Low energy neutrino observation and preparation for SK-Gd in Super-Kamiokande

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ICRR research Joint meeting, December 14th, 2019

(Supported by KAKENHI Grant-in-Aid for Scientific Research on Innovative Areas 26104008)
1 - Solar Neutrino in Super-Kamiokande

2 - Supernova Relic Neutrino

3 - Super-Kamiokande Gd project
Solar $\nu$ in Super-Kamiokande

- Super-Kamiokande is looking at $\nu_e$ from Sun $E_{\text{thr}}$ (SK-IV): $3.5 \text{ MeV} \rightarrow ^8\text{B} \nu$ (and hep?)

- Detection channel: $\nu-e^-$ elastic scattering

- Direction information used to select solar $\nu$

- Analysis goals:
  - Probe the inside of the Sun
  - Earth matter effect (day/night asymmetry)
  - Observation of the transition region between vacuum and matter oscillations (up-turn?)
Recent results in solar $\nu$ analysis (1/2) [Preliminary]

- Finalizing SK-IV analysis (Analyzed period Oct 2008 - May 2018)
- $^8$B flux is coherent over the different periods of SK (22 years)

<table>
<thead>
<tr>
<th>Period</th>
<th>Lifetime [day]</th>
<th>Extracted Signal</th>
<th>$^8$B flux [$\times 10^6$/cm$^2$/sec]</th>
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<tbody>
<tr>
<td>Last</td>
<td>2970</td>
<td>$57844^{+369}_{-367}$(stat)$\pm925$(syst)</td>
<td>$2.30 \pm 0.01$(stat)$\pm0.04$(syst)</td>
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<td>Previous</td>
<td>2860</td>
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Recent results in solar $\nu$ analysis (2/2) [Preliminary]

- Finalizing SK-IV analysis (Analyzed period Oct 2008 - May 2018)
- $^8$B flux is coherent over the different periods of SK (22 years)
- No correlation observed with the 11-years solar activity (62.8% prob. for constant flux)

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Other solar neutrino studies

- **Solar flare’s neutrinos:**
  
  - In case of rear solar flares, D. Fargion (2003) predicts a detectable amount of neutrino in SK ($\sim 7 \, \nu s$ in case of $10^{32}$ erg’s rear solar flares.)
  
  - No signal observed in the different SK periods.
  
  - High energy search is also performed (results are compatible with the BG level)
  
  - Some other solar neutrino studies are on-going (like sun anti-neutrino or non-standard interaction searches).

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Figure from Okamoto-san (ICRR)

**Low energy event search for Solar Flares in SK-IV:**

- Preliminary
Supernova Relic Neutrino

- The Supernova Relic Neutrinos (SRN) or “Diffuse Supernova Neutrino Background” are an expected background of $\nu$ produced by all the past supernovae.

- Theoretical flux prediction: $0.3 \sim 1.5 \text{ cm}^{-2}\text{s}^{-1} (17.3\text{MeV threshold})$

- Signal: Inverse $\beta$ decay reaction:

- Large background rate is affecting the analysis
Backgrounds

Difficult analysis due to large backgrounds

Atmospheric $\nu_\mu$ CC

$\nu_\mu \rightarrow n + p + \mu^- \quad (T < 50 \text{ MeV})$

$\bar{\nu}_\mu \rightarrow n + p + \mu^+ \quad (T < 50 \text{ MeV})$

Atmospheric $\nu_e$ CC

$\nu_e \rightarrow n + p + e^- \quad (T < 50 \text{ MeV})$

$\bar{\nu}_e \rightarrow n + p + e^+ \quad (T < 50 \text{ MeV})$
Signal produce one neutron, most BG interactions don’t

Neutron detection $\rightarrow$ BG reduction

**Atmospheric $\nu_\mu$ CC**

\[
\nu_\mu + p \rightarrow n + \mu^- \quad (T < 50 \text{ MeV})
\]

\[
\bar{\nu}_\mu + n \rightarrow \mu^+ + e^- \quad (T < 50 \text{ MeV})
\]

**Atmospheric $\nu_e$ CC**

\[
\nu_e + p \rightarrow n + e^- \quad (T < 50 \text{ MeV})
\]

\[
\bar{\nu}_e + n \rightarrow p + e^+ \quad (T < 50 \text{ MeV})
\]

**Atmospheric $\nu$ NC**

\[
\nu_x/\bar{\nu}_x + 16O \rightarrow e^- + \gamma
\]

\[
\nu_x/\bar{\nu}_x + 16O \rightarrow e^+ + \gamma
\]
Super-Kamiokande Gd project

- Super-Kamiokande-Gd project (SK-Gd): load Gd in SK in order to detect neutrons from $\bar{\nu}$ interactions.
  - Gd: largest neutron capture cross-section among stable elements, and clear signal ($\gamma$ cascade).
  - $\sim 80\%$ of neutron tagging efficiency with $0.1\%$ of Gd ($\sim 90\%$ of Gd-n capture)
- Expect Supernova Relic Neutrino detection!

![Diagram showing the reaction $\bar{\nu}_e + p \rightarrow n + e^-$ and the capture of Gd in water with efficiency curves.]
The SK-Gd was approved by the Super-Kamiokande collaboration in June 2015.

In order to achieve it, we needed to:

1. Developed a water system able to keep good transparency with Gd-loaded water.
   → EGADS has been running as a demonstrator for SK-Gd since 2014, achieving good water transparency.

2. Fix the leak of the SK tank by at least a factor 10.
   → In summer 2018, we opened the SK tank for an extensive cleaning and maintenance of the detector.

After the extensive cleaning of the detector, we even managed to reduce the BG of our LowE analysis!
One of the main goal of the tank opening work was to fix the leak of SK.

This is a critical condition before loading Gd in SK, in order to avoid letting Gd spreads in the environment.

Several studies were performed since the end of the tank opening, allowing to determine the leak was reduced to be less than 0.017 tons per day.

The current SK water leakage has been reduced to less than 1/200th the rate during the period before tank refurbishment.

Success!
Gadolinium powder status

- 14tons of Gd sulfate have been delivered to Kamioka by the end of September.
- Radioactivity screening is being performed on all the different lots in order to validate if the Gd-powder passes our requirements.
- 2/3 of the Gd powder have been screened in Kamioka (about half have been screened by Ge detectors outside Japan).
- So far, all the samples passed our requirements.

<table>
<thead>
<tr>
<th>Chain</th>
<th>Isotope</th>
<th>Requirement (mBq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>238U</td>
<td>238U</td>
<td>&lt; 5</td>
</tr>
<tr>
<td></td>
<td>226Ra</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>232Th</td>
<td>232Th</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>228Ra</td>
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<tr>
<td>235U</td>
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<td>&lt; 30</td>
</tr>
<tr>
<td></td>
<td>227Ac/Th</td>
<td>&lt; 30</td>
</tr>
</tbody>
</table>
Water system status

▶ A dedicated Gd water system has been developed in order to allow the purification of Gd-loaded water in SK.
▶ The installation of new resin tanks, ultra filters, and UV system has been completed
▶ New plumbing for the new system has also been completed
▶ The anion exchange resin tanks has been completely filled since the beginning of this month.
▶ The 2/3 of cation exchange resin tanks has been filled in November. The remaining will be filled in February 2020.
▶ The system is operated and being flushed since October.
### Gd loading plan

**Refurbishment:** Water filling was completed in January 2019.

<table>
<thead>
<tr>
<th>Year</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>202X</th>
<th>202X+n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work</td>
<td></td>
<td>Fill pure water (2.5 months)</td>
<td>Pure water Run</td>
<td>T₁: 10ton Gd₂(SO₄)₃</td>
<td>T₂: 100 ton Gd₂(SO₄)₃</td>
</tr>
<tr>
<td><strong>SK-V</strong></td>
<td></td>
<td></td>
<td></td>
<td>0.01%Gd run ~50% n cap. eff.</td>
<td>0.1%Gd run ~90% n cap. eff.</td>
</tr>
</tbody>
</table>

Plan to start 0.01% Gd run in spring 2020. (Adjusting schedule with T2K)

Ll. Marti et al. (EGADS group), “Evaluation of Gadolinium’s Action on Water Cherenkov Detector Systems with EGADS”, submitted to NIM-A

Paper in SK LowE starts to be more “Gadolinium related” as SK-Gd approach. There is good hope it will increase in a near future!
Summary

► Solar neutrino:
  ▶ We are finalizing the analysis of SK-IV data.

► SK-Gd:
  ▶ Following the tank opening work in 2018, we managed to reduce the internal BG of the detector.
  ▶ Currently no significant leak is observed with the upper limit of \(0.017 \text{ tons per day}\) (better than our requirements for the Gd loading)
  ▶ The Gd powder is currently in Kamioka, with an on-going screening of its radioactivity.
  ▶ The final preparation for the Gd-loaded water purification system are on-going.

► We expect to load 10 tons of Gd powder in SK in the next 4 to 6 months!
Supernova Relic Neutrino in SK-Gd

Dependence on the typical SN emission spectrum

In events/10 years

Significance is determined with 2 energy bins

Gd loading will have other impact on the physics capability of SK:

- Improvement of the pointing accuracy for galactic supernova: By a factor $\sim 2$ at at 10 kpc
- Detection of pre-Supernova Si-burning neutrinos
- Reduction of the proton decay background
- Neutrino/anti-neutrino discrimination
- Detection of reactor neutrinos
EGADS water transparency

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

Black dashed line: final Gd sulfate concentration

Sampling position:

- Bottom
- Centre
- Top

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

Cherenkov Light Left (%) at 15 m

0.02\% Gd$_2$(SO$_4$)$_3$
0.1\% Gd$_2$(SO$_4$)$_3$
0.16\% Gd$_2$(SO$_4$)$_3$
0.2\% Gd$_2$(SO$_4$)$_3$

Fast recirculation system off
Band pass system off
Water system maintenance
Band pass and fast recirc. systems off
Maintenance
In order to reduce the background in the SRNs and Solar $\nu$ analysis, the radioactivity background from Gd powder needs to be minimized.

New radio-purity measurement method developed in order to obtain more precise values.

<table>
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<tr>
<th>Chain</th>
<th>Isotope</th>
<th>Goal (mBq/kg)</th>
<th>Company A Ge</th>
<th>Company B Ge</th>
<th>Company C Ge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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<td>$&lt; 0.4$</td>
</tr>
<tr>
<td></td>
<td>227Ac/Th</td>
<td>$&lt; 3$</td>
<td></td>
<td>$&lt; 1.2$</td>
<td>$&lt; 1.7$</td>
</tr>
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Thanks to the work with the different companies, we are close to our goal.

EGADS prototype has been filled with Company C best sample to test it.
Dedicated water purification system for Gd-water

The radon emissions from the different parts of the system will be checked:

- Some parts were tested with Gd water → ex: membrane de-gasifier: Rn emission compatible with measurement system BG expectations (0.5 ± 0.3 mBq/m³)

After the tank opening, the system will be used in order to improve the water quality early right after the filling (first real test of the system).
The existence of day-night asymmetry on the $\nu$ flux is expected from the MSW effect.

Last day-night asymmetry significance from SK is $1.9\sigma$ from 0 (combined measurement)

<table>
<thead>
<tr>
<th>Period</th>
<th>Lifetime [day]</th>
<th>Day Night Asymmetry [%]</th>
<th>Significance</th>
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<tr>
<td>Combined</td>
<td>5805</td>
<td>$-2.4 \pm 1.0 \pm 0.8$</td>
<td>$1.9\sigma$ from 0</td>
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<td>SK-IV</td>
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<td>$-2.1 \pm 2.0 \pm 1.3$</td>
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