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INFLUENCE OF CP VIOLATION ON ENERGY SPECTRA IN $K^+ \to \pi^\pm \pi^\pm \pi^\mp$ DECAYS

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ABSTRACT

Using the chiral σ model with broken $U(3)_L \otimes U(3)_R$ symmetry we have calculated in the p^4-approximation a difference between the slope parameters g^+ and g^- describing the energy distributions of "odd" pions in $K^+ \to \pi^+\pi^+\pi^-$ and $K^- \to \pi^-\pi^-\pi^+$ decays. The result is: $(g^+ - g^-)/(g^+ + g^-) = -(1.9 \pm 0.8)10^{-2} s_2 s_3 \sin\delta$, where s_2, s_3 and δ are the parameters of the Kobayashi-Maskawa mixing matrix.

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1. INTRODUCTION

So far a search for the direct CP violation caused by the Kobayashi-Maskawa phase mechanism [1] was concentrated on measurements of the electric dipole moment of the neutron d_n and parameter ε' in $K^0 \to 2\pi$ decays. But the experimental limit $d_n < 1.2 \cdot 10^{-25}$ ecm is far from the expected magnitude $d_n^{th} < 10^{-31}$ecm [2]. As for the parameter ε', its magnitude crucially depends on t-quark mass and even zero value of ε' would not mean that the direct CP violation is absent, if the t-quark mass is big enough [3-5]. Besides, two measurements of ε' giving

$$\mathrm{Re}(\varepsilon'/\varepsilon) = \begin{cases} (2.3 \pm 0.7)10^{-3} & [6] \\ (0.6 \pm 0.7)10^{-3} & [7] \end{cases}$$

are not in good agreement.

In such a situation, a search for the direct CP violation in $K^+ \to 3\pi$ decays leading to difference of widths of $K^+ \to \pi^+\pi^+\pi^-$ and $K^- \to \pi^-\pi^-\pi^+$ decays and difference of the slope parameters in these decays becomes of great interest.

The calculations [8-12] of such effects fulfilled in the lowest, p^2-approximation in momentum expansion of the amplitude led to conclusion that the relative difference of the widths of $K^+\pi^+\pi^+\pi^-$ and $K^- \to \pi^-\pi^-\pi^+$ has to be of order of 10^{-6}.

In the lowest p^2-approximation, the CP-violating effects appear only thanks to interference of the $\Delta I = 1/2$ and $\Delta I = 3/2$ parts of the total amplitude. But in the p^4-approximation, the parts of the $\Delta I = 1/2$ amplitude corresponding to "penguin" and "non-penguin" diagrams become of different dynamical structure and an additional contribution to CP violating effects appears from $|A_{1/2}|^2$. It was claimed by Bel'kov *et al.* [13-15] that in the p^4-approximation the result for CP violating effects in $K^\pm \to \pi^\pm\pi^\pm\pi^\mp$ decays turns out to be larger by two orders in comparison with the value calculated in the p^2-approximation.

Be it true, the investigation of CP violation in $K^\pm \to 3\pi$ decays should be a paramount task for the planned ϕ factories.

In view of significance of the question and in connection with some doubts on results of Refs.[13-15] expressed in Refs.[10-16] (however, without the calculation at p^4 order), it is important to investigate the problem again using some independent approach. We do this in the framework of Chiral Pole Model (ChPM) based on linear σ model with broken $U_L(3) \otimes U_R(3)$ symmetry [17]. The application of this model allows to calculate the amplitudes of mesonic processes in any order in p^2 without any considerable difficulties. An employment of this model for a description of K_{ℓ_3} and K_{e_4} decays [18,19] led to the results practically indistinguishable from the ones obtained in the most general Chiral Perturbation Theory (ChPT) approach [20, 21].

The outline of the paper is as follows. In Sec. 2 we present a calculation of the $K^{\pm} \to 3\pi$ and $K \to 2\pi$ amplitudes in p^2-approximation neglecting effect of mixing between the isosinglet scalar $\bar{q}q$ state and gluonic scalar state $G^a_{\mu\nu}G^a_{\mu\nu}$.

The aim of such a calculation is to verify that our approach allows to reproduce the results obtained with algebra of currents and soft-pion technics. And using the data on $K \to 2\pi$ decays we also fix some constants necessary for $K^{\pm} \to 3\pi$ description.

Being convinced of self-consistency of our method, in Sec. 3 we take into account the mixing of the scalar $\bar{q}q$ state, with the gluonic one and calculate the explicit (at the tree-level) expressions of the amplitude under consideration.

Section 4 is devoted to the calculation of a difference between the slope parameters g^+ and g^- for $K^+ \to \pi^+\pi^+\pi^-$ and $K^- \to \pi^-\pi^-\pi^+$ transitions. These parameters are defined by the expression

$$|M(K^{\pm} \to \pi^{\pm} - \pi^{\pm}\pi^{\mp}|^2 \sim 1 + g^{(\pm)}Y + h^{(\pm)}Y^2 + k^{(\pm)}X^2 \qquad (1)$$

where $Y = (s_3 - s_0)/m_\pi^2$; $X = (s_2 - s_1)/m_\pi$; $s_i = (k - p_i)^2$; $s_0 = m_k^2/3 + m_\pi^2$; k and p_i are 4-momenta of K and π_i mesons.

The difference $g^+ - g^-$ is calculated in the p^4-approximation. It is done for two reasons. First, a calculation is more simple in this approximation and second, our result can be compared with the results of Refs.[13-15] directly. In our calculation we use an expansion of the $K^{\pm} \to 3\pi$ amplitude up to terms p^4/Λ^2 and the leading p^2-approximation for $\pi - \pi$ scattering amplitudes in calculation of the loop diagrams.

Section 5 contains the conclusions.

All formulae necessary for calculations of the amplitudes described by the diagrams of Figs.1-3 are presented in the Appendix.

2. EFFECTIVE $|\Delta S = 1|$ LAGRANGIAN IN LINEAR $U(3)_L \otimes U(3)_R$ σ MODEL

We start from the effective four-quark lagrangian for $|\Delta S = 1|$ transition in the form [22]

$$L(\Delta S = -1) = -\sqrt{2}\, G_F \sin\theta_C \cos\theta_C \sum_{i=1}^{6} c_i 0_i \qquad (2)$$

where

$$0_1 = \bar{s}_L\gamma_\mu d_L \cdot \bar{u}_L\gamma_\mu u_L - \bar{s}_L\gamma_\mu u_L \cdot \bar{u}_L\gamma_\mu d_L,\ (\{8_f\}), \Delta I = 1/2)$$
$$0_2 = 2\bar{s}_L\gamma_\mu d_L \cdot \left(\sum_{q=u,d,s} \bar{q}_L\gamma_\mu q\right) - 0_1,\ (\{8_f\}, \Delta I = 1/2)$$

$$0_3 = 0_2 - 5\bar{s}_L\gamma_\mu d_L \cdot \bar{s}_L\gamma_\mu s_L, \quad (\{27\}, \Delta I = 1/2)$$
$$0_4 = \bar{s}_L\gamma_\mu d_L \cdot \bar{u}_L\gamma_\mu u_L + \bar{s}_L\gamma_\mu u_L \cdot \bar{u}_L\gamma_\mu d_L - \bar{s}_L\gamma_\mu d_L \cdot \bar{d}_L\gamma_\mu d_L,\ (\{27\}, \Delta I = 3/2)$$
$$0_5 = \bar{s}_L\gamma_\mu\lambda^a d_L \cdot \left(\sum_{q=u,d,s} \bar{q}_R\gamma_\mu\lambda^a q_R\right),\ (\{8\}, \Delta I = 1/2)$$
$$0_6 = \bar{s}_L\gamma_\mu d_L \cdot \left(\sum_{q=u,d,s} \bar{q}_R\gamma_\mu q_R\right),\ (\{8\}, \Delta I = 1/2) \qquad (3)$$

Though this set of operators has to be supplemented by operators corresponding to electroweak penguin and box diagrams, it is sufficient for checking of results of Refs.[13-15] and we shall use this set in our calculations.

To solve the problem of presentation of the 4-quark operators 0_i in terms of products of the currents formed by physical scalar and pseudoscalar mesons the linear σ model with broken $U(3)_L \otimes U(3)_R$ symmetry can be used. The lagrangian is of the form [17,18]

$$L = \frac{1}{2}\, Tr(\partial_\mu U \partial_\mu U^+) - c\, Tr(UU^+ - A^2 t_0^2)^2 - c\xi(Tr(UU^+ - A^2 t_0^2))^2 + \frac{F\pi}{2\sqrt{2}}\, Tr[(U + U^+)M] + \Delta L_{PS}(U_1) \qquad (4)$$

where

$$U = \hat{\sigma} + i\hat{\pi}$$

and $\hat{\sigma}$ and $\hat{\pi}$ are 3×3 matrices of nonets of scalar and pseudoscalar mesons.

The quark currents forming the operators 0_{1-4} can be written in terms of U using the relations

$$\bar{q}_k\gamma_\mu q_\ell = i[\gamma_\mu U \cdot U^+ - U\partial_\mu U^+]^{\rm Vector}_{\ell k} = i(\partial_\mu\hat{\pi} \cdot \hat{\pi} - \hat{\pi}\partial_\mu\hat{\pi} + \partial_\mu\hat{\sigma} \cdot \hat{\sigma} - \hat{\sigma}\partial_\mu\hat{\sigma})_{\ell k}\ ,$$
$$\bar{q}_k\gamma_\mu\gamma_5 q_\ell = i[\partial_\mu U \cdot U^+ - U\partial_\mu U^+]^{\rm Axial}_{\ell k} = (\partial_\mu\hat{\sigma} \cdot \hat{\pi} - \hat{\sigma} \cdot \partial_\mu\hat{\pi} - \partial_\mu\hat{\pi} \cdot \hat{\sigma} + \hat{\pi}\partial_\mu\hat{\sigma})_{\ell k}\ . \qquad (5)$$

Using the relations [23]

$$\lambda^\alpha_\delta\ \lambda^\gamma_\beta = 2\delta^\alpha_\beta\ \delta^\gamma_\delta - \frac{2}{3}\ \delta^\alpha_\delta\ \delta^\gamma_\beta$$

$$\bar{s}\gamma_\mu(1 + \gamma_5)d \cdot \bar{q}\gamma_\mu(1 - \gamma_5)q = -2\bar{s}(1 - \gamma_5)q \cdot \bar{q}(1 + \gamma_5)d$$

we can present the operator 0_5 in the form

$$0_5 = -\bar{s}(1-\gamma_5)q \cdot \bar{q}(1+\gamma_5)d - \frac{1}{6}\ \bar{s}\gamma_\mu(1+\gamma_5)d \cdot \bar{q}\gamma_\mu(1-\gamma_5)q$$

But

$$\bar{q}_k(1-\gamma_5)q_\ell = \frac{\sqrt{2}F_\pi m_\pi^2}{m_u + m_d}\ U_{\ell k}\ , \quad F_\pi \cong 93 \text{ MeV } [24]$$

Then

$$0_5 = -\frac{2F_\pi^2\ m_\pi^4}{(m_u+m_d)^2}\ (U^+U)_{23} + \dots \tag{6}$$

In this formula we have omitted the part which does not contribute to $K^\pm \to 3\pi$ transition.

The operator 0_5 induces the non-diagonal transitions described by the effective lagrangian

$$L(0_5) = -\frac{2F_\pi^2\ m_\pi^4}{(m_u+m_d)^2}\left[K^+\pi^- - \frac{1}{\sqrt{2}}\ K^0\pi^0 + \sigma_{K^0}\sigma_{\eta'}\left(\frac{2}{\sqrt{3}}\cos\theta_S - \frac{\sin\theta_S}{\sqrt{6}}\right)\right.$$
$$\left. - \sigma_{K^0}\sigma_\eta\left(\frac{2}{\sqrt{3}}\sin\theta_S + \frac{1}{\sqrt{6}}\cos\theta_S) + \dots\right)\right] \tag{7}$$

where $\sigma_{K^0}, \sigma_{\eta'}$ and σ_η are the scalar partners of K^0, η' and η mesons and θ_S is a mixing angle between σ_0 and σ_8:

$$\begin{aligned} \sigma_{\eta'} &= \sigma_0\cos\theta_S + \sigma_8\sin\theta_S \\ \sigma_\eta &= -\sigma_0\sin\theta_S + \sigma_8\cos\theta_S\ . \end{aligned} \tag{8}$$

In absence of mixing of isosinglet scalar $\bar{q}q$ state with the gluonic state $G^a_{\mu\nu}G^a_{\mu\nu}$ $\theta_S = arcsin(1/\sqrt{3})$. This case corresponds explicitly to the situation when usual algebra of currents is working. In our approach, it corresponds to $\xi = 0$ in the lagrangian (4), and to verify our technics, it is useful to evaluate the $K^\pm \to 3\pi$ amplitude putting $\xi = 0$ to be confident that all known results are well reproduced. And only after that we shall take into account the effects of mixing σ_0 with the gluonic state playing an important role in reality.

The transition $K^+ \to \pi^+\pi^+\pi^-$ induced by operator 0_5 is described in our theory by diagrams shown in Fig.1. In the p^2-approximation corresponding to soft-pion approximation we get

$$< \pi^+(p_1)\pi^+(p_2)\pi^-(p_3)|0_5|K^+(k) >_{\xi=0} = \beta \cdot (s_1 + s_2 - 2m_\pi^2) \tag{9}$$

where $\quad \beta = 2m_\pi^4/[(m_u+m_d)^2\Lambda^2], \quad \Lambda^2 = m^2_{\sigma_\pi} - m^2_\pi \quad$ *) $\quad$ (10)

*) Though σ_π exchange does not contribute to the amplitude under consideration, a definition of Λ^2 through $m^2_{\sigma_\pi}$ is convenient in view of the mass relations between different scalars (see Appendix).

The result (9) can be written also in the form (see Ref.[24])

$$< \pi^+\pi^+\pi^-|0_5|K> = \frac{i}{2F_\pi} < \pi^+\pi^-|0_5|K_1^0 > (m_K^2 - m_\pi^2)^{-1}(s_1 + s_2 - 2m_\pi^2) \tag{11}$$

To calculate the contributions of the operators 0_{1-4} let us note that

$$\begin{aligned}
&\bar{u}\gamma_\mu u \Rightarrow i(\partial_\mu\pi^+ \cdot \pi^- - \partial_\mu\pi^- \cdot \pi^+) + \dots \\
&\bar{s}\gamma_\mu d \Rightarrow i(\partial_\mu\pi^- \cdot K^+ - \partial_\mu K^+ \cdot \pi^-) + i\partial_\mu\sigma_{K^0} < \sigma_{33} - \sigma_{22} >_0 + \dots \\
&\bar{s}\gamma_\mu d \Rightarrow \frac{i}{\sqrt{2}}(\partial_\mu K^+ \cdot \pi^0 - \partial_\mu\pi^0 \cdot K^+) + \dots \\
&\bar{u}\gamma_\mu d \Rightarrow i\sqrt{2}(\partial_\mu\pi^- \cdot \pi^0 - \partial_\mu\pi^0 \cdot \pi^-) + \dots \\
&\bar{u}\gamma_\mu\gamma_5 u \Rightarrow -F_\pi\partial_\mu\pi^0 + \dots \\
&\bar{d}\gamma_\mu\gamma_5 d \Rightarrow F_\pi\partial_\mu\pi^0 + \dots \\
&\bar{s}\gamma_\mu\gamma_5 d \Rightarrow \pi^-\partial_\mu\sigma_\mu\sigma_{K^+} - \partial_\mu\pi^- \cdot \sigma_{K^+} + \frac{1}{2}(\partial_\mu\pi^0 \cdot \sigma_{K^0} - \partial_\mu\sigma_{K^0}\pi^0) + \dots \\
&\bar{s}\gamma_\mu\gamma_5 u \Rightarrow -\sqrt{2}\ F_\pi\ R\partial_\mu\ K^+ + K^+\partial_\mu\left(\frac{2\sqrt{2}\sigma_0 - \sigma_8}{\sqrt{6}}\right) - \partial_\mu K^+ \cdot \left(\frac{2\sqrt{2}\sigma_0 - \sigma_8}{\sqrt{6}}\right) + \\
&\qquad + \frac{1}{\sqrt{2}}\ (\partial_\mu\sigma_{K^+}\pi^0 - \partial_\mu\pi^0\sigma_{K^+}) + \dots \\
&\bar{u}\gamma_\mu\gamma_5 d \Rightarrow -\sqrt{2}\ F_\pi\partial_\mu\pi^- + 2[\pi^-\partial_\mu\left(\frac{\sqrt{2}\sigma_0 + \sigma_8}{\sqrt{6}}\right) - \left(\frac{\sqrt{2}\sigma_0 + \sigma_8}{\sqrt{6}}\ \partial_\mu\pi^-\right) + \dots
\end{aligned} \tag{12}$$

where

$$R = F_K/F_\pi \tag{13}$$

We have omitted in Eq.(12) the parts of the currents which do not contribute into the amplitude under consideration. The currents $\sum\limits_{q=u,d,s} \bar{q}\gamma_\mu(1 \pm \gamma_5)q$ and $\bar{s}\gamma_\mu(1 \pm \gamma_5)s$ do not contribute to our amplitude.

The currents (12) induce the diagrams shown in Fig.2. In the p^2-approximation they give:

$$M(K^+(k) \to \pi^+(p_1)\pi^+(p_2)\pi^-(p_3))_{\xi=0} = \frac{1}{2\sqrt{2}}\sin\theta_C\cos\theta_C \cdot$$
$$\cdot\ [(c_1 - c_2 - c_3 - c_4 + 4_\beta\ c_5)(s_1 + s_2 - 2m_\pi^2) + 9c_4 \cdot (s_0 - s_3)] \tag{14}$$

$$M(K^+(k) \to \pi^0(p_1)\pi^0(p_2)\pi^+(p_3))_{\xi=0} = \frac{1}{2\sqrt{2}}\ \sin\theta_C\cos\theta_C \cdot$$
$$\cdot\left[(c_1 - c_2 - c_3 - c_4) + 4_\beta\ c_5)(s_3 - m_\pi^2) + \frac{9}{2}c_4(s_0 - s_3)\right]\ . \tag{15}$$

Using the same technics we can obtain

$$M(K_1^0 \to \pi^+\pi^-) = \frac{1}{\sqrt{2}}\, G_F \sin\theta_C \cos\theta_C (m_K^2 - m_\pi^2)[(c_1 - c_2 - c_3 + 4_\beta\ c_5) - c_4]$$
$$M(K_1^0 \to \pi^0\pi^0) = -\frac{1}{\sqrt{2}}\, G_F \sin\theta_C \cos\theta_C (m_K^2 - m_\pi^2)[(c_1 - c_2 - c_3 + 4_\beta\ c_5) + 2c_4]$$
$$M(K^+ \to \pi^+\pi^0) = \frac{1}{\sqrt{2}}\, G_F \sin\theta_C \cos\theta_C (m_K^2 - m_\pi^2)\frac{3c_4}{2}\ . \qquad (16)$$

Analysing the question on consistency of Eqs.(16) with the experimental data on $K \to 2\pi$ decays one has to take into account that due to $\pi - \pi$ scattering in the final state the combination

$$(c_1 - c_2 - c_3 + 4_\beta\ c_5)$$

acquires the phase factor $e^{i(\delta_0 - \delta_2)}$. Then from comparison with the no data $K \to 2\pi$ decays we obtain

$$c_4 = 0.328, \quad \delta_0 - \delta_2 \cong 54^\circ$$
$$c_1 - c_2 - c_3 + 4_\beta\ c_5 = -10.13 \qquad (17)$$

Combining the relations (14)-(16) we can represent the matrix elements (14) and (15) in the form

$$M(K^+ \to \pi^+\pi^+\pi^-(p_3)) = \frac{i}{3F_\pi}\ M(K_1^0 \to \pi^+\pi^-)[1 + y + 6\zeta y]$$
$$M(K^+ \to \pi^0\pi^0\pi^+(p_3)) = \frac{i}{6F_\pi}\ M(K_1^0 \to \pi^+\pi^-)[1 - 2y + 6\zeta y] \qquad (18)$$

where $y = 3E_3/m_K - 1$; and $\zeta = -\frac{M(K^+ \to \pi^+\pi^0)}{M(K_S \to \pi^+\pi^-)} = \frac{3c_4}{2(c_1 - c_2 - c_3 + 4_\beta c_5)}$

The results (18) are the well known results of PCAC and current algebra (see, for example, the review [25]).

CP violation connected with the Kobayashi-Maskawa phase δ leads to appearance of Im c_5. So, in the "tree" approximation the matrix elements (14) and (15) contain a small imaginary part which is of *opposite signs* for $K^+ \to \pi^+\pi^+\pi^-$ and $K^- \to \pi^-\pi^-\pi^+$ decays.

But to lead to observable effects this imaginary part must interfere with the imaginary part arising from $\pi - \pi$ scattering and having *the same signs* for K^+ and K^- decays. Besides, the appearing phase factors must be connected to different dynamical structures in the amplitude. In the p^2-approximation, as it follows from Eq.(14) a difference in dynamical structure takes place only between $\Delta I = 1/2$ and $\Delta I = 3/2$ parts of the total amplitude. Consequently, after addition of the imaginary part induced by the loop diagrams shown in Fig.3 to the amplitude (14), the CP-violating effects have to be proportional to interference between $\Delta I = 1/2$ and $\Delta I = 3/2$ parts of the amplitude.

The calculation fulfilled in Ref.[12] for the width difference gave the result

$$\left|\frac{\Gamma(K^+ \to \pi^+\pi^+\pi^-) - \Gamma(K^- \to \pi^-\pi^-\pi^+)}{\Gamma(K^+ \to \pi^+\pi^+\pi^-) + \Gamma(K^- \to \pi^-\pi^-\pi^+)}\right| \approx 8.4 \cdot 10^{-4} \beta c_4 |\text{Im } c_5|$$

which would give the number $(0.11 \pm 0.06)10^{-6}$ if Im c_5 is extracted from ε'/ε by the manner used before the appearance of the papers [3-5]. The close number was obtained in Ref.[8].

So, tl is result and results (18) show that ChPM approach works good enough reproducing all known results of calculation in the p^2-approximation. But our approach allows to take into account the next order corrections in p^2 and corrections caused by mixing of σ_0 state with the gluonic one. In fact, we need for such corrections to obtain the correct value of the slope parameter $g^\pm$ and probability.

Using the relations (17) and taking

$$c_1 - c_2 - c_3 - c_4 = -3.2 \quad [23] \qquad (22)$$

we should get

$$(g^+)^{th} = -0.168, \quad \Gamma(K^+ \to \pi^+\pi^+\pi^-)^{th} = 2.18 \cdot 10^{-9} \text{ eV} \qquad (23)$$

instead of experimental values [27]

$$(g^+)^{\exp} = -0.2154 \pm 0.0035 \quad \text{and} \quad \Gamma(K^+ \to \pi^+\pi^+\pi^-)^{\exp} = (2.97 \pm 0.03) \cdot 10^{-9} \text{ eV} \qquad (24)$$

And, of course, we need for such corrections to check the results of Refs.[13-15].

3. THE EFFECTS OF THE HIGHER-ORDER CORRECTIONS IN p^2 AND EFFECTS OF MIXING BETWEEN σ_0 AND GLUONIC STATE

As it was found before [19], the correct description of the observed behaviour of the K_{e4} form factors needs for the value

$$\xi = -0.225 \qquad (25)$$

of the parameter ξ introducing at the phenonomenological level the effects of mixing of the isosinglet scalar $\bar{q}q$ state with the gluonic one. The result (25) was obtained at the value

$$R = F_K/F_\pi = 1.176 \qquad (26)$$

following from the identification of the σ_π meson with the resonance $a_0(980)$ [17]. But this value is in accordance also with the calculation of R using the relations

$$F_K/F_\pi = (0.275 \pm 0.002)\left|\frac{V_{ud}}{V_{us}}\right|$$

and

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

and putting into them the values $|V_{ub}| < 0.007$ and $|V_{ud}| = 0.9735 \pm 0.0015$ used in Ref.[26].

The formulae of the Appendix then lead to the following value of the mixing angle θ_S defined by relations (8):

$$\theta_S = 18.3^o \tag{27}$$

At these magnitudes of ξ, R and θ_S the diagrams of Fig.1 give

$$< \pi^+(p_1)\pi^+(p_2)\pi^-(p_3)|0_5|K^+(k)> =$$
$$= \beta\, \Lambda^2 \sum_{j=1,2} (s_j - m_\pi^2) \left(\frac{0.4307}{m^2_{\sigma_{\eta'}} - s_j} + \frac{1.0899}{m^2_{\sigma_\eta} - s_j} - \frac{1.5206}{m^2_{\sigma_K} - s_j} \right) \tag{28}$$

or

$$= \beta \left[0.6273(s_1 + s_2 - 2m_\pi^2) + 2.1363\, \Lambda^{-2} \sum_{j=1,2} (s_j - m_\pi^2)^2 + \ldots \right] \tag{29}$$

or

$$\cong \beta \cdot \frac{2m_K^2}{3} \left(0.860 - \frac{3m_\pi^2}{2m_K^2}\, Y \cdot 1.168 + \ldots \right) . \tag{30}$$

The diagrams of Fig.2 give

$$< \pi^+(p_1)\pi^+(p_2)\pi^-(p_3)|4\bar{s}_L\gamma_\tau d_L \cdot \bar{u}_L\gamma_\tau u_L|K^+(k)> =$$
$$= 3(s_0 - s_3) = -3m_\pi^2\, Y . \tag{31}$$

$$< \pi^+(p_1)\pi^+(p_2)\pi^-(p_3)|4\bar{s}_L\gamma_\tau u_L \cdot \bar{u}_L\gamma_\tau d_L|K^+(k)> = -2m_k^2 +$$
$$+ \Lambda^2 \sum_{j=1,2} (s_j - m_\pi^2) \left(\frac{0.1803}{m^2_{\sigma_{\eta'}} - s_j} - \frac{0.6117}{m^2_{\sigma_\eta} - s_j} + \frac{1.4668}{m^2_{\sigma_K} - s_j} \right) \cong$$
$$\cong \frac{2m_K^2}{3} \left(-1.8087 - \frac{3m_\pi^2}{2m_K^2}\, Y \cdot 1.3608 \right) . \tag{32}$$

It follows from the last two formulae that

$$< \pi^+(p_1)\pi^+(p_2)\pi^-(p_3)|40_1|K^+(k)> =$$
$$= \sum_{j=1,2} \{ 1.96(s_j - m_\pi^2) - 1.45(s_j - m_\pi^2)^2\, \Lambda^{-2} + \ldots \} =$$
$$= \frac{2m_K^2}{3} \left(1.80 - 1.63\, \frac{3m_\pi^2}{2m_K^2}\, Y + \ldots \right) . \tag{33}$$

Comparing the expressions (29) and (33) we see that the dynamical structure of the "penguin" and "non-penguin" contributions become different when the terms of order p^4/Λ^2 are taken into account. It means, that some contribution to CP violating effects appears from $|A_{1/2}|^2$. But first of all, the correction from the mixing of σ_0 and $G^a_{\mu\nu}G^a_{\mu\nu}$ and higher p^2 corretions improve an agreement between the theoretical and experimental values of the slope parameter and width of $K^+ \to \pi^+\pi^+\pi^-$ decay.

Instead of Eq.(14) we have now

$$M(K^+ \to \pi^+\pi^+\pi^-) = \frac{1}{2\sqrt{2}}\, G_F \sin\theta_C \cos\theta_C \cdot \frac{2m_k^2}{3}\, [1.80(c_1 - c_2 -$$
$$- c_3 - c_4) + 0.86 \cdot 4_\beta c_5] \Big[1 -$$
$$- \frac{3m_\pi^2}{2m_K^2}\, Y\, \frac{1.63(c_1 - c_2 - c_3 - c_4) + 1.168 \cdot 4_\beta c_5 + 9c_4}{1.80(c_1 - c_2 - c_3 - c_4) + 0.86 \cdot 4_\beta c_5} + \ldots \Big] \tag{34}$$

where the terms proportional Y^2 and $X^2 = (s_1 - s_2)^2/m_\pi^4$ are omitted. At the value (17) and (22) of the coefficients c_i we obtain

$$(g^+)^{th} = -0.21 \quad \text{and} \quad \Gamma(K^+ \to \pi^+\pi^+\pi^-)^{th} = 2.9 \cdot 10^{-9}\ \text{eV} \tag{35}$$

in agreement with the experimental value (24).

Now, being convinced of the right infuence of the mixing of σ_0 with gluonium and correct influence of the higher-order corrections in p^2 we can pass to the evaluation of the effects of CP violation.

4. THE EFFECTS OF CP VIOLATION IN $K^\pm \to \pi^\pm\pi^\pm\pi^\mp$ DECAYS. THE p^4–APPROXIMATION

To calculate these effects we must know the imaginary part of the amplitude caused by $\pi - \pi$ re-scattering, that is, to know the integrals corresponding to the loop diagrams shown in Fig.3.

These integrals are

$$F_n = \frac{1}{32\pi^2} \int \Big\{ \frac{1}{2}\, f_n^{++-}(\tilde{s}_1, \tilde{s}_2) A^{++}(r_1, r_2; p_1, p_2) \delta^4(r_1 + r_2 - p_1 - p_2)\, \frac{d^3 r_1}{E_{r_1}} \cdot \frac{d^3 r_2}{E_{r_2}}$$
$$+ \Big[\Big(f_n^{++-}(s_1, \tilde{s}_1) A^{+-}(r_1, r_3; p_2, p_3) + \frac{1}{2}\, f_n^{00+}(s_1) A^{00}(r_1, r_3; p_2, p_3) \Big) \cdot$$
$$\cdot \delta^4(r_1 + r_3 - p_2 - p_3) + (f_n^{++-}(s_2, \tilde{s}_1) A^{+-}(r_1, r_3; p_1, p_3) +$$
$$+ \frac{1}{2}\, f_n^{00+}(s_2) A^{00}(r_1, r_3; p_1, p_3) \delta^4(r_1 + r_3 - p_1 - p_3) \Big] \frac{d^3_{r_1}}{E_{r_1}} \cdot \frac{d^3 r_3}{E_{r_3}} \Big\} , \tag{36}$$

where $s_i = (k-p_i)^2$, $\tilde{s}_i = (k-r_i)^2$ and A^{++}, A^{+-} and A^{00} are the amplitudes of $\pi^+\pi^+ \to \pi^+\pi^+, \pi^+\pi^- \to \pi^+\pi^-$ and $\pi^0\pi^0 \to \pi^+\pi^-$ scattering. We can use for these amplitudes the expressions in the lowest p^2-approximation. f_n^{++-} and f_n^{00+} are the matrix elements $< \pi^+\pi^+\pi^-|0_n|K^+ >$ and $< \pi^0\pi^0\pi^+|0_n|K^+ >$ respectively. In the p^4/Λ^2–approximation

$$f_1^{++-}(a,b) = \sum_{z=a,b} [1.96(z-m_\pi^2) - 1.45(z-m_\pi^2)^2/\Lambda^2]$$
$$f_5^{++-}(a,b) = \sum_{z=a,b} [0.627(z-m_\pi^2) + 2.136(z-m_\pi^2)^2/\Lambda^2] \; . \qquad (37)$$

The functions $f_{1,5}^{00+}(a)$ differ from $f_{1,5}^{++-}$ by aboliton of summing over the variable b.

$$f_4^{++-}(a,b) = 9\Big[-\frac{2}{3}\, m_k^2 + \sum_{a,b} (z-m_\pi^2)\Big] \qquad (38)$$

$$f_4^{00+}(a) = \frac{9}{2}\Big\{ s_0 - a + \frac{1}{3R(2R-1)\Lambda^2}[(k^2-2kr_1)^2 + (k^2-2kr_3)^2 - 2(a-m_\pi^2)^2]\Big\} \; . \qquad (39)$$

With the imaginary part induced by $\pi - \pi$ scattering in the final state, the amplitude under consideration has the form

$$M(K^+ \to \pi^+\pi^+\pi^-) = \frac{G}{2\sqrt{2}} \sin\theta_C \cos\theta_C \Big\{(c_1-c_2-c_3-c_4)(f_1^{++-} + i\, F_1) + c_4(f_4^{++-} + i\, F_4) + 4_\beta c_5(f_5^{++-} + i\, F_5)\Big\} \; , \qquad (40)$$

where c_{1-4}, f_n and F_n are the real values. The constant c_5 has small imaginary parts induced by phase δ. Then

$$|M(K^+ \to \pi^+\pi^+\pi^-)|^2 - |M(K^- \to \pi^-\pi^-\pi^+)|^2 = 2G_F^2 \sin^2\theta_C \cos^2\theta_C\; \beta\; \text{Im}\; c_5 \cdot \{(c_1-c_2-c_3-c_4)(F_1 f_5^{++-} - F_5 f_1^{++-}) + c_4(F_4 f_5^{++-} - F_5 f_4^{++-})\} \; . \qquad (41)$$

As it follows from the formulae (36)-(39), a non-zero value of $(F_1 f_5 - F_5 f_1)$ appears at the order Λ^{-2}:

$$(F_1 f_5^{++-} - F_5 f_1^{++-})_{\Lambda^{-2}} = \frac{1}{32\pi\Lambda^2 F_\pi^2}\left(\frac{m_K^2}{3}\right)^4 \left(0.32 - 11.9\,\frac{3m_\pi^2}{2m_K^2}\, Y\right) + 0(\Lambda^{-4}) \; . \qquad (42)$$

The value $(F_4 f_5^{++-} - F_5 f_4^{++-})$ differs from zero in the leading Λ^0–approximation:

$$(F_4 f_5^{++-} - F_5 f_4^{++-})_{\Lambda^0} = \frac{1}{32\pi F_\pi^2}\left(\frac{m_K^2}{3}\right)^3 35.4\, \frac{3m_\pi^2}{2m_K^2}\, Y + 0(\Lambda^{-2}) \; . \qquad (43)$$

Using Eq.(34) we find at the end that for $K^+ \to \pi^\pm\pi^\pm\pi^\mp$ decays

$$\frac{g^+ - g^-}{g^+ + g^-} = \frac{\beta\; \text{Im}\; c_5 m_K^2}{96\pi\, F_\pi^2}\left[35.4\, c_4 - \frac{11.9 m_K^2}{3\Lambda^2}\,(c_1-c_2-c_3-c_4)\right] \cdot \{[1.80(c_1-c_2-c_3-c_4) + 0.86\cdot 4_\beta c_5][1.63(c_1-c_2-c_3-c_4) + 1.17\cdot 4_\beta c_5 + 9c_4]\}^{-1} \cong \cong 1.9\; 10^{-2}\, \frac{\text{Im}\; c_5}{\text{Re}\; c_5} \; . \qquad (44)$$

At the value $|\text{Im}\; c_5 |\text{Re}\; c_5| = (1.3 \pm 0.7)10^{-3}$ used by Bel'kov *et al.* in Ref.[14] we should get

$$|(g^+ - g^-)/(g^+ + g^-)| = (2.5 \pm 1.3)10^{-5}$$

instead of the value $1.1 \cdot 10^{-3}$ obtained by authors of Ref.[14] themselves. Our result (45) shows that the contribution to CP violating effects from $|A_{1/2}|^2$ does not exceed 30% of the main contribution from $|A_{1/2}\, A_{3/2}^* + A_{3/2}\, A_{1/2}^*|$ and this result contradicts to the statement of Ref.[15]. Our final result on value of $g^+ - g^-$ depends on magnitude $\text{Im}\; c_5/\text{Re}\; c_5$. At present it would be careless to use the data on ε'/ε for extracting this value. We can use, however, the estimate

$$\text{Im}\; c_5/\text{Re}\; c_5 = -(1 \pm 0.4) s_2 s_3 \sin\delta \qquad (45)$$

based on old calculations of Voloshin [28] together with the fact that Im c_5 has a very weak dependence on m_t in the region $50 \le m_t \le 250$ GeV [3-5] *). Experimentally

$$s_2 s_3 < 2.6 \cdot 10^{-3} \; . \qquad (46)$$

Therefore we conclude that according to our calculations fulfilled in the framework of Chiral Theory the value $g^+ - g^-$ is limited by the relation

$$\frac{g^+ - g^-}{g^+ + g^-} \lesssim (5 \pm 2)10^{-5} |\sin\delta| \; . \qquad (47)$$

5. CONCLUSIONS

Our calculations pursued an object to verify the statement of Ref.[15] that the contribution to CP violating effects originating from the interference of "penguin" and "non-penguin" pieces of $\Delta I = 1/2$ part of the total $K^\pm \to 3\pi$ amplitude is considerable (by one–two orders) larger than the one caused by interference between $\Delta I = 1/2$ and $\Delta I = 3/2$ parts of the amplitude. We have found that the relative contribution to $g^+ - g^-$ from $|A_{1/2}|^2$ calculated in the p^4/Λ^2 approximation does not exceed 30% of the contribution from 2Re $(A_{1/2}\, A_{3/2}^*)$ calculated in the lowest p^2–approximation.

*) Our coefficient c_5 corresponds to c_6 of Refs.[4,5].

Our result (44) for $g^+ - g^-$ depends on magnitude of Im c_5/Re c_5. At the same value of this ratio as used in Ref.[14] our result is by 50 times smaller than obtained for $g^+ - g^-$ in Ref.[14]. At reasonable estimate (45) for Im c_5/Re c_5 we have the result

$$\left|\frac{g^+ - g^-}{g^+ + g^-}\right| \lesssim (5 \pm 2)10^{-5} |\sin\delta|$$

which is by twenty times smaller than the value obtained in Ref.[15].

There is no problem in our approach to calculate the $K^+ \to 3\pi$ amplitude in next orders in p^2, or take into account the contributions of so-called electroweak penguin and box operators. Such calculations are more cumbersome only. Together with calculation of the width difference $\Gamma(K^+ \to \pi^+\pi^+\pi^-) - \Gamma(K^- \to \pi^-\pi^-\pi^+)$ it will be done elsewhere.

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APPENDIX

Here we present the formulae for the coupling constants and masses of the scalar mesons necessary for calculation of the amplitudes described by the diagrams shown in Figs.1–3.

$$g_{\sigma_{\eta'}\pi^+\pi^-} = g_{\sigma_{\eta'}\pi^0\pi^0} = -\frac{\Lambda^2}{\sqrt{3}\,F_\pi}\left\{\sqrt{2}[1+\xi(2R+1)]\cos\theta_S + [1-4\xi(R-1)]\sin\theta_S\right\},$$

$$g_{\sigma_\eta\pi^+\pi^-} = g_{\sigma_\eta\pi^0\pi^0} = -\frac{\Lambda^2}{\sqrt{3}\,F_\pi}\left\{-\sqrt{2}[1+\xi(2R+1)]\sin\theta_S + [1-4\xi(R-1)]\cos\theta_S\right\},$$

$$g_{\sigma_{\eta'}K^+K^-} = g_{\sigma_{\eta'}K^0\bar{K}^0} = -\frac{\Lambda^2}{\sqrt{3}\,F_\pi}\left\{\sqrt{2}[R+\xi(2R+1)]\cos\theta_S - \right.$$
$$\left. -\frac{1}{2}[10R-9+8\xi(R-1)]\sin\theta_S\right\},$$

$$g_{\sigma_\eta K^+K^-} = g_{\sigma_\eta K^0\bar{K}^0} = -\frac{\Lambda^2}{\sqrt{3}\,F_\pi}\left\{-\sqrt{2}[R+\xi(2R+1)]\sin\theta_S \right.$$
$$\left. -\frac{1}{2}[10R-9+8\xi(R-1)]\cos\theta_S\right\},$$

$$g_{\sigma_{\bar{K}^0}K^+\pi} = g_{\sigma_K^+\bar{K}^0\pi^-} = \sqrt{2}\, g_{\sigma_{K^-}K^+\pi^0} = -\sqrt{2}\, g_{\sigma_{\bar{K}^0}K^0\pi^0} = -\frac{\Lambda^2(2R-1)}{\sqrt{2}\,F_\pi},$$

where $R = F_K/F_\pi$.

$$m^2_{\sigma_\pi} - m^2_\pi \equiv \Lambda^2 = (m^2_K - m^2_\pi)(R-1)^{-1}(2R-1)^{-1},$$
$$m^2_{\sigma_K} - m^2_\pi = \Lambda^2(2R-1)R,$$
$$m^2_{\sigma_{\eta'}} - m^2_\pi = \Lambda^2\left\{1 + 2R(R-1)(\cos\theta_S - \sqrt{2}\sin\theta_S)^2 + \right.$$
$$\left. + \frac{1}{3}\xi[(2R+1)\cos\theta_S - 2\sqrt{2}(R-1)\sin\theta_S]^2\right\},$$
$$m^2_{\sigma_\eta} - m^2_\pi = \Lambda^2\left\{1 + 2R(R-1)(\sin\theta_S + \sqrt{2}\cos\theta_S)^2 + \right.$$
$$\left. + \frac{1}{3}\xi[(2R+1)\sin\theta_S + 2\sqrt{2}(R-1)\cos\theta_S]^2\right\}.$$

The mixing angle θ_S depends on ξ and R as follows:

$$\theta_S = \frac{1}{2}\, arctan\left\{2\sqrt{2}\,\frac{1+\xi(2R+1)(3R)^{-1}}{1-\xi(2R+1)^2[1-8(R-1)^2(2R+1)^{-2}][6R(R-1)]^{-1}}\right.$$

At $\xi = 0$ $\sin\theta_S = 1/\sqrt{3}$:
At $\xi = -0.225$ and $R = 1.176$ the angle $\theta_S = 18.3°$.

It should be noted that the following equations take place:

$$\frac{g^2_{\sigma_{\eta'}\pi\pi}}{m^2_{\sigma_{\eta'}} - m^2_\pi} + \frac{g^2_{\sigma_\eta\pi\pi}}{m^2_{\sigma_\eta} - m^2_\pi} = \frac{\Lambda^2}{F^2_\pi}(1+2\xi),$$

$$\frac{g^2_{\sigma_{\eta'}\pi\pi}}{(m^2_{\sigma_{\eta'}} - m^2_\pi)^2} + \frac{g^2_{\sigma_\eta\pi\pi}}{(m^2_{\sigma_\eta} - m^2_\pi)^2} = \frac{1}{F^2_\pi},$$

$$\frac{g_{\sigma_{\eta'}KK}\, g_{\sigma_{\eta'}\pi\pi}}{m^2_{\sigma_{\eta'}} - m^2_\pi} + \frac{g_{\sigma_\eta KK}\, g_{\sigma_\eta\pi\pi}}{m^2_{\sigma_\eta} - m^2_\pi} + \frac{m^2_{\sigma_K} - m^2_K}{2F^2_\pi} =$$

$$= -\frac{\Lambda^2}{F^2_\pi}(1+2\xi)\ .$$

Due to these relations an expansion of the $\pi - \pi$ and $K - \pi$ scattering amplitudes begins from the p^2 (or $m^2_{K,\pi}$) terms:

$$A\left(\pi^+(k) \to \pi^+(p_1)\pi^+(p_2)\pi^-(p_3)\right) =$$

$$= -\frac{2\Lambda^2}{F^2_\pi}(1+2\xi) + \sum_{\left(\substack{\sigma=\sigma_\eta,\sigma_{\eta'} \\ i=1,2}\right)} \frac{g^2_{\sigma\pi\pi}}{m^2_\sigma - s_i} = \frac{1}{F^2_\pi}(s_1 + s_2 - 2m^2_\pi) + \dots$$

$$A\left(\pi^+(k) \to \pi^0(p_1)\pi^0(p_2)\pi^+(p_3)\right) =$$

$$= -\frac{\Lambda^2}{F^2_\pi}(1+2\xi) + \sum_{(\sigma=\sigma_\eta,\sigma_{\eta'})} \frac{g^2_{\sigma\pi\pi}}{m^2_\sigma - s_3} = \frac{1}{F^2_\pi}(s_3 - m^2_\pi) + \dots$$

where $s_i = (k - p_i)^2$.

For the $(2\pi 2K)$ amplitude the mixing between σ_0 and gluonium leads to some change of lowest-order expression. Namely,

$$A\left(K^+(k) \to K^+(p_1)\pi^+(p_2)\pi^-(p_3)\right) = -\frac{\Lambda^2}{F^2_\pi}(1+2\xi) + \frac{(m^2_{\sigma K} - m^2_K)}{2F^2_\pi(m^2_{\sigma K} - s_2)} +$$

$$+ \frac{g_{\sigma_{\eta'}KK}\, g_{\sigma_{\eta'}\pi\pi}}{m^2_{\sigma_{\eta'}} - s_1} + \frac{g_{\sigma_\eta KK}\, g_{\sigma_\eta\pi\pi}}{m^2_{\sigma_\eta} - s_1} = \frac{1}{2F^2_\pi}\left[s_2 - m^2_\pi + (s_1 - m^2_\pi)\gamma\right] + \dots$$

where

$$\gamma = 1 - 2F^2_\pi\left[g_{\sigma_{\eta'}\pi\pi}\, g_{\sigma_{\eta'}KK}/(m^2_{\sigma_{\eta'}} - m^2_\pi)^2 - g_{\sigma_\eta\pi\pi}\, g_{\sigma_\eta KK}/(m^2_{\sigma_\eta} - m^2_\pi)^2\right]\ .$$

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FIGURE CAPTIONS

Fig.1 Diagrams induced by operators 0_5. Open circles denote the vertices caused by strong interaction.

Fig.2 Diagrams induced by operators 0_{1-4}.

Fig.3 Loop diagrams taking into account the re-scattering of pions. Shadowed circles denote $K^+ \to \pi^+(\pi^0)\pi^-(\pi^0)\pi^+$ transition described by the diagram shown in Fig.1 and Fig.2.

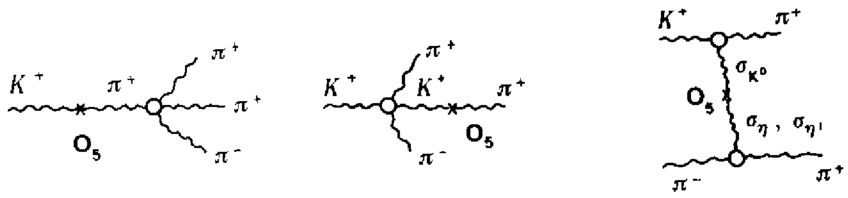

Fig.1

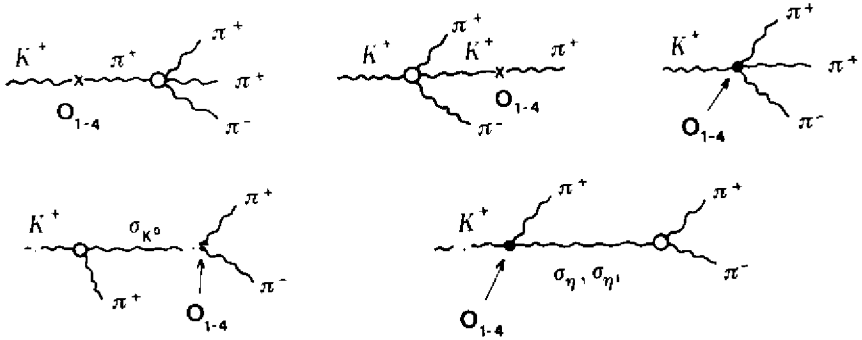

Fig.2

Fig.3