Status of GADZOOKS!: Neutron Tagging in Super-Kamiokande

Pablo Fernández, UAM
for the Super-Kamiokande collaboration
ICHEP2014, July 5th, Valencia
The Super Kamiokande Experiment
Outline

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GADZOOKS!: The upgrade of SK for identifying anti-neutrinos
- main physics outcomes
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GADZOOKS!: The upgrade of SK for identifying anti-neutrinos
   - main physics outcomes

EGADS: a full-system prototype of GADZOOKS!
   - status and latest results
   - other studies respecting the whole GADZOOKS!
   - possible timeline
Super Kamiokande

50 kton water Cherenkov detector

~1000m overburden, in Kamioka mine

SK started the proton decay and neutrino physics searches in 1996

among world’s best neutrino detectors

divided in inner and outer detector:
   inner: 11146 20”-PMTs
   outer: 1885 8”-PMTs

typical volume for physics 22.5kton
Super Kamiokande

Major achievements:

- Kamiokande, its predecessor: first detection of cosmic neutrinos (SN1987A)
- Oscillations from atmospheric neutrinos ➔ massive neutrinos
- Neutrinos coming from the Sun ➔ Solar neutrino problem, terrestrial effects
- As LBL far detector: confirmation of ATMν results (KEK), ν_e appearance (T2K)
- Best proton decay bounds
- Most stringent bounds on Diffuse SN neutrino background
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The scientific capabilities of SK would improve dramatically if it is able to distinguish neutrino from anti-neutrino interactions

One of the main interactions in SK, specially at sub-GeV energies

\[ \nu_\alpha + n \rightarrow l_\alpha + p \quad \bar{\nu}_\alpha + p \rightarrow \bar{l}_\alpha + n \]
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**neutron tagging**
GADZOOKS!  Gadolinium Antineutrino Detector Zealously Outperform Old Kamiokande Super!

- Gd has the largest thermal neutron capture cross section of all stable nuclei (~49000 barn)

- After the neutron has thermalized, it is captured by Gd which emits a **8 MeV γ cascade** at its de-excitation

\[ \Delta T \sim 30 \mu s \]
**GADZOOKS!**

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$\bar{\nu}e^+p\rightarrow p+e^+\gamma$  
$\Delta T \sim 30 \mu s$

$\bar{\nu}$ can be detected through **space-time coincidence** of charged lepton and neutron capture, with ~80% efficiency

Currently in SK:

very difficult to detect,  
**IBD efficiency ~15%**

$\bar{\nu}e^+p\rightarrow p+e^+\gamma$  
$\Delta T \sim 200 \mu s$

Beacom and Vagins,  
*Phys. Rev. Lett.* 93  
171101, 2004
Upgrading SK by adding 0.2% of Gd$_2$(SO$_4$)$_3$, enables highly efficient neutron tagging method:

- >5 times larger than neutron capture with hydrogen
- >100 reduction factor in the rate of fake inverse-β decay events as compared with using hydrogen

The selection of Gd$_2$(SO$_4$)$_3$:

- very well soluble in water
- very low corrosion
- low effect on light transmission
Diffuse Supernova Neutrino Background (DSNB)

One of our main motivation for this upgrade is to first detect DSNB, neutrinos from all the supernovae in the history of the universe.

This would be detected through anti-neutrinos interacting inverse-$\beta$.
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At the moment SK can only put upper limits and they are 2-4 times larger than the theoretical predictions.
With efficient neutron tagging, we expect to be able to reduce most of backgrounds and be sensitive to DSNB.

Expected number of events in 10 years in $E_{\text{vis}} = 10-30$ MeV

[Horiuchi et al. PRD, 79, 083013 (2009)]
Galactic Supernova Burst

With neutron tagging, we can extract the $\bar{\nu}_e$ and $\nu_e$ spectra. Provides much more detailed information about the core-collapse process than that without neutron tagging.
Pre-Supernova

Detection of $\bar{\nu}_e$ produced during late Si burning stage of nearby ($\leq 2$ kpc) stars, a few days before core-collapse

![Graph showing the detection of $\bar{\nu}_e$ events](image)

<table>
<thead>
<tr>
<th>Detector</th>
<th>Target mass</th>
<th>Min. $\bar{\nu}_e$ energy</th>
<th>Events 48-24 hours before collapse</th>
<th>Events 24-0 hours before collapse</th>
<th>Events 3-0 hours before collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-K</td>
<td>32 kt</td>
<td>5 MeV</td>
<td>0.6</td>
<td>173</td>
<td>158</td>
</tr>
<tr>
<td>GADZOOKS!</td>
<td>22.5 kt</td>
<td>3.8(1.8) MeV</td>
<td>9 (204)</td>
<td>442 (1883)</td>
<td>345 (1130)</td>
</tr>
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Reactor Neutrinos

Improve sensitivity to solar sector oscillation parameters using reactor neutrinos

Although the future of Japanese nuclear reactors is not clear, GADZOOKS! will detect a similar rate from Korean reactors as KamLAND when all the Japanese reactors were on

~5 years, only GADZOOKS! 95% C.L. by K. Bays
Reactor Neutrinos

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Others

Improve our knowledge of atmospheric and accelerator neutrino interactions and final states

Neutron tagging can help discriminating between $\nu$ and $\bar{\nu}$ at GeV scale

Neutron tagging also reduces background in proton decay searches by requiring final states with no neutrons
Facility for testing the effect of Gd in water-Cherenkov detectors:

- Selective filtration for Gd water
- $\text{Gd}_2(\text{SO}_4)_3$ “cleaning” and dissolving
- Water transparency monitoring
- Gd concentration uniformity
- Gd removal

Last summer it became an actual detector, instrumented with 240 PMTs
EGADS hall

Main 200-ton Water Tank

15-ton tank
Gd Pre-treatment
Mixing Tank

EGADS hall

Resin-based Gd
Removal System

Selective Water+Gd
Filtration System

Rn measuring and
Ra removal

UDEAL

Membrane Flushing System
EGADS tank fully instrumented...
EGADS tank fully instrumented... and already taking data
Water transparency measurement with UDEAL

UDEAL: Underground Device Evaluating Attenuation Length

- Beam splitter & Steerer
- Adjustable mirrors
- Pulsed laser pointers and professional diodes
- Integrating spheres and UV enhanced photodiodes

Cherenkov light left at 15 m

- SK-III & IV pure water: 74.7% - 82.1%
- EGADS Top
- EGADS Middle
- EGADS Bottom

Measurements at different heights
Water transparency measurement with UDEAL

Non-instrumented EAGDS
For pure water, transparency was very stable and very good quality.

Good behavior when introducing Gd, < 15% drop
Water transparency measurement with UDEAL

Non-instrumented EAGDS
For pure water, transparency was very stable and very good quality

Good behavior when introducing Gd, < 15% drop

Instrumented EAGDS
For pure water, transparency was not so good quality

Became worse during the procedure of adding Gd, when changing the water level

After investigation, we found that there was a bad material
Gd concentration measurement with AAS

Non-instrumented EAGDS

Concentration becomes rapidly uniform along the whole volume of the detector after each Gd insertion.

\( \text{Gd}_2(\text{SO}_4)_3 \) remains homogenously dissolved.
Gd concentration measurement with AAS

Non-instrumented EAGDS
Concentration becomes rapidly uniform along the whole volume of the detector after each Gd insertion
Gd$_2$(SO$_4$)$_3$ remains homogenously dissolved

Instrumented EAGDS
No major effect in uniformity and stability of Gd concentration once the PMTs were installed
EGADS calibrations

All calibrations show stable and reliable performance of the detector

- 1 photo-electron
- Timing resolution
- PMT Q uniformity

1 p.e = 2.434 pC

±1%

auto-Xe lamp

Precise monitoring of the detector variations
• Am - Be source

Used to test detector performance and check Gd neutron capture efficiency

\[ {^{241}\text{Am}} \rightarrow {^{237}\text{Np}} + a \]

\[ {^{9}\text{Be}} + a \rightarrow {^{12}\text{C}} + g(4.4\text{MeV}) + n \]

Neutron capture delay after prompt signal depends on Gd concentration as expected from Monte Carlo simulations

<table>
<thead>
<tr>
<th>Gd$_2$(SO$_4$)$_3$</th>
<th>Data [ms]</th>
<th>MC [ms]</th>
</tr>
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<tbody>
<tr>
<td>115ppm</td>
<td>215.6 ± 4.1</td>
<td>221.8 ± 2.3</td>
</tr>
<tr>
<td>230ppm</td>
<td>121.1 ± 0.9</td>
<td>124.8 ± 2.1</td>
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Others respecting the whole GADZOOKS!: Inverse-β reconstruction

We are thoroughly investigating with realistic Monte Carlo simulations procedures for reconstructing the inverse-β reaction in GADZOOKS!

This is affected by the effect of the \( \text{Gd}_2(\text{SO}_4)_3 \) on light transmission (~15%). Two extreme cases considered: either Absorption or Rayleigh scattering
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Current results for neutron capture efficiency and purity using a multivariate likelihood method:

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<td>(e) reconstruction</td>
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<td>Likelihood</td>
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<td>94.8%</td>
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<td><strong>Total eff.</strong></td>
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**efficiencies**

**un-purities**
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**efficiencies**

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Studies at U. C. Irvine point that the effect of Gd is mainly scattering of light
Others respecting the whole GADZOOKS!: radioactivity contamination of Gd$_2$(SO$_4$)$_3$

The Gd compound will be dissolved uniformly along the whole active material of the experiment. Its radiopurity is an important issue.

Most of the radioactivity measurements for GADZOOKS! are performed in the Canfranc Underground Laboratory.

The contaminations are non-negligible:

<table>
<thead>
<tr>
<th>Chain</th>
<th>sub-chain</th>
<th>Gd-0904</th>
<th>Gd-1008</th>
<th>Gd-1208</th>
<th>Gd-1302</th>
<th>Gd-1303</th>
<th>Gd-1308</th>
<th>Gd-1307a</th>
<th>Gd-1307b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}$U</td>
<td>$^{238}$U</td>
<td>51±21</td>
<td>&lt; 33</td>
<td>292±67</td>
<td>74±28</td>
<td>242±60</td>
<td>71±20</td>
<td>47±26</td>
<td>73±27</td>
</tr>
<tr>
<td></td>
<td>$^{226}$Ra</td>
<td>8±1</td>
<td>2.8±0.6</td>
<td>74±2</td>
<td>13±1</td>
<td>13±2</td>
<td>8±1</td>
<td>5±1</td>
<td>6±1</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$^{228}$Ra</td>
<td>11±2</td>
<td>270±16*</td>
<td>1099±12</td>
<td>205±6</td>
<td>21±3</td>
<td>6±1</td>
<td>14±2</td>
<td>3±1</td>
</tr>
<tr>
<td></td>
<td>$^{228}$Th</td>
<td>28±3</td>
<td>86±5</td>
<td>504±6</td>
<td>127±3</td>
<td>374±6</td>
<td>159±3</td>
<td>13±1</td>
<td>411±5</td>
</tr>
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<td>$^{235}$U</td>
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<td>&lt; 32</td>
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<td>&lt; 112</td>
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<td>&lt; 32</td>
<td>&lt;12</td>
<td>&lt;30</td>
</tr>
<tr>
<td></td>
<td>$^{227}$Ac</td>
<td>214±10</td>
<td>1700±20</td>
<td>2956±30</td>
<td>1423±21</td>
<td>175±42</td>
<td>295±10</td>
<td>&lt;6</td>
<td>&lt;18</td>
</tr>
<tr>
<td>Other</td>
<td>$^{40}$K</td>
<td>29±5</td>
<td>12±3*</td>
<td>101±10</td>
<td>60±7</td>
<td>18±8</td>
<td>3±2</td>
<td>3±2</td>
<td>8±4</td>
</tr>
<tr>
<td></td>
<td>$^{138}$La</td>
<td>8±1</td>
<td>&lt;</td>
<td>683±15</td>
<td>3±1</td>
<td>42±3</td>
<td>5±1</td>
<td>&lt;1</td>
<td>&lt;2</td>
</tr>
<tr>
<td></td>
<td>$^{176}$Lu</td>
<td>80±8</td>
<td>21±2</td>
<td>566±6</td>
<td>12±1</td>
<td>8±2</td>
<td>30±1</td>
<td>1.6±0.3</td>
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Others respecting the whole GADZOOKS!:
Effects of radioactivity contamination in Gd$_2$(SO$_4$)$_3$

Basically two measurements are affected

Estimate by using typical values measured in the different batches:

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Diffuse SN neutrino Background
expected signal: **5 events/year/22.5kton**
background: comes mainly from $^{238}\text{U}$ SF $\Rightarrow$ **5.5 events/year/22.5kton**
tested purification (AJ4400) $\Rightarrow$ < $3 \cdot 10^{-2}$ events/year/22.5kton
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**Solar analysis**

expected signal from 3.5 MeV: **200 events/day/22.5kton**

background: mainly from $^{208}$Tl $\beta$-decay \(\Rightarrow\) **~ 10^5 \text{ events/day/22.5kton}**

*Ra and Th removal and analysis methods under study*

Gd$_2$(SO$_4$)$_3$
a possible timeline for EGADS & GADZOOKS!

06/2014 - 08/2014: EGADS 200-ton tank works
08/2014 - 11/2014: new EGADS test
05/2015: Make a decision among the SK collaboration

the 200m³ tank and ancillary instruments after EGADS

EGADS will continue as instant supernova detector with all the advantages of neutron tagging, capable to measure

~ 100 events from core-collapse in the center of our galaxy
~ 100000 events from Betelgeuse

EGADS is part of the new Multimessenger SN Astronomy in Japan
Summary

Very efficient neutron tagging can be achieved by adding 0.2% $\text{Gd}_2(\text{SO}_4)_3$ into SK, which will greatly improve antineutrino identification.
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EGADS will soon provide the complete de proof-of-principle tests of a Gd-loaded Water Cherenkov detector.