A Search for T-violating Transverse Muon Polarization using Stopped $K^+ \to \pi^0 \mu^+ \nu$ Decay at J-PARC

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Abstract

We are preparing a new experiment to search for time-reversal 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 is competitive with other experiments currently being prepared. The detector system will be an upgraded version of our previous KEK-PS E246 experiment which should produce $\delta P_T \sim 10^{-4}$.

Key words: Kaon decay, Time-Reversal Violation, CP-Violation, Beyond the Standard Model
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1. Introduction

The Standard Model (SM) of subatomic physics provides an incredibly successful description of all existing experimental data. Nevertheless it is not thought to be the complete theory; it contains 26 free parameters including the non-zero neutrino masses and the CP-violating phase in the Cabbibo-Kobayashi-Maskawa (CKM) matrix. Numerous extensions to the SM have been proposed; most contain additional imaginary phases since it is well known that the CKM CP-violation is not large enough to explain the Baryonic Asymmetry of the Universe. Since any Lorentz invariant field theory conserves CPT, a non-zero measurement of Time-Reversal Violation (TRV) implies a corresponding CP-violation; therfore TRV searches can also reveal new sources of CPV[1].

The transverse muon polarization $P_T = \hat{s}_\mu \cdot (\hat{p}_{\mu^+} \times \hat{p}_{\pi^o})$ in $K^+ \to \pi^0 \mu^+ \nu$ ($K_{\mu 3}$) decay is a T-odd triple product correlation. This was first suggested by Sakurai[2] as a clear signature of TRV since the final state interactions (FSI), which arise from higher order

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loops in the electromagnetic interaction, are small ($\sim 10^{-5}$). Even more important is the fact that the SM contribution to P_T is considerably smaller ($\sim 10^{-7}$). Therefore, a P_T search is a search for physics beyond the SM. Various extensions to the SM such as multi-Higgs doublets, leptoquarks, R-parity violating or squark-family mixing SUSY allow P_T values as large as $\sim 10^{-3}$, just below the current experimental limit from our previous E246 experiment[3] at KEK. In the SM (V-A) theory the $K^+_{\mu 3}$ hadronic decay matrix element can be written in terms of two form factors, $f_\pm(q^2)$. Since the strong interaction conserves CP both these form factors must be real. Hence, if the ratio $\xi(q^2) = f_-(q^2)/f_+(q^2)$ has a non-zero imaginary component this TRV effect will imply the presence of a new scalar(S) or tensor(T) interaction. P_T is related to Im(ξ) by a kinematic factor which has been carefully optimized for our experiment.

2. Time-Reversal violation Experiment with Kaons (TREK) at J-PARC

We are currently preparing a new T-violation experiment at J-PARC[4] using an upgrade of our previous E246 detector[5]. TREK will have about ten times more acceptance, twenty times more integrated beam flux and substantially improved analyzing power compared to E246. This will produce a factor of 20 improvement in sensitivity ($\delta P_T \sim 10^{-4}$), which will put the experiment well into the region where new physics effects might appear.

In order to optimize the performance of the experimental system, several improvements to the detector system are now underway. The principal concept of the experiment, namely the use of a stopped K^+ beam with the application of the muon field in the azimuthal direction parallel to the P_T component is being retained. The following modifications (in relative order of importance) are being implemented: 1) an active muon polarimeter with a more uniform magnetic field for muon spin preservation, 2) new central region GEM chambers for improved charged particle tracking, 3) a new K^+ scintillating fibre target, 4) faster CsI(Tl) readout. Simulations indicate that a one year run (1.4×10^7s) at J-PARC with the new detector should provide a statistical and systematic accuracy of $\sim 10^{-4}$.

The most important upgrade item is the adoption of an active polarimeter and a new muon holding field magnet. This will allow a reduction in the background and also a determination of the muon stopping position for each event. This large acceptance ($\sim 3\pi$) polarimeter will measure both the positron energy and emission angle and it will greatly increase the analyzing power. In order to ensure the preservation of the muon spin polarization, a uniform 0.03 T magnetic field will be applied at the stopper. The 2.5 mm thick Al alloy stopper plates will be aligned parallel to the spectrometer gap, ie parallel to the incident muon momentum. A prototype drift chamber has been tested and a sector prototype magnet/polarimeter is now under construction.

At J-PARC, one of the serious systematic errors is the background contamination from kaon decay-in-flight ($K_{\pi 2}$-*dif*) events. In order to improve the tracking resolution we will add a new high-rate cylindrical GEM tracking chamber with a spatial resolution better than 0.1 mm around the target system plus 12 new GEM planar tracking chambers with < 0.1 mm resolution at the outer surface of the CsI calorimeter. Detailed simulations indicate that the $K_{\pi 2}$-*dif* fraction in the $K_{\mu 3}$ data should be $\sim$0.2%, which is small enough to reduce the resulting systematic error below $\delta P_T = 10^{-4}$.

The new scintillating fiber target (ϕ=7.5 cm) will consist of 492 square fibers (3.0mm). Each fiber will be read out using the new MPPCs currently being developed by Hamamatsu. Such small solid state PMTs offer the advantages of compactness and low cost compared to either conventional single or multi-anode PMTs.

Given the high rate environment at J-PARC, we will employ avalanche photo-diodes (APD) for the CsI(Tl) readout and a current preamplifier. The output from the amplifier system will be read by FADCs, which will provide a powerful method to resolve pulse pileup.

With these detector upgrades the total systematic error will be suppressed to below 10^{-4}. In E246, one of the largest contributions to the systematic error was the muon field alignment. The rotation (δ_z) around the z (K^+-beam) axis is the most troublesome introducing $\delta P_T \sim 5 \times 10^{-4}$ because its effect cannot be cancelled using the normal $fwd - bwd$ subtraction scheme. The precision of the field measurement ($\sim$ 1mr) with a Hall element is not sufficient to reduce the systematic uncertainty to the desired value, and therefore we plan to determine the δ_z misalignment using experimental data.

In order to solve this problem, we plan to implement a new analysis method using the arbitrary initial muon spin phases at the polarimeter (θ_0). The time integrated asymmetry due to any possible detector misalignments is a simple function of θ_0 namely, $\mathrm{A}(\theta_0) = \delta_r \cos\theta_0 - \delta_z \sin\theta_0$ where δ_r is the effect from a field rotation around the radial direction. We can then calculate two asymmetries A_{sum} and A_{diff} as the sum and difference of A_{fwd} and A_{bwd} using the measured asymmetries for forward and backward pions, respectively. This leads to

$$A_{sum}(\theta_0) = [A_{fwd}(\theta_0) + A_{bwd}(\theta_0)]/2 = \delta_r \cos\theta_0 - \delta_z \sin\theta_0 \tag{1}$$

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

where $F(P_T, \theta_0)$ is the A_T asymmetry arising from a non-zero P_T. Thus, we find no effects of P_T in A_{sum} and no effects of misalignments in A_{diff}, thereby enabling a very clean extraction of a small P_T signal even with finite magnetic field misalignments.

3. Summary

We are currently preparing a new experiment to search for TRV at J-PARC by measuring the transverse muon polarization in $K^+ \to \pi^0 \mu^+ \nu$ decays with a stopped K^+ beam. The detector system is an upgraded version of our previous KEK-PS E246 experiment. The improved detector will reduce both the statistical and the systematic errors by a factor of 20, bringing the discovery potential to $\delta P_T \sim 10^{-4}$. This will either reveal new physics or, at the very least, provide more stringent constraints on the existing extended SM theories.

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