV, $B_D=1$, $I(m_{b'}^2/M_W^2)=0.25$ and using $\Gamma_D=[4\cdot 10^{-13}\,{\rm s}]^{-1}$ we get:

$$x\equiv\frac{\Delta m_D}{\Gamma_D}\approx 0.01\left[\left(\frac{m_{b'}}{1\,{\rm GeV}}\right)|V_{cb'}\cdot V^*_{ub'}|\right]^2=0.01, \quad (10)$$

where the last number is the experimental result. So the product of CKM matrix elements is bounded by

$$|V_{cb'}\cdot V^*_{ub'}|<2\cdot 10^{-3}, \quad (11)$$

where the upper value corresponds to the dominance of $(b'\bar{b}')$ box in Δm_D (see also [10]). Comparing (8) and (6) we see that the fourth generation can enhance Standard Model result for $\Delta A_{\rm CP}$ by factor 40 and fit experimental result (2).

From the unitarity bound $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2+$ $+|V_{ub'}|^2=1$ and numerical values of the first three terms from [11] it follows that $|V_{ub'}|\leq 1.5\cdot 10^{-2}$ is allowed and taking $|V_{cb'}|>0.15$ we can obtain $|V_{cb'}V^*_{ub'}|=2\cdot 10^{-3}$.

In conclusion let us note that proposed mechanism can lead to CPV in $D^0-\bar{D}^0$ mixing at the level of present experimental constraints.

Even if we suppose following [12] that the product $|V_{cb'}V^*_{ub'}|$ times sine of its phase is one order of magnitude smaller than what we used, the factor $\ln(M_W/m_c)\approx 4$ enhancement of $\Delta A_{\rm CP}$ in case of four generations in comparison with SM result still remains and helps to explain the experimental number (2).

We congratulate our colleague, friend and penguin discoverer Arkady Vainstein with his 70^{th} birthday.

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