

# Searches for New Physics with the TREK Detector

C Djalali (for the TREK Collaboration)

Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA

E-mail: [chaden-djalali@uiowa.edu](mailto:chaden-djalali@uiowa.edu)

**Abstract.** The KEK Experiment E246 has provided the best upper limit of the transverse muon polarization in  $K_{\mu 3}$  decays to date. The E246 detector is now being upgraded by the TREK collaboration and upcoming experiments with this detector at the J-PARC facility will allow new high-precision measurements in search for physics beyond the Standard Model. The first round of planned experiments include the search for lepton universality violation in a measurement of the ratio of the  $K_{e2}$  and  $K_{\mu 2}$  decay widths, as well as the search for heavy sterile neutrinos and possible massive gauge boson  $A'$  in the 10 to 100 MeV mass range. The search for  $T$  violation in kaon decays requires a higher intensity hadron beam and will be carried out later.

## 1. Introduction

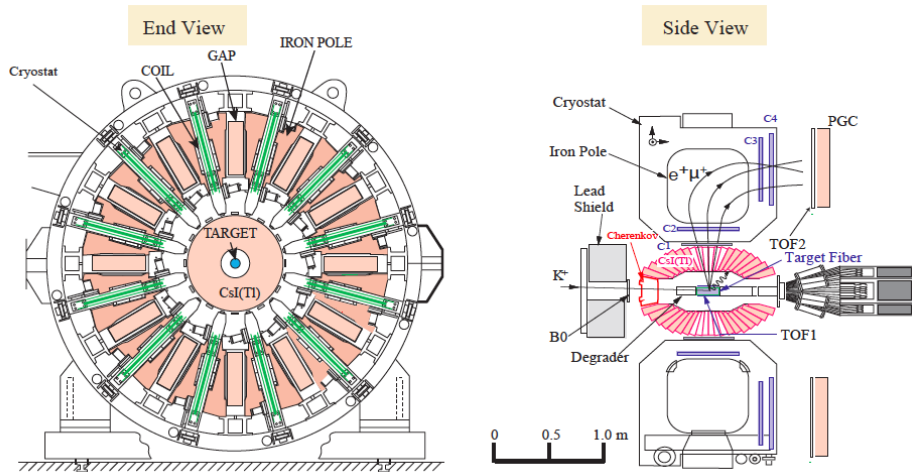
The discovery of the Higgs boson, which until recently was the only missing predicted particle in the Standard Model (SM), has further established the overwhelming success of the SM in explaining the majority of phenomena observed in particle physics. At the same time, it has become clear that the SM cannot be the ultimate theory. Issues such as the neutrino mass problem, the hierarchy problem, the baryogenesis problem and the dark matter and dark energy problem clearly show that the SM is an effective theory for the low energy scale ( $\sim$ TeV). New physics beyond the SM should lie in the energy region of a few TeV or higher. Among many theories beyond the SM, supersymmetry theory (SUSY), which predicts the existence of supersymmetric partners for all of the SM particles can elegantly explain many of the issues mentioned above. Among the experiments looking for physics beyond the SM, there are several precision measurements of various kaon decay channels. The TREK collaboration is preparing for two of these experiments with high-intensity kaon beams at the Japan Proton Accelerator Research Complex (J-PARC). Using the current J-PARC luminosity, experiment E36 [1] will measure the ratio  $R_K$  of the  $K_{e2}$  and  $K_{\mu 2}$  decay widths of stopped kaons and provide complementary data to previous in-flight-decay experiments. The data from E36 will also allow searching for a heavy sterile neutrino and a massive gauge boson  $A'$ , “dark photon”. Experiment E06 [2] will improve the limit on the magnitude of the  $T$ -odd transverse muon polarization,  $P_T$ , in  $K^+ \rightarrow \pi^0 \mu^+ \nu$  decays set by KEK experiment E246 [3] by a factor of 20.

## 2. The TREK detector

The detector system (Figure 1) will be an upgraded version of the previous KEK-PS E246 experiment [4]. A collimated mixed  $K^+/\pi^+$  beam of 800 MeV/ $c$  will pass through a beam Cherenkov counter — for kaon identification — and a degrader system before being stopped in a segmented, active fiber target. Final-state particles will be either detected in the CsI(Tl)



electromagnetic calorimeter or tracked (C1, C2, C3, and C4) and momentum analyzed in the toroidal spectrometer system. Time-of-flight counters (TOF1 and TOF2), an aerogel Cherenkov detector close to the target, and lead glass Cherenkov detectors (PGC) at the exit of the spectrometer will provide for excellent  $e/\mu$  separation. Additional improvements consist of a new readout system for the CsI(Tl) calorimeter, which allows for a high counting rate, and, new active polarimeters for the muons and decay positrons inside a new muon field magnet.



**Figure 1.** E246 detector upgraded for E06 and E36 J-PARC Experiments.

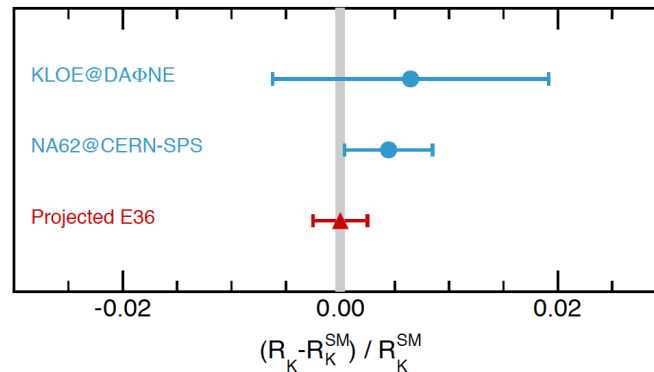
### 3. The E36 Experiment

Lepton universality, which requires the identical coupling constant of the three-lepton generations - the electron, muon, and tau - is a basic assumption in the SM. Violation of lepton universality will clearly indicate the existence of physics beyond the SM. Under the assumption of  $\mu$ -e universality, the ratio of the electric ( $K_{e2}$ ) and muonic ( $K_{\mu2}$ ) decay modes ( $R_K$ ) in the SM is known with excellent accuracy [5]:

$$R_K^{SM} = \frac{\Gamma(K^+ \rightarrow e^+ \nu_e [\gamma])}{\Gamma(K^+ \rightarrow \mu^+ \nu_\mu [\gamma])} = \frac{m_e^2}{m_\mu^2} \left( \frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 (1 + \delta_{QED}) = 2.477 \pm 0.001 \times 10^{-5} \quad (1)$$

Looking for deviations of  $R_K$  from  $R_K^{SM}$  provides a clean tool to detect or constrain physics beyond the SM such as lepton violating effects. The E36 experiment seeks to measure  $R_K$  with an accuracy of  $\Delta R_K/R_K$  of 0.2%. The  $K_{e2}$  and  $K_{\mu2}$  events will be identified by the charged lepton momenta,  $p_e = 247 \text{ MeV}/c$  and  $p_\mu = 236 \text{ MeV}/c$ , as determined in the spectrometer. Excellent particle identification is key to the measurement. Particle momenta as well as time-of-flight and Cherenkov detectors will be used to decrease the probability of misidentifying a  $\mu^+$  as  $e^+$  to less than  $10^{-8}$ . The CsI(Tl) calorimeter will serve as photon detector for the radiative processes. The  $R_K$  value is then derived from the detector-acceptance-corrected number of the identified  $K_{e2(\gamma)}$  and  $K_{\mu2(\gamma)}$  events, including those with the production of internal bremsstrahlung but excluding structure-dependent contributions. Figure 2 shows the KLOE [6] and NA62 [7] results as well as the projected uncertainties for E36.

The Neutrino Minimal Standard Model ( $\nu$ MSM) is an example of a renormalizable extension of the SM that contains three right-handed (sterile) neutrinos with masses below the electroweak



**Figure 2.** Expected TREK  $R_K$  value compared to current measurements. The projected uncertainty of E36 [1] (triangle) is shown at the Standard Model value.

scale [8]. The lightest of the three sterile neutrinos is a dark-matter candidate, the masses of the heavier two sterile neutrinos are degenerate in the  $\nu$ MSM,  $M_1 < M_2 \approx M_3$ . If the sterile neutrino is lighter than the kaon, it can give rise to leptonic and semi-leptonic decays with relatively large branching ratios. This gives a possibility to confirm or rule out the  $\nu$ MSM by looking for massive sterile neutrinos in kaon decay experiments. The E36 experiment will be looking for heavy sterile neutrinos (N) in the  $K^+ \rightarrow \mu^+ N$  decay using the  $\mu^+$  polarimeter. The  $\nu$ MSM predicts the branching ratio to be up to  $10^{-6}$ , which is accessible by the TREK experimental apparatus. This decay has some important features such as (1) a narrow peak structure in the momentum spectrum; (2) a 100%  $\mu^+$  polarization in the direction opposite of the muons from the  $K^+ \rightarrow \mu^+ \nu$  decay. Measuring both the  $\mu^+$  momentum and polarization will improve the sensitivity of the branching ratio to better than  $10^{-8}$ .

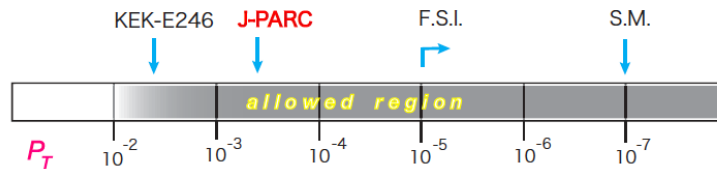
Furthermore, studying the  $K^+ \rightarrow \mu^+ \nu_\mu A'$  channel can provide constraints on the massive gauge boson  $A'$  (“dark photon”) in the 100 MeV mass range. The  $A'$  particle could be identified in the  $e^+e^-$  invariant-mass distribution through its decay,  $A' \rightarrow e^+e^-$ . In the E36 experiment the  $e^+e^-$  pair will be detected in the CsI(Tl) calorimeter. Preliminary, simulated invariant-mass distributions for various assumed masses ( $M_{A'} = 10 \text{ MeV}/c^2$  to  $100 \text{ MeV}/c^2$ ) show that  $A'$  with mixing parameters as low as  $\epsilon^2 \approx 10^{-6}$  can be detected. The observation of the  $K^+ \rightarrow \pi^+ A'$  could be an alternative signal process in this search. The  $A'$  would be identified in the  $\pi^+$  momentum distribution as measured in the TREK spectrometer.

#### 4. The E06 experiment

The transverse muon polarization ( $P_T$ ) in  $K \rightarrow \pi \mu \nu$  ( $K_{\mu 3}$ ) decays with T-odd correlation was suggested by Sakurai [9] about 50 years ago to be a clear signature of T violation. Unlike other T-odd channels such as in 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 ( $< 10^{-5}$ ) [10]. This argument applies most particularly to  $K_{\mu 3}^+$  decay where the FSI contribution is only from higher order loop levels and is calculable. Another important feature of a  $P_T$  study is the fact that the contribution to  $P_T$  from the SM is nearly zero ( $\sim 10^{-7}$ ). Therefore, any non zero  $P_T$  will be indicative of new physics beyond the SM (Figure 3).

The KEK experiment E246 studied the  $K_{\mu 3}$  decay of stopped kaons and put the most stringent limit to date on this observable,  $|P_T| < 5 \times 10^{-3}$  (90% C.L.) [3]. The new experiment E06 is aiming to improve that limit by a factor of, at least, 20 and to reach a sensitivity of  $\approx 2 \times 10^{-4}$  (90% C.L.) [2]. A factor of 20 improvement of the statistical uncertainty requires the high-

intensity  $K^+$  beam at J-PARC and a new active muon polarimeter with increased acceptance and sensitivity. The new polarimeter will also help reduce systematic uncertainties compared to what was achievable in E246.



**Figure 3.** Experimental status of  $K_{\mu 3}$   $P_T$  physics relative to the SM prediction. The Allowed region represents the range of possible non zero  $P_T$  from non-SM CP violation models.

## 5. Summary

In summary, the TREK collaboration has a rich experimental program looking for new physics beyond the SM by studying the decay of stopped kaons with two experiments, E36 and E06, at J-PARC. The first experiment, which does not require the high luminosity beam at J-PARC, is scheduled to run in 2015 and will search for lepton universality violation in a measurement of the ratio of the  $K_{e2}$  and  $K_{\mu 2}$  decay widths, for a heavy sterile neutrino in the muon-momentum distribution from  $K^+ \rightarrow \mu^+ N$ , and for a possible massive "dark photon" in the  $K^+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ \nu e^+ e^-$  and  $K^+ \rightarrow \pi^+ A'$  reactions. The second experiment will search for  $T$  violation in kaon decays through the measurement of the transverse muon polarization in the  $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$  reaction. Experiment E06 requires the active muon polarimeter and maximum kaon-beam intensities and will run when higher intensity beams are achieved at J-PARC.

## Acknowledgments

This work was supported in the US in part part by the National Science Foundation under the award NSF-0856010 and the DOE, the NSERC and NRC in Canada, the KAKEN-HI Grants-in-Aid for Scientific Research in Japan, and in Russia by the Ministry of Science and Technology. The Japan Proton Accelerator Research Complex (J-PARC) is jointly and cooperatively run by the Japan Atomic Energy Agency (JAEA) and KEK.

## References

- [1] Kohl M and Shimizu S 2010 *J-PARC Experiment E36: Measurement of  $\Gamma(K^+ \rightarrow e^+ \nu)/\Gamma(K^+ \rightarrow \mu^+ \nu)$  and Search for heavy sterile neutrinos using the TREK detector system*, [http://j-parc.jp/researcher/Hadron/en/pac\\_1007/pdf/KEK\\_J-PARC-PAC2010-04.pdf](http://j-parc.jp/researcher/Hadron/en/pac_1007/pdf/KEK_J-PARC-PAC2010-04.pdf)
- [2] Imazato J and Kohl M 2006 *J-PARC Experiment E06: Measurement of T-violating Transverse Muon Polarization in  $K^+ \rightarrow \pi^0 \mu^+ \nu$  Decays*, [http://trek.kek.jp/proposal/E06\\_proposal.pdf](http://trek.kek.jp/proposal/E06_proposal.pdf)
- [3] Abe M, Aliev M, Anisimovsky V, Aoki M et al. 2006 *Phys. Rev. D* **73** 072005
- [4] Abe M et al. 2003 *Nucl. Instrum. Meth. A* **506** 60, hep-ex/0302001.
- [5] Cirigliano V and Rosell I 2007 *Phys. Rev. Lett.* **99** 231801, 0707.3439
- [6] Ambrosino F et al. 2009 *Eur. Phys. J. C* **64** 627, 0907.3594
- [7] Lazzeroni C et al. 2013 *Phys. Lett. B* **719** 326, 1212.4012
- [8] Canetti L, Drewes M, and Shaposhnikov M 2013 *Phys. Rev. Lett.* **110** 061801, 1204.3902.
- [9] Sakurai J J 1957, *Phys.Rev.* **109** 980
- [10] Efrosinin V, Khriplovich I, Kirilin G and Kudenko Y 2000 *Phys. Lett. B* **493** 293, hep-ph/0008199.