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


DPF 2015
08/05/2015
A proposal to look for signs of sterile neutrinos through a muon neutrino disappearance experiment, dubbed “KPipe”

- Briefly describe experimental anomalies that motivate sterile searches
- Describe KPipe: its design and sensitivity
A number of experiments see a deficit or excess of neutrino events. Basically, the anomalies seem to indicate that there may be a new characteristic oscillation frequency mode (indicative of a new neutrino state).

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<th>Oscillation channel</th>
<th>Significance</th>
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Interpretable as coming from sterile neutrino oscillation with $\Delta m^2$ around 0.1-10 eV$^2$.

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- Anomalies motivating future experiments to verify each type of anomaly directly

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Accelerator experiments, e.g. MicroBooNE, Short Baseline Neutrino (SBN) program at Fermilab

Remeasuring reactor ν’s, e.g. Nucifer, Prospect

High intensity ν sources, e.g. SOX, IsoDAR, etc.
Future Experiments

- Experiments probing oscillations to/from $\nu_e$ ($\bar{\nu}_e$)
- Is there a complementary approach?

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Remeasuring reactor $\nu$'s, e.g. Nucifer, Prospect

High intensity $\nu$ sources, e.g. SOX, CeLAND, etc.
Future Experiments

What about $\nu_\mu$ disappearance?

If sterile neutrinos exist, there must be some amount of muon neutrino disappearance!

\[
P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4(1 - |U_{\mu 4}|^2) |U_{\mu 4}|^2 \sin^2 \left(1.27 \Delta m_{41}^2 L / E \right)
\]
KPipe

Overall Design

MLF Beam dump

3 GeV proton beam in

Monoenergetic 236 MeV $\nu_\mu$
from $K^+ \rightarrow \nu_\mu \mu$

Detector sits at $\cos \theta < 0$
with respect to the beam

Kpipe detector

(1) pure, mono-energetic flux
of muon neutrinos

(2) long detector to
measure the oscillation
wave
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<td><strong>Energy</strong></td>
<td>3 GeV</td>
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<tr>
<td><strong>Electrical Current</strong></td>
<td>0.333 uA</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>1 MW</td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td>25 Hz</td>
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Neutrino Fluxes

• Our flux simulation: 3 GeV protons hitting Hg target

KDAR Flux

• KDAR neutrinos: Energy known exactly
Neutrino Rates

- CCQE cross-section and muon production threshold suppresses much of the non-KDAR neutrino flux

- 98.5% of interactions will be KDAR neutrinos
KPipe

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K⁺ → ν_μ μ

Detector sits at cos θ < 0 with respect to the beam

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(1) pure, mono-energetic flux of muon neutrinos

(2) long detector to measure the oscillation wave
Detector

- A (BIG) high density polyethylene pipe, 3 m diameter and 120 m long, filled with liquid scintillator
Detector Location

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
1. 3 GeV protons on mercury target produces K+
2. K+ decay at rest (DAR) producing mono-energetic muon neutrinos (235.5 MeV)
3. Prompt signal from muon produced in the CCQE interaction
4. Delayed signal from the Michel electron
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• Divide volume into target and veto region

• Target region has 1200 hoops containing 100 silicon photomultipliers (SiPM) each

• Veto region has 122 hoops with 100 SiPMs each
Photon Detector: SiPMs

- Silicon photomultipliers
  - compact
  - low voltage ~ 27 V bias needed
  - inexpensive when ordered in bulk: ~$20/SiPM
- Small: 121K SiPMs only 0.4% photocoverage — need lots of light
What we want to measure

- Seeing the oscillation wave would be definitive evidence for sterile $\nu$'s

Recall: $E = 235.5$ MeV

$P(\nu_e \rightarrow \nu_\mu) = 0.05$ for $\Delta m^2 = 1$ eV$^2$, $\sin^2 2\theta_{\mu\mu} = 0.05$

$P(\nu_e \rightarrow \nu_\mu) = 0.05$ for $\Delta m^2 = 5$ eV$^2$, $\sin^2 2\theta_{\mu\mu} = 0.05$

$P(\nu_e \rightarrow \nu_\mu) = 0.05$ for $\Delta m^2 = 10$ eV$^2$, $\sin^2 2\theta_{\mu\mu} = 0.05$
## Sensitivity

<table>
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<th>Parameter</th>
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<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>MARS15 = 0.0073 K+/POT</td>
</tr>
<tr>
<td>Selection efficiency</td>
<td>75%</td>
</tr>
<tr>
<td>CR background rate</td>
<td>27 Hz</td>
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</table>
• Three years of running
• Exclude sizable portion of allowed regions at 5 sigma
• This is statistics limited.
Sensitivity Study

- Six years of running
- Extends limit at high mass splitting by an order of magnitude
- Complements SBN program
  - 6 years uBooNE
  - 3 years SBND
  - 3 years T600
## Costs

<table>
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<tr>
<th>Material</th>
<th>Quantity</th>
<th>Unit Price</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator (using NoVA) price</td>
<td>732 metric tonne</td>
<td>1.5k$/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>
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• Observation (or lack thereof) of muon neutrino disappearance is important in understanding sterile anomaly

• KPipe is a proposal to look for muon neutrino disappearance at around 1-10 eV$^2$

• Lots of power for less than 5 million dollars

• A paper with more details: http://arxiv.org/abs/1506.05811

• Presenting to JPARC today!
Thanks!


Massachusetts Institute of Technology
Columbia University
University of Michigan
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>
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<th>Total Rate</th>
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<td>photons</td>
<td>5%</td>
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<tr>
<td>neutrons</td>
<td>20%</td>
</tr>
<tr>
<td>muons only</td>
<td>60%</td>
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<tr>
<td>muons+others</td>
<td>15%</td>
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Signal to background ratio:
- 60:1 at front
- 3:1 at back
Timing of neutrinos should be well-known.

Look for interactions coming from neutrinos in the two windows.

Beam structure: 25 Hz.
Muon Neutrino Disappearance

- Not all experiments see anomalies
- In fact, no experiment has seen muon neutrino disappearance
- An important constraint
The width of the Z boson shows us that there are only 3 flavors of neutrinos that interact via the weak force.

- Reactor experiments indicate that there is a deficit in the electron flavored neutrinos.
- Calibration source experiments confirm this.
- Data from low L/E oscillation experiments observe ~3 sigma excess in \( \nu_e \) and \( \bar{\nu}_e \).

(backup) Sterile Hypothesis
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
- Include photon hits from interactions and 1.6 MHz dark rate
Selection Efficiency

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<th>Efficiency</th>
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<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>
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- removing cosmics comes at some cost to signal
Backgrounds

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60:1 at front
3:1 at back
Muon production target
(do we also get pions here?)

Location information:
• Experimental Hall 2, (Target station to west wall = 31.25 m)
• 36°26’53.8”N 140°36’14.2”E

1. Neutrino beamline tunnel
   underground and very large
   Muon production target
   (do we also get pions here?)

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

3. Closest point 35.7m.
   61 degrees from proton dir.
   Blocking No.2 Gateway
   Forward pions?
   Lots of space.

Experimental Hall 2

Proton direction

Section A’

Experimental Hall 1

Mercury target station

Forward pions?

Lots of space.