SEARCH FOR T VIOLATION IN $K^+ \to \pi^0 \mu^+ \nu$ DECAYS

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Abstract

The transverse muon polarization in $K^+ \to \pi^0 \mu^+ \nu$ decay is an excellent probe of T violation and it is very sensitive to new physics beyond the Standard Model. The most recent experimental effort was the E246 experiment at the KEK proton synchrotron, which set an upper-bound of $|P_T| \leq 0.0050$ (90% C.L.). A next generation experiment is now being planned for the high intensity accelerator J-PARC which is aiming more than one order of magnitude improvement in the sensitivity with $\sigma(P_T) \sim 10^{-4}$.

1. TRANSVERSE MUON POLARIZATION

The transverse muon polarization (P_T) in the three body $K \to \pi\mu\nu$ ($K_{\mu 3}$) decay is a clear signature of T violation with its T-odd correlation [1]. Over the last three decades dedicated experiments have been carried out in search of non-zero P_T. Unlike other T-odd channels in e.g. nuclear beta decays, P_T in $K_{\mu 3}$ has the advantage that the final state interactions (FSI), which may mimic T violation by inducing a spurious T-odd effect, are very small. This argument applies most particularly to $K^+ \to \pi^0 \mu^+ \nu$ ($K^+_{\mu 3}$) decay with only one charged particle in the final state where the FSI contribution is only from higher loop levels and has been shown to be small. The single photon exchange contribution from two-loop diagrams was estimated more than 20 years ago as $P_T^{FSI} \leq 10^{-6}$ [2]. Quite recently two photon exchange contributions have been studied [3]. The average value of P_T^{FSI} over the Dalitz plot was calculated to be less than 10^{-5}.

An important feature of a P_T study is the fact that the contribution from the Standard Model (SM) is nearly zero. Since only a single element of the CKM matrix V_{us} is involved for the semileptonic $K_{\mu 3}$ decay in the SM, no CP violation appears in first order. The lowest order contribution comes from radiative corrections to the $\bar{u}\gamma_\mu(1-\gamma_5)sW^\mu$ vertex, and this was estimated to be less than 10^{-7} [4]. Therefore, non-zero P_T in the range of 10^{-3}-10^{-4} would unambiguously imply the existence of a new physics contribution [4].

As candidate theories to give rise to sizable P_T, multi-Higgs doublet models, - namely CP violation in the Higgs sector- were intensively studied [5]. P_T can be induced due to interference between the charged Higgs exchange (F_S, F_P) and the W exchange (F_V, F_A) as shown in Fig.1. Also it is conceivable that the coupling of charged Higgs fields to leptons is strongly enhanced, when the vacuum expectation value (VEV) of the Higgs field that couples to leptons is greatly reduced relative to the VEV of the Higgs field coupling to the up-type quarks [6], leading to experimentally detectable P_T of $O(10^{-3})$. Thus, P_T could reveal a source of CP violation which escapes detection in $K \to 2\pi, 3\pi$ [4].

A number of other models also allow P_T at an observable level without conflicting with other experimental constraints, and non-observation of P_T can constrain those models. Among them the class of SUSY models such as the R-parity breaking model [7] and the SUSY model with large squark mixing [8] were investigated. Also, in the recent paper of a generic effective operator analysis [9], a P_T expression was given in terms of a cut-off scale Λ and the Wilson coefficients C_S and C_T, which in turn constrains the coefficients from P_T and Λ.

2. KEK E246 EXPERIMENT

The most recent and highest precision P_T experiment was performed at the KEK proton synchrotron. The experiment used a stopped K^+ beam with an intensity of $\sim 10^5$/s and a superconducting toroidal spectrometer setup (Fig.2). An elaborate detector system [10] consisting of a large-acceptance CsI(Tl) barrel

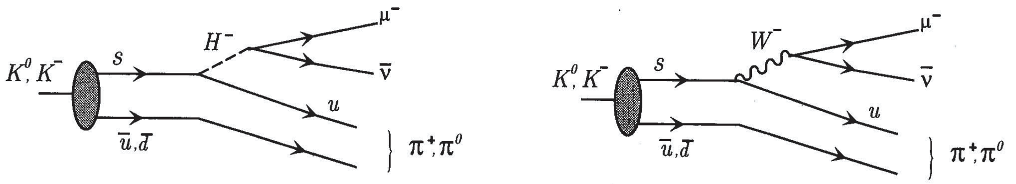

Fig. 1: Interfering two diagrams inducing P_T in the multi-Higgs model (from Ref.[4])

(to detect π^0), tracking chambers (to track μ^+), an active target (to stop K^+) , and muon polarimeters (to measure P_T) was constructed and data were taken between 1996 and 2000 for a total of 5200 hours of beam time. The muon polarization measurement was due to decay positron azimuthal asymmetry in a longitudinal magnetic field configuration using "passive polarimeters". Thanks to the stopped beam method which enabled total coverage of the decay phase space and hence a so-called a) $forward$ and $backward$ symmetric measurement with regard to the π^0 emission direction, and the b) high rotational symmetric structure of the toroidal system, systematic errors could be substantially suppressed.

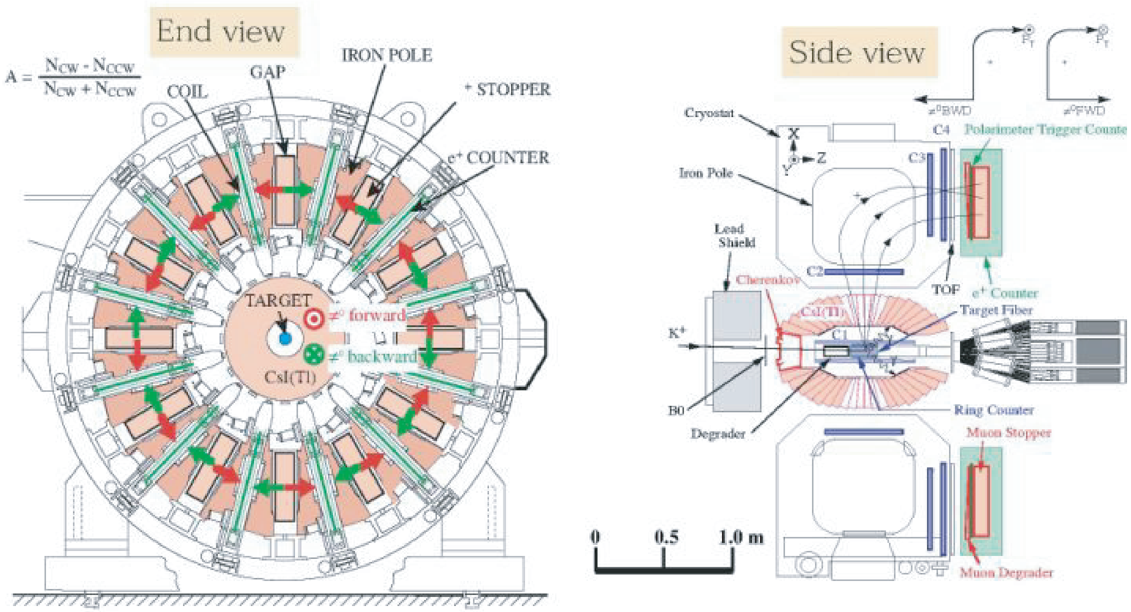

Fig. 2: E246 setup using the superconducting toroidal spectrometer

The T-odd asymmetry was deduced using a double ratio scheme as $A_T = (A_{fwd} - A_{bwd})/2$, where the $fwd(bwd)$ asymmetry was calculated using the "clockwise" and "counter-clockwise" positron emission rates N_{cw} and N_{ccw} as

$$A_{fwd(bwd)} = \frac{N^{cw}_{fwd(bwd)} - N^{ccw}_{fwd(bwd)}}{N^{cw}_{fwd(bwd)} + N^{ccw}_{fwd(bwd)}}. \tag{1}$$

P_T was then deduced using the analyzing power α and the average kinematic attenuation factor $< \cos\theta_T >$ to be $P_T = A_T/\{\alpha < \cos\theta_T >\}$. The final result was [11]

$$P_T = -0.0017 \pm 0.0023(stat) \pm 0.0011(syst) \tag{2}$$

$$\mathrm{Im}\xi = -0.0053 \pm 0.0071(stat) \pm 0.0036(syst) \tag{3}$$

corresponding to the upper limits of $|P_T| < 0.0050$ (90% C.L.) and $|\mathrm{Im}\xi| < 0.016$ (90% C.L.), respectively. Here Imξ is the physics parameter proportional to P_T after removal of the kinematic factor. This result constrained the three-Higgs doublet model parameter in the way of $|\mathrm{Im}(\alpha_1\gamma_1^*)| < 544(M_{H_1}/\mathrm{GeV})^2$, as the most stringent constraint to this parameter. Systematic errors were investigated throughly, although the total size was smaller than half of the statistical error. There were two items which could not be cancelled out by any of the two cancellation mechanisms of the 12-fold azimuthal rotation and π^0-fwd/bwd; the effect from the decay plane rotation, θ_z and the misalignment of the muon magnetic field, δ_z, which should both be eliminated in the next generation J-PARC experiment.

3. J-PARC E06(TREK) EXPERIMENT

The new P_T experiment E06 (TREK) at J-PARC is aiming at a sensitivity of $\sigma(P_T) \sim 10^{-4}$. J-PARC is a high-intensity proton accelerator research complex now under construction in Japan and the first beam is expected in 2008. In the initial phase of the machine, the main synchrotron will deliver a 9μA proton beam with 30 GeV. A low momentum K^+ beam of 3×10^6/s intensity will be available for stopped K^+, which is about 30 times the beam used for E246. An essentially same detector concept will be adopted; namely the combination of a stopped K^+ beam and the toroidal spectrometer, because this system has the advantage of suppressing systematic errors by means of the double ratio measurement scheme. However, the E246 setup will be upgraded significantly. The introduction of active polarimeters in place of the passive ones in E246, where the muon stoppers were sandwiched by left- and right-hand side positron counters, will substantially increase the positron acceptance as well as the analyzing power. As a result, 20 times higher sensitivity to P_T will be obtained after a one year of run. The systematic errors will be controlled with sufficient accuracy and a final experimental error of $\sim 10^{-4}$ will be attained. A full description of the experiment is found in the proposal [12].

The E246 detector will be upgraded in several parts so as to accommodate the higher counting rate and to better control the systematics. The major upgrades are the following:

- The muon polarimeter will become an active polarimeter. The muon stopping point (namely decay vertex point) is localized and the track of a decay positron is detected. This is done by employing a parallel plate muon stopper configuration with gaps which serve as drift chambers. The measurement of the e^+ emission angle (θ_{e^+}) as well as the gross energy (E_{e^+}) by means of range provides a larger analyzing power (higher sensitivity to P_T). The identification of the decay vertex enables essentially a background-free muon decay measurement.
- The magnetic field at the muon stopper is important to preserve the P_T polarization component and also to decouple any unwanted ambient stray fields. However, the misalignments of the field distribution, if any, affect the high-precision asymmetry measurement. In E246 the fringing field from the superconducting magnet was trimmed precisely and supplied as the polarization holding field. In the TREK experiment, new dipole magnets will be added to produce more parallel fields with much higher precision in the alignment.
- The CsI(Tl) calorimeter of E246 using PIN photo-diode readout is not fast enough for TREK. By keeping the crystals, readout elements and electronics will be replace in order to extract the maximum counting rate performance which is determined by the intrinsic crystal speed. APD of the reversed-bias-voltage type with large area are now under consideration.
- The tracking system and the active target will be improved for higher resolution. Two chambers will be added for muon tracking to achieve higher rejection ability of the background decay-in-flight μ^+ from π^+ coming from $K^+ \to \pi^0\pi^+$ under high rate conditions. GEM technology will be

employed for the new chambers. Finer segmentation of the fiber target strengthens this separation capability, and a simpler fiber readout system is required to realize high-precision alignment.

It is now proposed to run for net 10^7s corresponding to roughly one year of J-PARC beam-time under the above mentioned beam condition. This would yield 2.4×10^9 good $K^+_{\mu 3}$ events in the π^0-fwd/bwd regions, providing an estimate of $\sigma(P_T)_{stat} = 1.35 \times 10^{-4}$. An inclusion of other π^0 regions, enabled by the adoption of the active polarimeter, brings this statistical sensitivity further down to the 10^{-4} level. Regarding systematic errors, the most important factor is the alignment of the polarimeter and the muon magnetic field; in particular the δ_z is dangerous. Those misalignments will be able to be measured using real data and it has been shown in a Monte Carlo study that these effects can be suppressed down to the 10^{-4} level.

It is proposed to run TREK in the early stage of J-PARC operation, and the experiment group has already started relevant R&D for the upgrades after obtaining scientific approval last year. The exact schedule is still not determined now but it will become concrete after we receive initial funding from the various agencies.

Table 1: Goal of the J-PARC TREK experiment compared with the E246 result

Experiment	E246 @ KEK-PS	TREK @ J- PARC
Proton beam (E_p and I_p)	12 GeV; 1.0×10^{12}/s	30 GeV; 6×10^{13}/s
K^+ intensity	1.0×10^5/s	3×10^6/s
Detector	SC toroidal spectrometer	E246-upgraded
Run time	$\sim 2.0 \times 10^7$s	1.0×10^7s
$\sigma(P_T)_{stat}$	2.3×10^{-3}	$\sim 1.0 \times 10^{-4}$
$\sigma(P_T)_{syst}$	1.1×10^{-3}	$< 1.0 \times 10^{-4}$

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