Showering Muons in Super Kamiokande

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Super Kamiokande Detector

- 50kton water Cherenkov
  - Ultrapure Water
- 22.5 kton fiducial volume (32 kton for SN burst)
- 11,129 20-inch PMTs (inner), 1885 of 8-inch PMTs (outer)
- Phase Period inner PMTs coverage
  - SK-I 1996-2001 11,146 40%
  - SK-II 2002-2005 5,182 19%
  - SK-III 2006-2008 11,129 40%
  - SK-IV 2008-2018 (same as SK-III with new electronics)
  - SK-Gd 20XX-
- ~300 kt-years exposure
- Detects neutrinos from many sources
- T2K far detector
Introduction

• ~2 Hz muon rate
• Others usually consider it a MIP, which isn’t always the case
  • Large amount of energy can be deposited, especially in the form of a shower
• Issues arise when these cause spallation

5.6 $M_{pe} \approx 0.94$ TeV deposited within detector

Picture of Control Room Event Display
Spallation

• Spallation is caused largely by muon induced showers

• It can be long lived ($\tau \sim O(10s)$)
  • Troublesome when trying to perform specific analyses

• Shower does not guarantee spallation

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<table>
<thead>
<tr>
<th>Radioactive isotope</th>
<th>$\tau$ (s)</th>
<th>Decay mode</th>
<th>$E_{\text{kin}}$ (MeV)</th>
<th>Primary process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}$O</td>
<td>10.3</td>
<td>$\beta^-$</td>
<td>4.27+6.13($\gamma$)</td>
<td>$^{16}$O(n,p)$^{15}$N</td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>3.53</td>
<td>$\beta^-$</td>
<td>9.77</td>
<td>$^{16}$O(n,2p)$^{15}$C</td>
</tr>
<tr>
<td>$^{8}$B</td>
<td>1.11</td>
<td>$\beta^+$</td>
<td>$\sim$13.9</td>
<td>$^{16}$O($\pi^+,\alpha+2p$)$^{15}$B</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Radioactive isotope</th>
<th>$\epsilon$ (kton$^{-1}$day$^{-1}$)</th>
<th>$R_\gamma$ (kton$^{-1}$day$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$B</td>
<td>45.5%</td>
<td>19.8$\pm$0.1$\pm$1.0</td>
</tr>
<tr>
<td>$^{12}$N</td>
<td>56.2%</td>
<td>2.8$\pm$0.1$\pm$0.1</td>
</tr>
<tr>
<td>$^{16}$N</td>
<td>45.0%</td>
<td>39.7$\pm$3.3$\pm$2.8</td>
</tr>
<tr>
<td>$^{15}$Be</td>
<td>38.1%</td>
<td>&lt;16.9</td>
</tr>
<tr>
<td>$^{6}$Li</td>
<td>39.2%</td>
<td>0.9$\pm$0.3$\pm$0.3</td>
</tr>
<tr>
<td>$^{8}$He,$^{8}$C</td>
<td>22.2%, 50.2%</td>
<td>&lt;1.4</td>
</tr>
<tr>
<td>$^{8}$Li/$^{8}$B</td>
<td>42.8%, 51.3%</td>
<td>8.3$\pm$0.3$\pm$0.3</td>
</tr>
<tr>
<td>$^{15}$C</td>
<td>31.8%</td>
<td>&lt;6.7</td>
</tr>
</tbody>
</table>

Y. Zhang et al. (Super-Kamiokande Collaboration), Phys. Rev. D 93, 012004 (2016)
Muon Showers

- Shower can be hadronic or electromagnetic
- Both have large EM component
- Look at the energy deposited into detector along muon track
  - dE/dx plots
  - Map PMT hits back to the muon track
- Look for large deposits of energy in these plots
Effects

• Acts as a background to major analyses:
  • DSNB
  • Solar neutrinos

• Inhibits us from lowering the threshold for DSNB analysis

• Reducing this background is imperative to enhancing these searches
Hadronic Showers

- Hadn’t been seen directly before
- Beacom and Li theorized that a large number of neutrons would be in the shower accompanying a spallation causing muon
- Use WIT (Wideband Intelligent Trigger) system for a lower threshold to see 2.2 MeV gamma from n+p interactions
- All the following is preliminary

AmBe Source in SK

203.7 +/- 2.8 μs
Neutron Tagging

- Initial Data Set:
  - ~6 weeks of data
  - 20-500 μs after muon
  - E < 5.5 MeV kin
  - <5m from track
  - Anywhere in detector (no FV cut)
  - Basic cut used on some of the data
    - Simple time, goodness, lt cuts

- Sharply peaked closer to the track

SK Preliminary
June 2017
Event Correlation

• Events are tightly correlated
  • Maintain correlation to higher multiplicity
• Look in the future to use this as an isolated cut
  • ~0.7% muons have 2+ events with above cuts
  • A rough calculation finds ~51s a day of dead time for a +/- 2.5m and 60s cut from $x_{\text{avg}}$ for events with 2+ candidates
Time Correlation

- Use a simple exponential
  \[ N[dt] = e^{p_0 + p_1*dt} + p_2 \]
- Make a background calculation
  - High purity: \(~.0027\) accidentals/m of muon track
    - \(.067\) accidentals/25m muon
  - Still have good agreement when relaxing the purity cut

\[ \tau = 207 \pm 5.3 \, \mu s \]
Multiplicity

• Note
  • No background subtraction
    • Significantly < 0.5 accidentals/muon, even for low purity
  • Only events from sample
    • 0 bin is a lot bigger with all muons

• Everything shifts, but 0 peak does not grow significantly

• Efficiency:
  • 13.5% (17.2% in FV) efficiency for seeing MC generated neutrons
  • Drops to 4.2% (5.4% in FV) when making goodness and vertex correlation to true location cut
The Future

• SK-Gd
  • Increased capture efficiency on Gd
  • Easier to see the signal
    • Works with increased efficiency to improve tagging
  • Prepare for the signal that SK-Gd should be expecting to see

• Hyper-K
  • Bigger tank with possibly lower overburden
    • Neutrons become even more common as muon rate increases with more volume to interact with
Summary

• Even under 1 km of mountain, still see a non negligible muon rate
  • These muons cause issues in analyses by creating long lived spallation background

• Currently we look at the EM component of both kinds of showers to try and tag this background

• Recent efforts has shown it is possible to directly see the hadronic shower, specifically the neutrons produced

• Events are tightly correlated to each other and the preceding muon

• Efficiency of n capture on H is one of the biggest limiting factors, which should be enhanced with Gd
Super-Kamiokande Collaboration

• 10 nations
• ~42 institutions
• ~160 Researchers
• As of June 2017