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Study of $K^+ \to \pi^0 l^+ \nu_l \gamma$ decays in the CKM experiment and the search for T_{odd} correlation in these decays.

The T-invariance is one of the fundamental symmetries in physics (see, for example [1–3]). It is still an open problem to be tested experimentally with high precision. T-violation must exist, because if CPT-invariance, which is considered by majority of theories as a "must" works, it is nothing more than CP-violation which is already well established. T-invariance has been studied in many experiments. Typical example is searches for the electric dipole moment of elementary particles. Another possibility is to look for the T-odd correlations in particles decays, such as triple correlations including spin in the neutron decay. A well known example of the T-odd correlation in the kaon decays is the polarization of the muon normal to the decay plane in $K^+ \to \mu^+ \nu \pi^0$ ($K_{\mu 3}$) decay:

$$\sigma_\perp^\mu = \frac{\vec{\sigma}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)}{|\vec{p}_\pi \times \vec{p}_\mu|} \tag{1}$$

It was first suggested by J.J.Sakurai to look for T-violation by $\sigma_\perp^\mu$ measurement. The unique feature of these process is that the "fake" T-odd correlation due to the final state interaction (FSI) is very small: $\sigma_\perp^{FSI} \sim 5 \cdot 10^{-6}$ [4]. Although the SM predicts zero effect, in some models (like 3HDM of Weinberg type) a value higher than (several units)$\cdot 10^{-3}$ is predicted [5]. The best measurement of the $\sigma_\perp$, performed about 20 years ago at the BNL-AGS [6] gives: $\sigma_\perp = 0.0031 \pm 0.0053$. Current result from KEK E246 [7] is $\sigma_\perp < 10^{-2}$@90% C.L., they hope to reach $\sigma_\perp < 1.3 \cdot 10^{-3}$ at the end of the experiment. Even more sensitive projects to measure $\sigma_\perp$ were considered [8]

We do not plan at present to measure $\sigma_\perp^\mu$ in the CKM experiment: the energy of 22 GeV looks too high for that. On the contrary, we are seriously considering the possibility of measuring the triple T-odd correlation:

$$T_{\pi\mu\gamma} = \frac{\vec{p}_\gamma \cdot (\vec{p}_\pi \times \vec{p}_\mu)}{|\vec{p}_\gamma| \cdot |\vec{p}_\pi \times \vec{p}_\mu|} \tag{2}$$

in the decay $K \to \mu\nu\pi^0\gamma$. Such a measurement was proposed for the first time by J.Gevais, J.Iliopoulous and J.Kaplan in 1966 [9]. There are no theoretical predictions for the effect, at present. The "fake" FSI correlation must not be strong: naively it must be similar to $\sigma_\perp^{FSI}$ in $K \to \mu\nu\gamma$, which is $\sim 10^{-4}$. The $K^\pm$ beam gives a principle possibility of subtraction of the FSI: the FSI-correlation has the same sign in $K^\pm$, while the true effect changes the sign.

The other way to check the existence of direct effect of T violation and to have an estimation for possible "fake" asymmetry is to compare the triple correlations (2) $T_{\pi\mu\gamma}$ and $T_{\pi e\gamma}$ for $K^+ \to \pi^0\mu^+\nu_\mu\gamma$ and $K^+ \to \pi^0 e^+\nu_e\gamma$ decays. In multihiggs doublet models the real measurable T-violation effect is expected only through the interactions of Higgs bosons with muons in $K^+ \to \pi^0\mu^+\nu_\mu\gamma$ decays. Thus the comparison of $T_{\pi\mu\gamma}$ and $T_{\pi e\gamma}$ correlations will provide us with good criterium for observation the real T-violation effect and for evaluation of "fake" asymmetry.

It seems also that kinematical cuts for photons in $K \to \mu\nu\pi^0\gamma$ to separate direct emission radiative process and to suppress IB decay events will be important: we expect possible real T violation effects in direct photon emission and can use IB events for the fake asymmetry tests.

The decay $K \to \mu\nu\pi^0\gamma$ has not yet been observed, the prediction of the SM is $Br(K \to \mu\nu\pi^0\gamma) \sim 2\cdot 10^{-5}$. The only experimental measurement of the T-odd correlation in the decay $K \to e\nu\pi^0\gamma$ is from ISTRA set-up at IHEP 70 GeV accelerator [10]: $\frac{\vec{p}_\gamma\cdot(\vec{p}_\pi\times\vec{p}_e)}{|\vec{p}_\gamma|\cdot|\vec{p}_\pi\times\vec{p}_e|} = 0.03\pm0.08$; it is based on 192 reconstructed events, which correspond to the Br=$(2.7\pm0.2)\cdot 10^{-4}$ ($E_\gamma^{c.m.} >$ 10MeV; $0.6 < cos\theta_{e,\gamma} < 0.9$). Now it is planed to do the measurement of $T_{\pi\mu\gamma}$ correlation in the next IHEP kaon experiment "OKA" with the expected statistics of $\sim 10^6$ $K \to \mu\nu\pi^0\gamma$ decays [11]. The next step with increased statistics can be done in CKM experiment [12].

The IHEP theorists are performing now detailed calculations of the correlation (2) in SM and in the Weinberg's 3HDM. This model is known to be a benchmark for the CP violation searches beyond the SM. There are several parameters in the model relevant for our case: M_{H^+}- the mass of the lightest charged Higgs; $v_1; v_2; v_3$ - the VEV's of the 3 Higgs fields: $v_1^2 + v_2^2 + v_3^2 = 2\sqrt{2}G_F$; $\alpha_i, \beta_i, \gamma_i$; i=1,2- 6 complex Yukawa coupling constants which are related to each other by the conditions: [13]

$$\left.\begin{array}{l} \frac{Im(\alpha_2\beta_2^*)}{Im(\alpha_1\beta_1^*)} = \frac{Im(\beta_2\gamma_2^*)}{Im(\beta_1\gamma_1^*)} = \frac{Im(\alpha_2\gamma_2^*)}{Im(\alpha_1\gamma_1^*)} = -1 \\ \\ \frac{Im(\alpha_1\gamma_1^*)}{v_2^2} = -\frac{Im(\beta_1\gamma_1^*)}{v_1^2} = -\frac{Im(\alpha_1\beta_1^*)}{v_3^2} \end{array}\right\} \tag{3}$$

Further constraints on the model parameters can be extracted from the experimental data on d_n- the neutron electrical dipole moment; $\epsilon; \epsilon'$; ΔM_D etc. Given all the constraints, one still can expect a large value for $T_{\pi\mu\gamma}$, which soon will be estimated. Let us remind that these models predict a significant value for $\sigma_\perp^\mu$ in $K \to \mu\nu\pi^0$ decays.

To illustrate the possibilities for CKM experiments we estimated the expected efficiency for registration of $K^+ \to \pi^0\mu^+\nu_\mu\gamma$ and $K^+ \to \pi^0 e^+\nu_e\gamma$ and expected statistical precision for measurements of $T_{\pi\mu\gamma}$ and $T_{\pi e\gamma}$ asymmetry parameters. It is more convenient to use another normalization for this correlation $T'_{\pi\mu\gamma} = \frac{\vec{p}_\gamma\cdot(\vec{p}_\pi\times\vec{p}_\mu)}{M_K^3}$, which takes into account the information on momentum distribution of the particles in the final states. We performed the calculations for $K^+ \to \pi^0\mu^+\nu_\mu\gamma$ decays with cuts (in the rest frame of kaon) $E_\gamma > 30$ MeV and $\theta_{l\gamma} > 20^\circ$ to separate the direct photon emission process and to suppress IB radiation.[1]

As will be shown below we expect to obtain $1.1\cdot 10^7$ $K^+ \to \pi^0\mu^+\nu_\mu\gamma$ events and $> 10^8$ $K^+ \to \pi^0 e^+\nu_e\gamma$ events in the CKM experiment in parallel with the main $K^+ \to \pi^+\nu\bar{\nu}$ studies. For estimation of the statistical sensitivity for average asymmetry of $T'_{\pi\mu\gamma} = \frac{\vec{p}_\gamma\cdot(\vec{p}_\pi\times\vec{p}_\mu)}{M_K^3}$ distribution in $K^+ \to \pi^0\mu^+\nu_\mu\gamma$ decay we did a MC simulation for this distribution in the SM and have obtained the sensitivity $T'_{\pi\mu\gamma} = \pm 2.5\cdot 10^{-5}$ (for more common normalization $T_{\pi\mu\gamma} = \frac{\vec{p}_\gamma\cdot(\vec{p}_\pi\times\vec{p}_\mu)}{|\vec{p}_\gamma|\cdot|\vec{p}_\pi\times\vec{p}_\mu|} = \pm 3\cdot 10^{-4}$). For $K^+ \to \pi^0 e^+\nu_e\gamma$ the corresponding sensitivity is $T'_{\pi e\gamma} = \pm 7\cdot 10^{-6}$ ($T_{\pi e\gamma} = \pm 1\cdot 10^{-4}$).

[1]It must be bear in mind that may be we will need even more stringent cuts for this purpose

The main problems for T-asymmetry measurements in $K^+ \to \pi^0 \mu^+ \nu_\mu \gamma$ are background processes and systematical uncertainties. It seems that the main background processes are $K^+ \to \pi^0 \pi^0 \mu^+ \nu_\mu$ with one lost photon, $K^+ \to \pi^+ \pi^0 \gamma$ with $\pi^+ \to \mu^+ \nu_\mu$ decay in flight, $K^+ \to \pi^+ \pi^0 \pi^0$ with one lost photon and with $\pi^+ \to \mu^+ \nu_\mu$ decay in flight and $K^+ \to \pi^0 \mu^+ \nu_\mu$ with accidental "photon". We considered here the first 3 background processes.

In our first approach we consider only $K^+ \to \pi^0 \mu^+ \nu_\mu \gamma$ decays with all 3 photons detected in the Forward Veto System of the CKM setup [12] (FVS, see Fig. 1) for which we will have the best coordinate resolution for photon detection. But we met with serious problems in this approach:

1. The efficiency for $K^+ \to \pi^0 \mu^+ \nu_\mu \gamma$ registration was small enough ($\epsilon = 0.008$) even without additional cuts to suppress the main background processes.

2. The muon spectrum for these $K^+ \to \pi^0 \mu^+ \nu_\mu \gamma$ events is very soft – practically all muons have momenta $P_\mu < 10$ GeV. They are below the threshold for pion RICH of CKM. Pion RICH can not be used to reduce the background from $\pi \to \mu\nu$ decays in flight by double muon momenta measurement and the background from $K^+ \to \pi^+ \pi^0 \pi^0$ (with $\pi^+ \to \mu^+ \nu$; one $\pi^0 \to \gamma(\gamma)$) and from $K^+ \to \pi^+ \pi^0 \gamma$ (with $\pi^+ \to \mu^+ \nu$) was too big.

Thus we used another approach which opened more possibilities for background suppression with the help of additional cuts. In our GEANT simulation we selected the events with 3 photons from $K^+ \to \pi^0 \mu^+ \nu_\mu \gamma$ decays detected in FVS and VVS (Vacuum Veto System) and with a charge particle which was registered in DMS spectrometer and passed through pion RICH and Muon Veto System (MVS) of the CKM setup.

We used the requirements for signal photon registration in FVS $E_\gamma > 150$ MeV and in VVS $E_\gamma > 100$ MeV and included the energy and coordinate resolutions in our simulation. For both system the energy resolution was assumed to be $\delta E_\gamma / E_\gamma = 0.10/\sqrt{E_\gamma [GeV]} + 0.01$. The coordinate resolution for VVS was $\delta\phi = \pm\pi/16$ and $\delta z = \pm 12.5$ cm (this resolution is due to the mechanical structure of VVS, see [12]) and for FVS – $\delta x; \delta y = \pm 5\,\mathrm{mm}/\sqrt{E_\gamma [GeV]} + 1\,\mathrm{mm}$. For two signal photons the constraint for the table value of π^0 mass was imposed. The photon veto requirements for additional photons were used in the accordance to Table 11 of the CKM Proposal [12]. For charge particle we imposed the momentum cut $P > 10$ GeV.

After thorough study of different cuts to optimize the registration of the $K^+ \to \pi^0 \mu^+ \nu_\mu \gamma$ decay and the background rejection we chose the following additional cuts for the above decay and for background processes $K^+ \to \pi^+ \pi^0 \pi^0$ ($\pi^+ \to \mu^+ \nu$; one $\pi^0 \to \gamma(\gamma)$), $K^+ \to \pi^+ \pi^0 \gamma$ ($\pi^+ \to \mu^+ \nu$), $K^+ \to \pi^0 \pi^0 \mu^+ \nu_\mu$ (one $\pi^0 \to \gamma(\gamma)$):

1. For all the decays we defined 3 systems of particles in final states $X_1,\ X_2,\ X_3$ with different assumption for charge particle (π^+ or μ^+) and we found the missing masses for these systems $M_1,\ M_2$ and M_3 in $K^+ \to X_i + M_i$ decays:

   (a) $X_1 = \mu^+ \pi^0 \gamma$ (charge particle was assumed to be μ^+) and M_1 for $K^+ \to \pi^0 \mu^+ \nu_\mu \gamma$ is the mass of neutrino; we selected events with $-0.01 < M_1^2 < 0.01$ GeV^2.

(b) $X_2 = \pi^+\pi^0$ (charge particle was assumed to be π^+); for $K^+ \to \pi^+\pi^0\pi^0$ decay $M_2^2 = m_{\pi^0}^2$ and we used the cut $M_2^2 > 0.025$ GeV^2 or $-0.01 < M_2^2 < 0.01$ GeV^2, e.g we rejected the events with $-0.01 < M_2^2 < 0.025$ GeV^2. This cut reduced significantly the background from $K^+ \to \pi^+\pi^0\pi^0$

(c) $X_3 = \pi^0\gamma$ and we used the cut $M_3^2 > 0.04$ GeV^2 to reduce the background from $K^+ \to \pi^+\pi^0\gamma$

2. To reduce the background from $\pi \to \mu\nu$ decays in flight we used double measurement of muon momenta in DMS and in pion RICH velocity spectrometer

$$1.285 < R = \frac{P_{\text{charge part.}}(\text{RICH})}{P_{\text{charge part.}}(\text{DMS})} < 1.355$$

(in the existing program for pion RICH $R = 1$ corresponds to a pion and $R = 1.33$ – to a muon)

3. To increase the efficiency of photon veto system we used the cut for the coordinate of the kaon decay vertex in the beam $20 < z < 44$ m (this cut is different from the standard CKM cut $14 < z < 44$ m because Beam Interaction Veto System was not included in the simulation procedure. In the future this temporary limitation can be omitted.

In the GEANT simulation procedure to increase statistics for background estimations we forced $\pi^+ \to \mu^+\nu_\mu$ decay and then used corresponding weights (~ 0.1 in average) for proper background evaluation.

The results of the GEANT simulation are presented in the Table 1

Table 1: The result of GEANT simulation of $K^+ \to \pi^0\mu^+\nu_\mu\gamma$ decay and background processes for the CKM setup

Decay	BR	MC Statistics	The number of accepted events	Efficiency[2], ϵ	Backgr./Signal
$K^+ \to \pi^0\mu^+\nu_\mu\gamma$	$2 \cdot 10^{-5}$	80000	1320	1.4%	
$K^+ \to \pi^+\pi^0\pi^0$ $\hookrightarrow \gamma(\gamma)$ $\hookrightarrow \mu^+\nu$	$1.73 \cdot 10^{-2}$	300000	0	$< 2 \cdot 10^{-6}$ (90% c.l.)	$< 6 \cdot 10^{-2}$ (90% c.l.)
$K^+ \to \pi^+\pi^0\gamma$ $\hookrightarrow \mu^+\nu$	$2.75 \cdot 10^{-4}$	80000	452	$5.5 \cdot 10^{-5}$	$5.4 \cdot 10^{-2}$
$K^+ \to \pi^0\pi^0\mu^+\gamma$ $\hookrightarrow \gamma(\gamma)$	$\sim 0.7 \cdot 10^{-5}$	80000	1	$1.25 \cdot 10^{-5}$	$< 1.1 \cdot 10^{-3}$ (90% c.l.)

It is also instructive to see how general additional cuts reduce the efficiency of $K^+ \to \pi^0\mu^+\nu_\mu\gamma$ detection (Table 2). We see that by reducing the $\epsilon(K^+ \to \pi^0\mu^+\nu_\mu\gamma)$ by factor of 3 we can reduce background by more than an order of magnitude.

[2]Efficiency calculations included weights for forced $\pi^+ \to \mu^+\nu_\mu$ decay

Table 2: The influence of additional cuts for the efficiency of $K^+ \to \pi^0 \mu^+ \nu_\mu \gamma$ detection

Cuts	$\epsilon(K^+ \to \pi^0 \mu^+ \nu_\mu \gamma)$, %
Preliminary	4.7
$-0.01 < M_1^2 < 0.01$ GeV^2	4.4
$1.285 < R < 1.355$	4.0
$M_2^2 > 0.025$ GeV^2 or $-0.01 < M_2^2 < 0.01$ GeV^2	2.8
$M_3^2 > 0.04$ GeV^2	1.4

In the condition of CKM experiment it is possible to obtain $4.0 \cdot 10^{13}$ K^+ decays for 2 years of measurements ($0.51 \cdot 10^7\, K^+$ decays/spill; $1.4 \cdot 10^5$ spill/week; $0.50 \cdot 10^{12}$ decay/week with a dead time losses of 30%; 78 weeks of measurements per 2 years) [12]. This value corresponds to $1.1 \cdot 10^7$ $K^+ \to \pi^0 \mu^+ \nu_\mu \gamma$ decays which we discussed before.

References

[1] R.G.Sachs, The Physics of Time Reversal, Univ. of Chicago Press, 1987.

[2] G.C.Branko, L.Lavora, J.P.Silva, CP-violation, Clarendon Press, Oxford, 1999.

[3] I.J.Bigi, A.I.Sanda, CP-violation, Cambridge Univ. Press, 1999.

[4] A.R.Zhitnitskii, Yad.Fiz. **31**, 1014(1980);
V.P.Efrosinin et al., hep-ph/0008199 Aug,2000.

[5] Y.Grossman, Nucl. Phys. B**426**, 355(1994);
G.Bekanger, C.Geng, Phys.Rev. D **44**, 2789(1991);
R.Peccei, hep-ph/9909236, Overview of Kaon Physics to be published in the Proceedings of Kaon99, Chicago, Illinois, June 1999.

[6] S.Blatt et al., Phys. Rev. D **27**, 1056(1983).

[7] M.Abe et al., Phys. Rev. Lett. **83**, 4253(1999).

[8] L.Littenberg, Proc. of Intern. KEK Workshop

[9] J.Gevais, J.Iliopoulos, J.Kaplan Phys. Rev. D , 1020(1966).

[10] V.N.Bolotov et al., Yad.Fiz. **44**, 108(1998).

[11] L. G. Landsberg, V. F. Obraztsov, Proc. of the Workshop on K Physics (KAON-99), Chicago, USA, June 1999;
V. F. Obraztsov, L. G. Landsberg, hep-ex/0011033; Proc. int. Conf. on CP-Violation Phys., Ferrara, Italy, September 2000;
L.G.Landsberg, Preprint IHEP 2000-27, Protvino, 2000; Yad.Fiz. (in press).

[12] J.Frank et al., Charged Kaon at the Main Injector, Fermilab Proposal, 2001.

[13] H.Y.Cheng, Phys. Rev. D **26**, 143(1982).

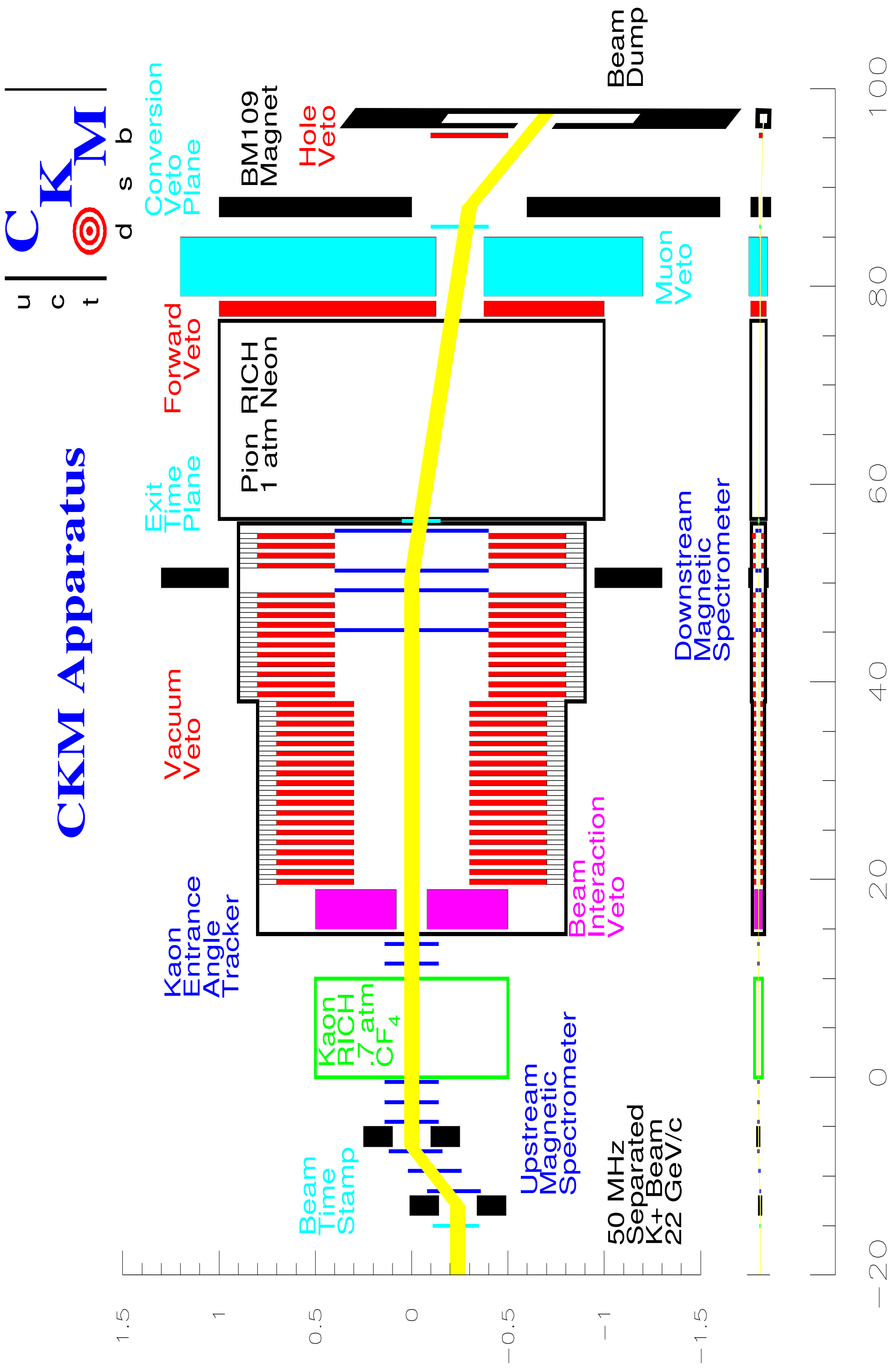

Figure 1: The CKM Detector. The lower section show the true proportions of the apparatus.