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**INTERNATIONAL CENTRE FOR
THEORETICAL PHYSICS**

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WITHIN CHIRAL PERTURBATION THEORY
AT THE QUARK LEVEL**

**INTERNATIONAL
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International Atomic Energy Agency
and
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CHIRAL ANOMALIES IN NON-LEPTONIC DECAYS
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AT THE QUARK LEVEL¹

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Abstract

By example of the $K^+ \rightarrow \pi^+\pi^0\gamma$ decay there has been investigated at the quark level the contribution of chiral anomalies to non-leptonic weak decays of K-mesons. The theoretical prediction for the probability of the $K^+ \rightarrow \pi^+\pi^0\gamma$ decay with the direct emission of a photon is $B(K^+ \rightarrow \pi^+\pi^0\gamma(DE))_{\text{anom}} \leq (1.1 \pm 0.2) \times 10^{-5}$. It is stressed that the mechanism of the $\Delta I = 1/2$ transition in the $K^+ \rightarrow \pi^+\pi^0\gamma$ decay differs from that governing the enhancement of the $\Delta I = 1/2$ transitions in the $K^0 \rightarrow \pi^+\pi^-$ decay.

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No doubts that the study of the influence of chiral anomalies [1] in non-leptonic weak decays of K-mesons plays a very important role for a deeper understanding of standard model, embodying standard electroweak model [2] and QCD.

In this paper we analyse the contributions of chiral anomalies in non-leptonic weak decays by example of the $K^+ \rightarrow \pi^+\pi^0\gamma$ (DE) decay amplitude caused by the direct emission (DE) of a photon. The effective weak Lagrangian, obtained within standard model and describing transitions with $\Delta S = 1$ and $\Delta I = 1/2$ selection rules and governing the $K^+ \rightarrow \pi^+\pi^0\gamma$ (DE) decay, takes the form [3]

$$L_{eff}^{\Delta S=1, \Delta I=1/2} = -\frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} : O_{\Delta I=1/2} : + h.c., \quad (1)$$

where

$$O_{\Delta I=1/2}(0) = C_1 O_1(0) + C_2 O_2(0) + C_3 O_5(0) \quad (2)$$

and C_i ($i = 1, 2, 5$) are Wilson coefficients being as function of heavy quark masses, Λ_{QCD} and renormalization scale μ . In SVZ-basis the operators O_i read [3a]:

$$O_1 = [\bar{s}\gamma_\mu(1-\gamma^5)u][\bar{u}\gamma^\mu(1-\gamma^5)d] - [\bar{s}\gamma_\mu(1-\gamma^5)d][\bar{u}\gamma^\mu(1-\gamma^5)u],$$

$$O_2 = O_1 + 2[\bar{s}\gamma_\mu(1-\gamma^5)d][\bar{q}\gamma^\mu(1-\gamma^5)q],$$

$$O_5 = [\bar{s}\gamma_\mu(1-\gamma^5)\lambda_c^A d][\bar{q}\gamma^\mu(1+\gamma^5)\lambda_c^A q], \quad (3)$$

where q is a column matrix with elements (u,d,s) such that the every quark flavour possesses N colour degrees of freedom; the matrices of $SU(N)_c$ colour group λ_c^A ($A = 1, \dots, N^2 - 1$) are normalized by the condition $\text{tr}_c(\lambda_c^A \lambda_c^B) = 2\delta^{AB}$. The symbol $....$ denotes the normal-ordering operation. Chiral properties and the problems of bosonization of the O_i ($i = 1, 2, 5$)-operators have been analysed in detail in refs. [4,5] within chiral perturbation theory at the quark level (CHPT)_q [6,7] based on the Extended Nambu-Jona-Lasinio model used as a low-energy approximation of QCD [8].

The analysis of chiral anomaly contributions to the $K^+ \rightarrow \pi^+\pi^0\gamma$ (DE) decay we shall perform within (CHPT)_q. However, the final result can be appraised as a model-independent one by owing to the exceptional state of chiral anomalies in low-energy hadronic physics.

Now let us proceed to the quark level evaluation of chiral anomaly contributions to the $K^+ \rightarrow \pi^+\pi^0\gamma$ decay. The diagrams describing $K^+ \rightarrow \pi^+\pi^0\gamma$ (DE) decay are depicted in Figs.1 and 2. The pole-diagrams in Fig.1 involve the transitions $\pi^+ \rightarrow \pi^+\pi^0\gamma$, $K^+ \rightarrow K^+\pi^0\gamma$ and $K^+ \rightarrow \pi^+K^0\gamma$ being fully determined by the anomalous γ PPP-vertices. This is due to the form factors of the VPP-interactions, vanishing at low-energies [9]. The diagrams in Fig.2 contain both anomalous and non-anomalous contributions. The latters are considered in ref.[10]. Here we are picking up only the anomalous ones.

First let us regard the contribution of diagrams in Fig.1. By keeping only the chiral anomalies of the γ PPP-type, one obtains

$$A(\pi^+(p) \rightarrow \pi^+(p_+)\pi^0(p_0)\gamma(q))_{\text{anom}} = A(K^+(p) \rightarrow K^+(p_+)\pi^0(p_0)\gamma(q))_{\text{anom}} = \\ = \frac{e}{4\pi^2 F_0^3} \epsilon_{\mu\nu\alpha\beta} e^\mu(q) p_+^\nu p_0^\alpha q^\beta, \quad (\epsilon_{0123} = 1),$$

$$A(K^+(p) \rightarrow \pi^+(p_+)K^0(p_0)\gamma(q))_{\text{anom}} = 0. \quad (4)$$

Now we have to evaluate the matrix elements of the $K^+ \rightarrow \pi^+$ transition. By using the results obtained in ref. [11] one gets at the leading order in large N expansion

$$\langle \pi^+(p) | : O_{1,2} : | K^+(p) \rangle = 2F_0^2 p^2, \\ \langle \pi^+(p) | : O_5 : | K^+(p) \rangle = -8F_0^2 \bar{v}^2 \left(1 + \frac{2p^2}{\Lambda_1^2} \right), \quad (5)$$

where $\bar{v} = -\langle 0 | \bar{q}q | 0 \rangle / F_0^2$, but Λ_1 is the slope parameter. In (CHPT)_q [4,5,11] these parameters are fixed in terms of chiral symmetry breaking scale $\Lambda_\chi = 0.94$ GeV and the constituent quark mass $m = 0.33$ GeV, calculated in the chiral limit, i.e.

$$\bar{v} = 4mI_1(m)/F_0^2 = 1.92 \text{ GeV}, \quad \Lambda_1 = (2m\bar{v})^{1/2} = 1.13 \text{ GeV}, \quad (6)$$

where

$$I_1(m) = \frac{N}{16\pi^2} \int \frac{d^4 k}{\pi^2 i} \frac{1}{m^2 - k^2} = \frac{N}{16\pi^2} \left[\Lambda_\chi^2 - m^2 \ln \left(1 + \frac{\Lambda_\chi^2}{m^2} \right) \right]. \quad (7)$$

As a result we can write down the contribution of the diagrams in Fig.1 to the $K^+ \rightarrow \pi^+\pi^0\gamma$ (DE) decay amplitude:

$$A(K^+(p) \rightarrow \pi^+(p_+)\pi^0(p_0)\gamma(q))_{\text{Fig.1a}} = \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \frac{1}{m_K^2 - m_\pi^2} \times \\ \times \left[(C_1 + C_2)m_K^2 - C_5 4\bar{v}^2 \left(1 + \frac{2m_K^2}{\Lambda_1^2} \right) \right] \frac{e}{2\pi^2 F_0} \epsilon_{\mu\nu\alpha\beta} e^\mu(q) p_+^\nu p_0^\alpha q^\beta, \\ A(K^+(p) \rightarrow \pi^+(p_+)\pi^0(p_0)\gamma(q))_{\text{Fig.1b}} = -\frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \frac{1}{m_K^2 - m_\pi^2} \times \\ \times \left[(C_1 + C_2)m_\pi^2 - C_5 4\bar{v}^2 \left(1 + \frac{2m_\pi^2}{\Lambda_1^2} \right) \right] \frac{e}{2\pi^2 F_0} \epsilon_{\mu\nu\alpha\beta} e^\mu(q) p_+^\nu p_0^\alpha q^\beta, \\ A(K^+(p) \rightarrow \pi^+(p_+)\pi^0(p_0)\gamma(q))_{\text{Fig.1c}} = 0. \quad (8)$$

The total contribution of the diagrams in Fig.1 sums to the following expression

$$A(K^+(p) \rightarrow \pi^+(p_+)\pi^0(p_0)\gamma(q))_{\text{Fig.1}} = \\ = \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \left(C_1 + C_2 - C_5 \frac{8\bar{v}^2}{\Lambda_1^2} \right) \frac{e}{2\pi^2 F_0} \epsilon_{\mu\nu\alpha\beta} e^\mu(q) p_+^\nu p_0^\alpha q^\beta. \quad (9)$$

It is necessary to remind that this result is obtained in the leading order of both large N and chiral expansions. Also it is safe to say that the result (9) is the model-independent one, being fully determined by the transformation properties of the starting effective weak Lagrangian (1).

Now let us pay our attention on the factor

$$\left(C_1 + C_2 - C_5 \frac{8\bar{v}^2}{\Lambda_1^2} \right), \quad (10)$$

produced in (9) by the structure of the Lagrangian (1), and match it with the corresponding factor, coming up in the $K^0 \rightarrow \pi^+\pi^-$ decay amplitude. The $K^0 \rightarrow \pi^+\pi^-$ decay amplitude, evaluated with the help of the Lagrangian (1) in the leading order of both large N and chiral expansions, reads [11]:

$$\frac{1}{i} A(K^0 \rightarrow \pi^+\pi^-) = G_F V_{us}^* V_{ud} F_0 \left(C_1 + C_2 - C_5 \frac{4\bar{v}^2}{\Lambda_1^2} \right) (m_K^2 - m_\pi^2). \quad (11)$$

It is seen that the factor

$$\left(C_1 + C_2 - C_5 \frac{4\bar{v}^2}{\Lambda_1^2} \right) \quad (12)$$

in (11) differs from the factor (10) in (9). This result underscores the distinction of mechanism of the $\Delta I = 1/2$ transitions in the $K^+ \rightarrow \pi^+\pi^0\gamma$ (DE) and $K^0 \rightarrow \pi^+\pi^-$ decays. The opposite point of view the reader can find in ref.[12,15,16].

Now let us proceed to the evaluation of the diagrams in Fig.2. These diagrams describe the structure part of the $K^+ \rightarrow \pi^+\pi^0\gamma$ (DE) decay amplitude containing the matrix elements $\langle \gamma\pi^0\pi^+ | : O_i(0) : | K^+ \rangle$. Let us stress that we shall keep only the anomalous parts of these matrix elements, i.e. the quantities $\langle \gamma\pi^0\pi^+ | : O_i(0) : | K^+ \rangle_{\text{anom}}$.

By using the vacuum saturation approximation being fully compatible with (CHPT)_q [4,5,11] we can present the matrix elements $\langle \gamma\pi^0\pi^+ | : O_i : | K^+ \rangle_{\text{anom}}$ in the form of the following decompositions

$$\langle \gamma\pi^0\pi^+ | : O_1 : | K^+ \rangle_{\text{anom}} = \langle \gamma\pi^+ | \bar{u}\gamma_\nu d | 0 \rangle \langle \pi^0 | \bar{s}\gamma^\nu u | K^+ \rangle + \\ + \langle \pi^0\pi^+ | \bar{u}\gamma_\nu d | 0 \rangle \langle \gamma | \bar{s}\gamma^\nu u | K^+ \rangle - \langle \gamma\pi^0 | \bar{u}\gamma_\nu u | 0 \rangle \langle \pi^+ | \bar{s}\gamma^\nu d | K^+ \rangle, \\ \langle \gamma\pi^0\pi^+ | : O_2 : | K^+ \rangle_{\text{anom}} = \langle \gamma\pi^0\pi^+ | : O_1 : | K^+ \rangle_{\text{anom}} + \\ + 2\langle \gamma\pi^0 | \bar{u}\gamma_\nu u + \bar{d}\gamma_\nu d | 0 \rangle \langle \pi^+ | \bar{s}\gamma^\nu d | K^+ \rangle,$$

$$\begin{aligned} \frac{1}{4} \langle \gamma \pi^0 \pi^+ | : O_5 : | K^+ \rangle_{\text{anom}} &= \langle \pi^+ | \bar{u} \gamma^5 d | 0 \rangle \langle \gamma \pi^0 | \bar{s} \gamma^5 u | K^+ \rangle + \\ &+ \langle \gamma \pi^0 \pi^+ | \bar{u} \gamma^5 d | 0 \rangle \langle 0 | \bar{s} \gamma^5 u | K^+ \rangle + \langle \pi^0 | \bar{d} \gamma^5 d | 0 \rangle \langle \gamma \pi^+ | \bar{s} \gamma^5 d | K^+ \rangle. \end{aligned} \quad (13)$$

Let us write down the analytical expressions of the matrix elements, incoming to the r.h.s. of the formulae (13) [4,5,11]:

$$\begin{aligned} \langle \gamma(q) \pi^+(p_+) | \bar{u} \gamma_\nu d | 0 \rangle &= -\frac{1}{\sqrt{2}} \frac{e}{4\pi^2 F_0} \epsilon_{\mu\nu\alpha\beta} e^\mu(q) p_+^\alpha q^\beta, \\ \langle \gamma(q) | \bar{s} \gamma_\nu u | K^+(p) \rangle &= \frac{1}{\sqrt{2}} \frac{e}{4\pi^2 F_0} \epsilon_{\mu\nu\alpha\beta} e^\mu(q) p^\alpha q^\beta, \\ \langle \gamma(q) \pi^0(p_0) | \bar{u} \gamma_\nu u | 0 \rangle &= -\frac{e}{2\pi^2 F_0} \epsilon_{\mu\nu\alpha\beta} e^\mu(q) p_0^\alpha q^\beta, \\ \langle \gamma(q) \pi^0(p_0) | \bar{u} \gamma_\nu u + \bar{d} \gamma_\nu d | 0 \rangle &= -\frac{e}{4\pi^2 F_0} \epsilon_{\mu\nu\alpha\beta} e^\mu(q) p_0^\alpha q^\beta; \end{aligned} \quad (14a)$$

$$\begin{aligned} \langle \pi^0(p_0) | \bar{s} \gamma_\nu u | K^+(p) \rangle &= -\frac{1}{\sqrt{2}} (p + p_0)_\nu, \\ \langle \pi^0(p_0) \pi^+(p_+) | \bar{u} \gamma_\nu d | 0 \rangle &= -\sqrt{2} (p_+ - p_0)_\nu, \\ \langle \pi^+(p_+) | \bar{s} \gamma_\nu d | K^+(p) \rangle &= -(p + p_+)_\nu; \end{aligned} \quad (14b)$$

$$\begin{aligned} \langle \gamma(q) \pi^0(p_0) | \bar{s} \gamma^5 u | K^+(p) \rangle &= -\frac{i\sqrt{2}F_0}{\bar{v}} \frac{\bar{v}^2}{\Lambda_1^2} A(K^+(p) \rightarrow K^+(p_+) \pi^0(p_0) \gamma(q))_{\text{anom}}, \\ \langle \gamma(q) \pi^0(p_0) \pi^+(p_+) | \bar{u} \gamma^5 d | 0 \rangle &= -\frac{i\sqrt{2}F_0}{\bar{v}} \frac{\bar{v}^2}{\Lambda_1^2} A(\pi^+(p) \rightarrow \pi^+(p_+) \pi^0(p_0) \gamma(q))_{\text{anom}}; \\ \langle \gamma(q) \pi^+(p_+) | \bar{s} \gamma^5 d | K^+(p) \rangle &= 0; \end{aligned} \quad (14c)$$

$$\langle \pi^+(p_+) | \bar{u} \gamma^5 d | 0 \rangle = \langle 0 | \bar{s} \gamma^5 u | K^+(p) \rangle = -i\sqrt{2}F_0\bar{v}. \quad (14d)$$

By using formulae (14) we can find the matrix elements $\langle \gamma \pi^0 \pi^+ | : O_i : | K^+ \rangle_{\text{anom}}$:

$$\begin{aligned} \langle \gamma \pi^0 \pi^+ | : O_1 : | K^+ \rangle_{\text{anom}} &= -7 \frac{e}{4\pi^2 F_0} \epsilon_{\mu\nu\alpha\beta} e^\mu(q) p_+^\nu p_0^\alpha q^\beta, \\ \langle \gamma \pi^0 \pi^+ | : O_2 : | K^+ \rangle_{\text{anom}} &= -3 \frac{e}{4\pi^2 F_0} \epsilon_{\mu\nu\alpha\beta} e^\mu(q) p_+^\nu p_0^\alpha q^\beta, \\ \langle \gamma \pi^0 \pi^+ | : O_5 : | K^+ \rangle_{\text{anom}} &= -\frac{16\bar{v}^2}{\Lambda_1^2} \frac{e}{4\pi^2 F_0} \epsilon_{\mu\nu\alpha\beta} e^\mu(q) p_+^\nu p_0^\alpha q^\beta. \end{aligned} \quad (15)$$

As a result the contribution of chiral anomalous parts of the diagrams in Fig.2 is given by the expression

$$\begin{aligned} A(K^+(p) \rightarrow \pi^+(p_+) \pi^0(p_0) \gamma(q))_{\text{Fig.2, anom}} &= \\ &= \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \left(7C_1 + 3C_2 + C_5 \frac{16\bar{v}^2}{\Lambda_1^2} \right) \frac{e}{4\pi^2 F_0} \epsilon_{\mu\nu\alpha\beta} e^\mu(q) p_+^\nu p_0^\alpha q^\beta. \end{aligned} \quad (16)$$

Now the total amplitude of the $K^+ \rightarrow \pi^+ \pi^0 \gamma(\text{DE})$ decay, caused by chiral anomaly contributions, we can obtain by summing up (9) and (16) i.e.:

$$\begin{aligned} A(K^+(p) \rightarrow \pi^+(p_+) \pi^0(p_0) \gamma(q)(DE))_{\text{anom}} &= \\ &= \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} (9C_1 + 5C_2) \frac{e}{4\pi^2 F_0} \epsilon_{\mu\nu\alpha\beta} e^\mu(q) p_+^\nu p_0^\alpha q^\beta. \end{aligned} \quad (17)$$

Since the C_5 -coefficient is cancelled out, so the penguin operator does not contribute to the anomalous part of the $K^+ \rightarrow \pi^+ \pi^0 \gamma$ decay amplitude at all. It confirms the statement that the mechanism of the enhancement of the $\Delta I = 1/2$ transition enhancement in the $K^+ \rightarrow \pi^+ \pi^-$ decay does not relate to the mechanism, governing the anomalous part of the $K^+ \rightarrow \pi^+ \pi^0 \gamma(\text{DE})$ decay amplitude. Indeed the latter is fully determined by the $O_{1,2}$ -operators with a left $\times$ left quark structure (3) giving small contributions to the $K^0 \rightarrow \pi^+ \pi^-$ decay amplitude [11].

The result being opposite to ours in (17) there was obtained by Bel'kov et al. [17]. By applying the approximation of the effective weak Lagrangian (1) at the hadronic level within a non-linear realization of chiral $SU(3) \times SU(3)$ symmetry Bel'kov et al. found a non-vanishing contribution of the Penguin operator to the anomalous part of the $K^+ \rightarrow \pi^+ \pi^0 \gamma(\text{DE})$ decay amplitude. The appearance of the non-vanishing contribution of the Penguin operator contradicts not only our results but also the results obtained by Bijmens, Ecker and Pich [12], who inferred that the Penguin operator does not contribute to the anomalous part of the $K^+ \rightarrow \pi^+ \pi^0 \gamma(\text{DE})$ decay.

Let us estimate the contribution of chiral anomalies to the probability of the $K^+ \rightarrow \pi^+ \pi^0 \gamma(\text{DE})$ decay

$$\begin{aligned} B(K^+ \rightarrow \pi^+ \pi^0 \gamma(\text{DE}))_{\text{anom}} &= \tau_{K^+} |G_F V_{us}^* V_{ud} (9C_1 + 5C_2)|^2 \times \\ &\times \frac{\alpha}{3.2^{14} \pi^6 F_0^2 m_K^3} \int_{4m_\pi^2}^{m_K^2} ds s (1 - 4m_\pi^2/s)^{3/2} (m_K^2 - s)^3 = (1.1 \pm 0.20) \times 10^{-5}, \end{aligned} \quad (18)$$

where $\tau_{K^+}^{-1} = \Gamma(K^+ \rightarrow \text{all}) = (5.32 \pm 0.03) \times 10^{-17}$ GeV [13], $|G_F V_{us}^* V_{ud}| = 2.5 \times 10^{-6}$ GeV $^{-2}$, $m_K = 0.50$ GeV and $m_\pi = 0.14$ GeV, $C_1 = 1.262$ and $C_2 = 0.063$. The uncertainty $(\pm 0.2) \times 10^{-5}$ is due to the theoretical uncertainty of $(\text{CHPT})_q$, being equal to 20% approximately [14]. The Wilson coefficients C_1 and C_2 depend on the renormalization scale μ , and the numerical values $C_1 = 1.262$ and $C_2 = 0.063$ are obtained at $\mu = \Lambda_\chi = 0.94$ GeV [14]. It should be noted that the numerical values of C_1 and C_2 are found at the complete neglect of the penguin diagrams contribution, i.e. $C_5 = 0$, which gives

$C_1 = C_-/2$ and $C_2 = C_+/10$ such that $C_-C_+^2 = 1$ [3]. The account for the penguin diagrams contribution to the $(V-A)\times(V-A)$ four quark operators yields to the change of the coefficients $C_1 = C_-/2 \rightarrow C_-/2 + C_5$ and $C_2 = C_+/10 \rightarrow C_+/10 + C_5$. Since $C_5 < 0$, so we have obtained the upper bound of the chiral anomaly contributions to the $K^+ \rightarrow \pi^+\pi^0\gamma$ decay with the direct emission of a photon.

Now let us compare the theoretical result (18) with experimental data. In Particle Data Group review [13] there are listed three experimental results

$$10^5 B(K^+ \rightarrow \pi^+\pi^0\gamma(DE))_{exp} = \begin{cases} 2.05 \pm 0.46 \pm_{0.23}^{0.39}, & (\text{Bolotov, 1987}) \\ 2.3 \pm 3.2, & (\text{Smith, 1976}) \\ 1.56 \pm 0.35 \pm 0.5, & (\text{Abrams, 1972}) \end{cases}$$

The world-average value is [13]

$$B(K^+ \rightarrow \pi^+\pi^0\gamma(DE))_{exp.w.av.} = (1.8 \pm 0.4) \times 10^{-5}.$$

Our result (18) agrees with experimental data within two standard deviations. The theoretical value (18) agrees numerically with the values of $B(K^+ \rightarrow \pi^+\pi^0\gamma(DE))$ obtained in refs.[12,15,16,17] at the hadronic level by applying the bosonized forms for the effective weak Lagrangian (1) within a non-linear realization of chiral $SU(3)\times SU(3)$ symmetry.

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Figure captions

Fig.1. Feynman diagrams, describing the (π, K) -pole contributions to the $K^+ \rightarrow \pi^+\pi^-\gamma(\text{DE})$ decay.

Fig.2. Feynman diagrams of the structure part of the $K^+ \rightarrow \pi^+\pi^0\gamma(\text{DE})$ decay.