TREK @ J-PARC: Investigating lepton universality with stopped kaon decays

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Outline

- **TREK Program**
  - E06: Search for Time Reversal Symmetry Violation
  - E36: Test of Lepton Universality
  - Search for Heavy Neutrinos
  - Search for Light Bosons

- **TREK Apparatus**

- **Status**

E36 data taking completed in 2015!

http://trek.kek.jp
The TREK program

- **E06**
  (Time Reversal Experiment with Kaons, TREK)
  “Measurement of T-violating transverse muon polarization ($P_T$) in $K^+ \to \pi^0 \mu^+ \nu$ decays”
  Proposal to PAC 1
  100-270 kW
  Stage-1 approved since July 2006
  Spokespeople: Jun Imazato and M.K.

- **E36** (Test of Lepton Universality, Search for Heavy Neutrinos and Light Bosons)
  “Measurement of $\Gamma(K^+ \to e^+\nu) / \Gamma(K^+ \to \mu^+\nu)$ and search for heavy sterile neutrinos using the TREK detector system”
  Proposal to PACs 10-11,13-18
  30-50 kW
  Stage-1 approved since August 2012
  Stage-2 approved since September 2013
  Spokespeople: M.K. and Suguru Shimizu
Timeline of TREK

- **2006:** E06 (T-violation) Proposal (PAC1)
- **2009:** J-PARC PS and HF start operating
- **2010:** E36 (LFU/HNS) Proposal (PAC10)
- **2011:** E36 stage-1 recommended (PAC11)
- **2012:** E36 stage-1 approved (PAC15)
- **2013:** E36 stage-2 recommended (PAC17)
- **2014:** E36 stage-2 approved (PAC18)
- **Detector preparation November 2014 – April 2015**
- **First commissioning run April 8 (24) – May 7, 2015**
- **Second commissioning run June 3 – 26, 2015**
- **Implemented improvements in summer 2015**
- **Production run October 14 – November 24, 2015**
- **Run extended until December 18, 2015**
- **2016:** Analysis in progress
**Limits of lepton universality (LU)**

- **e, μ, and τ**: Different masses, same gauge couplings, valid experimentally
- **μ-e universality has been rather well established**

\[
\begin{array}{cccc}
\frac{\Gamma_{\tau \to \nu_{\tau} e \bar{\nu}_e}}{\Gamma_{\mu \to \nu_{\mu} e \bar{\nu}_e}} & \frac{\Gamma_{\tau \to \nu_{\tau} \pi}}{\Gamma_{\mu \to \nu_{\mu} \pi}} & \frac{\Gamma_{\tau \to \nu_{\tau} K}}{\Gamma_{K \to \mu \bar{\nu}_\mu}} & \frac{\Gamma_{W \to \tau \bar{\nu}_\tau}}{\Gamma_{W \to \mu \bar{\nu}_\mu}} \\
|g_{\tau}/g_{\mu}| & 1.0007 \pm 0.0022 & 0.992 \pm 0.004 & 0.982 \pm 0.008 & 1.032 \pm 0.012 \\

|g_{\mu}/g_{e}| & 1.0018 \pm 0.0014 & 1.0021 \pm 0.0016 & 0.998 \pm 0.002 & 1.001 \pm 0.002 \\

\end{array}
\]

**Recent development of τ spectroscopy**

\[\tau_\tau, \frac{m_\tau}{m_\mu}, \frac{\tau_\tau}{\tau_\mu} = (m_\tau/m_\mu)^5 (g_{\tau}/g_{\mu})^2, \text{couplings to } W \text{ and } Z^0\]

- **LEP-II [PDG 2010]**

\[
R_{\tau \ell}^W = \frac{2 \text{BR}(W \to \tau \bar{\nu}_\tau)}{\text{BR}(W \to e \bar{\nu}_e) + \text{BR}(W \to \mu \bar{\nu}_\mu)} = 1.055(23) \quad 2.4 \sigma \text{ dev.}
\]

- **BABAR [Phys. Rev. D 82, 072005 (2010)]**

\[R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)} \ell^- \bar{\nu}_\ell)}\]

\[3.5 \sigma \text{ dev.}\]


\[\text{BR}(B^+ \to K^+ \mu^+ \mu^-) / \text{BR}(B^+ \to K^+ e^+ e^-) = 0.745^{+0.090}_{-0.074} \pm 0.0036 \quad 2.6 \sigma \text{ dev.}\]

- **Possible link to proton charge radius puzzle**

\[r_e (\mu H) = 0.84087 \pm 0.00039 \text{ fm, } r_e (\text{CODATA2010}) = 0.8775 \pm 0.0051 \text{ fm} \quad 7 \sigma \text{ dev.}\]
Lepton universality in Standard Model $K_{l2}$

**Standard Model:**

- $\Gamma(K_{l2}) = g_l^2 \frac{G^2}{8\pi} f_K^2 m_K m_l^2 \left(1 - \frac{m_l^2}{m_K^2}\right)^2$

- In the ratio of $\Gamma(K_{e2})$ to $\Gamma(K_{\mu2})$, hadronic form factors are cancelled

- $R^K_{SM} = \frac{\Gamma(K^+ \rightarrow e^+\nu)}{\Gamma(K^+ \rightarrow \mu^+\nu)} = \frac{m_e^2}{m_\mu^2} \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta_r)$

- Strong helicity suppression of the electronic channel enhances sensitivity to effects beyond the SM

- Highly precise SM value

\[ R^K_{SM} = (2.477 \pm 0.001) \times 10^{-5} \text{ (with } \delta_r = -0.036); \delta R_K/R_K = 0.04\%

Experimental status of $R_K$

- **Highly precise SM value**
  
  $R_K = (2.477 \pm 0.001) \times 10^{-5}$ (with $\delta_r = -0.036$), $\delta R_K/R_K = 0.04\%$
  

- **KLOE @ DAΦNE (in-flight decay)**
  
  $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$
  

- **NA62 @ CERN-SPS (in-flight decay)**
  
  $R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$
  
  C. Lazzeroni et al., PLB719, 105 (2013)

- **World average (2012)**
  
  $R_K = (2.488 \pm 0.009) \times 10^{-5}$, $\delta R_K/R_K = 0.4\%$

- **Systematics:**
  
  - In-flight-decay experiments: kinematics overlap
  - E36 stopped $K^+$: detector acceptance and target
  - E36 complementary to in-flight experiments

- **E36 goal:** $\delta R_K/R_K = \pm 0.2\%$ (stat) $\pm 0.15\%$ (syst)  [0.25% total]
Dark photon / light neutral boson search

- Dark photons (universal coupling) well motivated by dark matter observations (astronomical, direct, positron excess) and $g_{\mu} - 2$ anomaly
- Light neutral bosons (selective coupling) for proton radius puzzle
- Search for visible decay mode of $A' \rightarrow e^+ e^-$ in $K^+$ decays
  
  **Kaons:** $K^+ \rightarrow \mu^+ \nu A'$; $K^+ \rightarrow \pi^+ A'$ (also invisible decay);
  **Pions:** $\pi^0 \rightarrow \gamma A'$, using $K^+ \rightarrow \pi^+ \pi^0$ (21.13%) and $K^+ \rightarrow \mu^+ \nu \pi^0$ (3.27%)

**E36:** Dark photon exclusion limit

**E36:** Light boson expected signal

- Carlson Polar-Axial vector
- Required signal for proton radius
  
  $K^+ \rightarrow \mu^+ \nu e^+ e^-$
  
  $M_{A'} = 50$ MeV
  
  $\delta M_{ee} \sim 3$ MeV

**BR($K^+ \rightarrow \mu^+ \nu e^+ e^-$)**

$\sim 2.5 \times 10^{-5}$
Proton radius and New Physics

C. Carlson and B. Rislow, Phys. Rev. D 86, 035013 (2012); [arXiv1206.3587v2]

New Physics involving light U(1) bosons can explain proton radius puzzle
Fine tuning, preferred coupling to muon (not electron) – lepton non-universality
Emission of $A'$ as radiative correction to $K \rightarrow \mu \nu$ decay

Experimental limit from stopped kaons at Bevatron in 1970’s (INVISIBLE only):

E36 can probe entire allowed range: $\text{BR}(K^+ \rightarrow \mu^+ \nu A') \sim 10^{-8}$
Possible kaon decay channels in E36

\( K^+ \) decays \( \sim 10^{10} \)

Signal 1: \( K^+ \rightarrow \pi^+ A', A' \rightarrow e^+ e^- \)
Background: \( \text{BR}(K^+ \rightarrow \pi^+ e^+ e^-) \sim 2.9 \times 10^{-7} \sim 2,900 \text{ ev.} \)

Signal 2: \( K^+ \rightarrow \mu^+ \nu A', A' \rightarrow e^+ e^- \)
Background: \( \text{BR}(K^+ \rightarrow \mu^+ \nu e^+ e^-) \sim 2.5 \times 10^{-5} \sim 250,000 \text{ ev.} \)
Add. background from \( K^+ \rightarrow \mu^+ \nu \pi^0 \rightarrow \mu^+ \nu e^+ e^- (\gamma) \)

\( \pi^0 \) decays

1) \( 3 \times 10^8 \)
2) \( 2 \times 10^9 \)

\( \pi^0 \) production:
1) \( K^+ \rightarrow \mu^+ \nu \pi^0 (3.3\%) \)
2) \( K^+ \rightarrow \pi^+ \pi^0 (21.1\%) \)

Signal 3: \( \pi^0 \rightarrow \gamma A', A' \rightarrow e^+ e^- \)
Background: \( \text{BR}(\pi^0 \rightarrow \gamma e^+ e^-) \sim 1.2\% \sim 0.3 (2.3) \times 10^7 \text{ ev.} \)
The rare kaon decay $K^+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ \nu e^+ e^-$

**Signal**

C. Carlson & B. Rislow; T. Beranek

**Background**

- Background: SM process with time-like (virtual) photon exchange
  - Calculable in QED, $\text{BR}(K^+ \rightarrow \mu^+ \nu e^+ e^-) = 2.49 \times 10^{-5}$
  - Measured for $m_{ee} > 145$ MeV/c$^2$
Search for a new particle in $K^+ \rightarrow \mu^+ \nu e^+ e^-$

Investigated for E36:

- Detect $\mu^+$ in toroid, $e^+e^-$ in CsI(Tl)
- Simulate achievable resolution for invariant mass $m_{ee}$
- Simulate QED background (radiative decay $K^+ \rightarrow \mu^+ \nu e^+ e^-$)
- Sensitivity from QED background fluctuation
  $\rightarrow$ Exclusion limits for $\varepsilon^2$ versus $m_{ee}$

P. Monaghan, B. Dongwi (Hampton)
$K^+ \rightarrow \mu^+ \nu \ e^+ e^-$

Muon in gap

e+/e- pair in CsI(Tl); e+ || e- in AC

CsI threshold
Proton radius and New Physics

Exclusion limit with TREK/E36: simulation by Peter Monaghan (HU)
Existing limit: C. Pang, R. Hildebrand, G. Cable, and R. Stiening, PRD8, 1989 (1973)
Location of J-PARC

To get to JAERI from Tokai Station of JR Joban Line, it takes about 10 minutes by car and costs about 1,500 yen when a taxi is taken.

To get to KEK from Tsuchiura Station of JR Joban Line, it takes more than 20 minutes by car and costs about 3,500 yen when a taxi is taken.
J-PARC Hadron Experimental Hall

30~50 GeV primary beam

Production target (T1)

K1.8

K1.8BR

KL

K1.1 S-type

K0.8 C-type

Beam Dump
K1.1BR beamline

- K1.1BR constructed in 2009/10, commissioned by TREK Coll. in Oct. 2010
- Re-aligned after 11/3/11 earthquake, re-commissioned in June 2012
- J-PARC Hadron Hall operations restarted in April 2015

π/K ratio of ~1.3 observed, kaon flux within expectation (1.4x10^6/spill @ 40kW)

A major success!
The TREK apparatus for E36

Modest upgrade of KEK-PS E246

Stopped K method
- K1.1BR beamline
- Fitch Cherenkov
- $K^+$ stopping target

Tracking
- MWPC (C2, C3, C4)
- Spiral Fiber Tracker (SFT)

PID
- TOF1,2; TTC
- Aerogel Cherenkov (AC)
- Pb glass counter (PGC)

Gamma ray
- CsI(Tl)
μ⁺/e⁺ identification

**PID with:**
- TOF
- Aerogel Č
- Lead glass

**TOF**
- Flight length: 250 cm
- Time resolution: <100 ps
- Mis-ID probability: 7x 10⁻⁴

**Aerogel Č counter**
- Radiator thickness: 4.0 cm
- Refraction index: 1.08
- e⁺ efficiency: >98%
- Mis-ID probability: 3%

**Lead glass (PGC)**
- Material: SF6W
- Refraction index: 1.05
- e⁺ efficiency: 98%
- Mis-ID probability: 4%

\[ P_{\text{mis (total)}} = P_{\text{mis (TOF)}} \times P_{\text{mis (AČ)}} \times P_{\text{mis (LG)}} = 8 \times 10^{-7} < O(10^{-6}) \]
Scintillating-fiber kaon stopping target

- Built at TRIUMF (delivered to J-PARC in September 2014)
- 256 scintillating fibers (3x3 mm²), WLS fiber in groove
- MPPC readout
Spiraling fiber tracker (SFT)

- Double-layer fibers in 2 helicities wrapped around target bundle for near target vertex
- Using spare MPPC channels from fiber target
**CsI(Tl) calorimeter**

- **Crystal length**: 250 mm
- **Number of crystals**: 768
- **Segmentation**: 7.5°
- **Coverage**: ~75%
- **Readout**: PIN diodes
- **Maximum rate**: ~200 kHz

**Typical pileup events**

- Possible to separate with FADC
- Has been implemented successfully

**Detection of photons from** $K^+ \rightarrow \mu^+(e^+) \nu \gamma$ **from IB+SD**

**Detection of** $e^+, e^-$ **from A' decay**
TREK/E36 installation and commissioning

- Completed detector installation April 2015
- Electronics and DAQ set up and tested (area available only mid-January)
- Conditioning of MWPCs

- Commissioning of TGT+TOF1+SFT with cosmic rays
- Check-out of all detectors with beam
- Commissioning of toroidal magnet (cryogenics) after April 24

Bishoy Dongwi (Hampton U.)
Target performance

Kaon stop and track of decay particle

Kaon beam profile

June 2015 data

Preliminary
Track identification by central detector

SFT+Target consistency established with C-ray
Momentum determination

- Charged particle momentum determined by 3-point tracking (C2, C3, C4)
- Events selected requiring track consistency with target and SFT
- Monochromatic peaks from $K_{\mu2}$ and $K_{\pi2}$
Particle identification by AC, PGC, and TOF

- AC and PGC performing as expected
- TOF resolution below expectation due to TOF1 performance (June data)
- Suppression of muon mis-identification below $O(10^{-8})$ level achievable with refined analysis
- Refined analysis of PID performance in progress

Very preliminary

Particle identification by AC, PGC, and TOF

- AC and PGC performing as expected
- TOF resolution below expectation due to TOF1 performance (June data)
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Very preliminary
**Ke2 events**

- Observed Ke2 peak in the momentum spectrum after PID cuts
- Statistics from 100 runs in June 2015
- Improved trigger purity and dead time by additional trigger counter (TTC) and by requiring >1 target fiber hit in the trigger
- Collected ~40k Ke2 events in fall 2015 (estimate based on Kμ2)
Energy and timing obtained by pulse shape data from FADC (VF48)

Events from the $K^+$ decays were selected

$K_{\mu 2}$ events with single crystal hit used for the energy calibration

Deposited muon energy used for energy calibration of each crystal

Calibration data from early June
- $K_{\pi^2}$ events selected by analyzing momentum and TOF ($M^2$)
- $\pi^0$ invariant mass reconstructed by selecting two-cluster events
- Large $\pi^+ / \pi^0$ opening angle obtained
- Confirmed that the total E36 system works correctly and is consistent with E246

Very preliminary
Search for light boson events

- Search for visible decay mode of $A' \rightarrow e^+e^-$ in $K^+$ decays
  - Kaons: $K^+ \rightarrow \mu^+ \nu A'$; $K^+ \rightarrow \pi^+ A'$ (also invisible decay);
  - Pions: $\pi^0 \rightarrow \gamma A'$, using $K^+ \rightarrow \pi^+\pi^0 (21.13\%)$ and $K^+ \rightarrow \mu^+ \nu \pi^0 (3.27\%)$

- DP trigger: 3+ TOF1 bars

- $K^+ \rightarrow \mu^+ e^+ e^- \nu$ decays recorded in E36 data with DP trigger

- Reconstruct $K^+ \rightarrow \mu^+ e^+ e^- \nu$ decays with $\mu^+$ track in toroid and $e^+e^-$ pair in the CsI(Tl) calorimeter

- $e^+$ and $e^-$ are identified by the aerogel Cherenkov counters surrounding the $K^+$ stopping target

- Main backgrounds are $K^+ \rightarrow \pi^+\pi^0$ and $K^+ \rightarrow \mu^+\pi^0 \nu$, with $\pi^0 \rightarrow e^+e^-\gamma$

- [Can also use $\pi^0 \rightarrow e^+e^-\gamma$ as another signal channel!]
Search for light boson events

Correlate CsI $e^+e^-$ hits with AC sector

Evaluate $K^+ \rightarrow \mu^+ e^+ e^- \nu$ missing mass

Select $\mu^+$ momentum $> 205$ MeV/c ($K_{\pi2}$)
Evaluate $A' \rightarrow e^+ e^-\nu$ invariant mass
# TREK (E36/E06) collaboration

- ~30 collaborators

**Spokespeople:**
- M.K., S. Shimizu

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<tr>
<th>CANADA</th>
<th>USA</th>
<th>JAPAN</th>
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| University of British Columbia  
*Department of Physics and Astronomy*  
TRIUMF | University of South Carolina  
*Department of Physics and Astronomy*  
University of Iowa  
*Department of Physics*  
Hampton University  
*Department of Physics* | Osaka University  
*Department of Physics*  
Chiba University  
*Department of Physics*  
Rikkyo University  
*Department of Physics*  
High Energy Accel. Research Organization (KEK)  
*Institute of Particle and Nuclear Studies* |

**RUSSIA**

- Russian Academy of Sciences (RAS)  
*Institute for Nuclear Research (INR)*
Summary

- Substantial progress of TREK/E36 @ J-PARC
- **E36:** Measure $K_{e2}/K_{\mu2}$ ratio – test of lepton universality to 0.25% (beam power 30-40 kW)
- Searches for dark photon/light boson (and heavy sterile neutrino)
- Experiment has been fully commissioned in spring 2015
- Production running has been completed (Oct. 14 – Dec. 18, 2015)
- Pursue TREK/E06 (T-violation) in the future at extended Hadron Facility
Backup
TREK/E06: Transverse muon polarization

\[ P_T = -0.0017 \pm 0.0023 \text{(stat)} \pm 0.0011 \text{(sys)} \]
\[ (|P_T| < 0.0050 : 90\% \text{ C.L.}) \]

\( P_T \neq 0 \Rightarrow T \) violation
(CPT theorem) \( \Rightarrow CP \) violation
Sakurai 1957

- \( K^+ \rightarrow \pi^0 \mu^+ \nu \)
- Decay at rest
- T-odd correlation

\[ P_L = \frac{\vec{\sigma}_\mu \cdot \vec{p}_\mu}{|\vec{p}_\mu|}, \]
\[ P_N = \frac{\vec{\sigma}_\mu \cdot (\vec{p}_\mu \times (\vec{p}_\pi \times \vec{p}_\mu))}{|\vec{p}_\mu \times (\vec{p}_\pi \times \vec{p}_\mu)|}, \]
\[ P_T = \frac{\vec{\sigma}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)}{|\vec{p}_\pi \times \vec{p}_\mu|}. \]

M. Abe et al., PRL83 (1999) 4253
M. Abe et al., PRL93 (2004) 131601
M. Abe et al., PRD72 (2006) 072005

TREK/E06 T-violation to be pursued at J-PARC phase 2 – extended Hadron Hall
Lepton universality violation in $K_{l2}$

- **SUSY with LFV for $K_{e2}$**
  - Charged Higgs $H^+$ mediated LFV SUSY
  - Large enhancement from $m_\tau^2/m_e^2$
  - A sizable effect of $\Delta R_K/R_K \sim 1.3\%$ possible

- **General discussions on SUSY effects**
  - strong constraints from $B_s \to \mu^+\mu^-$ and $B_u \to \tau\nu$
  - $|\Delta R_K/R_K| \sim O(10^{-3})$

- **Neutrino mixing**
  - $R_K$ constrains neutrino mixing parameters within SM extensions involving
  - sterile neutrinos A. Abada et al., JHEP02, 048 (2013) [arXiv: 1211.3052]
Heavy neutrino search in $K^+ \rightarrow \mu^+N$, $e^+N$

- **Minimal Standard Model (νMSM)**
  - Explanation of DM and BAU
  - Possibility of $M_N \leq M_K$

- Search for monochromatic peaks in $K^+ \rightarrow \mu^+N$, $K^+ \rightarrow e^+N$

Heavy neutrino search in $K^+ \rightarrow \mu^+ N, e^+ N$

Projected TREK / E36

$BR(K^+ \rightarrow \mu^+ N, e^+ N) \lesssim 2 \times 10^{-8}$

$U^2 \lesssim 3 \times 10^{-8}$ for $M_N < 200$ MeV

sensitivity for $M_N > 200$ MeV needs more study

L. Canetti, M. Drewes, M. Shaposhnikov,