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Search for CP violation in B-meson decays

M V Danilov

Contents

Abstract. Prospects for the observation of CP violation in B-meson decays are briefly reviewed based on the talk given at the Russian Academy of Sciences Presidium session of January 20, 1998.

1. Introduction

The difference between the properties of matter and antimatter is, apparently, one of the most intriguing puzzles of nature. Most likely, without this difference the existence of our civilization would be impossible, since the baryons and antibaryons would all have had to annihilate at the early stages of the development of the Universe and there would be no matter left to form the Universe as we know it.

Lev Davidovich Landau contributed greatly to the formulation of this problem: he introduced the concept of combined inversion, i.e. combined mirror reflection and substitution of all particles to their antiparticles [1, 2]. It is in terms of combined inversion that the difference in the properties of matter and antimatter is usually discussed since, as Landau wrote [1], "a K^- meson is a K^+ meson reflected in a mirror.'

Studies in this area of research proceed in many directions. In the present paper we have concentrated on a very promising direction: on the search for the difference in the behavior of the so-called beauty particles and their antiparticles. Large accelerators and detector are being built for this purpose, and important results should soon emerge.

After briefly surveying the history of the problem, we discuss the results used to predict the marked difference in the properties of beauty and antibeauty particles. We also compare the experiments that try to detect this difference.

Thanks to science-fiction writers, today everybody knows what antimatter is. The development of the idea of antimatter, however, was excruciating. In 1928, P Dirac [3] derived his equation for electrons. Besides having solutions with positive energy, this equation had negative energy solutions. Dirac suggested [4] interpreting these solutions as protons. Such an interpretation was severely criticised, since protons and electrons would annihilate and since their masses differ so much. (Incidentally, R Oppenheimer and I E Tamm contributed greatly to the understanding of these problems [5].) Then, in 1931, Dirac introduced entirely new particles, an antielectron and an antiproton, to solve the problem [6]. This was indeed a revolutionary idea. To what extent it was revolutionary can be judged by the reaction of the famous physicist W Pauli. In 1932 he wrote [7]: "This explanation is unsatisfactory if only for the fact that the laws of nature in such a theory are perfectly symmetric with respect to electrons and antielectrons." And further: "We therefore do not believe that this approach can be seriously taken into account." In the same year, C D Anderson discovered the antielectron [8], and the belief that the Universe is charge symmetric, i.e. that the laws of nature are symmetric with respect to matter and antimatter, became universal. This symmetry is known as charge-conjugation symmetry, or C invariance. Note that the concept of charge-conjugation symmetry is not trivial, since our Universe is highly asymmetric. No indications that the Universe contains an appreciable amount of antimatter have been found, although the search continues [9]. In 1956, on the basis of an analysis of the experimental data on K-meson decay, T D Lee and C N Yang [10] predicted mirror-symmetry breaking, i.e. the breaking of left-right symmetry. This symmetry is also called P invariance (P for parity). In the same year, B L Ioffe, L B Okun and A P Rudik [11] found that the predicted way of parity violation would lead to violation of C invariance as well. The same conclusion was drawn a little later by T D Lee, R Oehme and C N Yang [12]. In 1957, C S Wu et al. observed parity violation [13], while R Garwin, L M Lederman, M Weinrich [14], and J I Friedman and

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M V Danilov State Scientific Center of Russian Federation "Institute of Theoretical and Experimental Physics",
ul. B. Cheremushkinskaya 25, 117218 Moscow, Russia
E-mail: danilov@iris1.itep.ru

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V L Telegdi [15] discovered charge-conjugation symmetry breaking. Landau, who was extremely opposed to the asymmetry of space with respect to mirror reflection, proposed the hypothesis of invariance with respect to combined inversion, which is now called CP invariance [1, 2]. Thus, the symmetry of matter and antimatter was reestablished on a new level. As before, the crew of a hypothetical space craft traveling from a distant star to the Earth had no way of telling us whether they consisted of matter or antimatter without passing on a piece of that matter. The conservation of CP rather than P symmetry allowed Landau [16, 2] to propose the theory of a two-component neutrino, in which ν and $\tilde{\nu}$ differed in sign of spirality. Analogous ideas were discussed by A Salam [17] and Lee and Yang [18]. Many experiments corroborated the CP-invariance hypothesis. However, there were researchers who doubted the validity of this hypothesis (see, e.g., Ref. [19]) and urged experimenters to continue the search for CP violation. In 1964, J H Christenson et al. [20] found a slight violation of CP invariance in decays of K mesons. And in 1967, Andreĭ Sakharov [21] demonstrated that to explain the baryon asymmetry of the Universe, i.e. the excess of matter in the Universe, there must be CP violation. Thus, it was realized that CP violation plays a fundamental role in the very fact of the existence of matter, and hence the existence of our civilization. The works of V A Kuz'min, V A Rubakov and M E Shaposhnikov [22, 23] played an important part in developing these ideas. A review of the current situation with an explanation of the baryon asymmetry of the Universe may be found in Ref. [24].

2. Mechanism of CP violation

Today we know of three generations of fundamental fermions (see Table 1). The first generation consists of the fermions of which the matter surrounding us is built, while the particles of the second and third generations (with exception of ν_μ and ν_τ) are the heavier unstable particles, which eventually decay to first-generation particles.

Table 1. Fundamental fermions.

Particles	Charge	Baryonic charge	Generations		
			1	2	3
Quarks	+2/3	1/3	u	c	t
	−1/3	1/3	d	s	b
Leptons	0	0	ν_e	ν_μ	ν_τ
	−1	0	e	μ	τ

2.1 The Cabibbo – Kobayashi – Maskawa matrix

But why are three generations needed? No clear answer to this question is known, but the probable reason for this multitude of generations is so that antimatter can be distinguished from matter. This distinction arises in a natural way if there are three generations of quarks [25].

The coupling constants of quarks belonging to different generations are described by what is known as the Cabibbo – Kobayashi – Maskawa (CKM) matrix. For example, the probability of a b quark becoming a c quark depends on the matrix element V_{cb}, and the probability of a b quark becoming an u quark depends on the matrix element V_{ub}. Altogether, in the case of three generations, the CKM matrix has nine complex elements. It can be shown that all depend solely on four parameters, three angles and one phase:

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\exp(-\mathrm{i}\delta) \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}\exp\mathrm{i}\delta & c_{12}c_{23} - s_{12}s_{23}s_{13}\exp(-\mathrm{i}\delta) & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}\exp\mathrm{i}\delta & -c_{12}s_{23} - s_{12}c_{23}s_{13}\exp\mathrm{i}\delta & c_{23}c_{13} \end{pmatrix},$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. In the modern theory, it is this phase that is responsible for the difference of properties of matter and antimatter. The parameters determining the CKM matrix are the fundamental parameters of the modern theory, which is usually called the Standard Model (SM). They are not predicted by the theory and must be determined from experiments.

Often, the CKM matrix is represented by Wolfenstein's approximate parametrization scheme [26]:

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 - \dfrac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - \mathrm{i}\eta) \\ -\lambda & 1 - \dfrac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - \mathrm{i}\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)\,.$$

Following Refs [27, 28], we use the relationships:

$$s_{12} = \lambda\,, \qquad s_{23} = A\lambda^2\,, \qquad s_{13}\exp(-\mathrm{i}\delta) = A\lambda^3(\rho - \mathrm{i}\eta)\,,$$

which yield

$$\rho = \frac{s_{13}}{s_{12}s_{23}}\cos\delta\,, \qquad \eta = \frac{s_{13}}{s_{12}s_{23}}\sin\delta\,.$$

There is an extremely useful geometrical relationship between the elements of the CKM matrix. Since this matrix is unitary, its columns must be orthogonal:

$$V_{\mathrm{ud}}V_{\mathrm{ub}}^* + V_{\mathrm{cd}}V_{\mathrm{cb}}^* + V_{\mathrm{td}}V_{\mathrm{tb}}^* = 0\,.$$

Here the matrix elements V_{ud} and V_{tb} describe the couplings between quarks belonging to the same generation and are approximately equal to unity, while the matrix element $V_{\mathrm{cd}} \approx -V_{\mathrm{us}} \approx -\lambda$ describes the coupling between first- and second-generation quarks and is well known from semileptonic decays of K mesons and hyperons: $V_{\mathrm{us}} = 0.2205 \pm 0.0018$ [29]. Hence the above expression reduces to a simpler one:

$$V_{\mathrm{ub}}^* - \lambda V_{\mathrm{cb}}^* + V_{\mathrm{td}} \approx 0\,,$$

which represents a triangle in the complex plane (Fig. 1). This triangle is known as the unitarity triangle. Its sides are equal to the absolute values of the elements of the CKM matrix,

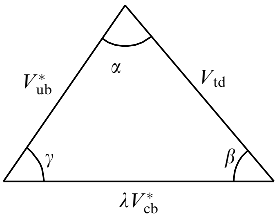

Figure 1. The unitarity triangle.

while its angles, as we will see shortly, determine the difference in the decays of the B^0 mesons, which consist of $(\bar{b}d)$ quarks, and $\bar{B}^0$ mesons.

Before discussing the way in which these angles can be measured, let us see what experiments helped in determining the sides of the unitarity triangle. Since a triangle is given by its three sides, measurements of these sides can yield useful information about the angles.

2.2 Determining V_{cb}

We begin by discussing the matrix element V_{cb}, which determines the coupling between second- and third-generation quarks. The unexpectedly long lifetime of B mesons discovered by the HRS and MAC groups [30] was a surprise and an indication that $|V_{cb}|$ is approximately five times smaller than the matrix element V_{us}, which determines the coupling between first- and second-generation quarks. Semileptonic decays of B mesons are most convenient for quantitative measurements of V_{cb}, since leptons do not participate in final-state interactions. Initial measurements of the branching fractions of inclusive semileptonic decays of B mesons [29] yielded values in the 10 – 14% range. Unfortunately, in these measurements the leptons from the primary decays $b \to cl^-\bar{\nu}_l$ were not separated from the leptons from the secondary decays $c \to sl^+\nu_l$. The need to subtract the background of secondary leptons led to a dependence of the results on the models chosen and to large systematic errors. The ARGUS Collaboration [31] found a way to overcome this difficulty. In the hard part of the spectrum there are practically no secondary leptons, so that from the sign of the lepton charge one can determine whether the decayed quark was a b quark or a $\bar{b}$ quark: b quarks decay to negative leptons, while $\bar{b}$ quarks decay to positive leptons. Since the b and $\bar{b}$ quarks are always created in pairs, by identifying one of them we immediately identify the other, and hence know the sign of the primary lepton in its decay. This makes it possible to eliminate the background of secondary leptons, which have the opposite sign, and to obtain a model-independent value of the branching fraction of semileptonic decays of B mesons. Recent values of this branching fraction and the lifetime of B mesons [32] lead to

$$|V_{cb}| = (38.7 \pm 0.9 \pm 1.9) \times 10^{-3} \, ,$$

where the second error takes into account the uncertainties in the theoretical description of inclusive semileptonic decays.

The matrix element V_{cb} can also be determined from the branching fraction of exclusive semileptonic decays of B mesons to D^* and D mesons (Fig. 2), first observed in the ARGUS experiment [33]. Here one must estimate the probability that the c quark, produced in the decay of the b quark, and the spectator quark form a $D^{(*)}$ meson. At the beginning such estimates were done by using different models, which introduced extremely large theoretical uncertainties into the extracted value of V_{cb}, especially in the case of a decay to D^* mesons. M B Voloshin and M A Shifman [34] discovered that in the case where the masses of b and c quarks are extremely large, the value of V_{cb} can be extracted from the data on $B \to D^*l\nu$ decay without resorting to a model. The underlying idea is simple and elegant. When q^2 is at its maximum, the c quark is at rest in the center-of-mass system of the b quark. Hence the spectator quark and the virtual gluons and the quark – antiquark pairs that surrounded the b quark simply do not notice that one heavy quark has been substituted for another and form a bound state with that quark (a D^* meson). The corrections that emerge because of the finiteness of the masses of the b and c quarks are small and can be estimated fairly well. Thanks to the efforts of N Isgur and M B Wise and many other researchers [35], it was realized that in the limit of infinitely large masses additional symmetries emerge, which led to a new avenue of theoretical research: the heavy-quark effective theory. This theory yields, with high accuracy, the value of V_{cb} from exclusive semileptonic decays $B \to D^*l\nu$ [32]:

$$|V_{cb}| = (39.1 \pm 2.7 \pm 1.3) \times 10^{-3} \, .$$

This value of V_{cb} agrees with the value extracted from the analysis of inclusive semileptonic decays. Analysis of $B \to Dl\nu$ decays gives a similar value of $|V_{cb}|$, but with somewhat larger uncertainties [32].

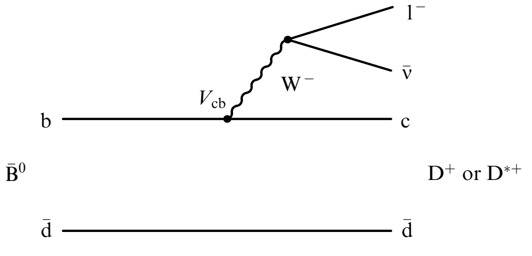

Figure 2. $\bar{B}^0 \to D^{(*)+}l^-\bar{\nu}_l$ decay diagram.

2.3 Determining V_{ub}

It is even more difficult to determine experimentally the next side of the unitarity triangle, V_{ub}, since it was found to be ten times smaller than V_{cb}, which means that all probabilities are about a hundred times smaller than in the previous case. The idea of the experiment is simple. Since the u quark is lighter than the c quark, the lepton in the decay of the b quark to the u quark is likely to have a higher momentum than it would in the decay of the b quark to the c quark and be above the kinematic limit for the latter transition. The problem is that the signal is extremely weak against the background, and this poses difficulties for the experimenter. Nevertheless, in 1989, the ARGUS and CLEO groups announced, practically simultaneously, that the $b \to ul^-\bar{\nu}$ transition had been detected [36]. Unfortunately, it is extremely difficult to extract the value of V_{ub} from these data, since one is forced to extrapolate from a narrow region where the measurements are conducted to the entire lepton momentum range. The latest value of $|V_{ub}/V_{cb}|$ proved to be [29]

$$\left|\frac{V_{ub}}{V_{cb}}\right| = 0.08 \pm 0.02 \, .$$

The CLEO group was successful in measuring the branching fractions of the $B \to \rho l\nu$ and $B \to \pi l\nu$ decays [37]. The values lead to $|V_{ub}| = (3.3 \pm 0.4_{\rm exp} \pm 0.7_{\rm theor}) \times 10^{-3}$ which agrees with the value obtained from inclusive decays.

2.4. Determining V_{td}

The third side of the unitarity triangle, V_{td}, was estimated from $B^0\bar{B}^0$ oscillations. Since the beauty quantum number is not conserved in weak interactions, the B^0 and $\bar{B}^0$ mesons can transform into each other through second-order processes. One of the dominating diagrams is shown in Fig. 3. Since the

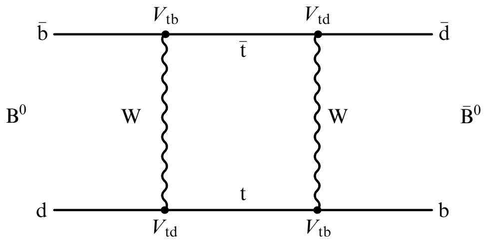

Figure 3. Diagram of the transition of a B^0 meson into a $\bar{B}^0$ meson.

B^0 and $\bar{B}^0$ particles mix, states with a well-defined mass are linear combinations of these particles, which have almost equal lifetimes τ_B, but slightly different masses m_1 and m_2. The probability of $\bar{B}^0$-mesons appearance in a beam of B^0 mesons is given by the following formula:

$$\bar{n}(t) = \frac{\exp(-t/\tau_B)}{2}(1 - \cos\Delta m t)\,,$$

where $\Delta m = m_1 - m_2$. Thus, in a beam of B^0 mesons, $\bar{B}^0$ mesons appear with the passage of time, and the fraction oscillates in time. The frequency of these oscillations, Δm, is proportional to the square of the mass of the t quark and the square of the matrix element V_{td} [38]:

$$\Delta m = \frac{G_F^2}{6\pi^2} B_B f_B^2 m_B |V_{tb}^* V_{td}|^2 m_t^2 F\left(\frac{m_t^2}{M_W^2}\right)\eta_{QCD}\,, \tag{1}$$

where G_F is the weak interaction coupling constant, $\eta_{QCD} = 0.55 \pm 0.01$ is the QCD correction [39], $F(m_t^2/M_W^2)$ is a reliably calculable function, and $f_B^2 B_B$ specifies the parametrization of the hadronic matrix element, which, so to say, fixes the probability that the $\bar{b}$ and d quarks in the B^0 meson are at the same point. By measuring the $B^0\bar{B}^0$ oscillations one can determine the mass of the t quark or the matrix element V_{td}. The probability of B^0 mesons becoming $\bar{B}^0$ mesons was expected to be extremely low, since the mass of the t quark was predicted to be not too large. More than that, there were indications of a t quark with a 40-GeV mass [40] (here we use a system of units in which $c = 1$ and $\hbar = 1$). Hence the $B^0\bar{B}^0$ oscillations discovered by the ARGUS Collaboration [41] were a big surprise.

As noted earlier, only negatively charged leptons can be produced in decays of the b quark and only positively charged leptons, in decays of the $\bar{b}$ quark. Since the production of a b quark is accompanied by the production of a $\bar{b}$ quark, and vice versa, only pairs of leptons with opposite signs can be produced in the absence of oscillations. Oscillations result in the production of pairs of leptons of the same sign. The ratio

$$\frac{N_{l^\pm l^\pm}}{N_{ll}} \approx \frac{x^2}{2 + 2x^2}\,,$$

depends on the parameter $x = \Delta m \tau_B$, and consequently, on the oscillation frequency.

Studying the $\Upsilon(4S)$ resonance, which decays to $B^0\bar{B}^0$ or B^+B^- pairs, the ARGUS Collaboration detected pairs of primary leptons of the same sign and thus discovered $B^0\bar{B}^0$ oscillations [41]. More than that, an event with two B^0 mesons in the final state was fully reconstructed, which was graphic proof of $B^0\bar{B}^0$ oscillations. The oscillation parameter was found to be unexpectedly large:

$$x = \Delta m \tau_B = 0.73 \pm 0.15\,.$$

This result yielded the first estimate of the matrix element V_{td} and indicated that the mass of the t quark is larger than 50 GeV.

A t quark with a mass of $m_t = 175 \pm 6$ GeV was detected by the CDF and D0 groups [42], and the accuracy in determining the parameter x was improved mainly thanks to experiments at the LEP collider:

$$x = 0.72 \pm 0.03\,.$$

Unfortunately, due to the theoretical uncertainties in f_B and B_B, there has been no noticeable improvement in the accuracy in determining $|V_{td}|$. From Ref. [32] it follows that

$$0.005 < |V_{td}| < 0.015$$

if one uses $f_B\sqrt{B_B} = 200 \pm 40$ MeV [43]. The value of the ratio $f_{B_d}^2 B_{B_d}/f_{B_s}^2 B_{B_s}$ can be predicted with a smaller theoretical uncertainty. Hence by measuring the B_s^0 oscillations, for which the parameter Δm_s is described by a formula similar to Eqn (1), we can determine $|V_{td}|$ with higher accuracy. At present we know [32] of only the lower bound $\Delta m_s > 9.2\ \text{ps}^{-1}$, which leads to additional limitations on V_{td} only for an optimistic estimate of the uncertainties in $f_{B_d}^2 B_{B_d}/f_{B_s}^2 B_{B_s}$. Therefore we will not use this information here.

Thus, we have described the measurements of all three sides of the unitarity triangle. Before we proceed with the angles, we would like to comment on the very large difference between the coupling constants of quarks belonging to different generations.

Within each generation, the coupling constants are approximately equal to unity (naturally, in units of the weak interaction coupling constant G_F). The coupling constant between the first and second generations is approximately 0.2, between the second and third it is about 0.04, and between the third and first it is smaller by a factor of ten than the previous one. The origin of this hierarchy of coupling constants is still unclear. We hope that experimental observations will open a new avenue to a complete theory, which will explain this hierarchy.

2.5 How to measure the angles?

The three sides of a triangle completely determine the angles in the triangle. Unfortunately, there are uncertainties in the measurements. Additional restrictions on the positions of the unitarity triangle vertices emerge from an analysis of CP violation in $K \to \pi\pi$ decays described by the parameter ϵ_K. The vertex at angle α lies on a hyperbola whose position is determined by the parameter ϵ_K and by m_t, V_{cb}, and B_K. If this requirement is taken into account, by measuring the sides of the unitarity triangle we can arrive at the constraints on the values of the triangle's angles. The allowed region for the vertices of the unitarity triangle is depicted in Fig. 4 [44]. In Fig. 4 the sides of the triangle are normalized to $\lambda|V_{cb}|$, with the result that the triangle's base is equal to unity.

The angles of the unitarity triangle prove to be large, and in the modern theory they are related directly to the asymmetry of the decays of B and $\bar{B}$ mesons. For instance, the asymmetry in the decays of B^0 and $\bar{B}^0$ mesons to $J/\psi K_s^0$ is determined by the angle β.

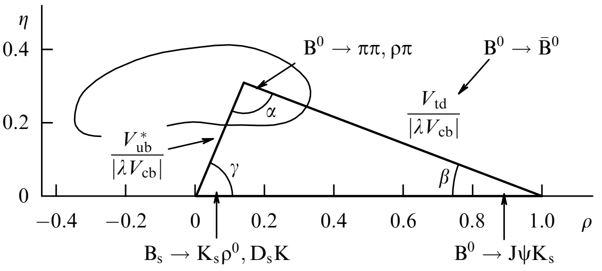

Figure 4. Allowed region for the vertex of the unitarity triangle (±1σ).

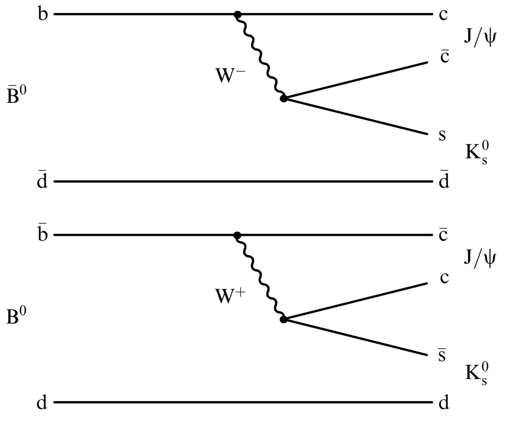

Figure 5. Diagrams of the decays of $\bar{B}^0$ and B^0 mesons to $J/\psi K^0_s$.

This asymmetry emerges because a B meson can decay to the final state $J/\psi K^0_s$ directly or first oscillate to the $\bar{B}^0$ meson and then decay to the same final state (Fig. 5). The interference of the possible decay routes leads to an asymmetry in the number of decays of the B and $\bar{B}$ mesons to $J/\psi K^0_s$. This asymmetry depends on the angle β of the unitarity triangle and on time:

$$a_{J/\psi K^0_s}(t) = \frac{n(t) - \bar{n}(t)}{n(t) + \bar{n}(t)} = -\sin(2\beta)\sin\frac{xt}{\tau_B}\,. \tag{2}$$

In this expression, the $\sin 2\beta$ emerges because the diagrams for the $B^0\bar{B}^0$ oscillations contain the matrix element $V_{td} = |V_{td}|\exp(-i\beta)$, and the second factor $\sin(xt/\tau_B)$ specifies the probability of oscillations.

Since $x = 0.72 \pm 0.03$ is a relatively large value, $\sin(xt/\tau_B)$ becomes large for times comparable to the B meson lifetime, i.e. not all B mesons have time to decay. Hence the asymmetry can be measured: while it becomes large there are still many B mesons. Thus, the discovery of unexpectedly large $B^0\bar{B}^0$ oscillations [41] made possible in the search for CP violation in B mesons.

Similarly, the asymmetry in the decay to $\pi^+\pi^-$ (Fig. 6) depends on $\beta + \gamma = \pi - \alpha$:

$$a_{\pi\pi}(t) = -\sin(2\alpha)\sin\frac{xt}{\tau_B}\,,$$

since the decay amplitude contains the matrix element $V_{ub} = |V_{ub}|\exp(-i\gamma)$. True, in this case the so-called penguin diagrams, one of which is depicted in Fig. 7, can contribute significantly and violate the simple relationship between asymmetry and $\sin 2\alpha$. Nevertheless, the angle α can still be found [45].

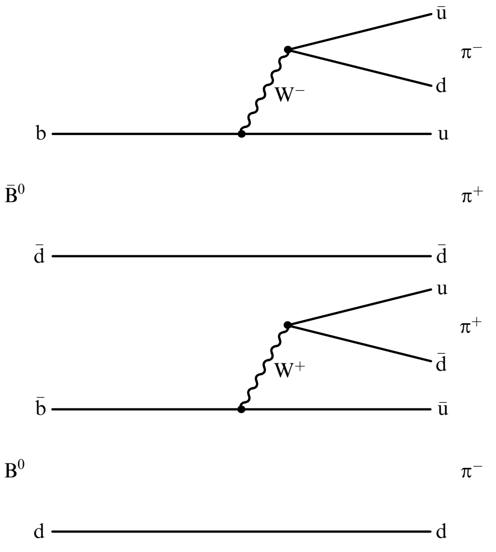

Figure 6. Diagrams of the $B \to \pi^+\pi^-$ decay.

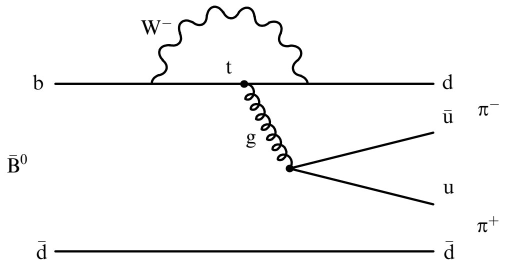

Figure 7. Penguin diagram for the $B \to \pi^+\pi^-$ decay.

In addition to the above examples, there is a large number of decays that can be used to determine the angles of the unitarity triangle. Some of these decays are listed in Table 2 and Fig. 4.

Except for the CP violation connected with $B^0\bar{B}^0$ oscillations, direct CP violation is possible, caused by the interference of partial amplitudes with different weak and strong phases, for example,

$$\Gamma(B^+ \to K^+\rho^0) \neq \Gamma(B^- \to K^-\rho^0)\,.$$

However, it is usually difficult to connect this direct CP violation with the angles of the unitarity triangle, and we shall discuss this no further.

Table 2. Accuracies in determining $\sin 2\beta$ and $\sin 2\alpha$ from different decays in the BaBar experiment after 1 year (10^7 s) of operation.

Decay	Br	$\sin\Phi$	σ
$J/\psi K^0_S$	0.5×10^{-3}	$\sin 2\beta$	0.10
$J/\psi K^0_L$	0.5×10^{-3}		0.16
$J/\psi K^{*0}$	1.6×10^{-3}		0.19
D^+D^-	6×10^{-4}		0.21
$D^{*+}D^{*-}$	7×10^{-4}		0.15
$D^{*\pm}D^{\pm}$	8×10^{-4}		0.15
$\pi^+\pi^-$	1.2×10^{-5}	$\sin 2\alpha$	0.20
$\rho\pi$	5.8×10^{-5}		0.11
$a_1\pi$	6×10^{-5}		0.24

Recently the search for CP violation in a system of B mesons has formed a new avenue of research in elementary particle physics. Two special large accelerators, known as B-factories, are being built at KEK (Japan) and SLAC (the United States). Also, four specialized detectors are being built: BaBar (SLAC), Belle (KEK), HERA-B (DESY, Germany), and LHCb (CERN). The search for CP violation in B mesons has been incorporated into the research programs involving the existing CDF and D0 detectors at the $p\bar{p}$ collider at FNAL. Such activity is a reflection of the great interest in the problem. In fact, it may well be that the modern theory of CP violation is either incorrect or incomplete, and instead of a unitarity triangle with matching sides and angles we may find something totally unexpected, the more so that there are strong theoretical indications that CP violation in the SM is not sufficient for the creation of the baryonic asymmetry of the Universe (e.g., see Ref. [46]).

2.6 CP violation outside the Standard Model

There are many scenarios in which CP violation differs from the SM. These scenarios usually require bringing new particles into the picture. A detailed discussion of this problem can be found, e.g., in Ref. [47]. Here we give only a few examples.

1. A fourth quark – lepton generation. In this case the unitarity triangle becomes a unitarity quadrangle. The probability that a fourth generation exists is low because of the absence of a fourth type of neutrino with a mass smaller than $M_Z/2$, although the possibility cannot be excluded entirely.

2. Neutral currents that change flavor. Such currents would contribute to the $B^0\bar{B}^0$ oscillations and hence change the SM predictions concerning CP violation. In this model, the unitarity triangle also becomes a quadrangle (Fig. 8). If $B^0\bar{B}^0$ oscillations are determined not by square SM diagrams (see Fig. 3) but by a new neutral current, the asymmetry in the $B^0 \to J/\psi K^0_s$ decay depends not on $\sin 2\beta$ but on $\sin 2\bar{\beta}$. Thus, in this model, CP asymmetries in B decays determine completely different angles.

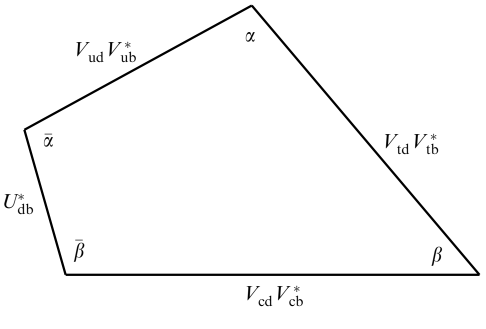

Figure 8. The unitarity quadrangle in the model with flavor changing neutral currents (characterized by U^*_{db}).

3. Additional Higgs doublets. In this case, charged and neutral Higgs bosons are added to the single neutral Higgs boson required by the SM. Charged bosons can contribute to $B^0\bar{B}^0$ mixing due to the diagrams depicted in Fig. 9. This leads to a change in the value of V_{td} extracted from the $B^0\bar{B}^0$-oscillation frequency. The neutral Higgs bosons may contribute to $B^0\bar{B}^0$ oscillations at the tree level and alter these oscillations considerably in comparison to those predicted by the SM. There are also models in which CP invariance is violated due to exchange of Higgs bosons, while the CKM matrix is real. In this case the unitarity triangle degenerates into a straight line.

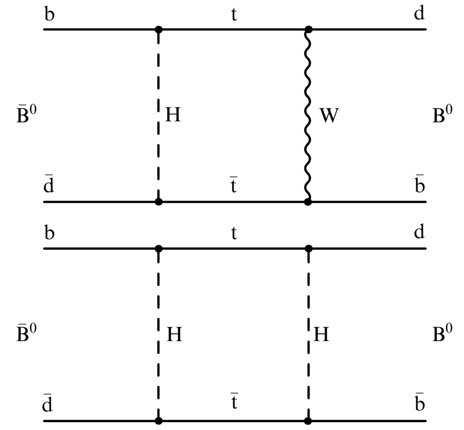

Figure 9. Diagrams of the transition of a $\bar{B}^0$ meson into a B^0 meson with an exchange of Higgs bosons.

The above examples illustrate the fact that measurements of CP asymmetry in B mesons are extremely sensitive to the 'new physics' lying outside the SM.

3. Measuring the CP asymmetry in decays of B mesons

We discuss the way in which the CP asymmetry could be measured in the decays of B mesons using the HERA-B detector as an example. After that we will comment on other approaches.

3.1 The HERA-B experiment

In the HERA-B detector, B mesons are produced on thin wires surrounding HERA's internal beam. This makes it possible to use the protons from the beam halo, which are otherwise lost.

The schematic of the HERA-B detector is depicted in Fig. 10. B mesons are produced on the wire target, and the vertices of the B-meson decays are registered by silicon microstrip detectors. The momenta of the charged particles are measured by drift and gas microstrip chambers placed inside and after the magnet. K mesons are identified by a Cherenkov counter, electrons are identified by a transition radiation detector and electromagnetic calorimeter, and muons are registered by a muon identifier. Nearly 600 K readout electronic channels are used in the device. For an illustration of the scale of the device Fig. 11 depicts the moment of assembly of the electromagnetic calorimeter.

The proton energy in the HERA accelerator is 820 GeV. At this energy the production cross-section of B mesons is approximately one million times smaller than the inelastic scattering cross-section. With allowance for the branching fractions of the decays [29] $Br(B^0 \to J/\psi K^0_s) = 5 \times 10^{-4}$, $Br(J/\psi \to l^+l^-) = 0.06$, and $Br(K^0_s \to \pi^+\pi^-) = 0.69$, it appears that there is only one event of interest for every 25000 B mesons. Hence establishing an effective system for selecting the necessary events, an effective trigger, is the key issue, the more so that the interaction frequency is extremely high (40 MHz). This problem is solved by using triggers at

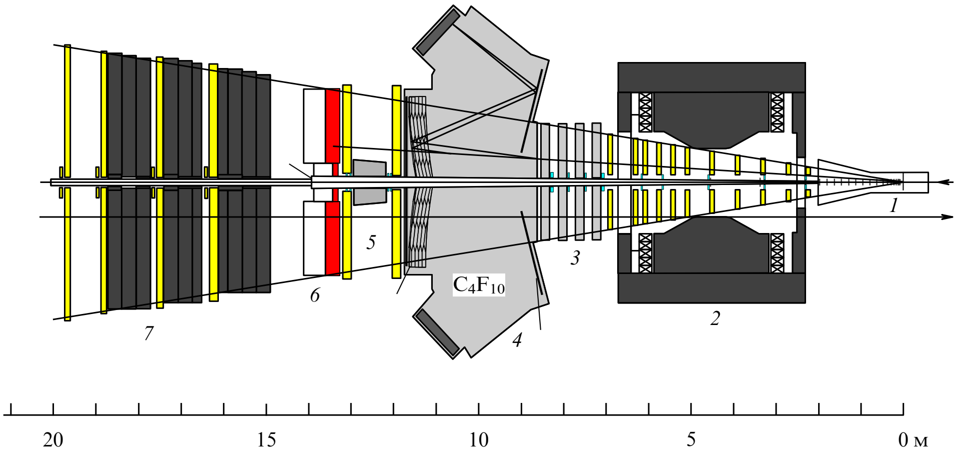

Figure 10. Schematic of the HERA-B detector: *1* — vertex detector; *2* — magnet; *3* — drift chambers; *4* — Cherenkov counter; *5* — transition radiation detector; *6* — electromagnetic calorimeter; *7* — muon identifier.

three levels, and at each level the amount of information processed is larger than at the previous level. At the first level, the calorimeter and the muon chambers are used to separate regions in the track system in which a lepton may pass and a search of such tracks is carried out. After the tracks are found, the invariant mass of the l^+l^- pair is calculated, which is matched with the mass of the J/ψ particle.

Specially designed processors are used to carry out all these operations in 12 μs, suppressing the background by a factor of 200 and yet retaining more than 60% of all the useful events in the process. At the second level, information about the secondary vertex is used, which makes it possible to suppress the background by an additional factor of 25. Finally, at the third level, the complete reconstruction of the event is achieved, which decreases the background by an additional factor of 20.

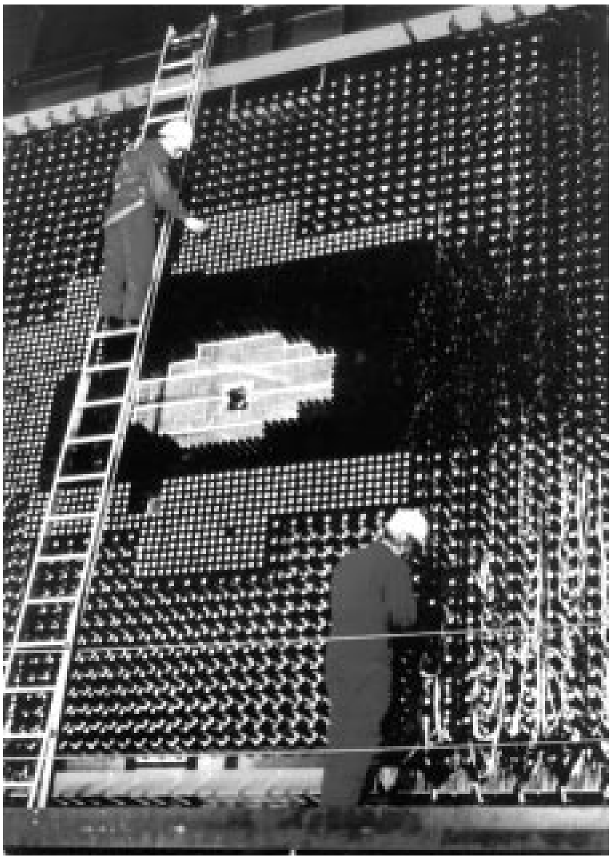

Figure 11. Electromagnetic calorimeter of the HERA-B detector.

In the final analysis, the separation of the $\mathrm{B} \to \mathrm{J}/\psi \mathrm{K}^0_s$ decay is achieved primarily by calculating the invariant mass of the candidate for the B meson and by imposing the requirement that the vertex of the decay of the B meson be several millimeters away from the primary vertex. Since for times much shorter than the lifetime of the B meson the CP asymmetry is small [see Eqn (2)], the requirement that the B-meson's decay length be large (up to $\gamma c t \lesssim 0.7 \gamma c \tau_{\mathrm{B}}$) practically does not affect the accuracy in determining the asymmetry.

To register the $\mathrm{B} \to \pi^+\pi^-$ and $\mathrm{B} \to \mathrm{K}^-\pi^+$ decays, a special trigger was developed to discriminate tracks with large transverse momenta [48]. The trigger circuit uses the correlations that exist between the deviation of a track in a magnetic field and its distance from the beam axis. The larger the distance, the greater the track angle and the smaller the momentum for a given p_{T}, and hence the larger the deviation in the magnetic field.

To calculate the CP asymmetry, the decays of B^0 and $\bar{\mathrm{B}}^0$ mesons must be separated. Since this cannot be done via the final states, which are identical, one must use the information about the second beauty (anti)particle that was produced together with the neutral B meson (this beauty particle can be identified by the sign of the leptons and K mesons produced in its decay). This 'tags' the B meson being investigated. By definition, beauty mesons and baryons contain a $\bar{\mathrm{b}}$ quark and decay to positive primary leptons and K mesons, and their antiparticles decay to the respective negative particles. Unfortunately, sometimes leptons and K mesons of the other sign are produced in the decays of beauty particles, which leads to errors in identification. In addition, hadrons can be incorrectly identified as leptons, and π mesons as K mesons. Finally, if the second beauty particle is a B^0 meson, it may oscillate into its own antiparticle, which again results in incorrect identification of the B meson under investigation. The quality of identification is described by a parameter D, which in the case of the HERA-B experiment amounts to 0.4.

The accuracy in determining the angles of the unitarity triangle is given by the following formula:

$$\Delta \sin 2\Phi = \frac{\sqrt{1 + B/S}}{D} \sqrt{\frac{K}{\epsilon N}} \, ,$$

where N is the number of registered events, B/S is the background-to-signal ratio, ϵ is the effectiveness of identifying B mesons, D is the quality of identification, and K is a factor allowing for the fact that the neutral B meson being studied can oscillate. In the HERA-B experiment, $K \approx 2$.

Figure 12 depicts the region in the $(\sin 2\alpha - \sin 2\beta)$ plane allowed by the SM and the expected accuracy of the HERA-B experiment after four years of running. We see that over practically the entire allowed region, CP asymmetry can be discovered with a statistical significance no less than four standard deviations. Of course, reality may be worse than the expectations. For example, the latest CLEO data indicate that the branching fraction of the decay $B^0 \to \pi^+\pi^-$ is half that used in the estimates. On the other hand, in addition to the two decays discussed above, other decays can be used to measure the angles of the unitarity triangle, e.g., $B^0 \to D^{*+}D^{*-}$ (the angle β) and $B^0 \to \pi^{\pm}a_1^{\mp}$ (the angle α). This should improve the accuracy.

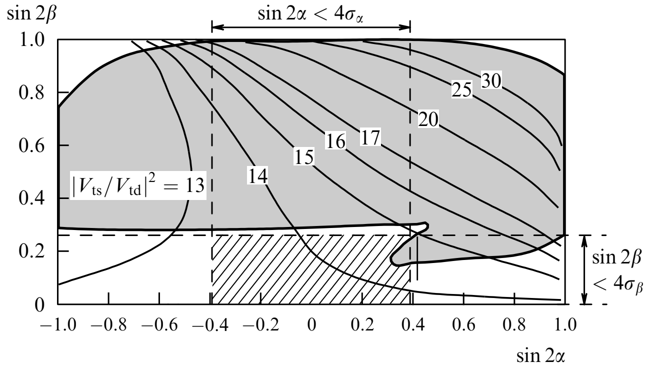

Figure 12. Region in the $(\sin 2\alpha - \sin 2\beta)$ plane allowed by the SM. The dashed lines depict the expected accuracy of the HERA-B experiment at the 4σ-level, and the hatched area indicates the region where the experiment's sensitivity is insufficient for discovering CP violation.

3.2 B-factories

When the B-factories become operational, they will work in the region of the $\Upsilon(4S)$ resonance, which decays to the pairs B^+B^- and $B^0\bar{B}^0$. This has certain advantages:

(1) there is no background of additional particles;

(2) the energy of the B mesons is well known, which makes it possible to use the kinematic constraints to suppress the background;

(3) the ratio of the B-meson production cross-section to the total cross-section is 25%.

B^0 and $\bar{B}^0$ mesons are produced in the decay of $\Upsilon(4S)$ in the P-wave. Because of Bose statistics, they remain in the coherent $B^0\bar{B}^0$ state as long as one of the mesons does not decay. Hence CP asymmetry depends not on the proper decay time but on the difference in the decay times of the two B mesons:

$$a(t) \sim \sin(\Delta m \Delta t) \, .$$

Integration over Δt nullifies the asymmetry. Hence to observe CP asymmetry we must at least know the sign of Δt. The value of Δt can be measured if $\Upsilon(4S)$ is produced not at rest but in motion with respect to the laboratory reference frame. Then $\Delta t \approx \Delta z/\gamma\beta$, where Δz is the distance between the vertices of B-meson decays, β is the velocity of $\Upsilon(4S)$ in the laboratory reference frame, and $\gamma = E_{\Upsilon(4S)}/M_{\Upsilon(4S)}$.

For $\Upsilon(4S)$ to move in the laboratory reference frame, the energies of the electrons and positrons in the B-factories are made to be different. For instance, in the B-factory at SLAC the electrons have an energy of 9 GeV and the positrons, of 3.1 GeV, which leads to a 250-μm average distance between the decay points of the B mesons. To produce a sufficient number of B mesons, the B-factories must have an extremely high luminosity. The design luminosity of the B-factory at SLAC is 3×10^{33} cm^{-2} s^{-1}, which should make it possible to produce three neutral B mesons every second. At present, a luminosity of 5.5×10^{32} cm^{-2} s^{-1} has been reached at the symmetric e^+e^- collider CESR (Cornell, USA), which operates also in the region of the $\Upsilon(4S)$ resonance.

Detectors for B-factories closely resemble the well known detector CLEO, which operates on a symmetric e^+e^- collider. However, they require a perfect vertex detector and better particle identification. The expected accuracies in determining $\sin 2\beta$ and $\sin 2\alpha$ for the BaBar detector are listed in Table 2.

3.3 The CDF and D0 experiments

The CDF and D0 experiments, which were carried out on the $p\bar{p}$ collider at FNAL, have been focusing primarily on studies of interactions at ultrahigh energies and the search for new particles and phenomena. However, the potential of these experiments for B-mesons studies is also high. So far, the highest number of $B \to J/\psi K_s^0$ decays has been registered in the CDF experiment. At present both the collider and the detectors are being modernized. After the upgrade has been completed, luminosity will reach 2×10^{32} cm^{-2} s^{-1}, which will allow CDF to register 10^4 decays to $J/\psi K_s^0$ in 1999 – 2001. Unfortunately, the quality D and effectiveness ϵ of 'tagging' the B^0 and $\bar{B}^0$ mesons will remain low even after completion of the CDF upgrade [49]. Hence the accuracy in determining $\sin 2\beta$ will amount to 0.08 – 0.13 and will be at the level of the sensitivity of B-factories and the HERA-B experiment, where the expected number of decays is smaller by an order of magnitude.

A new trigger is being built to measure the angle α in the CDF experiment. The trigger will use two tracks that emerge at the secondary vertex. More precisely, the two tracks must miss the primary beam by no less than 100 μm. This trigger will make it possible to register $B^0 \to \pi^+\pi^-$ decays and to measure $\sin 2\alpha$ with an accuracy of about 10%.

3.4 LHC

The study of CP violation in the B meson decays constitutes an important part in the research program involving the biggest pp collider LHC, which is currently being built at CERN. These studies will be carried out on the universal detectors ATLAS and CMS and on the LHCb detector, which has been specially optimized for studying B mesons. The expected accuracy in all three second-generation experiments is significantly higher than the accuracy of the first-generation experiments (by a factor of three to ten). This should not come as a surprise, since the number of B mesons produced by LHC will be five orders of magnitude higher than that produced by B-factories. With an expected accuracy of 1 – 3%, systematic errors begin to play an important role. The LHCb experiment, which is very similar to the HERA-B experiment and uses Cherenkov counters to identify particles, will monitor all these errors much better.

For completeness we should mention the BTeV experiment on the Tevatron $\mathrm{p\bar{p}}$ collider [50] which may be carried out before work starts on LHC. Its sensitivity is comparable with that of LHCb. However, this experiment has not yet been approved.

In addition, a search for CP violation, not connected with B-meson oscillations, is planned for the CLEO detector, working at the CESR symmetric $\mathrm{e^+e^-}$ collider, which should attain a luminosity of 2×10^{33} cm^{-2} s^{-1} after upgrading [51].

4. Conclusion

Table 3 lists the characteristics of the different experiments involved in the search for CP violation in B mesons. The errors in the angles of the unitarity triangle for one year of operation of the detectors are shown for the decays giving the best accuracy. Averaging over several decays may improve this accuracy. Also shown are the values of the parameter x_s, to which $\mathrm{B}_s^0\bar{\mathrm{B}}_s^0$ oscillations may be measured in the different experiments. The first three columns refer to first-generation experiments, for which data taking will begin in 1999. The biggest difference between these experiments is in the number of B mesons produced and in the ratio of the number of useful events to the background. The biggest problem in the experiment with production of B mesons on a fixed target (HERA) is the huge background: the B-meson production cross-section is only one millionth of the total cross-section. In the case of B-factories, the background is low, but so is the number of produced B mesons. Hence in the first case the main problem is to design and build a detector at the technological limit, while in the second case it amounts to building an accelerator with an exceptionally high luminosity. Finally, for the CDF and D0 experiments, the main problem will be improving the trigger and the quality of tagging — εD^2.

The expected accuracy in measuring the angles in the unitarity triangle is approximately the same in all first-generation experiments. The differences that Table 3 illustrates are inessential and most likely reflect the optimism of the different groups of researchers. Next-generation experiments will be much more accurate. Table 3 lists the parameters of only one such experiment, LHCb (a specialized experiment in B-meson physics), which is much more accurate than the universal ATLAS and CMS detectors, on which research on beauty particles is also planned.

Table 3. Experiments on the search for CP violation in B mesons.

Accelerator	HERA	B-factories	Tevatron	LHC
Detector	HERA-B	BaBar, BELLE	CDF, D0	LHCb
Becomes operational in	1999	1999	1999	2005
Interaction type	pCu	$\mathrm{e^+e^-}$	$\mathrm{p\bar{p}}$	pp
$\sigma_{\mathrm{b\bar{b}}}$	12 nb	1 nb	100 μb	500 μb
$\sigma_{\mathrm{b\bar{b}}}/\sigma_{\mathrm{in}}$	10^{-6}	2×10^{-1}	2×10^{-3}	5×10^{-3}
$N_{\mathrm{b\bar{b}}}$/year	4×10^{8}	3×10^{7}	2×10^{11}	5×10^{12}
$\delta(\sin 2\beta)$	0.13	0.10	0.08	0.01
$\delta(\sin 2\alpha)$	0.2	0.11	0.10	0.03
$\delta(\gamma)$	–	–	–	0.1
x_s	17	–	20	75

The mechanism of CP violation has yet to be established, and an important step toward understanding it will soon be taken. The predictions of large differences in the properties of beauty and antibeauty particles will be checked. There is no hope that the first experiments will be easy. However, after several years of operation, there is a high probability that CP violation in B mesons will be discovered if it is described by the SM. The next-generation experiments, which will start in 2005, should make it possible to quantitatively verify the predictions of the SM and will be sensitive with respect to the 'new physics.'

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References

1. Landau L D *Zh. Eksp. Teor. Fiz.* **32** 405 (1957) [*Sov. Phys. JETP* **5** 336 (1957)]
2. Landau L *Nucl. Phys.* **3** 127 (1957)
3. Dirac P A M *Proc. R. Soc. London Ser. A* **117** 610 (1928); **118** 351 (1928)
4. Dirac P A M *Proc. R. Soc. London Ser. A* **126** 360 (1930)
5. Oppenheimer J R *Phys. Rev.* **35** 562 (1930); Tamm I E *Z. Phys.* **62** 545 (1930)
6. Dirac P A M *Proc. R. Soc. London Ser. A* **133** 60 (1931)
7. Pauli W "Die allgemeinen prinzipien der wellenmechanik", in *Encyclopedia of Physics* Vol. 1, Part 1 (Berlin: Springer, 1958) [An earlier edition translated into Russian (Moscow: Gostekhizdat, 1947) p. 287]
8. Anderson C D, Neddermeyer S H *Phys. Rev.* **43** 1034 (1933)
9. Ting S C C et al. *Antimatter Magnetic Spectrometer Proposal* (1995)
10. Lee T D, Yang C N *Phys. Rev.* **104** 254 (1956)
11. Ioffe B L, Okun' L B, Rudik A P *Zh. Eksp. Teor. Fiz.* **32** 396 (1957) [*Sov. Phys. JETP* **5** 328 (1957)]
12. Lee T D, Oehme R, Yang C N *Phys. Rev.* **106** 340 (1957)
13. Wu C S et al. *Phys. Rev.* **105** 1413 (1957)
14. Garwin R L, Lederman L M, Weinrich M *Phys. Rev.* **105** 1415 (1957)
15. Friedman J I, Telegdi V L *Phys. Rev.* **105** 1681 (1957)
16. Landau L D *Zh. Eksp. Teor. Fiz.* **32** 407 (1957) [*Sov. Phys. JETP* **5** 337 (1957)]
17. Salam A *Nuovo Cimento* **5** 299 (1957)
18. Lee T D, Yang C N *Phys. Rev.* **105** 1671 (1957)
19. Okun' L B *Slaboe Vzaimodeĭstvie Élementarnykh Chastits* (Weak Interaction of Elementary Particles) (Moscow: Fizmatgiz, 1963) [Translated into English (Oxford, New York: Pergamon Press, 1965)]
20. Christenson J H et al. *Phys. Rev. Lett.* **13** 138 (1964)
21. Sakharov A D *Pis'ma Zh. Eksp. Teor. Fiz.* **5** 32 (1967) [*JETP Lett.* **5** 24 (1967)]
22. Kuz'min V A *Pis'ma Zh. Eksp. Teor. Fiz.* **12** 335 (1970) [*JETP Lett.* **12** 228 (1970)]
23. Kuzmin V A, Rubakov V A, Shaposhnikov M E *Phys. Lett. B* **155** 36 (1985)
24. Rubakov V A, Shaposhnikov M E *Usp. Fiz. Nauk* **166** 493 (1996) [*Phys. Usp.* **39** 461 (1996)]
25. Kobayashi M, Maskawa K *Prog. Theor. Phys.* **49** 652 (1973)
26. Wolfenstein L *Phys. Rev. Lett.* **51** 1945 (1983)
27. Schmidtler M, Schubert K R *Z. Phys. C* **53** 347 (1992)
28. Buras A J, Lautenbacher M E, Ostermaier G *Phys. Rev. D* **50** 3433 (1994)

29. Barnett R M et al. (Particle Data Group) *Phys. Rev. D* **54** 1 (1996)
30. Brom J-M et al. (HRS Collab.) *Phys. Lett. B* **195** 301 (1987); Ash W W et al. (MAC Collab.) *Phys. Rev. Lett.* **58** 640 (1987)
31. Albrecht H et al. (ARGUS Collab.) *Phys. Lett. B* **318** 397 (1993)
32. Gibbons L K *Plenary Talk at the 28th Int. Conf. on High Energy Phys.* (Poland, Warsaw: July 1996)
33. Albrecht H et al. (ARGUS Collab.) *Phys. Lett. B* **197** 452 (1987); *B* **229** 175 (1989)
34. Voloshin M B, Shifman M A *Yad. Fiz.* **45** 463 (1987) [*Sov. J. Nucl. Phys.* **45** 292 (1987)]; **47** 801 (1988) [**47** 511 (1988)]
35. Isgur N, Wise M B *Phys. Lett. B* **232** 113 (1989); *B* **237** 527 (1990); Neubert M *Phys. Rep.* **245** 259 (1994)
36. Albrecht H et al. (ARGUS Collab.) *Phys. Lett. B* **234** 409 (1990); Fulton R et al. (CLEO Collab.) *Phys. Rev. Lett.* **64** 16 (1990)
37. Alexander J P et al. (CLEO Collab.) *Phys. Rev. Lett.* **77** 5000 (1996)
38. Vysotskiĭ M I *Yad. Fiz.* **31** 1535 (1980) [*Sov. J. Nucl. Phys.* **31** 797 (1980)]
39. Buras A J, Jamin M, Weisz P H *Nucl. Phys. B* **347** 491 (1990)
40. (UA1 Collab.) *Talk at the XXII Int. Conf. on High Energy Phys.* (Leipzig, 1984)
41. Albrecht H et al. (ARGUS Collab.) *Phys. Lett. B* **192** 245 (1987)
42. Tipton P *Plenary Talk at the 28th Int. Conf. on High Energy Phys.* (Poland, Warsaw: July 1996)
43. Buras A J *Plenary Talk at the 28th Int. Conf. on High Energy Phys.* (Poland, Warsaw: July 1996)
44. Ali A, Giudice G F, Mannel T *Z. Phys. C* **67** 417 (1995)
45. Gronau M, London D *Phys. Rev. Lett.* **65** 3381 (1990); *Phys. Lett. B* **253** 483 (1991)
46. Gavela M B et al. *Mod. Phys. Lett. A* **9** 795 (1994)
47. Grossman Y, Nir Y, Rattazi R, Preprint CERN-TH/96-368 (1996); Gronau M, London D *Phys. Rev. D* **55** 2845 (1997)
48. Balagura V V et al. *Nucl. Instrum. Methods A* **379** 404 (1996); Lohse T et al. "HERA-B Design Report" DESY-PRC 95/01 (1995)
49. Huffman B T *Nucl. Instrum. Methods A* **384** 79 (1996)
50. Kasper P, http://xxx.lanl.gov, hep-ex/9803012 (1998)
51. Kopp S E *Nucl. Instrum. Methods A* **384** 61 (1996)