# Measurement of cosmogenic neutron production in SK-Gd

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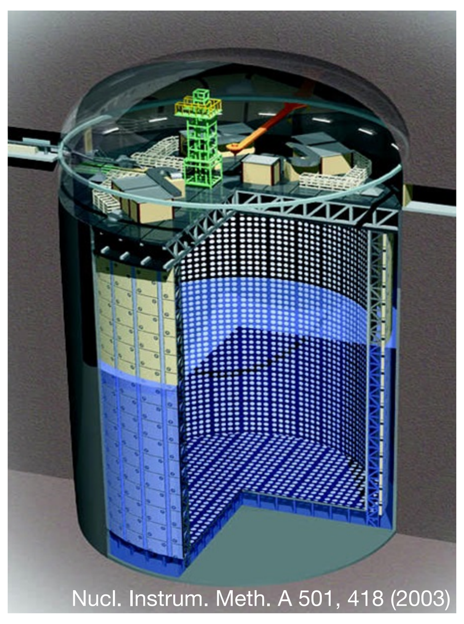
## Abstract

SK-Gd experiment has been started with gadolinium (Gd) added to ultra-pure water in Super-Kamiokande (SK). SK-Gd dramatically improves the sensitivity to supernova relic neutrino searches by tagging neutrons. Cosmic-ray muons flying into SK induce hadronic showers. Those break oxygen nuclei in water and produce unstable radioactive isotopes and neutrons, which are major background sources for supernova relic neutrino searches.

## 1. Introduction

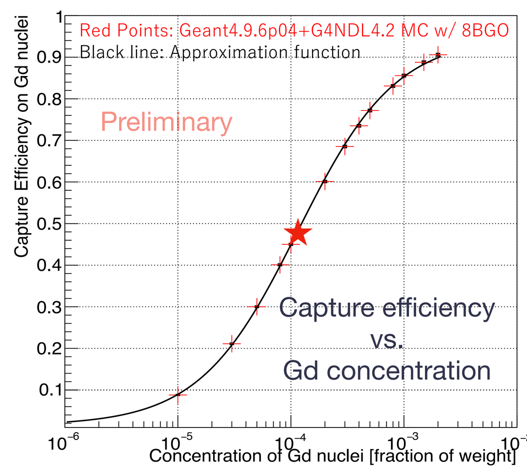
### Super-Kamiokande

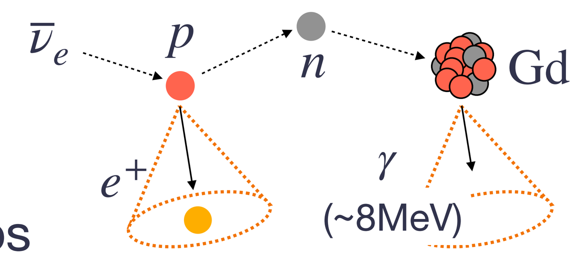



- 50-ktons water Cherenkov detector located at Kamioka, Japan
  - Overburden: 2,700 m.w.e.
- Diameter 39.3 m × Height 41.4 m
  - Fiducial volume: 22.5-ktons
- Detector wall is covered by PMTs.
  - Inner detector: >11,000 20” PMTs
  - Outer detector: >1,800 8” PMTs

### SK-Gd

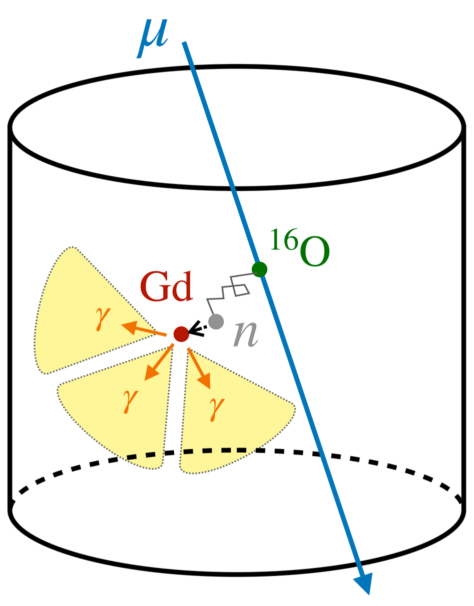
- SK-Gd experiment has been started with Gd sulfate dissolved in SK.
  - Gd mass concentration: ~110 ppm
  - The concentration will be increased step by step in the future.
- The detection efficiency of neutrons from neutrino interactions is improved dramatically.
- Major physics motivation:
  The first observation of supernova relic neutrinos

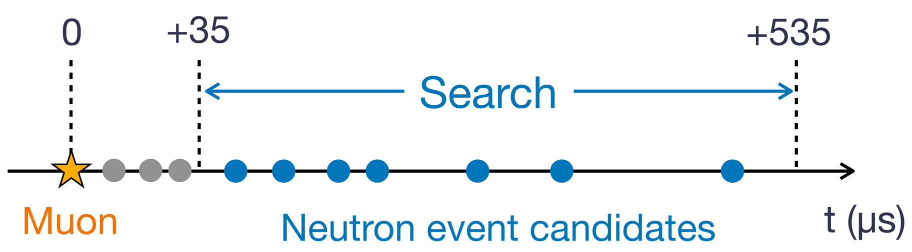



## 2. Cosmogenic neutron production

1. Cosmic-ray muons flying into SK induce hadronic showers.
2. Those break oxygen nuclei in water and produce neutrons.
3. These neutrons are thermalized and captured by Gd in ~115 μs.



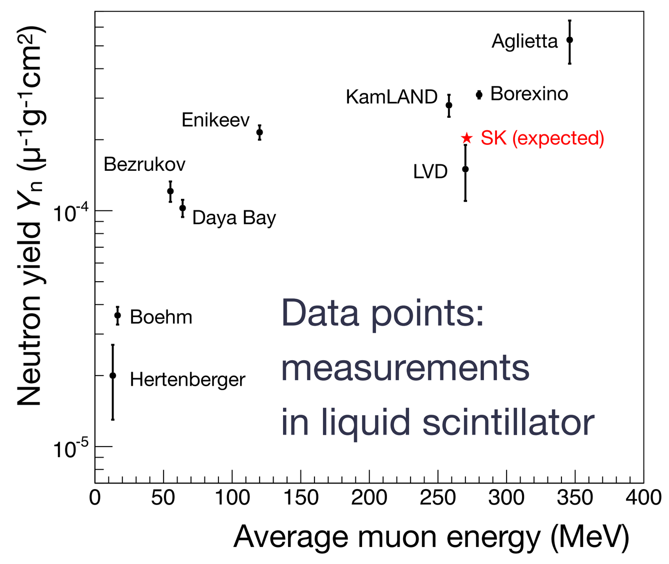

- Neutrons are searched in 35-535 μs.
- Events in 0-35 μs are not used to remove signals from decay-e and PMT after pulse.

Neutron production yield $Y_n$ is given as follows.

$$Y_n = \frac{N_n}{N_\mu L_\mu \rho_{Gd}}$$

- $N_n$ : Number of neutrons
- $N_\mu$ : Number of muons using for analysis
- $L_\mu$ : Muon path length
- $\rho_{Gd}$ : Gd water density

- Cosmogenic neutron production yield in water is not yet measured.
- Expected production yield in SK is
  $Y_n = 2.030 \times 10^{-4}\ \mu^{-1}\ g^{-1}\ cm^2$
  (S. Li and J. Beacom, Phys. Rev. C 89, 045801(2014))

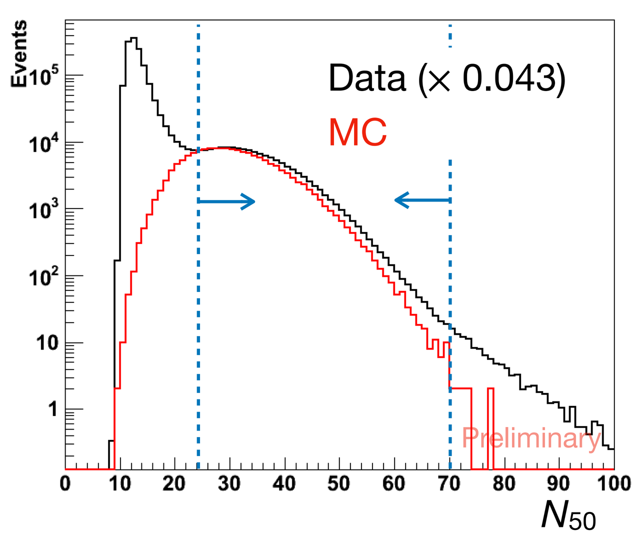


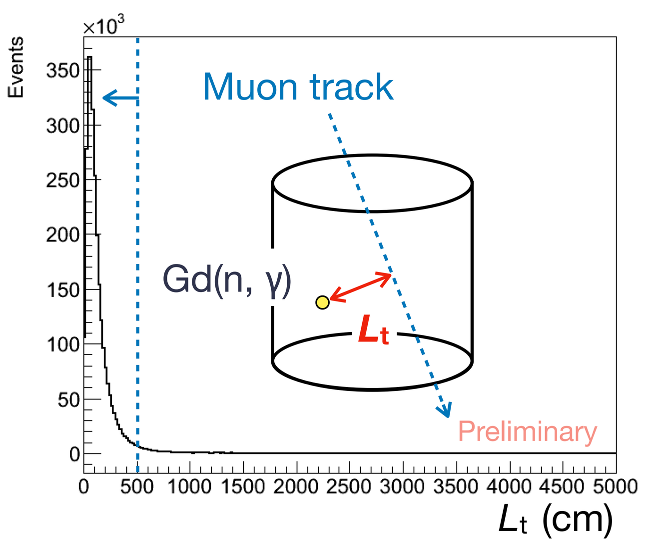

[Reference] Phys. Rev. C, 81, 025807 (2010), Phys. Rev. D, 97, 052009 (2018), Phys. Rev. C, 52, 3449 (1995), Phys. Rev. D, 62, 092005 (2000), Sov. J. Nucl. Phys. 17, 51 (1973), Sov. J. Nucl. Phys. 46, 1492 (1987), arXiv:hep-ex/9905047 (1999), JCAP 08, 049 (2013), Nuovo Cimento Soc. Ital. Fis. C 12 467 (1989)

## 3. Event selection

Neutron capture events are selected with 2 variables: $N_{50}$ and $L_t$.

- $N_{50}$: Number of PMT hits in 50 ns time window
- $L_t$: Transverse distance between muon track and neutron events



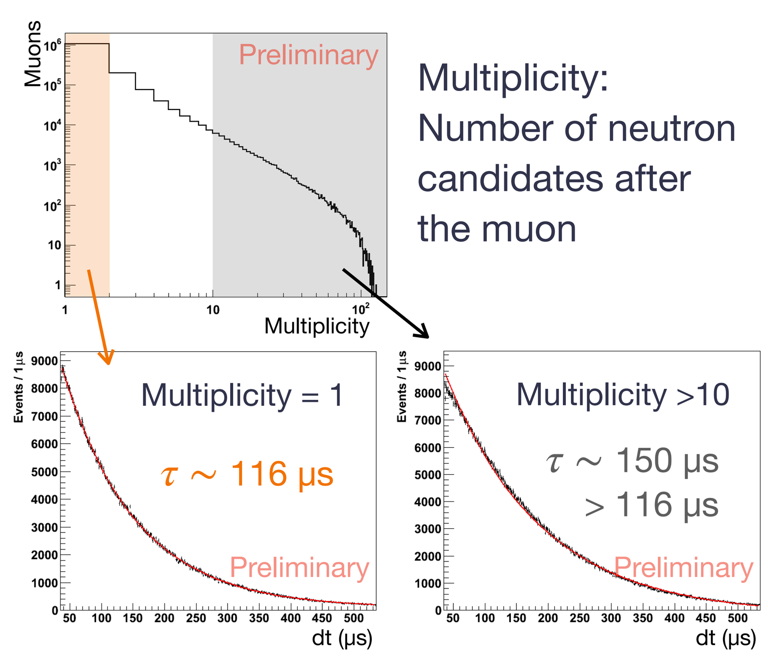




## 4. Stability and uniformity of Gd water quality

- Neutron capture time constant by Gd is determined by Gd concentration.
  116.2 ± 2.9 μs (w/ AmBe calibration source) ↔ 104 ± 2 ppm
- AmBe calibration & cosmogenic neutron measurement is complementary.

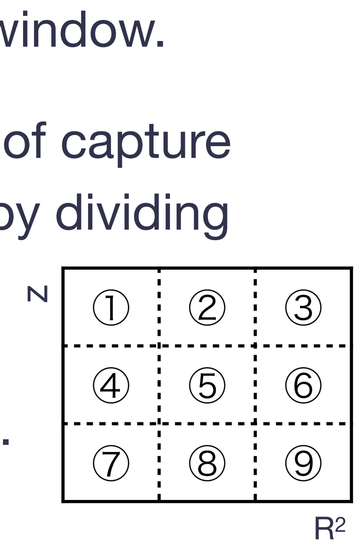
| Neutron source | Frequency | Position |
|---|---|---|
| AmBe | Every ~2 week | Specific (3-6 points) |
| Cosmic-ray muon | Continuous (~2Hz) | Uniform |

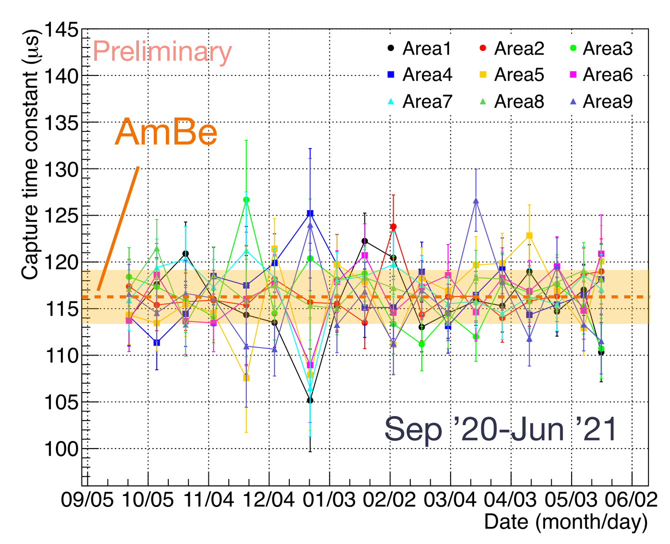
- Capture time constant is evaluated with the time difference ($dt$) between muon and neutron captured time.
- Cosmogenic neutrons from the muons with neutron multiplicity = 1 are used to check the consistency with AmBe.
  - For the muons with large multiplicity, the time constant is biased due to dead time by the trigger window.




- The stability and uniformity of capture time constant is evaluated by dividing the detector into 9 areas.

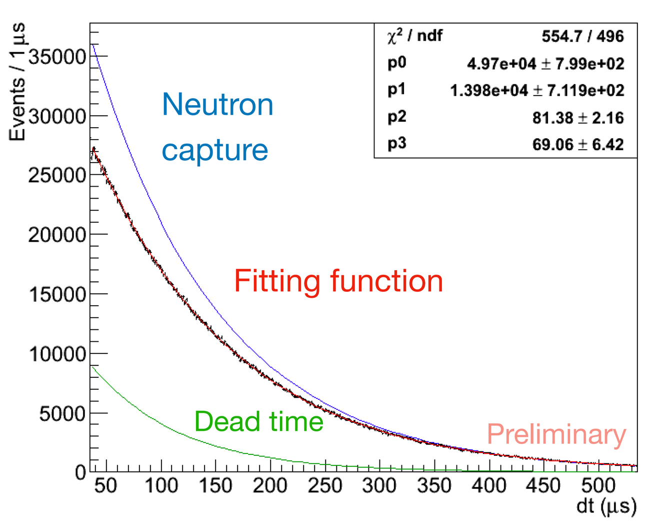
✓ Consistent with AmBe
✓ Gd water quality is stable.




## 5. Number of cosmogenic neutrons

- Neutron captured time follows exp. function.
- Dead time effect for event acquisition also follows exp. function.




- Fitting function

$$p_0 \exp\left(-\frac{dt}{116.2\,\mu s}\right) - p_1 \exp\left(-\frac{dt}{p_2}\right) + p_3$$

Neutron capture — Dead time — BG

- Number of neutrons

$$N_n = \epsilon^{-1} \times \int_{35\,\mu s}^{535\,\mu s} p_0 \exp\left(-\frac{dt}{116.2\,\mu s}\right) d(dt)$$

→ Systematic uncertainties are under investigation.

## Summary

- SK-Gd experiment had been started with Gd dissolved to SK and the detector is running stable.
- We are measuring the cosmogenic neutron production from SK-Gd data.
  - Cosmogenic neutron production yield will be evaluated, taking into account the systematic uncertainties.