Searching for the Sterile Wave:
A $\nu_\mu$-disappearance search using Kaon decay-at-rest


Workshop for Neutrino Programs with Facilities in Japan
August 5th, 2015
Introducing KPipe

• “KPipe” is a proposal for a short-baseline muon neutrino disappearance experiment — here at the J-PARC MLF — that uses neutrinos from Kaon Decay at Rest (KDAR)

• The goal is to provide evidence for or against the existence of sterile neutrino oscillations

• Advantage of KPipe:
  • effect of many systematic uncertainties reduced
  • measures osc. prob. over a range of L/E
KPipe

Overall Design

MLF Beam dump

3 GeV proton beam in

236 MeV $\nu_\mu$'s from $K^+ \rightarrow \nu_\mu \mu^+$

(1) pure, mono-energetic flux of muon neutrinos from Kaon decay at rest

(2) long detector to measure the oscillation wave
KPipe

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J-PARC MLF

- Beam at Materials and Life Science Facility at JPARC
- 3 GeV protons on Hg
- target power: 1 MW
- pulsed with tight beam windows:
  2 pulses with 80 ns width, 540 ns apart at 25 Hz
J-PARC MLF

- Beam at Materials and Life Science Facility at JPARC
- 3 GeV protons on Hg
- Target power: 1 MW

J-PARC is well suited for powerful sterile neutrino searches

With tight beam windows:
- 2 pulses with 80 ns width,
- 540 ns apart at 25 Hz
Neutrino Flux

- Beam at J-PARC unique in providing high flux of KDAR neutrinos

KDAR neutrinos: If one can isolate them:

1) energy known exactly

2) flux as a function distance: $1/L^2$
Neutrino Program with Facilities in Japan

T. Wongjirad     MIT

KPipe

1.

236 MeV $\nu_\mu$'s from $K^+ \rightarrow \nu_\mu \mu^+$

2.

MLF Beam dump

3 GeV proton beam in

$\nu_\mu$

Overall Design

$\nu_\mu$

$\nu_\mu$

$\nu_\mu$

Kpipe detector

(1) pure, mono-energetic flux of muon neutrinos from Kaon decay at rest

(2) long detector to measure the oscillation wave
KPipe Detector

A (BIG) pipe, 3 m diameter and 120 m long, filled with liquid scintillator
KPipe Detector

- Such a big stainless pipe is likely very expensive
- Found a company which sells and installs steel reinforced high density polyethylene vessels
- Used for sanitation, irrigation, wastewater

*DuroMaxx® – Steel Reinforced Polyethylene Technology*
KPipe Detector

Studied possible locations of pipe around MLF building

Chose location (highlighted in orange) based on sensitivity and available space

Want to be as close as possible to maximize rate

- Closest point 32.0m.
- 102 degrees from proton dir.
- There is a storage tank in the way
KPipe Detector

- Looking for numu CCQE interactions
• Looking for numu CCQE interactions
• Muon production threshold and CCQE cross-section suppresses much of the non-KDAR neutrino flux
• 98% of CCQE interactions will be KDAR neutrinos with known energy!

Flux

Rate, CCQE Cross Section
Detecting the Signal

strategy is to detect numu CCQE interactions through two coincident flashes of light: a prompt and Michel flash.

(1) prompt flash
(2) Michel flash

ν_μ → e
ν_μ → μ
ν_e → μ
Detecting the Signal

- Use Silicon Photomultipliers to detect light
  - compact
  - low voltage ~ 27 V bias needed
  - inexpensive when ordered in bulk: ~$20/SiPM
Detecting the Signal

- Divide volume into target and veto region (10 cm thick)
- target region has 1200 hoops containing 100 SiPMs each
- veto region has 122 hoops with 100 SiPMs each
Scintillator

- Even with 120K SiPMs only approx. 0.4% photocoverage — need lots of light!

- Fill vessel with liquid scintillator

- Detector simulations indicated that enough photons will be detected
Signal in Detector

For 3+1 model

\[ P(\nu_\mu \rightarrow \nu_\mu) = \begin{cases} 
0.92 & \text{if } \Delta m^2 = 1 \text{ eV}^2, \sin^2 2\theta_{\mu\mu} = 0.05 \\
0.94 & \text{if } \Delta m^2 = 5 \text{ eV}^2, \sin^2 2\theta_{\mu\mu} = 0.05 \\
0.96 & \text{if } \Delta m^2 = 10 \text{ eV}^2, \sin^2 2\theta_{\mu\mu} = 0.05 
\end{cases} \]

\[ \sin^2 2\theta_{\mu\mu} = \begin{cases} 
1 & \text{if } m_\Delta = 1 \text{ eV} \\
5 & \text{if } m_\Delta = 5 \text{ eV} \\
10 & \text{if } m_\Delta = 10 \text{ eV} 
\end{cases} \]

\[ \Delta m^2 = m_\Delta^2 - m_\mu^2 \]

Seeing the oscillation wave would be compelling evidence for sterile neutrinos.
If sterile $\nu$’s do exist, measuring the oscillation probability over this range could help distinguish between models.

3+2

3+3
Backgrounds

- Cosmic rays are main background
- No L/E dependence and rate can be measured
- But number of events that pass selection contribute to statistical uncertainty
- Timing, selection cuts, and veto need to bring rate down acceptable level
- Rate of events that pass studied via simulation
  - About 27 Hz: mostly stopping muons
  - Signal to background ratios: 60:1 at front, 3:1 at back
• Putting everything together, what is the sensitivity of KPipe?
Sensitivity Analysis

- We use a shape only analysis
- Note: uncertainty primarily from statistics of signal and cosmic ray events — others minimal:

<table>
<thead>
<tr>
<th>Energy Reconstruction</th>
<th>• minimized due to relatively pure selection of CCQE interactions from KDAR</th>
</tr>
</thead>
</table>
| Flux                   | • isotropic, almost point-like flux, goes as $1/L^2$  
                        | • KDAR $\nu$'s mono-energetic  
                        | • kaon production uncertainty affects only norm. |
| Cross section          | • norm. uncertainty |
Neutrino Program with Facilities in Japan

Sensitivity

- Three years of running
- Exclude sizable portion of allowed regions at 5 sigma
Sensitivity

• Six years of running

• Extends current numu-disappearance limits at high mass splitting by almost an order

• Complements SBN program
  • 6 years uBooNE
  • 3 years SBND
  • 3 years T600

(3 years=6.6x10^{20} POT from BNB)
## Costs

<table>
<thead>
<tr>
<th>Description</th>
<th>Quantity</th>
<th>Unit Price</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator (using NoVA)</td>
<td>732 tonnes</td>
<td>1.5 $/tonne</td>
<td>1.1 M$</td>
</tr>
<tr>
<td>SiPMs</td>
<td>121,200</td>
<td>$20</td>
<td>2.4 M$</td>
</tr>
<tr>
<td>Readout</td>
<td>1212 channels</td>
<td>$300</td>
<td>0.36 M$</td>
</tr>
<tr>
<td>Vessel</td>
<td>120 m</td>
<td>2400 $/m</td>
<td>0.29 M$</td>
</tr>
<tr>
<td>Vessel Installation</td>
<td>1</td>
<td>$22k</td>
<td>0.022 M$</td>
</tr>
<tr>
<td>SiPM panels</td>
<td>1056 m²</td>
<td>150 $/m²</td>
<td>0.16 M$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>4.6 M$</strong></td>
</tr>
</tbody>
</table>
Summary

- Observation (or lack there of) of muon neutrino disappearance is important in understanding if steriles exist.
- KPipe measures the oscillation probability over 120 m: distortions in the flux from one or more sterile can be differentiated.
- Use of KDAR makes measurement insensitive to typical uncertainties coming from flux, cross section and energy reconstruction uncertainties.

KPipe traces out the oscillation wave

![Graph showing the oscillation probability over distance and energy.](image-url)
Plans

- We aim to submit a proposal to the J-PARC PAC this winter
- We are looking for collaborators, especially in Japan
- Please come chat with me if you would like to discuss more
- A paper with more details: http://arxiv.org/abs/1506.05811
Thank you!
Backup Slides
Events vs. Distance

rate_numu_L

counts after 3 years
total 228508 events
(after 75% efficiency)
Building a Trench?

**SEWER SERVICE INSTALLATION COSTS**

The following is the schedule of prices to be charged by the Water Department, Division of Sewer Maintenance, City of Dayton, Ohio for Sanitary and Storm Sewer service taps, sewer service excavation, laying of pipe, backfilling and restoration of the surfaces in streets and alleys on and after July 1, 2007. Call 333-4915 for help in determining these charges.

**SCHEDULE OF PRICES - Twelve (12) inch services and smaller.**

<table>
<thead>
<tr>
<th>Trench Depth</th>
<th>Class 1 Concrete Pavement</th>
<th>Class 2 Brick on Concrete Base</th>
<th>Class 3 Asphalt on Concrete Base</th>
<th>Class 4 Asphalt on Brick Base</th>
<th>Class 5 Asphalt on Stone or Gravel Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feet</td>
<td>Cost Per L.F.</td>
<td>Cost Per L.F.</td>
<td>Cost Per L.F.</td>
<td>Cost Per L.F.</td>
<td>Cost Per L.F.</td>
</tr>
<tr>
<td>0 - 8</td>
<td>$270</td>
<td>$372</td>
<td>$237</td>
<td>$372</td>
<td>$202</td>
</tr>
<tr>
<td>8 - 16</td>
<td>$337</td>
<td>$465</td>
<td>$296</td>
<td>$465</td>
<td>$252</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trench Depth</th>
<th>Class 6 Gravel Roadway Plain or Oiled</th>
<th>Class 7 Concrete Sidewalks or Driveways</th>
<th>Class 8 Sodded Areas</th>
<th>Class 9 Grass or Unimproved Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feet</td>
<td>Cost Per L.F.</td>
<td>Cost Per L.F.</td>
<td>Cost Per L.F.</td>
<td>Cost Per L.F.</td>
</tr>
<tr>
<td>0 - 8</td>
<td>$193</td>
<td>$200</td>
<td>$210</td>
<td>$190</td>
</tr>
<tr>
<td>8 - 16</td>
<td>$243</td>
<td>$200</td>
<td>$210</td>
<td>$190</td>
</tr>
</tbody>
</table>

Using $300 per foot: 120 m trench with pipe is 120K USD
Building a Trench?

![Graph showing ground temperature for different trench depths over a year. Peaks and troughs are observed for each depth.]

- 0.5-foot depth
- 2-foot depth
- 5-foot depth
- 12-foot depth

Ground Temperature (Deg F) vs. Day of Year.
Building a Tunnel?

Strabag to build Toronto wastewater tunnel

Paula Wallis, *TunnelTalk*

Building on from its mega Niagara Falls hydro tunnel project, Strabag has landed another major tunneling contract in Canada, this time in Toronto. The company has secured the CAN$290 million (about €200 million) contract to build the 15km (9.3 mile) long wastewater tunnel for The Regional Municipality of York. Strabag outbid three other pre-qualified contractors that submitted proposals by the May 6th 2011 deadline (Table 1). All of the bids were well below the approved CAN$546.1 million budget for the sewer project.

290 million for 15 km of tunnel
120 m ~ 1.6 million
KDAR production
• Simple numerical study looked at confinement of muons vs. pipe radius

• Around 87% for 3 meter diameter pipe

• Geant4 simulation showed about the same acceptance
3+N?

Some tensions in 3+1 model, are 3+2, 3+3, models etc. corrected?

Is there a way to also provide info on the correct sterile model (provided they exist)?
Signal Simulation

- Estimated photons collected
- MC scintillator produces ~4500 photons/MeV
- With current coverage, seems to be enough light
- Estimate about 80 cm position resolution

![Graph](image1)

![Graph](image2)
### Parameters for sensitivity calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaon production uncertainty</td>
<td>+/- 0.2 m</td>
</tr>
<tr>
<td>baseline reconstruction uncertainty</td>
<td>0.8 m</td>
</tr>
<tr>
<td>Event generator model</td>
<td>NuWro</td>
</tr>
<tr>
<td>Kaon production models</td>
<td>GEANT4 = 0.0038 K+/POT</td>
</tr>
<tr>
<td></td>
<td>MARS15 = 0.00725 K+/POT</td>
</tr>
<tr>
<td>Selection efficiency</td>
<td>75%</td>
</tr>
<tr>
<td>CR background rate</td>
<td>27 Hz</td>
</tr>
</tbody>
</table>
Cross Sections

KDAR $\nu$ energy

At 236 MeV, interactions should be almost all CCQE interactions

little RES production of pions
Signal Simulation

- Include photon hits from interactions and 1.6 MHz dark rate
- Implemented pulse finding algorithm to pull out “double flash” signal from all the SiPM dark noise

prompt pulse

Michel pulse
FIG. 6: The number of photoelectrons in a 236 MeV \( \nu_{\mu} \) CC event’s first pulse versus the total kinetic energy (\( KE_{\text{tot}} = KE_\mu + \sum KE_p \)).
Signal Selection

• Signal events have neutrino-induced muon interactions. Remove backgrounds, which we expect will be mostly cosmic rays
  • 2 flashes: muon, then Michel electron
  • no veto hits
  • in time
  • 2 flashes close in Z
  • upper energy cut on both muon and Michel electron pulse, to remove high energy cosmic ray events
  • low energy threshold for noise
• Studied with detector MC
Selection Performance

- can define fairly conservative cuts for removing cosmics
- Efficiency mostly determined by ability to see Michel pulse

<table>
<thead>
<tr>
<th>Event Category</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events in target region</td>
<td>100%</td>
</tr>
<tr>
<td>Contained muons (calculation)</td>
<td>87%</td>
</tr>
<tr>
<td>Prompt pulse seen (above noise level)</td>
<td>87%</td>
</tr>
<tr>
<td>Michel seen</td>
<td>77%</td>
</tr>
<tr>
<td>Cuts for cosmic</td>
<td>75%</td>
</tr>
</tbody>
</table>
Backgrounds

• Cosmic ray simulation using package called CRY
• generates cosmic ray shower event at given latitude and altitude
• particles provided: muons, photons, pions, neutrons, protons, electrons
Backgrounds

- Backgrounds mostly from stopping muons that pass undetected by veto
- Above ground
- Photon showers, neutrons, electrons would be reduced if pipe is buried/shielded

<table>
<thead>
<tr>
<th></th>
<th>Total Rate</th>
<th>27 Hz (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>photons</td>
<td></td>
<td>5%</td>
</tr>
<tr>
<td>neutrons</td>
<td></td>
<td>20%</td>
</tr>
<tr>
<td>muons only</td>
<td></td>
<td>60%</td>
</tr>
<tr>
<td>muons+others</td>
<td></td>
<td>15%</td>
</tr>
</tbody>
</table>

signal to background ratio:
- 60:1 at front
- 3:1 at back
Beam Timing

- Timing of neutrinos should be well-known
- Will help greatly in rejecting cosmics

![Graph showing beam timing and structure](image_url)

Beam structure: 25 Hz
Scintillator

- received test piece of HDPE
- testing to see if material withstands attack from pseudocumumene
- in the process of trying to get some LAB
A proposal, with constraints

- A call for proposals from the DOE at the WINP workshop (Feb 2015)
- Must satisfy the following:
  - Not associated with Fermilab program (e.g. SBN)
  - Decisive within 3 years of running
  - be a fraction of 10 million dollars
    Changed to <2 million!