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CP violation in semi-inclusive decays $B^0 \to K_S X(c\bar{c})$

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We explore the possibility of using semi-inclusive decays of neutral B mesons to establish CP violation in the B system and determine the appropriate weak phase. The decay $B^0 \to K_S X(c\bar{c})$, for which we estimate a branching ratio of about 1%, offers some unique features. We show that the amplitudes from the same initial state to two CP-conjugated configurations of the final state can be equal. Then one expects a maximal interference between the decay amplitudes of B^0 and $\bar{B}^0$ to the same final state, a sizeable mixing-induced CP asymmetry and no dilution of the effect when summing over the available final states.

1. Introduction

Since its discovery [1] in 1964, CP violation has only been seen in the K^0–$\bar{K}^0$ system, in a few decay channels of the long-lived kaon K_L. Several experiments are in progress or planned [2] to measure CP violating parameters of this system. CP violation can be naturally implemented in the standard electroweak model [3] as long as there are (at least) three quark families [4] whereby the elements of the quark mixing matrix need not be relatively real (weak phases). In the case of three families the standard model has a great deal of predictive power as the complexity of the elements of the quark mixing matrix is governed by a single phase. The study of CP violation in the B decays [5] can therefore provide a clean test of the validity of the standard model. One can measure the angles of the "unitarity triangle" [6] associated with the unitarity constraint

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0 . \quad (1)$$

Physical CP violating effects that come from the complex phase factors in the quark mixing matrix require an interference between two amplitudes with different weak phases. This mechanism has been applied to the so-called "direct" CP violation in the decays of charged [7] and neutral [8] B decays following the pioneering work of Pais and Treiman [9]. In order to have a difference in the decay rates of a given process and its CP conjugate reaction one needs at least two amplitudes with different weak phases together with different "strong phases", where the latter refers to phases which do not change sign in going to the CP conjugate process. In the case of neutral B mesons there can be in addition "indirect" CP violation due to mixing of B^0 and $\bar{B}^0$. In fact in the kaon system this mechanism of CP violation, due to mixing, plays the most prominant role and there is at present conflicting evidence on the existence of "direct" CP violation. In the case of the B system, however, in the standard model one does not expect an observable CP violating effect to originate from the mixing alone. The reason being that, to a good approximation, the mixing amplitude is just a pure phase. The alternative has been to consider processes where one can have a mixing-induced interference of decay amplitudes appropriate for final states which can be reached from both B^0 and $\bar{B}^0$. Special emphasis has been put on two-body final states which are CP eigenstates [10] such as $J/\psi K_S$ or $\pi^+\pi^-$. The resulting asymmetry provides then a particularly clean determination of the appropriate weak phase because only one (dominant) decay amplitude intervenes in the process and it cancels in the asymmetry.

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The problem is, however, the limitation to a few decay channels with small branching ratios. To circumvent this limitation, it has been proposed that one could study the two or three body decays of neutral B mesons to final states which are not CP eigenstates [11]. These proposals can help in reducing the number of B mesons required by a factor of two to four.

In this paper we wish to explore the possibility of using semi-inclusive decays of neutral B mesons which we hope may serve the double purpose of establishing CP violation in the B system and determining the appropriate weak phase. As stated before, the CP violating asymmetry arises from the interference of two amplitudes which in the case of mixing-induced effect will come from the decay amplitudes of both B^0 and $\bar{B}^0$ to the same final state. The role of this final state is to be reachable from both B^0 and $\bar{B}^0$ so that the effect is enhanced if the two amplitudes have similar magnitudes. This is expected to happen when the final state, even if it is not a CP eigenstate, consists of a "self-conjugate" collection of particles in the sense that under a CP transformation one ends up with the same particles in the final state.

2. Semi-inclusive decays into $K_S K(c\bar{c})$

In the case of semi-inclusive decays $B \to K_S X$ which concern us here, the X in the final state must be a self-conjugate collection of quarks and antiquarks. This requirement leads us, for the dominant decays of B^0 (i.e., at the quark level the transitions $b \to c\bar{c}s$ and $b \to c\bar{u}d$ and their conjugate reactions), to consider the semi-inclusive processes

$$B^0 \to K^0 + X(c\bar{c}) \tag{2}$$

as depicted in the diagram of fig. 1. The final state in eq. (2) does not yet look self-conjugate as K^0 goes to

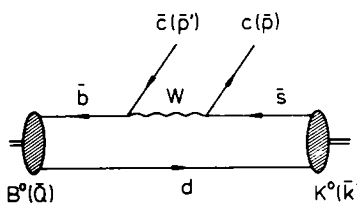

Fig. 1. Quark diagram associated with the semi-inclusive decay $B^0 \to K^0 + X(c\bar{c})$ Momenta are explicitly indicated

$\bar{K}^0$ under a CP transformation. However, by taking projections into the CP eigenstates (K^0_+ or K^0_-) the requirement of having a self-conjugate collection of particles in the final state will be satisfied. In the case considered in this paper we may neglect the CP violation in the kaon system whereby $K^0_+ \simeq K_S$ and $K^0_- \simeq K_L$.

Suppose now that at the time $t=0$ a B^0 is produced (or better filtered) by tagging the flavour on the "opposite side". Due to mixing, the B^0 will evolve in time into a state $|B^0(t)\rangle$ which is a linear combination of $|B^0\rangle$ and $|\bar{B}^0\rangle$:

$$|B^0(t)\rangle = \exp[-i(M_B - i\Gamma/2)t] \times [c(t)|B^0\rangle + i\omega s(t)|\bar{B}^0\rangle] . \tag{3}$$

Here M_B is the average mass of the neutral B meson eigenstates, their mass difference being Δm; τ is their common width (we neglect the difference of their widths) and $c(t) = \cos(\frac{1}{2}\Delta m t)$, $s(t) = \sin(\frac{1}{2}\Delta m t)$. The parameter ω, defined by

$$\omega = \frac{V_{td} V^*_{tb}}{V^*_{td} V_{tb}} = \exp(-2i\delta_m) , \tag{4}$$

arises from the box diagram description of the B^0–$\bar{B}^0$ mixing with δ_m being the appropriate weak phase originating from the quark mixing matrix.

Let us assume now that at a time t the decay into the final state $K^0_+ X$ is observed by appropriate selection of the K^0 decay channel. A specific kinematical configuration, at the $c\bar{c}$ quark level, is characterized by energies and helicities of the quarks (E, λ; $\bar{E}$, $\bar{\lambda}$). The energy E_K of the kaon, in the rest frame of the B, is related to the invariant mass M_X of the $c\bar{c}$ hadronic system through

$$E_K = \frac{M_B^2 + M_K^2 - M_X^2}{2M_B} . \tag{5}$$

The energies of the c and $\bar{c}$ quarks lie in the Dalitz plot shown in fig. 2, where the boundary of the allowed region has been calculated for the two extreme cases of a "light mass", $m_c = 1.2$ GeV, and a "heavy mass", $m_c = 1.7$ GeV, as well as for the intermediate value of $m_c = 1.45$ GeV. The first case has been particularly advocated [12] in order to approach the experimental value for the inclusive semileptonic decay $b \to cl\nu$. In the Dalitz plot of fig. 2, the charmonium states are situated in the area closest to the origin and

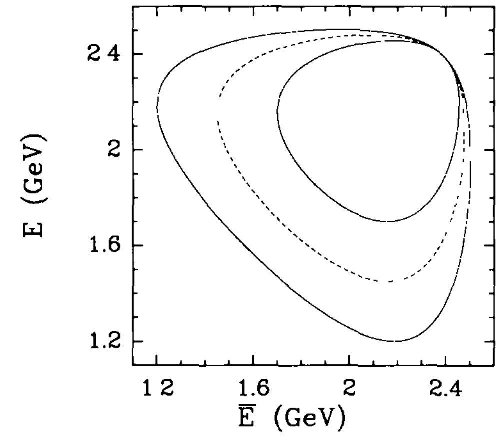

Fig. 2 Dalitz plot associated with the process B, $\bar{B}\to K_S c\bar{c}$. The boundary of the allowed region has been calculated for the two extreme cases of a light mass $m_c = 1.2$ GeV (external solid line) and a heavy mass $m_c = 1.7$ GeV (internal solid line), as well as for the intermediate value $m_c = 1.45$ GeV (dashed line)

the continuum lies further away. Furthermore, the kinematical configuration with a fixed value of E_K (or M_X) corresponds to a line of slope -1. Thus, in the semi-inclusive kaon spectrum, by moving this lines from the lower corner upwards one sweeps first over the charmonium states and then over the open-charm continuum.

The decay amplitude of the process in fig. 1, for a specific kinematical configuration $f \equiv (E, \lambda; \bar{E}, \bar{\lambda})$ of the final state ($c\bar{c}$ quarks), is of the form

$$\langle K_+^0 X_f | T | B^0 \rangle = \exp(i\delta) M_f \exp(i\alpha_f) ,$$
$$\langle K_+^0 X_f | T | \bar{B}^0 \rangle = \exp(-i\delta) M'_f \exp(i\alpha'_f) . \qquad (6)$$

Here the moduli of the transition matrix elements have been denoted by M and M' respectively and δ is the single decay weak phase associated with $V_{cs}V_{cb}^*$. The quantities α_f and α'_f are the "strong" phases, those which do not change sign when going from a transition to its CP conjugate process. The CP conjugate state of f, denoted by $\bar{f}$, corresponds to the kinematical configuration ($\bar{E}$, $-\bar{\lambda}$; E, $-\lambda$) for the $c\bar{c}$ system. In the Dalitz plot the CP conjugation amounts to a reflection with respect to the symmetry axis, i.e., the line of slope unity shown in fig. 2. The amplitudes for the CP conjugate transitions are given by

$$\langle \overline{K_+^0 X_f} | T | \bar{B}^0 \rangle = \exp(-i\delta) M_f \exp(i\alpha_f) , \qquad (7)$$

$$\langle \overline{K_+^0 X_f} | T | B^0 \rangle = \exp(i\delta) M'_f \exp(i\alpha'_f) . \qquad (7\text{ cont'd})$$

When the decay amplitudes in (6) and (7) are inserted into eq. (3) and the corresponding one for $\bar{B}^0(t)$ one finds the following four decay rates of the time-evolved $B^0(t)$ and $\bar{B}^0(t)$ into the two states $K_+^0 X_f$ and $\overline{K_+^0 X_f}$:

$$\frac{d^2\Gamma(B\to f)}{dE\,d\bar{E}} = \exp(-\Gamma t) R_f [1 + \Delta_f \cos(\Delta m t)$$
$$+ \sin(\Delta m t)(A_f \sin\phi + D_f \cos\phi)] ,$$
$$\frac{d^2\Gamma(\bar{B}\to \bar{f})}{dE\,d\bar{E}} = \exp(-\Gamma t) R_f [1 + \Delta_f \cos(\Delta m t)$$
$$+ \sin(\Delta m t)(-A_f \sin\phi + D_f \cos\phi)] ,$$
$$\frac{d^2\Gamma(\bar{B}\to f)}{dE\,d\bar{E}} = \exp(-\Gamma t) R_f [1 - \Delta_f \cos(\Delta m t)$$
$$+ \sin(\Delta m t)(-A_f \sin\phi - D_f \cos\phi)] ,$$
$$\frac{d^2\Gamma(B\to \bar{f})}{dE\,d\bar{E}} = \exp(-\Gamma t) R_f [1 - \Delta_f \cos(\Delta m t)$$
$$+ \sin(\Delta m t)(A_f \sin\phi - D_f \cos\phi)] . \qquad (8)$$

Here the four parameters associated with a definite configuration in the final state are

$$R_f = \tfrac{1}{2}(M_f^2 + M_f'^2)\Gamma_f^{(0)} ,$$
$$\Delta_f = \frac{M_f^2 - M_f'^2}{M_f^2 + M_f'^2} ,$$
$$A_f = \frac{2M_f M'_f \cos(\alpha_f - \alpha'_f)}{M_f^2 + M_f'^2} ,$$
$$D_f = \frac{2M_f M'_f \sin(\alpha_f - \alpha'_f)}{M_f^2 + M_f'^2} , \qquad (9)$$

where $\Gamma_f^{(0)}$ is the phase space factor and we have that $\Delta_f^2 + A_f^2 + D_f^2 = 1$. Thus these measurables correspond to three independent quantities. Furthermore $\phi = 2(\delta_m + \delta)$ is the CP violating weak phase for this process. Its presence can be exhibited by showing that either $d\Gamma(B\to f) \neq d\Gamma(\bar{B}\to \bar{f})$ or $d\Gamma(B\to \bar{f}) \neq d\Gamma(\bar{B}\to f)$. Using the Wolfenstein parametrization [14] of the quark mixing matrix, the angle ϕ is given by

$$\sin\phi \simeq \frac{-2\eta(1-\rho)}{(1-\rho)^2 + \eta^2} . \qquad (10)$$

A recent estimate by Ali gives [15]

$$-0.2 \leqslant \rho \leqslant 0.6, \quad 0.25 \leqslant \eta \leqslant 0.7 . \tag{11}$$

Note that the data does not exclude the most promising case of having $|\sin\phi| = 1$ which happens for $\eta = 1-\rho$. Unfortunately, there is no "universally" accepted convention for the three angles in the unitarity triangle of eq. (1). In recent literature [5] these angles are often denoted by α, β and γ. Then $\phi = 2\beta$ and the promising case corresponds to $|\beta| = 45°$.

Since there are four unknowns (the three independent quantities in eq. (9) and the angle ϕ) in principle they could be determined, up to discrete ambiguities, from the four rates given in (8), if a complete specification of f could be made.

3. Theoretical expectations

As seen from the diagram in fig. 1, we are interested in the nonleptonic transition $b \to c\bar{c}s$ which in a free quark picture is described by the nonleptonic hamiltonian

$$H_{\rm NL}^{\rm free} = \frac{G_{\rm F}}{\sqrt{2}} V_{cs} V_{cb}^{*} (\bar{b}c)_{\rm L} (\bar{c}s)_{\rm L} + {\rm h.c.}, \tag{12}$$

where $(\bar{b}c)_{\rm L}$ is the short-hand notation for the corresponding colour-singlet V–A current, etc. This hamiltonian is modified due to gluonic corrections which also induce mixings with the penguin-type diagrams. The terms in the QCD corrected hamiltonian relevant for us are of the form [13]

$$H_{\rm NL} = \frac{G_{\rm F}}{\sqrt{2}} V_{cs} V_{cb}^{*} (\bar{b}s)_{\rm L} [a_{\rm L} (\bar{c}c)_{\rm L} + a_{\rm R} (\bar{c}c)_{\rm R}] + {\rm h.c.} \tag{13}$$

Note that we have only retained the colour singlet operators $\bar{b}s$ which can give the transition $B \to K_{\rm S}$, using factorization. The quantities $a_{\rm L}$ and $a_{\rm R}$ are constants which at the zeroth order in $\alpha_{\rm s}$ are given by $a_{\rm L} = \frac{1}{3}$ and $a_{\rm R} = 0$. Their QCD corrected values have been recently updated by [13] taking into account that $m_t > M_W$. Using factorization, we write the amplitudes in eq. (6) as

$$\exp({\rm i}\delta) M_f \exp({\rm i}\alpha_f) = \frac{G_{\rm F}}{\sqrt{2}} V_{cs} V_{cb}^{*} \langle K_{\rm S}(\vec{k}) | \bar{b}\gamma^{\mu} s | B^0(\vec{Q}) \rangle \bar{u}_c(\vec{p}, \lambda) \times [(a_{\rm R} + a_{\rm L})\gamma^{\mu} + (a_{\rm R} - a_{\rm L})\gamma^{\mu}\gamma_5] v_c(\vec{p}\,', \bar{\lambda}) ,$$

$$\exp(-{\rm i}\delta) M'_f \exp({\rm i}\alpha'_f) = \frac{G_{\rm F}}{\sqrt{2}} V_{cs}^{*} V_{cb} \langle K_{\rm S}(\vec{k}) | \bar{s}\gamma^{\mu} b | \bar{B}^0(\vec{Q}) \rangle \bar{u}_c(\vec{p}, \lambda) \times [(a_{\rm R} + a_{\rm L})\gamma^{\mu} + (a_{\rm R} - a_{\rm L})\gamma^{\mu}\gamma_5] v_c(\vec{p}\,', \bar{\lambda}) . \tag{14}$$

Here the hadronic transition $B^0 \to K_{\rm S}$ can be parametrized in the form

$$\langle K_{\rm S}(\vec{k}) | \bar{b}\gamma^{\mu} s | B^0(\vec{Q}) \rangle = (Q+k)^{\mu} F_+(q^2) + q^{\mu} F_-(q^2) , \tag{15}$$

where $q = Q - k = p + p'$ and $F_{\pm}$ are form factors, which depend on the invariant $q^2 = M_X^2$. Hence we arrive at the important conclusion that

$$M_f \exp({\rm i}\alpha_f) = M'_f \exp({\rm i}\alpha'_f) . \tag{16}$$

Thus, the model gives, for quantities in eq. (9),

$$\Delta_f = 0, \quad A_f = 1, \quad D_f = 0 . \tag{17}$$

The crucial ingredients, in obtaining this result, are the low momenta involved with respect to M_W leading to a contact interaction together with the factorization hypothesis used in evaluating the matrix elements of the nonleptonic hamiltonian. The lesson to be learned from this result is that, even with two configurations $f \neq \bar{f}$ where f (and consequently also $\bar{f}$) is not a CP eigenstate the two amplitudes from the same initial state to these two conjugated configurations can be equal. In this case, in the time-evolved $B^0(t)$, eq. (3), the interference between the decay amplitudes of B^0 and $\bar{B}^0$ to the same final state reaches its maximum value, i.e., $A_f = 1$, as it is the case for those exclusive two-body decay modes, such as $J/\psi K_{\rm S}$, which are eigenstates of CP.

The equalities, exhibited in eq. (17) imply that there should be no dilution of the effect if one sums over all the available final states f and $\bar{f}$. Defining

$$\Gamma(t) = \frac{1}{2} \Big(\sum_f \Gamma(B \to f) + \sum_{\bar{f}} \Gamma(B \to \bar{f}) \Big)_t , \tag{18}$$

$$\Gamma(t)=\frac{1}{2}\left(\sum_f \Gamma(\bar{B}\to f)+\sum_f \Gamma(\bar{B}\to \bar{f})\right)_t, \tag{19}$$

one obtains that the CP asymmetry is given by

$$\mathscr{A}_{CP}(t)\equiv\frac{\Gamma(t)-\bar{\Gamma}(t)}{\Gamma(t)+\bar{\Gamma}(t)}. \tag{20}$$

In the model considered here, we have $\mathscr{A}_{CP}(t)=\sin(\Delta mt)\sin\phi$ for the integrated rates of the semi-inclusive processes B^0, $\bar{B}^0\to K_SX(c\bar{c})$.

A very essential issue concerns the rate $\Gamma(t=0)$. Unfortunately, it is not possible to predict it with precision. The theoretical estimate [12] of the total rate for $b\to sc\bar{c}$ has an uncertainty of a factor of two, mainly from the allowed range of the quark masses. We can give an estimate of the semi-inclusive rate $\Gamma(t=0)$ in the model of eq. (13). In order to do it, we need first of all to know the form factors F_+ and F_- in eq. (15). We have calculated them following the work of Casalbuoni et al. [16], who in the framework of an effective chiral lagrangian for heavy mesons have studied similar-looking form factors for transitions $D\to\pi$, etc. We assume that F_+ and F_- are dominated, in our case, by B_s^* and B_s poles, respectively and follow the prescription given in ref. [16] to compute $F_\pm$ at the maximal momentum transfer q^2_{max}. We obtain $F_+(0)\simeq-0.8$ and $F_-(0)\simeq+0.5$. Inserting these into expressions in eq. (14) we find first the helicity amplitudes and then the branching ratio for $B\to K_Sc\bar{c}$.

It is of interest to discuss the result for the helicity amplitudes. Even with the limited energy range available for the c and $\bar{c}$ quarks, the dominant helicity amplitude corresponds to $(\lambda=-,\bar{\lambda}=+)$, respectively. Only for kinematic configurations near the boundary of the allowed region of the Dalitz plot in fig. 2, a second helicity amplitude $(\lambda=-,\bar{\lambda}=-)$ for $E>\bar{E}$ or $(\lambda=+,\bar{\lambda}=+)$ for $\bar{E}>E$, becomes appreciable. The other two are always negligible.

We have performed numerically the integration over the variables $(E,\bar{E})$ of the Dalitz plot. As anticipated, the main uncertainty comes from the allowed region of the c-quark mass. Our results for the rate correspond to a branching ratio between 1.6% for $m_c=1.2$ GeV and 0.7% for $m_c=1.7$ GeV.

Another CP observable could be to compare the number of events with $E>\bar{E}$ with those where $\bar{E}>E$ for the two cases, i.e., where the initial meson is B^0 or $\bar{B}^0$. Here, again, E and $\bar{E}$ refer to the energies of the c and the $\bar{c}$ quarks respectively. The model of eq. (17) predicts that the Dalitz plot of fig. 2 is symmetric in both cases but the two distributions are not the same due to CP violation, see eq. (8). If one assumes the dominance of one helicity amplitude, as discussed above, one could then separate out the different terms of eq. (8), up to discrete ambiguities.

Before ending this section we wish to make a general comment. The reader may wonder whether we are here violating the restriction imposed by CPT invariance which says that the inclusive rates for $B\to f$ and its conjugate process are (for all practical purposes) equal. The answer is no. We are not considering the total inclusive rates but are projecting into the semi-inclusive reaction involving a K_S in the final state. Our model calculation tells us that, a priori, there is no reason to expect a dilution of the effect when summing over all possible states of $c\bar{c}$, in the final states $K_Sc\bar{c}$. The cancellation imposed by CPT manifests itself when we add the contribution of the final states $K_Lc\bar{c}$. We then find that for each CP asymmetry from the semi-inclusive $K_Sc\bar{c}$ there is the corresponding CP asymmetry from $K_Lc\bar{c}$ with equal magnitude and opposite sign.

4. Outlook

The b quark has two dominant decay modes, viz., $b\to c\bar{u}d$ and $b\to c\bar{c}s$. The relative strength of these transitions has been estimated in various models. In their recent update, Altarelli and Petrarca [12] find that the branching ratio for $b\to c\bar{c}s$ lies in the range 11% to 24%, by taking "heavy masses" or the favoured "light masses" for the quarks respectively. Our results indicate that about a 7% fraction of this transition should produce the semi-inclusive channel which we find to be of great interest for studying CP violation in the B system i.e., the transition B, $\bar{B}\to K_SX(c\bar{c})$. It is essential that this rate be measured to see whether the CP violation study proposed in this paper is feasible.

In the past few years silicon microstrip vertex detectors have opened completely new possibilities for observing short-lived particles and for tagging heavy flavours. This has been especially the case for the detectors at LEP [17]. If this progress should continue in the future one may have the techniques to resolve the decay vertices of the b as well as the c and $\bar{c}$ and to make sure that the K_S comes from the primary b decay vertex and not from the decay of the c or $\bar{c}$. Another requirement could be the identification, from charged leptons and/or D^*, of the $\bar{c}$ from $\bar{B}$ and of the c from B, indicating up to mixing that the event does not come from $b\to c\bar{u}d$ and from $\bar{b}\to\bar{c}u\bar{d}$ respectively.

Experimentally all we know about the inclusive decay channels of b involving kaons is that $B\to K^{\pm}$ *anything* and $B\to K^0/\bar{K}^0$ *anything* have [18] the branching fractions (85 ± 11)% and (63 ± 8)% respectively. Since the sum of these two branching fractions is larger than unity we may conclude that a substantial fraction of B decays (approximately 50%) produce (at least) two kaons. This result looks promising but is by no way conclusive. The mechanism $b\to c\bar{c}s$ is also responsible for J/ψ production in B decays. The inclusive branching ratio for $b\to J/\psi X$ is known to be [18,19] about 1%. Our estimate of the semi-inclusive branching ratio for $B\to K_S X(c\bar{c})$, in some sense complementary to this other process, is again about 1%.

We have explored the possibility of CP violating effects in semi-inclusive processes and found that the decay $B\to K_S X(c\bar{c})$ presents some unique expectations. Taking into account that the non-leptonic effective hamiltonian of eq. (13) should describe the inclusive transitions, we have shown that a sizeable mixing-induced CP asymmetry is expected without any dilution of the effect, when summing over the available configurations of the $X(c\bar{c})$ final state. This result comes as a consequence of having equal amplitudes from the same initial state to two CP-conjugated configurations.

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