Prospects for CP-violation searches in the future experiment with RF-separated $K^{\pm}$ beam @ U-70.

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The first description of the experimental program "OKA" with RF-separated $K^{\pm}$ at Protvino U-70 PS is presented. The parameters of the beam as well as the potential for CP-violation searches are discussed.

1. Introduction

If one looks at current (or recent) experiments with charged Kaons, quite some with unseparated beams of different energies and intensities can be found, few with very low energy electrostaticly separated beams, but there is no high energy separated beams in operation. The reason is that the relatively simple electrostatic $E \times B$ separation, which is very effective at low energies does not work above few GeV and one has to build a high power RF cavities which provide strong oscillating electrical field. The most popular Panofsky-Montague-Schnell scheme of separation is presented in Fig.1. The beam with definite momentum is sent to the system of two deflectors with "-1" optics in between. The phase shift between two deflectors is tuned in such a way that the "unwanted" particles (π in Fig.1) have equal relative phase in both deflectors. As a result, they get two deflections which , in presented scheme, compensate each other and are absorbed in the beam stopper. The distance between the deflectors is selected in such a way that Kaons, because of longer time-of-flight, have 180° shift with respect to pions, get double deflection and avoid the absorber(it is interesting to note that because of random relation $\frac{m_p^2-m_\pi^2}{m_K^2-m_\pi^2} \sim 4$, the protons are suppressed "for free" together with pions) .

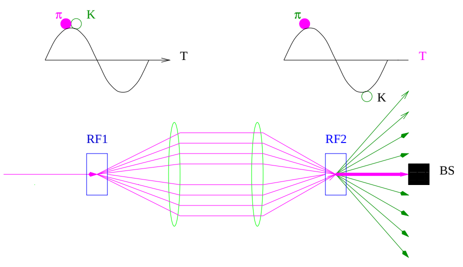

Figure 1. The principal scheme of RF separation.

The RF deflectors must be superconductive to be able to keep the field during slow extraction time of few seconds. Moreover, to get high quality factor of cavities it is necessary to cool them down to the superfluid He temperature of 1.8 K°. All these aspects make the design technologically complicated.

At present, there are two projects which aim to build RF-separated high intensity (slow extracted) beams:

1. FNAL Main Injector superconducting RF-separated beam for the CKM experiment [1].
2. IHEP, Protvino U-70 PS superconducting RF-separated beam for the "OKA" experiment, based on existing Karlsruhe-CERN superconductive deflectors.

2. The Karlsruhe-CERN superconductive RF-deflectors.

The only existing superconductive RF-separator was built at Karlsruhe(FRG) and used at CERN SPS at the end of 70^{es} [2]. It was an essential part of the S1 beam with $K^{\pm}$, $\bar{p}$ of different energies for the Ω-spectrometer. The parameters of the deflectors are summarized in Table 1. In 1998, after the negotiations with CERN, the deflectors were transported to Protvino. During 1998, the deflectors were connected to IHEP cryogenic system and in summer, 1999 they passed complex RF tests at 4.2 K°. It took one year more to build a cryogenic system capable to provide a temperature of T $\leq 2.5 K°$. The final tests should start end of October 2000.

Table 1
The parameters of the CERN deflectors.

Operating frequency(S-band)	2865 MHz
Wavelength, λ	$\sim$ 10.5 cm
Iris opening, 2a	40 mm
Effective deflector length	2.74 m
Number of cells/deflector	104
Mean deflecting field	$\sim$ 1.2 MV/m
Working temperature	T $\leq$ 2.5 K

3. The $K^{\pm}$ separated beam at U-70, based on Karlsruhe-CERN superconductive RF deflectors

The goal of the "OKA" project ("OKA" is a Russian abbreviation for "Experiments with Kaons") is to build a high intensity RF-separated $K^{\pm}$ beam based on the Karlsruhe-CERN superconductive deflectors using the slow extracted 70 GeV proton beam of U-70 PS of IHEP,Protvino.
The project comprises:
1. Improvement of the slow extraction system of U-70.
2. Beam-line design and construction.
3. Design and construction of the cryogenic system for the superconductive RF-cavities with the working temperature of $1.8 \div 2.5 K°$.
4. Physics program, Setup design and construction.

The schedule of the project assumes the start of the construction of the beam line in 2001. The first run with the kaon beam is scheduled for the spring of 2003.
The beam line design is completed, the parameters of the beam are presented in the Table 2. The basic working energy is 12.5 GeV, it is limited by the space available in the U-70 gallery. The second working point of 18 GeV corresponds to the condition of 360° shift between π and p and is supposed to be used for the experiments with a target, for the hadron spectroscopy in the Kaon beam, for example.
The intensity of the beam is limited by the relatively low deflection field in the cavities ($\sim$1.2 MeV/m). As a consequence, the vertical acceptance of the beam must be small.

Table 2
The parameters of the RF-separated beam.

Target	50 cm Be
Primary proton beam energy	70 GeV
Primary proton beam intensity	10^{13} ppp
Duty cycle	2/9 sec
Spill/h	4×10^2
Secondary beam momentum	12.5 or 18 GeV
Δp/p %	± 4
Horizontal acceptance	± 10 mrad
Vertical acceptance	± 1.9 mrad
Length of the beam line	$\sim$ 200 m
Distance between separators	76.3 m
Intensity of $K^+(K^-)$ at the end	$4(1.3) \times 10^6$
π^+, p contamination	$< 50\%$
Muon halo	$< 100\%$

4. Experimental set-up

Four major U-70 setups: SPHINKS, GAMS, ISTRA, HYPERON plan to join the "OKA" project. That gives a possibility to use existing equipment.
The upstream part of the setup is a beam spectrometer, with $\Delta P/P \sim 1\%$, based on 1mm small

Table 3
The expected kaon decays statistics, 3 month, $\epsilon = 50\%$

Decay	Br	acc.	PDG	Expect.
$K^+ \to \mu^+ \nu \pi^0$	$3.2 \cdot 10^{-2}$	0.27	10^4	$1.7 \cdot 10^9$
$K^+ \to e^+ \nu_e \pi^0$	$4.8 \cdot 10^{-2}$	0.18	$4 \cdot 10^4$	$1.7 \cdot 10^9$
$K^+ \to \pi^+ \pi^+ \pi^-$	$5.6 \cdot 10^{-2}$	0.62	$3 \cdot 10^6$	$7. \cdot 10^9$
$K^+ \to \pi^+ \pi^0 \pi^0$	$1.7 \cdot 10^{-2}$	0.17	10^5	$6 \cdot 10^8$
$K^+ \to e^+ \nu_e \pi^+ \pi^-$	$3.9 \cdot 10^{-5}$	0.26	$4 \cdot 10^5$	$2. \cdot 10^6$
$K^+ \to e^+ \nu_e \pi^0 \pi^0$	$2.1 \cdot 10^{-5}$	0.08	35	$3 \cdot 10^5$
$K^+ \to \mu^+ \nu_\mu \pi^+ \pi^-$	$1.4 \cdot 10^{-5}$	0.62	7	$2 \cdot 10^6$
$K^+ \to e^+ \nu$	$1.55 \cdot 10^{-5}$	0.45	10^3	$1.3 \cdot 10^6$
$K^+ \to \pi^+ \gamma \gamma$	$1.1 \cdot 10^{-6}$	0.30	31	$7 \cdot 10^5$
$K^+ \to \pi^+ \pi^0 \gamma$	$2.8 \cdot 10^{-4}$	0.21	$2. \cdot 10^4$	10^7
$K^+ \to \mu^+ \nu_\mu \gamma$	$5.5 \cdot 10^{-3}$	0.4	$2.5 \cdot 10^3$	$4.3 \cdot 10^8$
$K^+ \to e^+ \nu_e \gamma$	$3.8 \cdot 10^{-5}$	0.30	~ 100	$2.3 \cdot 10^6$
$K^+ \to e^+ \pi^0 \nu \gamma$	$2.6 \cdot 10^{-4}$	0.12	~ 250	$6 \cdot 10^6$
$K^+ \to \mu^+ \pi^0 \nu \gamma$	$2 \cdot 10^{-5}$	0.18		$7 \cdot 10^5$

gap PC's. In addition there are 3 beam $\check{C}$. The 12m long decay volume is surrounded by a photon veto system (~ 1000 LG blocks $10 \times 10 \times 40 cm^3$). The main magnetic spectrometer includes 3 Tm magnet ($200\times$ 70 cm^2 aperture) with 10K of PC's channels in front and 1K of 6cm ϕ mylar straw tubes after. The set-up has two large aperture gamma-spectrometers: GAMS-2000 downstream the straw's and former EHS gamma detector just after the decay volume, used as large-angle detector. The central part of GAMS-2000 has 500 PWO $2 \times 2 \times 20 cm^3$ crystals.

5. A sketch of the experimental program.

Let's make a brief estimate of the sensitivity of a "typical" experiment, with the RF-separated beam:
With ~ 13 % of 12.5 GeV Kaons decaying in the 12m decay volume we get 5×10^5 dec/spill. In three month of data taking it gives 4×10^{11} decays. That is, the sensitivity of the experiment is $5 \times 10^{-11} \div 5 \times 10^{-12}$ for the detection efficiency of $\epsilon = 0.05 \div 0.5$.
Such a sensitivity is by an order of magnitude higher than that in proposed experiments at the $DA\Phi NE$ ϕ-factory.
Table 3 shows the expected statistics for the main $K^\pm$ decays of interest. We have no possibility to discuss each line of the Table in details, let us just outline the main directions of the program:

1. Search for direct CP violation in $K^\pm \to \pi^\pm \pi^\pm \pi^\mp (\tau)$ and $K^\pm \to \pi^\pm \pi^0 \pi^0 (\tau')$ decays.
2. Search for T-odd correlations in the decay $K^\pm \to \mu^\pm \nu \pi^0 \gamma$.
3. Searches for S,P,T interactions in the decays $K^+ \to e^+ \nu$, $K^+ \to e^+(\mu^+) \nu \gamma$, $K^+ \to e^+(\mu^+) \nu \pi^0$.
4. Low energy hadron physics in the decays $K^+ \to \pi \pi e^+ \nu$, $K^+ \to \pi^+ \pi^0 \gamma$ etc.
5. Hadron spectroscopy and Primakoff physics with the $K^\pm$ beams.

In the following section we discuss in more details the points 1., 2. of the program relevant for the topic of the present conference.

6. Search for CP- violation in τ ($K^\pm \to \pi^\pm \pi^\pm \pi^\mp$) and τ' ($K^\pm \to \pi^\pm \pi^0 \pi^0$) decays.

The direct CP violation would manifest itself by the difference between the K^+ and K^- decay matrix elements if (see for example [3]), there are at least two amplitudes with different "weak" phases and different "strong" final state interaction phases. The decays $K^\pm \to \pi^\pm \pi^\pm \pi^\mp$ (τ)

and $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$ (τ') satisfy these requirements. The direct CP could be detected, in particular, by the observation of the difference $\frac{\delta g_{\pm}}{2g}$ in the slope parameters g$^{\pm}$ used in the conventional parametrization for the $|M|^2$:

$$|M_{3\pi}|^2 \sim 1 + gY + hY^2 + kX^2 + .. \qquad (1)$$

Here $Y = \frac{s_3 - s_0}{m_{\pi^2}}$; $X = \frac{s_2 - s_1}{m_{\pi^2}}$; $s_i = (p_K - p_i)^2$, $s_0 = \frac{1}{3}(s_1 + s_2 + s_3)$; π_3 is the odd pion. The measured values of g are: $g^{\tau} \sim .21$; $g^{\tau'} \sim 0.6$.
The theoretical predictions for the $\frac{\delta g_{\pm}}{2g}$ in the SM were originally spread in the wide range of $\frac{\delta g_{\pm}}{2g} = 2 \times 10^{-6} \div 10^{-3}$ [4]. Over last years they have converged to the value of $\sim 10^{-5}$ [3],[5]. In the extensions of the SM, where CP violation is not constrained to the CKM-matrix phases, larger values are possible. For example, in the three Higgs doublet model of Weinberg [6], where the origin of the CP violation comes from the Higgs sector, the value of $\sim 2 \cdot 10^{-4}$ is predicted [7].

6.1. Existing experimental results

There was only one old(1970!) dedicated experiment to measure the asymmetry in the τ decay [8], based on the statistics of $\sim 1.5 \cdot 10^6$ events of each sign. The result is $\frac{\delta g_{\pm}}{2g} = -0.70 \pm 0.53\%$.
The situation with the τ' is even worth: there was no dedicated experiment, the best measurement of g^- is that of "ISTRA" setup at U-70, Protvino(40 K events): $g_-^{\tau'} = 0,582 \pm 0,021$[9]. The best result for K^+ is from "HYPERON" setup at U-70(32K events): $g_+^{\tau'} = 0,736 \pm 0,02$[10]. Using these results, we get for the asymmetry: $\frac{\delta g_{\pm}}{2g} = 0.1 \pm 0.02$- 5 σ deviation from zero!

6.2. Current experiments

Before the discussion of the future results, it is useful to mention a simple formula which relates the statistical accuracy in the $\frac{\delta g_{\pm}}{2g}$ with the number of events:

$$\sigma(\frac{\delta g_{\pm}}{2g}) = R \cdot \frac{\sqrt{n_+ + n_-}}{2\sqrt{n_+ \cdot n_-}}; \qquad (2)$$

Here $n_+(n_-)$ is the number of the decays in the $K^+(K^-)$ beams; R depends on g: $R_{\tau} = 7.56$; $R_{\tau'} = 3.0$. It is seen that τ' is factor of 6 more "effective". Now let us turn to the current experiments:
The first one is the HyperCP experiment at FNAL, which is aimed at searches for CP violation in the hyperon decays [11]. The experiment had accumulated 204M of τ^+ and 75M of τ^- decays in the 1997 run, which according to (2) corresponds to the statistical accuracy of $\frac{\delta g_{\pm}}{2g} \sim 6 \times 10^{-4}$.
The second experiment[12] is the Tagged Neutrino Facility (TNF) at Protvino, U-70. The experiment is using the tagging station of the TNF, which consists of 60 m decay volume, 3 large area hodoscope stations and an e.m calorimeter. The aim of the first stage of the experiment is to accumulate $\sim$ 1M of τ' decay of each sign. That corresponds to $\frac{\delta g_{\pm}}{2g} \sim 2 \times 10^{-3}$.

6.3. Future experiments

There are two proposals, which aim to significantly improve the $\frac{\delta g_{\pm}}{2g}$ measurement. The first one is the NA48 proposal [13], and the second one is our proposal for the separated kaon beam at Protvino U-70. Table 4 shows the comparison of the two proposals. The advantage of the NA48 proposal is in the use of "simultaneous" $K^{\pm}$ beam, it allows to compensate the false asymmetry caused by the drift of the set-up parameters in time, as well as to have the same trigger conditions for the both beams. The advantage of the "OKA" is much lower total intensity of the beam

Table 4
The comparison of the NA48 and 'OKA" proposals

Proposal	NA48	OKA
Beam	5 %$K^{\pm}$	$> 50\% K^+(K^-)$
Beam p	60 GeV	12.5 GeV
Duty cycle	5s/19.2s	2s/9s
$K^{+(-)}$/cycle	$1.9(1.1) \cdot 10^6$	$4(1.3) \cdot 10^6$
$\tau(\tau')$eff.	32 %(50%)	50 %(15%)
N $\tau^+(\tau^-)$	$1.3(0.75) \cdot 10^9$	$3.8(2.1) \cdot 10^9$
N $\tau'^+(\tau'^-)$	$.82(0.47) \cdot 10^8$	$3.3(1.9) \cdot 10^8$
$\frac{\delta g}{2g}\tau(\tau')$	$1.7(3) \cdot 10^{-4}$	$1.0(1.3) \cdot 10^{-4}$

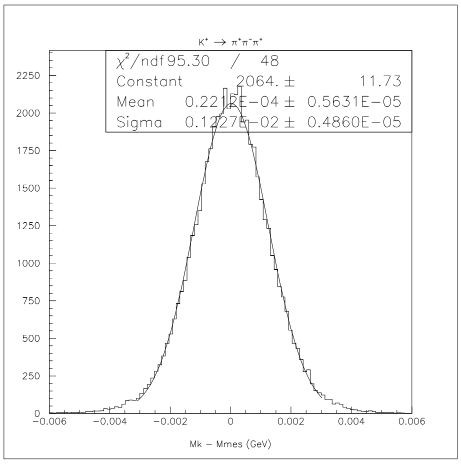

Figure 2. The reconstructed 3π mass.

and larger acceptance.
The main difficulty of the proposed experiments is to demonstrate that, indeed, there is no "dangerous" systematics at the level of 10^{-4}. In case of "OKA" a possible strategy of the measurements is the change of the polarities of all the beam elements, say , every 6 hours. It's important then to change the polarity of the main spectrometer magnet at the same time. The possible sources of the systematics are:
1. Difference in the hadronic interactions between π^+ and π^-.
2. Different parameters of the positive and the negative beams. In particular, the tilt of the beams with respect to each other is potentially dangerous.
3. Effects of the resolution.
4. Variation of the setup and the beam parameters with time etc....
We have started the detailed GEANT MC-studies of the different effects. The Fig. 2 shows the reconstructed 3π mass distribution, the resolution is $\sim$ 1.2 MeV; Fig. 3- the reconstructed z-coordinate of the decay vertex(z -is directed along the beam). Fig. 4 shows the acceptance of the setup versus z of the decay point. It is seen that the decay volume length of $\sim$ 12m is kind of op-

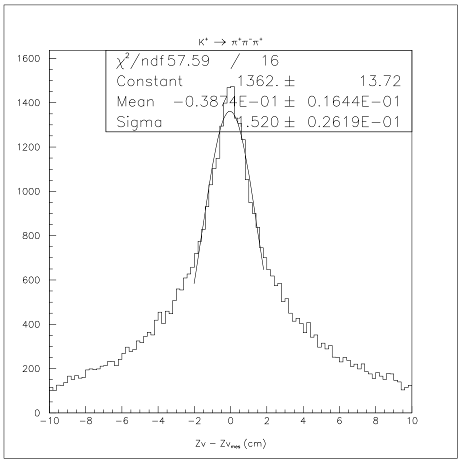

Figure 3. The reconstructed z of the decay vertex.

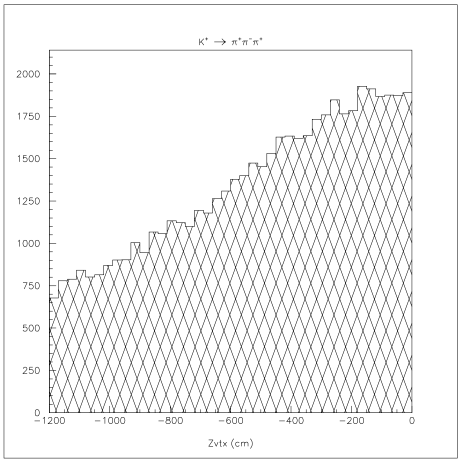

Figure 4. The acceptance of the setup versus z.

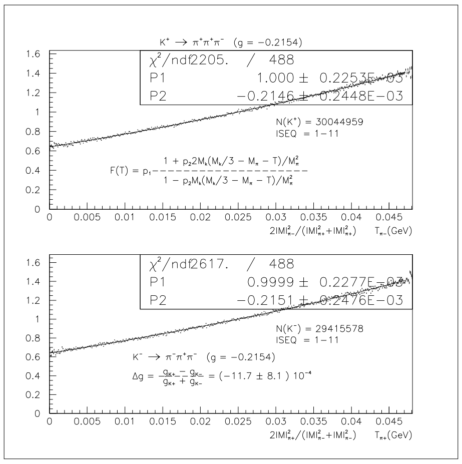

Figure 5. The events distribution over the kinetic energy of the "odd" π in the K-rest frame, normalized over the same distribution for the "even" pion. The top figure is for the K^+, the bottom for the K^-. The difference in the slopes $\frac{\delta g_\pm}{2g} < 10^{-3}$.

timum. At last, Fig. 5 shows the events distribution over the kinetic energy of the "odd" pion in the kaon rest frame for the case of K^+ and K^- decays. The both distributions are normalized to that for the "even" pions. These is the simplest way to remove the phase space dependance. To extract the g-slopes, the distributions are fitted with the formulae:

$$F(T) \sim \frac{1 + 2gM_K(M_K/3 - M_\pi - T)/M_\pi^2}{1 + gM_K(M_K/3 - M_\pi - T)/M_\pi^2} \qquad (3)$$

The denominator takes into account the "fake" slope for the "even" pion distribution which is $g/2$. The last figure corresponds to the statistics of about 30M decays. It is seen that the difference in the slopes due to the difference in hadronic interactions between π^+ and π^- is smaller than 10^{-3}. We'll continue these preliminary systematics studies in future, of course. What is interesting to mention, is that there are several decays, where the $K^\pm$ asymmetry must be negligible. For example, in the decay $K \to e(\mu)\nu\pi^0$ the asymmetry must be very small because there is practically no final state interaction. The intense decay $K \to \pi\pi^0$ is another example, here the expected effect is very small ($\frac{\Delta\Gamma}{2\Gamma} < 10^{-9}$), because the decay goes through one amplitude (S-wave, $\Delta T = 3/2$). These decays can be used to control the systematics.

7. Search for T-violation in $K^\pm$ decays.

The T-invariance is one of the fundamental symmetries in physics. 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 [14]. 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 $K^+ \to \mu^+\nu\pi^0$ ($K_{\mu3}$) decay:

$$\sigma_\perp^\mu = \frac{\vec{\sigma}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)}{|\vec{p}_\pi \times \vec{p}_\mu|} \qquad (4)$$

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: $\sigma_\perp^{FSI} \sim 5 \cdot 10^{-6}$ [15]. Although the SM predicts zero effect, in some models (like 3HDM of Weinberg [6]) a value higher than 10^{-3} is predicted. The best measurement of the $\sigma_\perp$, performed about 20 years ago at the BNL-AGS [16] gives: $\sigma_\perp = 0.0031 \pm 0.0053$. Current result from KEK E246 [17] is $\sigma_\perp < 10^{-2}$@90% C.L., they hope to reach $\sigma_\perp < 2.5 \cdot 10^{-3}$ at the end of the experiment.

7.1. T-odd correlations in $K \to \mu\nu\pi^0\gamma$ ($e\nu\pi^0\gamma$).

We do not plan at present to measure $\sigma_\perp^\mu$ in the "OKA" experiment: the energy of 12.5 GeV looks too high for that. On the contrary, we are seriously considering the possibility of measuring the triple T-odd correlation:

$$T_{\pi\mu\gamma} = \frac{\vec{p}_\gamma \cdot (\vec{p}_\pi \times \vec{p}_\mu)}{|\vec{p}_\gamma| \cdot |\vec{p}_\pi \times \vec{p}_\mu|} \quad (5)$$

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 [18]. 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 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 U-70 [19] : $\frac{\vec{p}_\gamma \cdot (\vec{p}_\pi \times \vec{p}_e)}{|\vec{p}_\gamma| \cdot |\vec{p}_\pi \times \vec{p}_e|} = 0.03 \pm 0.08$; it is based on 192 reconstructed events, which correspond to the Br=$(2.7 \pm 0.2) \cdot 10^{-4}$ ($E_\gamma^{c.m.} > 10$MeV ; $0.6 < cos\theta_{e,\gamma} < 0.9$).
The IHEP theorists are performing detailed calculations of the correlation (5) in SM and in the Weinberg's 3HDM [20]. 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: [21]

$$\frac{Im(\alpha_2\beta_2^*)}{Im(\alpha_1\beta_1^*)} = \frac{Im(\beta_2\gamma_2^*)}{Im(\beta_1\gamma_1^*)} = \frac{Im(\alpha_2\gamma_2^*)}{Im(\alpha_1\gamma_1^*)} = -1 \quad (6)$$

$$\frac{Im(\alpha_1\gamma_1^*)}{v_2^2} = -\frac{Im(\beta_1\gamma_1^*)}{v_1^2} = -\frac{Im(\alpha_1\beta_1^*)}{v_3^2} \quad (7)$$

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 $T_{\pi\mu\gamma}$. To illustrate, what one can expect, Fig.6 shows the T-odd correlation,

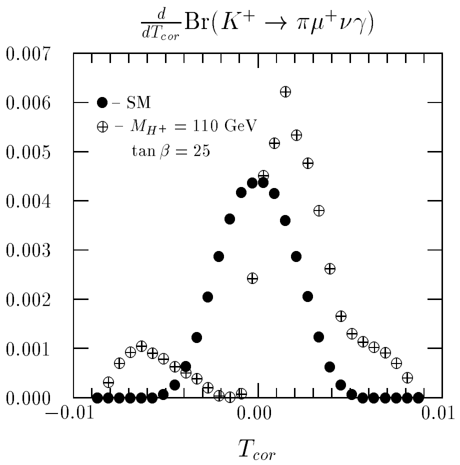

Figure 6. The T-odd correlation for the $K \to \mu\nu\pi^0\gamma$ decay for the SM (black circles) and 3HDM(open circles).

defined in a bit different way: $T_{cor} = \frac{\vec{p}_\gamma \cdot (\vec{p}_\pi \times \vec{p}_\mu)}{m_K^3}$ for the reasonable set of parameters in the 3HDM: $M_{H^+} = 110$ GeV; $tan(v_2/v_1) = 25$; $v_3/v_1 = 10$; $Im(\alpha_1\beta_1^*) = 0.8$, which is not excluded by any existing measurement. A cut of $\theta\mu\gamma > 20°$ and $E_\gamma > 30$ MeV was done in the kaon rest frame to suppress the "trivial" IB part of the process.
In "OKA" we can detect on the order of 7×10^5 events of the decay $K^+ \to \mu\nu\pi^0\gamma$, or $\sim 10^5$ events after the kinematical cuts, which is quite sufficient to detect the effect of Fig. 6. Detailed simulation is in progress.

8. Conclusions

The construction of the separated RF beam at U-70 PS of IHEP,Protvino will allow to carry out a wide program of experiments, in particular, CP-violation searches in $K^\pm$ decays with a good sensitivity, competitive with other experiments.

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