Geant4 based Simulation Study for Super-Kamiokande

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Abstract. Super-Kamiokande (SK) will start a new phase "SK-Gd" from next year. Currently, SK uses Geant3 based simulation, however, its development has already stopped. For the next 10 years of SK-Gd operation, updated detector simulation is essential. For diffuse supernova neutrino background search in SK-Gd, precise neutron simulation is crucial. Therefore, we developed Geant4 based SK simulation software, named SKG4. Starting from the construction of SK geometry, some comparisons with the current SK detector simulation has been done. In this presentation, the current status of the development for SKG4 and the result of the several physics simulations will be reported.

1. Introduction
Neutrinos that have been emitted from past core-collapse supernova (CCSN) are expected to drift in our universe. This is called Diffuse Supernova Neutrino Background (DSNB). One of the purpose of Super-Kamiokande (SK) in the future is to observe DSNB. In the DSNB, electron anti-neutrino has the largest cross-section via inverse beta decay (IBD) reaction \( (\bar{\nu}_e + p \to e^+ + n) \) in the energy range of few tens MeV.

To suppress much background event strongly and expand the energy region in search, the SuperKamiokande-Gadolinium project (SK-Gd) is in preparation[1]. Gd has the largest capture cross-section for thermal neutron among all stable elements. Also, the total energy of the gamma rays that are emitted from this reaction is \( \sim 8 \) MeV, which can be easily detected by SK. SK-Gd will enable to separate IBD channel from the background by detecting the delayed neutron signal with high detection efficiency.

2. Detector simulation
Currently, the detector simulation software of SK (SKDETSIM) is based on Geant3. More update of physics models in Geant3 are not available now, and the neutron interaction model is crucial for SK-Gd. To solve this problem, new detector simulation software based on Geant4[2] was constructed, this is named 'SKG4'. Geant4 uses the latest physics models which are suitable for the energy region of the SK experiment, enabling the unique model based on experiment to be used. Especially, the model of gamma-ray, which is emitted from neutron capture on Gd, is based on very accurate experimental result[3].
3. Physics process comparison with SKDetSim

Before comparing the experimental data, the comparison of the physics model between SKDETSIM and SKG4 was carried out.

3.1. Photon reaction on the PMT

SK PMT has Quantum-Efficiency (QE) that depends on wavelength. This is about 20% at 350 nm. Before proceeding, it should be confirmed that the reaction on the PMT surface is correctly implemented in SKG4. As a method of confirmation, the optical photons with a wavelength of 350 nm were generated at the center of the tank. The ratio between the number of photons arriving at PMT and generating photoelectrons (p.e.) was compared with SKDETSIM.

Table 1 shows the result of 100,000 photon events in comparison with SKDETSIM. As a result, the ratio shows good agreement with SKDETSIM, therefore, it was found that the PMT response method was correctly implemented.

|                  | SKDETSIM   | SKG4       |
|------------------|------------|------------|
| Photons Arriving PMT | 40804 ± 202.0 | 41037 ± 202.5 |
| Photons generating p.e.  | 7554 ± 86.9     | 7579 ± 87.1     |
| Ratio             | 18.5 ± 1.6%   | 18.5 ± 1.6%   |

3.2. Electromagnetic (EM) physics

The electromagnetic process is one of the most important for SK physics, as the Cherenkov photon emission is managed in this physics process. The number of emitted Cherenkov photons and hit on PMTs were compared with SKDETSIM by generating 10 MeV electron from the center of the tank. Table 2 shows the result of both simulations. The difference between 2.7% and 1.6% can be explained by the difference in the dependency on the wavelength of Cherenkov emission between SKDETSIM and SKG4.

| Number of generated photons | Number of Photons which emit p.e. |
|-----------------------------|----------------------------------|
| SKDETSIM                    | 1950                             | 88.82                            |
| SKG4                        | 1897                             | 87.42                            |
| Difference                  | 2.7 %                            | 1.6%                             |

4. Comparison with Ni/Cf Calibration data

After all the parameters tuning and implementing trigger simulations, a comparison with the real Ni/Cf calibration data was conducted. Ni/Cf is used as the calibration source for the detail measurement of QE for each PMT. $^{252}$Cf emits neutrons and gamma-rays by spontaneous fission with a 3% probability. Finally, 9 MeV gamma-rays are emitted by the neutron capture reaction on Ni.
For this comparison, the number of hits within 50 nsec (N50) was used. This value is often used for the evaluation of the energy scale in calibration analysis. The gamma-rays with energy \( \sim 9 \text{MeV} \), and the branching ratios following the neutron capture on Ni are generated from both simulations.

Figure 1 shows the schematic of Ni/Cf calibration and the result of the comparison. Both of the simulations had good agreement with real data at the peak position. Another peak can be seen in only real data around N50 \( \sim 20 \). It is due to the fission gamma-ray by the alpha decay and spontaneous decay, and gamma-ray emitted by the neutron capture on a proton in the water.

\[ \text{Figure 1. Left figure: Ni/Cf calibration source photo[4] and schematic. Right figure: The result of N50 comparison.} \]

5. Conclusion and Status
SK-Gd experiment will start in 2020. Walking toward SK-Gd, a new simulation software named SKG4 was constructed. In this article, the behavior of the charged particles and optical photons in SKG4 were compared with SKDETSIM. The difference in the number of p.e. from 10 MeV electron with SKDETSIM was 1.6%. This difference is well understood and can be tuned. The result of the comparison with real data was also discussed. N50 distribution showed good agreement in both simulations, and there were no large differences between the data and simulations at the peak position.

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