

REVIEWS OF TOPICAL PROBLEMS

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What can be expected from the further study of CP and T symmetry violation and CPT invariance tests

E P Shabalin

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Contents

Abstract. **Different CP and T violation models are discussed in view of using their particular features to experimentally ascertain which of these models are realized in nature. For example, recording the electric dipole moments of the neutron and electron close to their experimental limits or only one or two orders of magnitude smaller would be evidence for the presence of CP violation sources other than the Kobayashi – Maskawa phase in the Standard Model. As for CPT invariance, which predicts, in particular, the equality of the particle and antiparticle masses, the ratio of the difference between the K^0 and $\bar{K}^0$ masses to their sum being below 10^{-18} is considered to be the best test of CPT symmetry. However, an extremely small value of this ratio does not necessarily imply extremely small parameters of the CPT violation in $\{K^0, \bar{K}^0\}$-system decays. The existing data only indicate that these parameters must not exceed 30% of the known CP violation parameter η_{+-}. Other experiments for high-precision testing of CPT invariance are discussed.**

E P Shabalin Institute of Theoretical and Experimental Physics
B. Cheremushkinskaya ul. 25, 117218 Moscow, Russian Federation
Tel. (7-095) 129 95 47
Fax (7-095) 883 96 01
E-mail: shabalin@vitep5.itep.ru

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1. Introduction

The world of elementary particles is described by relativistic quantum field theory. It deals with the density of the Lagrangian that contains the local interaction and is invariant with respect to Lorentz rotations. The locality means that the Lagrangian density contains only field operators and finite order derivatives of them. Also, it is assumed that fields with integer spins satisfy ordinary commutation relations and fields with half-integer spins satisfy anticommutation relations.

Such a theory is called CPT-invariant, i.e. invariant with respect to the product of C, P, and T transformations [1, 2], where C is the charge conjugation operator, P is the operator of space reflection, and T is the time inversion operator.

The operator C converts particles into antiparticles, while the C-parity of neutral fields with an integer spin is determined by the C-parity of the states to which they can pass as a result of interactions conserving the C-parity. The ability of a photon to pass into a fermion – antifermion system with negative charge parity implies that the photon is a C-odd particle, whereas a π^0 meson decaying into two photons turns out to be a C-even object.

The operator P changes the signs of the space coordinates of the fields as well as the signs of the momentum and of the electric and pseudoscalar fields. The energy, spin and the magnetic and scalar fields do not change their signs.

The operator T substitutes the time $-t$ for t and reverses the process so that the initial and final particles replace each other.

Historically, the theory of elementary particles has been constructed for years so that the Lagrangian density be invariant with respect to each of the C, P or T transformations taken alone, regardless of the interaction type. The presence of such invariance in strong and electromagnetic interactions was confirmed experimentally, but its relevance to weak interactions remained to be clarified.

Although Michel [3] considered whether or not the P invariance is a strong symmetry as early as in 1952, later observations of neutral K meson decay into 2π and 3π states differing in P-parity cast serious doubt on P-parity conservation in weak interactions. Feynman expressed this doubt at the VI Annual Rochester Conference in 1956 [4], where he repeated the question once posed by Block, as to whether θ- and τ- are two parity-differing states of the same particle lacking a definite parity (which means parity nonconservation)[1]. Thereafter, possible consequences of P invariance violation in weak interactions were analyzed by Lee and Yang [5]. The experiment suggested by them and implemented by Wu and her co-workers [6] soon confirmed the nonconservation of P invariance in the β decay of polarized ^{60}Co nuclei. The number of electrons emitted along the direction of the nuclear spin and in the opposite direction proved to be different, suggesting the presence of a P-odd term $\boldsymbol{\sigma}\mathbf{p}_e$ in the expression for the decay probability.

Of great importance for the understanding of discrete symmetries was the observation [7] that such a correlation is impossible in the case of C invariance conservation. It was concluded in Ref. [7] that P-parity violation is accompanied by the violation of C-parity. Later, this issue was considered at greater length in Ref. [8] (see also Nobel lectures [9, 10] devoted to the discovery of CP invariance violation).

Further experimental studies confirmed that P-parity is not conserved in the series of decays $\pi \to \mu \to e$ [11] and in hyperon decays [12]. Correlations in decays $\pi \to \mu \to e$ gave evidence that neither spatial nor charge parity is conserved, unlike temporal parity.

Trying to save the symmetry of the microcosm, even if partially, Landau [13] suggested the hypothesis that interactions of elementary particles are invariant with respect to combined inversion, i.e. to the product of C and P transformations. In the $V-A$ theory of weak interactions formulated at the same period [14], P and C invariances were completely violated, but the interaction remained CP-invariant.

The hypothesis of CP invariance was short-lived. It was shown in 1964 [15] that CP symmetry is only approximate. Newly formed neutral K mesons are superpositions of states differing in CP parity [16]:

$$\mathrm{K}_1 = \frac{1}{\sqrt{2}}\left(\mathrm{K}^0 + \bar{\mathrm{K}}^0\right), \qquad \mathrm{K}_2 = \frac{1}{\sqrt{2}}\left(\mathrm{K}^0 - \bar{\mathrm{K}}^0\right), \tag{1}$$

where $\bar{\mathrm{K}}^0 = \mathrm{CP}(\mathrm{K}^0)$. One ($\mathrm{K}_1$) can decay into a CP-even system 2π, while the other (K_2) to a CP-odd system 3π. The significantly smaller phase volume of the 3π-system accounts for the long lifetime of the K_2 meson, and decays into 3π states should occur only far from the birth point of K^0 ($\bar{\mathrm{K}}^0$) mesons. The admixture of 2π decays detected at this point may imply the presence of $\mathrm{K}_2 \to \mathrm{K}_1$ transitions, i.e. the violation of CP invariance.

Search for decays $\mathrm{K}_2^0 \to \pi^+\pi^-$ forbidden by the CP invariance has been ongoing since 1958 [17, 18], but only in a Dubna experiment [19] was the total number of K_2^0 mesons (597) sufficient to observe one decay into $\pi^+\pi^-$. Unfortunately, this decay was not recorded in the observed set for statistical reasons, and the discovery of CP violation was delayed for two years. The history of studies that eventually resulted in the discovery of CP invariance violation is described in Ref. [20].

In experiments with neutral K mesons, the CP violation was of the order of 0.2%. Generally speaking, CP violation in weak processes may be either significantly smaller or much greater than in $\mathrm{K} \to 2\pi$ decays. For example, the current theory predicts CP-odd effects of the order of unity for rare decays $\mathrm{K}_L \to \pi^0 l^+ l^-$, $\mathrm{K}_L \to \pi^0 \nu\nu$, and for certain decays of the system of $\{\mathrm{B}^0, \bar{\mathrm{B}}^0\}$ mesons.

Thus, weak interactions appear to be noninvariant with respect to C, P, and CP transformations. What conclusions can be drawn as regards T invariance? If interactions between elementary particles are invariant with respect to the most fundamental CPT transformation, then T invariance violation should take place in the class of interactions with violated CP invariance, such that the T transformation offsets the noninvariance arising from the CP transformation.

Therefore, in the CPT-invariant world, the factors giving rise to CP-even effects are at the same time sources of T-odd effects. Among these factors is the complexity of certain coupling constants and amplitudes of single-particle transitions in the original theory. For example, in the effective Lagrangian of CP-odd $\mathrm{K}_1 \leftrightarrow \mathrm{K}_2$ transitions,

$$L(\mathrm{K}_1 \leftrightarrow \mathrm{K}_2) = g\mathrm{K}_1\mathrm{K}_2^* + g^*\mathrm{K}_1^*\mathrm{K}_2\,,$$

where the asterisk indicates complex conjugation, the constant g must be imaginary because, in accordance with (1), K_1 is an Hermitian field, K_2 is an anti-Hermitian field, and the Lagrangian must also be Hermitian.

The problem of CP invariance violation arose more than 35 years ago and has called into being numerous publications. The readers can familiarize themselves with the most important theoretical and experimental studies on the subject from papers, reviews, and monographs [21 – 34], which also consider possibilities of testing CP invariance. In particular, the development of ideas can be traced from the materials published in *Usp. Fiz. Nauk* [35].

The present review does not pretend to a comprehensive discussion of all CP and CPT problems touched upon in the literature. This ambitious task would require a much longer paper to be written. The author restricts himself to highlighting recent progress in the field of interest and comparing predictions of different CP violation models that can be used to check up the reality of various sources of such violation.

The sources of CP violation discussed in the literature are numerous. They include (1) the complexity of coupling constants of gauge interactions in the electroweak theory; (2) 'soft' (spontaneous) and 'explicit' violation of CP symmetry in the multi-Higgs sector, resulting in the complexity of the Yukawa coupling constants; (3) the complexity of coupling and mass constants in the supersymmetric generalization of the Standard Model of the theory; (4) superweak interaction altering the strangeness by two units, in combina-

[1] I am grateful to L B Okun', who brought to my attention Refs [3, 4] containing these historical facts.

tion with other CP violation mechanisms; and (5) other, more exotic sources.

Elucidation of CP violation sources responsible for a self-consistent picture of CP effects could facilitate understanding the nature of such violation. Self-consistency implies an explanation of such a global phenomenon (among others) as the cosmic disbalance between matter and antimatter. Conditions necessary for the baryon – antibaryon asymmetry of the Universe to arise (as formulated by Sakharov [36]; see also [37 – 39]) include C and CP invariance violation.

The most natural source of CP violation is source (1) realized in the framework of the Standard Model [40] and considered in Section 2. However, this source appears insufficient to obtain the observed baryon asymmetry

$$\frac{n_{\mathrm{B}} - n_{\bar{\mathrm{B}}}}{n_\gamma} \sim 10^{-9} - 10^{-10}\,,$$

[41, 42] (see also reviews [43])[2]. Other potential sources of CP violation are considered in Sections 3 – 5.

At present, there is no experimental evidence for CPT symmetry violation. But the interest in testing CPT invariance has not cooled since the time of discovery of CP violation because such a violation would mean that certain postulates of quantum theory are not completely adequate to what is observed in nature. Interest has been further fueled in recent decades by the creation of the theory of strings as nonlocal objects exhibiting nonlocal interactions [44, 45] and by the development of a modified quantum mechanics that admits the evolution of pure states into mixed ones [46, 47]. In the latter case, the estimate based on the assumption of CPT invariance violation on scales $l_{\mathrm{Pl}} = 1/m_{\mathrm{Pl}} \sim 10^{-33}$ cm indicates that this violation might make a 1% contribution to the CP violation in $\{\mathrm{K}^0, \bar{\mathrm{K}}^0\} \to 2\pi$ decays [48][3]. The situation pertaining to the verification of CPT symmetry is considered in Section 6.

2. CP and T invariance violation in the Standard Model

The Standard Model (SM) [40] deals with the Lagrangian density of the strong quark – gluon interaction in the form

$$L^{\mathrm{strong}} = -\frac{1}{4}\, G^a_{\mu\nu} G^a_{\mu\nu} + \sum_q \bar{q} \left(\mathrm{i}\gamma_\mu \frac{\partial}{\partial x_\mu} + g_{\mathrm{s}} G^a_\mu t^a \gamma_\mu - m_q \right) q\,, \tag{2}$$

where $G^a_{\mu\nu}$ is the antisymmetric tensor of the gluon field strength, G^a_μ and t^a are the generators of the color group SU(3). The number of different quarks is six: $q = \mathrm{u, c, t, d, s, b}$.

None of the general principles, including theory renormalizability, forbids the addition of the so-called θ-term [49]:

$$\Delta L = -\theta\, \frac{g_{\mathrm{s}}^2}{64\pi^2}\, \varepsilon_{\mu\nu\alpha\beta}\, G^a_{\mu\nu} G^a_{\alpha\beta}\,. \tag{3}$$

This term is explicitly CP-odd and must lead to the violation of CP invariance in processes with flavor conservation. The theory imposes no constraint on the value of the parameter θ, but it follows from the data on the neutron electric dipole moment (see below) that $\theta < 3 \times 10^{-10}$.

The use of the constraint on a T-noninvariant value (electric dipole moment) for a limitation on CP violation is dictated by the coincidence of these constraints in a CPT invariant theory, such as SM. Since the parameter θ is extremely small, the effects of the θ-term in processes with a change of flavor are also negligibly small. Effects of the θ-term in processes with conserved flavor will be considered in Section 2.8.

Weak interactions between quarks and charged W-bosons are described by the Lagrangian

$$L_{\mathrm{w}} = g \bar{U} \gamma_\mu\, \frac{1+\gamma_5}{2}\, V D W^-_\mu + \mathrm{H.\,c.}\,, \tag{4}$$

where

$$\bar{U} = (\bar{\mathrm{u}}, \bar{\mathrm{c}}, \bar{\mathrm{t}})\,, \qquad D = \begin{pmatrix} \mathrm{d} \\ \mathrm{s} \\ \mathrm{b} \end{pmatrix},$$

and V is the 3×3 matrix of flavor mixing in charged currents. In terms of CP violation, it is important that certain elements of this matrix may be complex. Specifically, non-zero phases are permitted to appear in a unitary $n \times n$ matrix at $n \geqslant 3$, their total number being $(n-1)(n-2)/2$.

The appearance of a phase in the theory with three quark generations was first noted by Kobayashi and Maskawa [50] for whom it was named. The matrix of flavor mixing was named after Cabibbo, Kobayashi, and Maskawa (CKM matrix). The CKM matrix in the modification of Kobayashi and Maskawa has the form

$$V = \begin{pmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 \exp \mathrm{i}\delta & c_1 c_2 s_3 + s_2 c_3 \exp \mathrm{i}\delta \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 \exp \mathrm{i}\delta & c_1 s_2 s_3 - c_2 c_3 \exp \mathrm{i}\delta \end{pmatrix}, \tag{5}$$

where $c_i = \cos\theta_i$, $s_i = \sin\theta_i$.

Other forms of parametrization are also frequently used, e.g. that proposed by Wolfenstein [51] and emphasizing the angle size hierarchy, $s_1 \gg s_2 \gg s_3$:

$$V = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - \mathrm{i}\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - \mathrm{i}\eta) & -A\lambda^2 & 1 \end{pmatrix}, \tag{6}$$

where $\lambda \approx s_1$ and A, ρ, η are real numbers of the order of unity. It should be stressed that the predicted physics of the phenomena is independent of the choice of parametrization.

The flavor is conserved and the corresponding coupling constants remain real in quark interactions with neutral Z-bosons. Quarks interact not only with vector mesons but also with the Higgs field doublet $\Phi = (\Phi^+, \Phi^0)$. In the case of a spontaneous symmetry breaking, three of the four real fields forming this doublet undergo conversion to longitudinal components of the vector fields W^+, W^-, Z^0, which, in turn, being massless transverse fields, become massive (see, for instance, Ref. [33]). The remaining neutral scalar field interacts with fermions in a CP-invariant mode. Hence, the complexity of matrix V elements is the sole source of CP violation in SM.

[2] Ref. [39] questions the validity of this inference.

[3] Such an estimate is optimistic. Generally speaking, it follows from naive dimensional considerations for the CPT-odd parameter Δ discussed in Section 6 that

$$\Delta \sim \frac{m_{\mathrm{K}}}{m_{\mathrm{K}_L} - m_{\mathrm{K}_S}} \left(\frac{m_{\mathrm{K}}}{m_{\mathrm{Pl}}} \right)^n.$$

Therefore, CPT violation is likely to be observed only in the case of $n = 1$, when $\Delta \sim 10^{-5}$.

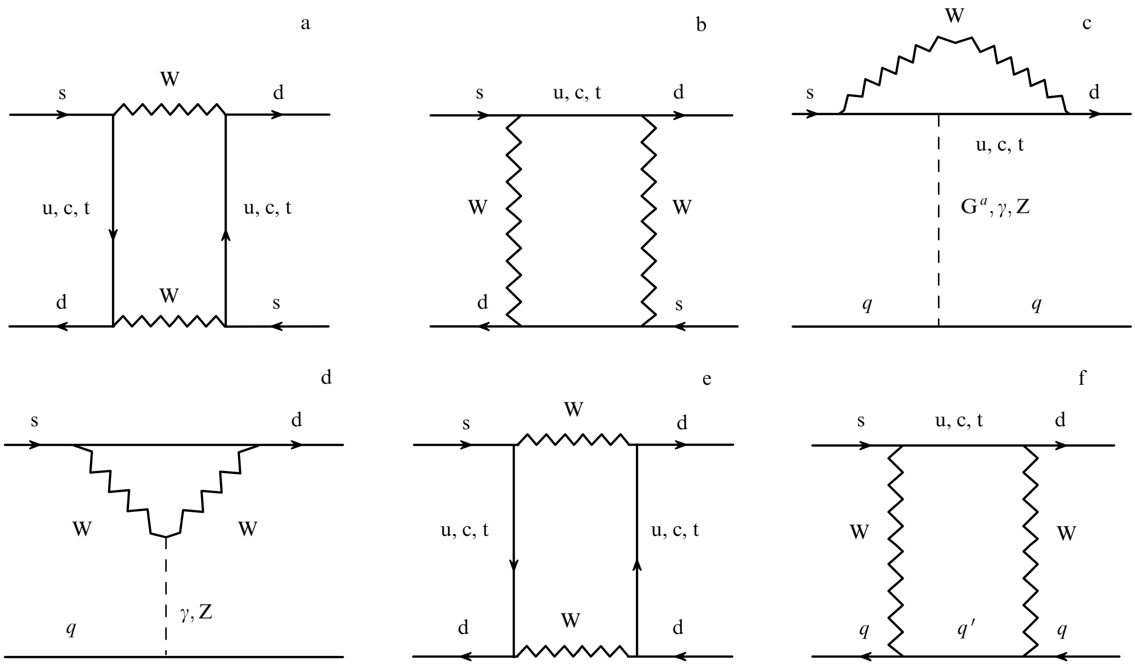

Figure 1. Diagrams contributing to the CP-conserving and CP-violating parts of the mass matrix of the $\{K^0, \bar{K}^0\}$ meson system (a, b) and to the direct violation of CP invariance in the decay amplitude (c – f).

2.1 CP effects in $\{\mathbf{K^0}, \bar{\mathbf{K}}^\mathbf{0}\} \to 2\pi$ decays

The complexity of certain interaction constants $\bar{q}qW$ is responsible for two kinds of CP violation in neutral K meson decays, as shown in the diagrams in Fig. 1. Diagrams 1a and 1b of the so-called 'box' type correspond to transitions with a change of strangeness by two units. Their real part determines the mass splitting of K_1 and K_2 mesons, while the imaginary part describes the CP violation leading to $K_1 \leftrightarrow K_2$ transitions. As a result, the states of neutral K mesons with a certain mass and lifetime are actually superpositions of states with different CP parities:

$$K_S = \frac{K_1 + \varepsilon K_2}{(1 + |\varepsilon|^2)^{1/2}}\,, \qquad K_L = \frac{K_2 + \varepsilon K_1}{(1 + |\varepsilon|^2)^{1/2}}\,. \tag{7}$$

The effects produced by diagrams 1a and 1b are very weak, because they arise in the second order with respect to the Fermi constant G_F. Thus,

$$2\,\frac{m_{K_L} - m_{K_S}}{m_K} \approx 1.4 \times 10^{-14}\,. \tag{8}$$

However, it is due to this smallness that the violation of CP invariance is not very small, since the decays $K_L \to 2\pi$ are described by the diagram in Fig. 2, in which the difference $m_{K_L} - m_{K_S}$ appears in the denominator and cancels out the smallness of the CP-odd part of the amplitude $\langle K_S|K_L\rangle$. Therefore, the CP-violation parameter ε is actually determined by the ratio of the imaginary to the real part in diagrams 1a and 1b, which lacks G_F^2 and contains a dependence on the parameters of the matrix V: $\varepsilon \sim s_2 s_3 \sin\delta \sim 10^{-3} \sin\delta$. The observed CP violation is small but incidentally, that is because of the smallness of the matrix V parameters s_2, s_3 rather than the smallness of the phase δ.

The imaginary part of diagram 1c describes a direct violation of CP invariance in the $K_L \to 2\pi$ decay amplitude. This violation occurs in that part of the amplitude which corresponds to the transition into a state of two π mesons with the isotopic spin $T = 0$. It would be indistinguishable from the violation initiated by diagrams 1a and 1b but for the presence of a part corresponding to the transition into the state $\langle 2\pi, T = 2|$ in the amplitude. Because $\pi^+\pi^-$ and $\pi^0\pi^0$ states are different compositions of the states with $T = 0$ and $T = 2$, the direct CP violation in these charge states is manifest to different degrees.

As a result, the CP violation in $K_L \to 2\pi$ decays is characterized by two parameters:

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon'\,, \tag{9}$$

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'\,, \tag{10}$$

where

$$\varepsilon' = \frac{A(K_2^0 \to 2\pi, T = 2)}{A(K_1^0 \to 2\pi, T = 0)}\,. \tag{11}$$

Similar to ε, the parameter ε' is proportional to $s_2 s_3 \sin\delta$ but has additional sources of smallness. Specifically, being manifest due to a small admixture of transitions to the state

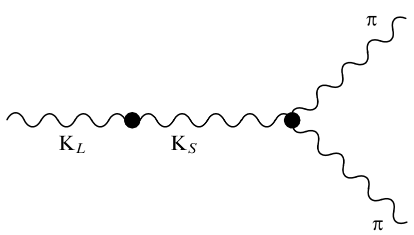

Figure 2. Diagram showing how the mechanism of CP violation represented by diagrams 1a and 1b makes possible the transition $K_L \to 2\pi$.

$T = 2$, it is proportional to the small ratio

$$\omega = \frac{\langle 2\pi; T = 2|\mathrm{K}_S\rangle}{\langle 2\pi; T = 0|\mathrm{K}_S\rangle} \approx \frac{1}{22} \tag{12}$$

and to $g_s^2/16\pi^2$ by virtue of the loop integration in diagram 1c. It is for this reason that the ε'/ε ratio was initially expected to be of the order of $(3-5)\times 10^{-3}$ (see, for instance, Ref. [52]).

However, the situation changed dramatically after it was found that diagram 1d with an intermediate photon is also of importance. The contribution corresponding to this diagram is suppressed by the factor $\alpha_{\mathrm{em}}/\alpha_{\mathrm{s}}$ but enhanced by the absence of the factor ω due to the isotopic noninvariance of the electromagnetic interaction. With the t-quark mass $m_{\mathrm{t}} = 150-180$ GeV, this contribution is negative and results in a significant decrease of the predicted ε'/ε ratio [53].

Theoretical calculations of ε'/ε were made taking into consideration corrections introduced by the 'clothing' of the diagrams in Fig. 1 with a gluon cloud and in view of various assumptions concerning the mode of transformation of four-quark operators associated with these diagrams into amplitudes of physical K and π mesons. Also, various assumptions concerning the mass of the virtual s-quark $m_{\mathrm{s}}(q^2)$ were employed.

Because of arising uncertainties, the theoretical predictions are characterized by a marked dispersion:

$$\left(\frac{\varepsilon'}{\varepsilon}\right)^{\mathrm{th}} = 10^{-4}\begin{cases} 6.7 \pm 0.7 & [54] \\ 3.1 \pm 2.5 & [55] \\ 17^{+14}_{-10} & [56] \\ 1.5-31.6 & [57] \end{cases}. \tag{13}$$

The current experimental data are

$$\left(\frac{\varepsilon'}{\varepsilon}\right)^{\mathrm{exp}} = 10^{-3}\begin{cases} 2.30 \pm 0.65 & [58] \\ 0.6 \pm 0.7 & [59] \\ 2.8 \pm 0.41 & [60] \\ 1.85 \pm 0.75 & [61] \end{cases}. \tag{14}$$

All available data except those reported in Ref. [59] as compatible with $\varepsilon' = 0$ appear to be evidence for a non-zero value of ε'. This excludes the Wolfenstein superweak interaction model [62] as the sole source of CP violation. The Lagrangian of this model has the form

$$L_{\mathrm{sw}} = \mathrm{i}g_{\mathrm{sw}}K^2 + \mathrm{H.\,c.}\,, \tag{15}$$

where K is the K^0 meson field and the constant g_{sw} is real. The Lagrangian (15) produces only $\varepsilon \neq 0$. However, superweak interaction could remain a source of the main contribution to ε if combined with other mechanisms capable of producing the observed ε' value.

One more CP-odd effect in K_L meson decays is charge asymmetry in semi-leptonic decays

$$\delta_L = \frac{\Gamma(\mathrm{K}_L \to \mathrm{l}^+\nu\pi^-) - \Gamma(\mathrm{K}_L \to \mathrm{l}^-\bar{\nu}\pi^+)}{\Gamma(\mathrm{K}_L \to \mathrm{l}^+\nu\pi^-) + \Gamma(\mathrm{K}_L \to \mathrm{l}^-\bar{\nu}\pi^+)} \approx 2\,\mathrm{Re}\,\varepsilon\,. \tag{16}$$

According to experimental data,

$$\delta_L = (3.33 \pm 0.14) \times 10^{-3}\,,$$

in agreement with the measured parameters η_{+-} and η_{00} defined by formulas (9) and (10):

$$\eta_{+-} \approx \eta_{00} \approx 2.28 \times 10^{-3} \exp(\mathrm{i}\cdot 44^\circ)\,.$$

2.2 Predictions of SM for CP effects in $\mathrm{K}^\pm \to 3\pi$ decays

Studies of CP effects in $\mathrm{K}^\pm \to 3\pi$ decays shed new light on the direct violation of CP invariance, the only one permitted in charged K meson decays, which is due to the relatively weak suppression of $\Delta T = 3/2$ transitions compared with $\Delta T = 1/2$ [63, 64].

The simplest case in terms of detection is the comparison of $\mathrm{K}^+ \to \pi^+\pi^+\pi^-$ and $\mathrm{K}^- \to \pi^-\pi^-\pi^+$ transitions. The observable CP effects include

$$\Delta\Gamma = \frac{\Gamma(\mathrm{K}^+ \to \pi^+\pi^+\pi^-) - \Gamma(\mathrm{K}^- \to \pi^-\pi^-\pi^+)}{\Gamma(\mathrm{K}^+ \to \pi^+\pi^+\pi^-) + \Gamma(\mathrm{K}^- \to \pi^-\pi^-\pi^+)}\,, \tag{17}$$

$$\Delta g = \frac{g^{(+)} - g^{(-)}}{g^{(+)} + g^{(-)}}\,. \tag{18}$$

Here, the slope parameters $g^{(\pm)}$ are given by the relation

$$\left|M\left(\mathrm{K}^\pm(k) \to \pi^\pm(p_1)\,\pi^\pm(p_2)\,\pi^\mp(p_3)\right)\right|^2 \sim 1 + g^{(\pm)}\,\frac{s_3 - s_0}{m_\pi^2} + \ldots\,, \tag{19}$$

with $s_3 = (k - p_3)^2$, $s_0 = (1/3)(m_{\mathrm{K}}^2 + m_\pi^2)$.

These effects become observable due to the presence of terms with differing dynamic structure in the amplitude and to the effect of π meson rescattering in the final state [4]. Indeed, the decay amplitude (conditionally) has the form

$$A(\mathrm{K}^+) = a(s_1, s_2, s_3)\exp\mathrm{i}(\delta_a + \varphi) + b(s_1, s_2, s_3)\exp\mathrm{i}\delta_b\,,$$
$$A(\mathrm{K}^-) = a(s_1, s_2, s_3)\exp\mathrm{i}(\delta_a - \varphi) + b(s_1, s_2, s_3)\exp\mathrm{i}\delta_b\,,$$

where functions a and b show a different dependence on their arguments, δ_a and δ_b are the phase shifts caused by π meson rescattering, and φ is a phase arising from the Kobayashi–Maskawa (KM) phase. Then,

$$\left|A(\mathrm{K}^+)\right|^2 - \left|A(\mathrm{K}^-)\right|^2 = 4ab\sin(\delta_b - \delta_a)\sin\varphi\,.$$

In the leading approximation of the momentum expansion, a and b are associated with those parts of the amplitude which correspond to transitions $\Delta T = 1/2$ and $\Delta T = 3/2$.

Although the b/a ratio in the decays being considered is not small, the expected CP effects are insignificant, $\Delta\Gamma \sim 10^{-7}$, due to the smallness of $\sin(\delta_b - \delta_a)$ [67–69]. For this reason, the statement of the authors of Ref. [70] that in the next approximation in p^2 these effects increase by almost two orders of magnitude gave rise to an interest and an urge to test this inference by independent calculations. In the p^4 approximation, the contributions of the 'penguin' [5] and other diagrams to the $A_{1/2}$ amplitude acquire a different (in p^4 terms) dynamic structure, thus making possible their interference inside the $A_{1/2}$ amplitude.

Unfortunately, this new source of CP-odd correlations is not very strong. According to estimates in Ref. [73] (made, however without real calculations of the p^4 corrections and taking into account only the smallness of the final particle rescattering phases), it might be expected that $\Delta g \sim 2 \times 10^{-6}$,

[4] Effects of final particle rescattering in the CP-invariant theory were considered in Refs [65, 66].

[5] The attribute 'penguin' was applied by J Ellis and co-workers [71] to diagram 1c first considered in Ref. [72] ,where its contribution was found to be responsible for a marked increase in the amplitude $\Delta T = 1/2$ in K meson decays.

$\Delta\Gamma \sim 6\times10^{-8}$. The real calculation of p^4 corrections yielded

$$\Delta g \leqslant 3\times10^{-5}\sin\delta\ [64]\,, \qquad \Delta\Gamma \leqslant 2.5\times10^{-6}\sin\delta\ [74]\,, \tag{20}$$

i.e. around 30 times smaller than in Ref. [70] at a KM phase value of $\delta = \pi/2$. It will be shown below that a certain increase of CP effects in $K^\pm \to 3\pi$ decays can be expected in the case of CP violation in the extended Higgs sector of the electroweak interaction theory.

2.3 Predictions of SM for rare decays of K mesons

In certain rare decays of K mesons, the CP-odd part of the amplitude is either comparable with the CP-even part or even predominates over it. This allows more reliable testing of SM predictions for CP-odd effects and a more accurate determination of CKM matrix parameters. Such decays are $K_L \to \pi^0 e^+ e^-$, $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$. In the first two decays, the amplitude contains both CP-even and CP-odd parts, while the third one has only a CP-odd amplitude [see Eqn (27)].

It is expected that the contribution of the CP-invariant transient 2γ state in the $K_L \to \pi^0 e^+ e^-$ decay gives the relative probability of decay [75]

$$\mathrm{Br}\,(K_L \to \pi^0 e^+ e^-)_{2\gamma} \leqslant 4\times10^{-12}\,. \tag{21}$$

For the CP-odd mixing $K_2 \to K_1$, it is [76]

$$\mathrm{Br}\,(K_L \to \pi^0 e^+ e^-)_{\mathrm{indirect}} = (1.6-6)\times10^{-12}\,. \tag{22}$$

Finally, the contribution of direct CP violation leads to [77]

$$\mathrm{Br}\,(K_L \to \pi^0 e^+ e^-)_{\mathrm{direct}} = (5\pm2)\times10^{-12}\,. \tag{23}$$

It follows from these estimates that, although the contribution of the direct CP violation is difficult to distinguish, it would be useful for testing SM to confirm that the main contribution to the decay probability comes from a CP-odd interaction. So far, experiments have given [78]

$$\mathrm{Br}\,(K_L \to \pi^0 e^+ e^-)^{\exp} < 4.3\times10^{-9}\,. \tag{24}$$

The probability of a $K^+ \to \pi^+\nu\bar{\nu}$ decay also depends on the CP-even and CP-odd parameters of the CKM matrix because it is proportional to

$$|V_{\mathrm{td}}|^2 = A^2\lambda^6\left[(1-\rho)^2+\eta^2\right].$$

Here, the parametrization (6) of the CKM matrix is used. Parameter η characterizes the degree of CP invariance violation.

Because of the presence of a transient c-quark loop, the full expression for the relative decay probability has a complicated form [79]. The decay probability is expected at a level of [80]

$$\mathrm{Br}\,(K^+ \to \pi^+\nu\bar{\nu}) \sim 10^{-10}\,. \tag{25}$$

Only single event has so far been observed, meaning that [81]:

$$\mathrm{Br}\,(K^+ \to \pi^+\nu\bar{\nu})^{\exp} = (1.5^{+3.5}_{-1.3})\times10^{-10}\,. \tag{26}$$

The $K_L \to \pi^0\nu\bar{\nu}$ decay is most interesting in terms of the specification of the CKM matrix parameters. In fact, this is virtually a CP-odd decay via direct CP violation because the hadronic component of its matrix element is

$$\left\langle \pi^0 \middle| V_{\mathrm{ts}}V^*_{\mathrm{td}}(\bar{s}d)_{V-A} - V^*_{\mathrm{ts}}V_{\mathrm{td}}(\bar{d}s)_{V-A} \middle| K_L \right\rangle \sim (V^*_{\mathrm{td}} - V_{\mathrm{td}}) \sim 2\mathrm{i}A\lambda^3\eta\,. \tag{27}$$

The potential corrections introduced by indirect CP violation and by the CP-invariant part of the amplitude are very small [82, 83]. In view of the next corrections in p^2 for the leading term of the amplitude momentum expansion, the relative probability of the decay is [80]

$$\mathrm{Br}\,(K_L \to \pi^0\nu\bar{\nu}) = (3.1\pm1.3)\times10^{-10}\,. \tag{28}$$

So far, $\mathrm{Br}\,(K_L \to \pi^0\nu\bar{\nu}) < 5.8\times10^{-5}$. Despite the difficulty of improving the accuracy of measurements by five orders of magnitude, three laboratories are about to start measuring this decay. The E391 experiment at KEK will be initiated in 2001. The E926 experiment (KOPIO) at Brookhaven is designed to collect 50 events [84]. The next phase of the KTeV experiment at Fermilab will be the quest for $K_L \to \pi^0\nu\bar{\nu}$ decays [85].

CP violation and the resulting T invariance violation has been observed in the $K_L \to \pi^+\pi^- e^+ e^-$ decay [86]. Its amplitude is determined by the diagrams in which the CP-violating $K_L \to \pi^+\pi^-$ decay is accompanied by the emission of a virtual bremsstrahlung photon subsequently converted into an e^+e^- pair and by the diagrams corresponding to the CP-invariant $K_L \to \pi^+\pi^-\gamma$ transition with a virtual photon emitted in the M1-transition and also converted into an e^+e^- pair. The interference of the two contributions leads to the differential decay probability

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\phi} = \Gamma_1\cos^2\phi + \Gamma_2\sin^2\phi + \Gamma_3\sin\phi\cos\phi\,, \tag{29}$$

where

$$\sin\phi\cos\phi = [\mathbf{n}_{\mathrm{e}}\times\mathbf{n}_\pi]\cdot\mathbf{z}(\mathbf{n}_{\mathrm{e}}\cdot\mathbf{n}_\pi)\,,$$

$\mathbf{n}_{\mathrm{e}}$ and $\mathbf{n}_\pi$ are the unit vectors perpendicular to the e^+e^- and $\pi^+\pi^-$ decay planes, and $\mathbf{z}$ is the unit vector along the sum of the π meson momenta.

The term Γ_3 in (29) is explicitly T-noninvariant. The presence of this term accounts for the integral asymmetry

$$A = \frac{\int_0^{\pi/2} - \int_{\pi/2}^{\pi}}{\int_0^{\pi/2} + \int_{\pi/2}^{\pi}}\,,$$

in $(\mathrm{d}\Gamma/\mathrm{d}\phi)\,\mathrm{d}\phi$, which was expected at a level of $A \approx 14\%$ in SM [87]. In experiment [86],

$$A = \big(13.6\pm2.5(\mathrm{stat})\pm1.2(\mathrm{syst})\big)\%\,. \tag{30}$$

2.4 CP invariance violation in hyperon decays

CP violation leads to the inequality of partial widths of non-leptonic decays of a hyperon and an antihyperon. For example, the width of the $\Sigma^+ \to p + \pi^0$ decay must differ from that of $\bar{\Sigma}^+ \to \bar{p} + \pi^0$ [88], although the equality

$$\Gamma(\Sigma^+ \to p+\pi^0) + \Gamma(\Sigma^+ \to n+\pi^+) = \Gamma(\bar{\Sigma}^+ \to \bar{p}+\pi^0) + \Gamma(\bar{\Sigma}^+ \to \bar{n}+\pi^-)$$

must be fulfilled for the total widths of non-leptonic decays.

CP-odd effects in hyperon decays can be examined with proton – antiproton machines in the reactions

$$p\bar{p} \to \Lambda\bar{\Lambda},\ \Sigma\bar{\Sigma},\ \Xi\bar{\Xi}, \ldots$$

with the subsequent observation of the decay

$$Y \to N + \pi\,.$$

The phenomenology of non-leptonic decays of hyperons with CP invariance conservation is described at length in Ref. [33]. The general form of their amplitude is

$$A(Y \to N\pi) = S + P\boldsymbol{\sigma}\mathbf{q}\,.$$

Here, $\mathbf{q} \equiv \mathbf{q}_\pi$ in a hyperon system at rest,

$$S = \sum_i S_i \exp i(\delta_i^S + \phi_i^S)\,, \qquad P = \sum_i P_i \exp i(\delta_i^P + \phi_i^P)\,,$$

where $\delta_i^{S,P}$ are the phase shifts in the i-channel of the reaction induced by the strong rescattering of final particles (the same for Y and $\bar{Y}$) and $\phi_i^{S,P}$ are the CP destroying phases, with $\phi(Y) = -\phi(\bar{Y})$.

In a resting-hyperon system, one of the possible CP-odd asymmetries has the form

$$A = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}\,,$$

where α for the hyperon decay is given by the relation

$$\alpha = 2\,\mathrm{Re}\,\frac{S^* P}{|S|^2 + |P|^2}\,,$$

and $\bar{\alpha}$ is the corresponding quantity for the decay of the antihyperon. It should be noted that $\alpha(Y) = -\alpha(\bar{Y})$ in the CP-invariant world. The anticipated value of A asymmetry in the case of Λ hyperons is $-(0.5-1.5)\times 10^{-5}$ in SM and -2.5×10^{-5} in the Weinberg model with broken CP symmetry in the Higgs sector [89]. Currently, this asymmetry is measured to an accuracy of 2×10^{-3} [90].

2.5 CP effects in $\{D, \bar{D}\}$-system decays

The phenomenology of CP violation in $\{D^0, \bar{D}^0\}$ meson system decays is analogous to that in $\{K^0, \bar{K}^0\}$ decays. In a CPT-invariant theory, the states of D^0 mesons with a given mass and lifetime are

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle\,, \qquad |D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle\,. \tag{31}$$

In the case of CP invariance, $p = q = 1/\sqrt{2}$, and for small violation of it

$$\frac{p}{q} = \frac{1+\varepsilon_D}{1-\varepsilon_D}\,, \tag{32}$$

where ε_D is the small complex parameter characterizing the magnitude of CP violation.

Unlike K^0 meson decays, the lifetimes $\tau(D_1)$ and $\tau(D_2)$ in D^0 meson decays are very similar and short (about 4×10^{-13} s) which makes it difficult to observe CP effects. Therefore, despite the value [91]

$$\varepsilon_D \approx \frac{\mathrm{Im}\,V_{cs}V_{su}V_{dc}V_{du}}{\mathrm{Re}\,V_{cs}V_{su}V_{dc}V_{du}} \sim s_2 s_3 \sin\delta \sim |\varepsilon_K| \sim 10^{-3}\,, \tag{33}$$

expected in SM, no CP violation has yet been recorded in decays of the system of $\{D^0, \bar{D}^0\}$ mesons.

In semi-leptonic decays, the vacuum transitions $D^0 \leftrightarrow \bar{D}^0$ result in the decays of the pair $D^0\bar{D}^0$ not only into the state $(K^-\mu^+\nu_\mu)(K^+\mu^-\bar{\nu}_\mu)$ but also into the states $(K^+\mu^-\bar{\nu}_\mu)(K^+\mu^-\bar{\nu}_\mu)$ and $(K^-\mu^+\nu_\mu)(K^-\mu^+\nu_\mu)$. If the numbers of such rare pairs are denoted by N^{++} and N^{--}, the expression for CP-violating charge asymmetry is given by the following formula [92]:

$$\delta_D = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \frac{4\,\mathrm{Re}\,\varepsilon_D\left(1 + |\varepsilon_D|^2\right)}{\left(1 + |\varepsilon_D|^2\right)^2 + 4(\mathrm{Re}\,\varepsilon_D)^2} \approx 4\,\mathrm{Re}\,\varepsilon_D\,. \tag{34}$$

In the case of the coherent production of D^0 and $\bar{D}^0$ mesons in a state with even orbital moment, the CP-odd asymmetry of pairs $N_- = (l^-X^+, K^+K^-)$ and $N_+ = (l^+X^-, K^+K^-)$ could be observed [93]:

$$\frac{N_- - N_+}{N_- + N_+} = -\frac{2x_D}{(1+x_D)^2}\,\mathrm{Im}\left(\frac{q}{p}\frac{\bar{M}}{M}\right), \tag{35}$$

where $x_D = \Delta m_D/\Gamma_D$, $\Delta m_D = M = m_{D_1} - m_{D_2}$, and $\bar{M}/M$ is either V_{cs}/V_{cs}^* or V_{cd}/V_{cd}^*. In SM, the quantity Δm_D arising from the 'box' diagram is very small [94]:

$$\Delta m_D \approx 0.5\times 10^{-8}\left(\frac{m_s}{0.2\ \mathrm{GeV}}\right)^4 \frac{f_D}{f_\pi}\,, \tag{36}$$

while the contribution of large distances can enlarge Δm_D to no more than 10^{-7} eV [95].

Because $\Gamma_D^{\exp} \approx 1.5\times 10^{-3}$ eV [78] and

$$\mathrm{Im}\left(\frac{q}{p}\frac{\bar{M}}{M}\right) \sim O(s_1^4) \sim 3\times 10^{-3}$$

[96], the asymmetry (35) expected in SM is of the order of $10^{-6}-10^{-7}$. This example shows that the smallness of the $D^0 \leftrightarrow \bar{D}^0$ mixing makes the associated CP effects extremely small. A consideration of CP effects produced by the interference between the CP-violating phase and the phases of final particle rescattering leads to a similar conclusion in the framework of SM [96]. This mechanism of CP violation is also realized in decays of charged D mesons.

If the amplitude of D^+ meson decays

$$A = a\exp i\delta_1 + b\exp i\delta_2\,,$$

and the corresponding CP-conjugate amplitude

$$\bar{A} = a^*\exp i\delta_1 + b^*\exp i\delta_2\,,$$

where $\delta_{1,2}$ are the phases of final particles rescattering, then the CP-violating amplitude is given by the formula

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = \frac{2\,\mathrm{Im}\,(ab^*)\sin(\delta_2 - \delta_1)}{|a|^2 + |b|^2 + 2\,\mathrm{Re}\,(ab^*)\cos(\delta_2 - \delta_1)}\,.$$

For two-particle Cabibbo-forbidden decays of $D^\pm$ mesons, such as $D^+ \to \rho^+\pi^0, \bar{K}^{*0}K^+$, the value of A_{CP} is expected to be close to 3×10^{-3} and for $D_s^+ \to K^{*+}\pi^0, K^{*+}\eta'$ decays, at a level of $(6-8)\times 10^{-3}$. These estimates were made in Ref. [97], where a number of other two-particle decays were also considered.

The results of experiments in the quest for CP violation in D meson decays have been summarized in Ref. [98]. Currently, the errors of A_{CP} measurement for different modes of $\mathrm{D}^0_{\mathrm{tag}}$ and D^+ meson decays[6] range from 1 to 8%. Mean asymmetry values are of the same order. If they do not change with the further improvement of the measurement accuracy, this will suggest other sources of CP violation, beyond the KM phase in SM.

2.6 CP invariance violation in $\{\mathrm{B}^0, \bar{\mathrm{B}}^0\}$-system decays

It has been mentioned above that the smallness of CP violation in decays of the $\{\mathrm{K}^0, \bar{\mathrm{K}}^0\}$ meson system is incidentally associated with the smallness of the parameters $s_i = \sin\theta_i$ that appear in the K decay amplitude and with the fact that the direct violation of CP symmetry does not play any important role in $\mathrm{K}_L \to 2\pi$ transitions. For a system of $\{\mathrm{B}^0, \bar{\mathrm{B}}^0\}$ mesons, the parameter ε_{B} is also small (of the order of $10^{-4}-10^{-3}$). However, the CP-odd parts of the quark amplitudes

$$\mathrm{b} \to \mathrm{c}\bar{\mathrm{c}}\mathrm{s}\,, \quad \mathrm{b} \to \mathrm{u}\bar{\mathrm{u}}\mathrm{d}$$

are large and appear as early as at the 'tree' level. Therefore, the *time-dependent* CP-violating asymmetry

$$A_{\mathrm{B}}(\tau) = \frac{\Gamma(\mathrm{B}^0_{t=0} \to \mathrm{f}_{t=\tau}) - \Gamma(\bar{\mathrm{B}}^0_{t=0} \to \mathrm{f}_{t=\tau})}{\Gamma(\mathrm{B}^0_{t=0} \to \mathrm{f}_{t=\tau}) + \Gamma(\bar{\mathrm{B}}^0_{t=0} \to \mathrm{f}_{t=\tau})} \tag{37}$$

(f being the state with a definite CP parity) in certain processes, e.g. in the decays

$$\{\mathrm{B}^0, \bar{\mathrm{B}}^0\} \to \mathrm{J}/\psi\mathrm{K}_S\,, \qquad \{\mathrm{B}^0, \bar{\mathrm{B}}^0\} \to \pi^+\pi^-\,,$$

may be of the order of unity.

In a 'tree' approximation, there is a simple proportionality of the $A_{\mathrm{B}}(\mathrm{J}/\psi\mathrm{K}_S)$ and $A_{\mathrm{B}}(\pi^+\pi^-)$ asymmetries to the combinations of the CKM matrix parameters known as the sines of the double angles α and β in the unitarity triangle depicted in Fig. 3 (see Refs [99, 79]):

$$A_{\mathrm{B}}(\mathrm{J}/\psi\mathrm{K}_S) \sim \sin 2\beta = \frac{2\eta(1-\rho)}{\eta^2 + (1-\rho)^2}\,, \tag{38}$$

$$A_{\mathrm{B}}(\pi^+\pi^-) \sim \sin 2\alpha = \frac{2\eta\left[\eta^2 + \rho(\rho-1)\right]}{\left[\eta^2 + (1-\rho)^2\right]\left[\eta^2 + \rho^2\right]}\,, \tag{39}$$

where η and ρ are the parameters of matrix (6).

The above triangle reflects the property of orthogonality of CKM matrix columns [100]. Specifically, the orthogonality of the first and third columns gives the relation

$$V_{\mathrm{ud}}V^*_{\mathrm{td}} + V_{\mathrm{us}}V^*_{\mathrm{ts}} + V_{\mathrm{ub}}V^*_{\mathrm{tb}} = 0\,,$$

which, since

$$V_{\mathrm{ud}} \simeq V_{\mathrm{tb}} \simeq 1\,, \qquad V^*_{\mathrm{ts}} \simeq -V_{\mathrm{cb}}\,,$$

turns into

$$V_{\mathrm{ub}} + V^*_{\mathrm{td}} = V_{\mathrm{us}}V_{\mathrm{cb}}\,, \tag{40}$$

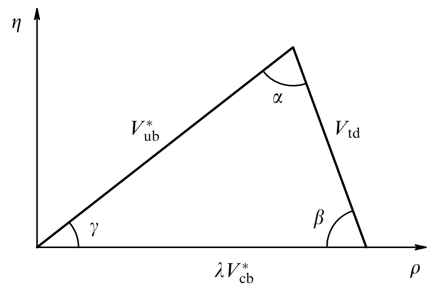

Figure 3. Representation of the unitarity triangle formed by the matrix elements V^*_{ub}, V_{td}, and $\lambda V^*_{\mathrm{cb}}$ of the CKM matrix (6) in the complex plane.

representable in the complex plane of parameters ρ and η in the form of a triangle (see Fig. 3).

Therefore, the observation of CP-odd asymmetries in B meson decays allows, in principle, specifying the parameters of the CKM matrix. Unfortunately, simple relations of the 'tree' approximation are violated if the contribution of 'penguin' diagrams is taken into account [101], and $\sin 2\beta$ and $\sin 2\gamma$ can be determined in this case only with the aid of more sophisticated measuring schemes. For example, the probability of $\mathrm{B}^0 \to 2\pi$, $\mathrm{B}^+ \to \pi^+\pi^0$ decays and their charge-conjugate counterparts needs to be evaluated to find the 'tree' contribution to the asymmetry $A_{\mathrm{B}}(\pi^+\pi^-)$. Such an assessment allows the identification of the amplitude of the transition into state 2π with an isospin of $T = 2$, which is insensitive to 'penguin' diagrams. The calculation of these diagrams contains theoretical uncertainties [102].

The uncertainties related to the contribution of 'penguin' diagrams can be eliminated by measuring the asymmetries of B meson decays into CP-mixed states [103]. Technical details concerning the determination of CKM matrix parameters from B meson decays can be found in Refs [104, 105].

Turning back to the subject of the magnitude of potential CP-odd effects, it is worthwhile to note that in decays $\mathrm{B}^0, \bar{\mathrm{B}}^0 \to \mathrm{J}/\psi\mathrm{K}_S$ at a mean value[7] of $\sin 2\beta \simeq 0.7$ the following integral asymmetry was expected [107]:

$$A_{\mathrm{B}}(\mathrm{J}/\psi\mathrm{K}_S) \simeq -0.47\sin 2\beta \simeq -0.3\,.$$

Recent measurements yielded [108]

$$\sin 2\beta = 0.79 \pm 0.43\,. \tag{41}$$

Although the mean $\sin 2\beta$ turned out to be close to the expected value, ensuing from the experimental constraints on the parameters of the CKM matrix, the large error in (41) indicates that a reliable confirmation of SM predictions remains to be obtained. It should be recalled that a previous measurement [109] gave $\sin 2\beta > 1$.

For charged B mesons, the asymmetries are expected to be at a level of a few percent or less [110] and in semi-leptonic decays at a level of [111]

$$A_{\mathrm{B_d}}(l^\pm\nu\mathrm{X}) \leqslant (1-3)\times 10^{-3}\,, \qquad A_{\mathrm{B_s}}(l^\pm\nu\mathrm{X}) \leqslant O(10^{-4})\,.$$

2.7 Search for T invariance violation in processes with a change of strangeness

A test of T-invariance implies a comparison of direct and reverse reactions. It was first undertaken for the system of

[6] D mesons are formed in $\mathrm{D}^0, \bar{\mathrm{D}}^0$ pairs. The sign of the lepton charge in the decay of one of the mesons indicates whether it was a D^0 or $\bar{\mathrm{D}}^0$ decay. Then, the other meson that decayed into hadrons can be classified as a particle or antiparticle. This is called a 'tagged' meson.

[7] In agreement with the CKM matrix parameters $0.55 \leqslant \sin 2\beta \leqslant 0.94$ in Ref. [106].

$\{K^0, \bar{K}^0\}$ mesons by the CPLEAR collaboration in 1998 [112]. Since a weak interaction does not conserve strangeness, a propagating K^0 meson may transform into $\bar{K}^0$; and vice versa, a $\bar{K}^0$ meson may transform into K^0.

T invariance means that all characteristics of the latter process can be derived from the former. In particular, the probability P that a particle produced at time $t = 0$ as K^0 will be observed as $\bar{K}^0$ after a time τ should equal the probability that a particle produced at time $t = 0$ as $\bar{K}^0$ will be observed as K^0 after the same time τ has elapsed. In other words, the difference of the asymmetry

$$\frac{P(\bar{K}^0 \to K^0)_\tau - P(K^0 \to \bar{K}^0)_\tau}{P(\bar{K}^0 \to K^0)_\tau + P(K^0 \to \bar{K}^0)_\tau}$$

from zero characterizes the magnitude of T invariance violation.

In the CPLEAR experiment, the type of a neutral K meson produced at time $t = 0$ was determined from its charged partner in the reaction

$$\bar{p}p \to \begin{cases} K^-\pi^+K^0 \,, \\ K^+\pi^-\bar{K}^0 \,, \end{cases}$$

while the fact of $K^0 \to \bar{K}^0$ and $\bar{K}^0 \to K^0$ transformations after time τ was documented based on the decay into the mode $e^+\pi^-\nu$ permitted by the $\Delta Q = \Delta S$ rule for K^0 or into the mode $e^-\pi^+\bar{\nu}$ permitted for $\bar{K}^0$.

Measurements in the time interval $\tau_S < \tau < 20\tau_S$ (where τ_S is the lifetime of K_S meson) gave the following result:

$$\frac{P(\bar{K}^0_{t=0} \to (e^+\pi^-\nu)_{t=\tau}) - P(K^0_{t=0} \to (e^-\pi^+\bar{\nu})_{t=\tau})}{P(\bar{K}^0_{t=0} \to (e^+\pi^-\nu)_{t=\tau}) + P(K^0_{t=0} \to (e^-\pi^+\bar{\nu})_{t=\tau})} = (6.6 \pm 1.6) \times 10^{-3} \,. \quad (42)$$

This value agrees with the expected one in the case of CPT invariance:

$$4\,\mathrm{Re}\,\varepsilon = (6.04 \pm 0.02) \times 10^{-3} \,.$$

It should be recalled that T invariance violation in SM is due to the same causes as CP violation, which accounts for their correlation.

Another way to test T invariance consists in the examination of effects arising in the absence of T invariance-associated constraints on the form factors of the amplitude of the process, i.e. when the form factors, which must be either purely real or purely imaginary in the case of T invariance, become complex. The resultant T-odd correlations between particle momenta or between particle spins and momenta are proportional to $\sin\chi_{ij}$, where χ_{ij} is the phase difference between the form factors in channels i and j of the process. Since the phase shift may be also due to a T-invariant interaction in the final state, the full value of the correlation considered is actually dependent on $\sin(\chi_{ij} - \delta_i + \delta_j)$, where δ_i and δ_j are the rescattering phases of final particles in channels i and j of the reaction.

For strongly interacting particles, the phases δ_i and δ_j are rather large, and their measurement accuracy does not yet exceed a few degrees. The phases resulting from weak T noninvariance are small; therefore, search for T-odd effects is based on the processes in which interactions between final particles can be neglected taking into account the expected measurement accuracy. Such processes are [113,114]

$$K^+ \to \pi^0\mu^+\nu \,, \qquad K^+ \to \gamma\mu^+\nu \,, \qquad K^+ \to \pi^0 l^+\nu\gamma \,.$$

The corresponding T-odd correlations have the form

$$\boldsymbol{\sigma}_\mu[\mathbf{p}_\mu \times \mathbf{p}_\pi] \,, \qquad \boldsymbol{\sigma}_\mu[\mathbf{p}_\mu \times \mathbf{p}_\gamma] \,, \qquad \mathbf{p}_\pi[\mathbf{p}_l \times \mathbf{p}_\gamma] \,.$$

In the $K^+_{\mu 3}$ decay, the hadronic component of the matrix element contains two form factors:

$$\langle \pi(p)|J^W_\alpha|K(k)\rangle = f_+(q^2)(p+k)_\alpha + f_-(q^2)(p-k)_\alpha \,,$$

where $q^2 = (k-p)^2$. The transverse polarization of a muon is proportional to the imaginary part of the ratio of two form factors:

$$P^\mu_\perp \sim \mathrm{Im}\left(\frac{f_-}{f_+}\right) \boldsymbol{\sigma}_\mu[\mathbf{p}_\mu \times \mathbf{p}_\pi] \,.$$

The $P^\mu_\perp$-dependence of the differential probability of the decay was calculated in Ref. [115], which also contains references to previous publications. In SM, a transverse polarization of a muon is absent in the 'tree' approximation, and a simulation of the T violation resulting from the electromagnetic interaction in the final state in $K^0 \to \pi^-\mu^+\nu$ and $K^+_{\mu 3}$ decays leads to $P^\mu_\perp \sim 2 \times 10^{-3}$ [115] and $P^\mu_\perp \sim 10^{-6}$ [116], respectively. For this reason, the ongoing studies of $P^\mu_\perp$ in the $K^+ \to \pi^0\mu^+\nu$ decay have the objective to find other mechanisms of violation of T invariance and, therefore, CP invariance (CP violation in the multi-Higgs sector of extended SM in particular). The effect and the accuracy of $P^\mu_\perp$ measurement achieved in these studies will be evaluated in Section 3.3 below.

In the case of the $K^+ \to \mu^+\nu\gamma$ decay, the average transverse polarization of a muon attributable to T-odd electromagnetic interactions between final particles and imitating T invariance violation is expected to occur at a level of 4×10^{-4} [117].

Such T-odd characteristics of elementary particles also include their electric dipole moments considered in the next section.

2.8 T and CP effects in processes with flavor conservation

It has been mentioned that SM may contain another source of CP violation, besides the Kobayashi–Maskawa phase (KM phase), e.g. the θ-term in the gluonic part of the strong-interaction Lagrangian. This source is important only for processes proceeding without a change in flavor. Therefore, two cases, $\theta = 0$ and $\theta \neq 0$, must be distinguished if these processes are to be considered.

The $\theta = 0$ case. In processes with flavor conservation, CP effects in the first order in G_F are absent because in this case the amplitudes are proportional to the product of CKM matrix elements $V_{ij}V^*_{ij}$ (no summation over dummy indices) lacking in the KM phase. In the second order in G_F, imaginary parts of the amplitude appear; they are proportional to

$$\mathrm{Im}\,(V_{ij}V^*_{kj}V_{kl}V^*_{il}) \,, \qquad \mathrm{Im}\,(V_{il}V^*_{kl}V_{kj}V^*_{ij})$$

(again, without summation over dummy indices). For the observed CP- and T-odd effects to be manifest, these two parts (opposite in charge) should not cancel each other.

As a result, there is an additional dynamic suppression of the observed effects, besides the suppression due to the factor G_F^2. In particular, this can be exemplified by the electric dipole moments (EDM) of elementary particles.

The EDM of the neutron. The EDM of a system of charges is

$$\mathbf{D} = \int \mathbf{r}\rho(\mathbf{r})\,\mathrm{d}^3 r\,,$$

where $\rho(\mathbf{r})$ is the charge distribution density; it is a polar vector, whose interaction with the electric field is T-invariant. In the case of an elementary particle, the sole spatial vector in its rest system is the spin (an axial vector), and the $\boldsymbol{\sigma}\mathbf{E}$ interaction results in P and T, and hence CP, violation.

Similar to the charge and magnetic moment, the EDM of the baryon is a static limit to the effective vertex of baryon–electromagnetic field interaction. For this reason, the EDM of the baryon, similar to the baryon electromagnetic moment, which can be expressed through the magnetic moments of the constituent quarks (see, for instance, Ref. [118]), can be considered in the framework of the static SU(6)-symmetry. Assuming that the baryons of an octet with $J^P = (1/2)^+$ are three-quark states with $L = 0$ and the permutation quark symmetry in the nucleon is the SU(6) symmetry, the following expression can be derived for the EDM of the neutron:

$$d_\mathrm{n} \approx \frac{4}{3}\,d_\mathrm{d} - \frac{1}{3}\,d_\mathrm{u}\,.$$

In a Lorentz-covariant representation, the interaction between the quark EDM and the electromagnetic field tensor has the form

$$L = \frac{\mathrm{i}}{2}\,d\bar{q}\left(p + \frac{k}{2}\right)\gamma_5\sigma_{\mu\nu}\,q\left(p - \frac{k}{2}\right)F_{\mu\nu}(k)\,. \tag{43}$$

Here, q is the four-dimensional spinor of the quark field. In the nonrelativistic limit, this interaction assumes the form

$$L^{\text{non-rel}} = d\boldsymbol{\sigma}\mathbf{E}\,,$$

where $\boldsymbol{\sigma}$ is the spin vector. Hence, the EDM is characterized by the quantity d and measured in units of electric charge multiplied by unit length.

As has already been mentioned, the quark EDM can be induced in the G_F^2 order. The EDM of, say, a d-quark can be nonzero if the imaginary parts of the diagrams in Fig. 4 (differing by an inner quark permutation) do not compensate each other.

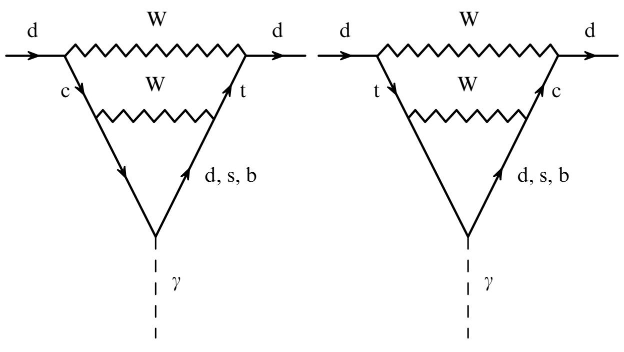

Figure 4. Two-loop diagrams with non-zero contributions to the quarks EDM, which are, however, nullified in the sum of the diagrams.

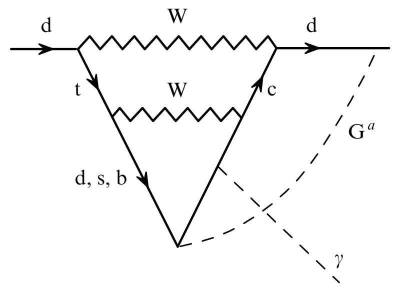

Figure 5. Three-loop diagram contributing to the quark EDM.

However, as shown in Refs [119, 120], such a compensation does take place, and only the difference in t(c)-quark propagation conditions possible in the case of the exchange of an additional virtual gluon [121] can lead to an EDM $d_\mathrm{d} \neq 0$. But the value of $d_\mathrm{d}/e \sim 10^{-34}$ cm reported in [121] appears to be underestimated. The thing is that the calculation of diagrams exemplified by Fig. 5 gives an expression having the following structure:

$$\bar{q}(p)(a\hat{p} + m_q)\sigma_{\mu\nu}\gamma_5 q(p-k)\,F_{\mu\nu}(k)\,.$$

Here, $|a| \sim 1$, and m_q is the mass of a quark in the loop containing a gluon G^a connected with the external quark line.

Since

$$\bar{q}(p)\,\hat{p} = M_q\,\bar{q}(p)\,,$$

where M_q is the outer quark mass, it is important for the final estimate of the EDM whether the outer quarks are considered to be current or constituent ones. Ref. [121] considered the current mass, in conflict with the use of the static approximation to express the neutron EDM via the EDMs of individual quarks. Conversely, if M_q is the constituent mass, the EDM of the d-quark (hence of the neutron) increases by two orders of magnitude, in agreement with the value of $d_\mathrm{n}/e \sim 10^{-32}$ cm obtained in Ref. [120] with interquark forces in the neutron taken into account.

Such a small EDM of the neutron predicted by SM leaves no hope for measuring it in the near future. Suffice it to recall that the result

$$\left|\frac{d_\mathrm{n}}{e}\right| < 1.6\times10^{-24}\ \text{cm}$$

obtained by Lobashov and his co-workers in 1979 [122] with a specific sophisticated technique was reduced by the same authors in 1992 [123] to the value

$$\left|\frac{d_\mathrm{n}}{e}\right| < 1.1\times10^{-25}\ \text{cm}\,.$$

During the next 7 years, the upper limit was lowered only to the value [124]

$$\left|\frac{d_\mathrm{n}}{e}\right| \leqslant 6\times10^{-26}\ \text{cm}\,. \tag{44}$$

Therefore, there is no chance to experimentally verify the SM prediction for d_n. Nevertheless, a further improvement of the

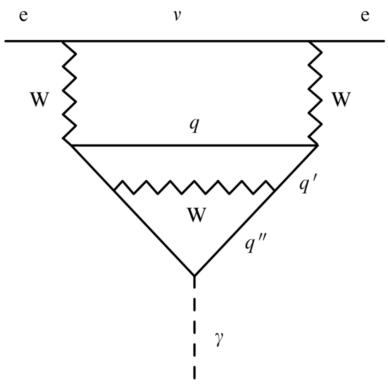

Figure 6. Three-loop diagram making a nonzero contribution to the electron EDM, which is, however, cancelled after the summation of all three-loop diagrams.

measurement accuracy for the EDM of the neutron is of primary importance because other sources of CP- and T-invariance violation (considered below) do not exclude d_{n} values close to the known upper bound.

The EDM of the electron. The EDM of the electron in SM might be induced by the inner quark loops in three-loop diagrams such as shown in Fig. 6, that is, due to the EDM of the vector W-boson. This is not the case, however [125], for the same reason for which the EDM of the quark vanishes in the two-loop approximation [119,120]. The exchange of a virtual gluon can alter the situation; in this case (in accord with the optimistic estimate [126]), the EDM of the W-boson is expected to be

$$\left|\frac{d_{\mathrm{W}}}{e}\right| \sim 8 \times 10^{-30}\ \mathrm{cm}\,.$$

The integral over the upper loop of the diagram in Fig. 6 gives [127]

$$d_{\mathrm{e}} = -\frac{G_{\mathrm{F}} m_{\mathrm{e}} M_{\mathrm{W}}}{4\sqrt{2}\,\pi^2}\left[\ln\frac{\Lambda^2}{M_{\mathrm{W}}^2} + O(1)\right] d_{\mathrm{W}}\,.$$

Hence, the expected value of d_{e}, if the term in brackets equals unity, is [8]

$$\left|\frac{d_{\mathrm{e}}}{e}\right| \sim 6 \times 10^{-38}\ \mathrm{cm}\,. \qquad (45)$$

A more conservative estimate gives [128]

$$\frac{d_{\mathrm{e}}}{e} < 10^{-40}\ \mathrm{cm}\,. \qquad (46)$$

An experimental constraint on d_{e} is [129]

$$\left|\frac{d_{\mathrm{e}}^{\mathrm{exp}}}{e}\right| < 4 \times 10^{-27}\ \mathrm{cm}\,. \qquad (47)$$

Decays η, $\eta' \to 2\pi$. These decays are known to violate P and CP invariance [130]; they are possible due to the transition of η, η' into the transient states $\mathrm{K}^0, \bar{\mathrm{K}}^0$, $\mathrm{B}^0, \bar{\mathrm{B}}^0$, etc., which in turn pass to the system 2π. It has been calculated [131] that the KM-phase-induced $\langle \mathrm{K}_S|\eta\rangle$- and $\langle 2\pi|\mathrm{K}_S\rangle$-transition phases partly cancel each other, and the relative probability of the decay is

$$\mathrm{Br}\,(\eta \to \pi^+\pi^-) = 2\mathrm{Br}\,(\eta \to \pi^0\pi^0) \simeq (6.6^{+6.3}_{-3.2}) \times 10^{-28} \sin^2\delta\,. \qquad (48)$$

The relative probability of the decay $\eta' \to 2\pi$ proves to be even 40 times smaller. Therefore, the relative probabilities of the $\eta, \eta' \to 2\pi$ decays are too small to be observed in experiment.

The case of $\theta \neq 0$. In the language of effective pion–nucleon Lagrangians, the θ-term leads to the replacement of the real nucleon mass m by $m + \mathrm{i}\mu\gamma_5$ [132], to the substitution of the interaction $\mathrm{i}\bar{N}\gamma_5\boldsymbol{\tau}N\boldsymbol{\pi}$ by $\bar{N}(\mathrm{i}\gamma_5 + \varepsilon)\boldsymbol{\tau}N\boldsymbol{\pi}$, or to the appearance of the transition $\boldsymbol{\pi\sigma}$ and the contact vertex $\boldsymbol{\pi\pi}\eta_0$, where $\boldsymbol{\sigma}$ is the isotriplet scalar meson with a mass of the order of 1 GeV and η_0 is the singlet pseudoscalar meson with a mass of 958 MeV [134].

Calculations taking into consideration these possibilities for the EDM of the neutron give [132, 133]

$$\left|\frac{d_{\mathrm{n}}}{e}\right| = (2-3.6) \times 10^{-16}|\theta|\ \mathrm{cm}\,. \qquad (49)$$

The estimate in the Skyrme neutron model [135] yields [136, 137]

$$\left|\frac{d_{\mathrm{n}}}{e}\right| = (1.2-2) \times 10^{-16}|\theta|\ \mathrm{cm}\,. \qquad (50)$$

We conclude from the comparison of (49) and (50) with the experimental finding (44) that

$$|\theta| \leqslant 3 \times 10^{-10}\,. \qquad (51)$$

Calculations for the $\eta \to 2\pi$ decay induced by the θ-term lead to [133, 138]

$$\mathrm{Br}\,(\eta \to 2\pi) \simeq 350\,\theta^2\,. \qquad (52)$$

Hence,

$$\mathrm{Br}\,(\eta \to 2\pi)_\theta \leqslant 3 \times 10^{-17}\,. \qquad (53)$$

Although this is ten orders of magnitude higher than at $\theta = 0$, such a small decay is unobservable. At present, the experimental values are $\mathrm{Br}\,(\eta \to 2\pi^0) < 4.3 \times 10^{-4}$ [78, 139], whence $|\theta| \leqslant 2 \times 10^{-3}$.

3. CP and T invariance violation in the theory with an extended Higgs field sector

The simplest extension of SM is an increase in the number of Higgs' doublets. In such a theory, the vacuum expectation values of the neutral (but complex) fields H_i^0 may be phase shifted; moreover, the Higgs field potential may contain complex coupling constants. This results in an additional source of CP violation, which alters the general aspect and quantitative results of the minimal SM.

Although the introduction of additional Higgs doublets looks at first sight like an unwarranted complication of SM, nature itself appears to demand it. In particular, the supersymmetric extension of SM (SUSY) requires two Higgs'

[8] A numerical error in the recalculation from d_{W} to d_{e} in Ref. [126] is responsible for the underestimation of d_{e} by three orders of magnitude.

doublets, and a solution to the problem of baryogenesis in the Universe is possible (see Section 1) if new sources of CP violation are available. On the contrary, the source of CP-violation in the multi-Higgs sector of the theory is in principle sufficient for the solution of this problem [140].

The renormalizable potential of the Higgs fields forming the doublets

$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix},$$

can be chosen in a form invariant with respect to the discrete transformation[9] $\Phi_1 \to -\Phi_1$ (or $\Phi_2 \to -\Phi_2$):

$$\begin{aligned} V(\Phi_1, \Phi_2) = &-\mu_1^2 \Phi_1^\dagger \Phi_1 - \mu_2^2 \Phi_2^\dagger \Phi_2 + h_1 (\Phi_1^\dagger \Phi_1)^2 \\ &+ h_2 (\Phi_2^\dagger \Phi_2)^2 + f_{12} (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + g_{12} (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ k_{12} (\Phi_1^\dagger \Phi_2)^2 + k_{12}^* (\Phi_2^\dagger \Phi_1)^2 , \end{aligned} \tag{54}$$

where all the constants except k_{12} are real because the Hamiltonian is Hermitian.

Spontaneous symmetry violation means that the neutral components of the doublets acquire vacuum expectation values v_1 and v_2:

$$\Phi_1^0 = \frac{v_1}{\sqrt{2}} \left(1 + \frac{\mathrm{H}_1 + \mathrm{i}\chi_1}{|v_1|} \right), \quad \Phi_2^0 = \frac{v_2}{\sqrt{2}} \left(1 + \frac{\mathrm{H}_2 + \mathrm{i}\chi_2}{|v_2|} \right);$$

$|v_1|$ and $|v_2|$ themselves and the relative phase between v_1 and v_2 are determined from the requirement that the shifted potential should contain no terms linear in the fields H_1 and H_2 or $(\chi_1/|v_1| - \chi_2/|v_2|)$. In this case, the vacuum field values correspond to the minimal potential.

Among the constraints that arise, a necessary condition is, in particular,

$$B_3 \equiv \mathrm{Im} \left[k_{12} (v_1^* v_2)^2 \right] = 0 , \tag{55}$$

which excludes the only term suitable for the violation of CP invariance from the Higgs field mass matrix:

$$\mathrm{Im} \left[k_{12} (v_1^* v_2)^2 \right] \left(\frac{\mathrm{H}_1}{|v_1|} + \frac{\mathrm{H}_2}{|v_2|} \right) \left(\frac{\chi_1}{|v_1|} - \frac{\chi_2}{|v_2|} \right). \tag{56}$$

Due to condition (55), there is no CP violation in the Higgs sector. The situation changes in two cases.

(1) CP violation is possible if the potential $V(\Phi_1, \Phi_2)$ is supplemented by a part that violates discrete symmetry with respect to the substitution $\Phi_1 \to -\Phi_1$, e.g. if we add

$$V' = \mu'^2 \Phi_1^\dagger \Phi_2 + \mathrm{H.c.}$$

with a complex constant μ'^2. In this case, however, a flavor-changing interaction between neutral currents occurs, besides CP violation. In order to avoid contradiction with the absence of such interactions in experiment, the constant μ'^2 must be sufficiently small.

(2) In a theory lacking flavor-changing neutral currents, CP symmetry can be broken if the number of Higgs doublets is increased to at least three [141]. In this case, the Higgs potential can be obtained from $V(\Phi_1, \Phi_2)$ by increasing the number of indices to three. The constructions B_1, B_2, B_3 with different permutations of indices appear instead of B_3, while condition (55) is replaced by the condition [142]

$$B_1 = B_2 = B_3 \equiv B , \tag{57}$$

where B is no longer necessarily zero, as the two-doublet case required.

In the 3×3 mass matrix for the charged states Φ_1^+/v_1, Φ_2^+/v_2, Φ_3^+/v_3, there are CP-odd elements:

$$\begin{pmatrix} 0 & \mathrm{i}B & -\mathrm{i}B \\ -\mathrm{i}B & 0 & \mathrm{i}B \\ \mathrm{i}B & -\mathrm{i}B & 0 \end{pmatrix}.$$

For the flavor to be naturally conserved in the interaction of neutral currents, a necessary condition arises according to which the doublet Φ_1 gives masses to 'up' quarks $U_j = \mathrm{u}, \mathrm{c}, \mathrm{t}$, the doublet Φ_2 to 'down' quarks $D_j = \mathrm{d}, \mathrm{s}, \mathrm{b}$, and the doublet Φ_3 does not interact with quarks at all [141]. Then, a change in flavor is possible only due to an exchange by charged W bosons and charged Higgs bosons. In the latter case, the Lagrangian has the form

$$\begin{aligned} L_{\mathrm{W}} = &-\frac{\Phi_1^{+*}}{v_1^*} (m_{\mathrm{d}} \bar{\mathrm{d}}_R V_{1j} + m_{\mathrm{s}} \bar{\mathrm{s}}_R V_{2j} + m_{\mathrm{b}} \bar{\mathrm{b}}_R V_{3j}) \mathrm{u}_{Lj} \\ &+ \frac{\Phi_2^+}{v_2} (m_{\mathrm{u}} \bar{\mathrm{u}}_R V_{j1} + m_{\mathrm{c}} \bar{\mathrm{c}}_R V_{j2} + m_{\mathrm{t}} \bar{\mathrm{t}}_R V_{j3}) \mathrm{d}_{Lj} + \mathrm{H.c.}, \end{aligned} \tag{58}$$

where V_{ij} are the elements of the CKM matrix and the indices L and R indicate left-handed and right-handed quarks, respectively.

The appearance of the elements V_{ij} in (58) is related to the fact that the interaction between quarks and Higgs bosons has the form

$$L_{qq\Phi} = g_{ij}^a \bar{q}_{Li} \Phi_{ij}^a q_{Rj} + \mathrm{H.c.}$$

Here, q_{Rj} are singlets in the weak isospin space and q_{Li} are the doublets

$$\begin{pmatrix} \mathrm{u} \\ \mathrm{d}' \end{pmatrix}_L, \quad \begin{pmatrix} \mathrm{c} \\ \mathrm{s}' \end{pmatrix}_L, \quad \begin{pmatrix} \mathrm{t} \\ \mathrm{b}' \end{pmatrix}_L,$$

while the structure of d', s', b' (as CKM-mixed combinations of quarks with charge $-1/3$) is fixed by the gauge interaction with W-bosons, i.e. by the matrix (5).

For the mass matrix of the quark Lagrangian to be diagonal, q_{Rj} must be taken in the form

$$q_{Rj} = \mathrm{u}_R, \ \mathrm{c}_R, \ \mathrm{t}_R, \ \mathrm{d}_R, \ \mathrm{s}_R, \ \mathrm{b}_R .$$

It follows from expression (58) that phases v_1 and v_2 may be assumed to be arbitrary phases of charged Higgs mesons, and CP violation is characterized by the single parameter B defined by formula (57). In the literature, other parametrizations of CP violation in the Higgs sector are used as well, e.g., in Refs [141, 143],

$$\mathrm{Im}\, A \equiv \frac{\langle 0 | T\{\Phi_1^{+*} \Phi_2^+\} | 0 \rangle}{v_1^* v_2} . \tag{59}$$

[9] This kind of discrete symmetry makes it possible to eliminate the interaction of neutral flavor-changing quark currents in processes with intermediate Higgs mesons [141].

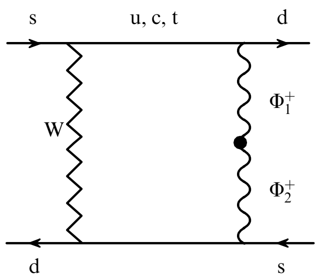

Figure 7. Diagram contributing to the parameter ε in the Weinberg theory.

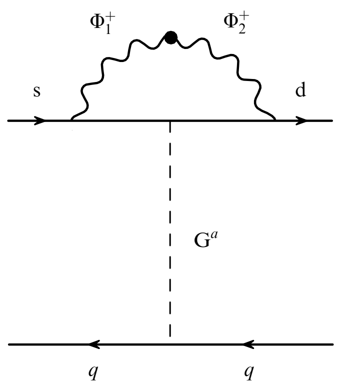

Figure 8. Diagram contributing to the operator O_1^{W} that arises in the Weinberg CP violation theory.

Were the Weinberg mechanism the sole source of CP violation, the value of $\operatorname{Im} A$ could be obtained from the comparison of the amplitude corresponding to the diagram in Fig. 7 and the parameter ε observed in the $\mathrm{K}_L \to 2\pi$ decays. However, the substitution of this value of $\operatorname{Im} A$ into the diagram in Fig. 8 would give too large an ε'/ε ratio [10] [144–146]. It should therefore be concluded that the main contribution to the parameter ε comes from other sources of CP invariance violation, e.g. the KM phase or superweak Wolfenstein interaction [62]. The Weinberg mechanism may serve as an additional source of CP violation.

3.1 The ε'/ε ratio in the theory with an additional Weinberg CP violation mechanism

As shown in Section 2.1, the theoretical values predicted by SM for the ε'/ε ratio turn out to be either significantly smaller than experimental ones or so indeterminate that their further specification does not exclude their disagreement with experiment. The Weinberg mechanism could resolve this ε'/ε ratio problem [146].

For convenience, such a possibility may be discussed using one more parametrization of CP violation in the Higgs sector, which is also known from the literature. Namely, the diagonalization of the mass part of the Lagrangian of the fields Φ_1^+ and Φ_2^+ can be used to transfer the CP violation from the non-diagonal term $\Phi_1^{+*}\Phi_2^+$ into the constants of interaction between new physical spinless fields $H_{1,2}^+$ and quark fields. Then, the interaction Lagrangian assumes the form [147, 148]

$$L = 2^{3/4} G_{\mathrm{F}}^{1/2} \bar{U} \left[M_U V \sum_{i=1}^{2} Y_i \mathrm{H}_i^+ \, \frac{1+\gamma_5}{2} - V M_D \sum_{i=1}^{2} X_i \mathrm{H}_i^+ \, \frac{1-\gamma_5}{2} \right] D \,, \tag{60}$$

where M_U and M_D are the mass matrices of 'upper' and 'lower' quarks, V is the CKM matrix, and $2^{3/4} G_{\mathrm{F}}^{1/2} X_i$ and $2^{3/4} G_{\mathrm{F}}^{1/2} Y_i$ are the complex constants to which $(v_1^*)^{-1}$ and $(v_2)^{-1}$ are converted in formula (58) after the diagonalization of the mass matrix of Higgs fields. It should be noted that $|v_1|^2 + |v_2|^2 + |v_3|^2 = (2\sqrt{2} G_{\mathrm{F}})^{-1}$. The doubling of the number of constants in (60) is due to the fact that diagonalization converts each of the fields Φ_1^+ and Φ_2^+ into a linear combination of new fields H_1^+ and H_2^+.

The consideration of CP violation can be simplified by assuming that $m_{\mathrm{H}_2} \gg m_{\mathrm{H}_1}$ and taking into account only the effects of the exchange of the lightest charged boson $\mathrm{H}_1^+ \equiv \mathrm{H}^+$. In this case, CP-odd effects are proportional to $\operatorname{Im}(XY^*)$. Surprisingly, the upper bound on this new parameter can be obtained from the data on the $\mathrm{b} \to \mathrm{s}\gamma$ decay [11] [149]:

$$\operatorname{Im}(XY^*) \leqslant \left(\frac{\operatorname{Br}(\mathrm{b} \to \mathrm{s}\gamma)}{C} \right)^{1/2} F_{\mathrm{H}}^{-1}(x) \,,$$

where $C \approx 3 \times 10^{-4}$, $x = m_{\mathrm{t}}^2 / m_{\mathrm{H}}^2$, and the function $F_{\mathrm{H}}(x)$ is found in Ref. [148].

Together with the estimate [150]

$$\operatorname{Br}(\mathrm{b} \to \mathrm{s}\gamma) = (3.11 \pm 0.80 \pm 0.72) \times 10^{-4} \,,$$

the limits are as follows:

$$\operatorname{Im}(XY^*) \leqslant 2 \,, \quad m_{\mathrm{H}} = 100 \text{ GeV} \,,$$
$$\operatorname{Im}(XY^*) \leqslant 3 \,, \quad m_{\mathrm{H}} = 175 \text{ GeV} \,,$$
$$\operatorname{Im}(XY^*) \leqslant 4.7 \,, \quad m_{\mathrm{H}} = 300 \text{ GeV} \,,$$

and the ratio of the direct CP violation parameter in the Weinberg model $\varepsilon'_{\mathrm{W}}$ to the parameter ε is given by the formula

$$\frac{\varepsilon'_{\mathrm{W}}}{\varepsilon} = \operatorname{Im}(XY^*) \times 10^{-3} \times \begin{cases} 0.846\left[1 + 0.184(1-6)\right] , & m_{\mathrm{H}} = 100 \text{ GeV} \,, \\ 0.315\left[1 + 0.364(1-6)\right] , & m_{\mathrm{H}} = 175 \text{ GeV} \,, \\ 0.117\left[1 + 0.623(1-6)\right] , & m_{\mathrm{H}} = 300 \text{ GeV} \,. \end{cases}$$

The second term in the square brackets in these relations contains an uncertainty in the value of $s_2^2 = 3.3 \times 10^{-4}(1-6)$, where s_2 is the CKM matrix parameter. This term was absent in the estimate for the effect under study given in Ref. [151] and makes the final $\varepsilon'_{\mathrm{W}}/\varepsilon$ ratio much more stable once s_2^2 is close to its upper limit. Then, $\varepsilon'_{\mathrm{W}}/\varepsilon \leqslant (2.6-3.5) \times 10^{-3}$ for $100 \leqslant m_{\mathrm{H}} \leqslant 300$ GeV.

[10] In Ref. [146], the contribution of the diagram depicted in Fig. 8 to the parameter ε' proved to be one order of magnitude smaller than in Refs [144, 145], but an additional contribution of the diagram in Fig. 9 was found which gives too large a value of ε' if $\operatorname{Im} A$ is the principal source contributing to the parameter ε.

[11] This constraint arises from the assumption that the real part of the $\mathrm{b} \to \mathrm{s}\gamma$ transition amplitude is practically non-existent because the contributions from an intermediate W-boson and intermediate Higgs' bosons cancel each other.

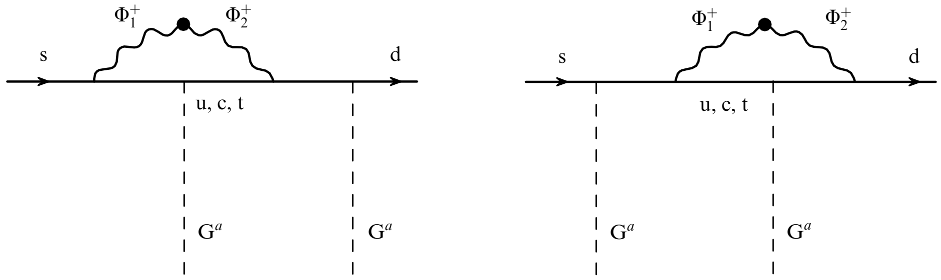

Figure 9. Diagrams producing the operator O_2^{W}.

3.2 CP effects in decays $K^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}$

The violation of CP invariance in the Higgs sector of the theory brings about additional CP-odd operators [146]

$$O_{\mathrm{W1}}^{\mathrm{CP}=-1} = \frac{g_{\mathrm{s}}\bar{C}\xi}{3m_{\mathrm{G}}^2}\left[M_{\mathrm{s}}\bar{\mathrm{s}}(1-\gamma_5)q\bar{q}(1+\gamma_5)\mathrm{d} + M_{\mathrm{d}}\bar{\mathrm{s}}(1+\gamma_5)q\bar{q}(1-\gamma_5)\mathrm{d}\right],$$

$$O_{\mathrm{W2}}^{\mathrm{CP}=-1} = \frac{g_{\mathrm{s}}\bar{C}I\zeta}{3m_{\mathrm{K}}^2}(G_{\mu\nu}^a)^2\,\bar{\mathrm{s}}(1+\gamma_5)\mathrm{d}.$$

These operators contain contributions from short- and long-range interactions, thus making it difficult to determine the renormalization coefficients ξ and ζ. If the 'clothing' of the diagrams in Figs 9 and 10 with additional virtual gluons is disregarded, then $\xi = \zeta = 1$.

In the constituent quark model, $I = 1.54$, the effective mass of the intermediate gluon G^a shown in Fig. 8 is $m_{\mathrm{G}}^2 = 0.64 m_{\mathrm{K}}^2$, $M_{\mathrm{d}} = 328$ MeV, $M_{\mathrm{s}} = 480$ MeV [146], and $\bar{C}$ is the imaginary part of the effective constant C of the quark–gluon operator

$$L(\mathrm{sdG}) = C\,\bar{\mathrm{s}}(1+\gamma_5)\sigma_{\mu\nu}\,\frac{\lambda^a}{2}\,\mathrm{d}\,G_{\mu\nu}^a.$$

In the leading momentum approximation, the new operators give

$$\left\langle \pi^+(p_1)\,\pi^+(p_2)\,\pi^-(p_3)\middle|O_{\mathrm{W1}}^{\mathrm{CP}=-1} + O_{\mathrm{W2}}^{\mathrm{CP}=-1}\middle|\mathrm{K}^+(k)\right\rangle = -\mathrm{i}(s_1+s_2-2m_\pi^2)g_{\mathrm{s}}\bar{C}r\left[\frac{\xi r(M_{\mathrm{s}}+M_{\mathrm{d}})}{6\Lambda^2 m_{\mathrm{G}}^2} + \frac{4\pi I\zeta}{27\alpha_{\mathrm{s}} m_{\mathrm{K}}^2}\right].$$

Here, $r = 2m_\pi^2/(m_{\mathrm{u}}+m_{\mathrm{d}})$, $\Lambda^2 = 0.94$ GeV^2, $m_{\mathrm{u}}+m_{\mathrm{d}} \approx 11$ MeV, $s_i = (k-p_i)^2$. In the chiral theory, Λ is the parameter of momentum expansion of the amplitudes of meson-involving processes.

The parameter $\bar{C}$ enters the expression for $\varepsilon'_{\mathrm{W}}$ and can be found on the assumption that the observed value of $\varepsilon' \simeq 2\times 10^{-3}\varepsilon^{\exp}$ is first and foremost controlled by the Weinberg CP-violation mechanism. Then, for the CP-odd effects in decays $K^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}$ considered in Section 2.2 [152],

$$\left|\frac{\Delta\Gamma}{\Gamma}\right|_{\mathrm{SM+W}} = 2.5\times 10^{-3} Z\left[1 + \frac{1.88\rho}{(\text{few})}\left(1 + 2.5\,\frac{\xi}{\zeta}\right)\right],$$
$$\left|\frac{\Delta g}{g}\right|_{\mathrm{SM+W}} = 3.8\times 10^{-2} Z\left[1 + \frac{1.88\rho}{(\text{few})}\left(1 + 2.5\,\frac{\xi}{\zeta}\right)\right], \tag{61}$$

where $\rho = (\varepsilon'/\varepsilon)^{\exp}/(2\times 10^{-3})$, $Z = 10^{-4}(\text{few})$, $(\text{few}) = 10^4\,(\varepsilon'/\varepsilon)_{\mathrm{SM}}^{\mathrm{th}}$ [see (13)]. It follows from (61) that CP effects in the decays of charged K mesons to three π mesons could be doubled via the Weinberg mechanism if $\xi \sim \zeta$.

3.3 Effect of CP violation in the Higgs sector on $K^+ \to \pi^0\mu^+\nu$ decays

As mentioned above, the transverse polarization of muons under the $K^+ \to \pi^0\mu^+\nu$ decay in SM can be expected to occur at a level of $\langle P_\perp^\mu\rangle \sim 10^{-6}$, its appearance being not related to the nonconservation of T and CP parity. This polarization is especially sensitive to the scalar interaction of hadrons and leptons (see below), and its observation at a higher level may provide data on CP violation in the scalar sector of the theory.

The amplitude of the $K_{\mu 3}$ decay can be represented in the form [153]

$$A(\mathrm{K}(k)\to\pi(p)\mu\nu) = \frac{G_{\mathrm{F}}}{2}\sin\theta_{\mathrm{C}}\left[f_+(q^2)(k+p)_\alpha + f_-(q^2)(k-p)_\alpha\right]\bar{\mu}\gamma_\alpha(1+\gamma_5)\nu$$
$$= G_{\mathrm{F}}\sin\theta_{\mathrm{C}}\,f_+(q^2)\left[k_\alpha\,\bar{\mu}\gamma_\alpha(1+\gamma_5)\nu + f_S\,m_\mu\,\bar{\mu}(1+\gamma_5)\nu\right],$$

where $f_S = (f_- - f_+)/2f_+$. Then [154],

$$\langle P_\perp^\mu\rangle = \frac{m_\mu}{m_{\mathrm{K}}}\,\frac{|\mathbf{p}_\mu|}{E_\mu + |\mathbf{p}_\mu|\,\mathbf{n}_\mu\,\mathbf{n}_\nu - m_\mu^2/M_{\mathrm{K}}}\,\mathrm{Im}\,f_S \approx 0.2\,\mathrm{Im}\,f_S.$$

In the case of the Weinberg model,

$$\mathrm{Im}\,f_S \simeq \mathrm{Im}\,(XY^*)\,\frac{v_2^2}{v_3^2}\,\frac{M_{\mathrm{K}}^2}{m_{\mathrm{H}}^2}.$$

The analysis of possible v_2/v_3 values in Ref. [155] leads to

$$\frac{v_2}{v_1} < 21\left(\frac{m_{\mathrm{H}}}{\mathrm{GeV}}\right)^{1/2},$$
$$\frac{v_2}{v_3} \leqslant \frac{1}{2\,\mathrm{Im}\,(XY^*)}\left[1 + \left(\frac{v_2}{v_1}\right)^2 + \left(\frac{v_3}{v_1}\right)^2\right]^{1/2}.$$

For $m_{\mathrm{H}} = 100$ GeV,

$$\langle P_\perp^\mu\rangle \leqslant 1.2\times 10^{-2}.$$

Recent measurements yielded [156]

$$\langle P_\perp^\mu\rangle^{\exp} = (4.2\pm 4.9\pm 0.9)\times 10^{-3}. \tag{62}$$

The accuracy achieved so far is still insufficient for a conclusion on whether the considered mechanism of CP and T violation actually exists.

3.4 The neutron EDM in the Weinberg model

As mentioned above, the EDM of the neutron can be obtained by the summation of the EDMs of individual constituent quarks. These EDMs are (see, for instance, Ref. [148])

$$d_{\mathrm{d}} = \frac{\sqrt{2} G_{\mathrm{F}} e}{12\pi^2}\, m_{\mathrm{d}} \sum_{q=\mathrm{u,c,t}} |V_{q\mathrm{d}}|^2 \,\mathrm{Im}\,(XY^*)\, F_{\mathrm{d}}(x_q)\,,$$

$$d_{\mathrm{u}} = \frac{\sqrt{2} G_{\mathrm{F}} e}{12\pi^2}\, m_{\mathrm{u}} \sum_{q=\mathrm{d,s,b}} |V_{\mathrm{u}q}|^2 \,\mathrm{Im}\,(XY^*)\, F_{\mathrm{u}}(x_q)\,,$$

where

$$F_{\mathrm{d}}(x_q) = \frac{x_q}{(1-x_q)^2}\left[\frac{3}{4} - \frac{5}{4}\,x_q + \frac{2-3x_q}{2(1-x_q)}\ln x_q\right],$$

$$F_{\mathrm{u}}(x_q) = \frac{x_q}{(1-x_q)^2}\left[x_q - \frac{1-3x_q}{2(1-x_q)}\ln x_q\right],$$

and $x_q = m_q^2/m_{\mathrm{H}}^2$. Since the EDM of the outer quark is proportional to the squared mass of the intermediate quark, while the masses of c- and t-quarks are significantly greater than those of s- and b-quarks, the neutron EDM equals $(4/3)d_{\mathrm{d}}$ with a good accuracy.

In the case of $m_{\mathrm{H}} = 100$ GeV, $m_{\mathrm{c}} = 1.25$ GeV, $m_{\mathrm{t}} = 175$ GeV, the upper bound for d_{n} is

$$\left|\frac{d_{\mathrm{n}}}{e}\right| \leqslant \left[1.6 + 0.67(1\text{--}6)\right] \times 10^{-27}\ \mathrm{cm} \leqslant 5.6 \times 10^{-27}\ \mathrm{cm}\,. \qquad (63)$$

Here, the limit $\mathrm{Im}\,(XY^*) \leqslant 2$ for $m_{\mathrm{H}} = 100$ GeV is used taking into account that the parameter s_2 of the CKM matrix is still characterized by a high degree of uncertainty: $s_2^2 = 3.3 \times 10^{-4}(1\text{--}6)$ (see Section 5). The obtained value of d_{n} is only one order of magnitude lower than the upper limit (44).

It should be borne in mind that (63) does not take into account the effect of d_{n} renormalization due to gluon corrections, the potential admixture of $\bar{\mathrm{s}}\mathrm{s}$ pairs in the neutron wave function, and the contribution of the so-called chromoelectric dipole moment of quarks. The two latter effects enhance d_{n}, whereas the former significantly reduces d_{n}.

A discussion of all these effects can be found in Ref. [157], but the numerical estimates reported there need to be corrected taking into consideration the current constraints on m_{H} and $\mathrm{Im}\,A$, that is, $m_{\mathrm{c}}^2|\mathrm{Im}\,A| = 0.3G_{\mathrm{F}}$ should be substituted by

$$m_{\mathrm{c}}^2|\mathrm{Im}\,A| = 2\sqrt{2}\,G_{\mathrm{F}}\left(\frac{m_{\mathrm{c}}^2}{m_{\mathrm{H}}^2}\right)\mathrm{Im}\,(XY^*) \leqslant 9 \times 10^{-4} G_{\mathrm{F}}$$

for $m_{\mathrm{H}} \geqslant 100$ GeV. With this correction, the value of d_{n} from Ref. [157] is close to the naive estimate (63).

Thus, CP invariance violation in propagators of charged Higgs fields is not at variance with the upper limit on the neutron EDM. It remains to consider the effects initiated by CP violation in propagators of neutral Higgs fields conceivable in theories with three and two Higgs doublets.

3.5 The EDM of elementary particles in the two-doublet theory

The violation of CP invariance in the two-doublet theory is possible if an interaction between flavor-changing neutral currents is permitted [158]. The original doublets Φ_1 and Φ_2 can be represented as linear combinations of eigenstates $\tilde{\Phi}_1$ and $\tilde{\Phi}_2$:

$$\Phi_1 = \cos\beta\,\tilde{\Phi}_1 - \sin\beta\,\tilde{\Phi}_2\,,$$

$$\Phi_2 = (\sin\beta\,\tilde{\Phi}_1 + \cos\beta\,\tilde{\Phi}_2)\exp\mathrm{i}\theta\,.$$

Here,

$$\tilde{\Phi}_1 = \begin{pmatrix} \mathrm{G}^+ \\ \dfrac{v + \mathrm{H}_1 + \mathrm{i}\mathrm{G}^0}{\sqrt{2}} \end{pmatrix}, \qquad \tilde{\Phi}_2 = \begin{pmatrix} \mathrm{H}^+ \\ \dfrac{\mathrm{H}_2 + \mathrm{i}\mathrm{A}}{\sqrt{2}} \end{pmatrix}, \qquad (64)$$

$v = (v_1^2 + v_2^2)^{1/2} = (\sqrt{2}\,G_{\mathrm{F}})^{-1/2}$, and G^+, G^0 are the Goldstone states absorbed by the longitudinal components of massive $\mathrm{W}^{\pm}$- and Z-bosons, and the angle β is determined by the relation

$$\tan\beta = \frac{|v_2|}{|v_1|}\,. \qquad (65)$$

CP violation is due to the mixing of the neutral pseudoscalar field A [see (64)] and the scalar fields $\mathrm{H}_{1,2}$; it can be parametrized in the form [159, 160]

$$\langle \mathrm{H}_1\mathrm{A}\rangle = \frac{1}{2}\sin 2\beta \sum_n \frac{\mathrm{Im}\,Z_{0n}}{q^2 - m_{\mathrm{n}}^2}\,,$$

$$\langle \mathrm{H}_2\mathrm{A}\rangle = \frac{1}{2}\sum_n \frac{\cos 2\beta\,\mathrm{Im}\,Z_{0n} - \mathrm{Im}\,\bar{Z}_{0n}}{q^2 - m_{\mathrm{n}}^2}\,, \qquad (66)$$

where n numbers the eigenstates of the neutral Higgs fields H_1, H_2, A, while Z_{0n}, $\bar{Z}_{0n}$ are new dimensionless parameters.

The index n in (66) can be omitted if the sums are supposed to be saturated with the lightest Higgs boson with mass m_{H}. The dominant contribution to the charged fermion EDM comes from diagrams similar to those in Fig. 10, in which the upper loop contains heavy particles t, b, c, W^+, H^+, τ [160–162]. All the diagrams, regardless of their type, contribute to the neutron EDM, but only the first and the third contribute to the electron EDM.

The contribution of the diagram in Fig. 10a with the t-quark in the upper loop to the EDM of the d-quark proves to be [160]

$$\left(\frac{d_{\mathrm{d}}}{e}\right)^{\text{t-loop}} = 1.4 \times 10^{-26}\Big\{\mathrm{Im}\,Z_0\left[f(z) + g(z)\right] - \mathrm{Im}\,\bar{Z}_0\left[f(z) - g(z)\right]\Big\}\ \mathrm{cm}\,. \qquad (67)$$

Here, $z = m_{\mathrm{t}}^2/m_{\mathrm{H}}^2$ and the functions f and g result from the two-loop integration in diagrams of Fig. 10 [160]. At $z = 1$, they differ from unity by approximately 20%, with $g(z) > 1 > f(z)$.

Diagram 10b could make an even greater contribution to the EDM of the d-quark if the estimate $(d_{\mathrm{d}}/e) \approx d^{\mathrm{c}}$ [163], where d^{c} is the chromoelectric dipole moment, were true. Its validity is called in question by attempts to close the gluon line and connect the photon line with the charged particles of the diagram in Fig. 10b. Then, the relation

$$\frac{d_q}{e} \sim \frac{g_{\mathrm{s}}}{(4\pi)^2}\, d_q^{\mathrm{c}}$$

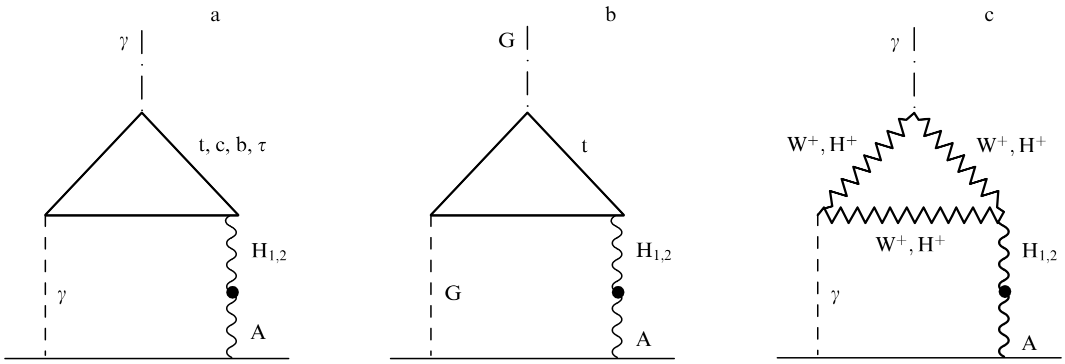

Figure 10. Diagrams contributing to the quark EDM in the theory with two Higgs doublets.

looks more natural [164]. According to Ref. [160], the electron EDM is

$$\left(\frac{d_e}{e}\right)^{\text{t-loop}} = -2.8 \times 10^{-27}\Big\{\operatorname{Im} Z_0 \left[f(z)+g(z)\right] - \operatorname{Im}\bar{Z}_0\left[f(z)-g(z)\right]\Big\}\ \text{cm}\,. \qquad (68)$$

There is, however, no direct relation between the EDMs of electron and neutron because the loops with b, τ, W^+, H^+ make dissimilar contributions to these quantities, which depend differently on the parameters Z_0 and $\bar{Z}_0$ [160].

A direct relationship between the EDMs of electron and neutron appears in a specific model [165] in which all fermions, except the t-quark, receive a mass from the vacuum average v_1 of the doublet Φ_1, while the t-quark receives its mass from the vacuum average v_2 of the doublet Φ_2. The difference of m_t from the masses of the remaining fermions is large, since $|v_2/v_1| \sim m_t/m_b$. The largest contribution to d_e comes from the loops with b and τ fermions:

$$\left(\frac{d_e}{e}\right)^{\text{b},\,\tau\text{-loops}} = -\frac{m_e\alpha\sqrt{2}\,G_F}{(4\pi)^3}\tan^2\beta \times\left\{\frac{4}{3}\left[f(\mathrm{b})+g(\mathrm{b})\right]+4\left[f(\tau)+g(\tau)\right]\right\}(\operatorname{Im} Z_0+\operatorname{Im}\bar{Z}_0)\,, \qquad (69)$$

where $\mathrm{b} = m_b^2/m_H^2$, $\tau = m_\tau^2/m_H^2$, and the largest contribution to d_n is made by the b-quark loop [166]:

$$d_n \sim d_d^{\text{b-loop}} = 6\times 10^{-25}\left[f(\mathrm{b})+g(\mathrm{b})\right]\tan^2\beta\,(\operatorname{Im} Z_0+\operatorname{Im}\bar{Z}_0)\,. \qquad (70)$$

At $\tan\beta \gg 1$, the relation [166]

$$\left|\frac{d_e}{d_n}\right| \sim 2\times 10^{-3}\,,$$

holds, which is independent of the parameters $\operatorname{Im} Z_0$ and $\operatorname{Im}\bar{Z}_0$.

It is worthwhile to note that these parameters of the two-doublet theory are virtually unrelated to the parameters of CP invariance violation in $\{K^0, \bar{K}^0\} \to 2\pi$ decays.

Taken together, the above formulas and results of other studies cited in Ref. [163] lead to the conclusion that the EDMs of the electron and neutron might be close to the known bounding values of these quantities.

In the Weinberg model with three Higgs doublets, the mixing of neutral Higgs mesons is characterized by the same parameter as the mixing of charged fields Φ_1^+ and Φ_2^+ is [142]. Once the latter gives $\varepsilon'_W/\varepsilon \sim 2\times 10^{-3}$, this parameter leads to d_n and d_e values close to or exceeding the known bounds for these quantities. The situation can be resolved on the assumption that neutral Higgs mesons are much heavier than their charged partners.

Certain studies have been devoted to the contribution to the EDM of baryons from the effective three-gluon operator of dimension 6, such as [167]

$$-c f_{abc} G^{\rho}_{a\mu} G_{b\rho\nu} G_{c\sigma\eta}\varepsilon^{\mu\nu\sigma\eta}\,;$$

this operator destroys P and CP invariance and arises in a theory with several Higgs doublets. The contribution of purely gluon operators of dimension 8, like [168]

$$g_s^4 \tilde{G}^a_{\mu\nu} G^{a\mu\nu} G^b_{\alpha\beta} G^{b\alpha\beta}$$

was also considered. The results of the evaluation of the effects of these operators do not contradict the possibility of a neutron EDM approaching the experimental limit [160, 169].

3.6 Decays $\eta, \eta' \to 2\pi$ in the Weinberg model

In the case of a decay with flavor conservation, the part of the matrix element of the $\eta \to 2\pi$ transition corresponding to the diagram in Fig. 8 but having identical terminal quarks is equal to zero. What remains is the contribution of diagrams with identical outer quarks shown in Fig. 9. An estimate taking into account only an intermediate c-quark is [146]

$$\mathrm{Br}\,(\eta \to \pi^+\pi^-) = 2\mathrm{Br}\,(\eta \to \pi^0\pi^0) \leqslant 1.2\times 10^{-15}$$

[cf. (53)], which is still unobservable.

4. CP-odd effects in the supersymmetric theory

The emergence of many new, so far hypothetical, particles in the supersymmetric generalization of the Standard Model (SUSY) opens up the possibility for the appearance of new CP violation parameters. Specifically, the Majorana masses of superpartners of ordinary gauge fields, scalar-quark masses, and the constant of the three-particle scalar interaction can be complex quantities. These sources modify the SM predictions due to two different effects: (1) the appearance of new diagrams with superpartners of ordinary particles in transient states (in this case the CP violation is proportional to the KM phase, but the magnitude of the effects alters) and (2) the appearance of new phases unrelated to the KM phase.

By way of illustration, we present here the calculated corrections for the parameters ε_K, ε'_K and the EDM of the neutron obtained in the minimal supersymmetric SO(10)-model [170]. The 'box' diagram with intermediate gluinos gives for an indirect CP violation

$$|\varepsilon_K|^{\tilde{g}} \simeq 2 \times 10^{-2} \sin(\phi_d - \phi_s) \left(\frac{300\ \text{GeV}}{M_3}\right)^2 \times \left|\frac{V_{ts}V_{td}}{4 \times 10^{-4}}\right|^2 \left|\frac{180\ \text{MeV}}{m_s + m_u}\right|^2,$$

where M_3 is the b-squark mass and ϕ_d and ϕ_s are the new phases appearing in the SO(10)-model. The ε'/ε ratio for decays $\{K^0, \bar{K}^0\} \to 2\pi$ admits the correction

$$\left|\frac{\varepsilon'_K}{\varepsilon_K}\right|^{\tilde{g}} = 3 \times 10^{-4} \left(\frac{300\ \text{GeV}}{M_3}\right)^2 \frac{A_b + \mu \tan\beta}{M_3} \times \frac{\sin(\phi_d - \beta) + \sin(\phi_s - \beta)}{2}.$$

The neutron EDM is

$$d_n \simeq 4 \times 10^{-26} \frac{m_b(M_3)}{2.7\ \text{GeV}} \left|\frac{V_{td}}{0.01}\right|^2 \left(\frac{300\ \text{GeV}}{M_3}\right)^2 \times \frac{A_b + \mu \tan\beta}{M_3} \sin(\phi_d - 2\beta).$$

In the last two formulas, A_b and μ are interaction parameters of three scalar fields and β is a function of the KM phase.

According to these formulas, the mechanisms of CP violation in SUSY yield an $\varepsilon'_K/\varepsilon_K$ ratio at least one order of magnitude smaller than observed in experiment. This conclusion was also made in other studies of supersymmetry published before [60]. Ref. [60] was followed by a series of papers [171] in which the authors reported examples of theories with $\varepsilon'/\varepsilon \sim 3 \times 10^{-3}$.

The neutron and electron EDMs in SUSY can be very close [172] to experimental values. Moreover, in the minimal supersymmetric Standard Model (MSSM), theoretical predictions for these quantities tend to overrun their experimental values [173].

For the transverse muon polarization in the $K^+ \to \pi^0\mu^+\nu$ decay, the anticipated effect of supersymmetric CP violation is very small [174, 175]. For the parameter $\operatorname{Im} f_S$ defined in Section 3.3, Ref. [174] gives

$$\operatorname{Im} f_S \approx \frac{M_K m_s}{m_{\tilde{g}}^2} \frac{\alpha_s}{12\pi} \sin\phi_{\text{SUSY}},$$

where $\tilde{g}$ is a gluino and ϕ_{SUSY} is the CP-violating phase of the gluino mass. However, it follows from the constraints on the neutron EDM that $\sin\phi_{\text{SUSY}} \leqslant 10^{-7} m_{\tilde{g}}^2/\text{GeV}^2$ [175].

In the decays of the $\{B^0, \bar{B}^0\}$ meson system, the parameters ε_B and ε'_B are also subject to alteration. They may be quite different from those expected in SM. This is true of CP-odd asymmetries as well. For example, in accord with SM, the asymmetry in $\{B_s^0, \bar{B}_s^0\}$ meson decays is deemed to be less than 2%. In these decays, the New Physics generates the asymmetry [176]

$$A(B_s \to J/\psi\phi) \sim \sin(2\zeta^{\text{New Phys}}).$$

The occurrence of an asymmetry exceeding the SM predictions would be evidence for the existence of the New Physics. New sources of CP violation appearing in SUSY allow, in principle, explaining the observed baryonic asymmetry of the Universe (see review [43]).

5. Other models of CP and T violation

Among the models in which other sources of CP invariance violation are possible, models with (broken) left–right symmetry have been given especially much attention [177]. These models contain left-handed and right-handed $W^{\pm}$-bosons, the mass of the latter being much greater than that of the former. CP violation is due to the complex masses of the nondiagonal transitions $W_L \leftrightarrow W_R$ and $\nu_L \leftrightarrow N_R$, where N_R is the right-handed helical component of the hypothetical heavy neutrino. In these models, the T-odd EDMs d_n and d_e generated by CP violation can reach the known experimental limits. In some of them, the d_n and d_e values are related to the parameter ε' characterizing direct CP violation in $K_L^0 \to 2\pi$ decays [178].

In the $\{B^0, \bar{B}^0\}$ sector, the theory based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)$ predicts a significant difference in the *time-dependent* CP asymmetry between the decays $B \to J/\psi K_S$ and $B \to \phi K_S$ (in SM, this asymmetry must be the same for both decays [179]). The angle γ of the unitarity triangle of the CKM matrix in electroweak processes described by 'penguin' diagrams also differs from the angle predicted by SM [180].

The 'mirror fermions' model [181], correlates the family of hypothetical heavy right-handed helical doublets and left-handed helical singlets to the known family of fermionic left-handed helical doublets. The source of CP violation is the complexity of the coupling constants of H^0-, W-, and Z-bosons with left-handed and right-handed fermions. The EDM of the neutron and electron can reach the respective experimental limits.

In models with horizontal gauge interactions [182], heavy neutral horizontal vector bosons can interact with fermions with a change in flavor, and the corresponding coupling constants may be complex. The strength of this source can be evaluated from the restriction on μe-conversion [183], and the corresponding threshold for the electron EDM proves to be $d_e/e < 2 \times 10^{-27}$ cm.

6. What is known about CPT invariance

Abandoning any constraints on the Lagrangian density in the commonly accepted relativistic quantum field theory makes a proof of the CPT theorem impossible [2].

The violation of CP invariance occurs in a theory based on the infinite-component-field (ICF) concept [184]. The development of this concept was stimulated by an idea of dynamic symmetry that consists in reducing a composite system with an infinite mass (or energy) spectrum to a single ICF as a more 'elementary' object (see references in [184]). However, as shown in Ref. [185], the ICF theory implies an infinite spin degeneracy of mass, in contrast to what is observed in the realm of elementary particles.

Another source of CP noninvariance might be the existence of self-conjugate multiplets of field operators with a half-integer isotopic spin of the type

$$\begin{pmatrix} V^+ \\ V^{+*} \end{pmatrix}, \quad \begin{pmatrix} V^{-*} \\ V^- \end{pmatrix},$$

where V denotes spin-1 fields, and $V^+ \neq V^{-*}$. The interaction between such hypothetical fields and charged hadronic currents, one of which changes flavor, leads, on mixing of V^+- and V^{-*}-bosons, to T-invariance-conserving but CP-odd (hence, CPT-odd) hadronic amplitudes [186]. Thus far, however, there is no evidence of such multiplets.

The neglect of local interactions also precludes a proof of the CPT theorem. Therefore, CPT-invariance violation could take place in a theory describing the interaction between strings, i.e. nonlocal objects [44, 45]. One more source of CPT symmetry breaking could be the violation of the Lorentz invariance [187]. It can not be excluded that quantum fluctuations and the appearance of virtual black holes [46, 47] responsible for at least partial irreversibility of the processes may cause the loss of quantum coherence and, as a result, CPT-invariance violation.

Thus, the theory does not exclude the possibility of CPT violation, but there is so far no realistic model with which to compute, proceeding from first principles, CPT effects in interactions between elementary particles. What remains is to assess the phenomenological consequences of CPT invariance, such as the equality of masses and lifetimes between a particle and its antiparticle, and other things [188].

Reference [78] reports the following most precise data:

$$\frac{m_{e^+} - m_{e^-}}{m_e} < 8 \times 10^{-9}\,, \qquad \frac{\tau_{\mu^+} - \tau_{\mu^-}}{\tau_\mu} = (2 \pm 8) \times 10^{-5}\,,$$

$$\frac{|m_p - m_{\bar{p}}|}{m_p} < 5 \times 10^{-7}\,, \qquad \frac{|m_{K^0} - m_{\bar{K}^0}|}{m_K} < 10^{-18}\,.$$

The last result is believed to be the best test of CPT invariance. However, it must be an order of magnitude smaller if we assume the possibility of direct CPT violation in the $K_L \to 2\pi$ decay amplitude [189]. Moreover, this result does not at all mean that the parameters characterizing the magnitude of CPT violation are much smaller than the CP violation parameters.

It follows from a detailed analysis that CPT invariance in the decays of the $\{K^0, \bar{K}^0\}$ meson system has been verified to an accuracy of only 30% of the observed CP violation. This can be accounted for by the fact that the difference $\Delta m_{K\bar{K}} = m_{K^0} - m_{\bar{K}^0}$ is initially smaller than $3 \times 10^{-13} m_K$, being a part of the nondiagonal element $\langle \bar{K}^0 | K^0 \rangle$ of the mass matrix in the system of $\{K^0, \bar{K}^0\}$ mesons, i.e. a $G_F^2 m_K^5 s_1^2$-order effect. Hence, it is more natural to compare this difference with a CPT and CP-even effect, i.e. with the difference $m_{K_L} - m_{K_S}$, which is also proportional to $G_F^2 m_K^5 s_1^2$. This was done when the parameters of CP violation η_{+-} and η_{00} were determined. With such an approach, constraints on the parameters of CPT violation are rather weak. Let us consider this situation at greater length.

Since CP invariance is known to be broken in neutral K meson decays, CPT invariance can be tested by simply considering the phenomenology in which CP violation is not compensated by T-invariance violation, i.e. by adding the T-invariance-conserving parts to the definition of the $K_{S,L}$ meson wave functions. Then, these functions assume the form [25, 26, 28]

$$K_S = \frac{K_1 + (\varepsilon + \Delta) K_2}{\left(1 + |\varepsilon + \Delta|^2\right)^{1/2}}\,, \tag{71}$$

$$K_L = \frac{K_2 + (\varepsilon - \Delta) K_1}{\left(1 + |\varepsilon - \Delta|^2\right)^{1/2}}\,, \tag{72}$$

where the parameter ε describes, as before, the CP-violating but CPT-conserving part in the $K_{S,L}$ meson wave functions, while the parameter Δ describes the CPT-violating part.

Moreover, if CP and CPT invariances are violated in direct transitions of the $\{K^0, \bar{K}^0\}$ meson system into the final states, several new parameters appear [24 – 26, 28]:

$$a = \frac{A(K_2^0 \to 2\pi;\, T = 0)}{A(K_1^0 \to 2\pi;\, T = 0)}\,, \qquad \text{CPT} = -1\,, \tag{73}$$

$$\frac{1 - y_l}{1 + y_l} = \frac{A(K^0 \to l^+ \nu \pi^-)}{A^*(\bar{K}^0 \to l^- \bar{\nu} \pi^+)}\,, \quad \text{CPT} = -1, \text{ if } \; y_l \neq 0\,. \tag{74}$$

For semi-leptonic decays of neutral K mesons, additional parameters characterizing the magnitude of the violation of the $\Delta Q = \Delta S$ rule are introduced:

$$x_l = \frac{A(\bar{K}^0 \to l^+ \nu \pi^-)}{A(K^0 \to l^+ \nu \pi^-)}\,, \qquad \bar{x}_l = \frac{A^*(K^0 \to l^- \bar{\nu} \pi^+)}{A^*(\bar{K}^0 \to l^- \bar{\nu} \pi^+)}\,. \tag{75}$$

The inequality $x_l \neq \bar{x}_l$ implies CPT invariance violation.

As a result, the parameters of CP violation observed in $K_{S,L} \to 2\pi$ decays assume the form [25, 26, 28]

$$\eta_{+-} \cong \varepsilon - \Delta + \varepsilon' + a\,, \tag{76}$$

$$\eta_{00} \cong \varepsilon - \Delta - 2\varepsilon' + a \tag{77}$$

[cf. (9) and (10)], while the parameter of charge asymmetry in semi-leptonic K_L meson decays is given by the formula

$$\delta_L \cong 2\,\mathrm{Re}\,(\varepsilon - \Delta) - 2\,\mathrm{Re}\, y_l - \mathrm{Re}\,(x_l - \bar{x}_l)\,. \tag{78}$$

$\mathrm{Im}\, y_l$ appears only in the common normalization coefficients for the time-dependent amplitudes of semi-leptonic decays of K^0 and $\bar{K}^0$ mesons (see [28, Table 1]).

It is clear from relations (76) – (78) that data on K_L decays alone are insufficient to conclude whether a violation of CP invariance is inevitably accompanied by a CPT-violation. Additional data on K_S decays are necessary, the formulas for which contain a different combination of CPT-even and CPT-odd parameters. In particular, the following parameter must be known:

$$\delta_S = \frac{\Gamma(K_S \to l^+ \nu \pi) - \Gamma(K_S \to l^- \bar{\nu} \pi)}{\Gamma(K_S \to l^+ \nu \pi) + \Gamma(K_S \to l^- \bar{\nu} \pi)}$$

$$\cong 2\,\mathrm{Re}\,(\varepsilon + \Delta) - 2\,\mathrm{Re}\, y_l + \mathrm{Re}\,(x_l - \bar{x}_l)\,. \tag{79}$$

In the current theory with the known quark content, the $\Delta Q = \Delta S$ rule is violated in the second order in the weak constant G_F, so that the upper bound for $\mathrm{Re}\,(x_l - \bar{x}_l)$ does not exceed $G_F m_K^2 \approx 2 \times 10^{-6}$. Neglecting this small effect leads to

$$\mathrm{Re}\, \Delta = \frac{1}{4} (\delta_S - \delta_L)\,. \tag{80}$$

Estimates for $\mathrm{Re}\, \Delta$ and $\mathrm{Im}\, \Delta$ taking into account the fact that $\mathrm{Re}\, y_l$ may differ from zero [12] were first inferred in Ref.

[12] If the possibility of direct CPT violation in semi-leptonic kaon decays is disregarded, as in Ref. [26], i.e, it is assumed that $y_l = 0$, the resultant constraint on the parameter Δ is two orders of magnitude better than that in Ref. [26].

[190] from previously obtained data on K^0_{e3} and $\bar{K}^0_{e3}$ decays:

$$\mathrm{Re}\,\Delta = 0.018 \pm 0.020\,, \qquad \mathrm{Im}\,\Delta = 0.021 \pm 0.037\,. \tag{81}$$

Recent measurements [191] yielded

$$\mathrm{Re}\,\Delta = (2.4 \pm 2.8) \times 10^{-4}\,, \qquad \mathrm{Im}\,\Delta = (-1.5 \pm 2.3) \times 10^{-2}\,. \tag{82}$$

The limit on Re Δ was lowered by two orders of magnitude, but the accuracy of measurement of Im Δ remained the same as in Ref. [190].

It was shown in Refs [25, 26, 30] that the limiting value of Im Δ can be significantly diminished using the Bell – Steinberger unitarity relation [22]. Then, in agreement with the measured values of the parameters [192] that appear in this relation,

$$\mathrm{Im}\,\Delta = (2.4 \pm 5.0) \times 10^{-5}\,. \tag{83}$$

For other CPT-violating parameters [192],

$$\begin{aligned}
&\mathrm{Re}\,y_l = (0.3 \pm 3.1) \times 10^{-3}\,,\\
&\mathrm{Im}\,x_l = (-2.0 \pm 2.7) \times 10^{-3}\,,\\
&\mathrm{Re}\,\bar{x}_l = (-0.5 \pm 3.0) \times 10^{-3}\,.
\end{aligned} \tag{84}$$

Let us now turn to determining the mass difference $m_{K^0} - m_{\bar{K}^0}$ given by the relation [26, 28]

$$m_{K^0} - m_{\bar{K}^0} = 2(m_L - m_S)(\mathrm{Re}\,\Delta - \mathrm{Im}\,\Delta \cdot \tan^{-1}\Phi_{\mathrm{sw}})\,, \tag{85}$$

Then, it follows from (82) and (83) that

$$\frac{|m_{K^0} - m_{\bar{K}^0}|}{m_{K^0}} \leqslant 1.2 \times 10^{-17}\,. \tag{86}$$

The result in (86) is an order of magnitude higher than reported in Ref. [78, p. 67], where the formula

$$\frac{m_{K^0} - m_{\bar{K}^0}}{m_{K^0}} = \frac{2(m_L - m_S)}{m_{K^0}}\left[|\eta|\left(\frac{2}{3}\,\Phi_{+-} + \frac{1}{3}\,\Phi_{00} - \Phi_{\mathrm{sw}}\right) + a + \mathrm{Im}\left(\frac{1}{\Gamma_S}\sum_f \alpha_f\right)\tan^{-1}\Phi_{\mathrm{sw}}\right] \tag{87}$$

was used, and the last two terms in the square brackets of this expression were neglected.

However, the sole estimate that was available in the literature [28],

$$a = (-0.75 \pm 6) \times 10^{-3}\,, \tag{88}$$

significantly exceeded the part proportional to the phase combination and gave no reason to exclude a from consideration. On the contrary, a comparison of the two expressions for the mass difference can be used to derive a new restriction on direct CPT violation, namely

$$|a| \leqslant 8 \times 10^{-4}\,. \tag{89}$$

It follows from (82), (84), and (89) that the upper limit on the CPT violation parameter in $\{K^0, \bar{K}^0\}$-system decays is only three times lower than the known CP-violation parameter $|\eta| \cong 2.3 \times 10^{-3}$.

The loss of quantum coherence mentioned at the beginning of this section, which leads to dissipation, irreversibility, and, therefore, the violation of CPT invariance, can be taken into account by adding the $\Delta H\rho$ term, forbidden in conventional quantum mechanics, to the equation of neutral-kaon evolution [193]:

$$\frac{\partial\rho(t)}{\partial t} = -\mathrm{i}\,H\rho(t) + \mathrm{i}\,\rho(t)\,H^{\dagger} + \Delta H\,\rho(t)\,, \tag{90}$$

where $\rho(t)$ is the density matrix of the $\{K^0, \bar{K}^0\}$ meson system, which can be represented in the form of an expansion in Pauli matrices and the unit matrix σ_0 [31]: $\rho = \rho_\mu\sigma_\mu$. Then, the addition ΔH can be parametrized by a 4×4 matrix [193]

$$\Delta H = -2\begin{pmatrix} 0 & 0 & 0 & 0\\ 0 & a & b & c\\ 0 & b & \alpha & \beta\\ 0 & c & \beta & \gamma \end{pmatrix} \tag{91}$$

with six real parameters.

Reference [194] gives the following values for five of them:

$$\begin{aligned}
&a = (2.5 \pm 2.6) \times 10^{-17}\ \mathrm{GeV}\,,\\
&c = (0.7 \pm 1.2) \times 10^{-17}\ \mathrm{GeV}\,,\\
&\alpha = (1.8 \pm 4.4) \times 10^{-17}\ \mathrm{GeV}\,,\\
&\beta = (-0.7 \pm 1.3) \times 10^{-17}\ \mathrm{GeV}\,,\\
&\gamma = (0.1 \pm 22.0) \times 10^{-20}\ \mathrm{GeV}\,.
\end{aligned} \tag{92}$$

Since the loss of quantum coherence could result from a disturbance of space – time properties at distances of the order of the inverse Planck mass (where gravity becomes strong), it is not unlikely that the parameters in (92) are of the order of $m_K^2/m_{\mathrm{Pl}} \sim 10^{-19}$ GeV. It follows from the closeness of this estimate to that reported in Ref. [194] that a further search for CPT effects in neutral-K-meson decays is in order.

In the charged K meson sector, the precision of CPT-invariance testing is still low $(m_K^+ - m_K^-)/m_K = (-0.6 \pm 1.8) \times 10^{-4}$. The measurement accuracy for the ratio of the difference between the $K^+ \to \mu^+\nu$ and $K^- \to \mu^-\bar{\nu}$ widths to the width for either of these decays is $(-0.5 \pm 0.4)\%$; for $K^+ \to \pi^+\pi^0$ and $K^- \to \pi^-\pi^0$, this ratio is $(0.8 \pm 1.2)\%$. With the DAPhNE facility at Frascati, for which the numbers of K^+ and K^- mesons are equal, the accuracy of such measurements can be improved by two orders of magnitude, whereas the accuracy in comparisons of the remaining partial widths for K^+ and K^- mesons can be made as high as 10^{-4} [30].

Antihydrogen experiments discussed in the literature, in which the comparison of the frequencies of the $(1s-2s)$ 2γ transition and the corresponding transition in hydrogen is possible to an accuracy of $10^{-15}-10^{-18}$ [195], appear especially promising. On the assumption that a particle and an antiparticle have charges equal in absolute magnitude, such a measurement could reduce the constraint on the combination

$$\frac{m_e - m_{e^+}}{m_e} + \frac{m_e}{m_p}\,\frac{m_p - m_{\bar{p}}}{m_p}$$

to $10^{-15}-10^{-18}$. This would mean a decrease of the existing limits on $(m_e - m_{e^+})/m_e$ by seven to ten and on $(m_p - m_{\bar{p}})/m_p$ by five to eight orders of magnitude. At present, the constraint on this combination results from the restriction on the difference between the electron and positron masses and equals 8×10^{-9}.

One more high-precision test of CPT invariance is possible in the case of an interaction converting a neutron to an antineutron. At $m_{\rm n} - m_{\bar{\rm n}} \equiv \Delta m_{\rm n\bar{n}} \leqslant 1/t$ (where t is the neutron-beam free-flight time in vacuum), the observation of $\rm n \to \bar{n}$ transitions could give an upper bound $\Delta m_{\rm n\bar{n}} \leqslant (10^{-22} - 10^{-23}) m_{\rm n}$ [196]. Thus far, no transitions at a level of $\tau_{\rm n\bar{n}} > 0.86 \times 10^8$ s have been recorded [197]. A more detailed discussion of the problem of $\rm n \to \bar{n}$ transitions with references to planned experiments can be found in Ref. [198].

7. Problems and prospects of further CP violation studies using accelerators

The objective of further experimental studies of CP invariance violation is to improve the accuracy of measuring the known effects and to search for new CP-odd effects allowing either the verification of SM predictions or the reveal of deviations from them. The latter case would imply the presence of additional sources of CP violation. This section considers the prospects of such ongoing and future studies with the use of accelerators.

7.1 The ε'/ε ratio

An experiment currently underway with the KLOE detector of the DAPhNE ϕ facility (Frascati) is designed to measure the ε'/ε ratio in the process

$$\rm e^+e^- \to \phi(1020) \to K^0\bar{K}^0$$

to an accuracy of $\delta(\varepsilon'/\varepsilon) \sim 10^{-4}$ [199]. This experiment is important so far as it uses a measuring technique completely different from that employed in previous studies.

7.2 $\rm K^\pm \to 3\pi$

In the K-IHEP experiment that is in preparation at the Institute of High Energy Physics, Serpukhov, the difference Δg between the slope parameters [see (18)] in $\rm K^+$ and $\rm K^-$ decays will be measured to an accuracy of 10^{-4} [200]. Simultaneously, the experiment will measure the widths of $\rm K^+ \to \pi^+\pi^0\gamma$ and $\rm K^- \to \pi^-\pi^0\gamma$ decays with an accuracy of $\Delta\Gamma/2\Gamma \leqslant 4 \times 10^{-4}$.

A CERN project is expected to measure Δg at a level of 10^{-4} (see [201, Table 10]). A similar accuracy of Δg measurements is achievable with the KLOE detector [202].

7.3 $\rm K_{\it L,S} \to \pi^0e^+e^-$

$\rm K_{\it L} \to \pi^0e^+e^-$ decays will be studied on the KAMI facility at Fermilab. A part of the amplitude corresponding to indirect CP violation can be singled out by an independent measurement of Br $(\rm K_{\it S} \to \pi^0e^+e^-)$ possible using the KLOE detector on DAPhNE [203].

7.4 $\rm K^+ \to \pi^+\nu\bar{\nu}$

The E787 experiment at Brookhaven in which a unique event of $\rm K^+ \to \pi^+\nu\bar{\nu}$ decay was recorded will be followed by the E949 experiment [204] designed to seek more such decays. The CKM experiment at Fermilab to be launched in 2005 is expected to detect as many as about 100 events in two years [205].

7.5 $\rm K_{\it L}^0 \to \pi^0\nu\bar{\nu}$

The prospects of studying $\rm K_{\it L}^0 \to \pi^0\nu\bar{\nu}$ decays were discussed in Section 2.3. Suffice it to mention here that in the E391 KEK experiment (Tsukuba) only a limit of Br $(\rm K_{\it L}^0 \to \pi^0\nu\bar{\nu}) \leqslant 10^{-10}$ will be achieved. It is hoped that in further studies of this decay with the Japan Hadron Facility (JHF) to be commissioned at KEK, the number of such events should reach 10^3 [206].

7.6 T noninvariance in K decays

The measurements of the T-odd transverse polarization of muons in $\rm K^+ \to \pi^0\mu^+\nu$ decays underway at KEK will be continued on the future JHF accelerator. It is supposed that the accuracy of $P_\perp^\mu$ measurements (see Section 2.7) will be no worse than 5.5×10^{-5} [207, 208].

Also, it is expected that measuring $P_\perp^\mu$ will be possible at an accuracy as high as 1.4×10^{-4} in the AGS923 experiment at Brookhaven [208] and a level of 5×10^{-4} should be achieved with the DAPhNE ϕ facility [209].

7.7 CP violation in hyperons

A project has been developed at Fermilab to measure the CP-odd asymmetry between the $\Lambda \to \rm N\pi$ and $\bar{\Lambda} \to \rm \bar{N}\pi$ decays to an accuracy A_Λ (see Section 2.4) as high as 10^{-5} [210].

7.8 CP violation in D mesons

The information about charmed particles has so far come from four sources: (1) $\rm e^+e^-$ at energy $E_{\rm c.m.} = m_\Upsilon$ (CLEO II.V, Cornel), (2) $\rm Z^0$ decays (ALEPH, LEP, CERN), (3) hadron photoproduction (FOCUS/E831, Fermilab), and (4) hadron production (E791, Fermilab) [98]. In these experiments, events were reconstructed at a level of 10^6. Statistical errors in the measurement of CP-odd asymmetries amounted to 10 – 20%. Systematic errors were an order of magnitude smaller. This means that the accuracy of $A_{\rm CP}(\rm D)$ measurements can be improved by one order of magnitude with a larger volume of statistics. In the ongoing experiments using B facilities, the anticipated potential of the reconstructed D-meson decays is 10^7; it is $10^8 - 10^9$ on the BTeV (Fermilab) and LHCb (CERN) facilities (see below).

7.9 CP violation in B mesons

A study of CP violation in B-meson decays would be especially interesting because CP effects in certain decay channels may be conspicuous. Moreover, such a study would not only document the fact of CP-invariance violation but also give more precise parameters of the CKM matrix.

B-meson experiments are carried out and planned with the use of both hadron accelerators and electron – positron colliding beams. In the latter case, the best option for a study of CP-odd effects is provided by machines with asymmetric energy of electrons and positrons, in which the excited intermediate resonance $\Upsilon(4S)$ of the reaction $\rm e^+e^- \to \Upsilon(4\it S) \to \rm B^0\bar{B}^0$ moves in the laboratory frame of reference. For substantially different relative probabilities of $\rm B^0 \to f_1$ and $\rm \bar{B}^0 \to f_2$ decays, the distance between their vertices in the laboratory system increases approximately V/v-fold compared with that for a resting $\Upsilon(4S)$ meson (V is the velocity of the $\Upsilon(4S)$ meson, v is the velocity of the $\rm B^0$ meson in the resting-$\Upsilon(4S)$ system). The same distance in the $\Upsilon(4S)$ system (about 30 – 50 μm) is too small to enable the $\rm B^0$ decay to be distinguished from the $\rm \bar{B}^0$ decay with current techniques; this precludes measurements of CP asymmetry.

Such machines are PEP-II [Stanford; $\rm e^-(9\ GeV) + e^+(3.1\ GeV)$] with the BaBar facility and KEK-B [Tsukuba; $\rm e^-(8\ GeV) + e^+(3.5\ GeV)$] with the BELLE facility.

The BaBar setup will be used to continue studies of $\rm \{B_d^0, \bar{B}_d^0\} \to J/\psi K_{\it S}$ decays, which should be instrumental in deriving the value of $\sin 2\beta$ from the CP-odd asymmetry to an accuracy of 0.12 – 0.14 at an integrated luminosity of 30 fb^{-1}. In other decay modes, the accuracy of $\sin 2\beta$ measurements will be 0.30 – 0.60 [211, 212]. Moreover, the BaBar collaboration is considering possibilities of measuring $\sin 2\alpha$ in the modes of $B^0 \to \pi^+\pi^-$, $\pi^+\pi^-\pi^0$ [213].

The BELLE facility is also being used to study B-meson decays into the $J/\psi K_S$ state. The accuracy of the $\sin 2\beta$ measurement based on the analysis of 6×10^9 B pairs is currently ± 0.44.

Ample opportunities to study CP violation in B mesons are provided by the improved hadron colliders and the planned HERA-B (DESY) proton accelerator. The latter machine will enable researchers to study CP-odd correlations in B_s^0-meson decays, which cannot be done using the BaBar and BELLE installations.

Comparisons of data for different channels of B_d^0 decay dominated by the decay into $J/\psi K_S$, based on 1500 reconstructed events, will allow $\sin 2\beta$ measurements with an accuracy of ± 0.13.

In the near future, the improved CDF and D0 detectors will be commissioned at Fermilab, which will produce 10^{11} B pairs per year each during the first years. The CDF detector will be used to study 20,000 $B_s^0 \to D_s^-\pi^+$, $D_s^-\pi^+\pi^+\pi^-$ events with the $D_s^- \to \phi\pi^-$, $K^{*0}K^-$ decay; also, it is planned to measure $\sin 2\beta$ to an accuracy of ± 0.15 and the CP-odd asymmetry in $B_d^0 \to \pi^+\pi^-$ decays to an accuracy of $\delta A_{CP} \approx 0.09$. This asymmetry is linked to $\sin 2\alpha$, where α is another angle of the unitarity triangle [see (39)]. However, the derivation of α requires that corrections from 'penguin' diagrams be taken into account.

In the remote future, after 2005, the ATLAS, CMA, and LHCb facilities (CERN) will start accumulating data on B mesons (and concurrently, D-mesons). At approximately the same time, the BTeV machine should be commissioned at Fermilab. It is expected that the results of experiments using these installations and the data obtained with BaBar, BELLE, HERA-B, CDF, and D0 will collectively ensure $\sin 2\beta$ measurements to an accuracy of ± 0.04 [214], studies on CDF and D0 will give $\sin 2\beta$ with an accuracy of ± 0.015, and those on LHCb and BTeV with an accuracy of ± 0.025 [215].

Furthermore, measurements of B_s^0 oscillations in CDF and D0 experiments taken together with the results of studies on the HERA-B accelerator will be used to more accurately determine the length of the unitarity triangle's side opposite to the angle β, based on the relation [78]

$$\frac{|V_{td}|^2}{|V_{cb}|^2} \approx \left|\frac{\Delta m_d}{\Delta m_s}\right| ,$$

where Δm_d is the mass difference between different eigenstates of the $\{B_d^0, \bar{B}_d^0\}$ system and Δm_s is the analogous parameter for the $\{B_s^0, \bar{B}_s^0\}$ system.

With the LHCb machine, $\sin 2\gamma$ will be measured by examining six time-integrated asymmetries in the $B_d^0 \to D^0K^{*0}, \bar{D}^0K^{*0}, D_{1,2}^0K^{*0}$ channels and their charge-conjugate counterparts with D^0 mesons decaying into $K^-\pi^+$ and $D_{1,2}^0$ mesons decaying into K^+K^- and $\pi^+\pi^-$. These measurements are expected to ensure a 10° accuracy in determining the angle γ [216]. Also, LHCb experiments will give an opportunity to validate the relation $2\beta + \gamma = \pi + \beta - \alpha$ to an accuracy of 9° by studying $B_d^0 \to D^{*+}\pi^-$ decays.

The BTeV machine will be used to determine γ with an accuracy of 13° from the data on $B^\pm \to D^0/\bar{D}^0K^\pm$ decays, with D^0 and $\bar{D}^0$ decaying into the same final states.

Such are the prospects for further research of CP violation with the use of accelerators.

8. Conclusions

The sum of available knowledge about interactions between elementary particles is adequately described by SM, and the mechanism of CP violation postulated by this model looks fairly natural. Recent findings [108] of the marked asymmetry in $\{B^0, \bar{B}^0\} \to J/\psi K_S$ decays [see (41)] predicted by SM can be considered evidence for the Kobayashi – Maskawa mechanism unless they are refuted upon the improvement of the measurement accuracy.

The direct violation of CP invariance in $K_L \to 2\pi$ decays predicted by SM is out of question after a series of recent experiments [60, 61]. What remains is to establish whether the observed value of the parameter ε' agrees with that expected in SM. Thus far, theoretical calculations give either significantly smaller than the experimental or highly uncertain ε' values. If further studies fail to correlate the observed and predicted values of ε', additional sources of CP violation will have to be assumed.

Unique evidence that the KM phase is not the sole source of CP violation realizable in nature would be provided by the finding of a neutron or electron EDM differing but slightly from the known experimental limits. Thus far, the d_n and d_e values predicted by SM are 7 and 11 – 13 orders of magnitude smaller than the corresponding upper limits, respectively. The majority of additional sources of CP violation considered in this review admit the possibility of d_n and d_e values close to their known limits.

Since the problem concerning the sources of CP invariance violation is of paramount importance for both the theory of elementary particles and cosmology, priority must be given to a search for d_n and d_e. It is expected that the accuracy of d_e measurements using paramagnetic molecules of YbF will be increased 10-fold within the next 3 years [217]. In the future, this method will allow the error of d_e measurements to be further decreased by two orders of magnitude [217]. The accuracy of d_n measurements is expected to increase threefold within a few years and 100 times more within the next decade when new neutron-storing facilities operating at liquid helium temperatures become available [217].

In experiments with neutral K mesons, priority is being given to a search for the CP-odd $K_L \to \pi^0\nu\bar{\nu}$ decay, the measurement of its probability providing a unique opportunity to specify the CKM matrix parameters.

In the sector of charged kaons, priority is accorded to measuring the transverse muon polarization in the $K^+ \to \mu^+\pi^0\nu$ decay and also to the search for T-odd correlations in $K^+ \to \mu^+\nu\gamma$ and $K^+ \to \pi^0 l^+\nu\gamma$ decays, where only CP (hence, T) violation sources supplementary to the KM phase are likely to produce measurable effects.

Were the already observed average values retained upon an increase in the measurement accuracy in the studies of CP-odd asymmetries in $\{D^0, \bar{D}^0\}$-system decays, this would give evidence for CP violation sources other than those predicted by SM.

An immediate task in B meson experiments is a 3 – 6-fold improvement of the measurement accuracy for the CP-odd asymmetry in $\{B^0, \bar{B}^0\} \to J/\psi K_S$ decays. This would conclusively establish the validity of SM predictions concerning these decays and yield more precise values of $\sin 2\beta$ for the unitarity triangle. The solution of this problem is supposed to be a matter for the near future [218]. Because SUSY does not exclude a marked CP violation in $\{B_s^0, \bar{B}_s^0\} \to J/\psi\phi$ decays (see Section 4), studies of this asymmetry are of crucial importance.

Priority studies of the most characteristic manifestations of CP violation also include a search for potential violations of CPT invariance. Since such a possibility is associated with changes in the space–time properties on scales $m_{Pl} \sim 10^{19}$ GeV, CPT effects are expected to occur at a level of $(E/m_{Pl})^n$, which implies that the ratio of the difference between the masses of a particle and its antiparticle to the particle mass at $n = 1$ is $m/m_{Pl} \sim 10^{-19}$. Although CPT effects are extremely weak, their observation is deemed feasible in neutral kaon studies with an improved measurement accuracy [48, 192, 194] and in other high-precision experiments [195, 196].

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