CP-invariance violation and coherence in the decay of neutral B mesons

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A new property of the cascade decay of neutral B mesons has been demonstrated: The CP-invariance violation in the primary decay can affect the time evolution of secondary decays

1. One of the most important current problems of the physics of electroweak interactions is the determination of the nature of CP-invariance violation. It is unlikely that its nature can be determined until some new manifestation of this effect is observed. The most promising in this regard is the decay of B mesons. Many possible effects have already been suggested in the literature. Basically, they can be divided into two groups: 1) integrated effects which describe the yields of various states in the decay of particles and antiparticles (see, e.g., Refs. 1–3), and 2) differential effects such as the oscillations of the time evolution of the decay of particles or antiparticles (see, e.g., Refs. 4 and 5).

In this letter we will show that there is yet another group of effects, which stem from the fact that the decay products of B mesons retain their coherence, and that if there is an interference in the secondary decay, then oscillatory phenomena, which are in no way related to the characteristics of B mesons, will appear on the time scale.

2. For definiteness, we will consider a decay chain

$$B_d(\bar{B}_d) \to J/\psi \underbrace{K^0(\bar{K}^0)}_{\hookrightarrow \pi^+\pi^-}, \qquad (1)$$

although similar results can also be obtained for other cascades.

The states which at $t=0$ correspond to a pure B^0 ($\overline{B}^0$) meson evolve in the form

$$B^0(t)=f_B^+(t)B^0+f_B^-(t)\frac{1-\epsilon_B}{1+\epsilon_B}\overline{B}^0,$$
$$\overline{B}^0(t)=f_B^-(t)\frac{1+\epsilon_B}{1-\epsilon_B}B^0+f_B^+(t)\overline{B}^0. \qquad (2)$$

If at $t=t_1$ there is a decay into $J/\psi K^0$ ($\overline{K}^0$), this process gives rise to states with the wave function

$$\Psi_B(t_1,t)=f_B^+(t_1)a_B K^0(t)+f_B^-(t_1)\frac{1-\epsilon_B}{1+\epsilon_B}\bar{a}_B\overline{K}^0(t),$$
$$\Psi_{\overline{B}}(t_1,t)=f_B^-(t_1)\frac{1+\epsilon_B}{1-\epsilon_B}a_B K^0(t)+f_B^+(t_1)\bar{a}_B\overline{K}^0(t), \qquad (3)$$

where the new reference point of the time scale is the time of the primary decay, and a_B and $\bar{a}_B$ are the amplitudes of the decays $B^0\to J/\psi K^0$ and $\overline{B}^0\to J/\psi\overline{K}^0$. The explicit reference to J/ψ, which is applicable to all terms, is omitted in the final states (3). A further change in these states is determined by the evolution of K^0 and $\overline{K}^0$ in accordance with (2).

Let us now assume that at $t=t_2$ there is a secondary decay K^0 ($\overline{K}^0$) $\to\pi^+\pi^-$. The t_2 dependence of the yield of $\pi^+\pi^-$ can be determined by integrating over t_1. For an initially pure B^0 meson this dependence is given by

$$\left|\frac{a_B}{1+\epsilon_K}\right|^{-2}N(t_2)\propto Ae^{-t_2\Gamma_s}+2\mathrm{Re}[Be^{it_2\Delta M_K}]e^{-t_2(\Gamma_s+\Gamma_L)/2}+Ce^{-t_2\Gamma_L}, \qquad (4)$$

where Γ_s,Γ_L, and $\Delta M_K=M_s-M_L$ are the widths and the difference in the masses of K_s and K_L. The coefficients in (4) are

$$A=A_{11}-A_{12}\lambda-A_{21}\lambda^*+A_{22}|\lambda|^2,$$
$$B/\eta_{+-}=A_{11}+A_{12}\lambda-A_{21}\lambda^*-A_{22}|\lambda|^2, \qquad (5)$$
$$C/|\eta_{+-}|^2=A_{11}+A_{12}\lambda+A_{21}\lambda^*+A_{22}|\lambda|^2,$$

where A_{ik} are expressed in terms of standard parameters, $x=\Delta M/\Gamma$ and $y=\Delta\Gamma/2\Gamma$, for the decay of neutral B mesons:

$$A_{11}+A_{22}=2/(1-y_B^2),\qquad A_{11}-A_{22}=2/(1+x_B^2),$$
$$A_{12}+A_{21}=2y_B/(1-y_B^2),\quad A_{12}-A_{21}=2ix_B/(1+x_B^2), \qquad (6)$$

The parameter λ is linked with the CP violation in the decay of B^0 ($\overline{B}^0$)

$$\lambda = \frac{\bar{a}_B}{a_B}\,\frac{1-\epsilon_B}{1+\epsilon_B}\,\frac{1+\epsilon_K}{1-\epsilon_K}\,, \tag{7}$$

and η_{+-} is the standard ratio of the amplitudes of K_L, $K_s \to \pi^+\pi^-$.

The t_2 dependence for an initially pure $\bar{B}^0$ meson is different:

$$\left|\frac{\bar{a}_B}{1-\epsilon_K}\right|^{-2}\bar{N}(t_2) \propto \{(4) \to [\eta_{+-} \to -\eta_{+-},\ \lambda \to \frac{1}{\lambda}]\}. \tag{8}$$

The corresponding factors in expressions (4) and (8) were dropped.

The time evolution of the secondary decays [expressions (4) and (8)] thus contains, in general, not only purely exponential terms but also oscillating terms. These terms, we might note, would be absent if the CP parity in the K^0 ($\bar{K}^0$) decay were conserved (i.e., at $\eta_{+-}=0$), since there would be no K_s and K_L interference in this case.

An important and quite interesting point is that violation of CP invariance in the primary B decays (the parameter λ) affects the oscillations of the secondary decays. The mixing of B^0 and $\bar{B}^0$ plays a crucial role here. In the absence of mixing (i.e., at $x_B = y_B = 0$, and hence at $A_{22} = A_{12} = A_{21} = 0$) the oscillations would be trivial and would correspond to the decays of pure states of K^0 or $\bar{K}^0$. This situation also applies to the secondary decays (such as semileptonic) in which there is no interference of K^0 or $\bar{K}^0$.

In practice, expressions (4) and (8) are simplified, because in the standard model $y_B \ll 1$ and $\lambda \simeq e^{2i\beta}$, so that Eqs. (5) become

$$A/2 = 1 + \frac{x_B}{1+x_B^2}\sin 2\beta, \quad B/2\eta_{+-} = \frac{1}{1+x_B^2}(1 + ix_B\cos 2\beta),$$
$$C/2|\eta_{+-}|^2 = 1 - \frac{x_B}{1+x_B^2}\sin 2\beta. \tag{9}$$

We can now use the numerical values $x_{Bd} \simeq 0.7$ (Refs. 6 and 7) and $2\beta \simeq 0.17$ (Ref. 8), so that we can write distributions (4) and (8) in the form

$$N(t_2) \propto e^{-t_2\Gamma_s} + 2\mathrm{Re}[\eta_{+-}(0.62 + i\cdot 0.43)e^{it_2\Delta M_K}]e^{-t_2(\Gamma_s+\Gamma_L)/2} + 0.85|\eta_{+-}|^2 e^{-t_2\Gamma_L},$$
$$\bar{N}(t_2) \propto e^{-t_2\Gamma_s} + 2\mathrm{Re}[\eta_{+-}(0.72 + i\cdot 0.50)e^{it_2\Delta M_K}]e^{-t_2(\Gamma_s+\Gamma_L)/2} + 1.17|\eta_{+-}|^2 e^{-t_2\Gamma_L}. \tag{10}$$

For comparison, we give the time evolution of the secondary decays in the absence of CP violation in the decay of B mesons (i.e., at $\lambda = 1$)

$$\overset{(-)}{N}_0(t_2) \propto e^{-t_2\Gamma_s} \pm 2\mathrm{Re}[\eta_{+-}(0.67 + i\cdot 0.47)e^{it_2\Delta M_K}]e^{-t_2(\Gamma_s+\Gamma_L)/2} + |\eta_{+-}|^2 e^{-t_2\Gamma_L}, \tag{11}$$

and also the change in the yield of the decays $K^0(\overline{K}^0) \to \pi^+\pi^-$ for the initially pure K^0 ($\overline{K}^0$) states

$$\overset{(-)}{N}_K(t) \propto e^{-t\Gamma_s} \pm 2\mathrm{Re}[\eta_{+-} e^{it\Delta M_K}] e^{-t(\Gamma_s+\Gamma_L)/2} + |\eta_{+-}|^2 e^{-t\Gamma_L}. \tag{12}$$

Distributions (10)–(12) were normalized to a single factor in the first term. The absolute normalizations of these distributions are different.

Similar distributions can also be written for B_s decays of the type

$$B_s \to \pi^0 K^0 \to \pi^0 \pi^+ \pi^-.$$

The relevant phase cannot yet be determined reliably.[8] But x_{B_s} is expected to be rather large ($\gtrsim 5$), which would decrease the role of the CP violating terms and would considerably reduce the effectiveness of the approach we are discussing in the case of B_s.

3. It is thus possible to look for CP-invariance violation in a new way. If a cascade decay of a B^0 meson [type (1)] takes place, then CP violation in the primary decay may affect the characteristics of the secondary decay, including its time evolution.

An interesting point is the ambiguity of this approach. We know that in integrated effects the parameters of CP violation can be determined only by directly comparing the B^0 and $\overline{B}^0$ decays, whereas in differential effects it is sufficient to measure the time evolution of only one decay (see Refs. 4 and 5). The time evolution of the secondary decay is obviously the integrated quantity of the primary decay of a cascade like (1). This quantity is similar, however, to the differential quantities in the sense that the evolution of only one of the two states, B^0 or $\overline{B}^0$, must be known.

It is experimentally important that the time scale for the onset of the secondary-decay effects is not related to Γ_B or ΔM_B, but rather to the K-meson parameters Γ_s, Γ_L, and ΔM_K. To find these effects, it is not necessary, therefore, to detect very short mean-free paths. The scale of these effects for B_d can be deduced from a comparison of distributions (10)–(12).

The approach which we have proposed obviously poses some problems (such as low branching ratios). Increasing the number of methods, however, to search for CP-invariance violation will, at any rate, increase the probability that one of them will produce results experimentally.

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