Super-K Gd project: Neutron-tagging algorithm

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- Summary
Super-K Gd Project: 0.2% Gd$_2$(SO$_4$)$_3$ dissolved in water, enables efficient neutron tagging with neutron capture on Gd

Detector simulator is upgraded to include Gd-interaction

Different features between H-capture & Gd-capture → Develop new (Gd-specific) n-tag algorithm with MC

$\Delta T \sim \text{few tens of } \mu \text{s}$
~86% Gd-capture, ~14% H-capture

**Gd-water vs. Pure water**

- Neutron capture time ($\tau \sim 200 \mu s$)
- Neutron capture time ($\tau \sim 30 \mu s$)

**Decay-time $\tau \sim 200 \mu s$**

**Total gamma energy (MeV)/n-capture**

100% H-capture

**Gamma multiplicity/n-capture**

Gd-gamma spectrum is from GEANT4.9.6p04 “photon evaporation model” + G4NDL4.2

**Individual gamma energy (MeV)**

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Event display

Super-Kamiokande IV
Run 989389 Sub 0 Event 71
17-06-0411224(7)146
Invert 2 hits, 40 pe
Outer: 2 hits, 0 pe
Trigger: 0x00
Ewall: 1609.0 ke
Eev: 0.9 peW

Super-Kamiokande IV
Run 989389 Sub 0 Event 21
27-06-04132147(1)148
Invert 10 hits, 12 pe
Outer: 0 hits, 0 pe
Trigger: 0x00
Ewall: 1550.0 ke
Eev: 0.4 peW

Gd-capture

H-capture

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Neutron-tagging algorithm

- Two-step selection process to maximize efficiency and minimize background rate
- Step 1. Initial selection
  - perform candidate selection from raw PMT hits
  - background from e.g. muon decays, PMT afterpulse, dark noises also included
- Step 2. Multivariate analysis with TMVA
  - make use of >20 variables
  - separating signals & backgrounds
Step 1: Initial selection

- Use a 10ns time window to search for PMT hit clusters

- Selection criteria:
  1. Neutron candidate time $dt < 200 \mu s$
  2. $N_{10}^{\text{cut}} = 7 \leq N_{10} \leq 50$, $N_{200} \leq 140$

For atm. neutrino events,

<table>
<thead>
<tr>
<th>$N_{10}^{\text{cut}}$</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
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<tr>
<td>Eff.</td>
<td>0.87</td>
<td>0.84</td>
<td>0.81</td>
<td>0.78</td>
<td>0.75</td>
<td>0.71</td>
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<tr>
<td>Bkg/evt</td>
<td>6.72</td>
<td>2.20</td>
<td>0.90</td>
<td>0.44</td>
<td>0.26</td>
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<td>Purity</td>
<td>0.23</td>
<td>0.47</td>
<td>0.67</td>
<td>0.80</td>
<td>0.87</td>
<td>0.90</td>
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Signal & Bkg distribution after Step 1

All captures
H-capture
Gd-captures

Background distribution

decay-electron bkg
Bkg from PMT after-pulse
(Residual ions and gas in tube cause additional hits)
Step 2: Multivariate analysis with TMVA

- TMVA: Toolkit for Multivariate Data Analysis with ROOT
- Machine learning environment developed by CERN
- Typical application: event classification & regression
- Consists of “training” & “application” → train “classification methods” every time MC setting is changed, tune & choose the best method
Step 2: Multivariate analysis with TMVA

- Input variables
  - Basic hit variables: neutron candidate time $dt$, number of PMT hits in XXns time window (NXX), etc.
Step 2: Multivariate analysis with TMVA

- Input variables
  - Neutron fitter variables: vertex position, energy, fit goodness, etc.

![Graphs showing distributions of input variables](image)

- Input variable: tbswall (distance to wall, cm)
- Input variable: tbsenergy (reconstructed energy, MeV)
- Input variable: tbsovaq (fit goodness)
Step 2: Multivariate analysis with TMVA

- Input variables
  - Isotropy variables*: measures the isotropy of PMT hits in space

\[ \beta_I = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} P_i(\cos \theta_{ij}) \]

* Taken from S. N. Ahmed et al. (SNO Collaboration), Phys. Rev. Lett. 92, 181301
Step 2: Multivariate analysis with TMVA

- Training outputs

![Background rejection versus Signal efficiency graph]

Best one: BDT
Overall signal efficiency & background rate (after Steps 1 & 2)

At Classifier cut = 0.00:
- Selection Purity = 0.97
- Efficiency = 0.81
- Gd-Efficiency = 0.92
- H-Efficiency = 0.29
- Bkg/evt = 0.06

Fine-tune of classifier cut can be done for specific analysis.
Preliminary error studies

- Impacts of different Gd-gamma models on simulation:
  - Geant4.9.6 “photon evaporation” (default, consistent with EGADS)
  - GLG4sim
  - Geant4.10 “photon evaporation”

<table>
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<tr>
<th>Setting</th>
<th>Geant4.9</th>
<th>GLG4sim</th>
<th>Hagiwara et al.</th>
<th>Geant4.10</th>
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<tbody>
<tr>
<td>Efficiency</td>
<td>0.81</td>
<td>0.81</td>
<td>0.80</td>
<td>0.78</td>
</tr>
<tr>
<td>Gd-Efficiency</td>
<td>0.92</td>
<td>0.91</td>
<td>0.90</td>
<td>0.87</td>
</tr>
<tr>
<td>H-Efficiency</td>
<td>0.29</td>
<td>0.29</td>
<td>0.29</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Individual gamma energy (MeV)
Preliminary error studies

- Possible worsening of water transparency due to dissolved $\text{Gd}_2(\text{SO}_4)_3$

![Graph showing Cherenkov light left at 15 m for EGADS detector]

Setting | Default: SKIV | Degraded-water transparency
---|---|---
Efficiency | 0.81 | 0.80
Gd-Efficiency | 0.92 | 0.91
H-Efficiency | 0.29 | 0.25
Summary

- Super-K Gd project: upgrade for improved neutron tagging that enables many physics targets.
- Neutron tagging algorithm specific for Gd-capture is developed, achieving 80% overall tagging efficiency (90% for Gd-capture).
- Efficiency change due to Gd-gamma model (5%) and water transparency (1%) is estimated.
- Super-K Gd related analysis tools are ready. More realistic sensitivity studies coming.