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Observation of CP violation in B-meson decays

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Contents

Abstract. **With this review, *Physics – Uspekhi* continues to discuss one of the most mysterious phenomenon in particle physics, that of CP violation. Recent research in this area has focused especially on the properties of B mesons. Successful B-factory experiments have allowed both the detection and detailed study of CP violation in B-meson decays. Presented here is a state of the art review of the field.**

1. Introduction

1.1 Symmetries in particle physics

Symmetries play a fundamental role in understanding the laws of nature. Linear and angular momentum conservation laws are associated with *continuous* translation and rotation symmetries in three-dimensional space. These symmetries are characterized by continuously varying parameters over a certain domain, and the existence of such symmetries guarantees the independence of the laws of Nature from these parameters. Apart from continuous symmetries, *discrete* symmetries play a significant role. These are symmetries under the transformations of groups with discrete topologies (with a finite or countable number of elements). In particular, the spatial inversion symmetry (P parity) implies the invariance of the laws of Nature under the simultaneous flip in the sign of all spatial coordinates ($x \to -x$, $y \to -y$, $z \to -z$), while the charge conjugation symmetry (C parity) involves a replacement of particles by antiparticles. The very notion of an antiparticle appeared in the late 1920s, soon after Dirac formulated his famous equation [1] that predicted the existence of an anti-electron. This first antiparticle was named a positron and differed from an electron by the sign of its electric charge. The positron was discovered in 1933 by Anderson [2].

All available experimental data point to the conservation of P and C parities in electromagnetic and strong interactions, but both these parities were found to be violated in weak interactions. Weak interactions also violate the symmetry under the combination of P and C transformations (CP parity). In the modern theory, the Standard Model (SM), the P and C parity violation mechanisms have a different nature. To describe the experimental data, P violation in weak interactions is postulated by defining the weak coupling differently for left- and right-handed leptons and quarks. Although CP violation appears naturally in the SM in the case of three quark generations, the question of why there are exactly three generations remains unanswered.

The hypothesis of spatial parity violation in weak interactions was proposed to resolve the so-called $\theta - \tau$ puzzle. In the 1950s, two particles — θ^+ and τ^+ — were discovered, with identical masses and lifetimes, but decaying into their final states with a different number of π-mesons.

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Angular analysis of the final-state particles in the decay $\tau^+ \to \pi^+\pi^+\pi^-$, carried out by Dalitz [3], showed that the P parities of the π meson system in these two decays are opposite. P parity conservation suggested that θ^+ and τ^+ are different particles, and the equality of their masses and lifetimes (given significantly different decay dynamics) is a mere coincidence. If the P parity is violated,[1] the $\theta-\tau$ puzzle is resolved easily by stating that θ^+ and τ^+ are in reality the same particle.[2] Physicists are not inclined to believe in coincidences. Lee and Yang [5] found that none of the experiments thus far had tested the conservation of P parity, and proposed a way to do it. Soon after the Lee and Yang publication, the proposed experiments were carried out and fully confirmed the hypothesis of spatial parity violation in weak interactions. The first such experiment was performed by Wu et al. [6].

Before the first experimental results appeared, it had been noted in the works by Ioffe, Okun, and Rudik [7] and independently by Lee, Oehme, and Yang [8], that the observation of P parity violation with the technique proposed by Lee and Yang is possible only if the charge parity is simultaneously violated in weak interactions. Immediately after this was realized, Landau [9] introduced the combined CP parity and assumed that it is conserved in weak interactions. Landau's assumption was based on the fact that it is exactly the CP transformation that turns particles into antiparticles. Therefore, CP conservation provides a symmetry between matter and antimatter.[3]

For a long time, the belief that the physical properties of matter and antimatter should be identical was so strong that the experimental observation of CP violation in long-lived neutral kaon decays in 1964 [10] came as a shock. The work by Sakharov [11] published in 1967 helped to reconcile us to the existence of this phenomenon. It did not answer why CP violation occurs, but instead explained why it should exist. In Nature, we observe an excess of matter over antimatter, which has served as the construction material to build the world that surrounds us. Sakharov's idea was as follows: without CP violation, the 'building blocks' of matter would not be kept intact: matter would annihilate with antimatter completely, and the Universe would only be filled with photons. Somewhat later, in 1973, Kobayashi and Maskawa [12] proposed an elegant and simple way to introduce CP violation into the SM, which is discussed in detail below.

Presently, CP violation is giving us new surprises, however. Attempts to quantitatively explain the magnitude of the observed excess of matter over antimatter in the SM framework did not succeed. This points to the existence of additional sources of CP violation [13]. Moreover, the absence of CP violation in other interactions also constitutes a problem in modern theory. Besides the absence of the strict prohibition on CP violation in strong interactions, there are effects that should lead to it. Experiments allow concluding that if CP violation exists in strong interactions, it is negligibly small. This puzzle is called the 'strong CP problem.'

The historical review above presents the basic steps in the formation of our knowledge about the nature of symmetry violation only briefly. For more information on how these remarkable discoveries were made and on the wonderful ideas that never became a commonly accepted theory, we refer the reader to the review by Okun [4].

[1] Such a possibility was discussed at the beginning of 1956 at the Rochester conference (see [4]).

[2] Which is now known as the K^+ meson.

[3] With the simultaneous change of left and right.

1.2 CP violation in the neutral K-meson system

Neutral kaons K^0 and their antiparticles $\bar{K}^0$, unlike many truly neutral particles,[4] are not identical. The difference in the properties of K^0 and $\bar{K}^0$ becomes apparent in strong and electromagnetic interactions. For instance, the process $pp \to p\Lambda K^0$ is allowed, but $pp \to p\Lambda\bar{K}^0$ is not. It is convenient to introduce a new quantum number, strangeness, which is conserved in strong and electromagnetic interactions, and assign a positive strangeness to K^0 ($S = 1$) and negative to $\bar{K}^0$ ($S = -1$). However, strangeness is violated in weak interactions because both K^0 and $\bar{K}^0$ decay into strangeless final states with $S = 0$. Two neutral kaon states are related by the CP transformation:

$$\mathcal{CP}(K^0) = \exp(2i\xi_K)\,\bar{K}^0\,, \qquad \mathcal{CP}(\bar{K}^0) = \exp(-2i\xi_K)\,K^0\,, \tag{1}$$

where ξ_K is an experimentally unobservable phase.[5]

Because K^0 and $\bar{K}^0$ mesons can decay into the same final state, a transition between K^0 and $\bar{K}^0$ must exist. Keeping this in mind and using the C transition symmetry, Gell-Mann and Pais [14] showed in 1955 that the combinations

$$K_1^0 = \frac{K^0 + \bar{K}^0}{\sqrt{2}}\,, \qquad K_2^0 = \frac{K^0 - \bar{K}^0}{\sqrt{2}} \tag{2}$$

have definite masses and lifetimes. The later discovery of the C symmetry violation does not change this statement if CP is conserved [8, 9]. We note that the two states K_1^0 and K_2^0 have sufficiently different lifetimes (the K_2^0 lifetime is approximately 600 times larger than that of K_1^0). Before the publication of [14], only K_1^0 had been observed experimentally, while nobody expected the existence of K_2^0.

The large difference in lifetimes is related to the different CP parities of K_1^0 and K_2^0. Indeed, based on Eqn (2) and applying CP transformations (1), it is easy to verify that K_1^0 and K_2^0 are eigenstates of the $\mathcal{CP}$ operator, K_1^0 having a positive CP parity and K_2^0 having a negative one. Due to CP conservation, K_1^0 can decay only into final states with $CP = 1$ (e.g., into the $\pi^+\pi^-$ pair, having positive CP parity due to Bose statistics), while for K_2^0, only decays into $CP = -1$ final states are allowed (e.g., into the $\pi^+\pi^-\pi^0$ state having negative CP parity if the angular momentum between π^0 and $\pi^+\pi^-$ is zero). Therefore, the large phase-space difference of the two- and three-body decays explains the large difference in the lifetimes. The discovery of the long-lived neutral kaon [15] confirms the idea in [14] and, as is now understood, the idea of CP parity conservation.

Although the scenario of restoring symmetry between particles and antiparticles at the new level (which also explains the large K_2^0 lifetime) is exceptionally attractive, physicists were uninclined to rely unconditionally on conservation laws. Experimental tests on CP symmetry in neutral kaon decays have started. The best upper limit on the $K_2^0 \to 2\pi$ decay probability (no candidates per 597 reconstructed K_2^0) was obtained in 1962 in an experiment in Dubna [16]. One year later, in a hydrogen-chamber experi-

[4] Particles having not only the electric charge but also all the other charges equal to zero, like the photon, Z^0, π^0, η, and ϕ.

[5] Which for convenience is assumed to be zero in what follows.

ment in Brookhaven, a large number of two-pion events in K_2^0 decays was observed [17]. This experiment was unable to answer whether the effect was related to the CP parity violation; in particular, it could be explained by K_1^0 regeneration in the chamber walls (the transformation of K_2^0 to K_1^0 in a medium). To test the observed phenomenon, Christenson, Cronin, Fitch, and Turlay proposed a more precise experiment, where decays of a long-lived neutral kaon to a pion pair have been observed [10], supporting CP parity violation. The probability of such a transition relative to the CP-conserving decay into three pions has the small magnitude $\sim 2 \times 10^{-3}$. Nevertheless, the observation of such a subtle effect has resulted in a radical reconsideration of the laws of Nature.

1.3 The Kobayashi – Maskawa mechanism

CP violation had remained a mystery for almost a decade until 1973, when Kobayashi and Maskawa [12] found a way to include this effect in the SM framework in a natural way. We recall two important ideas that preceded the discovery of the Kobayashi – Maskawa mechanism.

In the 1950s, a large volume of experimental data on weak decays was accumulated, which allowed concluding that almost all the weak decay probabilities are proportional to one universal interaction constant (G_F^2). As usual, the picture was spoiled by the strange particles, which decayed much more slowly, as if their decay constant were approximately 4.5 times smaller. At that time, the universality of the weak interaction was not generally accepted, but its violation looked unnatural. In 1963, it was shown by Cabibbo [18] that all the weak decays of strange particles can be described by a universal constant, although somewhat smaller than the Fermi constant.

In the modern terminology, the difference in the decay probabilities of strange and strangeless particles is explained as follows. All the weak decays known by the end of the 1960s can be described by u-, d-, and s-quark transitions. The matrix element of the weak decay involves only the combination $u\bar{d}'$, where

$$d' = d\cos\theta_C + s\sin\theta_C\,, \tag{3}$$

and θ_C is the Cabibbo angle. Therefore, the probability of the π^+ decay caused by the $u \to d$ transition is determined by the constant $\cos^2\theta_C\, G_F^2 \approx 0.95\, G_F^2$, and the probability of the K^+ decay caused by the $u \to s$ transition is proportional to $\sin^2\theta_C\, G_F^2 \approx 0.05\, G_F^2$.

The next significant step made in 1970 was the introduction of the fourth quark needed to explain the small probability of the $K_L^0 \to \mu^+\mu^-$ decay proceeding via so-called box diagrams and the small $K^0 - \bar{K}^0$ mixing amplitude. In the model with the three quarks known at that time, the integrals in the corresponding amplitudes diverged. To solve this problem, Glashow, Iliopuolos, and Maiani [19] proposed canceling the integrand by the contribution of a new (fourth) quark.[6] It was assumed to have a mass intermediate between the light quark masses and the weak interaction scale ($\sim$ 100 GeV), with its interaction with the other quarks proceeding via the transition $c \to s'$, where

$$s' = -d\sin\theta_C + s\cos\theta_C\,. \tag{4}$$

The coupling constants responsible for the $u \to d'$ and $c \to s'$ transitions are the same, providing the universality of the weak interaction. Such a mechanism (called the GIM mechanism after its authors' names) leads to the compensation of the contributions of the u- and c-quarks, entering the box diagrams with opposite signs. The GIM mechanism has two major consequences. First, the symmetry between quarks and leptons is restored, although unexplained, but this is without a doubt an advantage of the theory. Second, the equality of the upper (with the charge $+2/3$) and the lower (with the charge $-1/3$) quarks is restored: the pairs of the upper and lower quarks enter the weak current (j_μ) symmetrically, rotated by the same angle

$$j_\mu = (\bar{u},\bar{c})_L\gamma_\mu \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}_L\,, \tag{5}$$

where the subscript L corresponds to left quarks and γ_μ are Dirac matrices.

The introduction of the fourth quark solved a set of problems; however, the theory still lacked a CP violation mechanism. CP conservation in the theory with two quark generations is driven by the fact that the mixing matrix can always be chosen real. Kobayashi and Maskawa noticed that in the case of six quarks (three generations, or pairs, of quarks) CP violation may emerge due to the unavoidable imaginary part in the mixing matrix. It is remarkable that this idea was proposed long before the discovery of third-generation quarks and leptons, and even a year before the charmed quark was found, which completed the second generation of quarks.

In weak interaction processes involving charged currents, the transitions $u \leftrightarrow d'$, $c \leftrightarrow s'$, and $t \leftrightarrow b'$ occur. The quark states (d', s', b') are linear combinations of the (d, s, b) quarks:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \tag{6}$$

The complex matrix V is called the Cabibbo – Kobayashi – Maskawa (CKM) matrix. The universality of the weak interaction leads to the unitarity of the CKM matrix. The mixing of the antiquarks is determined by the complex-conjugate matrix V_{ij}^*. Because $V_{ij}^* \neq V_{ij}$, the quark and antiquark couplings differ, eventually leading to CP violation. Unfortunately, specific values of the CKM matrix elements are not predicted by the SM and can only be obtained experimentally.

Information about the absolute values of the CKM matrix elements was obtained from measurements of the lifetimes and weak decay probabilities of various mesons and baryons [20, 21]. The CKM matrix turned out to be nearly diagonal. Moreover, a hierarchy between the values of the off-diagonal elements was noticed:

$$|V_{ub}| \approx |V_{td}| \ll |V_{cb}| \approx |V_{ts}| \ll |V_{us}| \approx |V_{cd}|\,. \tag{7}$$

Taking the hierarchy into account, the CKM matrix can be written, as proposed by Wolfenstein [22], using four real parameters A, ρ, η, and λ, with $A, \rho, \eta \sim 1$ being of the order of unity and $\lambda \ll 1$. Finally,

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)\,, \tag{8}$$

[6] Which is called a charmed quark and is denoted by c.

where λ is the expansion parameter. We note that in the leading order in λ, only the elements V_{td} and V_{ub}, responsible for the transitions between the first and the third generations, contain an imaginary part.

The Kobayashi – Maskawa model was not the only way to introduce CP violation into theory that was discussed in the 1970s [23 – 26], but it was the simplest one. Later, the discovery of the third generation of leptons and quarks [27, 28] provided important, although only partial, support for the Kobayashi – Maskawa hypothesis. The existence of three generations is not sufficient to explain CP violation: for example, the CKM matrix could be real. Only in the 1990s was the CKM matrix shown to contain an imaginary part. The task was by no means easy, taking into account that all the experiments that do not observe CP violation measure only the absolute values of the CKM elements $|V_{ij}|$, while their phases are not observable. The existence of an imaginary part was discovered by simultaneously measuring the absolute values of several matrix elements with high accuracy and using the unitarity requirement, as we show in Section 2.2.

Neutral kaons have long remained the only system with observable CP violation. Although experiments with kaons have presently reached a very high accuracy, the CP asymmetry is measured only in three processes: $K_L^0 \to \pi^+\pi^-$, $K_L^0 \to \pi^0\pi^0$, and $K_L^0 \to \pi^{\pm} l^{\mp} \nu$. Before 1999, all these measurements could only confirm that CP violation exists in the transitions $K^0 \leftrightarrow \bar{K}^0$ with $|\Delta S| = 2$, and all three decays measured one parameter ε that characterizes the admixture of K_1^0 in K_L^0:

$$K_L^0 = \frac{K_2^0 + \varepsilon K_1^0}{\sqrt{1+\varepsilon^2}} \approx K_2^0 + \varepsilon K_1^0 \,. \tag{9}$$

The parameter ε, now known with high accuracy ($\varepsilon = (2.284 \pm 0.014) \times 10^{-3}$), depends, in its turn, on the CKM matrix parameters. One can try to relate the parameter ε to the measured absolute values of the CKM matrix and thus to test the model. This attempt fails: the CKM matrix elements responsible for CP violation in kaons turn out to differ by orders of magnitude, and, to obtain their relative angle in the complex plane using the CKM matrix unitarity, the larger elements should be measured with the same absolute precision as the smaller ones. This problem can hardly be solved now.

Finally, in 1999, direct CP violation was observed [29, 30]:

$$\frac{\mathcal{B}(K_L^0 \to \pi^+\pi^-)}{\mathcal{B}(K_S^0 \to \pi^+\pi^-)} \neq \frac{\mathcal{B}(K_L^0 \to \pi^0\pi^0)}{\mathcal{B}(K_S^0 \to \pi^0\pi^0)} \tag{10}$$

[where $\mathcal{B}(\ldots)$ are the probabilities of the corresponding decays], which is evidence of CP violation in the K^0 decay itself with $|\Delta S| = 1$. Direct CP violation is characterized by a parameter ε':

$$\frac{\mathcal{B}(K_L^0 \to \pi^0\pi^0)/\mathcal{B}(K_S^0 \to \pi^0\pi^0)}{\mathcal{B}(K_L^0 \to \pi^+\pi^-)/\mathcal{B}(K_S^0 \to \pi^+\pi^-)} \approx 1 - 6 \times \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right), \tag{11}$$

which is presently measured relatively precisely: $\varepsilon'/\varepsilon = (1.67 \pm 0.26) \times 10^{-3}$ [20]. Such an additional independent measurement would seemingly serve as a real test of the Kobayashi – Maskawa model. But in practice, due to high uncertainty in the calculation of the strong interaction contribution, no definite conclusion can be reached. Numerous calculations predict the ratio ε'/ε in the range -1×10^{-3} to 3×10^{-3} [31 – 38], i.e., even the sign of the effect is unknown. It can only be claimed that the measurement of direct CP violation in the kaon system agrees with the Kobayashi – Maskawa model by an order of magnitude, but does not reject other possibilities.

We now summarize the status of the CP violation theory at the end of the last century before CP violation measurement in B-mesons. The Kobayashi – Maskawa model proved to be correct, containing the CP violation mechanism. But after nearly thirty years of experimental tests, we cannot even claim that the Kobayashi – Maskawa mechanism makes the dominant contribution to the effect it was proposed to explain.

2. CP violation in B-meson decays

CP violation in B mesons is predicted to be larger because the contributions of all three quark generations are comparable. In the case of K mesons, due to the CKM matrix element hierarchy, the third generation only weakly affects both the mixing and the decay amplitudes. As mentioned in Section 1.3, the contribution of all three generations is a necessary condition of CP violation in the Kobayashi – Maskawa model. Consequently, if the effects leading to CP violation in B mesons do not accidentally cancel, it could be of the order of unity and experimentally measurable. Moreover, a measurement of this kind is the only real test of the Kobayashi – Maskawa model, because the same weak phase that is a free parameter of the theory is determined in several independent ways, and the consistency of the results serves as proof of the correctness of the theoretical approach.

In the 1980s, it became apparent that although the effect of CP violation in B decays is expected to be large, the experimental techniques developed for neutral kaons are not applicable to B mesons. Indeed, the lifetime difference of the B_d^0 mass eigenstates was expected to be too small ($\Delta\Gamma/\Gamma = \mathcal{O}(10^{-2})$) to create a 'beam' of long-lived B mesons, as is done in experiments with neutral kaons, where to study K_L^0 meson properties it suffices to wait until the short-lived component K_S^0 decays. On the other hand, the CP asymmetry in the semileptonic B-meson decays turned out to be negligibly small.

In 1980, Carter and Sanda [39, 40] proposed a method for searching for CP violation in B-meson decays. We consider the decay of a B meson into the final state (f) common to B_d^0 and $\bar{B}_d^0$; two amplitudes contribute to this decay: the direct transition $B_d^0 \to f$ and a chain of successive transitions $B_d^0 \to \bar{B}_d^0 \to f$.[7] Due to the existence of the imaginary part in the CKM matrix, these complex amplitudes may have different weak phases. The observable decay probability, proportional to the absolute value squared of the sum of two amplitudes, depends on the initial state (B_d^0 or $\bar{B}_d^0$) of the decaying particle:

$$\mathcal{B}(B_d^0 \to f) \neq \mathcal{B}(\bar{B}_d^0 \to f) \,. \tag{12}$$

As shown by Carter and Sanda, CP asymmetry in these decays ranges from one to ten percent. We note that this

[7] Here, we assume that similarly to K-mesons, the transitions $B_d^0 \leftrightarrow \bar{B}_d^0$ exist and are not small. In 1979, Asimov and Anselm [41] discussed the possibility of observing CP violation in B-meson decays even in the absence of mixing.

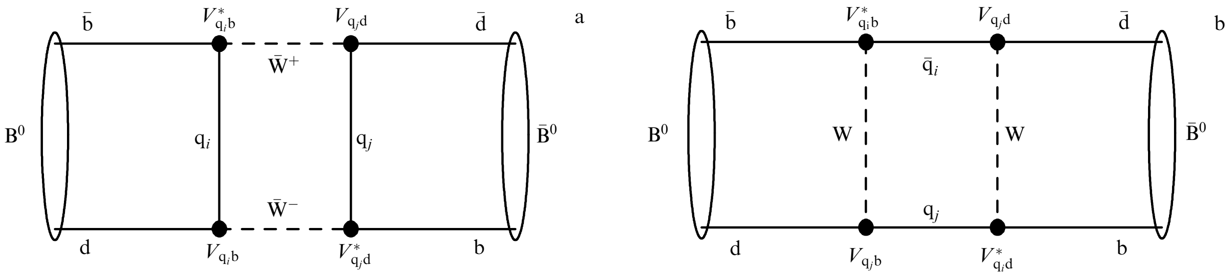

Figure 1. Quark diagrams illustrating the $B^0_d - \bar{B}^0_d$ mixing.

idea was proposed before the experimental observation of B mesons, although no doubts about the existence of these particles were left after the discovery of the b quark in 1977 [28].

After several years, B mesons were observed in the ARGUS [42] and CLEO [43] experiments. Starting from that moment, these particles have been intensively investigated. B-meson decays have been reconstructed in many final states, part of which can be used in the search for CP violation.

An unexpectedly high probability of $B^0_d - \bar{B}^0_d$ mixing measured by ARGUS [44] and confirmed by CLEO [45] has highly increased the chances of measuring the CP asymmetry. Indeed, because the transition $B^0_d - \bar{B}^0_d$ proceeds relatively quickly, a significant part of B^0_d turns into $\bar{B}^0_d$ before they decay. The measurement of the $|V_{cb}|$, $|V_{ub}|$, and $|V_{td}|$ CKM matrix elements in B-meson decays has shown that the magnitude of CP violation is expected to be significantly larger than Carter and Sanda predicted. It is rare when Nature turns out to be more favorable to physicists than even the greatest optimists could expect. A favorable situation has arisen for the construction of specialized experimental facilities aimed at the study of CP violation in B-meson decays.

The most convenient decay to measure CP violation from both the theoretical and experimental standpoints is $B^0_d \to J/\psi K^0_S$ with the branching ratio $\sim 0.05\%$. Because of the J/ψ transition to the lepton pair l^+l^-, such a final state is easily observed in experiment. Another advantage of this decay is the possibility of relating the magnitude of the CP violation to the specific combination of CKM matrix elements with the theoretical uncertainty less than 1%.

We next discuss the physics of this phenomenon in more detail. In the next three sections, we use simple yet cumbersome calculations. The reader may skip the derivation of the formulas, paying attention only to the final expressions that are needed in the discussion of the experimental results.

2.1 $B^0 - \bar{B}^0$ mixing

Two neutral B mesons exist: B^0_d containing $\bar{b}$ and d quarks ($\bar{b}$d), and B^0_s ($\bar{b}$s). Each of them can mix with its antiparticle; we consider the mixing of only one of them, B^0_d, as an example. Similarly to the kaon case (see Section 1.2), in addition to the two fixed-flavor states[8] B^0_d and $\bar{B}^0_d$, two states with definite masses and lifetimes exist, B_H (heavy) and B_L (light), which are convenient for describing the evolution of particles in time. In the SM, there is an interaction shown in Fig. 1 (each diagram is a sum over all the upper quarks $q_{i(j)} = u, c, t$), resulting in the transition $B^0_d \leftrightarrow \bar{B}^0_d$, and therefore mass eigenstates are not states with definite flavor.

Produced as a pure flavor state, B^0_d or $\bar{B}^0_d$ evolves in time and space,[9] and at an instant t it is given by a mixture of states

$$a(t)|B^0_d\rangle + b(t)|\bar{B}^0_d\rangle \quad (13)$$

with the coefficients $a(t)$ and $b(t)$ determined from

$$i\partial_t \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\boldsymbol{\Gamma}\right)\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}, \quad (14)$$

where the Hermitian (numerical) matrices $\mathbf{M}$ and $\boldsymbol{\Gamma}$ describe the dispersive and absorptive parts of the $B^0_d - \bar{B}^0_d$ mixing.

The light (B_L) and heavy (B_H) states are eigenstates of the matrix Hamiltonian $\left(\mathbf{M} - (i/2)\boldsymbol{\Gamma}\right)$ and are superpositions of B^0_d and $\bar{B}^0_d$:

$$|B_{L,H}\rangle = p|B^0_d\rangle \pm q|\bar{B}^0_d\rangle, \quad (15)$$

where

$$\frac{q}{p} = \sqrt{\frac{M^*_{12} - (i/2)\Gamma^*_{12}}{M_{12} - (i/2)\Gamma_{12}}} \approx \frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}} \exp(2i\xi_B). \quad (16)$$

In the last equation, we keep an arbitrary phase ξ_B to show that it cancels in the final expression for the CP asymmetry; we also use the smallness of the off-diagonal elements of the $\boldsymbol{\Gamma}$ matrix due to the small contribution of the large (much larger than $1/m_b$) distances to mixing, and estimate the off-diagonal elements of $\mathbf{M}$ from the diagrams in Fig. 1. The states B_L and B_H have different masses ($\Delta m_d = M_{B_H} - M_{B_L}$), while the width difference is very small ($\Delta\Gamma \equiv \Gamma_{B_L} - \Gamma_{B_H} \ll \Delta m_d \sim \Gamma$). The value of Δm_d can be estimated theoretically [47] up to a small uncertainty in the QCD calculations for a dimensionless formfactor B_B and the decay constant f_B. Omitting lengthy calculations, we quote the final result:

$$\Delta m_d \sim G_F^2 m_t^2 f_B^2 m_B \,\mathrm{Re}\,(V^*_{td}V_{tb})^2,$$

where m_t and m_B are the masses of the t quark and the B meson.

[8] Here, the flavor is a quantum number equal to +1 for a meson and −1 for an antimeson, which is conserved in strong and electromagnetic interactions.

[9] Here, we consider the oscillations in time, while experimentally the oscillations in space are observed. Measuring the spatial coordinates of B-meson production and decay allows measuring the time in its rest frame. A thorough consideration of this effect in terms of space oscillations can be found in [46].

We write evolution equation (13) explicitly by solving Eqn (14) for physical states produced as pure B_d^0 or $\bar{B}_d^0$:

$$\left|B^0_{\text{phys}}(t)\right\rangle = \exp(-iMt)\exp\left(-\frac{\Gamma t}{2}\right)\left(\cos\left(\frac{\Delta m_d t}{2}\right)|B^0_d\rangle + i\,\frac{q}{p}\sin\left(\frac{\Delta m_d t}{2}\right)|\bar{B}^0_d\rangle\right),$$
$$\left|\bar{B}^0_{\text{phys}}(t)\right\rangle = \exp(-iMt)\exp\left(-\frac{\Gamma t}{2}\right)\left(i\,\frac{p}{q}\sin\left(\frac{\Delta m_d t}{2}\right)|B^0_d\rangle + \cos\left(\frac{\Delta m_d t}{2}\right)|\bar{B}^0_d\rangle\right), \tag{17}$$

where t is the time in the B-meson rest frame. This equation is needed for calculating the time-dependent CP asymmetry in B-meson decays. All the arguments are also applicable to the $B_s^0 - \bar{B}_s^0$ system, once V_{td} is replaced by V_{ts}. Because $|V_{ts}|$ is larger than $|V_{td}|$, the $B_s^0 - \bar{B}_s^0$ oscillations are faster, with practically equal B_d^0 and B_s^0 lifetimes, mostly determined by the $|V_{cb}|$ element.

The mixing of the neutral B mesons was first observed experimentally in 1987. In the experiment UA1, where B_d^0, B^+, and B_s^0 mesons were produced in high-energy proton and antiproton interactions, the events with two energetic leptons of the same sign from B-meson decays were observed [48], which was evidence of the mixing. But its quantitative parameters were not measured in this experiment because it became impossible to find which type of B^0-meson oscillations led to events with leptons of the same sign. This task was solved for B_d^0 in the ARGUS experiment in e^+e^- colliding beams several months later [44]. Because B_s^0 mesons were not produced in the ARGUS experiment, the presence of the same-sign lepton events was unambiguous evidence for the B_d^0 mixing. Comparing the number of events with opposite-sign and same-sign leptons, one can measure Δm_d as

$$\chi_d \equiv \frac{N_{l^+l^+} + N_{l^-l^-}}{N_{l^+l^-} + N_{l^-l^+} + N_{l^+l^+} + N_{l^-l^-}} = \frac{x_d^2}{2(1+x_d^2)}, \tag{18}$$

where

$$x_d \equiv \frac{\Delta m_d}{\Gamma}. \tag{19}$$

The best precision can be reached by measuring the time dependence of the oscillations to obtain Δm_d directly from Eqn (17). Such measurements have been performed in experiments at LEP, SLC, and Tevatron. Currently, the value of Δm_d is known to a high precision [20], mainly from the precision measurements at B-factories:

$$\Delta m_d = (0.507 \pm 0.004)\ \text{ps}^{-1}. \tag{20}$$

Determining the oscillation period using the number of same-charge leptons for B_s^0 is much harder, because B_s^0 oscillates several times during its lifetime. As a result, $\chi_s \approx 1/2$, and an unprecedented precision is needed in the measurement of χ_s to determine Δm_s. Almost twenty years were needed before the D0 and CDF experiments were able to directly measure Δm_s [49]:

$$\Delta m_s = (17.31^{+0.35}_{-0.18} \pm 0.07)\ \text{ps}^{-1}. \tag{21}$$

2.2 Indirect CP violation in B meson decays

We let A denote the amplitude of the B_d^0 decay into the CP eigenstate f_{CP}, and $\bar{A}$ denote the corresponding $\bar{B}_d^0 \to f_{CP}$ amplitude. Assuming that $|A| = |\bar{A}|$ (i.e., that direct CP violation is absent, which is possible if the amplitude $B_d^0 \to f$ is the only one or several amplitudes have the same weak phases) and using Eqns (16) and (17), we obtain the time dependence of the B_d^0 and $\bar{B}_d^0$ decay probabilities:

$$\Gamma\left(B_d^0(t) \to f_{CP}\right) \sim \left|\left\langle f_{CP}|H|B^0_{\text{phys}}(t)\right\rangle\right|^2 \sim \exp(-\Gamma t)|A|^2\left[1 + \text{Im}\left[\frac{q}{p}\frac{\bar{A}}{A}\right]\sin(\Delta m_d t)\right],$$
$$\Gamma\left(\bar{B}_d^0(t) \to f_{CP}\right) \sim \left|\left\langle f_{CP}|H|\bar{B}^0_{\text{phys}}(t)\right\rangle\right|^2 \sim \exp(-\Gamma t)|A|^2\left[1 + \text{Im}\left[\frac{p}{q}\frac{A}{\bar{A}}\right]\sin(\Delta m_d t)\right]. \tag{22}$$

CP parity is conserved if $\text{Im}\left[(p/q)(A/\bar{A})\right] = 0$. In this case, B_d^0 and $\bar{B}_d^0$ decay exponentially. For a CP asymmetry to appear, the relative phase between the complex quantities p/q and $A/\bar{A}$ must differ from zero (and π). CP violation of this kind is called 'CP violation in the interference between decays with and without mixing,' or more succinctly 'indirect CP violation.' [10]

Before we continue the discussion of CP violation for definite B-meson decay modes, we return to the consideration of the CKM matrix properties and obtain some useful relations. The unitarity means that $V^{*T}V \equiv I$ (I is the identity 3×3 matrix). This condition gives nine relations for the CKM matrix elements. One of them, the most important for the Kobayashi – Maskawa model and B-meson decay physics,

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0, \tag{23}$$

can be illustrated by a *unitarity triangle* [11] on the complex plane. If its sizes are normalized to $|V_{cd}V^*_{cb}|$, its vertex coordinates become equal to $(0,0)$, $(1,0)$, and $(\bar{\rho},\bar{\eta})$, where ρ and η are Wolfenstein parameters (8) (Fig. 2).

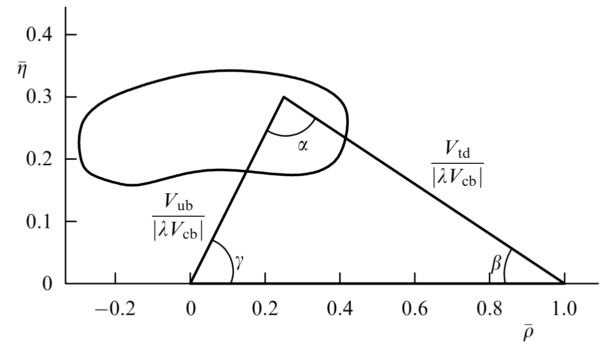

Figure 2. The unitarity triangle; λ, ρ, and η are Wolfenstein parameters (8). The sides are normalized to $|V_{cd}V^*_{cb}|$. The contour shown represents the allowed region for the triangle vertex $\bar{\rho} - \bar{\eta}$ obtained from the measurements of $|V_{ub}/V_{cb}|$, Δm_d, and CP violation in neutral kaons before B-factory operation.

The three sides of the unitarity triangle are known to good precision from the measurements of B-meson lifetimes, the

[10] Such a succinct term leads to some confusion: in the case of kaons, indirect CP violation was caused by mixing only (without the decay diagram contribution). Unfortunately, the use of this term has already become common.

[11] Interestingly, 6 possible different unitarity triangles have the same area.

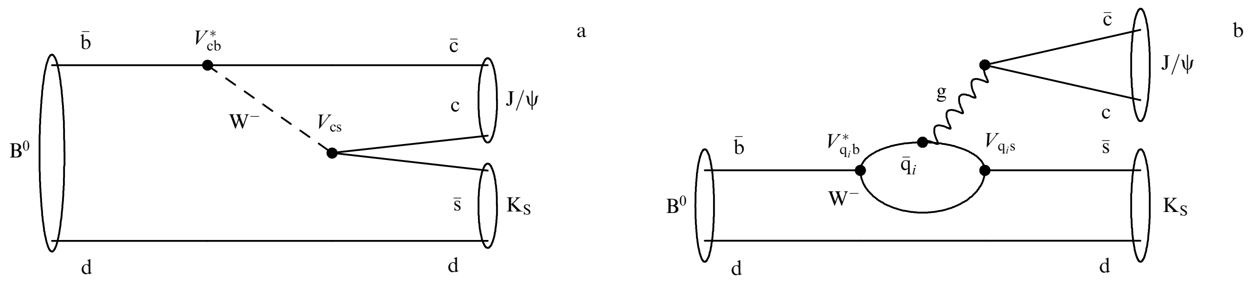

Figure 3. Quark diagrams of the decay $B_d^0 \to J/\psi K_S^0$: (a) 'tree', (b) 'penguin' with the emission of a hard gluon g.

semileptonic decay probability ($|V_{cb}|$), the charmless decays fraction ($|V_{ub}|$), and the frequency of $B_d^0 - \bar{B}_d^0$ oscillations ($|V_{td}|$). CP asymmetry in B meson decays is conveniently represented in terms of unitarity triangle angles α, β, and γ (sometimes an alternative notation ϕ_2, ϕ_1, and ϕ_3 is used). It is useful to note that because the sides of the triangle are all of the same order, none of the angles is small. For further consideration, the angle $\beta(\phi_1)$ is of special importance:

$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]. \qquad (24)$$

One of the most convenient B-decay modes for CP asymmetry measurements is $B_d^0 \to J/\psi K_S^0$ ('the golden mode'). This decay proceeds via the transition $b \to c\bar{c}s$, whose diagram is shown in Fig. 3a. The amplitude of the 'tree' diagram (the term emphasizes the absence of loops) is proportional to the product of the CKM matrix elements V_{cb} and V_{cs}^*. The contribution of the decay diagrams, including quark loops (Fig. 3b),[12] should be suppressed compared to the tree diagrams. Estimating the total effect of the penguin contributions requires calculating the sum of the diagrams with u-, c-, and t-quark lines in the loop. Taking into account that the amplitude with the u quark is small ($V_{ub}V_{us}^* \ll V_{cb}V_{cs}^*$) and using the unitarity requirement, we obtain $V_{tb}V_{ts}^* = V_{cb}V_{cs}^*$ with good precision. As a result, the weak phase of the sum of penguin contributions for $b \to c\bar{c}s$ is determined by the product of the same CKM matrix elements ($V_{cb}V_{cs}^*$) as for the tree amplitude.

We now calculate the CP-violating contribution for $B_d^0 \to J/\psi K_S^0$. Since $B_d^0 \to J/\psi K^0$ and $\bar{B}_d^0 \to J/\psi \bar{K}^0$ are decays into different final states, interference is possible only due to the $K^0 - \bar{K}^0$ mixing, and the additional factor

$$\left(\frac{p}{q}\right)_K = \frac{V_{cd}^*V_{cs}}{V_{cd}V_{cs}^*} \qquad (25)$$

occurs in the ratio $\bar{A}/A$. With this factor taken into account, the ratio of the B_d^0 and $\bar{B}_d^0$ decay amplitudes becomes

$$\frac{\bar{A}_{J/\psi K_S^0}}{A_{J/\psi K_S^0}} = (-1)\,\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\,\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}\exp(-2i\xi_B)\,, \qquad (26)$$

where an additional factor -1 accounts for the negative CP parity of the $J/\psi K_S^0$ state. Using this ratio together with Eqns (16) and (24), it is easy to verify that the relative phase between q/p and $\bar{A}_{J/\psi K_S^0}/A_{J/\psi K_S^0}$ equals -2β. Now, to obtain the dependence of the CP asymmetry on time, we must substitute q/p and $A_{J/\psi K_S^0}/\bar{A}_{J/\psi K_S^0}$ in expression (22):

$$a_{f_{CP}} = \frac{\Gamma(\bar{B}_d^0 \to J/\psi K_S^0) - \Gamma(B_d^0 \to J/\psi K_S^0)}{\Gamma(\bar{B}_d^0 \to J/\psi K_S^0) + \Gamma(B_d^0 \to J/\psi K_S^0)} = \sin 2\beta \sin(\Delta m_d t)\,. \qquad (27)$$

The theoretical uncertainty of the CP asymmetry in the $B_d^0 \to J/\psi K_S^0$ decay is less than 1%. Such a low uncertainty remains in the decays of B mesons into other charmonium states and K^0 ($B_d^0 \to (c\bar{c})K^0$).

2.3 CP violation measurement in B-meson decays from $\Upsilon(4S)$

One of the most convenient ways to produce B mesons is to use the decays of the $\Upsilon(4S)$ resonance. This resonance is produced at e^+e^- colliding beam facilities with a high cross section, and always decays into a pair of B mesons (charged or neutral) without additional particles. B mesons are produced in $\Upsilon(4S)$ decays in a coherent state with the relative orbital momentum $L = 1$. The coherence of B_d^0 and $\bar{B}_d^0$ is preserved until either particle decays; up to this moment, the wave function of the system is an asymmetric combination of B_d^0 and $\bar{B}_d^0$, which is a consequence of the fundamental properties of particle physics, the Bose statistics and the CPT symmetry conservation in all known interactions. After one of the particles decays, the other continues evolving in time, and due to the $B_d^0 - \bar{B}_d^0$ mixing, we can observe events with both particles decaying as B_d^0 or $\bar{B}_d^0$ (but only if the decays occur at different times).

To understand how the CP violation effect manifests itself in the case of coherent $B_d^0 - \bar{B}_d^0$ pair production, a sequence of simple but lengthy transformations is needed. The wave function of the two-particle state in the decay of $\Upsilon(4S)$ can be explicitly represented as

$$S(t_f, t_b) = \frac{1}{\sqrt{2}}\left[B^0_{phys}(t_f,\theta,\phi)\bar{B}^0_{phys}(t_b,\pi-\theta,\phi) - \bar{B}^0_{phys}(t_f,\theta,\phi)B^0_{phys}(t_b,\pi-\theta,\phi)\right]\sin\theta\,, \qquad (28)$$

where θ is the polar and ϕ is the azimuthal angle of the flight direction of mesons relative to the direction of the electron beam in the $\Upsilon(4S)$ rest frame, t_f is the proper time of the B meson from the forward hemisphere ($\theta_f < \pi/2, \phi_f$), and t_b is the proper time of the opposite meson ($\pi - \theta_f, \phi_f + \pi$). Because B mesons have the same absolute value of the momentum in this frame, $t_f = t_b$. Until one of the B mesons decays, the two-particle wave function has only one B_d^0 and one $\bar{B}_d^0$. Using relations (17) and (28), we obtain the amplitude of the process with one of the B mesons decaying into the

[12] Such diagrams are called 'penguins.'

f_1 final state at the instant t_1, and the other to the state f_2 at the instant t_2:

$$A(t_1,t_2)=\frac{1}{\sqrt{2}}\exp\left[-\left(\frac{\Gamma}{2}+\mathrm{i}M\right)(t_1+t_2)\right]$$
$$\times\left[\cos\frac{\Delta m_\mathrm{d}(t_1-t_2)}{2}\,(A_1\bar{A}_2-\bar{A}_1A_2)\right.$$
$$\left.-\,\mathrm{i}\sin\frac{\Delta m_\mathrm{d}(t_1-t_2)}{2}\left(\frac{p}{q}\,A_1A_2-\frac{q}{p}\,\bar{A}_1\bar{A}_2\right)\right]\sin\theta_1\,,\qquad(29)$$

where A_i and $\bar{A}_i$ are the respective amplitudes of the B^0_d and $\bar{B}^0_d$ decays into f_i.[13] For any flavor-specific final state f, either A_f or $\bar{A}_f$ is equal to zero.

We calculate the time-dependent probabilities of the $B^0_d-\bar{B}^0_d$ system decay to the final states f_1 and f_2:

$$R(t_1,t_2)=C\exp\left[-\Gamma(t_1+t_2)\right]$$
$$\times\left\{\left(|A_1|^2+|\bar{A}_1|^2\right)\left(|A_2|^2+|\bar{A}_2|\right)^2\right.$$
$$-\,4\,\mathrm{Re}\left(\frac{q}{p}\,A_1^*\bar{A}_1\right)\mathrm{Re}\left(\frac{q}{p}\,A_2^*\bar{A}_2\right)$$
$$-\cos\left(\Delta m_\mathrm{d}(t_1-t_2)\right)\left[\left(|A_1|^2-|\bar{A}_1|^2\right)\left(|A_2|^2-|\bar{A}_2|^2\right)\right.$$
$$\left.+\,4\,\mathrm{Im}\left(\frac{q}{p}\,A_1^*\bar{A}_1\right)\mathrm{Im}\left(\frac{q}{p}\,A_2^*\bar{A}_2\right)\right]$$
$$+\,2\sin\left(\Delta m_\mathrm{d}(t_1-t_2)\right)\left[\mathrm{Im}\left(\frac{q}{p}\,A_1^*\bar{A}_1\right)\left(|A_2|^2-|\bar{A}_2|^2\right)\right.$$
$$\left.\left.-\left(|A_1|^2-|\bar{A}_1|^2\right)\mathrm{Im}\left(\frac{q}{p}\,A_2^*\bar{A}_2\right)\right]\right\}.\qquad(30)$$

In this expression, the integration over all the flight directions of B was performed. As a result, the angular dependence disappeared, but an overall normalization factor C emerged. Moreover, the approximation $|q/p|=1$ was used.

Measuring the CP asymmetry requires detecting events with one of the B mesons decaying into a CP eigenstate f_{CP} at the instant t_{CP}, and the other decaying into a specific-flavor mode at t_{tag}. The use of the mode with $A_2=0$ and $\bar{A}_2=\bar{A}_{tag}$ for determining the B flavor identifies the $B(t_2)=B(t_{tag})$ meson as B^0_d. We note that Eqn (30) also holds if the tagging decay occurs after the decay into a CP eigenstate. In this case, the state of the tagging B meson in the time range $t_{CP}<t<t_{tag}$ should be the mixture $B^0_d-\bar{B}^0_d$, which evolves into the B^0_d state at $t=t_{tag}$. As a result, expression (30) becomes

$$R(t_{tag},t_{CP})=C\exp\left[-\Gamma(t_{tag}+t_{CP})\right]|\bar{A}_{tag}|^2|A_{f_{CP}}|^2$$
$$\times\left\{1+|\lambda_{f_{CP}}|^2+\cos\left[\Delta m_\mathrm{d}(t_{CP}-t_{tag})\right]\left(1-|\lambda_{f_{CP}}|^2\right)\right.$$
$$\left.-\,2\,\mathrm{Im}\,(\lambda_{f_{CP}})\sin\left[\Delta m_\mathrm{d}(t_{CP}-t_{tag})\right]\right\},\qquad(31)$$

where

$$\lambda_{f_{CP}}\equiv\frac{q}{p}\,\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}=\xi_{f_{CP}}\,\frac{q}{p}\,\frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}\,.\qquad(32)$$

To obtain expression (32), we use the property

$$\bar{A}_{f_{CP}}=\xi_{f_{CP}}\bar{A}_{\bar{f}_{CP}}\,,\qquad(33)$$

where $\xi_{f_{CP}}$ is the CP parity of the final state f_{CP}.

In the case where $\bar{A}_2=0$ and $A_2=A_{tag}$, when the second meson is identified as $\bar{B}^0_d$ at the instant t_{tag}, an expression similar to (31) is obtained, with the flip of the sign in the terms proportional to the sine and cosine. The quantity that characterizes the CP asymmetry is the difference in the probabilities, normalized to their sum:

$$a_{f_{CP}}=\frac{1}{1+|\lambda_{f_{CP}}|^2}\left\{\left(1-|\lambda_{f_{CP}}|^2\right)\cos\left[\Delta m_\mathrm{d}(t_{CP}-t_{tag})\right]\right.$$
$$\left.-\,2\,\mathrm{Im}\,(\lambda_{f_{CP}})\sin\left[\Delta m_\mathrm{d}(t_{CP}-t_{tag})\right]\right\}.\qquad(34)$$

We now calculate the asymmetry in the $B^0_d\to J/\psi K^0_S$ decay. Using relations (16) and (24)–(26), we obtain the value of $\lambda_{J/\psi K^0_S}$ as

$$\lambda_{J/\psi K^0_S}=\xi_{J/\psi K^0_S}\,\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\,\frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}\,\frac{V^*_{cs}V_{cb}}{V_{cs}V^*_{cb}}\,,\qquad(35)$$

which yields

$$|\lambda_{J/\psi K^0_S}|=1\,,\qquad \mathrm{Im}\,(\lambda_{J/\psi K^0_S})=-\xi_{J/\psi K^0_S}\sin 2\beta\,.\qquad(36)$$

Finally, we obtain an expression similar to (27):

$$a_{J/\psi K^0_S}=-\xi_{J/\psi K^0_S}\sin(2\beta)\sin\left[\Delta m_\mathrm{d}(t_{CP}-t_{tag})\right].\qquad(37)$$

If expression (37) is integrated over $t_{CP}-t_{tag}$ from $-\infty$ to $+\infty$, the asymmetry vanishes[14]; therefore, to observe CP violation in the process $\Upsilon(4S)\to B^0_d\bar{B}^0_d$, one needs at least to know which of the B mesons decayed earlier. In principle, the time difference $t_{CP}-t_{tag}$ can be obtained by measuring the flight path of the B mesons until they decay; however, the B mesons produced in the $\Upsilon(4S)$ decay are too slow. Their mean path length is only several dozen microns. The measurement of the decay vertex with such precision is impossible with current vertex detector technology. Moreover, to determine the decay time difference, one needs to know the point of the $B^0_d\bar{B}^0_d$ pair production, which can only be done with the precision up to the size of the colliding beam interaction region.

The solution to this problem was found by Alexan et al. [50]. For the measurement of the flight path to be possible, the B mesons should move quickly in the laboratory frame (relative to the detector). Technically, this requires asymmetric energies of the electron and positron beams: the $\Upsilon(4S)$ resonance produced in such collisions moves with high velocity in the direction of the more energetic beam, and the B mesons have a significant path length. In this case, $\Delta t=\Delta z/\beta\gamma c$, where $\Delta z=z_{CP}-z_{tag}$ is the measured distance along the beam line between the two B-meson decay vertices. Because B mesons move along the same line, there is no need to know their production point. A beautiful idea solves two problems at once.

[13] We use the equation $\sin(2\pi-\theta)=-\sin\theta$ for angular dependence (29) on θ_1 defined in the range $(0,\pi)$.

[14] Such cancellation is a consequence of the asymmetry of the wave function of a $B^0_d\bar{B}^0_d$ pair produced at the e^+e^- colliding beams. If the $B^0_d\bar{B}^0_d$ pair is in an s-wave state, such cancellation does not occur.

3. B-factories

At the beginning of the 1990s, several projects regarding asymmetric B-factories were proposed, two of which have been successfully implemented: PEP-II at the Stanford Linear Accelerator Center (SLAC), USA, and KEKB at the High Energy Accelerator Research Organization (KEK), Japan. To prepare and carry out experiments on the observation of CP violation in the $B_d^0\bar{B}_d^0$ system, two international collaborations, BaBar and Belle, were organized.

In addition to the ability to measure the decay time difference of the B mesons, asymmetric B-factories should have high luminosity, because the probability of a B meson decay into a CP eigenstate is small (for $J/\psi K_S^0$, it equals 0.05%; the probability of J/ψ decay into a lepton pair is $\sim 10\%$). For an asymmetric B-factory consisting of two independent rings for electrons and positrons, the natural strategy of obtaining the maximum possible luminosity is chosen: while keeping the parameters of the colliding beams leading to record luminosity at previous-generation facilities, the number of bunches in the accelerator ring is increased to several thousand.[15] Certainly, the accumulation of a large number of bunches is related to some technical problems, in particular, the need to increase the RF power to compensate for synchrotron energy loss, cooling of the beam pipe heated by the synchrotron radiation and induced currents, and suppression of the beam instability due to collective effects. These difficult problems have been successfully solved in both projects.

For PEP-II, the energy was chosen equal to 9.0 GeV for the electron beam and 3.1 GeV for the positron beam, yielding the relativistic parameter characterizing the $\Upsilon(4S)$ velocity in the laboratory frame $\beta\gamma = 0.55$. At the KEKB accelerator, to ease the separation of beams at the parasitic interaction points, the beams collide at a small angle (± 11 mrad), and the corresponding factor is $\beta\gamma = 0.45$.

So far, the peak luminosity reached at PEP-II is 10^{34} cm^{-2} s^{-1}, and the KEKB luminosity has exceeded 1.7×10^{34} cm^{-2} s^{-1}. In one day, each collaboration collects the integrated luminosity exceeding the total statistics of the first-generation experiments ARGUS and CLEO-I, accumulated over many years. Figure 4 shows the history of data collection of BaBar and Belle since the beginning of their operation. Both curves demonstrate the growing rate of data collection, which indicates serious efforts by both teams to improve their experimental facilities.

The BaBar and Belle detectors have a similar design and are superconducting magnetic spectrometers with a large solid angle. A large part of the detector elements is inside the magnetic field (1.5 T). Charged particle tracks are reconstructed in drift chambers and in silicon vertex detectors (with the spatial resolution ~ 30 μm). In BaBar, the charged hadrons are identified (i.e., the sort of particle is determined: a pion, a kaon, or a proton) using the ionization losses in the drift chamber and the Cherenkov radiation angle in the quartz plates. Due to the total internal reflection in the plates, Cherenkov light is guided out of the inner detector part and is detected by a system of $\sim 10{,}000$ photomultipliers. In Belle, to identify the charged hadrons, combined information from three detector systems is used: the ionization losses in the drift chamber, the particle time of flight measured by scintillation counters, and the amount of Cherenkov light in the aerogel[16] threshold Cherenkov counters. Photons in both detectors are reconstructed in the electromagnetic calorimeters based on cesium iodide (CsI) crystals doped with thallium. These crystals are very efficient heavy scintillators. The energy of the electromagnetic cascade absorbed by the crystals is transformed into scintillation light detected by sensitive semiconductor photodiodes. The amount of light allows precisely reconstructing the energy of the detected photon. Information about the total energy and its spatial distribution in the calorimeter for the charged particles is also used to identify electrons. Muons are detected by the resistive plate chambers located inside the magnet yoke. The same chambers are used to reconstruct the interaction points of K_L^0 with the magnet yoke medium. The layouts of both detectors are shown in Fig. 5.

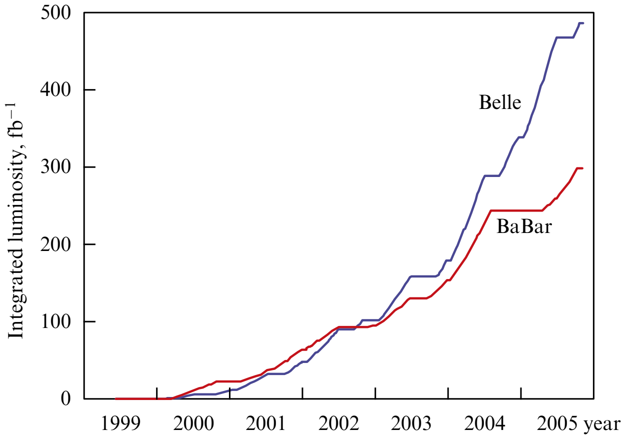

Figure 4. Integrated luminosity collected by B-factories since the beginning of their operation in 1999.

4. $\sin 2\beta$ measurement in $B_d^0 \to (c\bar{c})K^0$ decays

Measurement of CP asymmetry consists of three main steps. First, events with a decay of one B meson into a CP-eigenstate,[17] e.g., $B_d^0 \to J/\psi K_S^0$, must be selected. The easiest way is to fully reconstruct the B_{CP} meson by combining all detected particles presumably coming from the decay of interest. To reconstruct the $B_d^0 \to J/\psi K_S^0$ decay, a J/ψ candidate must be found in the event by constructing it from two oppositely charged leptons and checking that their invariant mass is consistent with the J/ψ mass (if the candidate mass does not correspond to the correct mass, it should be rejected). Then a similar procedure should be applied to a K_S^0 meson decaying to a $\pi^+\pi^-$ pair, taking into account that the two pions are produced in a secondary vertex due to a significant flight length of K_S^0. The mass and energy of the selected J/ψ and K_S^0 candidate combination should be equal within measurement errors to the B-meson mass and expected energy. An example of one of the reconstructed events of the $B_d^0 \to J/\psi K_S^0$ ($J/\psi \to \mu^+\mu^-$; $K_S^0 \to \pi^+\pi^-$) decay is shown in Fig. 6a. Charged particle tracks are shown with

[15] The maximum number of particles in the bunch is limited by so-called beam – beam effects: at a certain charge of the bunch, the disturbing action of the opposite beam becomes so large that the particle motion in the accelerator becomes unstable.

[16] A light, highly transparent, porous material based on amorphous silicon dioxide with the small refraction coefficient 1.01 to 1.035.

[17] This B meson is denoted as B_{CP} in what follows.

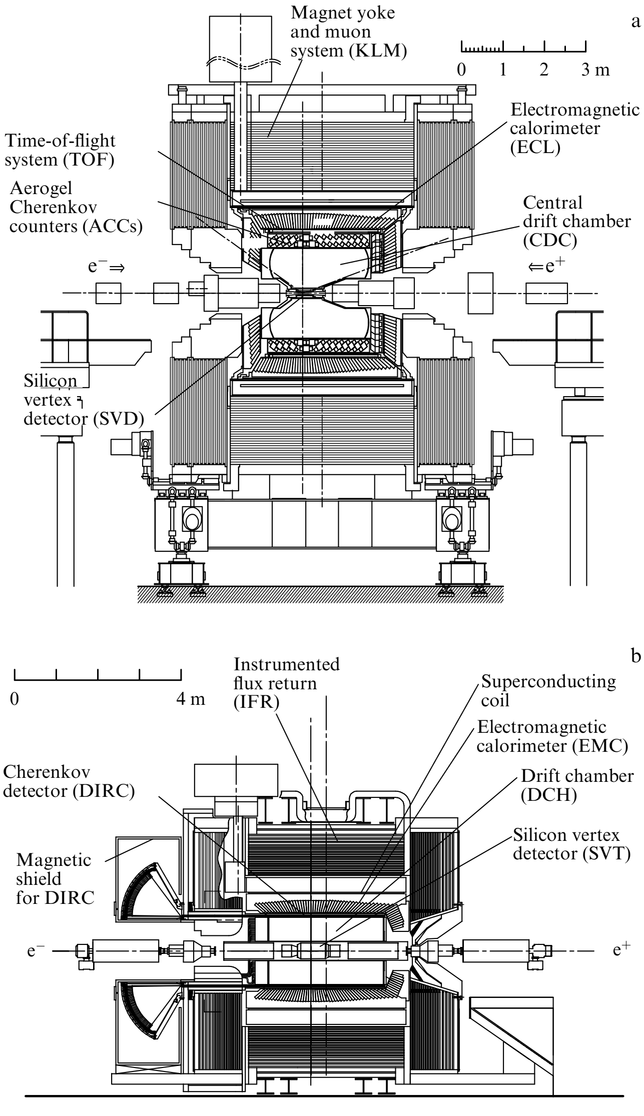

Figure 5. General layout of the Belle (a) and BaBar (b) detectors.

arcs reconstructed from the hit coordinates in the drift chamber and the vertex detector. Another event, shown in Fig. 6b, is a $B_d^0 \to J/\psi K_L^0$ decay candidate. K_L^0 is reconstructed from the cluster in the resistive plate chambers caused by the nuclear interaction of K_L^0 with the magnet yoke medium.

At the next stage, the flavor of the tagging B_{tag} meson must be determined (whether the B meson decayed as B_d^0 or as $\bar{B}_d^0$). Taking into account that $\Upsilon(4S)$ decays into a B-meson pair without additional particles, all the detected charged particles not used for the $B_d^0 \to J/\psi K_S^0$ reconstruction have to be treated as the decay products of B_{tag}. The charge and the type of these particles give information about the B_{tag} flavor. To illustrate the flavor tagging algorithm, we consider the event with the $B_d^0 \to J/\psi K_S^0$, shown in Fig. 6a. Except for the muon and the pion pairs from J/ψ and K_S^0 decays, eight more particles are reconstructed in the event. One of them is identified as the charged kaon. Because this kaon has a negative charge, we may assume that $B_{tag} = \bar{B}_d^0$ with high probability in this event (because $\bar{B}_d^0$ decays mainly to the D^0 or D^+ states mostly containing negative kaons). Looking at this event more carefully, we also note that one of the eight tracks is due to a soft positive-charged pion (the track with the highest curvature). This pion can be produced in the $D^{*+} \to D^0\pi^+$ decay, which supports the hypothesis that the tagging B meson is a $\bar{B}_d^0$.

At the third step, the decay vertices of both B mesons must be reconstructed. Their position in the plane transverse to the beam axis is well known, because the transverse size of the colliding beams is small (the size of the beam at the interaction point is 1 – 2 μm in the vertical direction and 150 μm in the horizontal direction). The coordinates of the B meson vertices along the beam direction (z) are determined from the particle tracks, which are measured with high precision in the silicon vertex detector. To determine the B_{CP} decay vertex, lepton tracks from J/ψ are used. For each of them, the intersection with the known beam interaction region is calculated. All the remaining tracks, except for the decay products of the long-lived particles, are used to reconstruct the tagging B_{tag} vertex.

After events with one of the B mesons reconstructed in the CP eigenstate are selected, the flavor of the other B meson is determined from its decay products (with some uncertainty), the positions of both vertices are measured with an appropriate precision, and the distribution of $t_{CP} - t_{tag}$ (for these events separated into two groups in accordance with the B_{tag} flavor) gives the most probable value of $\sin 2\beta$.

The first reliable observation of CP violation in B-meson decays was reported by the BaBar and Belle collaborations in the summer of 2001, two years after the data taking started [51, 52]. Presently, the results obtained by BaBar [53] and Belle [54] are based on the respective statistics of 316 fb^{-1} and 492 fb^{-1} available for analysis in the summer of 2006. That corresponds to $\sim 3.5 \times 10^8$ and $\sim 5.35 \times 10^8$ $B_d^0\bar{B}_d^0$ pairs produced in these experiments. Because the data analysis is performed in similar ways, we use the result of both collaborations in turn in what follows.

4.1 Results of CP asymmetry measurements

The decays $b \to c\bar{c}s$ are of special interest for the measurement of CP violation. Among all possible final states due to this quark diagram, several decay modes can be reconstructed with high efficiency and a relatively low background level. These include both CP-odd ($J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, and $\eta_c K_S^0$) and CP-even ($J/\psi K_L^0$) final states. J/ψ and $\psi(2S)$ mesons are effectively reconstructed in decays into the lepton pair l^+l^-; in addition, $\psi(2S)$ and χ_{c1} can be reconstructed in the respective cascade decays $J/\psi\pi^+\pi^-$ and $J/\psi\gamma$. To detect the lightest charmonium state η_c, decays into hadrons $K_S^0K^-\pi^+$ and $K^+K^-\pi^0$ are used.

The advantage of the colliding e^+e^- facilities operating at an energy of the $\Upsilon(4S)$ resonance production is the information gained about the total energy of B mesons, which equals the beam energy in the center-of-mass (CM) frame. This allows not only suppressing the background but also significantly improving the resolution of the B-meson mass. The invariant mass of the reconstructed B-meson candidate is calculated as

$$M_{bc} = \sqrt{E_{beam}^2 - \left(\sum \mathbf{p}_i\right)^2}\,,$$

where E_{beam} is the CM beam energy and $\mathbf{p}_i$ are the momenta of the B-meson decay products in the same frame. Additional background suppression is achieved by the constraint on the energy difference $\Delta E = \sum E_i - E_{beam}$, where E_i are the energies of the B-meson decay products. For signal events, M_{bc} should be close to the B-meson mass, and ΔE should be close to zero. These two variables weakly correlate and allow

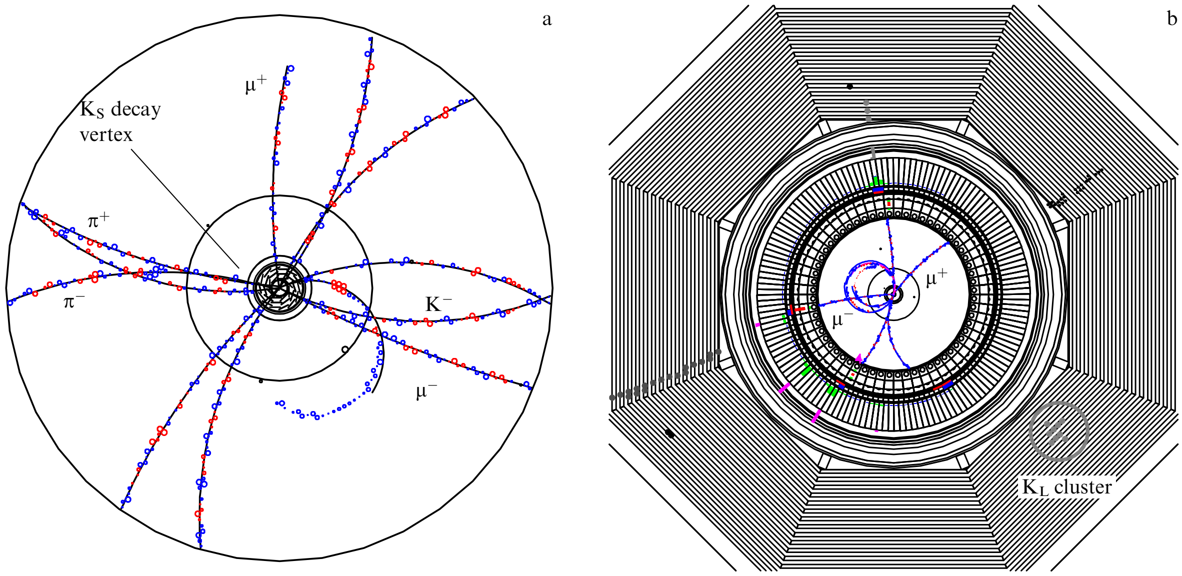

Figure 6. Events reconstructed in the Belle detector, containing the candidates to the decays $B_d^0 \to J/\psi K_S^0$ (a) and $B_d^0 \to J/\psi K_L^0$ (b).

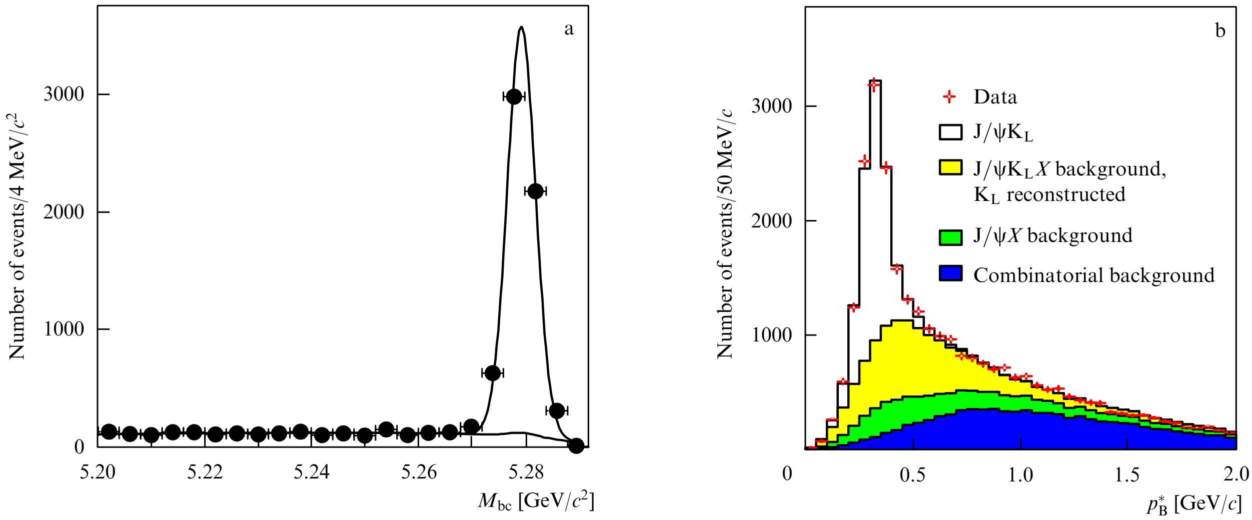

Figure 7. (a) Spectrum of invariant masses of B_{CP} candidates detected in the $J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, and $\eta_c K_S^0$ final states (BaBar). (b) CM momentum distribution of candidates for the $B_d^0 \to J/\psi K_L^0$ decay obtained in the Belle experiment.

selecting B-decay events efficiently. Distributions of B-meson candidate masses for different final states obtained in the BaBar experiment are shown in Fig. 7a. Similar distributions have been obtained by Belle.

The K_L^0 meson from the $B_d^0 \to J/\psi K_L^0$ decay is reconstructed using its interaction in the electromagnetic calorimeter or magnet yoke, based on signals from cesium iodide crystals or resistive plate chambers. This information allows determining the direction of K_L^0 flight in the event, but not the magnitude of its momentum, which can be calculated using the known total energy of the B-meson decay products. This means that the constraint on ΔE cannot be used anymore to suppress background events, which leads to a worse signal-to-noise ratio for the $B_d^0 \to J/\psi K_L^0$ mode. The distribution of B_d^0-meson candidate momenta obtained in the Belle experiment is presented in Fig. 7b. The expected value of the momentum for the signal events is equal to 340 MeV/c, the momentum of the B meson in the CM frame.

4.2 B-meson flavor tagging

After the reconstruction of decay into a CP eigenstate, all the remaining charged particles in the event are used to determine the flavor of the second B meson. The charge sign of fast leptons from the $B_d^0 \to Xl^+\nu$ decay, kaons produced in the cascade decay $B_d^0 \to \bar{D}^0 \to K^+$, and soft pions from D^{*+} decays is related to the type of tagging meson, B_d^0 or $\bar{B}_d^0$. For each event, combining all the available information allows determining the value of q, equal to $+1$ for a more probable decay of B_d^0, and -1 for $\bar{B}_d^0$.

Beyond any doubt, none of the feature categories mentioned above gives absolute confidence in the correctness of the tagging B meson flavor identification. The total efficiency of the correct flavor tagging can be characterized by the quantity

$$Q = \sum_i \varepsilon_i (1 - 2\omega_i)^2 \,, \tag{38}$$

where ε_i is the probability of finding a feature of the ith category and ω_i is the probability of false flavor determination in this category. Among all mentioned features, the most confident determination of the tagging B flavor is performed by fast leptons, although the highest tagging efficiency is provided by charged kaons (the probability of finding a charged kaon in an event is around 50%). To reach a higher tagging efficiency, all the events are separated into groups by the degree of certainty of the B flavor identification. Although the tagging algorithms in BaBar and Belle differ significantly, the values of the total tagging efficiency are almost equal ($Q \sim 28\%$).

To obtain CP asymmetry, the wrong-tag probability should be known, because the measured asymmetry is related to the true one as $\mathcal{A}_{\text{true}} = \mathcal{A}_{\text{measured}}/(1-2\omega)$. In both experiments, the wrong-tag probability was determined directly from data using B_d^0 decays into states with definite flavor, in particular, $D^{*+}l^-\bar{\nu}$, $D^-\pi^+$, $D^{*-}\pi^+$, and $D^-\rho^+$, and the flavor of the partner was obtained by the standard tagging algorithm. In this case, the amplitude of the oscillations in time is directly related to the probability ω_i of false B flavor determination,

$$\frac{N_{\text{OF}} - N_{\text{SF}}}{N_{\text{OF}} + N_{\text{SF}}} = (1-2\omega_i)\cos(\Delta m \Delta t)\,, \tag{39}$$

where N_{SF} and N_{OF} are the numbers of events with the same flavor and with the opposite flavor of B mesons. Because the number of fixed-flavor events is much larger than that used for the CP asymmetry measurement, the statistical precision of the wrong-tag probability measurement does not affect the precision of the CP violation measurement. The results of the measurement of flavor oscillations for the $B_d^0 \to D^{*+}l^-\bar{\nu}$ decay mode in the Belle experiment are shown in Fig. 8.

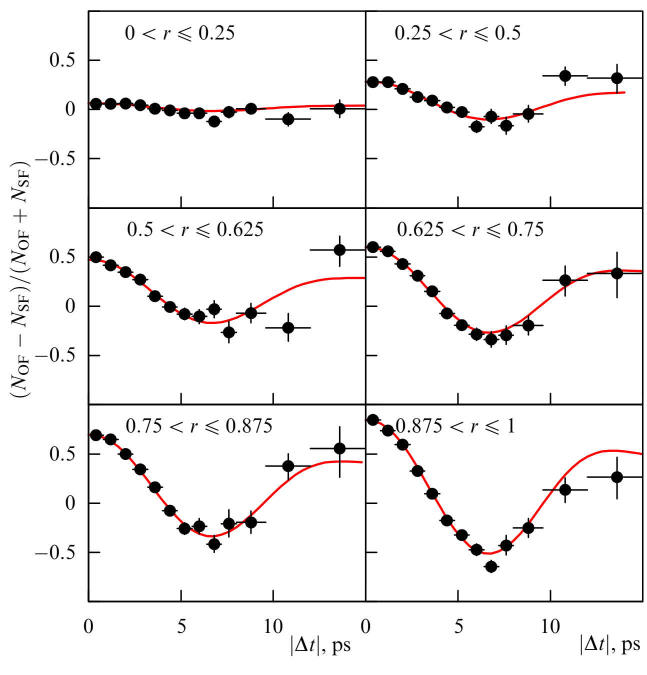

Figure 8. The ratio $(N_{\text{OF}} - N_{\text{SF}})/(N_{\text{OF}} + N_{\text{SF}})$ as a function of Δt for six event categories, separated by the tagging quality, in the Belle experiment. The oscillation amplitude is changed from small for the category with the worst tagging quality ($0 < r \leqslant 0.25$) to the maximum close to unity for $0.875 < r \leqslant 1$.

4.3 Vertex reconstruction of B-meson decays

The position of the CP eigenstate decay vertex is measured by the point of intersection of the lepton tracks from J/ψ ($\psi(2S)$) or fast hadron tracks from η_c with the known interaction region of colliding beams. The spatial resolution in the z_{CP} coordinate obtained is 50 μm for BaBar and 70 μm for Belle. The position of the tagging B_{tag} decay vertex is determined by reliably reconstructed tracks not used in the B_{CP} reconstruction. Because part of the tracks comes from secondary vertices of the long-lived particles (D mesons, K_S^0, Λ, etc.), successive iterations are used to find and exclude such tracks. The resolution obtained for the tagging B meson vertex z_{tag} is ~ 140 μm in both experiments. Although the resolutions in Δz are similar, some difference in the $\Upsilon(4S)$ velocity in the laboratory frame leads to different Δt resolutions: $\sigma_{\Delta t} \approx 1.1$ ps (BaBar) and $\sigma_{\Delta t} \approx 1.4$ ps (Belle).

4.4 Determination of the CP asymmetry value

The dependence of the number of detected events on Δt for different groups of events is presented in Fig. 9. The results of the BaBar collaboration are shown for $\text{CP} = -1$ and $\text{CP} = +1$ states, for both B_d^0- and $\bar{B}_d^0$-tagged events. The distributions obtained by Belle are presented for two sets of events: with $q\xi_f = +1$ and $q\xi_f = -1$. In both experiments, a large CP asymmetry is observed (see Fig. 9).

To measure the CP asymmetry, a value of the parameter $\sin 2\beta$ must be found that best describes the distributions after corrections for the wrong-tag probability and for the decay vertex coordinate resolution. For each of the selected events, the probability density as a function of $\sin 2\beta$ can be obtained as

$$\mathcal{P}(\Delta t, q, \omega, \xi_f, \Delta t) = \frac{\exp\left(-|\Delta t|/\tau_{B_d^0}\right)}{4\tau_{B_d^0}} \times \left[1 - \xi_f q(1-2\omega)\sin 2\beta \sin(\Delta m_d \Delta t)\right]. \tag{40}$$

The probability of observing a given event with the measured Δz can be obtained by convolving the probability density with the Δt resolution function $R(\Delta t)$ obtained, like ω, from the data:

$$P_i = \int \mathcal{P}(\Delta t')\, R_i(\Delta t - \Delta t')\, \mathrm{d}\Delta t'\,. \tag{41}$$

The product of the probabilities for all the selected events gives a global likelihood function (LF) for the probability of observing a given ensemble of events. The value of $\sin 2\beta$ is treated as a free parameter for determining the maximum LF value. From the statistical standpoint, the technique described is optimal, because the LF accounts for the individual sensitivity of each event to the $\sin 2\beta$ parameter, depending on the specific CP mode, tagging quality, decay vertex coordinate resolution, and many other properties of the event.

The values of the CP asymmetry are in good agreement:

$$\begin{aligned} \sin 2\beta &= 0.697 \pm 0.041 \pm 0.019 \quad (\text{BaBar})\,, \\ \sin 2\beta &= 0.643 \pm 0.038 \pm 0.017 \quad (\text{Belle})\,. \end{aligned} \tag{42}$$

Systematic errors include the uncertainties in the knowledge of the decay vertex reconstruction precision, wrong tag probability, and the background of the $B_d^0 \to J/\psi K_L^0$ decay. Both collaborations have performed various tests of their result. The values of the asymmetry measured for different

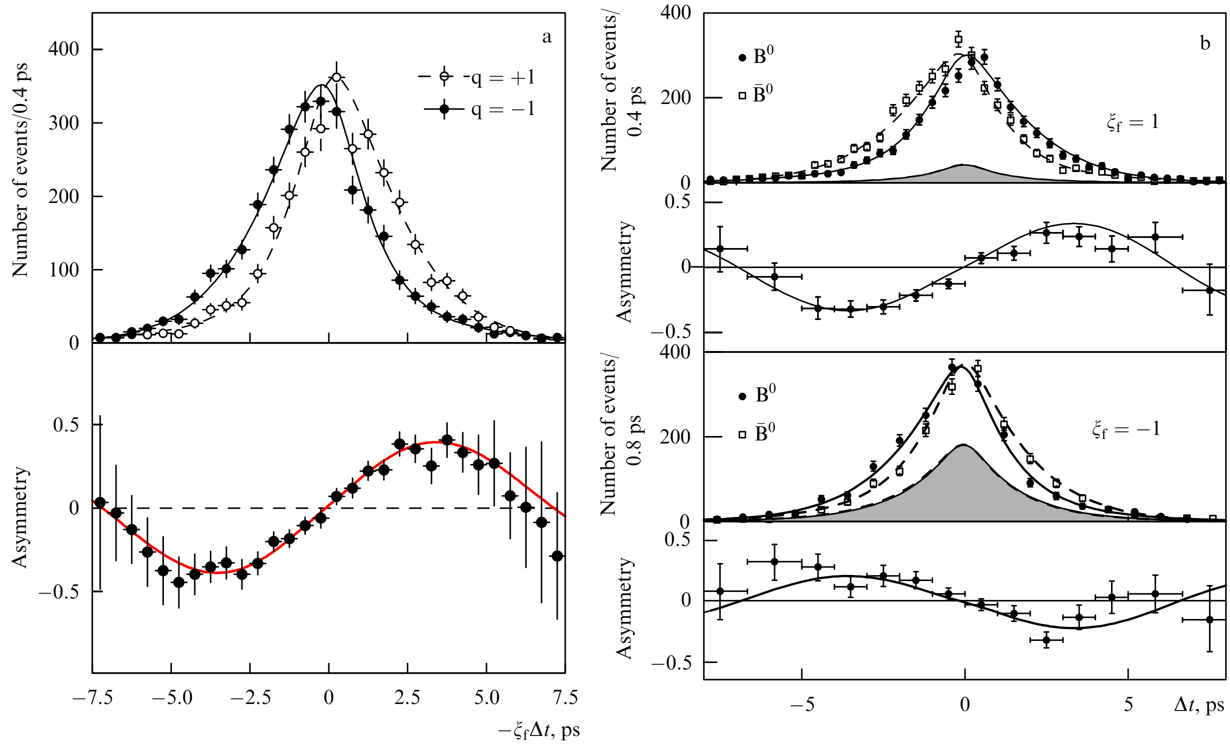

Figure 9. CP-asymmetric Δt distributions observed in the (a) Belle and (b) BaBar experiments.

final states and tagging categories agree within the statistical errors. The application of the whole procedure of the CP asymmetry measurement to the final states $B_d^0 \to D^{(*)-}\pi^+$, $D^{(*)-}\rho^+$, $J/\psi K^{*0}(\to K^-\pi^+)$, and $D^{*-}l^+\nu$, where the significant CP violating effects are not expected, yields the value of the asymmetry compatible with zero.

4.5 Discussion of sin 2β measurement results

The value of $\sin 2\beta$ averaged over the BaBar and Belle results is

$$\sin 2\beta = 0.675 \pm 0.026\,. \tag{43}$$

To compare the measured $\sin 2\beta$ with the prediction of the Kobayashi–Maskawa model, we use the unitarity triangle. The constraints on its upper vertex obtained from various measurements are presented in Fig. 10 [55]. The shaded region bounded by hyperbolas shows the expected vertex position (at a 95% confidence level) found by CP violation studies in K mesons. The annuli correspond to the measurements of the triangle sides: the left side is determined by $b \to u$ transitions and the right one from the frequency of the $B_d^0 - \bar{B}_d^0$ and $B_s^0 - \bar{B}_s^0$ oscillations. Finally, the constraints from $\sin 2\beta$ measurements are shown with sectors coming from the vertex at the point $(0, 1)$: the light sector corresponds to the constraint at a 95% confidence level and the dark one at a 67% level. There is an ambiguity in calculating the angle from the sine of the doubled angle, reflected by the two allowed regions. The contour around the upper vertex corresponds to its allowed position at a 95% confidence level. Excellent agreement among different measurements is observed.

In conclusion, a crucial test of the SM ended up with its confirmation. However, this indicates not the absence of New Physics but the smallness of its contribution in B mesons. A search for New Physics effects is in progress, and Sections 4.6 and 5 provide evidence of this.

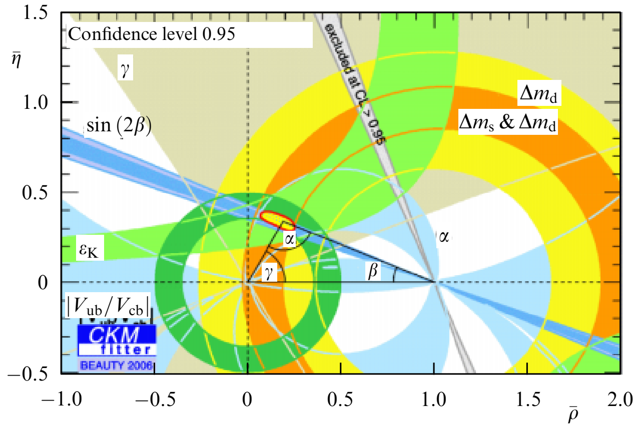

Figure 10. Constraints on the unitarity triangle vertex (ρ, η) from different measurements.

4.6 Search for CP asymmetry in other decays

Besides the 'golden mode,' the first attempts to find CP asymmetry were made in other decay channels sensitive to $\sin 2\beta$. Below, we briefly list these decays and the B-factory results; the accuracies are still insufficient to make any conclusions.

In the decays proceeding via the $b \to c\bar{c}d$ tree amplitude, e.g., $B_d^0 \to J/\psi\pi^0$ and $B_d^0 \to D^{(*)\pm}D^{(*)\mp}$, the CP asymmetry amplitude is expected to be related to $\sin 2\beta$. But because the contribution of the penguin transitions has a different weak phase, possible deviations of the CP asymmetry amplitude from $\sin 2\beta$ may reach 10%. Due to large experimental errors, this uncertainty is not significant at the moment. The results of the measurements shown in Fig. 11a are currently in good agreement with expectations, and one needs to wait for higher statistics for precise checks.

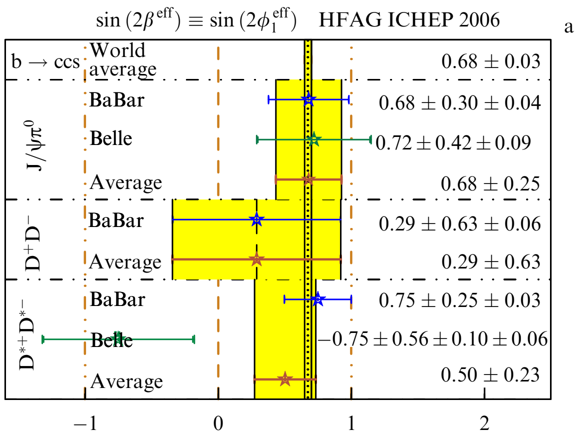

Figure 11. The results of CP asymmetry amplitude measurements and their comparison with $\sin 2\beta$ in the decays: (a) due to the tree $b \to c\bar{c}d$ amplitude; (b) due to the penguin $b \to s\bar{s}s$ and $b \to s\bar{q}q$ amplitudes.

Another type of decay useful for testing the theory is related to the penguin $b \to s\bar{s}s$ and $b \to s\bar{q}q$ transitions, in which, in contrast, a tree diagram is strongly suppressed and leads to some uncertainty in the relation between the measured CP asymmetry and $\sin 2\beta$. For $b \to s\bar{s}s$ transitions, this uncertainty is almost as small as for the golden mode $B_d^0 \to J/\psi K_S^0$ due to the expected smallness of the tree contribution.

The results of CP asymmetry measurements in various channels with penguin transitions are presented in Fig. 11b. The CP asymmetry parameter averaged over all measured $b \to s\bar{q}q$ decay modes,

$$\sin 2\beta_{\text{eff}} = 0.53 \pm 0.05\,, \qquad (44)$$

turns out to be $2.6\,\sigma$ times smaller than that measured in $b \to c\bar{c}s$ decays. Theoretical predictions favor values of $\sin 2\beta_{\text{eff}}$ larger than those of the golden mode. Whether this difference is a statistical fluctuation or evidence of the New Physics will be found in the near future. We only remind the reader that these are the loop diagrams that are expected to include the new effects not described by the SM.

5. Measurement of the other unitarity triangle angles

5.1 Search for CP asymmetry in the $B_d^0 \to \pi^+\pi^-$ decay

Before discussing the experimental aspects of the CP asymmetry measurement in this decay, we recall the difference between the CP violation mechanisms in $B_d^0 \to \pi^+\pi^-$ and $B_d^0 \to J/\psi K_S^0$ decays. Because the tree diagram of the first decay proceeds via the $b \to u(\bar{u}d)$ transition (Fig. 12a), the CP asymmetry is related to the angle α of the unitarity triangle, $\alpha = \arg\left[-V_{ud}V_{ub}^*/(V_{td}V_{tb}^*)\right]$. A more fundamental issue is the additional contribution of the penguin diagram $b \to d(\bar{u}u)$ (Fig. 12b), having the weak phase different from that of the tree contribution. The comparison of the B_d^0 decay probabilities to $\pi^+\pi^-$ and $K^+\pi^-$ final states allows concluding that the penguin contribution is not small compared to the tree one. As a result, two new effects are expected in the study of CP violation in $B_d^0 \to \pi^+\pi^-$ decays. First, the amplitude of the indirect CP violation is proportional not to the sine of an independent unitarity triangle angle (α, as we would want) but to the sine of a certain combination of these angles. The second effect is the existence of direct CP violation: the decay probabilities of B_d^0 and $\bar{B}_d^0$ (integrated over time) into the $\pi^+\pi^-$ final state may differ due to a different relative phase between the tree and penguin amplitudes for a particle and an antiparticle. This difference may emerge even without the $B_d^0 - \bar{B}_d^0$ mixing contribution (at $\Delta t = 0$, when this contribution is absent).

The penguin diagram contribution is difficult to estimate theoretically due to the uncertainties in the hadronization of quarks into observable hadrons. Another difficulty occurs in summing the upper quarks in the penguin loop $b \to d(\bar{u}u)$: three upper quarks make comparable contributions, each having its own weak phase. This complicates calculations significantly compared to the case with the penguin contribu-

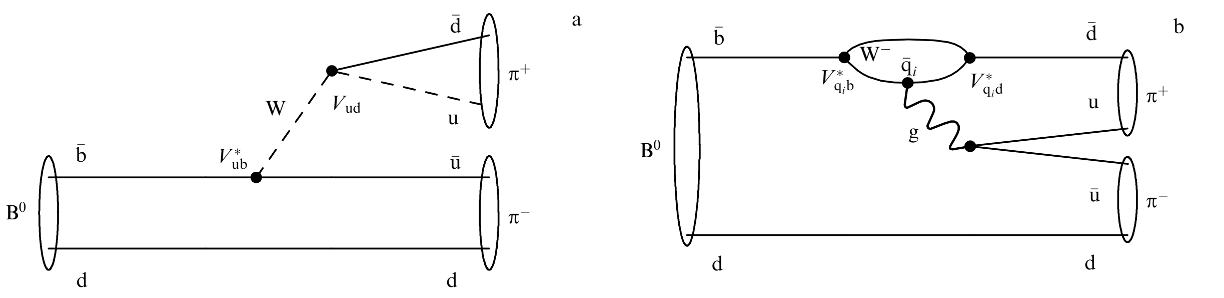

Figure 12. Quark diagrams of the $B_d^0 \to \pi^+\pi^-$ decay: (a) 'tree', (b) 'penguin' with the emission of a hard gluon g.

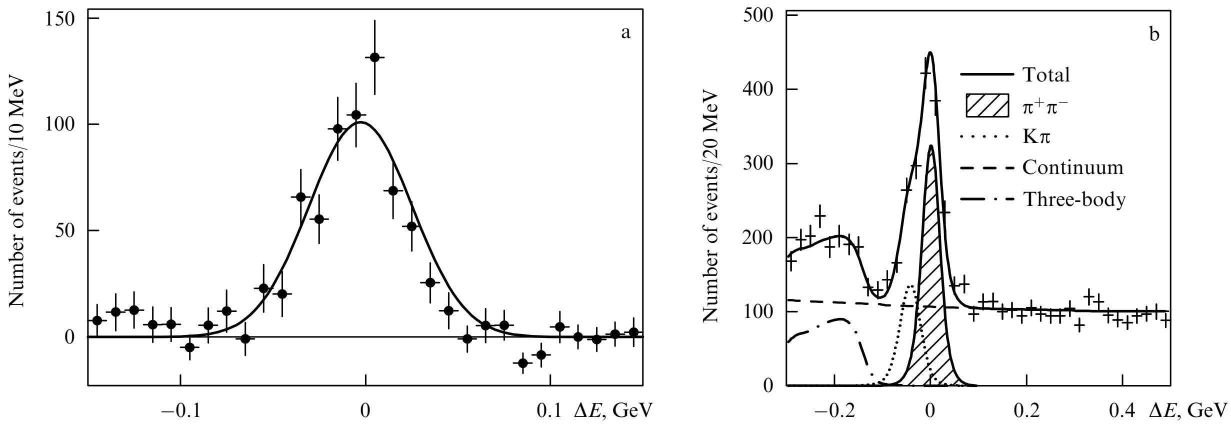

Figure 13. ΔE distributions for $B^0_d \to \pi^+\pi^-$ candidates in BaBar (a) and Belle (b) experiments. In the distribution of BaBar, all the backgrounds are subtracted.

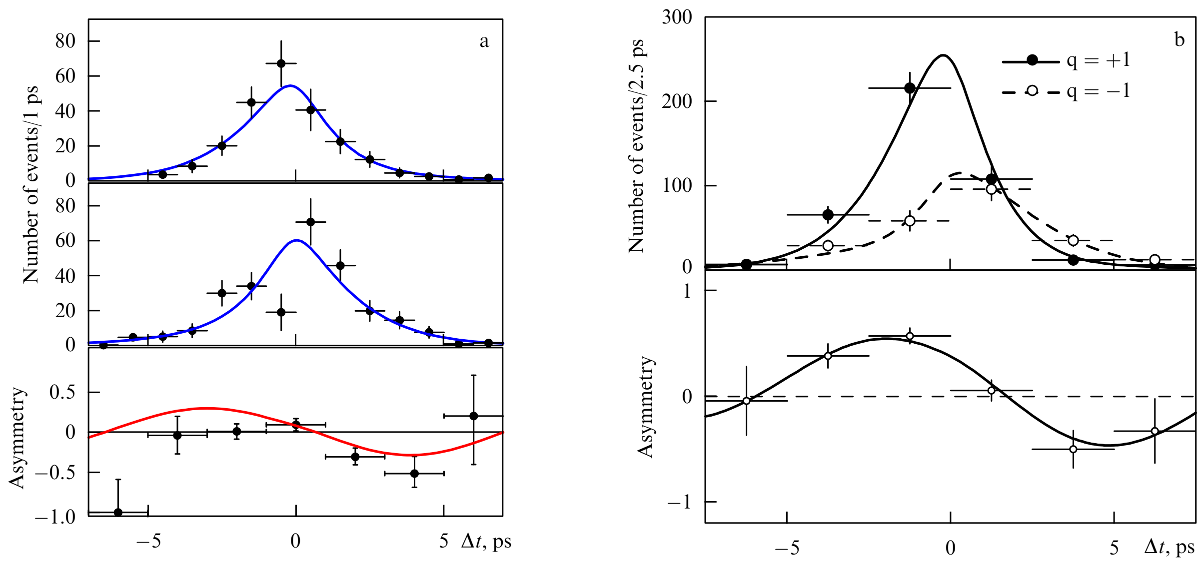

Figure 14. CP-asymmetric Δt distributions for $B^0_d \to \pi^+\pi^-$ candidates observed by the BaBar (a) and Belle (b) experiments.

tion to the $B^0_d \to J/\psi K^0_S$ decay, where the u quark contribution was negligible and the phases of c- and t-quarks were equal to good precision due to the same smallness of the u quark contribution and the unitarity of the CKM matrix. Although there are ways to estimate the penguin diagram contribution using the experimental data, they are not discussed here because the experimental precision needed for these estimates is still insufficient. The distribution of the $B^0_d \to \pi^+\pi^-$ decay probability as a function of time for a tagging B^0_d ($\bar{B}^0_d$) has the form

$$f_{\pm} = \frac{\exp\left(|\Delta t|/\tau\right)}{4\tau}\left[1 \pm \mathcal{S}_{\pi\pi}\sin\left(\Delta m_d \Delta t\right) \mp \mathcal{C}_{\pi\pi}\cos\left(\Delta m_d \Delta t\right)\right], \qquad (45)$$

where $\mathcal{S}_{\pi\pi}$ and $\mathcal{C}_{\pi\pi}$ are the respective parameters of the indirect and direct CP violations.

Similarly to the $B^0_d \to J/\psi K^0_S$ decay, the full reconstruction is used to select B^0_d-candidates: the combination of two oppositely charged tracks compatible with the pion hypothesis is formed, after which its mass and energy are determined. The background conditions turn out to be less favorable compared to those for the $B^0_d \to J/\psi K^0_S$ decay due to the absence of intermediate states. The major part of the background comes from the events of e^+e^- annihilation into hadrons, not related to $\Upsilon(4S)$ production. Wrong charged-particle identification introduces an additional background from the $B^0_d \to K^+\pi^-$ decay, which contributes to both M_{bc} and ΔE distributions near the expected signal peaks. The use of the special selection criteria allows not only rejecting the background significantly but also reliably estimating the effect of the remaining part. Figures 13a and b demonstrate the $\Delta E \equiv E_{beam} - E_B$ distributions for the selected events obtained by BaBar and Belle.

The method of B-meson flavor determination and the calculation of the B-meson decay time difference for a CP eigenstate and the tagging mode is identical to that in the procedure of β angle measurement. A minor difference in the CP asymmetry measurement is the existence of two free parameters. The Δt distributions for the events tagged as B^0_d and as $\bar{B}^0_d$, obtained by the BaBar and Belle collaborations, are shown in Fig. 14.

As a result, the following values of the CP violation parameters have been obtained by BaBar [56] and Belle [57], with the respective statistics of 347×10^9 and 535×10^9 $B_d^0\bar{B}_d^0$-pairs:

$$\begin{aligned} &\mathcal{S}_{\pi\pi} = -0.53 \pm 0.14 \pm 0.02\,, \\ &\mathcal{C}_{\pi\pi} = -0.16 \pm 0.11 \pm 0.03 \quad (\text{BaBar})\,; \\ &\mathcal{S}_{\pi\pi} = -0.61 \pm 0.10 \pm 0.04\,, \\ &\mathcal{C}_{\pi\pi} = -0.55 \pm 0.08 \pm 0.05 \quad (\text{Belle})\,. \end{aligned} \tag{46}$$

The significant difference in the results can be explained by statistical fluctuations, and we have to wait for additional data to reveal the true values of these parameters. In the Belle analysis, carried out using larger statistics, the absence of direct CP violation ($\mathcal{C}_{\pi\pi} = 0$) is excluded at the level of 5.5 standard deviations.

Despite the good precision of the $\mathcal{C}$ and $\mathcal{S}$ determination, the value of the angle α has a significant uncertainty due to the unknown penguin amplitude contribution. In particular, BaBar excludes the values of α larger than 41° at a 90% confidence level, while Belle obtains the allowed intervals $0 < \alpha < 9°$ and $81° < \alpha < 180°$ at the 90% confidence level.

The decay $B_d^0 \to \rho^+\rho^-$ allows measuring the angle α with better precision. Because the decay $B_d^0 \to \rho^0\rho^0$ is not observed [58], we can conclude that the penguin contribution to the $B_d^0 \to \rho^+\rho^-$ decay is small, and the corresponding theoretical uncertainty of the angle α is only 11°. But the presence of wide ρ resonances and neutral pions in the final state leads to a difficult analysis. Moreover, because ρ mesons are vector particles, the decay amplitude contains states with different polarizations (two transverse and one longitudinal), and the values of $\mathcal{S}_{\rho\rho}$ and $\mathcal{C}_{\rho\rho}$ for each of them are different. Fortunately, the angular analysis of the decay products allows concluding that the state with the longitudinal polarization dominates (the fraction of this amplitude is larger than 95%).

The BaBar [59] and Belle [60] collaborations, using the respective statistics 316 fb^{-1} and 253 fb^{-1}, obtained values for $\mathcal{S}_{\rho\rho}$ and $\mathcal{C}_{\rho\rho}$ compatible with the absence of CP violation in the $B_d^0 \to \rho\rho$ decay:

$$\begin{aligned} &\mathcal{S}_{\rho\rho} = -0.19 \pm 0.21^{+0.05}_{-0.07}\,, \\ &\mathcal{C}_{\rho\rho} = -0.07 \pm 0.15 \pm 0.06 \quad (\text{BaBar})\,; \\ &\mathcal{S}_{\rho\rho} = 0.08 \pm 0.41 \pm 0.09\,, \\ &\mathcal{C}_{\rho\rho} = 0.00 \pm 0.30 \pm 0.09 \quad (\text{Belle})\,. \end{aligned} \tag{47}$$

Because $S = \sin 2\alpha$, in the absence of the penguin contribution, the angle α must be close to 0° or 90°. Choosing a value in the vicinity of 90°, which is preferred by other unitarity triangle measurements, BaBar obtains the constraint $79° < \alpha < 123°$, and the Belle result is $59° < \alpha < 115°$ (at a 90% confidence level).

5.2 Direct CP violation in B-meson decays

Direct CP violation emerges in both neutral and (contrary to the CP violation in mixing) charged B-meson decays, when the ratio

$$\mathcal{A}_{\text{CP}}(\text{B} \to \text{f}) \equiv \frac{\Gamma(\text{B} \to \text{f}) - \Gamma(\bar{\text{B}} \to \bar{\text{f}})}{\Gamma(\text{B} \to \text{f}) + \Gamma(\bar{\text{B}} \to \bar{\text{f}})} \tag{48}$$

differs from zero. It can occur if there are at least two contributions to the $\text{B} \to \text{f}$ decay amplitude with different CP-violating weak and CP-conserving strong phases. In this case, the decay amplitude can be expressed as

$$\begin{aligned} A(\text{B} \to \text{f}) &= |A_1| \exp(\text{i}\delta_1) \exp(+\text{i}\varphi_1) \\ &\quad + |A_2| \exp(\text{i}\delta_2) \exp(+\text{i}\varphi_2)\,, \\ A(\bar{\text{B}} \to \bar{\text{f}}) &= |A_1| \exp(\text{i}\delta_1) \exp(-\text{i}\varphi_1) \\ &\quad + |A_2| \exp(\text{i}\delta_2) \exp(-\text{i}\varphi_2)\,, \end{aligned} \tag{49}$$

where $\delta_{1,2}$ are the CP-conserving strong phases generated by the interaction of the decay products in the final state and $\varphi_{1,2}$ are the CP-violating weak phases. Using Eqns (49), we obtain

$$\mathcal{A}_{\text{CP}}(\text{B} \to \text{f}) = \frac{-2|A_1||A_2| \sin(\varphi_1 - \varphi_2) \sin(\delta_1 - \delta_2)}{|A_1|^2 + 2|A_1||A_2| \cos(\varphi_1 - \varphi_2) \cos(\delta_1 - \delta_2) + |A_2|^2}\,. \tag{50}$$

As follows from this expression, the magnitude of direct CP violation in B-meson decays $\mathcal{A}_{\text{CP}}(\text{B} \to \text{f})$ is related to the difference of both the weak and the strong phases. This leads to significant theoretical difficulties in obtaining the value of the weak phase difference from the value of the observed asymmetry, taking into account that it is practically impossible to calculate the strong phases theoretically.

5.3 Observation of direct CP violation in $B_d^0 \to K^+\pi^-$ decays

The most significant direct CP violation is currently observed in $B_d^0 \to K^+\pi^-$ decays. This decay involves both tree and penguin diagrams, similarly to $B_d^0 \to \pi^+\pi^-$ discussed above (see Fig. 12). The final states $K^+\pi^-$ from B_d^0 decays and $K^-\pi^+$ from $\bar{B}_d^0$ decays are different, and mixing-induced CP asymmetry does not appear. The asymmetry of the decay probabilities $B_d^0 \to K^+\pi^-$ and $\bar{B}_d^0 \to K^-\pi^+$ was measured by both collaborations:

$$\begin{aligned} &A_{\text{CP}} = -0.133 \pm 0.030 \pm 0.009 \quad \text{BaBar [61]}\,; \\ &A_{\text{CP}} = -0.101 \pm 0.025 \pm 0.005 \quad \text{Belle [62]}\,. \end{aligned} \tag{51}$$

Potentially, the measured asymmetry includes information about the angle γ of the unitarity triangle. However, extracting this information currently appears to be impossible: the absolute value of the ratio of two interfering amplitudes must be known. The analysis of the isospin-coupled channels ($B^+ \to K^+\pi^0$; $K^0\pi^+$) does not allow extracting this information due to the contributions of the electroweak penguin amplitudes that violate the isotopic symmetry. In the approximation of isospin conservation, CP asymmetries in the $B_d^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays should be equal. This is not confirmed by the experimental data: A_{CP} in charged B-meson decays into $K^+\pi^0$ appears to be compatible with zero. Nevertheless, reliable experimental evidence of direct CP violation in B decays serves as a qualitative check of the Kobayashi – Maskawa mechanism.

5.4 Measurement of the angle γ in $B^\pm \to DK^\pm$ decays

The measurement of the angle γ is based on the method proposed by Gronau, London, and Wyler, and usually referred to as the GLW method [63, 64]. The decays $B^+ \to \bar{D}^0K^+$ and $B^+ \to D^0K^+$ are described by the tree diagrams shown in Fig. 15. In the Wolfenstein parameterization of the CKM matrix, the amplitudes of these two

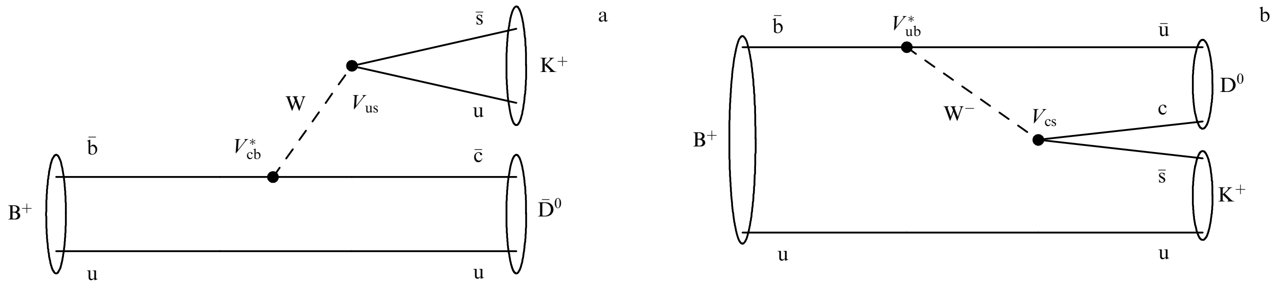

Figure 15. Quark diagrams of the $B^+ \to \bar{D}^0K^+$ (a) and $B^+ \to D^0K^+$ (b) decays.

diagrams are expressed as

$$A(B^+ \to \bar{D}^0K^+) \equiv A_1 \sim V_{cb}^* V_{us} \sim A\lambda^3\,,$$
$$A(B^+ \to D^0K^+) \equiv A_2 \sim V_{ub}^* V_{cs} \sim A\lambda^3(\rho + i\eta)\,. \quad (52)$$

The amplitude A_2 also includes the contribution of the annihilation diagram, but because it contains the same weak phase, it changes only the strong phase value.

In general, these two final states are different and the two contributions cannot interfere. But if D^0 and $\bar{D}^0$ decay into the same final state, e.g., a CP-eigenstate (we let D^0_+ denote it for a CP-even and D^0_- for a CP-odd state), interference and CP violation become possible because the amplitudes A_2 and A_1 have different weak phases. As seen from Fig. 2, the difference of weak phases (the argument of the complex quantity $\rho + i\eta$) is the angle γ of the unitarity triangle. We consider how this information can be used to measure the angle γ. With

$$|D^0_+\rangle = \frac{1}{\sqrt{2}}\big(|D^0\rangle + |\bar{D}^0\rangle\big)\,, \quad (53)$$

we easily obtain the following two relations for the decay amplitudes:

$$\sqrt{2}A(B^+ \to D^0_+K^+) = A(B^+ \to D^0K^+) + A(B^+ \to \bar{D}^0K^+)\,,$$
$$\sqrt{2}A(B^- \to D^0_+K^-) = A(B^- \to \bar{D}^0K^-) + A(B^- \to D^0K^-)\,. \quad (54)$$

These relations can be illustrated as two triangles in a complex plane. Assuming CP parity conservation in the D^0 meson decay, additional equations can be obtained:

$$A(B^+ \to \bar{D}^0K^+) = A(B^- \to D^0K^-)\,,$$
$$A(B^+ \to D^0K^+) = A(B^- \to \bar{D}^0K^-)\exp(2i\gamma)\,, \quad (55)$$

which allow obtaining the angle γ as is shown in Fig. 16. Unfortunately, the sides of these triangles are significantly different, because the ratio

$$\frac{|A(B^+ \to \bar{D}^0K^+)|}{|A(B^- \to D^0K^-)|} \equiv r_B \approx 0.1 - 0.2$$

is determined by the ratio of the coefficients $|V_{ub}^*V_{cs}|/|V_{cb}^*V_{us}| \sim 0.38$ times the color suppression factor $\sim 1/3$. The latter occurs because in the amplitude A_2, the quark and antiquark occurring from the W-boson decay enter different mesons, and their color should correspond to the color of the spectator quark.

Usually, the following experimental observables are used in the GLW method:

$$R_\pm = \frac{\mathcal{B}(B^- \to D^0_\pm K^-) + \mathcal{B}(B^+ \to D^0_\pm K^+)}{\big[\mathcal{B}(B^- \to D^0K^-) + \mathcal{B}(B^+ \to \bar{D}^0K^+)\big]/2}\,,$$
$$A_\pm = \frac{\mathcal{B}(B^- \to D^0_\pm K^-) - \mathcal{B}(B^+ \to D^0_\pm K^+)}{\mathcal{B}(B^- \to D^0_\pm K^-) + \mathcal{B}(B^+ \to D^0_\pm K^+)}\,, \quad (56)$$

where $\mathcal{B}(B^\pm \to D^0_\pm K^\pm)$ are the probabilities of the corresponding $B^\pm$ meson decays. $R_\pm$ and $A_\pm$ can be expressed using the parameters r_B and γ and the strong phase difference δ_B between the $B^+ \to D^0K^+$ and $B^+ \to \bar{D}^0K^+$ decay amplitudes:

$$R_\pm = 1 + r_B^2 \pm 2r_B\cos\delta_B\cos\gamma\,,$$
$$A_\pm R_\pm = \pm 2r_B\sin\delta_B\sin\gamma\,. \quad (57)$$

As a result, there are four equations, three of which are independent (because $A_+R_+ = -A_-R_-$), and three unknowns, which allows extracting the value of γ without any theoretical assumptions about hadronization in the final state (and related uncertainties).

The latest BaBar [65] and Belle [66] results on γ measurement using the GLW method are based on the respective statistics 211 and 253 fb^{-1}. The states $\pi^+\pi^-$ and K^+K^- are used as CP-even D^0 final states, and $K^0_S\pi^0$, $K^0_S\omega$, and $K^0_S\phi$ are used as CP-odd ones. The following values of the CP asymmetries $A_\pm$ and ratios $R_\pm$ are obtained:

$$R_+ = 0.90 \pm 0.12 \pm 0.04\,, \quad R_- = 0.86 \pm 0.10 \pm 0.05\,,$$
$$A_+ = 0.35 \pm 0.13 \pm 0.04\,, \quad A_- = -0.06 \pm 0.13 \pm 0.04 \quad \text{(BaBar)}\,;$$
$$R_+ = 1.13 \pm 0.16 \pm 0.08\,, \quad R_- = 1.17 \pm 0.14 \pm 0.14\,,$$
$$A_+ = 0.06 \pm 0.14 \pm 0.05\,, \quad A_- = -0.12 \pm 0.14 \pm 0.05 \quad \text{(Belle)}\,. \quad (58)$$

The statistically significant CP asymmetry has not been observed yet, and hence the measurement of the angle γ using the GLW method is not yet possible. However, this

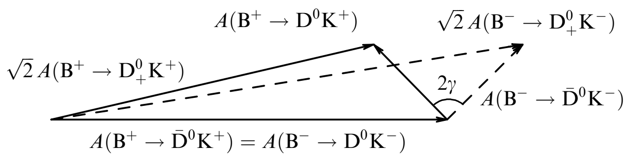

Figure 16. Determination of the angle γ from $B^\pm \to \{D^0, \bar{D}^0, D^0_+\}K^\pm$ decays.

method can be used in combination with others discussed below. In addition, the measured quantities allow constraining the value of r_B. BaBar obtains the value $r_B^2 = -0.12 \pm 0.08 \pm 0.03$, which gives an upper limit on r_B in good agreement with other measurements.

The difficulties in the implementation of the GLW method are mainly due to the small expected CP asymmetry in the $B^{\pm} \to D_{CP}K^{\pm}$ decays. An alternative approach was proposed by Atwood, Dunietz, and Soni [67, 68] (the ADS method). Instead of using the D^0 decay into the CP eigenstates, they proposed utilizing the so-called doubly Cabibbo-suppressed and Cabibbo-favored decays. The Cabibbo-favored decay $D^0 \to K^-\pi^+$ is described by the weak amplitude $c \to s\bar{d}u$ and is proportional to the product of the elements $|V_{cs}V_{ud}^*| \sim 1$; the amplitude of the $\bar{D}^0 \to K^-\pi^+$ decay ($\bar{c} \to \bar{d}u\bar{s}$) is suppressed by the smallness of two CKM matrix elements $|V_{cd}V_{us}^*| \sim \lambda^2$, and is therefore called doubly Cabibbo-suppressed. In the decay chains $B^+ \to [K^-\pi^+]_D K^+$ and $B^- \to [K^+\pi^-]_D K^-$, where the Cabibbo-favored decay corresponds to the suppressed D^0 decay, and vice versa, the interfering amplitudes are of the same order and a large CP asymmetry is expected. Unfortunately, the probabilities of the decays mentioned above appear to be so small that they cannot be revealed with the currently available experimental statistics. Nevertheless, this analysis gives the constraint on the value of r_B:

$$\begin{aligned} &r_B < 0.23 \text{ at a 90\% confidence level, BaBar [69]}, \\ &r_B < 0.18 \text{ at a 90\% confidence level, Belle [70]}, \end{aligned} \qquad (59)$$

which turns out to be somewhat better than the one obtained with the GLW method.

The Belle collaboration [71] and independently Giri et al. [72] proposed the method of γ measurement using three-body decays of the D^0meson. The most convenient of them is the decay $D^0 \to K_S^0\pi^+\pi^-$, having the probability 2.9%. This decay proceeds via several intermediate states, including the CP-eigenstates ($D^0 \to K_S^0\rho^0$), doubly Cabibbo-suppressed decays ($D^0 \to K^{*+}\pi^-$), and Cabibbo-favored decays ($D^0 \to K^{*-}\pi^+$). Thus, the use of three-body final states combines the advantages of the GLW and ADS methods. Moreover, the amplitudes of different intermediate states vary over the final state phase space, and there are regions where sensitivity to the CP asymmetry is maximal.

Two parameters suffice for describing coordinates in the phase space of the three-body decay. The event density in the space of these parameters is called the Dalitz distribution, and is determined by the matrix element of the decay. It is convenient to use the squared invariant masses of the two pairs of the final-state particles as the Dalitz distribution parameters; in this case, the event density is proportional to the squared absolute value of the amplitude. The Dalitz distribution for more than 270 thousand $\bar{D}^0 \to K_S^0\pi^+\pi^-$ events and its projections onto squared invariant masses $m_+^2 = m_{K\pi^+}^2$, $m_-^2 = m_{K\pi^-}^2$, and $m_{\pi\pi}^2$, are shown in Fig. 17. To plot this distribution, the process $D^{*+} \to D^0\pi^+$ is used,[18] where the D^0 meson flavor is determined by the sign of the pion: D^0 corresponds to the positive pion and $\bar{D}^0$ to the negative one.

The density of the events on the Dalitz distribution is proportional to $|f_D(m_-^2, m_+^2)|^2$, where $f_D(m_-^2, m_+^2)$ is the amplitude of the $\bar{D}^0 \to K_S^0\pi^+\pi^-$ decay. Its complex form can be obtained from the description of the decay by the sum of two-body components, whose amplitudes and phases are determined from the best fit to the experimental data. In the analysis of the Belle collaboration, the model included 18 resonant amplitudes. The largest contribution comes from the $K^*(892)^-\pi^+$ state, indicated in Fig. 17d as the dense strips at the invariant masses m_-^2 around 0.8 [GeV^2/c^4]. Also significant is the contribution of the $D^0 \to K_S^0\rho^0$ amplitude (the peak at $m_{\pi\pi}^2 \sim 0.5\ \text{GeV}^2/c^4$ in Fig. 17c and the diagonal strip in Fig. 17d).

As soon as the amplitude f_D is known, r_B, γ, and δ_B can be obtained from the Dalitz distributions of the D meson decay into the $B^+ \to DK^+$ and $B^- \to DK^-$ processes. The decay amplitude of the mixture of D^0 and $\bar{D}^0$ states from the $B^+ \to DK^+$ process is equal to

$$f_{B^+} = f_D(m_+^2, m_-^2) + r_B \exp(i\gamma + i\delta_B)\, f_D(m_-^2, m_+^2)\,. \qquad (60)$$

For the process $B^- \to DK^-$, the corresponding amplitude is

$$f_{B^-} = f_D(m_-^2, m_+^2) + r_B \exp(-i\gamma + i\delta_B)\, f_D(m_+^2, m_-^2)\,. \qquad (61)$$

Thus, the squared absolute values of the amplitudes $|f_{B^+}|^2$ and $|f_{B^-}|^2$ are different, and hence the Dalitz distributions of the D meson decay from $B^+ \to DK^+$ and $B^- \to DK^-$ are different.

We consider in more detail how the angle γ is measured, taking the analysis carried out by the Belle collaboration [73, 74] as an example. The selection of $B^{\pm} \to DK^{\pm}$ events is performed using the standard technique based on the B candidate invariant mass

$$M_{bc} = \sqrt{E_{beam}^2 - \left(\sum \mathbf{p}_i\right)^2}$$

and the energy difference $\Delta E = \sum E_i - E_{beam}$ (see Section 4.1). Figure 18 shows the distributions of the ΔE and M_{bc} parameters for the experimental $B^{\pm} \to DK^{\pm}$ events and the contributions of the signal and background events. The signal events are concentrated near $M_{bc} = 5.28\ \text{GeV}/c^2$ and $\Delta E = 0$; the peak at $\Delta E = 0.05$ GeV is due to the background from the $B^{\pm} \to D\pi^{\pm}$ process with the π misidentified as a K; and random combinations of particles have a uniform distribution.

The Dalitz distributions of the D decay from the signal region of $B^- \to DK^-$ and $B^+ \to DK^+$ processes are shown in Fig. 19. The axes in the $B^+ \to DK^+$ distribution are swapped such that the two distributions would look identical if the CP asymmetry were absent. The most probable values of the r_B, γ, and δ_B parameters from the fit to the $B^{\pm} \to DK^{\pm}$ data, as well as the regions corresponding to one, two, and three standard deviations, are shown in Fig. 20a and b as projections onto the (γ, r_B) and (γ, δ_B) planes. We note that all the methods described (including ADS and GLW) involve an ambiguity: changing γ and δ to $\gamma + 180°$ and $\delta + 180°$ does not change the observables.

The Dalitz-analysis method currently gives the best constraint on the angle γ of all direct measurements. To increase its precision, Belle and BaBar use not only the $B \to DK$ decay but also the $B \to D^*K$ and $B \to DK^*$ processes, where a similar effect should be observed (although with different values of r_B and δ_B). The Belle measurement using the 356 fb^{-1} [74] statistics, as a combina-

[18] D^{*+} mesons are produced abundantly at B-factories in the process $e^+e^- \to c\bar{c}$.

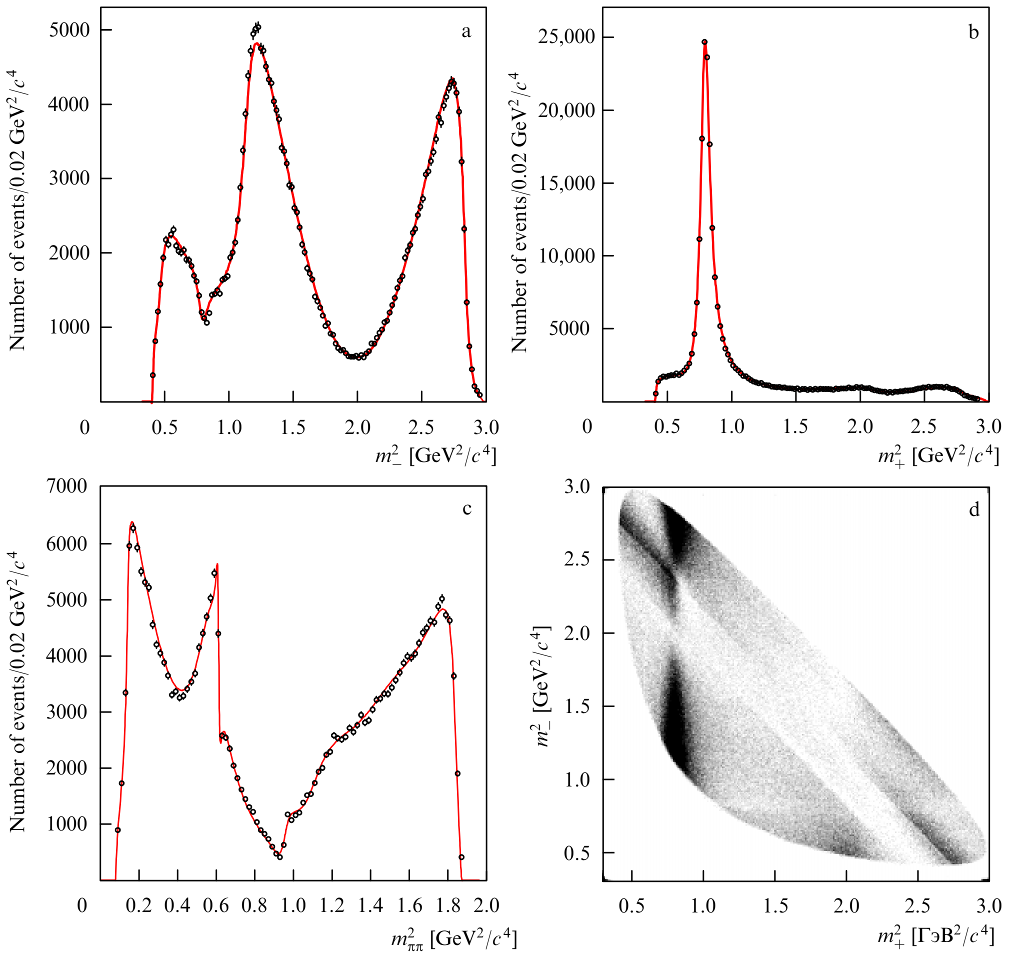

Figure 17. Projections onto m_-^2 (a), m_+^2 (b), and $m_{\pi\pi}^2$ (c) axes and the Dalitz distribution (d) for $\bar{D}^0 \to K_S^0\pi^+\pi^-$ decays from the $D^{*\pm} \to D\pi^\pm$ process in the Belle experiment. The points with error bars are the data, the smooth curve is the fit result.

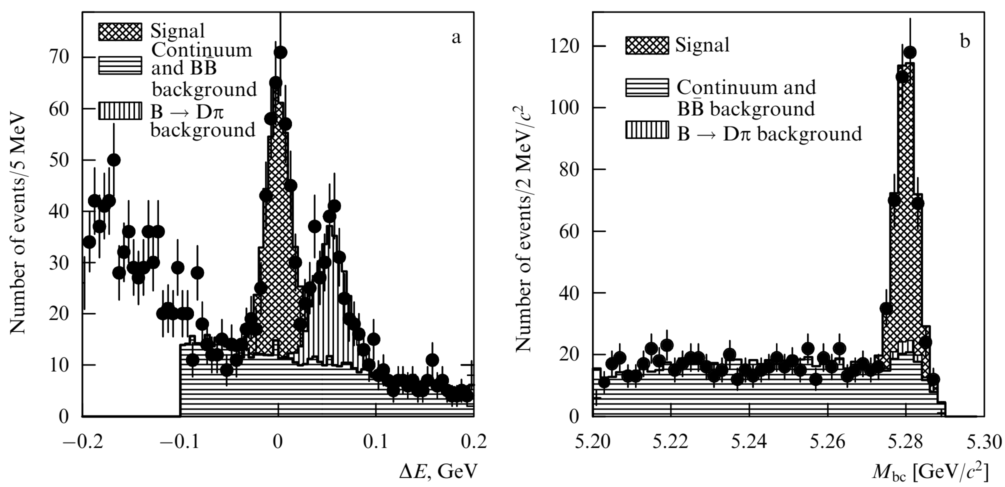

Figure 18. ΔE (a) and M_{bc} (b) distributions for $B^\pm \to DK^\pm$, $D \to K_S^0\pi^+\pi^-$ decays.

tion of the three processes mentioned above, yields $\gamma = 53^\circ\,^{+15^\circ}_{-18^\circ} \pm 3^\circ \pm 9^\circ$. BaBar obtains (with 211 fb^{-1} [75, 76]) $\gamma = 67^\circ \pm 28^\circ \pm 11^\circ \pm 13^\circ$. Here, the first error is statistical, the second is the experimental systematical error, and the third is the uncertainty due to the D^0 decay model. The last one is currently smaller than the statistical error. In the future, as the statistics accumulated by B factories increase, this uncertainty will start to dominate the γ measurement.

Giri et al. [72] proposed an approach to eliminate the model uncertainty in the method described above. The idea is that complete knowledge of the strong phase in $f_D(m_+^2, m_-^2)$ is not needed. The same combination of phases as that in the D^0 decay from $B^\pm \to DK^\pm$ occurs in the decay of the D meson

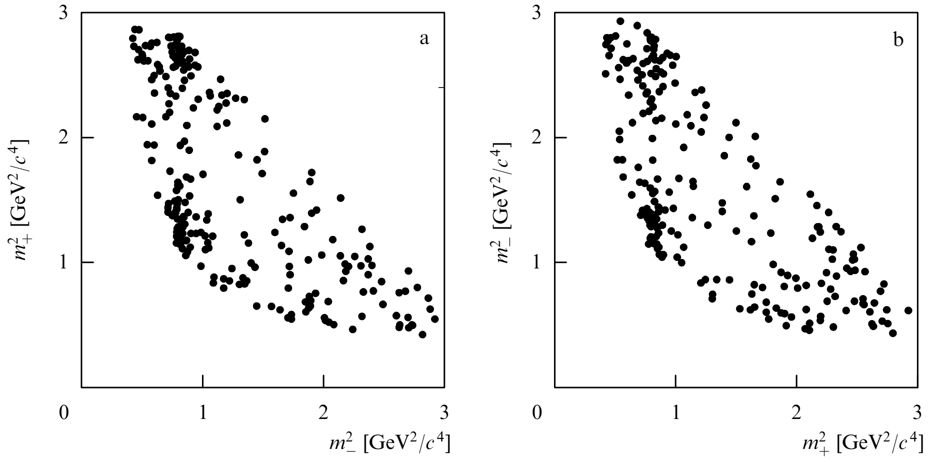

Figure 19. Dalitz distributions of the neutral D meson decays from $B^- \to DK^-$ (a) and $B^+ \to DK^+$ (b) processes.

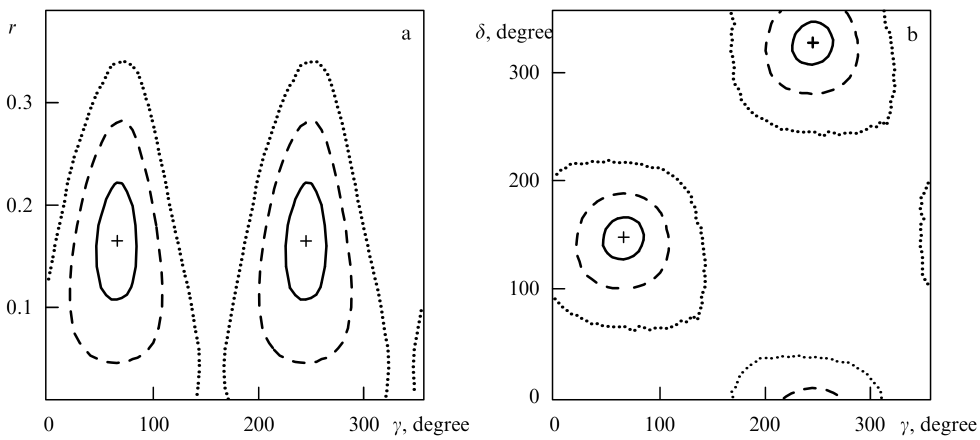

Figure 20. Projections of the regions corresponding to one, two, and three standard deviations, onto (γ, r_B) (a) and (γ, δ_B) (b) planes.

in a CP-eigenstate, and can be extracted from the experiment. The decays of the D meson in a CP-eigenstate into $K_S^0\pi^+\pi^-$ can be studied in the process $e^+e^- \to \psi(3770) \to D\bar{D}$. If one of the D mesons is reconstructed in a CP-eigenstate, e.g., K^+K^-, then, due to the antisymmetry of the wave function of the $D\bar{D}$ system, the other D meson decaying into $K_S^0\pi^+\pi^-$ should have the opposite CP parity. The decays of D_{CP}^0 can be provided by experiments in the region of $\psi(3770)$ production, such as CLEO-c [77 – 80] or the BES-III facility currently being built [81]. In this model-independent approach, the error of the γ measurement depends on the statistics of both the B and D_{CP}^0 decays. The Monte Carlo study [82] of this approach shows that the future Super-B factory [83] with the integrated luminosity 50 ab^{-1} will allow measuring γ with a precision better than 2°. To make the contribution of D_{CP}^0 statistics below that level, about 10^4 decays of the D meson in the CP eigenstate to $K_S^0\pi^+\pi^-$ are needed.

The method of Dalitz analysis of the D^0 decay discussed above can also be used for other measurements. In the $B_d^0 \to D^0\pi^0$ decay, the analysis of the $D^0 \to K_S^0\pi^+\pi^-$ Dalitz distribution as a function of Δt allows obtaining the value of $\cos 2\beta$ and thus eliminating the ambiguity in the extraction of β from $\sin 2\beta$. The value $\cos 2\beta = 1.87^{+0.40+0.22}_{-0.53-0.32}$ obtained by Belle [84] excludes the second solution for β at a 98% confidence level.

6. Conclusion

Thanks to the remarkable results obtained at B-factories over the last 5 – 6 years, our understanding of CP violation mechanisms has improved significantly. Direct experimental observation of large CP asymmetry in B-meson decays has been obtained, which agrees with the predictions of the Kobayashi – Maskawa model. Moreover, all three angles of the unitarity triangle can be measured from CP violation in B meson decays, with the precision of the angle β being better than 1.5°. The precision of the direct measurements of the other two angles still remains low, about 10° – 20°. No significant deviations that might disturb the consistent picture have been found. Are further attempts to improve the measurement precision needed? We answer some questions to clarify this point.

(1) The discovery of the third generation and the measurement of the CKM matrix elements (both their phases and absolute values) have proven that the Kobayashi – Maskawa model is valid and explains the CP violation. Are any additional proofs needed?

Answer: Although there are no well-grounded reasons to doubt the validity of the Kobayashi – Maskawa model, it is still unknown whether this mechanism is the only source of CP parity violation in Nature.

(2) What are the reasons to expect the existence of several CP violation sources? At first sight, since the theory of particle interactions should be based on a single principle, it is natural to assume one source of CP violation.

Answer: It must be remembered that the SM, in its current form, cannot claim to be the theory explaining 'everything' from first principles. It is probably only a low-energy approximation of such a theory, and the single source of CP violation at high energies breaks up into several sources at low energies. Moreover, cosmology suggests that CP violation due to the Kobayashi – Maskawa mechanism is insufficient to explain the observed matter – antimatter asymmetry in the universe.

(3) What are the reasons to expect 'New Physics' (NP) effects in CP violation in B-meson decays?

Answer: There are several reasons why studies of B mesons give a good opportunity to search for NP:

— SM mechanisms of B-meson decays are suppressed by the small values of CKM matrix elements, which allows the NP contribution to compete with the SM processes;

— a significant part of B-meson decays proceeds via loop diagrams. Even very heavy new particles, if they exist, can take part in these processes and show up as the experimental precision increases. We note that the high b-quark mass significantly increases the loop contribution in some cases (e.g., in the $B \to K^{(*)} l^+ l^-$ decay);

— a search for NP effects in B-meson decays, forbidden or strongly suppressed in the SM (e.g., $B \to \phi\pi$, $K^{(*)} l^+ l^-$), seems to be one of the most promising, particularly if the NP contribution leads to CP violation, because the observed effect then depends linearly (not quadratically, as for the decay probability) on the ratio of the NP and SM amplitudes;

— in the cases where the predictions for CP violation in the SM are exact, any statistically significant deviation from the expectations can be regarded as the 'New Physics' effect.

The history of CP violation in B-meson decays is still not completed, and the attempts to further improve the precision of the experiments will continue in the near future. In 2007, the Large Hadron Collider (LHC) at CERN, constructed by international collaboration to search for 'New Physics' effects at the highest possible energies, will start operation. Not least in the experimental program of this facility is the LHCb experiment [85, 86], where the precision of CP violation measurement in B_d^0 and B^+ decays can be improved. In addition, the high energy of the colliding particles also allows producing and studying B_s^0 mesons, where many interesting effects related to CP violation are expected, which will open the possibility for a further test of the Kobayashi – Maskawa model.

Although the number of B mesons to be produced in the LHCb experiment is incomparably larger than at B-factories, many important final states (e.g., $B^+ \to \tau\nu_\tau$, $B_d^0 \to \pi^0\pi^0$) are difficult to study. Therefore, an important role in such studies will still be played by B-factories. It is clear already now that the productivity of these facilities should be increased. Different options for a significant improvement of the luminosity are being considered presently [83]; practically, this means the construction of new-generation colliders with a luminosity exceeding that of the existing facilities by two orders of magnitude.

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