Нарушение *CP* инвариантности для кварков и нейтральных мезонов в слабых взаимодействиях

Х. М. Бештоев

Аннотация

Эта работа посвящена рассмотрению возможных схем введения CP нарушения для нейтральных мезонов и кварков в слабых взаимодействиях. Отмечено, что в общем случае является некорректным введение CP фазы только для первого и третьего семейств. Такие фазы нужно вводить и для остальных семейств и при этом не обязательно, чтобы эти фазы были одинаковыми для всех семейств. Кроме этого рассмотрены нарушения CP инвариантности для K^o, D^o, B^o_d, B^o_s мезонов, где кроме CP фаз появляются углы смешивания $\beta'_1, \beta_c, \beta_d, \beta_s$. Получены выражения для вероятностей переходов при CP нарушении для этих мезонов. В заключение обсуждается схема CP нарушения для d, s, b кварков, где появляются углы их смешивания и фазы.

Introduction

Previously it was supposed that P parity is a well number, however, after theoretical [1] and experimental [2] works it has become clear that in weak interactions P parity is violated. Then in work [3], there has been an advanced supposition that CP parity is conserved in weak interactions but not P parity. Work [4] has reported that there is two π decay mode in K_L decays with a probability of about 0.2%, which is a detection of CP parity violation.
It has been detected that strangeness -S also is violated in weak interactions [5] (also see references in [6]). In order to solve this problem, N. Cabibbo [6] proposes to introduce matrix mixing of d, s quarks. Then we can connect the decay modes of mesons (for example π and K mesons) or giperons. For this aim, it is necessary to use charged weak interactions current j_F^μ of d, s quarks (of two quark families) in the following form:

$$j_F^\mu = \begin{pmatrix} \bar{u}\bar{c} \end{pmatrix}_L \gamma^\mu V \begin{pmatrix} d \\ s \end{pmatrix}_L, \quad V = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & cos\theta \end{pmatrix}, \tag{1}$$

where V characterizes the mixing of d and s quarks and θ is the angle mixing of d, s quarks

$$\begin{pmatrix} d' \\ s' \end{pmatrix}_L = V \begin{pmatrix} d \\ s \end{pmatrix}_L. \tag{2}$$

This approach was then extended for the case of three quark families by Kobayashi

M., Maskawa K. in [7]. In the case of three quark families, there appears a parameter violating CP parity, while in the case of two quark families this parameter is absent. For introduction of the three quark mixings, we will use again charged vector current J^μ, which has the following form:

$$J^\mu = (\bar{u}\bar{c}\bar{t})_L \gamma^\mu V \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L , \tag{3}$$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}, \qquad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L = V \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L , \tag{4}$$

It is more suitable to choose parametrization of V in the following form, which was proposed by L. Maiani [8]:

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\gamma & s_\gamma \\ 0 & -s_\gamma & c_\gamma \end{pmatrix} \begin{pmatrix} c_\beta & 0 & s_\beta \exp(-i\delta) \\ 0 & 1 & 0 \\ -s_\beta \exp(i\delta) & 0 & c_\beta \end{pmatrix} \begin{pmatrix} c_\theta & s_\theta & 0 \\ -s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$$c_\theta = \cos\theta, s_\theta = \sin\theta, c_\beta = \cos\beta, c_\gamma = \cos\gamma, \exp(i\delta) = \cos\delta + i\sin\delta. \tag{5}$$

where θ, β, γ are mixing angles of three quarks and δ is the parameter of *CP* violation. It is important to remark that the parameter of *CP* violation is the same for all three quark families, i.e., it is a global parameter.

The common case of CP violation

Before considering CP violation, let us consider the case of Kobayashi-Maskawa matrix V' when the parameter of CP violation is zero ($\delta = 0$)

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

$$V' = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\gamma & s_\gamma \\ 0 & -s_\gamma & c_\gamma \end{pmatrix} \begin{pmatrix} c_\beta & 0 & s_\beta \\ 0 & 1 & 0 \\ -s_\beta & 0 & c_\beta \end{pmatrix} \begin{pmatrix} c_\theta & s_\theta & 0 \\ -s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{6}$$

Values of 9 parameters $V_{a,b}, a = 1-3, b = 1-3$ are established [9] by now. The values of θ, β, γ, are established also, but value of δ has not been estibleshed with high precision. Besides, the expression for V in (5) can have another form. For expample, it can be in the form

$$V_2 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\gamma & s_\gamma \\ 0 & -s_\gamma & c_\gamma \end{pmatrix} \begin{pmatrix} c_\beta & 0 & s_\beta \\ 0 & 1 & 0 \\ -s_\beta & 0 & c_\beta \end{pmatrix} \begin{pmatrix} c_\theta & s_\theta \exp(-i\delta) & 0 \\ -s_\theta \exp(i\delta) & c_\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{7}$$

or in the form

$$V_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\gamma & s_\gamma \exp(-i\delta) \\ 0 & -s_\gamma \exp(i\delta) & c_\gamma \end{pmatrix} \begin{pmatrix} c_\beta & 0 & s_\beta \\ 0 & 1 & 0 \\ -s_\beta & 0 & c_\beta \end{pmatrix} \begin{pmatrix} c_\theta & s_\theta & 0 \\ -s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{8}$$

It is not obligatory that the parameter δ in V, V_2, V_3 must be the same. It can be different: δ, δ_2, δ_3.

Let us consider more realistic case, but first consider CP violation for neutral K^o, D^o, B^o mesons.

CP violation in meson sector

Сперва кратко рассмотрим CP нарушение для $K^o, \bar{K}^o$ мезонов, а потом перейдем к рассмотрению CP нарушения для D^o, B^o_d, B^o_s мезонов.

The case of $K^o, \bar{K}^o$ mesons.

At strangeness violation $K^o, \bar{K}^o$ mesons are transformed into superposition states of K^o_1, K^o_2 mesons

$$K^o = \frac{K^o_1 + K^o_2}{\sqrt{2}}, \qquad \bar{K}^o = \frac{K^o_1 - K^o_2}{\sqrt{2}}, \tag{9}$$

and it leads to $K^o, \bar{K}^o$ meson oscillations via K^o_1, K^o_2, which dominate in the time range $t \simeq 0.0 \div 8\tau_{K^o_1}$ ($\tau_{K^o_1}$ is the life time of K^o_1 and $\tau_{K^o_1} \cong \tau_{K_S}$ mesons).
CP violation in the system of K^o mesons was widely researched experimentally [1, 4, 9, 10] and theoretically [11, 12]. At CP violation in the system of K^o mesons oscillations are absent and there is realized interference between K_S, K_L states, which appear at CP violation

$$\begin{array}{c} K^o_1 = cos\beta_1 K_S + sin\beta_1 e^{i\delta_1} K_L, \\ K^o_2 = -sin\beta_1 e^{-i\delta_1} K_S + cos\beta_1 K_L, \end{array} \tag{10}$$

where β_1 is angle mixing at CP violation and δ_1 is CP phase.

There can be the case [11], when

$$K_1^o = cos\beta_1 K_S + sin\beta_1 e^{i\delta_1} K_L,$$
$$K_2^o = -sin\beta_1 e^{i\delta_1} K_S + cos\beta_1 K_L, \quad (10')$$

The probability of $K_1^o(t)$ meson state presence in dependence on time t for primary K^o meson is given by the following expression:

$$|K_1^o(t)|^2 \simeq \frac{1}{2}[exp^{(-\Gamma_S t)} + \varepsilon^2 exp^{(-\Gamma_L t)} + 2\varepsilon exp^{(\frac{1}{2}(\Gamma_S + \Gamma_l)t)} cos((E_L - E_S) - \delta_1)t], \quad (11)$$

and the probability of $K_1^o(t)$ meson state presence in dependence on time t for primary $\bar{K}^o$ meson is given by the following expression:

$$|K_1^o(t)|^2 \simeq \frac{1}{2}[exp^{(-\Gamma_S t)} + \varepsilon^2 exp^{(-\Gamma_L t)} - 2\varepsilon exp^{(\frac{1}{2}(\Gamma_S + \Gamma_l)t)} cos((E_L - E_S) - \delta_1)t], \quad (12)$$

where $\varepsilon = sin\beta_1$, Γ_S, Γ_L are decay widths of K_S, K_L meson states [12].
Value for sin $\beta_1 \simeq 2.32 \cdot 10^{-3}$, $\delta_1 \simeq 43^o$ (see [1, 4, 9, 10]). K_S, K_L meson interference dominates at $t > 8\tau_{K_S}$. It is important not to mix it up with $K^o, \bar{K}^o$ meson oscillations, which dominate at $t < 8\tau_{K_S}$!

The case of $D^o, \bar{D}^o$ mesons.

The case of $D^o, \bar{D}^o$ mesons fundamentally differs from the $K^o, \bar{K}^o$ meson case, since they consist of c, u quarks $D^o = c\bar{u}$ and $\bar{D}^o = \bar{c}u$. It is supposed that u, c, t quark states are not mixed in weak interactions, while d, s, b quarks are in mixed states (see expr. (4)). Therefore the quark block diagram for $D^o, \bar{D}^o$ meson oscillations will strongly differ from the $K^o, \bar{K}^o$ meson oscillations case. We will not come to detailed consideration of $D^o, \bar{D}^o$ meson oscillations, since we are interested in CP violation. However it is necessary to remark that observation of $D^o, \bar{D}^o$ meson oscillations is a very difficult problem. The task to detect CP violation in this case is also very hard problem.

At violation of d, s, b-number in weak interactions, $D^o, \bar{D}^o$ mesons are transformed into superpositions of D^o_{1c}, D^o_{2c} mesons

$$D^o = \frac{D^o_{1c} + D^o_{2c}}{\sqrt{2}}, \qquad \bar{D}^o = \frac{D^o_{1c} - D^o_{2c}}{\sqrt{2}}, \tag{13}$$

and it leads to $D^o, \bar{D}^o$ meson oscillations via D^o_{1c}, D^o_{2c}.

At CP violation in the system of $D^o, \bar{D}^o$ mesons, oscillations have to be absent and there is realized interference between D_{Sc}, D_{Lc} states, which appear at CP violation

$$\begin{array}{c} D^o_{1c} = cos\beta_c D_{Sc} + sin\beta_c e^{i\delta_c} D_{Lc}, \\ D^o_{2c} = -sin\beta_c e^{-i\delta_c} D_{Sc} + cos\beta_c D_{Lc}, \end{array} \tag{14}$$

where β_c is angle mixing at CP violation and δ_d is CP phase.
There can be case [11] when

$$\begin{aligned} D^o_{1c} &= cos\beta_c D_{Sc} + sin\beta_c e^{i\delta_c} D_{Lc}, \\ D^o_{2c} &= -sin\beta_c e^{i\delta_c} D_{Sc} + cos\beta_c D_{Lc}, \end{aligned} \tag{14'}$$

The probability of $D^o_{1c}(t)$ meson state presence in time t dependence for primary D^o_d meson is given by the following expression:

$$|D^o_{1c}(t)|^2 \simeq \frac{1}{2}[exp^{(-\Gamma_{Sc}t)} + \varepsilon_c^2 exp^{(-\Gamma_{Lc}t)} + 2\varepsilon_c exp^{(\frac{1}{2}(\Gamma_{Sc}+\Gamma_{Lc})t)} cos((E_{Lc} - E_{Sc}) - \delta_c)t], \tag{15}$$

and the probability of the presence of $D^o_{1c}(t)$ meson state in time t dependence for primary $\bar{D}^o_d$ meson is given by the following expression:

$$|D^o_{1c}(t)|^2 \simeq \frac{1}{2}[exp^{(-\Gamma_{Sc}t)} + \varepsilon_c^2 exp^{(-\Gamma_{Lc}t)} - 2\varepsilon_c exp^{(\frac{1}{2}(\Gamma_{Sc}+\Gamma_{Lc})t)} cos((E_{Lc} - E_{Sc}) - \delta_d)t], \tag{16}$$

where $\varepsilon_d = sin\beta_c$, Γ_{Sc}, Γ_{Lc} are decay widths of D_{Sc}, D_{Lc} meson states [12].
Until now, an indication of strong presence of CP violation in experiments with $D^o, \bar{D}^o$ mesons [13] has not been found.

The case of $B^o, \bar{B}^o$ mesons.

In this case $B^o, \bar{B}^o$ mesons consist of quarks, which are in mixed states in the framework of weak interactions. In contrast to the K^o meson case, here will be two states $B^o_d = b\bar{d}$ and $B^o_s = b\bar{s}$. The quark block diagram for $B^o, \bar{B}^o$ mesons will work in analogy with the $K^o, \bar{K}^o$ meson case (i.e., oscillations will take place there). Now we will consider come CP violation. As in the case of K^o mesons, at CP violation there has to arise interference between $CP = \pm 1$ states. But observation of this interference term in experiments is a very hard task, since B^o_d, B^o_s have big masses and hence very many decay canals. Unfortunately, an indication of strong presence of CP violation has not been found until now in experiments [14] with $B^o_d, \bar{B}^o_d$ and $B^o_s, \bar{B}^o_s$ mesons. Nevertheless, we can introduce in analogy with K^o meson parameters (mixing angles) and phase δ_{ds} of CP violation.

At violation of b-number in weak interactions, $B^o_d, \bar{B}^o_d$ mesons are transformed into superpositions of B^o_{1d}, B^o_{2d} bosons

$$B^o_d = \frac{B^o_{1d} + B^o_{2d}}{\sqrt{2}}, \qquad \bar{B}^o_d = \frac{B^o_{1d} - B^o_{2d}}{\sqrt{2}}, \tag{17}$$

and it leads to $B^o_d, \bar{B}^o_d$ meson oscillations via B^o_{1d}, B^o_{2d}.

At CP violation in the system of $B^o, \bar{B}^o$ mesons, oscillations have to be absent and there is realized interference between B_{Sd}, B_{Ld} states, which appear at CP

violation

$$B^o_{1d} = cos\beta_d B_{Sd} + sin\beta_d e^{i\delta_d} B_{Ld},$$
$$B^o_{2d} = -sin\beta_d e^{-i\delta_d} B_{Sd} + cos\beta_d B_{Ld}, \quad (18)$$

where β_d is angle mixing at CP violation and δ_d is CP phase.
There can be case [11] when

$$B^o_{1d} = cos\beta_d B_{Sd} + sin\beta_d e^{i\delta_d} B_{Ld},$$
$$B^o_{2d} = -sin\beta_d e^{i\delta_d} B_{Sd} + cos\beta_d B_{Ld}, \quad (18')$$

The probability of $B^o_{1d}(t)$ meson state presence in time t dependence for primary B^o_d meson is given by the following expression:

$$|B^o_{1d}(t)|^2 \simeq \frac{1}{2}[exp^{(-\Gamma_{Sd}t)} + \varepsilon_d^2 exp^{(-\Gamma_{Ld}t)} + 2\varepsilon_d exp^{(\frac{1}{2}(\Gamma_{Sd}+\Gamma_{Ld})t)} cos((E_{Ld}-E_{Sd})-\delta_d)t], \quad (19)$$

and the probability of the presence of $B^o_{1d}(t)$ meson state in time t dependence for primary $\bar{B}^o_d$ meson is given by the following expression:

$$|B^o_{1d}(t)|^2 \simeq \frac{1}{2}[exp^{(-\Gamma_{Sd}t)} + \varepsilon_d^2 exp^{(-\Gamma_{Ld}t)} - 2\varepsilon_d exp^{(\frac{1}{2}(\Gamma_{Sd}+\Gamma_{Ld})t)} cos((E_{Ld}-E_{Sd})-\delta_d)t], \quad (20)$$

where $\varepsilon_d = sin\beta_d$, Γ_{Sd}, Γ_{Ld} are decay widths of B_{Sd}, B_{Ld} meson states [12].

At violation of b-number in weak interactions, $B_s^o, \bar{B}_s^o$ mesons are transformed into superpositions of B_{1s}^o, B_{2s}^o bosons

$$B_s^o = \frac{B_{1s}^o + B_{2s}^o}{\sqrt{2}}, \qquad \bar{B}_s^o = \frac{B_{1s}^o - B_{2s}^o}{\sqrt{2}}, \tag{21}$$

and it leads to $B_s^o, \bar{B}_s^o$ meson oscillations via B_{1s}^o, B_{2s}^o.
In the case of $B_s^o, \bar{B}_s^o$ mesons we have B_{Ss}, B_{Ls} states, which appear at CP violation

$$\begin{aligned} B_{1s}^o &= cos\beta_s B_{Ss} + sin\beta_s e^{i\delta_s} B_{Ls}, \\ B_{2s}^o &= -sin\beta_s e^{-i\delta_s} B_{Ss} + cos\beta_s B_{Ls}, \end{aligned} \tag{22}$$

where β_s is angle mixing at CP violation and δ_s is CP phase.
There also can be case [11] when

$$\begin{aligned} B_{1s}^o &= cos\beta_s B_{Ss} + sin\beta_s e^{i\delta_s} B_{Ls}, \\ B_{2s}^o &= -sin\beta_s e^{i\delta_s} B_{Ss} + cos\beta_s B_{Ls}, \end{aligned} \tag{22'}$$

The probability of the presence of $B_{1s}^o(t)$ meson state in time t dependence for primary B_s^o meson is given by the following expression:

$$|B_{1s}^o(t)|^2 \simeq \frac{1}{2}[exp^{(-\Gamma_{Ss}t)} + \varepsilon_s^2 exp^{(-\Gamma_{Ls}t)} + 2\varepsilon_s exp^{(\frac{1}{2}(\Gamma_{Ss}+\Gamma_{Ls})t)} cos((E_{Ls} - E_{Ss}) - \delta_s)t], \tag{23}$$

and the probability of the presence of $B^o_{1s}(t)$ meson state in time t dependence for primary $\bar{B}^o_s$ meson is given by the following expression:

$$|B^o_{1s}(t)|^2 \simeq \frac{1}{2}[exp^{(-\Gamma_{Ss}t)} + \varepsilon_s^2 exp^{(-\Gamma_{Ls}t)} - 2\varepsilon_s exp^{(\frac{1}{2}(\Gamma_{Ss}+\Gamma_{Ls})t)} cos((E_{Ls} - E_{Ss}) - \delta_s)t], \tag{24}$$

where $\varepsilon = sin\beta_s$, Γ_{Ss}, Γ_{Ls} are decay widths of B_{Ss}, B_{Ls} meson states [12].

Матрицу Ву и Янга нужно нормировать на единицу и этот коэффициент есть:

$$N = \frac{1}{1 + 2sin(x)cos(\delta)}.$$

CP violation in the quark sector

Now let us return to *CP* violation for quarks, but with another approach than it was done in [7]. There *CP* violation becomes apparent by using *CP* phase δ. But at consideration of *CP* violation in the case of $K^o, \bar{K}^o$ mesons we see that there appears a new angle mixing β_1 and the phase δ_1, while angle mixing β_1 in [7] is absent. For simplification we will consider *CP* violation in quark sector using pairs of quarks. For the first pair we have

$$\left(\begin{array}{c} d'' \\ s'' \end{array}\right)_L = \left(\begin{array}{cc} cos\beta'_1 & sin\beta'_1 e^{i\delta'_1} \\ -sin\beta'_1 e^{i\delta'_1} & cos\beta'_1 \end{array}\right) \left(\begin{array}{c} d' \\ s' \end{array}\right)_L . \quad (25)$$

It is obvious that $\beta'_1 \neq \beta_1$ and $\delta'_1 \neq \delta_1$.

For the second pair of quarks we have

$$\left(\begin{array}{c} d'' \\ b'' \end{array}\right)_L = \left(\begin{array}{cc} cos\theta'_1 & sin\theta'_1 e^{i\delta'_2} \\ -sin\theta'_1 e^{i\delta'_2} & cos\theta'_1 \end{array}\right) \left(\begin{array}{c} d' \\ b' \end{array}\right)_L . \quad (26)$$

For the third pair of quarks we have

$$\left(\begin{array}{c} s'' \\ b'' \end{array}\right)_L = \left(\begin{array}{cc} cos\gamma'_1 & sin\gamma'_1 e^{i\delta'_3} \\ -sin\gamma'_1 e^{i\delta'_3} & cos\gamma'_1 \end{array}\right) \left(\begin{array}{c} s' \\ b' \end{array}\right)_L . \quad (27)$$

Probably origin of all above parameters $\beta'_1, \theta'_1, \gamma'_1, \delta'_1, \delta'_2, \delta'_3$ has a dynamic character and, therefore, for computation of values of these parameters, it is necessary to know the precise dynamic nature of *CP* violation.

Заключение

1. CP нарушение в матрице Кобаяши-Маскавы вводится с использованием фазы δ, которая является одним и тем-же для всех семейств. Отмечено, что в общем случае является некорректным введение CP фазы только для первого и третьего семейств. Такие фазы нужно вводить и для остальных семейств и при этом не обязательно, чтобы эти фазы были одинаковыми для всех семейств.
2. Рассмотрены нарушения CP инвариантности для K^o, D^o, B_d^o, B_s^o мезонов, где кроме CP фаз появляются углы смешивания $\beta_1', \beta_c, \beta_d, \beta_s$. Получены выражения для вероятностей переходов при CP нарушении для этих мезонов.
3. В заключение обсуждается схема CP нарушения для d, s, b кварков, где появляются углы их смешивания и фазы.

- Lee T.D., Yang C.N., Phys. Rev., 1956, v.104, p.254.
- Wu C. S. et al., Phys. Rev., 1957, v.105, p.1413;
  Phys. Rev., 1957, v.106, p.1361.
- Landau L. D., Sovet J.JETP, 1957, v.32, p.405.
- Christenson J.H. et al., Phys. Rev. Lett., 1964, v.13, p.138.
- Roe B. P. et al., Phys. Rew. Lett., 1961, v.7, p.346.
- Cabibbo N., Phys. Rev. Lett., 1963, v.10, p.531.
- Kobayashi M., Maskawa K., Prog. Theor. Phys., 1973, v.49, p.652;
  Okun L. B., Leptons and Quarks, M. Nauka, 1990.
- Maiani L., Proc. Int. Symp. on Lepton-Photon Int., Hamburg, DESY, 1977, p.867.
- Phys. Lett.B, Review of Part. Phys, 2008, v. 667, p.145, 733.
  Phys. Rev. D, Review of Part. Phys, 2012, v. 86, 010001, p. 157, 852.
- R. Adler et al., Phys. Lett.B, 1995, v.363, p. 243;
  A. Apostolakis et al., Phys. Letters B 1999, v. 458, p. 545;

Marianna Testa (Kloe Collab.), hep-ex/0505015v.1, 2006.

Wu T.T. and Yang C.N., Phys. Rev. Lett., 1964, v.13, p.380.

Beshtoev Kh. M., Nuclear Physics B (Proc. Supl.), 2011, v.219-220, p.276-280;
hep-ph/1401.5989v.2, Febr 2014.

Phys. Lett.B, Review of Part. Phys, 2008, v. 667, p. 783;
Phys. Rev. D, Review of Part. Phys, 2012, v. 86, 010001, p. 903. 1066

Phys. Lett.B, Review of Part. Phys, 2008, v. 667, p. 914;
Phys. Rev. D, Review of Part. Phys, 2012, v. 86, 010001, 1066.

CP нарушение в матрице Кобаяши-Маскавы вводится с использованием фазы δ, которая является одним и тем-же для всех семейств. Однако, анализ CP нарушения у K^0 мезонов показал, что при CP нарушении появляется новый малый угол смешивания кроме CP фазы.