Double-Flavor Oscillations and Properties of Heavy Mesons

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Abstract

Phenomenon of coherent double-flavor oscillations is discussed. They can arise when heavy flavored neutral mesons decay with production of neutral kaons. The oscillations may be used to study detailed properties of the heavy mesons and may give new insight into the problem of CP-violation. In particular, they provide the only known way to the complete unambiguous measurements of CP-violating parameters for neutral B-meson decays. The corresponding experiments seem to be hard, but possible at hadron facilities.

Oscillations in decays of flavored neutral mesons is now a well-known phenomenon. They are induced by the meson-antimeson mixing due to flavor non-conservation. The strangeness oscillations in propagation of neutral kaons provide the best studied example. Similar oscillations of beauty have been observed for $B_d, \overline{B}_d$ mesons (B_d is $\bar{b}d$). Flavor oscillations should exist also for $B_s, \overline{B}_s$ and $D^0, \overline{D}^0$ (B_s and D^0 are $\bar{b}s$ and $c\bar{u}$ correspondingly), and common belief is that they do exist, though not measured yet.

Some years ago I suggested a new possible phenomenon in decays of heavy neutral mesons, many-flavor oscillations [1, 2]. Indeed, such a meson oscillates itself, then it can decay, e.g., with producing neutral kaons which demonstrate oscillations of strangeness. Non-trivial is that the initial flavor oscillations and the final strangeness oscillations may be coherent.

A simple example is given [1, 2] by the primary decay

$$B_d(\overline{B}_d) \to J/\psi K^0(\overline{K}^0)\,, \tag{1}$$

followed by secondary decays of the kaon

$$K^0(\overline{K}^0) \to \pi\pi \quad \text{or} \quad K^0(\overline{K}^0) \to \pi^{\mp} l^{\pm} \nu_l(\bar{\nu}_l)\,. \tag{2}$$

At the quark level this cascade is induced by the quark processes $\bar{b} \to \bar{c}W^+$, $W^+ \to c\bar{s}$, $\bar{s} \to \bar{u}W^+$ and charge-conjugate. We see that only transitions

$$B_d \to K^0\,, \quad \overline{B}_d \to \overline{K}^0 \tag{3}$$

are possible in decay (1), while transitions $B_d \to \overline{K}^0$, $\overline{B}_d \to K^0$ cannot go [1]. Therefore, K-meson content of the state generated by the B-meson decay is unambiguously determined by the initial B-meson state and its evolution up to the decay. The later K-evolution appears to be coherent continuation of B-evolution before the decay.

Such double coherence has many analogues in other physical phenomena. Analogy with propagation of the polarized light through optically active substances (rotating its polarization plane) was discussed in ref. [2]. Analogy with the famous quantum effect of Einstein-Podolsky-Rosen [4] was emphasized in ref. [5].

Coherence of the secondary kaon evolution with processes at the previous stage(s) of the cascade decay allows to use the well-known kaon properties for studying unknown properties of heavy mesons (B-mesons in the above cascade) and their decays. To illustrate how this approach can work we consider here some examples. We will mainly trace the corresponding ideas and will not go into every detail of calculations which can be found in the referred papers. After that we will briefly discuss possibilities of the corresponding experiments.

1. Let us first assume, for simplicity, exact CP-conservation and compare a direct semileptonic decay of the neutral flavored meson with similar decay of the secondary neutral kaon after decay (1).

[1] The situation is just opposite if the same cascade is initiated by B_s, see ref.[3].

Take, for definiteness, the pure B-meson initial state. It is the superposition of two eigenstates, $B_\pm$, with definite CP-parities ± 1. They have definite masses and widths. Their simple laws of evolution provide the relative factor $\exp(i\Delta m_B t_B)$ after the lifetime t_B. Semileptonic decay amplitudes for the eigenstates are the same (or have the opposite sign). Therefore, their interference in any direct semileptonic decay gives a contribution to the decay rate proportional to $\cos(\Delta m_B t_B)$. Its study measures the absolute value of the mass difference Δm_B, but does not allow to find its sign, i.e. to determine which of the states, B_+ or B_-, is heavier or lighter.

The situation is the same for all neutral flavored mesons. However, special experiments for neutral kaons were capable to show that the lighter kaon eigenstate is the (nearly) CP-even K_S, rapidly decaying to two pions. This goal was achieved by observing kaon semileptonic decays after coherent regeneration in foils (compilation of results and references see in ref.[6]). The measurements appeared in agreement with later calculations in the Standard Model. Such experiments are, surely, impossible for any other neutral flavored mesons because of much shorter mean lifetimes.

Let us consider now the same semileptonic decay, but for the secondary kaon, produced in the primary decay (1). Again, we start with the pure B-meson and, for time being, assume CP to conserve. Then, considered in terms of eigenstates, decays (1), as explained in ref.[2], have two branches

$$B_+ \to J/\psi K_L\,, \quad B_- \to J/\psi K_S\,, \tag{4}$$

each with a simple law of evolution in both lifetimes t_B and t_K before and after decays (4). Contributions of the branches to the secondary decay amplitude have the relative phase determined by multiplication of two relative factors, $\exp(i\Delta m_B t_B)$ and $\exp(-i\Delta m_K t_K)$, coming from B- and K-evolutions. The decay rate, after such double-flavor evolution, contains a term proportional to $\cos(\Delta m_B t_B - \Delta m_K t_K)$. Thus, contrary to the familiar single-flavor evolution, the cascade decay with double-flavor evolution allows one to measure both the value and sign of Δm_B, in respect to the known sign of Δm_K.

It is just the sign of Δm_d that stays unknown today for B_d, while its absolute value has been measured with good precision in direct decays [7]. Cascade decays for B_s-meson may appear even more useful [3] since the large value of $|\Delta m_s|$ generates too rapid oscillations in direct decays which are hard to resolve.

2. CP-violation makes two more eigenstate transitions

$$B_+ \to J/\psi K_S\,, \quad B_- \to J/\psi K_L \tag{5}$$

be possible as well [2], in addition to transitions (4). The cascade decay amplitude contains contributions from all four transitions. Note, however, that only the same two transitions (3) are admissible in terms of flavored states, independently of conservation or violation of CP.

Essential problem under CP-violation is how to identify eigenstates. CP-parities cease to be good quantum numbers, so one needs to use some other properties. Neutral kaons are experimentally identified by their mean lifetimes as short- or long-lived, K_S or K_L. This way cannot be useful for eigenstates of heavier mesons since differences of their lifetimes are too small. Many authors identify the eigenstates by their masses as heavy and light (e.g., B_H, B_L), but do not suggest how to relate such identification with any other properties. The usual statement that B_H is CP-odd in the Standard Model (just as for kaons; see, e.g., ref.[8]) may appear uncertain because of uncertainty of the CP-parity itself (it can be mode dependent, see discussion below).

Cascade decay (1) suggests another way of identification for the eigenstates. According to ref.[2], we can define the states $B_\pm$ as having approximate CP-parities ± 1, in the sense that transitions (4) are more intense than transitions (5) (considered then, by definition, as CP-suppressed). Similar procedure is possible also for direct B-meson decays into final states with definite CP-parities, but only if the difference of eigenwidths is measurable (more details see in ref.[2] for cascade decays and in ref.[9] for direct decays). Such identification by the approximate CP-parity reminds the earlier identification of neutral kaon eigenstates as θ- or τ-particles according to their decays into final states of two or three pions, with opposite space parities and CP-parities.

Having identified the eigenstates by their approximate CP-parities we can study time distributions of the cascade (1),(2) to determine experimentally which of states is heavier or lighter (detailed expressions see in ref.[2]). Of course, these two identifications, by CP-parity and by mass, should be equivalent. The only problem is how to relate them. Cascade decays just open such a possibility. Any other way has not been suggested yet.

3. Here appears one more interesting point. Let us compare violations of space parity and CP-parity. In decays caused by strong interactions, where the space parity is violated only to a very small extent, we can unambiguously determine parity of an unstable state (e.g., resonance) as the parity of any of its final states. In weak decays the situation is different: various final states may have various parity values. As a result, for example, the space parity of the charged kaon is opposite when determined from two- or three-pion final states. This is possible due to the intrinsically large parity violation in weak interactions. Nevertheless, manifestations of the parity violation in a concrete weak decay may be very small or even not observable at all due to some special reasons (e.g., absence of pseudoscalars because of kinematical reasons).

CP-violation is usually believed to be intrinsically small, or even "superweak" [10]. However, till now it has been definitely observed only in decays of neutral kaons and only in three of their decay modes ($\pi^0\pi^0$, $\pi^+\pi^-$, $\pi^+\pi^-\gamma$). All of them give evidence for small CP-violation (in particular, they all ascribe the same CP-parities to K_S, K_L). However, it might be due to some "kinematical" reasons since all the kaon decays correspond mainly to the same weak quark transition $s \to uW^-$ (other transitions, e.g., penguins $s \to dg$, seem to be relatively small).

B-mesons have much richer variety of decay modes, which can be induced by various underlying quark transitions. Therefore, they allow much deeper studies of CP-violation. In particular, there are different cascades, similar to (1), but induced by different quark processes, e.g.,

$$B_d(\overline{B}_d) \to \rho^0 K^0(\overline{K}^0)\,. \tag{6}$$

They might give other CP-parities for B_H, B_L, than cascade (1). In this sense the approximate CP-parity of, say, B_L might appear decay-mode dependent. In direct similarity to the case of P-violation, this would mean that CP-violation is really intrinsically large and appears to be small in kaon decays only "kinematically". We see [2], that cascade decays of B-mesons suggest an experimental way appropriate to discover such a possibility [2].

4. Now we consider direct non-leptonic decays to final states of definite CP-parity. The simplest example for kaons is the decay

$$K^0(\overline{K}^0) \to \pi^+\pi^-\,. \tag{7}$$

Its well-known time distribution contains the oscillating term proportional to $\cos(\phi_{+-} - \Delta m_K t)$, where ϕ_{+-} is the phase of the CP-violating parameter η_{+-}. Note that the famous parameters η's are inevitably defined in terms of eigenstates with definite CP-parities (at least approximate), so to have $|\eta| < 1$. The states being identified as heavy or light (or in any other way) may be used only if their CP-parities are known. So, Δm_K in the time distribution is the mass difference of kaon eigenstates of definite (m.b., approximate) CP-parity and, *a priori*, may have an arbitrary sign. We see, therefore, that the sign of ϕ can be measured only in respect to the sign of Δm_K. In other words, unambiguous measurements of η's are possible only when we know what are CP-parities of heavier and lighter eigenstates. As we mentioned above, for kaons it was really done in special experiments.

The situation is the same for neutral B (or D) mesons [9]. The only difference is that the sign of, say, Δm_B cannot be measured in the same way as for kaons. It can be determined only in cascade decays with double-flavor oscillations. As a result, experiments with cascade decays are a necessary step for complete unambiguous measurements of CP-violating parameters in decays of neutral B mesons [9] (see also ref.[11]; similar discussion in terms of the CKM-angle β is given in ref.[12]).

Furthermore, the double-time distribution in cascade decays (1),(2) (over t_B and t_K) contains the CP-violating parameter of a new kind. It can be presented as

$$\eta_{BK}^{J/\psi} = \frac{1+\lambda_{BK}^{J/\psi}}{1-\lambda_{BK}^{J/\psi}}\,, \tag{8}$$

where [2]

$$\lambda_{BK}^{J/\psi} = \frac{1-\epsilon_B}{1+\epsilon_B}\,\frac{1+\epsilon_K}{1-\epsilon_K}\,\frac{< J/\psi \overline{K}^0|\overline{B}^0 >}{< J/\psi K^0|B^0 >}\,. \tag{9}$$

[2] I thank I.Dunietz for discussions which imply that present data on the CKM-matrix may lead just to the opposite CP-parities of, say, B_L as determined from cascades (1) and (6).

This parameter determines the relative value of contributions of "suppressed" branches (5) to the total decay amplitude in comparison with "unsuppressed" branches (4). Note that the exact CP-conservation would lead to $\lambda_{BK}^{J/\psi} = -1$ and to the vanishing of $\eta_{BK}^{J/\psi}$. Similar parameters should appear in other cascade decays as well. An interesting specific property of these new parameters is that they reveal interplay of CP-violation in both neutral B- and neutral K-mesons (e.g., $\eta_{BK}^{J/\psi}$ could not vanish even if CP were conserved for B-mesons, but violated in a usual way for kaons). Therefore, their measurements may lead to deeper insight into the problem of CP-violation.

5. Let us discuss time dependence of the cascade decays. The familiar opinion is that sequential decays (i.e. having several consequent stages) have factorisable time dependence determined by multiplication of time dependencies for each stage. This is not true for the cascade (1),(2). Its amplitude [2] can be presented in the form

$$A_{B(0)\to final\ state}(t_B, t_K) \propto A_{+L} + A_{-S} + \eta_{BK}^{J/\psi}(A_{+S} + A_{-L})\,, \tag{10}$$

where the first two terms correspond to amplitudes of branches (4), while the last two terms come from branches (5). Double-time dependence of the amplitude for each branch is factorisable in t_B and t_K. However, the dependencies are different for all the branches, so the total amplitude is non-factorisable. The decay yield is surely non-factorisable as well.

Nevertheless, the double-time dependence is really not very complicated [2]. As the function of t_K, in similarity with decays (2), it generally combines four terms:

$$\exp(-\Gamma_S t_K)\,,\ \ \exp(-\Gamma_L t_K)\,,\ \ \exp\left(-\frac{\Gamma_S+\Gamma_L}{2}t_K\right)\cos(\Delta m_K t_K)\,,\ \ \exp\left(-\frac{\Gamma_S+\Gamma_L}{2}t_K\right)\sin(\Delta m_K t_K)\,.$$

Their coefficients, in difference with decays (2), are not constant. They are functions of t_B, each one combining again four terms:

$$\exp(-\Gamma_+ t_B)\,,\ \ \exp(-\Gamma_- t_B)\,,\ \ \exp\left(-\frac{\Gamma_++\Gamma_-}{2}t_B\right)\cos(\Delta m_B t_B)\,,\ \ \exp\left(-\frac{\Gamma_++\Gamma_-}{2}t_B\right)\sin(\Delta m_B t_B)\,.$$

Coefficients of these combinations (see ref.[2]) depend on the initial B-meson state and on properties of decays (1) and (2). As the above discussion shows, the total amplitude (10) is sensitive to the sign of Δm_B, if the sign of Δm_K is fixed and the eigenstates $B_\pm$ are identified so that $|\eta_{BK}^{J/\psi}| < 1$ (or, equivalently, $\mathrm{Re}\,\lambda_{BK}^{J/\psi} < 0$).

Non-factorisable structure of the amplitude (10) leads to one more interesting consequence. Integration over one of lifetimes, t_B or t_K, produces single-time distributions of the cascade, which "remember" many properties of its double-time distribution. Experimentally, it looks reasonable to integrate over t_B (because of very small mean lifetime of B-mesons) and study distribution over the secondary-decay time t_K to search for effects of double-flavor oscillations [2, 9]. Principally, it might be sufficient, e.g., for determination of approximate CP-parities of B_H, B_L (or, equivalently, the sign of Δm_B at fixed approximate CP-parities of eigenstates).

6. Let us discuss possibilities to accomplish experiments on double-flavor oscillations. They look to be difficult experiments indeed!

First of all, the present experimental data [7] for branching ratios at various steps of the cascade (1),(2), appended by tagging $J/\psi \to l^+l^-$, provide the small effective branching

$$(\mathrm{Br})_{eff} \approx 5\cdot 10^{-5} \tag{11}$$

for any of secondary decays (2). And this is not the end of the story.

A necessary element for observations of double-flavor oscillations is the interference of both B_+, B_- (or B_H, B_L) and K_S, K_L. Eigenstates of neutral B-mesons in the decay (1) have really the same mean lifetimes and interfere at any t_B. Contrary to them, K_S and K_L effectively interfere only in a limited interval of t_K, thus producing, besides of small branching (11), some additional smallness (its estimates see below).

As a result, the necessary experimental statistics seems to be quite inaccessible at any of the projected B-factories (corresponding distributions were, nevertheless, studied in ref.[13]). LHC or some other hadron facility may be promising, but statistics of the dedicated detector LHC-B being planned to work at moderate luminosity and produce about 10^8 B's/year [14] looks insufficient as well [9]. The desired effects might be searched for either by other LHC detectors or by LHC-B working at full luminosity.

An essential question for planning future experiments is which of kaon decays (2) in the cascade (1),(2) would be preferable. All the papers [9, 12, 13] observe some evidence that the semileptonic decays might be more favorable than two-pion ones. We can explain this here as follows. The smallness of K_S, K_L interference in each particular two-pion mode may be characterized by the small parameter $|\eta_{\pi\pi}| \approx 2.26 \cdot 10^{-3}$. Note that the two-pion yield in decays of pure K_L, as compared to pure K_S, is suppressed by $|\eta_{\pi\pi}|^2$.

At first sight, K_S, K_L interference in semileptonic decays should not have any smallness since their decay amplitudes are the same (or differ only in sign). Some effective smallness exists, nevertheless. Yield of semileptonic decays of pure K_S, in comparison with pure K_L, would be suppressed by the factor $\tau_S/\tau_L \approx 1.7 \cdot 10^{-3}$. Interference is linear in each amplitude, so, the net (not at particular t_K!) effects of K_S, K_L interference in the semileptonic channels should be characterized by the parameter $(\tau_S/\tau_L)^{1/2} \approx 4.2 \cdot 10^{-2}$, which is also small, but about 20 times higher than $|\eta_{\pi\pi}|$. This simple estimate quantitatively coincides with the result of ref. [9] obtained in a different way. It influences requirements to necessary experimental statistics and explains why semileptonic decays of the secondary kaon might be more efficient than two-pion decays to look for double-flavor oscillations. There is, however, a problem of experimental efficiencies which should be studied separately for each particular detector.

In summary, briefly explained here are the origin and some features of coherent double-flavor oscillations, a new phenomenon which is specific for decays of heavy neutral flavored mesons. Its observation would provide unique important information on properties of heavy mesons and better understanding of CP-violation in their mixing and decays. Experiments searching for such oscillations are really hard, but look promising at hadron facilities.

Correspondence with B.Kayser during my work at this written version of the talk was helpful to achieve better formulations of my ideas.

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