Measurement of T-violating transverse muon polarization in $K^+ \to \pi^0\mu^+\nu$ decay at J-PARC

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We have proposed a new experiment to search for time reversal invariance violation by measuring the transverse muon polarization (P_T) in $K^+ \to \pi^0\mu^+\nu$ decay at J-PARC. The physics potential in terms of the discovery of new physics along with the power to constrain exotic models is shown to be competitive with other experiments being planned or prepared. The detector system will be an upgraded version of the previous KEK-PS E246 experiment. Major changes are 1) a more highly segmented K^+ target, 2) improved charged particle tracking by incorporating state-of-the-art GEM detectors, 3) a new readout system for the CsI(Tl) calorimeter with APD, 4) introducing active polarimeters for the muons and decay positrons inside a new muon field magnet. Also, a new analysis procedure using arbitary initial muon spin phases at the polarimeter will be applied. These arrangements will improve both the statistical and the systematic errors and should produce $\Delta P_T \sim 10^{-4}$.

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1. Introduction

Time reversal symmetry (T) has long been a subject of interest, since it implies microscopic reversibility of motion. In modern quantum field theories, it has received renewed attention as a discrete symmetry of space/time along with charge conjugation and parity reflection [1].

The transverse muon polarization (P_T) in $K^+ \to \pi^0\mu^+\nu$ ($K_{\mu 3}$) with T-odd correlation was first suggested by Sakurai to be a clear signature of T-violation [1]. P_T in $K_{\mu 3}$ has the advantage that the final state interactions (FSI) are very small. This effect is only from higher order loop levels and can be accurately calculated to be $P_T \sim 10^{-5}$. Also, an important feature of a P_T study is the fact that the contribution to P_T from the Standard Model (SM) is nearly zero ($P_T \sim 10^{-7}$). Therefore, in a P_T search we investigate new physics beyond the SM. As candidate theories to give rise to sizable P_T ($\sim 10^{-3}$ or even $\sim 10^{-2}$), multi-Higgs doublet model, leptoquark model, and SUSY with R-parity violation and s-quark mixing have been studied. The physics potential in terms of the discovery of new physics along with the power to constrain exotic models is shown to be competitive with other experiments being planned or prepared.

The $K_{\mu 3}$ matrix element based on the V−A theory can be written as,

$$M \propto [f_+(q^2)(P_K^\lambda + P_{\pi^0}^\lambda) + f_-(q^2)(P_K^\lambda - P_{\pi^0}^\lambda)][\bar{u}_\mu \gamma_\lambda (1-\gamma_5) u_\nu], \tag{1.1}$$

where $f_+(q^2)$ and $f_-(q^2)$ are the dimensionless form factors of the hadron current as a function of momentum transfer squared $q^2 = (P_K - P_{\pi^0})^2$. P_K and P_π are the four momenta of the K^+ and π^0, respectively. Eq.(1.1) can be rewritten as,

$$M \propto f_+(q^2)[(P_K^\lambda + P_{\pi^0}^\lambda)\bar{u}_\mu \gamma_\lambda (1-\gamma_5) u_\nu + \xi(q^2) m_l \bar{u}_\mu (1-\gamma_5) u_\nu], \tag{1.2}$$

where $\xi(q^2)$ is the ratio of $f_-(q^2)$ to $f_+(q^2)$, which is often introduced for the analysis of K_{l3} data. P_T can be written in terms of $\mathrm{Im}\xi$ and a kinematical factor as,

$$P_T = \mathrm{Im}\xi \cdot \frac{m_\mu}{m_K} \cdot \frac{|\vec{p}_\mu|}{[E_\nu + |\vec{p}_\mu|\vec{n}_\nu \cdot \vec{n}_\nu - m_\mu^2/m_K]} \tag{1.3}$$

The quantity $\mathrm{Im}\xi$, sensitive to the T-violation, can be determined from a P_T measurement.

2. KEK-PS E246 experiment

The most recent and so far highest precision experiment was performed at the KEK proton synchrotron, the KEK-PS E246 experiment. A schematic view of the experimental setup is shown in Fig. 1. The experiment used stopped K^+ in conjunction with superconducting Toroidal spectrometer. An elaborate detector system consisting of a large-acceptance CsI(Tl) barrel, tracking chambers, an active K^+ target and passive muon polarimeters was constructed. The features of the $K_{\mu 3}$ detection are (1) μ^+ momentum determination by means of a tracking system and a fiber bundle target inside the spectrometer, (2) μ^+ identification by time-of-flight measurement, and (3) π^0 detection as two photons or one photon with relatively large energy by the calorimeter. The muon polarization measurement relied on the sensitivity of the decay positron emission asymmetries in a longitudinal magnetic field with $\langle B \rangle || P_T$ using a passive polarimeter. The stopped beam method

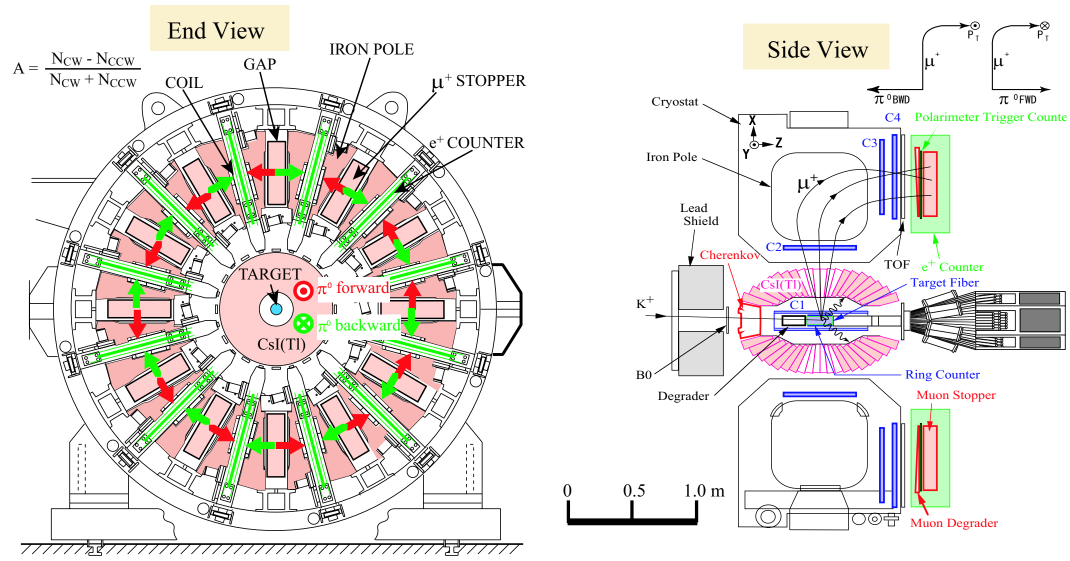

Figure 1: Experimental setup of the KEK-PS E246 experiment: (a) cross section side view and (b) end view. The E246 experiment employed the stopped K^+ beam in conjunction with a superconducting Toroidal spectrometer. The detector system consisted of a large-acceptance CsI(Tl) barrel, tracking chambers, an active K^+ target, and passive muon polarimeters. See [2] for details.

enabled a so-called forward (fwd) and backward (bwd) symmetric measurement with regard to the π^0 emission direction, and the highly rotational symmetric structure of the toroidal magnet, helped to substantially suppress the systematic errors.

The T-violating asymmetry was deduced as $A_T = (A_{fwd} - A_{bwd})/2$, where the π^0- fwd and bwd asymmetries were calculated using the “clockwise” and “counter-clockwise” positron emission rate N_{cw} and N_{ccw} as,

$$A_{fwd(bwd)} = \frac{N^{cw}_{fwd(bwd)} - N^{ccw}_{fwd(bwd)}}{N^{cw}_{fwd(bwd)} + N^{ccw}_{fwd(bwd)}} \tag{2.1}$$

Then, P_T was deduced using the analyzing power α and the kinematical attenuation factor $\langle\cos\theta_T\rangle$ to be $P_T = A_T/\alpha\langle\cos\theta_T\rangle$. The final result was deduced to be $P_T = -0.0017 \pm 0.0023(stat) \pm 0.0011(syst)$ and $\mathrm{Im}\xi = -0.0053 \pm 0.0071(stat) \pm 0.0036(syst)$, corresponding to the upper limits of $|P_T| < 0.0050$ (90% $C.L.$) and $|\mathrm{Im}\xi| < 0.016$ (90% $C.L.$), respectively. Details of the detector system and the analysis are well described in [2].

3. New T-violation experiment at J-PARC

3.1 Overview

We have proposed a new T-violation experiment at J-PARC using the E246 detector system with reasonable upgrading [3]. Our aim is to perform an experiment which, in comparison to E246, will have about ten times more acceptance and twenty times more integrated beam flux, to achieve a factor of 20 improvement in sensitivity ($\Delta P_T \sim 10^{-4}$). This sensitivity puts the experiment well into the region where new physics effects might appear.

In order to optimize the performance of the experimental system, several improvements in the detector system must be undertaken. We will keep the principal concept of the experiment, namely the application of the muon field in the azimuthal direction parallel to the P_T component, and the object of measurement in this experiment is primarily cw/ccw position asymmetry in the azimuthal direction, i.e., we keep the fwd/bwd scheme by employing a stopped K^+ beam.

3.2 Detector upgrade

In addition to the previous E246 experimental apparatus, we can accomplish the new T-violation experiment with the following modifications. A one year run at J-PARC should provide a statistical accuracy of 10^{-4} with the new system.

1. K^+ **target**: The 6cm diameter scintillating fiber target will consist of 432 square fibers(2.5mm). Each fiber will be read out using the new MPPCs currently being developed by Hamamatsu Photonics in Japan. Such small solid state PMTs offer the advantages of compactness and lower cost.

2. **Tracking**: One of serious systematic errors is given by the background contamination from π^+ decay-in-flight from $K^+ \to \pi^+\pi^0$ ($K_{\pi2}$) events. For sufficient identification and suppression, we will place a cylindrical chamber and a planer chamber with a spatial resolution better than 0.1 mm around the target system and at the outer surface of the CsI calorimeter, respectively. Both new trackers will be based on recently developed GEM technology. The $K_{\pi2}$ fraction in the $K_{\mu3}$ sample is estimated to be 0.2% which is small enough to reduce the resulting systematic error below $\Delta P_T = 10^{-4}$

3. **CsI(Tl) readout**: Given the high rate environment at J-PARC, we will employ avalanche photo-diodes (APD) of the reverse type for the CsI(Tl) readout . APDs with a multiplication factor of about 100 with reasonably large sensitive areas are now commercially available. Instead of a charge preamplifier, a current preamplifier will be used. The output from the amplifier system will be read by FADCs. The time resolution of about 3 ns was obtained for $15-20$ MeV energy deposition in the crystal using cosmic muons.

4. **Active polarimeter**: The most important feature of this new J-PARC experiment is the adoption of an active polarimeter. The active polarimeter can determine the muon stopping position for each event. Moreover, detection of the decay positrons in all directions provides a large acceptance polarimeter. In order to ensure the preservation of the muon spin polarization, a magnetic field is applied at the stopper. The stopper plates will be made of a light metal (alloy of) such as Al or Mg arranged in a parallel orientation to the spectrometer gap.

3.3 Analysis method

In E246, the largest contributions to the systematic error were ambiguities in the muon stopping distribution (MuS), shift of the decay plane distribution (SDP), and the muon field misalignment, which introduced $\Delta P_T \sim 10^{-3}$. Mus effect is completely removed by measuring the muon stopping position by the active polarimetr. SDP effect is corrected and no longer the systematic error. However, the field rotation around z axis (K^+-beam axis in each gap) is troublesome (δ_z)

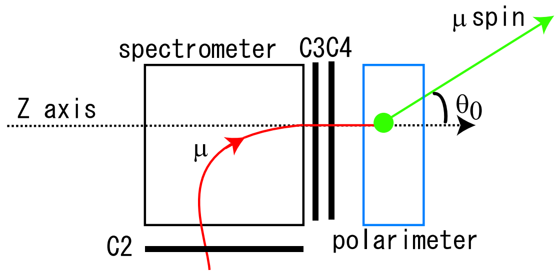

Figure 2: Definiion of θ_0 angle.

because its effect cannot be canceled in the normal $fwd - bwd$ subtraction scheme. The precision of the field measurement ($\sim$ 1mr) with a Hall element is not sufficient to give an error to the correction of similar size. In order to solve this problem, a new analysis method using arbitrary initial muon spin phases in the median plane of the polarimeter (θ_0) will be introduced. The time integrated asymmetry due to the misalignments can be written as a function of θ_0 as,

$$A(\theta_0) = \delta_r \cos\theta_0 - \delta_z \sin\theta_0 \tag{3.1}$$

where δ_r is the effect from a field rotation around the radial direction. It should be noted that the spurious asymmetry from the misalignments depend only on θ_0. We can now calculate two asymmetry A_{sum} and A_{sub} as the sum and difference of A_{fwd} and A_{bwd} with the asymmetries for forward and backward pions, respectively. This leads to

$$A_{sum}(\theta_0) = [A_{fwd}(\theta_0) + A_{bwd}(\theta_0)]/2 = \delta_r \cos\theta_0 - \delta_z \sin\theta_0 \tag{3.2}$$

$$A_{sub}(\theta_0) = [A_{fwd}(\theta_0) - A_{bwd}(\theta_0)]/2 = F(P_T, \theta_0) \tag{3.3}$$

where $F(P_T, \theta_0)$ is the A_T asymmetry from P_T origin. Thus, we have no effects of P_T in A_{sum} and no effects of misalignments in A_{sub}, enabling a very clean the extraction of a P_T signal even with finite misalignments. The total systematic error is estimated to be better than 10^{-4} from the simulation.

4. Summary

We have proposed a new experiment to search for time reversal invariance violation at J-PARC by measuring the transverse muon polarization in the $K^+ \rightarrow \pi^0\mu^+\nu$ decays with a stopped K^+ beam. The detector system is an upgraded version of the previous KEK-PS E246 experiment. The upgraded system will reduce both statistical and systematic errors and improve the E246 result by a factor of 20, bringing the discovery potential to $\Delta P_T \sim 10^{-4}$ in our quest for new physics.

References

[1] I. I. Bigi and A. I. Sanda, “CP Violation”, Cambridge University Press (2000); J. J. Sakurai, Phys. Rev. **109**, 980 (1957).

[2] M. Abe *et al.*, Phys. Rev. Lett. **93** 131601 (2004); M. Abe *et al.*, Phys. Rev. **D73** 072005 (2006) J. A. Macdonald *et al.*, Nucl. Instrum. Methods A **506** 60 (2003).

[3] http://j-parc.jp/; http://www-ps.kek.jp/e06/E06_proposal.pdf