SuperK-Gd

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On behalf of

The Super-Kamiokande Collaboration

- physics benefits
- the EGADS demonstrator
- implementation in Super-Kamiokande

EPS-HEP 2017
2017/07/06, Lido, Venice
Super-Kamiokande: superb physics thanks to **water-cherenkov technique**

- discovery of $\nu$ oscillations in the atmospheric sector
- key in the understanding of the solar-$\nu$ problem
- ....
- evidence for the appearance of atmospheric $\nu_\tau$
- first indication of terrestrial matter effects on solar-$\nu$

most stringent limits on:
- nucleon decay
- WIMP-type Dark Matter from indirect search
- Diffuse Supernova Neutrino Background

**Superk-Gd** (GADZOOKS!): go further with **high efficiency neutron tagging**


adding a 0.2 % by mass of a Gd compound, $\text{Gd}_2(\text{SO}_4)_3$, to SK water, the majority of final state neutrons produced in the interactions (90% captured $\times$ 90% reconstructed) will, after thermalized, be **captured by Gd** after $\sim$30 $\mu$s and detected through the **8 MeV $\gamma$ ray cascade** from its de-excitation
→ anti-neutrino tagging at inverse $\beta$ reaction

• be in position of discovering DSNB from the very much reduced background

• improve pointing accuracy for Supernova
• Supernova early warning from Si burning $\nu_s$
• high precision solar- $\nu_s$ elements from reactor $\nu_s$ (if available)
- neutrino / anti-neutrino discrimination by neutron counting

\[ E_\nu : [0.5, 0.7] \text{ GeV} \]

- neutron veto
\[ p \rightarrow e^+ \pi^0 \text{ MC} \]

- Atmospheric \( \nu \) MC

- Background probability reduced from 44% to 9%

- and more ....
EGADS @ hall near the SK area
Evaluating Gadolinium’s Action on Detector Systems

200 m³ tank with 240 PMTs

15 m³ tank to dissolve Gd
Gd water circulation system (purify water with Gd)
Gd-loaded water transparency within the SK ultrapure range

→ lossless (>99.99%) Gd-capable water system [ > 500 turnovers so far]
Some **calibration results:**
mimicking inverse $\beta$ decay signals with an Am/Be source and BGO scintillator

\[ ^{241}Am \rightarrow ^{237}Np + \alpha \]
\[ \alpha + ^{9}Be \rightarrow ^{12}C^* + n, ^{12}C + n \]
\[ ^{12}C^* \rightarrow ^{12}C + \gamma (4.43 \text{MeV}) \]

<table>
<thead>
<tr>
<th>Gadolinium Sulfate Octahydrate Concentration</th>
<th>Data</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2178 ± 76 ppm</td>
<td>29.89 ± 0.33</td>
<td>30.03 ± 0.77</td>
</tr>
<tr>
<td>1055 ± 37 ppm</td>
<td>51.48 ± 0.52</td>
<td>53.45 ± 1.19</td>
</tr>
<tr>
<td>225 ± 8 ppm</td>
<td>130.1 ± 1.7</td>
<td>126.2 ± 2.0</td>
</tr>
</tbody>
</table>

mean capture time of neutron (µsec)
wonderful cleanness and shininess all around after more than two years

This is 0.2% Gd$_2$(SO$_4$)$_3$ water. The EGADS tank has been fully loaded for over two years.
Radioactivity Contamination at Gd$_2$(SO$_4$)$_3$ very seriously assessed [source of severe background signals all along the Fiducial Volume]

Typical activities of salts in the market: (from over 10 samples from 5 providers)

<table>
<thead>
<tr>
<th>Radioactive chain</th>
<th>Part of the chain</th>
<th>mBq/kg</th>
<th>SRN (mBq/kg)</th>
<th>Solar $\nu$ (mBq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}U$</td>
<td>$^{238}U$</td>
<td>50</td>
<td>&lt; 5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$^{226}Ra$</td>
<td>5</td>
<td>-</td>
<td>&lt; 0.5</td>
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<tr>
<td>$^{232}Th$</td>
<td>$^{228}Ra$</td>
<td>10</td>
<td>-</td>
<td>&lt; 0.05</td>
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<tr>
<td></td>
<td>$^{228}Th$</td>
<td>100</td>
<td>-</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>$^{235}U$</td>
<td>$^{235}U$</td>
<td>32</td>
<td>-</td>
<td>&lt; 3</td>
</tr>
<tr>
<td></td>
<td>$^{227}Ac / ^{227}Th$</td>
<td>300</td>
<td>-</td>
<td>&lt; 3</td>
</tr>
</tbody>
</table>

Physics based requirements for radioactive contaminations

work done mostly at the Canfranc Underground Laboratory

- salts from different providers had in general similar contaminations
- Superk-Gd can not afford those amounts of RI, approaches to reduce them
  - by ourselves from received batches [a lot of work being done in Kamioka, not discussed here]
  - Cooperative development of pure salts with chemical Co.
we are cooperating with the following companies:  

In the good track: reductions of x20 – x50 already achieved

<table>
<thead>
<tr>
<th>Chain</th>
<th>main subchain isotope</th>
<th>GSF-1703-C9-702142</th>
<th>ICPMS meas.</th>
<th>GSF-1604-C7-160303</th>
<th>ICPMS meas.</th>
<th>GSF-1611-C8-003</th>
<th>GSF-1703-C8-(RGD-OSF-005)</th>
<th>ICPMS meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>238U</td>
<td>238U</td>
<td>&lt; 13</td>
<td>0.7</td>
<td>&lt; 20</td>
<td>0.2</td>
<td>&lt; 13</td>
<td>&lt; 9.2</td>
<td>0.1</td>
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<tr>
<td></td>
<td>226Ra</td>
<td>0.7 ± 0.4</td>
<td>&lt; 0.64</td>
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<td>✔</td>
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<tr>
<td>232Th</td>
<td>228Ra</td>
<td>&lt; 0.39</td>
<td>1.3</td>
<td>&lt; 0.67</td>
<td>0.2</td>
<td>&lt; 0.3</td>
<td>&lt; 0.26</td>
<td>0.2</td>
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<tr>
<td></td>
<td>228Th</td>
<td>1.7 ± 0.4</td>
<td>0.5 ± 0.2</td>
<td></td>
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<td></td>
<td></td>
<td>✔</td>
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<tr>
<td>235U</td>
<td>235U</td>
<td>&lt; 1.3</td>
<td>&lt; 0.7</td>
<td>&lt; 0.6</td>
<td>&lt; 0.51</td>
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<td>✔</td>
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<tr>
<td></td>
<td>227Ac/227Th</td>
<td>&lt; 3.1</td>
<td>&lt; 2.3</td>
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<td></td>
<td>✔</td>
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Intensive work at  
- Canfranc Underground Laboratory  
- Kamioka Observatory  
- Boulby Underground Observatory (recently joined)  
- probably LNGS also joints
SuperK-Gd time line \( \rightarrow \) 3-phase procedure:

- \( T_0 \): drain + leak stop work
- \( T_0 \): fill + purify water
- \( T_0 \): pure water circulation
- \( T_1 \): load \( \text{Gd}_2(\text{SO}_4)_3 \) up to 0.02%
- \( T_1 \): stabilize water transparency
- \( T_2 \): full \( \text{Gd}_2(\text{SO}_4)_3 \) up to 0.2%
- \( T_2 \): stabilize water trans. measurement

Decision about when to trigger it \( (T_0) \) taken jointly by T2K and SK:
- \( \rightarrow \) proposed to start refurbishment by middle 2018
- \( \rightarrow \) final decision will be made at J-PARC PAC meeting (July 24-26)

Further key items:
- refurbishment / leak stop
- the new water system
Estimating the location of the leak

The data indicate that it is near the bottom of the SK detector.
• double coating with
  1. BIO-SEAL 197 epoxy resin: sneaks into small gaps
  2. Mine Guard C viscous material: allows more displacement (less penetration though)

**BIO-SEAL 197**

cover welded places with sealing material

Particularly suspicious: barrel PMT frame anchor at bottom
fixing the leak at SK tank
detailed, day-to-day schedule prepared by Mitsui & Co. Ltd:

<table>
<thead>
<tr>
<th>项目</th>
<th>1月</th>
<th>2月</th>
<th>3月</th>
<th>4月</th>
<th>5月</th>
<th>6月</th>
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</table>

- **water level**
- preparation
- primer coating for barrel
- Bio-Seal and primer coating for bottom
- MineGuard coating for bottom
- MineGuard coating for barrel
- water purification

In total: ~ 6 months needed for the job
SuperK-Gd water System  

60 m³/hr selective filtration system

Scale-up of the EGADS system with sophisticated powder transport and dissolving systems
SuperK-Gd water system being built in Hall G (4K m³)

SK water system

SuperK- Gd water system hall
Summary / Conclusions / Outlook

- Superk-Gd enlarges significantly the window of SK’s physics measurements
- EGADS has demonstrated its viability and reliability
- The implementation of SuperK-Gd will most probably begin in 2018
additional
The Super-Kamiokande experiment at Kamioka Observatory

Kamioka Observatory

Mt. Ikenoyama

1000 m

SK

50 Kt water tank

40m $\Omega$ x 40m H

PMT, s

ID: 11148, 20''$\Omega$

OD: 1885, 8''$\Omega$

SK measures Cherenkov radiation
### DSNB events number with 10 years observation

<table>
<thead>
<tr>
<th>model</th>
<th>10-16MeV (evts/10yrs)</th>
<th>16-28MeV (evts/10yrs)</th>
<th>Total (10-28MeV)</th>
<th>significance (2 energy bin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{eff}}$ 8MeV</td>
<td>11.3</td>
<td>19.9</td>
<td>31.2</td>
<td>5.3 $\sigma$</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ 6MeV</td>
<td>11.3</td>
<td>13.5</td>
<td>24.8</td>
<td>4.3 $\sigma$</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ 4MeV</td>
<td>7.7</td>
<td>4.8</td>
<td>12.5</td>
<td>2.5 $\sigma$</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ SN1987a</td>
<td>5.1</td>
<td>6.8</td>
<td>11.9</td>
<td>2.1 $\sigma$</td>
</tr>
<tr>
<td>BG</td>
<td>10</td>
<td>24</td>
<td>34</td>
<td>----</td>
</tr>
</tbody>
</table>

→ Improvement of $E_\nu$ reconstruction with tagged neutrons

→ NC / CC discrimination by n-tagging

\[ E_{\text{mis}} / E_{\text{vis}} \]

\[ \# \text{Gd-tagged neutrons} \]

$E_\nu > 1$ GeV
The key to Superk-Gd:

Selective Water Purification System

Pure water plus $\text{Gd}_2(\text{SO}_4)_3$

Ultrafilter

$\text{Gd}_2(\text{SO}_4)_3$ plus smaller impurities (UF Product)

Nanofilter

Impurities larger than $\text{Gd}_2(\text{SO}_4)_3$ (UF Reject flushed periodically)

Impurities smaller than $\text{Gd}_2(\text{SO}_4)_3$ (NF Product)

Reverse Osmosis

Larger and smaller impurities to drain (UF Flush + RO Reject)

Pure water (RO product) plus $\text{Gd}_2(\text{SO}_4)_3$

$\text{Gd}_2(\text{SO}_4)_3$ (NF Reject)
Selective Water Purification System: sketch of its EGADS implementation
water transparency measurement

UDEAL measures absolute attenuation lengths at 7 wave-lengths: in nm (its contribution to Cherenkov light is indicated in brackets)

337 (0.25), 375 (0.25), 405 (0.21), 445 (0.14), 473 (0.11), 532 (0.04), 595 (.003)
## Measured radioactivity in $mBq/kg$ for the $\text{Gd}_2(\text{SO}_4)_3$ batches purchased to date

<table>
<thead>
<tr>
<th>Chain</th>
<th>Sub-chain</th>
<th>Standford Materials 09/04</th>
<th>Standford Materials 10/08</th>
<th>Beijing Jinhonganxin 12/08</th>
<th>Changshu Huanyu 13/02</th>
<th>Beijing Jinhonganxin 13/03</th>
<th>Standford Materials 13/08</th>
<th>HK Tai Kun 13/07a</th>
<th>HK Tai Kun 13/07b</th>
<th>Standford Materials 14/12</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$</td>
<td>$^{238}\text{U}$</td>
<td>$51 \pm 21$</td>
<td>$&lt; 33$</td>
<td>$292 \pm 6$</td>
<td>$74 \pm 28$</td>
<td>$242 \pm 6$</td>
<td>$71 \pm 20$</td>
<td>$47 \pm 26$</td>
<td>$73 \pm 27$</td>
<td>$&lt; 76$</td>
</tr>
<tr>
<td>$^{226}\text{Ra}$</td>
<td>$8 \pm 1$</td>
<td>$2.8 \pm 0.6$</td>
<td>$74 \pm 2$</td>
<td>$13 \pm 1$</td>
<td>$13 \pm 2$</td>
<td>$8 \pm 1$</td>
<td>$5 \pm 1$</td>
<td>$6 \pm 1$</td>
<td>$&lt; 1.4$</td>
<td></td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$^{228}\text{Ra}$</td>
<td>$11 \pm 2$</td>
<td>$270 \pm 16$</td>
<td>$1099 \pm 12$</td>
<td>$205 \pm 6$</td>
<td>$21 \pm 3$</td>
<td>$6 \pm 1$</td>
<td>$14 \pm 2$</td>
<td>$3 \pm 1$</td>
<td>$2 \pm 1$</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$^{228}\text{Th}$</td>
<td>$28 \pm 3$</td>
<td>$86 \pm 5$</td>
<td>$504 \pm 6$</td>
<td>$127 \pm 3$</td>
<td>$374 \pm 6$</td>
<td>$159 \pm 3$</td>
<td>$13 \pm 1$</td>
<td>$411 \pm 5$</td>
<td>$29 \pm 2$</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>$&lt; 32$</td>
<td>$&lt; 32$</td>
<td>$&lt; 112$</td>
<td>$&lt; 25$</td>
<td>$&lt; 25$</td>
<td>$&lt; 32$</td>
<td>$&lt; 12$</td>
<td>$&lt; 30$</td>
<td>$&lt; 1.8$</td>
<td></td>
</tr>
<tr>
<td>$^{227}\text{Ac}$</td>
<td>$214 \pm 10$</td>
<td>$1700 \pm 20$</td>
<td>$2956 \pm 30$</td>
<td>$1423 \pm 21$</td>
<td>$175 \pm 42$</td>
<td>$295 \pm 10$</td>
<td>$&lt; 6$</td>
<td>$&lt; 18$</td>
<td>$190 \pm 6$</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>$^{40}\text{K}$</td>
<td>$29 \pm 5$</td>
<td>$12 \pm 3$</td>
<td>$101 \pm 10$</td>
<td>$60 \pm 7$</td>
<td>$18 \pm 8$</td>
<td>$3 \pm 2$</td>
<td>$3 \pm 2$</td>
<td>$8 \pm 4$</td>
<td>$&lt; 5$</td>
</tr>
<tr>
<td></td>
<td>$^{138}\text{La}$</td>
<td>$8 \pm 1$</td>
<td>$&lt; $</td>
<td>$683 \pm 15$</td>
<td>$3 \pm 1$</td>
<td>$42 \pm 3$</td>
<td>$5 \pm 1$</td>
<td>$&lt; 1$</td>
<td>$&lt; 2$</td>
<td>$23 \pm 1$</td>
</tr>
<tr>
<td></td>
<td>$^{176}\text{Lu}$</td>
<td>$80 \pm 8$</td>
<td>$21 \pm 2$</td>
<td>$566 \pm 6$</td>
<td>$12 \pm 1$</td>
<td>$8 \pm 2$</td>
<td>$30 \pm 1$</td>
<td>$1.6 \pm 0.3$</td>
<td>$&lt; 2$</td>
<td>$2.5 \pm 0.6$</td>
</tr>
</tbody>
</table>

### For DSNB
- Expected signal $\sim 5$ events/year/FV
- $^{238}\text{U}$ Spontaneous Fission:
  - $\sim 5.5 \left[ \gamma (E_\gamma > 10.5 \text{ MeV}) + 1n \right] / \text{year} / \text{FV}$ x10 reduction desirable

### For solar neutrino
- Current BG $\sim 200$ events/day/FV
- U (n) $\sim 320$ events/day / FV x10 reduction desirable
- Th/Ra ($\beta, \gamma$) $\sim 3 \times 10^5$ events/day / FV x$10^3$ reduction needed
Procedure

• **Barrel**
  – If the origin of the leak is at the place, the strain deformation is the reason of the leak.
  – Bio-seal will break if the strain deformation happens.
  – → Do only the MineGuard-C *(reduce the total working time)*

• **Bottom**
  – Defect of welding might be the reason. If the distortion is expected to be less than 0.01mm, painting Bio-Seal will work.
  – → Do Bio-Seal and cover the MineGuard-C