CP Noninvariance: A Charm Possibility

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ABSTRACT

CP noninvariance in charm meson decays is discussed in comparison to that in the B and K mesons. It is pointed out that in the case of higher than three generations of quarks, CP noninvariance effects can be substantial in charm decays. It is also pointed out how inclusive semileptonic decays can be used to measure $D^0\overline{D}^0$ mixing and mass-matrix CP noninvariance.

I. Introduction: The K meson case

The observation of $\epsilon' \neq 0$ signifies that the decay-amplitude CP noninvariance in addition to the mass-matrix CP noninvariance ϵ as observed quater of a century ago. We can see this from the following: the CERN NA31 experiment measured[1]

$$|\eta_{+-}/\eta_{00}|^2 - 1 = 6\ Re(\epsilon'/\epsilon) = 0.0035 \pm 0.007 \pm 0.004 \pm 0.0012, \tag{1}$$

where

$$\begin{aligned}\eta_{+-} &= \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \frac{(1+\bar{\epsilon})A(K^0 \to \pi^+\pi^-) - (1-\bar{\epsilon})\bar{A}(\bar{K}^0 \to \pi^+\pi^-)}{(1+\bar{\epsilon})A(K^0 \to \pi^+\pi^-) + (1-\bar{\epsilon})A(\bar{K}^0 \to \pi^+\pi^-)} \\ &= \frac{A_{+-}/\bar{A}_{+-} - p/q}{A_{+-}/\bar{A}_{+-} + p/q} = \epsilon + \epsilon', \end{aligned} \tag{2}$$

$$\eta_{00} = \frac{A_{00}/\bar{A}_{00} - p/q}{A_{00}/\bar{A}_{00} + p/q} = \epsilon - 2\epsilon', \tag{3}$$

where $\overset{(-)}{A_i} = A(\overset{(-)}{K} \to f_i)$, and $p = 1 - \bar{\epsilon}$, $q = 1 + \bar{\epsilon}$; ϵ is the CP violating parameter of the amplitude of isospin zero of the two pions; and ϵ', of the isospin two. Here both the mass-matrix and the decay-amplitude CP violations are involved. In the ratios $A_{+-}/\bar{A}_{+-}$, $A_{00}/\bar{A}_{00}$ the strong-interaction phases cancel. Without decay-amplitude CP violation in weak interactions, any phases in $A_{+-}/\bar{A}_{+-}$ and $A_{00}/\bar{A}_{00}$ can be simultaneously taken away by choosing a proper phase convention so that $A_{+-}/\bar{A}_{+-} = 1 = A_{00}/\bar{A}_{00}$, thus $\eta_{+-}/\eta_{00} = 1$. The reverse is also true, i.e., if $\eta_{+-}/\eta_{00} = 1$, then $A_{+-}/\bar{A}_{+-} = A_{00}/\bar{A}_{00}$, and $|A_{+-}/\bar{A}_{+-}| = |A_{00}/\bar{A}_{00}| = 1$, (the second relation must also be true is due to the fact that the K^0, $\bar{K}^0$ to two pions are closed systems and CPT theorem applies, i.e. $\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(K^0 \to \pi^0\pi^0) = \Gamma(\bar{K}^0 \to \pi^+\pi^-) + \Gamma(\bar{K}^0 \to \pi^0\pi^0)$. Therefore if $|A_{+-}/\bar{A}_{+-}| < 1$, then $|A_{00}/\bar{A}_{00}| = |\bar{A}_{+-}/A_{+-}| > 1$. We cannot have a situation $|A_{+-}/\bar{A}_{+-}| = |A_{00}/\bar{A}_{00}| \neq 1$). It indicates decay-amplitude CP violations if $|A/\bar{A}| \neq 1$, or even when both $|A_{+-}/\bar{A}_{+-}| = |A_{00}/\bar{A}_{00}| = 1$, but no phase convention can be found such that $A_{+-}/\bar{A}_{+-}$ and $A_{00}/\bar{A}_{00}$ are both real. Therefore $\eta_{+-}/\eta_{00} \neq 1$, i.e. $\epsilon' \neq 0$, is a necessary and sufficient indication of decay-amplitude CP violation.

A natural and direct way to measure decay-amplitude CP noninvariance is to measure the partial decay-rate difference of $K^0, \bar{K}^0$, i.e.,

$$R_{+-} \equiv \frac{\Gamma(K^0 \to \pi^+\pi^-)}{\Gamma(\bar{K}^0 \to \pi^+\pi^-)} = 1 + 2Re(\epsilon'), \quad (4a)$$

$$R_{00} \equiv \frac{\Gamma(K^0 \to \pi^0\pi^0)}{\Gamma(\bar{K}^0 \to \pi^0\pi^0)} = 1 - 4Re(\epsilon'). \quad (4b)$$

Here the partial decay-rate-difference effects exist only at the instance when $K^0, \bar{K}^0$ are tagged, since $K^0, \bar{K}^0$ mix maximally.

Thus, to see such effects directly, tagging and time-evaluation measurements are necessary. The CERN LEAR experiment PS195 is designed to make such measurements:

$$R_{+-} = \frac{\Gamma(P\overline{P} \to \pi^- K^+ \overline{K}^0 \to \pi^- K^+ \pi^+\pi^-)}{\Gamma(P\overline{P} \to \pi^+ K^- K^0 \to \pi^+ K^- \pi^+\pi^-)} = 1 + 2R_e(\epsilon'), \quad (5a)$$

$$R_{00} = \frac{\Gamma(P\overline{P} \to \pi^- K^+ \overline{K}^0 \to \pi^- K^+ \pi^0\pi^0)}{\Gamma(P\overline{P} \to \pi^+ K^- K^0 \to \pi^+ K^- \pi^0\pi^0)} = 1 - 4R_e(\epsilon'). \quad (5b)$$

Such tagged $K^0, \bar{K}^0$ partial-decay-rate-difference measurements are a more direct and generic way to measure decay amplitude CP noninvariance. Another important reason for such tagged $K^0, \bar{K}^0$ measurements is that it provides a different measurement of ε'. Note that NA31 measures $Re(\varepsilon'/\varepsilon)$, i.e., the projection of ε' on ε, while tagged $K^0, \bar{K}^0$ experiments measures $Re(\varepsilon')$. Under CPT invariance, one can show that [phase (ϵ)] $\approx 90^\circ - (\delta_2 - \delta_1) = 90^\circ + (-45.3^\circ \pm 4.6^\circ) \approx 45^\circ$ which is very much close to [phase (η_{+-})] $= \phi_{+-} = 44.6^\circ \pm 1.20^\circ$. So ε' is expected to be parallel to ϵ. Therefore, from CPT theorem we expect

$$Re(\varepsilon') \approx Re(\varepsilon'/\varepsilon) \cdot |\, \varepsilon \,| \cdot \cos 45^\circ = 0.0035 \cdot |\, \varepsilon \,| \cdot \cos 45^\circ. \quad (6)$$

A measurement of $Re(\varepsilon')$ different from this predicted value is a clear indication of CPT invariance violation.[2]

II. Generic Way of Studing Decay - Amplitude CP noninvariance

Thus we can see that the generic way of observing decay-amplitude CP noninvariance is to study partial decay rate differences between particles and antiparticles. For such studies, the quark diagram scheme is most natural and useful. A general survey of such effects in the KM scheme were done quite some time ago.[3] Such a general survey of CP noninvariance was based upon the quark diagram scheme: weak decays of mesons are given unambiguously in terms of the quark-mixing matrix and six decay amplitudes[4] $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, $\mathcal{D}$, $\mathcal{E}$, $\mathcal{F}$, (respectively, the external W-emission, internal W-emission, the W-exchange, the W-annihilation, the horizontal W-loop, its one-gluon exchange approximation is the so called Penguin diagram, and the vertical W-loop diagrams). To explain how particle-antiparticle decay-amplitude differences arise, let us use an explicit example:[5]

The process $D_s^+ \to K^0\pi^+$ is given in terms of the quark diagrams as follows,

$$A = V_{ud}V_{cd}^*(\mathcal{A} + \mathcal{E}_{s-b}) + V_{us}V_{cs}^*(\mathcal{D} + \mathcal{E}_{s-b}) \equiv V_{ud}V_{cd}^*(A_1) + V_{us}V_{cs}^*(A_2), \quad (7a)$$

and $D_s^- \to \bar{K}^0\pi^-$ is given by

$$\overline{A} = V_{ud}^*V_{cd}(\mathcal{A} + \mathcal{E}_{s-b}) + V_{us}^*V_{cs}(\mathcal{E}_{s-b}) \equiv V_{ud}^*V_{cd}(A_1) + V_{us}^*V_{cs}(A_2). \quad (7b)$$

Note that the difference between particle and antiparticle decays are in $V_{ij} \rightleftarrows V_{ij}^*$. A_1 and A_2 are not changed. This is because of CP invariance in strong reactions.

From this example we see that the decay amplitude CP noninvariance comes from the decay amplitude into a specific channel for particle and anitparticle are different, i.e. $A/\overline{A} \neq 1$.

The partial-decay rate difference is then given by

$$\Delta \equiv \frac{|A|^2 - |\overline{A}|^2}{|A|^2 + |\overline{A}|^2} = \frac{-4Im[(V_{ud}V_{cd}^*(V_{us}V_{cs}^*)^*]Im(A_1A_2^*)}{|V_{ud}V_{cd}^*A_1 + V_{us}V_{cs}^*A_2|^2 + |V_{ud}^*V_{cd}A_1 + V_{us}^*V_{cs}A_2|^2}, \quad (8)$$

Here we see that the important ingredients for nonzero partial-decay rate difference are: first, that $Im[V_{ud}V_{cd}^*(V_{us}V_{cs}^*)^*] \neq 0$, which is provided by the KM mechanism from the interference of at least two distinct weak decay amplitudes; therefore such decay-amplitude CP noninvariance necessarily only happens in mixing-matrix suppressed decays; and second, $Im(A_1A_2^*) \neq 0$, which means that there must be two independent types of nonleptonic decay amplitudes, e.g., the interference of the $I = \frac{1}{2}$, $I = \frac{3}{2}$ amplitudes in $D_s^+ \to K^0\pi^+$.

The same formulation applies to other charm meson decays, and for decays of the B, strange, and top-quark mesons. The interesting point is that for the 3-generation quark-mixing matrix, shown in Ref. [6] that the same X_{cp} appears in the numerator for all partial-decay-rate-differences, i.e. the partial-decay rate differences have the following generic form

$$\Delta = \frac{X_{cp}\ Im(A_1 A_2^*)}{|A|^2 + |\overline{A}|^2}, \quad \text{and} \quad X_{cp} = s_x s_y s_z s_\phi c_x c_y c_z^2 \approx s_x s_y s_z s_\phi \approx 10^{-4}, \tag{9}$$

where the sines are parameters of the KM matrix:

$$V = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_y & s_y \\ 0 & -s_y & c_y \end{bmatrix} \begin{bmatrix} c_z & 0 & s_z e^{-i\phi} \\ 0 & 0 & 0 \\ -s_z e^{i\phi} & 0 & c_z \end{bmatrix} \begin{bmatrix} c_x & s_x & 0 \\ -s_x & c_x & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{matrix} & \text{d} & \text{s} & \text{b} & \\ = & \left[\begin{matrix} c_x c_z \\ -s_x c_y - c_x s_y s_z e^{i\phi} \\ s_x s_y - c_x c_y s_z e^{i\phi} \end{matrix}\right. & \begin{matrix} s_x c_z \\ c_x c_y - s_x s_y s_z e^{i\phi} \\ -c_x s_y - s_x c_y s_z e^{i\phi} \end{matrix} & \left.\begin{matrix} s_z e^{-i\phi} \\ s_y c_z \\ c_y c_z \end{matrix}\right] & \begin{matrix} u \\ c \\ t \end{matrix} \end{matrix}$$

$$\underset{s_i \approx 0}{\approx} \begin{bmatrix} 1 & s_x & s_z e^{-i\phi} \\ -s_x - s_y s_z e^{i\phi} & 1 - s_x s_y s_z e^{i\phi} & s_y \\ s_x s_y - s_z e^{i\phi} & -s_y - s_x s_z e^{i\phi} & 1 \end{bmatrix}. \tag{10}$$

Important features of this parametrization is that it takes advantage of all the experimental information: each sine is directly related to one type of experiment,

$$s_x \approx 0.22, \quad \text{determined from strange particle decays,} \tag{11a}$$

$$s_y \approx 0.05, \quad \text{from b particle life time,} \tag{11b}$$

$$s_z \lesssim 0.01, \quad \text{from bounds on } (b \to u)/(b \to c). \tag{11c}$$

and the phase factor appears at the smallest matrix element. All these make the matrix easy to use. Of course physics does not depend upon how one makes the parametrization.

It is a matter of choice whether one wants to avoid unnecessary complications and to see things more clearly. This X_{cp} was later called J by Jarlskog, who noted its important relation to certain invariants of the mass matrix.[7] The s_x, s_y, s_z here were later renamed as s_{12}, s_{23}, s_{13} in the Particle Properties Data Booklet.

The phase ϕ is related to that of the Kobayashi -Maskawa δ by the following triangle:

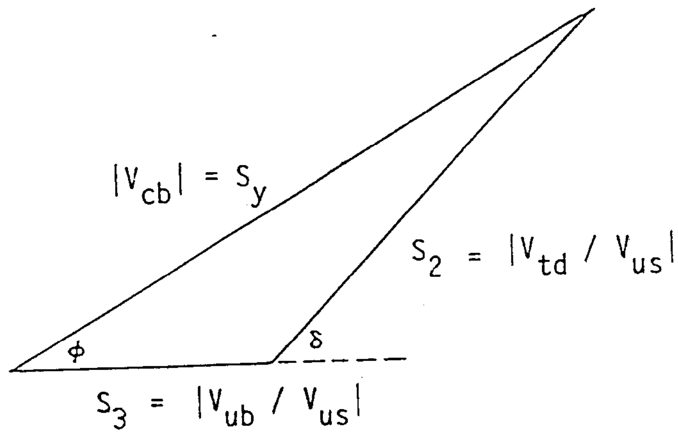

Fig. 1. Figure, taken from Ref.(6), shows the relation between the parametrization used here and that of KM.

We see that as $\phi \to 0$, $\delta \to 0$ and collapses the triangle, and this triangle was later called the Bjorken triangle.

Phenomenologically the uniqueness of X_{cp} for all CP noninvariant decays in the three generations of quarks carries an important message. Even without knowing the detailed dynamics, we can conclude that we will have better luck in getting large partial decay rate differences in those channels where the decay rates are suppressed, i.e. where the denominators in Eq. (8) are suppressed. This fact has been borne out in many model calculations.[5] The partial decay rates in many rare B meson decays can be as large as (few $\times$ 10%). The reason can be simply seen as follows. If there is no reason for dynamical suppression, from Eq.(8) we can easily obtain the partial-decay-rate difference in B decays to be

$$\Delta_B \sim \sin\phi, \tag{12}$$

which can be of order one when ϕ is near 90°. However, in charm decays they are typically less than 1%,

$$\Delta_C \approx 10^{-2} \sin\phi. \tag{13}$$

This is just a reflection of the larger decay rates of quark-matrix suppressed decays of charm mesons comparing to those of B meson decays. Actually this is the same reason that the K and B meson systems are the best systems for neutral particle-antipartical mixing. Thus we anticipate that the B meson will be a very useful source for interesting physics just like the K mesons have been. However the charm meson decays in the scenario of three generation of quarks can have very small particle decay-rate differences; these general observations were born out in practical calculations,[5] see Table 1.

III. The Charm Possibility

When there are more than three generations of quarks, we can generalize the sequential rotation matrices with phases as given in Eq. (10). Explicitly, the quark-mixing matrix of four quarks can be written as follows:[8]

$$V_4 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c_u & s_u \\ 0 & 0 & -s_u & c_u \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c_v & 0 & s_v e^{-i\phi_3} \\ 0 & 0 & 1 & 0 \\ 0 & -s_v e^{i\phi_3} & 0 & c_v \end{bmatrix} \times$$
$$\begin{bmatrix} c_w & 0 & 0 & s_w e^{-i\phi_2} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_w e^{i\phi_2} & 0 & 0 & c_w \end{bmatrix} \begin{bmatrix} & & & 0 \\ & V_3 & & 0 \\ & & & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{14}$$

where V_3 is the 3×3 matrix given in Eq. (10). The striking new phenomena are the proliferation of the number of X_{CP}'s. They are

$$(X_{CP})_{ij}^{\alpha\beta} = (V_{\alpha j}^* V_{\alpha i} V_{\beta i}^* V_{\beta j}), \tag{15}$$

where α, β, i, j run from 1 to 4 with $\alpha < \beta, i < j$. We see that the three-generation case is a rather special case where there is a unique rephasing invariant CP noninvariance parameter. Therefore the estimates of partial decay rates can be very different in the presence of higher than three generations of quarks. One important effect is that the partial decay rate differences in charm particle decays can be large, too. Of special interest to note is that some of these large CP–noninvariance effects involve only tree graph interferences. They are independent of the masses of the higher-than-three generations of quarks, and are dependent solely on the existence of higher generations of quarks. The partial decay rate difference between

$$D_s^+ \to K^0\pi^+, \; D_s^- \to \bar{K}^0\pi^- \tag{16}$$

is such an example.[9] Their partial-decay rate differences mainly come from the interference between external W-emission diagram $\mathcal{A}$ and the W-annihilation diagram $\mathcal{D}$. Currently there is evidence for the annihilation diagram in D_s decays. The partial-decay-rate difference of Eq. (16) can be as large as 20%.

With this scenario of the possible existence of higher than three generations of quarks it is very worthwhile to be on the lookout for CP noninvariant decays in experiments where charm particles are or will be copiously produced, e.g. Fermilab, and BEPC (the Beijing electron–positron collider), and the machine this workshop is discussing.

Recently the mixing of B_d^o $\overline{B}_d^o$ mesons had been observed. Here I would like to remind the readers in-principle a simple way to measure $D^0\overline{D}^0$ mixing and mass matrix CP noninvariance for charm mesons by measuring tagged inclusive lepton decays of neutral charm mesons. Such tagging is available for neutral charm mesons:

$$\begin{aligned} e^+e^- \to \psi(4160, 4415) &\to D^0\pi^+D^- \to \ell^\pm X\pi^+D^-, \\ &\overset{\text{or}}{\to} \overline{D}^0\pi^-D^+ \to \ell^\pm X\pi^-D^+. \end{aligned}$$

The time integrated fractional difference between D^0, $\overline{D}^0 \to \ell^+X$ becomes

$$\Delta_I(D^0,\; \overline{D}^0 \to \ell^+X) \approx -\frac{2Re(\bar{\epsilon})}{1+|\bar{\epsilon}|^2} + \frac{\Gamma_S\Gamma_L}{(\Delta m)^2 + (\tilde{\Gamma})^2} \tag{17}$$

for either D^0, or $\overline{D}^0$,

$$\Delta_I(D^0,\; \overline{D}^0 \to \ell^-X) \approx -\frac{2Re(\bar{\epsilon})}{1+|\bar{\epsilon}|^2} - \frac{\Gamma_S\Gamma_L}{(\Delta m)^2 + (\tilde{\Gamma})^2} \tag{18}$$

for either D^0, or $\overline{D}^0$, where $\tilde{\Gamma} = (\Gamma_S + \Gamma_L)/2$.

By taking the sum of Eqs. (17) and (18) we obtain the measurement of the mass-matrix CP noninvariance parameter $4Re(\bar{\epsilon})/(|+|\bar{\epsilon}|^2)$. By taking the difference between Eqs. (17) and (18), we obtain the measurement of mixing between D^0 and $\overline{D}^0$, $2\Gamma s\Gamma l/\left[(\Delta m)^2+(\tilde{\Gamma}|^2\right]$.

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Table I: Branching ratios and partial-rate differences for rare exclusive D_s, and B decays in the case of three generations of quarks. (Here $|V_{ub}| \lesssim 0.005$ is used. Though we use the same generic notations $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, $\mathcal{D}$, $\mathcal{E}$, and $\mathcal{F}$ the amplitudes for $B \to PV$ are not related to those for $B \to PP$.) This table is taken from papers in Ref. (5).

Reaction	Amplitude	$\|\Delta\|$	$(Br)_{theor}$	$(Br)_{exp}^{Ref.(*)}$
$D_s^+ \to K^0\pi^+$	$V_{ud}V_{cd}^*(\mathcal{A} + \mathcal{E}_{s-b})$	-3.6×10^{-4}	1.8×10^{-3}	
	$+V_{us}V_{cs}^*(\mathcal{D} + \mathcal{E}_{s-b})$	(-2×10^{-3})	(3.4×10^{-3})	
$B_u^+ \to K^+\rho^0$	$V_{us}V_{ub}^*\frac{1}{\sqrt{2}}(\mathcal{A}' + \mathcal{B}' + \mathcal{D}' + \mathcal{E}_{u-t})$	0.4	1×10^{-5}	$< 2.6\times10^{-4}$
	$+V_{cs}V_{cb}^*\frac{1}{\sqrt{2}}(\mathcal{E}_{c-t})$			
$\to \rho^0\pi^+$	$V_{ud}V_{ub}^*\frac{1}{\sqrt{2}}(\mathcal{A}' + \mathcal{B}' + \mathcal{E}_{u-t} - \mathcal{E}'_{u-t})$	0.1	4×10^{-5}	$< 6\times10^{-4}$
	$+V_{cd}V_{cb}^*\frac{1}{\sqrt{2}}(\mathcal{E}_{c-t} - \mathcal{E}'_{c-t})$			
$B_d^0 \to K^0\rho^0$	$V_{us}V_{ub}^*\frac{1}{\sqrt{2}}(\mathcal{B}' - \mathcal{E}_{u-t}) + V_{cs}V_{cb}^*\frac{1}{\sqrt{2}}(-\mathcal{E}_{c-t})$	$0.1 \sim 0.3$	4×10^{-6}	$< 8.0\times10^{-4}$
$\to K^0\phi$	$V_{us}V_{ub}^*(\mathcal{E}'_{u-t}) + V_{cs}V_{cb}^*(\mathcal{E}'_{c-t})$	$0.1 \sim 0.3$	4×10^{-5}	$< 13.0\times10^{-4}$
$B_d^0 \to \pi^+\pi^-$	$V_{ud}V_{ub}^*(\mathcal{A} + \mathcal{C}+\mathcal{E}_{u-t})_{pp} + V_{cd}V_{cb}^*(\mathcal{E}_{c-t})_{pp}$	$0.1 \sim 0.3$		$< 2\times10^{-4}$
$\to K^+\pi^-$	$V_{us}V_{ub}^*(\mathcal{A} + \mathcal{E}_{u-t})_{pp} + V_{cs}V_{cb}^*(\mathcal{E}_{c-t})_{pp}$	0.2	1×10^{-4}	$< 3.2 \times 10^{-4}$
$B_s^0 \to \overline{K}^0\phi$	$V_{ud}V_{ub}^*(\mathcal{E}_{u-t}) + V_{cd}V_{cb}^*(\mathcal{E}_{c-t})$	$0.2 \sim 0.4$	8×10^{-6}	
$\to K^+K^{*-}$	$V_{us}V_{ub}^*(\mathcal{A}' + \mathcal{C}'+\mathcal{E}_{u-t}) + V_{cs}V_{cb}^*(\mathcal{E}_{c-t})$	$0.2 \sim 0.4$	3×10^{-5}	
$B_s^0 \to K^+K^-$	$V_{us}V_{ub}^*(\mathcal{A} + \mathcal{C}+\mathcal{E}_{u-t}) + V_{cs}V_{cb}^*(\mathcal{E}_{c-t})$	$0.2 \sim 0.4$	1×10^{-4}	
$\to K^-\pi^+$	$V_{ud}V_{ub}^*(\mathcal{A}+\mathcal{E}_{u-t}) + V_{cd}V_{cb}^*(\mathcal{E}_{c-t})$	2×10^{-2}	1×10^{-4}	

Ref (*): P. Avery et al. (CLEO collabration), phys. Lett. B183 (1987) 429.

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