Silicon Burning Neutrinos at Super-K with Gadolinium

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Super-Kamiokande

- 50ktons water, 22.5 kton fiducial volume
- Under mountain to reduce cosmic muon rate
- Inner detector instrumented with >11000 20 inch PMTs
- Detects Cherenkov light from charged particles passing though water
- Running >20 years so far

- Studies atmospheric and solar neutrinos
- Far detector for T2K
- Waiting for supernova detection
- Proton decay search
Super-K with Gadolinium

- Soon to be upgraded for next phase with gadolinium doping
- By adding 0.2% Gd salt by mass, will detect 80% of neutrons
- Detect the diffuse supernova neutrino background
- Enhance pointing ability for a supernova burst
Diffuse Supernova Neutrino Background

- Neutrinos from all past supernovae in the universe should still exist
- SK has set limits, but is background limited
- By eliminating backgrounds, SK-Gd will detect DSNB within two years of full Gd loading

Gadolinium has a high **thermal neutron capture** cross section
High energy of gamma ray cascade gives highly efficient neutron tagging

Allows IBD events to be separated from background, and from other neutrino events
EGADS

EGADS is a smaller 200 ton tank used to test detector systems

It will now run as an autonomous supernova detector while SK is down.

Recommend Nakajima-san’s slides from NNN17 for more details
Light @ 15 meters and Gd conc. in the 200-ton EGADS tank

High flow (121 l/min)

Blue band: SK-III and SK-IV water transparency values

Black dashed line: final Gd sulfate concentration

Normal (41 l/min band-pass + 40 l/min fast recirc)

EGADS Gd$_2$(SO$_4$)$_3$ + x · H$_2$O concentration [ppm]

Sampling position:
- Bottom
- Centre
- Top

After two and a half years at full Gd loading, during stable operations EGADS water transparency remains within the SK ultrapure range.

→ No detectable loss of Gd after more than 650 complete turnovers. ←

Slide credit: Mark Vagins
Development of pure Gd powder

- U and Th/Ra contamination in Gd powder becomes backgrounds for solar neutrino measurements
- Intensively developing pure Gd powder with several companies
- Radio impurity measured w/ two methods:

Ge detector: Sensitive to ~1 mBq/kg (Canfranc, Boulby and Kamioka)
ICPMS: For isotopes w/ long life (Kamioka) [arXiv:1709.03417 (accepted by PTEP)]

<table>
<thead>
<tr>
<th>Series</th>
<th>Isotope</th>
<th>Typical</th>
<th>Goal*</th>
<th>Company A</th>
<th>Company B</th>
<th>Company C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ge</td>
<td>ICPMS</td>
<td>Ge</td>
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<tr>
<td>238U</td>
<td>238U</td>
<td>50</td>
<td>&lt; 5</td>
<td>&lt; 13</td>
<td>~ 0.7</td>
<td>&lt; 20</td>
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<tr>
<td></td>
<td>226Ra</td>
<td>5</td>
<td>&lt; 0.5</td>
<td>0.7 ± 0.4</td>
<td>—</td>
<td>&lt; 0.6</td>
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<tr>
<td>232Th</td>
<td>232Th</td>
<td>100</td>
<td>&lt; 0.05</td>
<td>—</td>
<td>~ 0.3</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>228Ra</td>
<td>10</td>
<td>&lt; 0.05</td>
<td>&lt; 0.4</td>
<td>—</td>
<td>&lt; 0.7</td>
</tr>
<tr>
<td></td>
<td>228Th</td>
<td>100</td>
<td>&lt; 0.05</td>
<td>1.7 ± 0.4</td>
<td>—</td>
<td>0.5 ± 0.2</td>
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<tr>
<td>235U</td>
<td>235U</td>
<td>30</td>
<td>&lt; 3</td>
<td>&lt; 1.3</td>
<td>—</td>
<td>&lt; 0.7</td>
</tr>
<tr>
<td></td>
<td>227Ac/Th</td>
<td>300</td>
<td>&lt; 3</td>
<td>&lt; 3.1</td>
<td>—</td>
<td>&lt; 2.3</td>
</tr>
</tbody>
</table>

* Goal for 0.2% Gd-sulfate loading

U, Ra: Achieved our goal, Th: Close to our goal
Each company is still making rapid progress on reducing radio impurity
EGADS is a success

✓ Operated fully loaded with Gd sulfate for over 650 turnovers
✓ No loss of gadolinium
✓ Low radioactivity Gd produced by working with manufacturers
✓ Water transparency maintained at SK-III/IV quality
✓ Gd removed successfully with resin at end of period

SK-Gd is ready to go!

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SK-Gd Plan

• Open tank in summer 2018
  • Seal leaks
  • Install new Gd water system
  • Replace failed PMTs

• Gadolinium sulphate loaded in two stages 0 -> 0.02% -> 0.2% in near future
  Gd will capture 50%(90%) of neutrons at 0.02% (0.2%) loading)
Silicon Burning Basics

A massive star (initial mass >13 M\(_\odot\) ), at the end of its life contracts and gets hotter...

Silicon burns first at core, until iron core forms

Silicon continues to burn in a shell, over a timescale of a few days

Weak nuclear reactions and pair annihilations produce more antineutrino emission at higher energies

... and this can be followed by a core collapse!

<table>
<thead>
<tr>
<th>Supernova Neutrinos</th>
<th>Silicon Burning Neutrinos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Energy ~20 MeV</td>
<td>Mean Energy ~2 MeV</td>
</tr>
<tr>
<td>Hours before light from SN</td>
<td>Days before light from SN</td>
</tr>
<tr>
<td>Detected in 1987</td>
<td>Never detected before</td>
</tr>
<tr>
<td>1000s of events in seconds at SK at &gt;10kpc</td>
<td>100s of events in a day at SK-Gd for stars at &lt;1kpc</td>
</tr>
</tbody>
</table>
The supernova burst neutrinos have much higher luminosity and energy... compared to those from silicon burning.

Data from:
arXiv:1606.04915
Benefits of Detection

• “Supernova forecast” – we would be able to warn of a nearby supernova well before the main burst!
  • Don’t miss the supernova
  • Warn the community

• Probes late stellar burning – very interesting to many astrophysicists

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Inverse Beta Decay at SK-Gd

Two event categories
• *Coincidence*: both the positron and neutron capture are detected in coincidence
• *Neutron single*: only the neutron capture is detected

See GADZOOKS! *Anti-neutrino spectroscopy with large water Cherenkov detectors*, Beacom and Vagins, PRL 53, 2004
Signal event rate at 0.2kpc

Masses and ranges chosen to reflect Betelgeuse Oscillation and detector efficiency will reduce the event rate

Event rate at SK-Gd will increase rapidly in final days before supernova

data from Odrzywolek
http://th.if.uj.edu.pl/~odrzywolek/

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For an early warning we need to detect *neutron singles* (events with no visible positron), as well as *coincidence* type events.

Positrons will be *mostly* invisible to SK.

More visible positrons in final hours

*(From the 15M Odrzywolek model)*
• Reactor and geo neutrino flux from geoneutrinos.org
• Intrinsic background estimated from existing trigger data
• ‘low background’ = low reactor + current intrinsic background
• ‘high background’ scenario = max reactor + double intrinsic background
Signal Alarm Example

- Intrinsic radioactive background dominant BG in *neutron singles* bin
- Reactor background important in coincidence bins
- Low energy of signal positrons shows WIT importance

Signal at $15M_{\text{solar}}$, 150 parsec, 11 hours before collapse

Likely reactor background

Intrinsic radioactive background

WIT = “Wide Intelligent Trigger” this is a software trigger system at SK. Parallel computers are used to examine every single hit, reducing the energy threshold to the minimum possible.

Signal efficiency estimated from detector and trigger simulation

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Signal Alarm Example

- Analysis in 2 bins
- Null likelihood is calculated for both bins from Poisson distribution, combined with Fisher’s method
- Alarm threshold is chosen based on the desired rate of false alarms (type 1 errors)

Signal at 15$M_{\text{Solar}}$, 150 parsec, 11 hours before collapse
Likely reactor background
Intrinsic radioactive background
Main sources of uncertainty are the stellar models and mass hierarchy.
# Short range warning time compared to KamLAND

<table>
<thead>
<tr>
<th>Case</th>
<th>Distance (parsec)</th>
<th>SK-Gd warning (hours)</th>
<th>KamLAND warning (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 $M_{\text{solar}}$</td>
<td>250</td>
<td>8 - 10</td>
<td>11 - 17</td>
</tr>
<tr>
<td>15 $M_{\text{solar}}$</td>
<td>150</td>
<td>10 - 15</td>
<td>46 - 87</td>
</tr>
</tbody>
</table>

- KamLAND assumes 0.071 – 0.355 background events per day
- The stellar mass assumptions are chosen to reflect Betelgeuse
- Normal mass hierarchy is assumed
- Threshold is 1 per 740 days
- Have not considered Poisson fluctuations of signal

KamLAND from arXiv:1506.01175

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• KamLAND assumes 0.071 background events per day for low BG
• Low background assumption used in both cases (in reality, more reactors have already turned on since 2015)

(normal hierarchy, low background case, 1 per 740 days false alarm)
Summary

• Super-Kamiokande will be gadolinium doped
  • Detect the DSNB in 2 years
  • Improve pointing for supernova burst
• Necessary refurbishment will happen this summer (2018)

• Pre supernova stars burn silicon and are powerful antineutrino sources
• SK-Gd will be able to detect this in advance of a supernova, provided the star is close enough
• Max range is about 700 parsecs, max warning is about 19 hours, but this is dependent on stellar models and mass hierarchy