Letter of Intent for a JHF experiment Search for T-violation in K^+ decays

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Abstract

We propose a measurement of the T–violating muon polarization in the decays $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \mu^+\nu\gamma$ at JHF. The method employs complete reconstruction of kinematics in these decays using high-resolution π^0-detector, active muon polarimeter and near 4π efficient photon veto system. The goal of this proposal is to reach a statistical sensitivity to T–violating muon polarization $\sim 10^{-4}$ in both decays.

1 Physics motivation

Measurement of the muon transverse polarization, P_T, in the decays $K^+ \to \pi^0\mu^+\nu$ ($K_{\mu3}$) and $K^+ \to \mu^+\nu\gamma$ ($K_{\mu2\gamma}$) can provide insight into the origin of CP-violation beyond the Standard Model (SM). In the $K_{\mu3}$ decay, P_T is a T-odd observable $\mathbf{s}_\mu \cdot (\mathbf{p}_\pi \times \mathbf{p}_\mu)$ determined by the π^0 momentum $\mathbf{p}_\pi$ and the muon momentum $\mathbf{p}_\mu$ and spin $\mathbf{s}_\mu$. In

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the case of $K_{\mu 2\gamma}$ decay, P_T is proportional to $\mathbf{s}_\mu \cdot (\mathbf{q} \times \mathbf{p}_\mu)$, where $\mathbf{q}$ is the photon momentum. These observables are very small in the SM [1], but they are interesting probes of various non-SM CP-violation mechanisms [2–4] where P_T could be as large as 10^{-3} in either $K_{\mu 3}$ or $K_{\mu 2\gamma}$. Measurement of P_T in both decays would help to distinguish between models in the case of a non-zero effect. For example in the three-Higgs doublet model [4] a non-zero P_T can be generated as an interference between the standard W exchange and charged Higgs exchange diagrams, as shown in Fig. 1. As shown in [4], there is a correlation between values of P_T for $K_{\mu 3}$ and

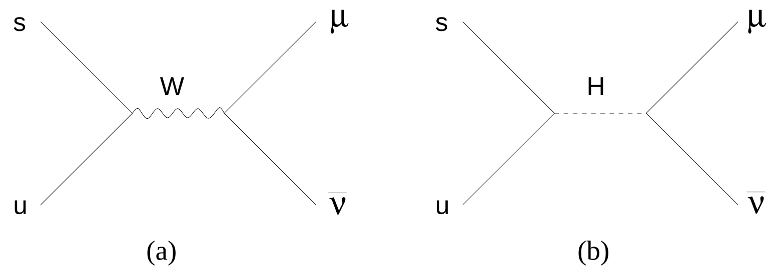


Figure 1: Diagram of the $K_{\mu 3}$ decay in three-Higgs doublet model. An interference between W^+ and H^+ exchange provides the main contribution to P_T.

$K_{\mu 2\gamma}$ in this model

$$P_T(K_{\mu 3}) \sim 2P_T(K_{\mu 2\gamma}). \tag{1}$$

In SUSY with squark mixing

$$P_T(K_{\mu 3}) \sim 0, \quad P_T(K_{\mu 2\gamma}) \neq 0, \tag{2}$$

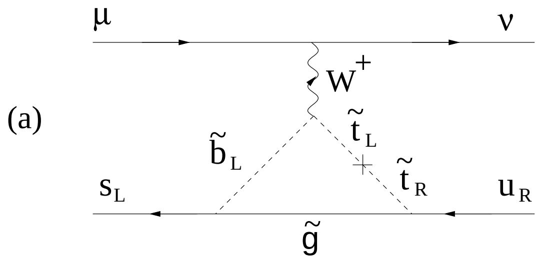
when the exchange is provided by W^+ [2] (see Fig. 2(a)) and

$$P_T(K_{\mu 3}) \sim -2P_T(K_{\mu 2\gamma}), \tag{3}$$

due to Higgs boson exchange [2] (see Fig. 2(b)). However, the electromagnetic final-state interactions (FSI) can generate a physics background, i.e. nonvanishing P_T, in both decays. The value of P_T due to the FSI is expected to be about 4×10^{-6} for $K_{\mu 3}$ decay [5, 6], i.e. much smaller than the potential non-SM effects. For the $K_{\mu 2\gamma}$ decay, the FSI can induce a P_T of $\lesssim 10^{-3}$ [7], but this background can be reliably calculated.

2 Experimental situation and expected result

At the KEK-PS we performed the E246 experiment using the toroidal spectrometer set-up and essentially improved the experimental limit on P_T in the $K_{\mu 3}$ decay [8]. The preliminary result recently obtained by E246 $P_T = (-1.12 \pm 2.17(stat) \pm$



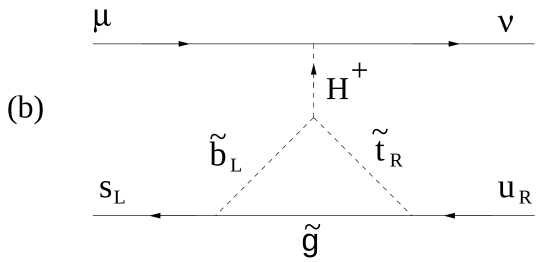


Figure 2: Diagram of the $K_{\mu 3}$ decay induced by squark mixing (a) W^+, (b) H^+

$0.90(syst)) \times 10^{-3}$ and $\mathrm{Im}(\xi) = (-0.28 \pm 0.69(stat) \pm 0.30(syst)) \times 10^{-2}$, consistent with no T-violation in $K_{\mu 3}$ [9]. E246 is completed, and final sensitivity to P_T is expected at the level of about 1.5×10^{-3} that corresponds to $\delta\mathrm{Im}(\xi) \sim 0.6 \times 10^{-2}$. Since the E246 detector is not optimized to the measurement of $K^+ \to \mu^+\nu\gamma$, we will be able to reach a 1% level for P_T in this decay.

This proposal is the continuation of the E246 research activity by the Collaboration using new concept and new detector for a high-intensity kaon beam. The experimental method for measurement of T-violating muon polarization in kaon decays using stopped positive kaons is already established by E246. This proposal has much better sensitivity to P_T for $K_{\mu 3}$ and $K_{\mu 2\gamma}$ decays and is capable to reach a statistical sensitivity to T-violating muon polarization $\sim 10^{-4}$ in both decays. This is by a factor 20(100) better for $K_{\mu 3}(K_{\mu 2\gamma})$ than the expected final sensitivity of the E246.

3 Description of the experiment

3.1 Principles of measurement

This proposal is based on a new method of measurement of T-odd polarization in the two decays $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \mu^+\nu\gamma$ described in Ref. [10]. The basic principles could be briefly formulated as follows: a) a high resolution measurement of π^0 from the $K_{\mu 3}$ decay of stopped K^+s; b) an active muon polarimeter which provides information about stopped muons (stopping point, momentum), positron direction, and it also detects photons; c) a highly efficient photon veto covering nearly 4π solid angle.

The energy of the neutral pion can be defined as

$$E^2_{\pi^0} = \frac{2m^2_{\pi^0}}{(1-\cos\eta)(1-X^2)}, \tag{4}$$

where η is the opening angle between two photons from $\pi^0 \to \gamma\gamma$ decay, E_1 and E_2 are the laboratory photon energies giving

$$X = \frac{E_1 - E_2}{E_1 + E_2}. \tag{5}$$

If both photon energies are nearly equal, X^2 is small and an accurate measurement of η provides good energy resolution for π^0. The contribution to the pion energy resolution from the uncertainty in reconstruction of η (σ_η) is given by

$$\Delta E^\eta_{\pi^0}(\mathrm{rms}) = \frac{m_{\pi^0}}{2}\gamma^2\beta\sigma_\eta, \tag{6}$$

where $\beta = p/E$ and $\gamma = E/m_{\pi^0}$. The π^0 energy resolution due to uncertainty in the photon energies (σ_{E_γ}) in the case of $E_1 \approx E_2$ [11] is

$$\Delta E^\gamma_{\pi^0}(\mathrm{rms}) = \sqrt{3}\frac{\sigma^2_{E_\gamma}}{E_{\pi^0}}. \tag{7}$$

Assuming that the above mentioned quantities are independent, and parameters of a photon detector are $\sigma_\eta \sim 5$ mrad and $\sigma_{E_\gamma} \sim 0.015/\sqrt{E(\mathrm{GeV})}$, one can obtain $\sigma_p/p \sim 1$–2% ($|X| \leq \beta$) for pions from $K_{\pi 2}$ decay. Such a momentum resolution of the π^0 is expected to provide a narrow peak for the $K_{\pi 2}$ decay which then can be easily rejected by applying a simple cut on the π^0 energy.

3.2 Detector

Fig. 3 shows a schematic view of the proposed detector. The kaon beam of 600-700 MeV/c is stopped in a scintillating fiber target. The π^0s from the $K_{\mu 3}$ decays at rest are detected by both the preshower detector and the photon calorimeter providing a separate measurement of the photon direction and energy. The momentum of the muon is determined through its range in the segmented active polarimeter (Al plates + MWPCs + plastic counters), shown in Fig. 4. In principle, it is possible to put the tracking part of the detector in a solenoidal field to do the analysis of the momentum of a charged particles with a higher resolution. This scheme is now also under consideration. The polarization of stopped muons is measured by

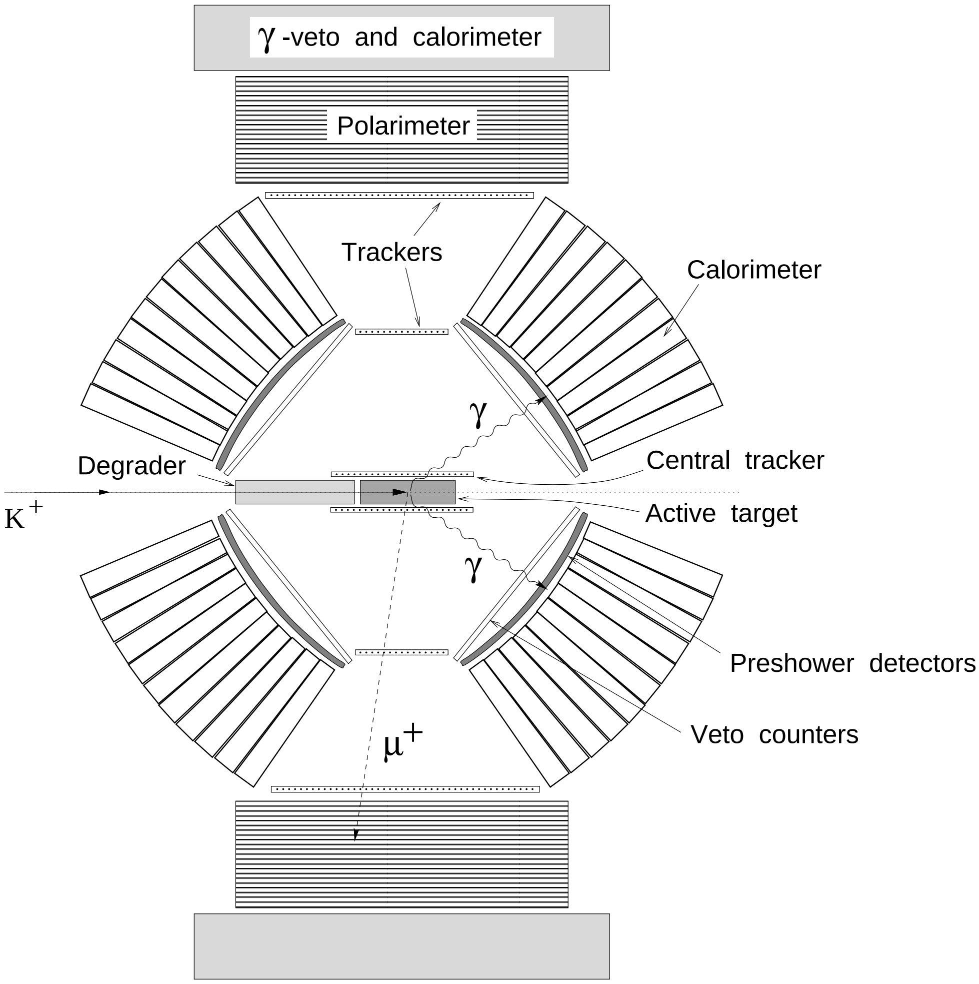


Figure 3: The schematic side view of the detector.

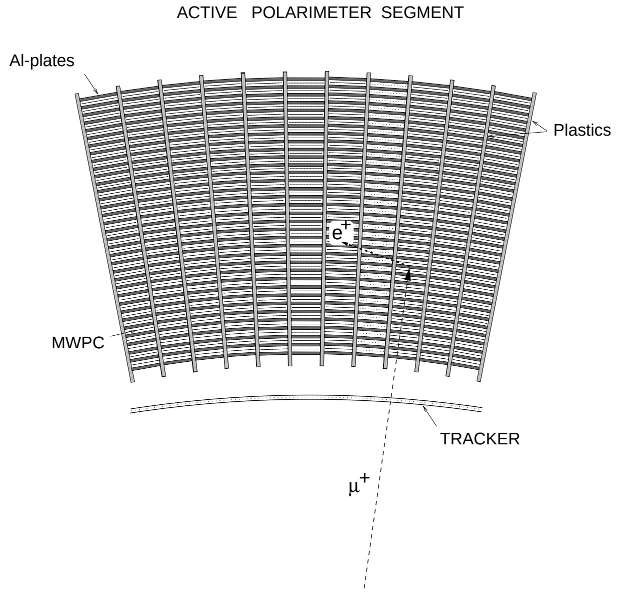


Figure 4: The active muon polarimeter.

detecting the positron from the decay $\mu^+ \to e^+\nu\bar{\nu}$, which is emitted preferentially in the muon spin direction. The polarimeter, which also serves as a photon veto detector, is surrounded by an additional photon veto system. Charged particle tracking is provided by fiber trackers and wire chambers. P_T is directed in a screw sense around the beam axis and will generate an asymmetry

$$A_T = \frac{N_{cw} - N_{ccw}}{N_{cw} + N_{ccw}} \tag{8}$$

in the counting rate between clockwise (cw) and counter-clockwise (ccw) emitted positrons. The sign of A_T for forward-going π^0 (fwd) events is opposite to that of backward-going π^0 (bwd) events. A double ratio between these two types of events is one of the key factors for cancellation of most systematic uncertainties.

3.3 Monte Carlo simulation

The results of Monte-Carlo simulations of $K_{\mu3}$, $K_{\pi2}$ and $K_{\mu2\gamma}$ modes of 10^6 K^+ decays at rest using GEANT3.21 code with the detector parameters $\sigma_\eta \sim 5$ mrad and $\sigma_{E_\gamma} \sim 1.5\%$ at 1 GeV are shown in Figures 5 and 6. Fig. 5a shows the momentum spectrum of the π^0s for $K_{\mu3}$ and $K_{\pi2}$ events. The numbers of events simulated for these modes are proportional to their branching ratios and no cuts were applied. The separation of the $K_{\mu3}$ events from those of $K_{\pi2}$ is obtained by the requirement for the angle between the charged and neutral particle to be less than 175°, as seen in Fig. 5b. An additional cut on the π^0 direction (selection of $K_{\mu3}$ events with forward- and backward-going pions, $\theta \geq 110°$ and $\theta \leq 70°$, respectively) eliminates the $K_{\pi2}$ mode as shown in Fig. 5c. It should be noted that muons from

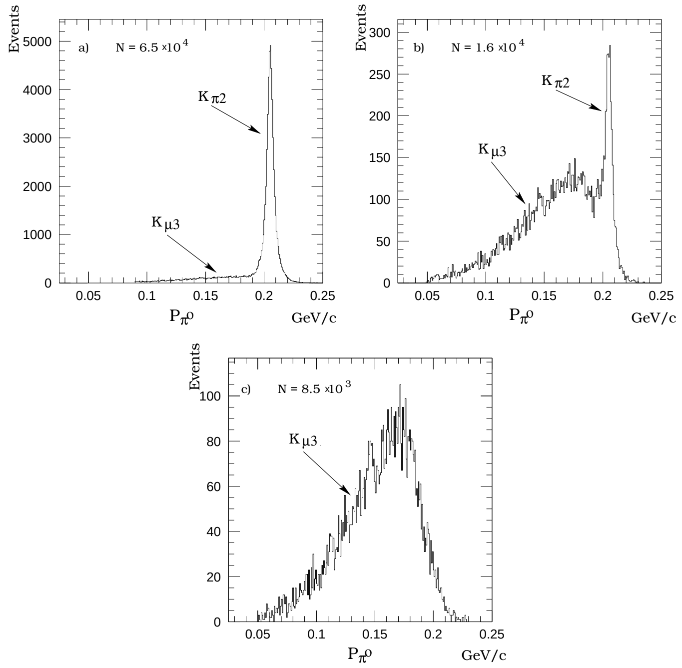


Figure 5: The momentum distribution of π^0's for $K_{\mu 3}$ and $K_{\pi 2}$. (a) no cuts, (b) $\theta_{\pi^0\mu^+} < 175°$, (c) events with forward- and backward-going pions.

the in-flight π^+ decays of the $K_{\pi 2}$ mode, accepted as muons from $K_{\mu 3}$ decays in the case of charged particle momentum measurement, will be completely removed from the accepted $K_{\mu 3}$ events after the requirement that the momentum of neutral pion must be less than 190 MeV/c. After applying these cuts, the $K_{\mu 3}$ events are practically free of the background from other K^+ decay modes. The $K_{\pi 3}$ background is removed by using an efficient photon veto.

This apparatus is also able to measure P_T in $K^+ \to \mu^+\nu\gamma$ decay. The background events for this decay appear from the $K_{\mu 3}$ and $K_{\pi 2}$ modes when one photon is missed. To suppress these events an additional photon veto detector consisting of alternating layers of lead and plastic can be installed to detect photons which pass through the polarimeter. In the Monte-Carlo simulations, an average photon detection inefficiency of the veto detector in the energy range of 10–250 MeV was safely assumed to be 2%, which is larger than that of the experiment E787/949 at BNL. The photon spectra measured by the photon detector after applying cuts on $E_\mu \geq 200$ MeV, $20 \leq E_\gamma \leq 200$ MeV and the opening angle between photon and muon $\leq 100°$ are shown in Fig. 6. The signal-to-background ratio of about 8 is obtained, i.e. the physical background from copious $K_{\mu 3}$ and $K_{\pi 2}$ decays is suppressed by a factor $\sim 10^2$–10^3. The main contribution to the background comes from the $K_{\pi 2}$ mode, which can not make a false P_T and only dilutes the detector

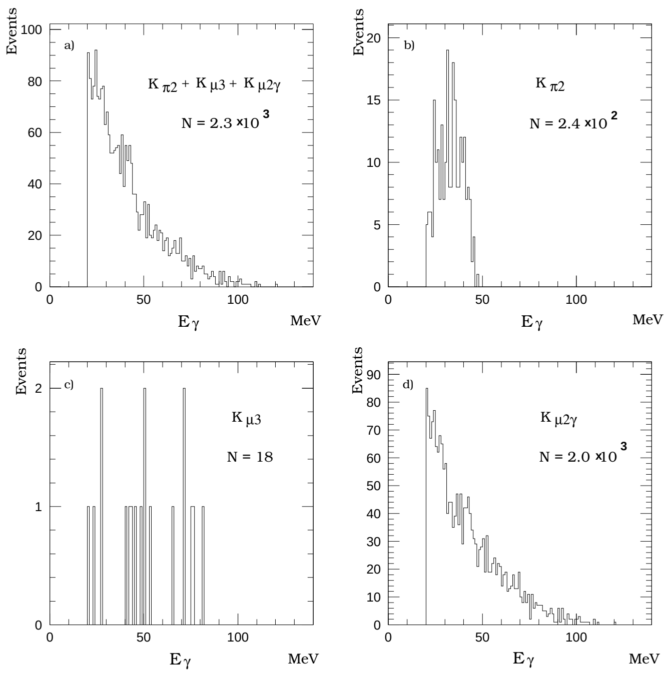


Figure 6: The energy distribution of one-photon events. The branching ratios of are taken into account in the MC simulation.

sensitivity to polarization in $K^+ \to \mu^+\nu\gamma$ decay. The detector acceptance to $K_{\mu 2\gamma}$ for these cut parameters is calculated to be about 0.7×10^{-4} per incident kaon. The E_γ threshold of 50 MeV eliminates $K_{\pi 2}$ events, and very clear $K_{\mu 2\gamma}$ events can be obtained in the region of 50–200 MeV, but at the expense of the detector acceptance. The background from the $K_{\mu 3}$ events is found to be at very safe level of less than 1%, as seen from Fig. 6c.

4 Sensitivity and systematics

To estimate the statistical sensitivity to P_T we used detector parameters summarized in Table 1. The number of accumulated events was estimated according to the expected kaon beam intensity at JHF (see Table 2). The analyzing power of the polarimeter is estimated by Monte Carlo to be ≥ 0.30, and the attenuation factor due to not ideal reconstruction of a decay kinematics and finite solid angle is about 0.8. The estimated background level is about 20%. Then, statistical sensitivity to P_T (1σ)

$$\delta P_T = \frac{\sqrt{1.2}}{0.30 \cdot 0.8 \cdot \sqrt{1.3 \times 10^{10}}} \simeq 4 \times 10^{-5} \qquad (9)$$

Table 1: Detector acceptance for the decay $K^+ \to \pi^0 \mu^+ \nu$

Solid angle ($\mu \times \pi^0$)	0.10
Muon stopping efficiency	0.89
Gamma conversion and reconstruction	0.30
Efficiency of positron detection	0.78 (1 counter)
	0.35 (2 counters)
Kaon stopping efficiency	0.30
Branching ratio	3.18×10^{-2}
Total acceptance per K^+	2.0×10^{-4}
Acceptance for $fwd + bwd$ π^0 per K^+	1.3×10^{-4}

Table 2: Statistical sensitivity to P_T for $K_{\mu 3}$

Analyzing power	0.30
Attenuation factor	0.80
Kaon intensity, 1/s	1×10^7
Running time, s	1×10^7
Background	20%
Total number $K_{\mu 3}$ events	2.0×10^{10}
Total number $fwd + bwd$ $K_{\mu 3}$ events	1.3×10^{10}

In the case of the $K_{\mu 2\gamma}$ decay, the acceptance per K^+ is about 0.7×10^{-4} ($E_\gamma = 20 - 200\text{MeV}, E_\mu \geq 200\text{MeV}$ and $\theta \leq 120°$) that allows us to accumulate about 0.7×10^{10} $K_{\mu 2\gamma}$ events in the Dalitz plot region determined by these cut parameters for 10^7 s of data taking. Statistical sensitivity of $\delta P_T \sim 0.7 \times 10^{-4}$ can be obtained in this decay.

The systematic uncertainty in E246 was suppressed to the level $\delta P_T \simeq 10^{-3}$ by using two main factors: the detector azimuthal symmetry and double ratio [8]. In the proposed experiment, there are several additional factors which help us to push down the systematics: the highly segmented active polarimeter, fast preshower and photon calorimeter, and more symmetrical distribution of stopped kaons in the target. We expect a reduction of systematics by a factor of 2 from the polarimeter segmentation and powerful systematics suppression by > 5 times from measurement of the muon stopping distribution in the polarimeter and the positron direction. Polarimeter background will be also substantially reduced by using information about muon and positron tracks. High energy and space resolution of photons will provide more accurate definition of the decay planes for $K_{\mu 3}$ and $K_{\mu 2\gamma}$. From this crude estimation, we expect $\delta P_T(sys) \sim 10^{-4}$, i.e. by a factor of 10 better than the value of systematic error obtained in E246.

5 Kaon beam

This experiment requires a stopped K^+ beam with high intensity. From the experience of the E246 experiment, it is known that the maximum stopping rate of K^+ can be achieved for the beam momentum between 600 and 700 MeV/c taking into account all the factors of production cross section, decay-in-flight loss and reaction loss in the degrader. In order to realize good π/K ratio of $\lesssim 1$, a double stage separate beam will be essential.

Since one suffers interaction of out going particles with the target material, smaller target is desirable. It is only possible when the beam has small enough momentum bite (say 2.0-2.5%) and achoromaticy at the target point. Our sensitivity estimate is based on the kaon flux of 10^7 K^+/s.

In the initial plan of the experimental hall a low momentum separate kaon beam line is planned at the second target T2. However, we seek for a possibility to perform the experiment in Phase1 hall in case the Phase2 will come far in the future. We would like to request to install a low momentum separate line at the T1 target.
Beam requirements can be briefly summarized as follows:

- Slow extracted proton beam
- Kaon intensity $10^7 K^+$/s
- Kaon momentum: 600-700 MeV/c

- Double stage separator, $\pi/K < 1$
- $\delta p/p = (2.0 - 2.5)\%$

6 Miscellaneous

- Competition-
  There are no other experiments searching for T violation in K^+ decay running now. There was once an approved experiment at BNL using decay-in-flight method aiming for one order of magnitude better sensitivity than E246. But the chance of realization dissappeared. In any case the in-flight-decay method suffers a disadvantage of associated larger systematic errors.

- Collaboration -
  There is an experienced group which built the E246 detector and executed the experiment. Some people of this group will form a core of the new collaboration. It is now under discussion about the collaboration forming.

- Cost and funding -
  The cost of the new detector is estimated roughly 3-4 M$ including electronics. The funding of the experiment is now under discussion. Although there will be funding efforts in constituent countries, it is thought that we have to rely much on the JHF operation money.

- Schedule -
  Although there is no urgency in view of international competition, we would like to start the experiment as early as possible by seeking for funding. The construction of the new detector will take three-four years after the start of the funding including the R&D of the new calorimeter. Some electronics of E246 can be used for the new detector.

We proposed an experiment to search for T-violation in the K^+ decays at JHF. A compact large acceptance detector includes a fast preshower detector, an electromagnetic calorimeter, an active polarimeter, tracking detector for charged particles, and photon veto systems. The final goal of this experiment is to reach the sensitivity $P_T \leq 10^{-4}$ in both $K_{\mu 3}$ and $K_{\mu 2\gamma}$ decays.

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