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# Searches for New Physics with the TREK Detector

**Steffen Strauch**[*†] **for the TREK Collaboration**
*University of South Carolina*
*E-mail:* strauch@sc.edu

The KEK Experiment E246 has provided the best upper limit of the transverse muon polarization in $K_{\mu 3}$ decays to date. The TREK collaboration is now upgrading the E246 detector 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. These measurements include the search for $T$ violation in kaon decays, the search for lepton universality violation in the ratio of the $K_{e2}$ and $K_{\mu 2}$ decay widths, as well as the search for a heavy sterile neutrino and a massive gauge boson $A'$.

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## 1. Introduction

Despite its overwhelming success, the Standard Model (SM) of particle physics is incomplete. It does not account for neutrino oscillations and cold dark matter nor does it explain the matter-antimatter asymmetry in the universe. Among many experiments looking for physics beyond the Standard Model, precision measurements of various kaon decay channels allow searching for physics beyond the Standard Model. The TREK collaboration is preparing for two stage-1 approved experiments with high-intensity kaon beams at the Japan Proton Accelerator Research Complex (J-PARC): Experiment E06 [1] will improve the limit on the magnitude of the $T$-odd transverse muon polarization, $P_T$, in $K^+ \to \pi^0 \mu^+ \nu$ decays set by KEK experiment E246 [2, 3, 4] by a factor of 20. Experiment E36 [5] 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 light". Experimental results from this program will have the potential for discovery of physics beyond the Standard Model or will constrain the parameter space of new physics.

The experiments will utilize the superconducting toroidal spectrometer of E246 [6] with upgraded instrumentation. A schematic view of the TREK detector for experiment E36 after upgrade from the KEK E246 apparatus is shown in Fig. 1. 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.

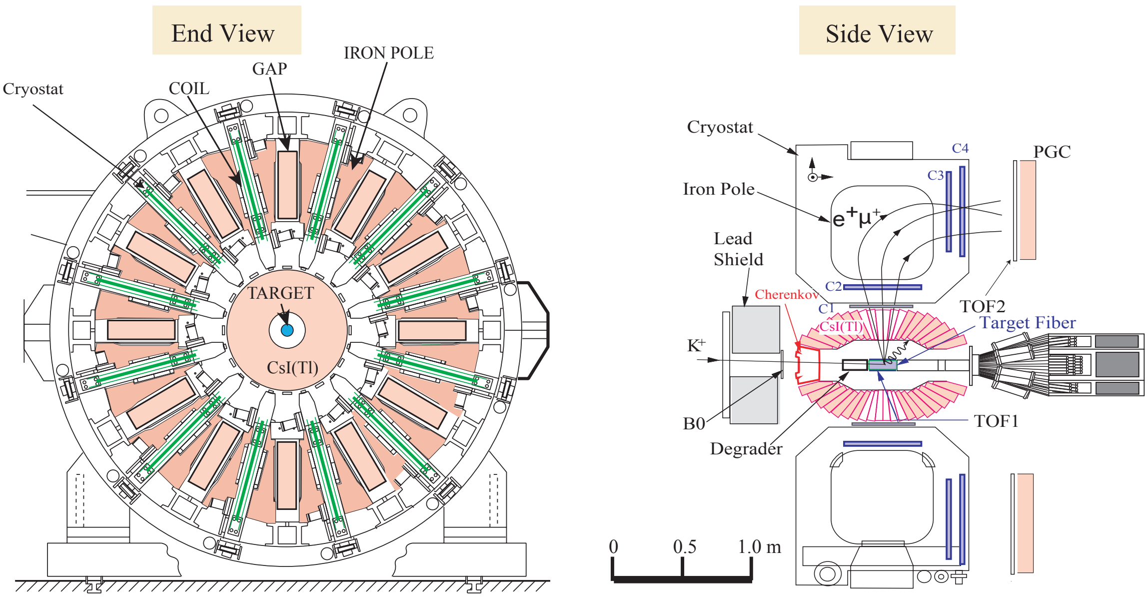


**Figure 1:** Schematic view of the TREK detector for experiment E36 [5] after upgrade from the KEK E246 apparatus.

## 2. Search for $T$ violation in $K^+ \to \pi^0 \mu^+ \nu$ decays

The transverse muon polarization in the $K^+ \to \pi^0 \mu^+ \nu$ decay is a $T$-odd observable and an excellent tool for the search of signatures of $T$ (or $CP$) violation. It is given by

$$P_T = \frac{\vec{\sigma}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)}{|\vec{p}_\pi \times \vec{p}_\mu|}, \tag{2.1}$$

where $\vec{p}$ are particle momenta and $\vec{\sigma}_\mu$ is the muon polarization vector. It is particularly useful for searches of $T$-violation effects from non-SM physics as it vanishes in the Standard Model at the tree level and $T$-odd contributions from final-state interactions (FSI) are very small, $< 10^{-5}$ [7]. Thus, any measurement of $|P_T|$ in the experimentally reachable region of $10^{-3}$ to $10^{-4}$ would unambiguously imply physics beyond the Standard Model. The interference of $W^+$ and $H^+$ boson-mediated amplitudes could be an origin of possible $CP$ and $T$ violations in this channel [8]. If fact, non-SM mechanisms are predicted to be as large as $10^{-3}$ [9].

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, 4]. The new experiment E06 (TREK) at J-PARC 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.) [1]. 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.

## 3. Search for lepton-universality violation in a measurement of $R_K$

Lepton universality is a central assumption of the SM. The ratio of the $K_{e2[\gamma]}$ and $K_{\mu 2[\gamma]}$ decay widths, $R_K$, is given under this assumption as

$$R_K^{SM} = \frac{\Gamma(K^+ \to e^+ \nu_e[\gamma])}{\Gamma(K^+ \to \mu^+ \nu_\mu[\gamma])} = \frac{m_e^2}{m_\mu^2} \left( \frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 (1 + \delta_{QED}), \tag{3.1}$$

with the masses of the involved particles, $m_K, m_\mu, m_e$ and $m_\nu \approx 0$, and radiative corrections, $\delta_{QED}$. The ratio is free of hadronic uncertainties as the hadronic form factor, $f_K$, cancels in the ratio of the decay widths. The ratio $R_K$ has been calculated in Chiral Perturbation Theory to order $e^2 p^4$ with small uncertainty, $R_K^{SM} = 2.477(1) \times 10^{-5}$ [10]. This provides a clean reference to look for deviations of precise measurements of $R_K$ from $R_K^{SM}$ to detect or constrain physics beyond the Standard Model. $R_K$ is sensitive to lepton-flavor violating effects. In a model, where charged Higgs exchange is the dominant SUSY contribution, an increase of $R_K$ by $\mathcal{O}(1\%)$ could be possible [11]. $R_K$ is also sensitive to neutrino mixing parameters with SM extensions involving a fourth generation of quarks and leptons [12] or sterile neutrinos [13]. Indeed, new physics that differentiates between lepton species has been discussed, *e.g.* [14, 15], as possible explanation for the proton-radius puzzle [16]. The proton-radius puzzle is the disagreement between extractions of the proton radius from muonic hydrogen data [17, 18] on the one hand, and from electronic hydrogen or elastic electron-proton scattering on the other hand.

Recent high-precision measurements or $R_K$ come from the KLOE [19] and NA62 [20, 21, 22] collaborations, with relative uncertainties, $\delta R_K/R_K$, of 1.3% and 0.4% respectively. The uncertainties in the KLOE result are dominated by statistical uncertainties. While NA62 studied the in-flight decay of high-momentum kaons, KLOE has used low-momentum kaons resulting from $\phi$-meson decays. The proposed experiment E36 is a complementary measurement with a stopped $K^+$ beam and has systematic uncertainties very different from those of KLOE and NA62. The total relative uncertainty is expected to be 0.25% for this measurement. The $K_{e2}$ and $K_{\mu 2}$ events will be identified by the charged lepton momenta, $p_e = 247$ MeV/$c$ and $p_\mu = 236$ 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 $K_{\mu 2(\gamma)}$ events, including those with the production of internal bremsstrahlung but excluding structure-dependent contributions. Figure 2 shows the KLOE and NA62 results as well as projected uncertainties of E36. The width of the vertical bar at zero indicates the relative uncertainty of the SM value.

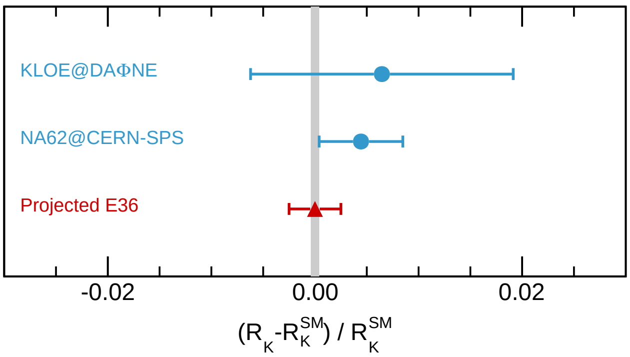


**Figure 2:** Relative deviations of recent high-precision measurements of $R_K$ from the standard-model value $R_K^{SM}$. Experimental results (full circle) are from the KLOE [19] and NA62 [20, 21, 22] collaborations. These experiments are ongoing. The projected uncertainty of E36 [5] (triangle) is shown at the standard-model value.

## 4. Search for a heavy sterile neutrino

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 scale. It can explain neutrino oscillations, dark matter as sterile neutrinos, and the baryon asymmetry induced from leptogenesis via sterile neutrino oscillation [23]. 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, $M_1 < M_2 \approx M_3$.

Searches for massive neutrinos in various decay channels have been performed at CERN PS191 [24]. No massive neutrino was found, but tight limits were put on the couplings of a hypothetical massive neutrino with ordinary $\nu_e$ and $\nu_\mu$. A neutral heavy neutrino could be produced in the reaction $K^+ \to \mu^+ N$ and identified as peak in the charged lepton momentum spectrum.

Figure 3 shows results of a Monte Carlo simulation of the $\mu^+$ momentum spectrum in the E36 experiment. Events from the $K_{\mu 3}$ decay constitute the main background in the search for heavy neutrinos. This decay channel will be suppressed in the experiment with an additional $\pi^0$ veto system. The black histogram shows the suppressed $K_{\mu 3}$ spectrum. The red histogram is the result of a simulated $K^+ \to \mu^+ N$ decay with an assumed branching ration of $2 \times 10^{-8}$ and $M_N = 220$ MeV/$c^2$. The TREK collaboration has also been exploring the possibility to increase the sensitivity of the heavy-neutrino search with the additional information of the $\mu^+$ polarization.

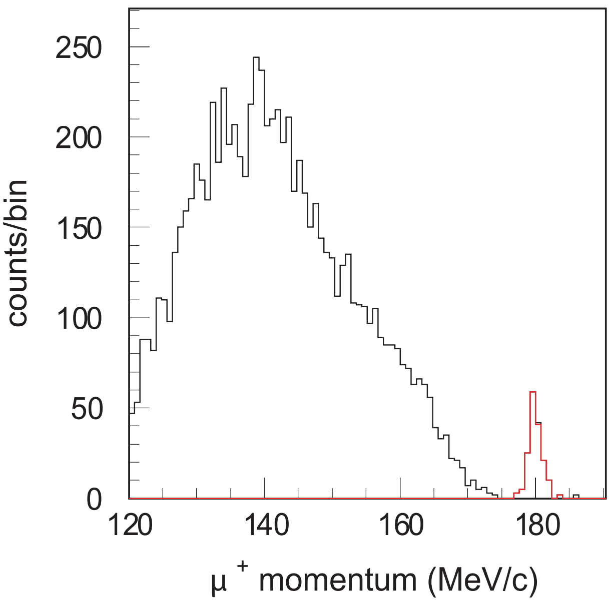


**Figure 3:** Monte Carlo simulation of the $\mu^+$ momentum distribution in E36 with $K_{\mu 3}$ spectrum (black) and $K^+ \to \mu^+ N$ spectrum (red) assuming $BR(K^+ \to \mu^+ N) = 2 \times 10^{-8}$ and $M_N = 220$ MeV/$c^2$.

## 5. Search for dark light

Another extension of the Standard Model includes an additional $U(1)_D$ gauge group manifesting itself in a massive gauge boson $A'$ ("dark photon") in the MeV to GeV mass range, *e.g.* [25] and references therein. Recent searches for dark photons have been performed by the KLOE-2 [26], APEX [27], Mainz A1 [28], and BABAR [29] collaborations and put upper limits on the coupling of the massive gauge boson to charged particles.

Rare kaon decay can provide constraints on the $A'$ parameters [25]. Specifically, the observation of the process $K^+ \to \mu^+ \nu_\mu A'$ is a possible signal from the dark sector. The $A'$ particle could be identified in the $e^+e^-$ invariant-mass distribution through its decay, $A' \to e^+e^-$. In the E36 experiment the $e^+e^-$ pair will be detected in the CsI(Tl) calorimeter. Preliminary, simulated invariant-mass distributions for various assumed $A'$ are shown in Fig. 4. The dominant background

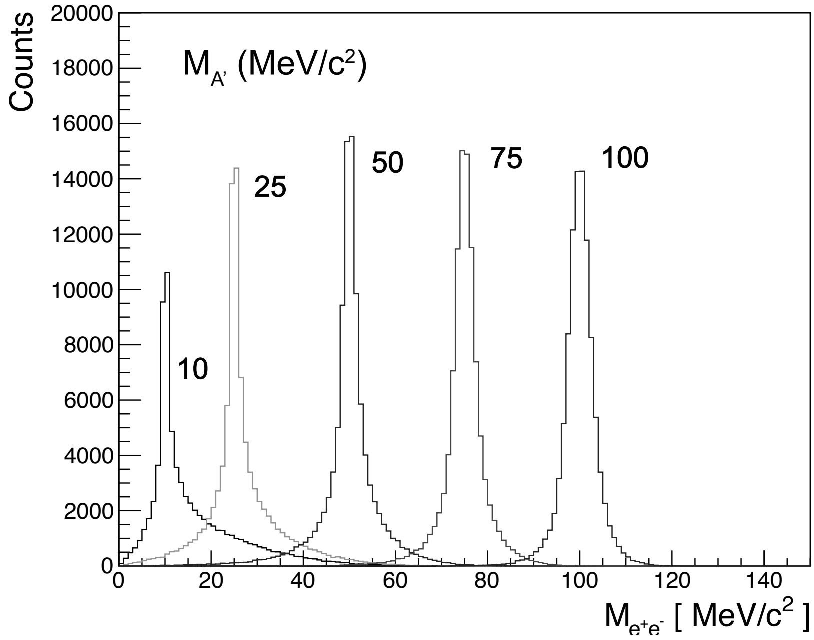


**Figure 4:** Various invariant mass distributions, $M_{e^+e^-}$, for $e^+e^-$ pairs from simulated decays of heavy photons, $A' \to e^+e^-$. The lepton pairs are detected in the TREK CsI(Tl) calorimeter with an assumed angular resolution of $\Delta\theta = 4^\circ$ and relative momentum resolution of $\Delta p/p = 5\%$. The assumed mass of the heavy photon ranges from $M_{A'} = 10$ MeV/$c^2$ to 100 MeV/$c^2$ as indicated.

in this search comes from the $K^+ \to \mu^+\nu_\mu e^+e^-$ reaction. The calculated full phase-space value for the branching ratio for that background channel is $\approx 2.49 \times 10^{-5}$ [30]. This background is not included in Fig. 4. However, initial studies of the E36 sensitivity for the dark-light search indicate that $A'$ with mixing parameters as low as $\varepsilon^2 \approx 10^{-6}$ are detectable. The observation of the $K^+ \to \pi^+A'$ 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.

## 6. Summary

The TREK collaboration is pursuing searches for new physics in the study of the decay of stopped kaons with two experiments, E06 and E36, at J-PARC. The program includes the search for $T$ violation in kaon decays through the measurement of the transverse muon polarization in the $K^+ \to \pi^0\mu^+\nu_\mu$ reaction, the search for lepton universality violation in a measurement of the ratio of the $K_{e2}$ and $K_{\mu 2}$ decay widths, the search for a heavy sterile neutrino in a peak in the muon-momentum distribution from $K^+ \to \mu^+N$, and the search for dark light in the $K^+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$ and $K^+ \to \pi^+A'$ reactions.

It is planned to install and run E36 in 2014/2015. Experiment E06 requires the active muon polarimeter and maximum kaon-beam intensities and will run later.

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