Prospects of search for *CP* nonconservation in beauty hadrons

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The possibility of observing various *CP*-odd effects in *B* particles in the standard model is analyzed. Principal attention is paid to e^+e^- collisions. The statistics required is practically independent of the specific value of $|V_{ub}|/|V_{cb}|$. The most promising are the KM-forbidden $b\to u$ decays $B_d^0\to\pi^+\pi^-$, $\pi^\pm\rho^\mp$, and $\pi^\pm a^\mp$, where about $3\cdot10^7\,\Upsilon(4S)$ resonances are needed to observe *CP* asymmetry on the 3σ level at quite moderate values of the parameters. Simple dependences of the asymmetries and of the required statistics on the specific values of the employed hadron parameters (f_B, B_K, ...) are given. Other *CP*-odd asymmetries in *B* particles are analyzed.

1. INTRODUCTION

Explanation of the *CP*-nonconservation phenomenon is not merely a fundamental aspect of the standard model (SM), but is in fact one of the most critical points where many modern theoretical concepts must be verified. From the viewpoint of canonical SM premises, beauty particles may turn out to be the only promising proving ground for the study of *CP*-odd effects apart from *K* mesons. An important advantage is here the large magnitude of the expected effects in certain decays.

Study of *CP* nonconservation in *B* particles occupies a prominent place in programs of future experiments on both hadronic and e^+e^- collisions. It is tremendously important at present to plan a search strategy for this phenomenon and develop an experimental technique. These questions are already the subject of dozens of studies (see, e.g., the reviews[1-7]). A qualitatively new situation obtains now, in which it is possible, in the context of the SM, to make sufficiently reliable predictions of expected effects in a number of cases, and more or less specific experimental requirements can be formulated (see also Refs. 5–10). The possibility of obtaining quantitative predictions is due primarily to the accumulated experimental data, particularly on decay of beauty particles. Of crucial importance here is the large B_d^0–$\bar B_d^0$ mixing observed by the ARGUS group[11] and confirmed by the CLEO experiment.[12] The experiment not only limits the ranges of the SM parameters, but permits a critical selection of various approaches to the calculation of the characteristics of heavy hadrons. It is particularly important, as will be explained in detail below, that estimates of the number of events needed to observe *CP* nonconservation are quite stable with respect to the permissible variations of the SM parameters.

Significant advantages are offered by measurements of the temporal distributions *B*-meson decays.[13,14] Moreover, it is precisely these measurements that offer promises of finding *CP*-invariance violation for B_S^0 mesons, and also for B_d^0 mesons produced in the $\Upsilon(4S)$ resonance.

The present paper is devoted to a discussion of the prospects of searching for *CP* nonconservation in beauty particles. Principal attention is paid to e^+e^- collisions. The focus is on presently planned high-luminosity facilities, especially the so-called *B* factories.[4,15]

Our outline is the following. In Sec. 2 we describe a graphic method of representing in the SM model the mixing parameters that determine the *B*-particle physics, and present the corresponding results of the analysis and the dependence of the *CP*-odd phases on the employed purely hadronic quantities. Section 3 is devoted to neutral *B*-mesons, where the largest effects are expected, and to a more definite interpretation in terms of the SM parameters. In Sec. 4 we describe briefly the picture of the expected *CP*-odd effects in which no B^0–$\bar B^0$ mixing is assumed. In Sec. 5 are given estimates of the necessary statistics of a number of the most promising decays: it turns out to be practically independent of $|V_{ub}|/|V_{cb}|$. The Conclusion summarizes our estimated prospects of searching for SM *CP* violation in beauty particles.

2. QUARK MIXING PARAMETERS IN THE SM AND THE UNITARITY TRIANGLE

It is known that *CP* violation in the SM is due to the presence of a nontrivial phase in the Kobayashi–Maskawa (KM) matrix. Particularly convenient for the examination of *CP* violation in beauty hadrons is the simple method,[7] independent of the parametrization, of geometrically mapping the V_{ij} phases. This method uses one of the *V* unitarity conditions, in the form

$$V_{ub}^*V_{ud}+V_{cb}^*V_{cd}+V_{tb}^*V_{td}=0; \tag{1}$$

$V_{qb}^*V_{qd}$, as vectors on a complex plane, form a closed triangle (see Fig. 1a). Different parametrizations of the matrix *V* correspond here only to different rotations of one and the same triangle. It is important that many properties of beauty particles have a simple geometric interpretation in terms of this "unitarity triangle" (UT). Thus, all the combinations of the V_{ij} phases that determine the *CP* nonconservation effects are angles of the UT or very simply related to them. The described triangle permits thus a graphic representation of the necessary *CP*-odd phases.

The side *AB* of the UT is known relatively reliably: $|V_{cd}|\approx|V_{us}|=\sin\theta_c\approx0.22$, and $|V_{cb}|\approx0.049$ (Ref. 16). Recall that

$$|V_{cb}|^2\propto(z_c\tau_B(1+R))^{-1},\quad R=\frac{\Gamma_{sl}(b\to u)}{\Gamma_{sl}(b\to c)}\simeq2.1\left|\frac{V_{ub}}{V_{cb}}\right|^2, \tag{2}$$

where Γ_{sl} is the semileptonic-decay width.

The side *AC* is connected with the KM amplitude of the forbidden $b\to u$ transition. Normalizing the UT sides to the known length *AB*, we get

$$\frac{|AC|}{|AB|}=\frac{|V_{ub}|}{|V_{cb}|}\frac{1}{\operatorname{tg}\theta_c}\approx(10R)^{1/2}. \tag{3}$$

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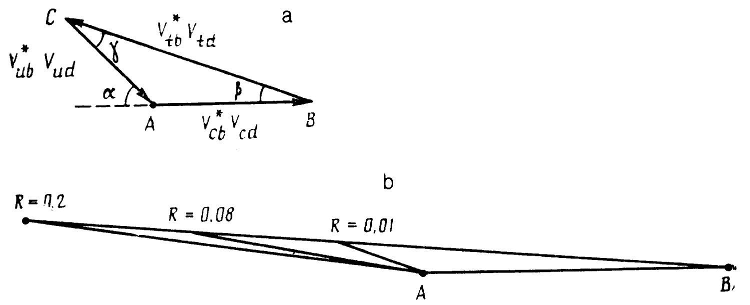

FIG. 1.

The side BC is due to B^0_d–$\bar{B}^0_d$ mixing. Knowing the t-quark mass m_t and the constant f_B we can express $|BC|$ in terms of the experimental value of the parameter $x_{B_d} = (\Delta m/\Gamma)_{B_d} \approx 0.7$ (Refs. 11,12). Note that the unitarity triangle for $R \approx 0.1$ ($|V_{ub}| \approx \sin\theta_c \cdot |V_{cb}|$) is isosceles.

The experimental data on V_{ub} are quite scanty. The usually cited upper bound is $R \lesssim 0.005$–0.5 (e.g., Refs. 16 and 17). The bound $R \lesssim 0.05$ follows from an analysis of lepton spectra, but is not strongly model-dependent. The bound $R < 0.2$–0.5 is obtained by counting the number of c-quarks in B-particle decays.[16]

Information on the CP-odd phase (the UT angles) can actually be obtained only by analyzing CP-violation effects in K decays. Let us formulate the consequences[7,8] for the V_{ij} elements that follow from comparison of the SM predictions for x_{B_d} and the known parameter ε_K at the "standard" values of the parameters $x_{B_d} = 0.7$, $f_B = 100$ MeV, $B_K = B_B = 1$, $z_c\, m_b^5 = 0.39\cdot(5\ \text{MeV})$,[5] $R \gtrsim 10^{-3}$, where z_c is the factor of the suppression of the decay $b \to ce\nu$ due to the c-quark mass and radiative corrections, f_B is the B-meson axial constant, and B_K and B_d are factors describing the possible differences between the matrix elements of the K-$\bar{K}$ and B-$\bar{B}$ mixings from the so-called "vacuum run."

1. The angles α, β, and γ all lie in the first quadrant, $0 < \alpha, \beta, \gamma < \pi/2$, i.e., the UT actually agrees with the one shown in Fig. 1a.

2. The angle β, as well as the angles α and γ for $R \gtrsim 10^{-2}$, should be small, so that the triangle is close to degenerate.

3. The angle β in the UT does not depend on V_{ub}: it hardly varies in the entire interval of the possible values of R (Refs. 8 and 10). For the hadron parameter employed, $\beta \approx 0.085 \approx 5°$. The real form of the UT at $R = 0.2$, 0.08, and 0.01 is shown in Fig. 1b.

Let us discuss briefly the uncertainties connected with the estimate of the UT angles. Absent direct measurements of the $b \to u$ transitions,[1)] the lower bound of R, and hence of the form of the UT, follows only from the requirement $m_t \lesssim 200$ GeV (Ref. 17) ($x_{B_d} \propto m_t^2 \zeta(m_t^2/m_W^2)|BC|^2$, where $\zeta(m_t^2/m_W^2)$ is a known function (see, e.g., Ref. 8), and corresponds literally to $R \gtrsim 0.01$. The role of this bound, however, depends substantially on the value of f_B. Thus, if actually $f_B \gtrsim 130$ MeV, than for the extremely small $R \ll 0.01$ the UT may no longer be acute, and the angles α and γ can even exceed $\pi/2$ somewhat. The angle β is always small at reasonable values of f_B and B_K.

We emphasize that the stability of β does not by itself mean that it can be exactly predicted, inasmuch as the uncertainty of β involves the accuracy of the theoretical calculations of ε_K. It is easy to show that the angle β (and hence also α and γ for $R \gtrsim 10^{-2}$, when all three angles are small) has the following dependence on the parameters[2)]:

$$\beta \sim \frac{B_B f_B^2}{x_{B_d}} B_K^{-1} \tau_B^2 B_{sl}^{-1} (z_c m_b^5). \tag{4}$$

Let us ascertain the cause of the stability of β. The expression for ε_K contains two terms having different dependences of V_{ij} and m_t (see, e.g., Ref. 8). The first term is initially proportional to $[\ln(m_t^2/m_c^2) - 1 - H]$, where H is a known numerical factor and is actually practically independent of m_t if $m_t \gtrsim m_W$, whereas the second is proportional to m_t^2, and its dependence on m_t is identical with the Δm_B dependence. All the V_{ij} combinations can be expressed in terms of the UT parameters, using for the common normalization the absolute value of $|V_{ij}|$ determined from the lifetime τ_B. We obtain thus

$$\varepsilon_K \approx \frac{a\tau_B^{-1} h_S + b\tau_B^{-2} x_{B_d} \sin 2\beta}{1+R},$$

where a and b are constants, h_S is the height of the UT drawn from the vertex C (see Fig. 2). If x_{B_d} is appreciable, the second term predominates, and it is this which makes β independent of V_{ub} (m_t). We emphasize that this stability turns out to be even much higher because of the additional cancellation of the first term by the denominator. The same equation leads also to the relation (4).

To conclude this section, we note that the prediction for $(\varepsilon'/\varepsilon)_K$ takes in the SM the form[3)]

$$(\varepsilon'/\varepsilon)_K \approx 2.0\cdot 10^{-2} \frac{(10R)^{1/2}}{1+R} \sin\alpha. \tag{5}$$

It is easily seen that $(\varepsilon'/\varepsilon)_K \sim h_s$. Therefore $(\varepsilon'/\varepsilon)_K$ decreases slowly with decrease of R. The mean value $(\varepsilon'/\varepsilon)_K \approx 2.8\cdot 10^{-3}$ for $R \approx 0.05$ agrees well with the CERN NA31 data.[17,18]

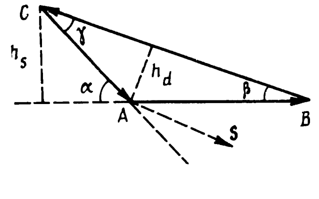

FIG. 2.

3. *CP*-ODD ASYMMETRIES IN NEUTRAL *B* MESONS

a) "Superweak" *CP* nonconservation

In this case different phases of the dispersion ($M_{B\bar{B}}$) and absorption ($\Gamma_{B\bar{B}}$) parts of the total $B^0\to\bar{B}^0$ transition lead, for example, to charge asymmetry of dileptons of like sign[19]:

$$A_B=\frac{N(B^0\bar{B}^0\to l^+l^+)-N(B^0\bar{B}^0\to l^-l^-)}{N(B^0\bar{B}^0\to l^+l^+)+N(B^0\bar{B}^0\to l^-l^-)}. \tag{6}$$

The "superweak" *CP* nonconservation is expressed in terms of the parameter $\bar{\varepsilon}_B$ of the B^0 and $\bar{B}^0$ mixing:

$$A_B=\frac{4\,\mathrm{Re}\,\bar{\varepsilon}_B}{1+|\bar{\varepsilon}_B|^2}\approx-\mathrm{Im}\frac{\Gamma_{B\bar{B}}}{M_{B\bar{B}}}. \tag{7}$$

In the SM, unfortunately, *CP*-odd mixing of heavy neutral mesons is negligibly small. The main cause of the suppression is the smallness of $\Gamma_{B\bar{B}}$ compared with $M_{B\bar{B}}$:

$$\left|\frac{\Gamma_{B\bar{B}}}{M_{B\bar{B}}}\right|\sim\frac{3\pi}{2}\frac{m_b^2}{m_t^2\zeta(m_t^2/m_W^2)}. \tag{8}$$

In the SM the phase difference is additionally suppressed by the factor $\sim m_c^2/m_b^2$. The charge asymmetry, say for $R=0.05$, is as a result

$$A_{B_d}\approx-10^{-4},\quad A_{B_S}\approx10^{-5}.$$

It is interesting that in the SM the quantity A is expressed in terms of the UT area S. Calculation using the simplest quark diagrams yields

$$\begin{aligned}A_{B_d}&\approx-10\left(\frac{f_B}{100\ \mathrm{MeV}}\right)^2\frac{S}{x_{B_d}}\\&\approx-\frac{1.2\cdot10^{-3}}{1+R}\left(\frac{f_B}{100\ \mathrm{MeV}}\right)^2\frac{\tilde{S}}{x_{B_d}}\\A_{B_S}&\approx10\left(\frac{f_{B_S}}{100\ \mathrm{MeV}}\right)^2\frac{S}{x_{B_S}}\\&\approx\frac{1.2\cdot10^{-3}}{1+R}\left(\frac{f_{B_S}}{100\ \mathrm{MeV}}\right)^2\frac{\tilde{S}}{x_{B_S}},\end{aligned} \tag{9}$$

where $\tilde{S}$ is the area of the UT normalized by the condition that the side AB is equal to unity. Thus, the following relation should hold in the SM:

$$\frac{A_{B_d}}{A_{B_S}}=-\frac{x_{B_S}}{x_{B_d}}\left(\frac{f_{B_d}}{f_{B_S}}\right)^2. \tag{10}$$

According to (9), A_{Bd} falls off somewhat when R is decreased. More than 10^{11} $B\bar{B}$ pairs are needed to observe such an asymmetry.

It is important to emphasize that the smallness of A_B is inevitable in the SM. In fact, from (8) we have $|\Gamma_{B\bar{B}}/M_{B\bar{B}}|\lesssim2\cdot10^{-2}$; in addition, *CP*-odd effects are always proportional to a small phase $\beta\lesssim0.1$. The main claim made in Ref. 20 to a standard calculation of A_{B_d} and A_{B_S} might concern only the extent to which the simplest quark diagrams accord with the value of $\Gamma_{B\bar{B}}$ (particularly for the $c\bar{c}$ intermediate state, and accordingly actually suppress A_B by cancelling the contributions of the $c\bar{c}$, $c\bar{u}$, $u\bar{c}$, $u\bar{u}$ channels. Recall, however, that this suppression is approximately $8/3m_c^2/m_b^2\approx0.25$ even for the quark diagrams. Therefore even total absence of such a suppression would increase the asymmetry by only four times. In particular, if the contributions of the channels with c quarks to $\Gamma_{B\bar{B}}$ is omitted altogether, we have

$$\begin{aligned}A_{B_d}&\approx-\frac{3\pi}{2}\frac{m_b^2}{m_t^2\zeta(m_t^2/m_W^2)}\mathrm{Im}\left(\frac{V_{ub}^*V_{ud}}{V_{tb}^*V_{td}}\right)^2\\&\approx-\frac{5\cdot10^{-3}}{1+R}\left(\frac{f_B}{100\ \mathrm{MeV}}\right)^2\frac{\tilde{S}_c}{x_{B_d}},\end{aligned}$$

where S_C ($\tilde{S}_C$) is the area of the triangular part of the UT with vertices at the points C and A and with height h_d to the base. This corresponds to an increase of A_{B_d}, even for an isosceles UT, by only a factor of 2.

It was assumed in this analysis that the inclusive quantities such as the differences of the total widths are correctly described by quark diagrams. The corresponding QCD corrections were estimated in Ref. 21 and turned out to be extremely small. It is therefore not very probable that the asymmetry of A_B in the SM could exceed $O(10^{-4})$. At the same time, it is possible that their exact values do not agree literally with the estimates (9).

b) "Milliweak" *CP* nonconservation

The most promising for the search of *CP* nonconservation are effects not directly connected with *CP*-invariance violation in B^0–$\bar{B}^0$ mixing. For the final states into which both B^0 and $\bar{B}^0$ can decay, the widths of the $B^0\to f$ and $\bar{B}^0\to f$ resonances are given by (see Refs. 9 and 13 for details)

$$\begin{aligned}\Gamma(B^0\to f)&\propto1+|\rho_f|^2+\frac{1-|\rho_f|^2}{1+x^2}+\frac{2x}{1+x^2}\mathrm{Im}\left(\frac{q}{p}\rho_f\right),\\\Gamma(\bar{B}^0\to\bar{f})&\propto1+|\rho_f|^2+\frac{1-|\rho_f|^2}{1+x^2}-\frac{2x}{1+x^2}\mathrm{Im}\left(\frac{q}{p}\rho_f'^*\right),\end{aligned} \tag{11}$$

where

$$\rho_f=\frac{A(\bar{B}^0\to f)}{A(B^0\to f)},\quad\rho_f'=\frac{A(B^0\to\bar{f})}{A(\bar{B}^0\to\bar{f})},\quad\frac{q}{p}=\frac{1+\bar{\varepsilon}_B}{1-\bar{\varepsilon}_B}. \tag{12}$$

Here $A(B^2\to\overset{(-)}{f}$ and $A(\bar{B}^0\to\overset{(-)}{f})$ denote the amplitudes of the direct transitions $B^0\to\overset{(-)}{f}$ and $\bar{B}^0\to\overset{(-)}{f}$). It is assumed in Eq. (11) that $|A(B^0\to f)|\approx|A(\bar{B}^0\to f)|$ and $|A(B^0\to\bar{f})|\approx|A(\bar{B}^0\to f)|$. We put here and hereafter $|q/p|=1$. We emphasize that even though $|\rho_f|\approx|\rho_f|$, the relation $\rho_f'=\rho_f^*$ may be violated if the phases generated by the strong interaction in the final state (the FSI phases) are different in the amplitudes of the transitions $B^0\to f$ and $\bar{B}^0\to f$. In the absence of these phases, the *CP* asymmetry is equal to

$$a=\frac{\Gamma(B^0\to f)-\Gamma(\bar{B}_0\to\bar{f})}{\Gamma(B^0\to f)+\Gamma(\bar{B}^0\to\bar{f})}\approx\frac{2x\,\mathrm{Im}[(q/p)\rho_f]}{(2+x^2)+x^2|\rho_f|^2}. \tag{13}$$

Note that if $x\gg1$ the value of a decreases because of the averaging of the effect over the $B^0\rightleftarrows\bar{B}^0$ oscillations during the evolution of the initial state. The decrease is very substantial in B_S^0 mesons, for which the mixing parameter is $x_{B_S}>7$. Indeed, the distribution of the decays in time takes the form

$$\frac{dN[B^0(\bar{B}^0)\to f(\bar{f})]}{dt}$$

$$\sim e^{-\Gamma t}\Big[(1+\cos(t\Delta m))+(1-\cos(t\Delta m))|\rho_f|^2+(-)$$

$$+(-)2\sin(t\Delta m)\,\mathrm{Im}\Big(\frac{q}{p}\rho_f^{(\prime *)}\Big)\Big]. \qquad (14)$$

Thus, to investigate the *CP* odd effects at $\Delta m \gg \Gamma$ we must study the time dependences of the number of decays,[13,14] since a strong cancelation takes place in the integral effects. Such measurements permit, in principle, separate determination of Δm, Γ, and $|\rho_f|$ as well as the two phases $(q/p)\rho_f$ and $(q/p)\rho_f'^*$ that determine separately both the *FSI* complexities and the *CP* nonconservation.

Since the *FSI* phases are unknown, the possibility of predicting *CP*-odd effects decreases substantially. In addition, there are uncertainties in the hadronic matrix elements contained in the widths of the decays $B^0\to f$ and $\bar{B}^0\to f$. These difficulties are absent if f is a state having a definite *CP* parity η_f. In this case $|\rho_f|\approx|\rho_f'|\approx 1$, $\rho_f'=\rho_f^{-1}\approx\rho_f^*$, and the *CP*-odd effects are determined by a single phase Φ:

$$(q/p)\rho_f \approx -\eta_f e^{2i\Phi}. \qquad (15)$$

The phase Φ depends only on the V_{ij} matrix elements that determine the $B^0\to f$ decay and the $B^0\to\bar{B}^0$ transition, but not on a specific final state. The asymmetry (13) for such decays is equal to

$$a\approx -\eta_f\frac{x}{1+x^2}\sin 2\Phi. \qquad (16)$$

In the SM, noticeable *CP*-odd asymmetries are expected for the following three principal types of decay[4]:

1) KM-allowed decays of B_d on account of the $b\to c\bar{c}s$ transition, for example, $B_d\to J/\Psi + K_s$ (or Cabibbo-forbidden $b\to c\bar{c}d$ decays of type $B_d\to D^+D^-$);

2) KM-forbidden decays of B_d via the $b\to u\bar{u}d$ channel, of the type $B_d\to\pi^+\pi^-$;

3) KM-forbidden decays of B_S via the transition $b\to u\bar{u}d$, for example $B_S\to\pi^0K_s$.

It is easy to verify[7] that the phases Φ for these decays coincide precisely with the UT angles:

$$\begin{array}{llll} 1) & B_d{}^0: & b\to c\bar{c}s\ (b\to c\bar{c}d), & \Phi=-\beta. \\ 2) & B_d{}^0: & b\to u\bar{u}d, & \Phi=\gamma. \\ 3) & B_S{}^0: & b\to u\bar{u}d, & \Phi=\alpha, \end{array} \qquad (17)$$

see Fig. 1. The phase Φ for $b\to c\bar{c}s$ (and $b\to c\bar{c}d$) decays of B_S^0 is extremely small:

$$\Phi\approx\sin^2\theta_C\cdot(10R)^{1/2}\sin\alpha.$$

The general final states for B_d^0 and $\bar{B}_d^0$ can contain also a charmed quark, if the decay of B_d^0 or $\bar{B}_d^0$ proceeds via different quark transitions, for example $B_d^0\to D^-\pi^+$ $(\bar{b}\to\bar{c}ud)$ and $\bar{B}_d^0\to D^-\pi^+$ $(b\to u\bar{c}d)$, or $B_d^0\to\bar{D}^0K_S$ $(\bar{b}\to\bar{c}u\bar{s})$ and $\bar{B}_d^0\to\bar{D}^0K_S$ $(b\to u\bar{c}s)$. The *CP*-odd phase difference 2Φ is given for most B_d^0 decays by an expression of the form

$$2\Phi_c\approx\arg\{(V_{tb}{}^*V_{td})^2\cdot V_{cb}V_{cd}{}^*\cdot V_{ub}V_{ud}{}^*\}, \qquad (18)$$

i.e., Φ_c is equal to the angle between the external bisector of the angle *CAB*, **s**, and the side *BC* of the unitarity triangle: $2\Phi_c\approx\alpha-\beta$, see Fig. 2. For $R\approx 0.1$ the asymmetry in such decays vanishes; it can become noticeable only for small ($\lesssim 0.01$) and large ($\gtrsim 0.2$) values of R. The corresponding *CP*-odd phase $2\Phi_c$ for the analogous decays of B_S^0 is equal to α.

Thus, a number of B^0-meson decays can have a large *CP* asymmetry, on the order of 0.2–0.5.

Let us discuss briefly the dependence of the described effects on the unknown ratio R. The number of B mesons needed to observe *CP*-odd asymmetry is statistically proportional to $N_B\sim a^{-2}\mathrm{Br}(B\to f)^{-1}$, where Br is the branching ratio. Therefore, as follows from Fig. 2, the number of B mesons needed at $\alpha,\beta,\gamma\ll 1$ for *both* types of B_d^0 decay (17) is inversely proportional to the square of the altitude h_d of the UT: $N_{Bd}\propto|h_d|^{-2}$. Thus, when the stability of β is taken into account, the number N_{B_d} is practically independent of R. In particular, for KM-forbidden decays of type $B_d\to\pi^+\pi^-$ the decrease of the probability with decrease of R is completely compensated by the increase of the asymmetry.

For KM-forbidden B_S^0 decays, the statistical significance is determined by the square of the altitude h_S, i.e., N_{B_S} increases slowly with increase of R:

$$N_{BS}\propto 1/[1+(10R)^{1/2}]^2. \qquad (19)$$

The numerical value of B_{B_S} is tripled when R is decreased from 0.2 to 0.015. This stability of the *CP*-odd effects permits the probability of their observation to be predicted more definitely and allows a theoretical interpretation of the results.

The dependence of N_B on the hadronic matrix elements in $|V_{cb}|^2$ is given by Eq. (4):

$$N_B\sim B_K{}^2f_B{}^{-4}\tau_B{}^{-4}B_{sl}{}^{-2}. \qquad (20)$$

It must be emphasized that at $R\ll 0.01$, when the angles α and γ become large, the value of N_B in KM-forbidden decays is increased by the additional factors, $\cos^{-2}\gamma$ or $\cos^{-2}\alpha$, which were left out by us above. If $\gamma=\pi/2$ or $\alpha=\pi/2$ the corresponding asymmetries vanish altogether.

A number of decays that do not lead to states with definite *CP* parity are also promising. They can have arbitrary $|\rho_f|\approx|\rho_f'|$. The phases of the ratios of ρ_f and ρ_f' are, strictly speaking, also unknown. Denoting by Δ_+ the difference between the corresponding *CP*-even *FSI* phases, and by Δ_- the *CP*-odd phase of the product of the KM-matrix elements, we get

$$\mathrm{Im}\Big(\frac{q}{p}\rho_f\Big)\approx|\rho_f|\sin(\Delta_++\Delta_-),$$

$$-\mathrm{Im}\Big(\frac{q}{p}\rho_f{}'^*\Big)\approx|\rho_f|\sin(\Delta_+-\Delta_-). \qquad (21)$$

Equations (14) show that, in principle, an investigation of the time distributions of the decays in f and in $\bar{f}$ permits an experimental determination of both the ratio $|\rho_f|$ of the absolute values of the $B^0\to f$ and $\bar{B}^0\to f$ decays and the difference Δ_+ of their *FSI* phases, as well as the *CP*-nonconservation effect — the difference Δ_- between the *CP*-odd phase and 0 or π (strictly speaking, Δ_+ and Δ_- are non-uniquely defined, accurate to substitutions of the type $\Delta_-\to\pm(\pi/2-\Delta_+)$, $\Delta_+\to(\pi/2\mp\Delta_-)$). It turns out here[7] that Δ_- for B_d^0 mesons can be separated without substantially decreasing the statistical significance, in view of the unknown value of Δ_+, at least for small *FSI* phases.[5)]

Additional information on the relative values and phases of the $B^0 \to f$ and $\bar{B}^0 \to f$ transition amplitudes might be obtained from decays of coherently created $B^0\bar{B}^0$ pairs, one of which is registered by decay into a state g with known *CP*-parity η_g, for example

$$\Upsilon(4S) \to B^0\bar{B}^0 \to \underbrace{(\pi^+\pi^-)}_{g} + \underbrace{(\pi^+\rho^-)}_{f}. \tag{22}$$

Even in the absence of real mixing of B^0 and $\bar{B}^0$, the interpretation of the amplitudes of the $B^0 \to f$ and $\bar{B}^0 \to f$ transitions in such decays is important. Neglecting *CP* nonconservation, the branching ratio of such events is

$$\mathrm{Br}(B^0\bar{B}^0 \to g+f)$$
$$\approx \mathrm{Br}(B\to g)[\mathrm{Br}(B^0\to f)\mathrm{Br}(\bar{B}^0\to f)]^{1/2}(|\rho_f|+1/|\rho_f|+2\eta_g\cos\Delta_+), \tag{23}$$

where $\Delta_+ = \arg(A(\bar{B}^0\to f)/A(B^0\to f))$ (the KM factors have been left out). Of greatest interest in a search for *CP* nonconservation are decays for which $|\rho_f| \sim 1$; in this case the probability (23) depends strongly on the difference Δ_+ of the *FSI* phases. Unfortunately, the decay probabilities of both B mesons via such channels amount to only 10^{-7} although, here too, it is possible to take jointly into account the results of searches for decays with different states g.

One of the main difficulties of investigating *CP* nonconservation in B particles is the use of few-particle decay modes, which have a low probability. A change to more inclusive asymmetries should decrease the effect strongly (see, e.g., Ref. 7 for details). Of course, the results depend radically on the choice of the states taken into account. One can, however, estimate this suppression for the case when the summation is over all final states for a definite quark channel. For many channel this means in fact calculation of the mean *CP* parity $\langle\eta\rangle$ of the final state. Using the simplest quark diagrams to calculate the corresponding inclusive characteristics,[21] we obtain

$$\langle\eta\rangle \approx \varkappa \frac{8\pi^2 f_B^2}{m_b^2}, \tag{24}$$

where $\varkappa$ is a factor that takes into account the corrections for the quark masses and the QCD corrections. For channels having, say, a charm of definite sign (of type $B^0 \to D^-\pi^+$) the mean *CP* parity is zero, but the corresponding suppression factor due to averaging can be similarly calculated for any decay. We use for this factor the same symbol $\langle\eta\rangle$, recognizing that such a terminology is somewhat incorrect. The corresponding estimates are:

$\langle\eta\rangle$	B_d^0	B_S^0
without c-quarks	0.03	0.05
one c-quark	0.05	0.09
two c-quarks	0.11	0.19

(25)

Actually $\langle\eta\rangle = 0$ for the most interesting decays into a state with strangeness, $b\to c\bar{c}s$ for B_d^0 and $b\to u\bar{u}d$ for B_S^0, since these states are not common to B^0 and $\bar{B}^0$ from the standpoint of the quark makeup, because of the opposite strangeness in B^0 and $\bar{B}^0$ decay. It is actually necessary here to know the value of $\langle\eta\rangle$ over the states containing, say, K_S (the factor $\langle\eta\rangle$ for K_L is exactly equal, but of opposite sign). An estimate of such a characteristic is extremely difficult. It is natural to assume that, owing to the possible cascades of the type $B^0 \to K^{*+} + X \to K^0\pi^+ + X$, which actually "mark" the flavor of the initial B meson with the sign of the pion, the value of $\langle\eta\rangle$ is in this case smaller than estimated in (25). If, however, the experimental conditions permit effective exclusion of such "tagging" cascades, it can be assumed that $\langle\eta\rangle$ will be of the order given in (25).

Note that in principle it is possible to determine $\langle\eta\rangle$ in $\Upsilon(4S)$. In reactions of type (22) the probability of decay into $g+f$ yields the fraction of the states in f having a *CP* parity equal to $-\eta_g$. Indeed, if *CP* is conserved in the reactions (22), the *CP* parities of the decay products of both B mesons should be opposite.

It is of interest to track the origin of the additional suppression of the charge asymmetry A compared with the "semi-inclusive" asymmetries, where account is taken of all the decays generated by one quark transition, say $b\to u\bar{u}d$ (asymmetry $\sim -5\cdot10^{-3}$) or $b\to c\bar{c}d$ (asymmetry $\sim 1.5\cdot10^{-2}$) for B_d^0 mesons.

First of all, allowance for semileptonic decays, without changing the width difference, increases greatly the total width, thereby "diluting" the asymmetry substantially. The asymmetry is similarly decreased also by allowed hadron channels that lead to different final states for B^0 and $\bar{B}^0$ (for example, $b\to c\bar{u}d$ or the channel $b\to c\bar{c}s$, where the noticeable *CP* asymmetries in certain modes with K_S or K_L mesons cancel one another completely when taken jointly into account. This suppresses *CP*-odd effects by a factor of order $\sin^2\theta_c \simeq 1/20$.

Next, a noticeable cancellation of the *C*-odd asymmetry takes place in the SM for summation over different quark channels in which c quarks are replaced by u quarks. Thus, for $R\approx0.1$, the asymmetries in decays to states containing one c-quark or on c-antiquark vanish at $R\approx0.1$, so that only the channels $b\to u\bar{u}d$ and $b\to c\bar{c}d$ actually cancel out in this case. In the general case the corresponding turns out to be of the order of[13] $8/3(m_c^2/m_b^2)$. Its origin is obvious - the SM becomes *CP*-invariant at $m_c^2 = m_u^2$, and the inclusive *CP*-odd effects are caused by the difference, due to the quark masses, between the amplitude and phase spaces for decays into light and charmed quarks.

Finally, in accordance with (7), "superweak" *CP* nonconservation is inversely proportional to the B^0-meson mass difference Δm_B. The decrease of the asymmetry at a large mass difference, which is quite substantial for B_S^0, is actually due to the averaging of the effect over the $B^0 \rightleftarrows \bar{B}^0$ oscillations, and can be avoided in a "semi-inclusive" study of actual quark channels by investigating the time dependences of the number of decays.

Wolfenstein[22] has noted that investigation of the decays of both B mesons in reactions (22) affords one more possibility of observing *CP*-nonconservation. Indeed, for $\eta_f = \eta_g$ this process can proceed only with *CP* violation. Its probabilities are expressed in terms of the phases Φ_i [Eqs. (15) and (17)]:

$$\mathrm{Br}(B^0\bar{B}^0 \to f_1 f_2)$$
$$\approx 2\,\mathrm{Br}(B\to f_1)\mathrm{Br}(B\to f_2)\Big\{1-\eta_1\eta_2\cos 2(\Phi_2-\Phi_1) + \eta_1\eta_2\frac{x^2}{1+x^2}\sin 2\Phi_1\cdot\sin 2\Phi_2\Big\} \tag{26}$$

(the probability is half as large for identical f_1 and f_2). We have neglected here the difference between the B^0-mesons [see also the remark following Eq. (23)]. Unfortunately, this probability is extremely small, since we must confine ourselves to rare modes for both B mesons. The expression in the curly brackets of (26) is numerically approximately 0.07 (at $R \approx 0.05$) in decay via different quark channels, and about 0.01 for $b \to c$ and 0.02 for $b \to u$ (at $R \approx 0.05$) in decay via identical channels.

4. *CP*-NONCONSERVATION WITHOUT ASSUMPTION OF $B^0 \rightleftarrows \bar{B}^0$ TRANSITIONS

The partial widths of charge-conjugate processes can be different also for decays to states that are possible only, say, for B but not for $\bar{B}$, for example in charged particles or baryons. This difference requires interference of two amplitudes having different KM phases $\alpha_{1,2}$. It is necessary, here, however, that these amplitudes have also different *CP*-odd *FSI* phases. The asymmetry is then equal to

$$\delta = \frac{\Gamma(B\to f) - \Gamma(\bar{B}\to \bar{f})}{\Gamma(B\to f) + \Gamma(\bar{B}\to \bar{f})}$$
$$= \frac{2|A_1||A_2|}{|A_1|^2+|A_2|^2+2|A_1||A_2|\cos(\alpha_1-\alpha_2)\cos(\delta_1-\delta_2)}$$
$$\times \sin(\alpha_2-\alpha_1)\cdot\sin(\delta_1-\delta_2). \qquad (27)$$

For most decays of interest, the *CP*-odd phase difference $\alpha_2 - \alpha_1$ is determined by the angle α of the unitarity triangle. As to the *CP*-odd phases δ, it is impossible at present to predict their values with any degree of reliability. It is difficult therefore to predict even the sign of the effect; interpretation of the measured effect in terms of the fundamental parameters of the theory also seems problematic. It must be noted, however, that such decays need no tagging and include many modes that can be conveniently recorded.

In the most interesting decays of this type, interference takes place between the doubly suppressed $b \to u\bar{u}s$ transitions and the so-called penguin amplitudes induced by the operator (for $b \to s$ transitions)

$$O_P = c_P \frac{G_F}{2^{1/2}} V_{cb} V_{cs}^* \left(\bar{s}\gamma_\mu(1-\gamma_5)\frac{t^a}{2} b\right) \sum_{q=u,d,s,c} \bar{q}\gamma_\mu \frac{t^a}{2} q,$$
$$c_P \approx -\frac{\alpha_s}{3\pi} \ln \frac{M_W^2}{m_b^2} \approx -0.07. \qquad (28)$$

The point is that the $c\bar{c}$-pair "pickup" processes, or formation of a charm-free final state in the $b \to c\bar{c}s$ transition, which are needed for interference to set in, are strongly suppressed. The overall value of such a suppression is, in the best case, of the order of c_P in amplitude, i.e., corresponds approximately to suppression of $b \to u\bar{u}s$ transitions at reasonable values of R.[7] This leads, in accordance with (27), to the largest effects. Examples of such processes are the decays $B^+ \to K^+ \rho^0$, $\Lambda_B \to \Lambda\pi$ and $B^0 \to K^+\pi^-$. Their probabilities are expected to be of order $\sim O(10^{-5})$.

Reactions with interference of penguin and "tree" amplitudes are sometimes assumed to be more definite from the standpoint of *FSI* phases. The reason is that the penguin operator has an intrinsic absorption part due to real $c\bar{c}$ intermediate states. The corresponding *CP*-even phase δ_P can in principle be calculated. Actually, however, in b decays of typical configuration the $c\bar{c}$-quark energy exceeds the threshold value only insignificantly, so that the absorption part is not determined by the local operator, and δ_P is strongly suppressed and depends on the concrete decay. Its values (without allowance for QCD corrections) can be roughly estimated at $\sim$0.1–0.15. Notwithstanding published arguments that in a number of cases the remaining *FSI* phases are small even for exclusive processes (see, e.g., Ref. 5), there are no grounds, in our opinion, to assume that they are smaller than δ_P. Moreover, the QCD corrections can be estimated in the case of inclusive effects, they turn out to be larger than the phase δ_P, and are of opposite sign. One might attempt to introduce definite cutoffs in the s-quark momentum, excluding the region where the virtual $c\bar{c}$ are located lower than and near the threshold (say, $E_s \lesssim 1.5$ GeV), and by the same token effectively increase δ_P, but such a cutoff is actually difficult to effect; in addition, it can be accompanied by extra phases connected with the form factors.

The phase δ_P is somewhat larger for "penguins" generated by $b \to u\bar{u}d$ transitions, but the corresponding amplitudes are very small and difficult to separate from the "tree" processes, so that here, too, the theoretical-prediction possibility seems doubtful.

We note finally that in any case one can expect large *FSI* phases in color-suppressed decays.

Thus, although considerable *CP*-odd asymmetries, up to 10–20%, are possible in a number of decays discussed in the present section, they do not lend themselves to unambiguous predictions and interpretation. Different modes can therefore not be combined without a substantial loss of the effect. Analysis shows that inclusive asymmetries of this type should either vanish altogether, or amount to less than one percent at a probability not more than $5\cdot 10^{-3}$.

5. NUMERICAL ESTIMATES

In spite of the potentially large effects, investigation of *CP* nonconservation in B particles is a very complicated experimental task. A general strategy for its search is at present more or less clear for e^+e^- collisions, and we confine ourselves mainly to this case. Analysis shows[7] that threshold machines and Z factories have here approximately equal capabilities at equal luminosity. Therefore, aiming at realistically discussed projects, we describe the expected effects for e^+e^- collisions in $\Upsilon(4S)$ resonance.

Investigation of *CP* nonconservation that appears in B^0 mesons as a result of $B^0 \to f$ and $B^0 \to \bar{B}^0 \to f$ interference, calls for tagging the B mesons by decays of the second B particle. It is known, however, that for the C-odd $B^0\bar{B}^0$ state the integral asymmetries of the type

$$a_- = \frac{N(l^+X, f) - N(l^-X, \bar{f})}{N(l^+X, f) + N(l^-X, \bar{f})}$$

vanish because of the antisymmetry of the interference term to the permutation $t_l \leftrightarrow t_f$ (t_l and t_f are the times elapsed from the creation of the $B^0\bar{B}^0$ pair to decays into a lepton and in the state f, respectively). *CP*-odd asymmetries appear in investigations of the temporal distributions. Thus, combining the difference between the number of events with e^+ and e^- events of equal sign for the cases $t_l > t_f$ and $t_l < t_f$, we can obtain a nonzero asymmetry that coincides with the case

TABLE I. Estimates of the $B_d^0 \to \gamma$ branching ratios.

Final state	Br	εBr	N	a *)	a/σ_a
		$b \to c\bar{c}s$			
$J/\Psi + K_S$	$3 \cdot 10^{-4}$	$2 \cdot 10^{-5}$	400	$-0{,}08$	1,6
$J/\Psi + K^{*0}$, $\hookrightarrow K_S\pi^0$	$4 \cdot 10^{-4}$	$2 \cdot 10^{-5}$	400	$<0{,}08$	$<1{,}6$ *
		$b \to u\bar{u}d$ **)			
$\pi^+\pi^-$	$5 \cdot 10^{-5} z$	$3{,}5 \cdot 10^{-5} z$	$700z$	$-0{,}11 z^{-1/2}$	3.0
$\pi^+\rho^-$	$5 \cdot 10^{-5} z$	$2{,}5 \cdot 10^{-5} z$	$500z$	$-0{,}15 z^{-1/2}$	3.3
$\pi^-\rho^+$	$10^{-4} z$	$5 \cdot 10^{-5} z$	$1000z$	$-0{,}065 z^{-1/2}$	2.1
$\pi^\pm a_1^\mp$	$1{,}5 \cdot 10^{-4} z$	$5 \cdot 10^{-5} z$	$1000z$	$-0{,}09 z^{-1/2}$	2.9
$\rho^+\rho^-$	$10^{-4} z$	$4 \cdot 10^{-5} z$	$800z$	$<0{,}11 z^{-1/2}$	<3.1 ***)
$\rho^\pm a_1^\mp$	$1{,}5 \cdot 10^{-4} z$	$4 \cdot 10^{-5} z$	$800z$	$<0{,}11 z^{-1/2}$	<3.1 ***)

*For $b \to u\bar{u}d$ transitions the equation for a is valid at $R > 2 \cdot 10^{-3}$.
**$z = R/0.05$
***The presence of different orbital momenta decreases the asymmetry.

(13), (16) of an absolutely tagged beam:

$$\tilde{a}_- = \frac{\int_0^\infty dt_1\, dt_2\, \mathrm{sign}(t_2 - t_1)\, \{N[l^-(t_1), f(t_2)] - N(l^+(t_1), \bar{f}(t_2))\}}{N_{tot}(l^-, f) + N_{tot}(l^+, \bar{f})} = a. \tag{29}$$

It is convenient to carry out measurements of this type in asymmetric e^+e^- collisions.

Table I lists the estimated branching ratios (Br) of the $B_d^0 \to f$ decays, the registration efficiency ε, the number of reconstructed events (N), and the statistical dependence of the CP-odd effect (a/σ_a) for a number of interesting decays of neutral B_d mesons. The overall normalization corresponds to 10^8 $B\bar{B}$ pairs [10^8 nb^{-1} in $\Upsilon(4S)$]. We assume a moderate effective tagging $\varepsilon_{\rm tag} = 0.2$ and a possibility of determining only the sign of the difference $t_l - t_f$. We use standard values $f_B = 100$ MeV, $B_B = B_K = 1$, $x_{B_d} = 0.7$, $B_{sl} = 0.1$, $\tau_B = 1.15$ ps, and $z_c m_b^5 = 0.39 \cdot (5\ \mathrm{GeV})^5$; the changeover to other values of the parameters, for any asymmetry, is easy by using Eqs. (4) and (20).

According to Table I, at $R \gtrsim 10^{-3}$ exclusive decays via the $b \to u$ channel require smaller statistics than via the allowed $b \to c$. This is due primarily to the high registration efficiency of decays of the former type, and also to the suppression in color of the discussed exclusive $b \to c\bar{c}s$ reactions containing a K^0 meson. Summing the effect over the modes $\pi^+\pi^-$, $\pi^\pm\rho^\mp$ and $\pi^\pm a_1^\mp$, we can expect for a $\Upsilon(4S)$ statistics equal to 10^8 a statistical significance of about 6 σ.

In view of the large expected value $x_{B_S} \gtrsim 7$, an investigation of analogous effects in B_S^0 mesons is promising only substantially above the $b\bar{b}$ threshold, i.e., at the Z^0 peak or in hadron colliders. We present only tentative estimates for the academic case of unity tagging efficiency and an ideal determination of the proper time prior to the B_S^0 decay. Assuming a probability $10^{-5} R/0.05$ of decay via the channel $B_S^0 \to \rho^0 K_S$, an asymmetry $\sin 2\alpha \approx 0.17[1 + (0.1/R)^{1/2}]$ for $R \gtrsim 10^{-2}$, and a final-state registration efficiency 0.5, we find that the number of B_S^0 needed for the 3σ effect is $2 \cdot 10^7$. Summation of channels of type

$$B_S^0 \to (\pi^0, \eta, \eta', \rho^0, \omega^0)\, K_S \text{ and}$$

$$B_S^0 \to (\pi^0, \eta, \eta' \ldots) + K^{0*} \hookrightarrow K_S\pi^0,$$

might possibly lower this number to several million.

For hadron experiments, particular interest attaches to CP asymmetries in the so-called self-tagging decays, where the final state offers evidence of the sign of the beauty of the initial hadron. In particular, baryon decays can also be investigated here.

An example is the decay $B^+ \to K^{*+}\pi^0$. Its probability is estimated at $\sim 5 \cdot 10^{-5}$, and in the factorization approximation the moduli of the interfering amplitudes are approximately equal at $R \approx 0.05$. Thus, the asymmetry in this decay can be of the order of $\sin\alpha \cdot \sin(\delta_1 - \delta_2) \approx 0.2 \sin(\delta_1 - \delta_2)$. Assuming (quite arbitrarily) an FSI-phase difference on the order of 0.2, we find that about $2 \cdot 10^8 B^\pm$ mesons are needed to obtain the 3σ effect. Unfortunately, the sign of the effect in different decays can be arbitrary, and summation over different channels is impossible; it should lead to a strong decrease of the symmetry. Similar estimates are obtained also for baryon decays of the type $\Lambda_b \to pK^-$ or $\Lambda_b \to \Lambda\pi^-$.

We note finally that observation of CP nonconservation in the reaction proposed by Wolfenstein, when both B mesons in (4S) decay into states with identical CP parity, calls for an order of 10^{10} $B\bar{B}$ pairs.

6. CONCLUSION

According to present predictions, intensive investigation of B-particle physics, using a new generation of detectors, should begin in the middle 90s. It is important at present to plan the strategy for searching and investigating here CP-violation effects. In the present paper we have discussed, in the SM, the prospects of such a search. The obtained estimates of the expected number $N_{B\bar{B}} \sim 10^8$ of events needed to observe *CP* nonconservation were found to be quite stable to variations of the (as yet) unknown SM parameters.

An increase of the prediction reliability calls for a more detailed verification of the modern theoretical concepts. Of great interest from this standpoint is an investigation of rare decays of beauty hadrons and, in particular, measurement of their probabilities and of the corresponding scattering phases.

Without counting on the unexpected, the possibilities of observing *CP* nonconservation in the next-generation experiments are connected in the SM mainly with the mechanism of the "milliscale" *CP* violation. The most promising here is the $b \to u\bar{u}d$ channel for B_d^0 mesons. Only in this case is an $N_{B\bar{B}}$ statistics $\sim 10^8$ sufficient to observe *CP* nonconservation in the SM. Increasing $N_{B\bar{B}}$ by 1–3 more orders would increase considerably the number of *CP*-odd effects that can be investigated, including the rarer decay channels. It would be possible in this case to change from a simple search for manifestations of *CP*-invariance violation to a detailed investigation that permits a more accurate quantitative check of the SM predictions.

It must be borne in mind that at a luminosity $\mathscr{L} \sim 10^{34}$ $cm^{-2} \cdot s^{-1}$, B factories can produce $\sim 10^8$ $B\bar{B}$ pairs annually. This yield, even assuming 100% registration efficiency, is equivalent only to the initial stage of the now expected experiment on *B*-physics in hadron collisions, particularly with the Tevatron collider. The promises of a detailed investigation of *CP*-odd effects in *B* particles are therefore presently seen in hadron colliders (Tevatron, LHC, SSC) using future-generation high-power detectors.

We emphasize that we have adhered to the canonical path of realizing a program of study of *CP* violation in *B* hadrons, based on the SM scenario. One can hardly imagine, of course, that in the long period (5–10 years) that separates us from the launching of real experiments, no new facts will become known and will require significant correction of the present predictions. But even if no explicit indications of deviations from the SM appear, a definite correction may be introduced by measurements of the *t*-quark mass and of the ratio *R*, by a refinement of the parameter $(\varepsilon'/\varepsilon)_K$ and by a determination of the mixing parameter x_{B_S} of B_S mesons.

Indications pointing to a new physics outside the SM might be, for example, observation of a relatively light *t*-quark, and observation of a small value $x_{B_s} < 7$ and a large value of ε_B ($\sim 10^{-2}$).

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1) According to available communications (see the reports of the ARGUS and CLEO groups at the 14th Lepton-Photon Symposium, Stanford, August 1989), the ARGUS and CLEO groups observe an excess of leptons in a region kinematically forbidden to $b \to u$ transitions. The corresponding mean value corresponds to $|V_{ub}|/|V_{cb}| \approx 0.1$ ($R \approx 0.02$).

2) We include among them the probability B_{sl} of semilepton decays, since their present-day experimental value is somewhat lower than expected from theory.

3) We use for the corresponding factor H the value $H = 0.7$, which is preferable for the explanation of the ΔT-1/2 rule.

4) For a discussion of the doubly suppressed decays $b \to u\bar{u}s$ see Sec. 4.

5) Note that there are no *FSI* phases in the standard factorization approach.

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