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Evaluation of neutron tagging efficiency for SK-Gd experiment

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The world-largest water Cherenkov detector Super-Kamiokande was upgraded by loading 13 tons of gadolinium (Gd) sulfate octahydrate as a new experimental phase "SK-Gd". Thermal neutron capture on Gd emits gamma-rays with a total energy of about 8 MeV, so we can detect the neutron signal in SK-Gd more efficiently than in the pure-water phase. Therefore, an increase in the sensitivity of the search for the Supernova Relic Neutrino will be expected in the SK-Gd. Accurate evaluation of the neutron tagging efficiency is essential for SK-Gd. For the evaluation of neutron tagging efficiency, measurement using Am/Be neutron source was carried out. In this proceedings, the result of the evaluation of the neutron tagging efficiency and comparison with simulation will be reported.

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[*] Speaker

1. Introduction

Detecting neutrons are crucial for the Super-Kamiokande (SK) experiment to improve many kinds of physics sensitivity. However, the 2.2 MeV gamma-ray event due to neutron capture on protons, which is a primary neutron signal in the pure-water detector, is difficult to distinguish from PMT dark noise because of its low energy for the SK. Although neutron tagging algorithms using machine learning have been developed to identify as much of this signal as possible, the typical efficiency is only about 20% [1].

To improve neutron tagging efficiency, in 2020, SK loaded 13 tons of gadolinium sulfate octahydrate to its 50 kilo-tons of ultra-pure water [2]. This marked the beginning of a new phase, SK-Gd. The total energy of gamma rays from the thermal neutron capture on Gd is $\sim$ 8 MeV in total. This higher energy makes it possible to identify the neutron capture reaction more effectively. By dissolving $\sim$ 0.02% of the $Gd_2(SO_4)_3$ in mass concentration, roughly 50% of neutrons will be captured on Gd nuclei. Figure 1 shows the basic idea of the delayed coincidence method, which uses a prompt positron signal and a delayed neutron signal.

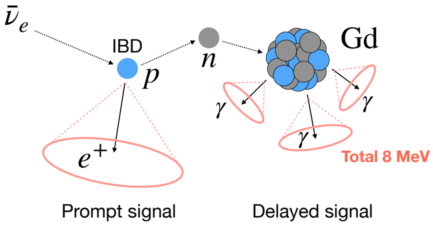

Figure 1: Idea of the delayed coincidence method for identification of inverse beta decay(IBD) in SK-Gd.

2. Am/Be source measurement

Evaluation of the neutron tagging efficiency is essential to estimate physics sensitivity in SK-Gd. Therefore, a study of neutron detection using Americium-241/Berylium-9 (Am/Be) radioactive source was carried out. Am/Be is famous for its neutron emission accompanying gamma rays. The main reaction can be written as $^{9}\text{Be} + \alpha \rightarrow {}^{12}\text{C} + \text{n} + \gamma(4.4\ \text{MeV})$. This measurement uses the delayed neutron signal and the prompt 4.4 MeV gamma ray as the target of the delayed coincidence.

For separating 4.4 MeV gamma ray from other low-energy events, we installed the source with the BGO scintillator crystal to enhance gamma-ray light yield. To estimate the unexpected effect of BGO crystal on the tagging efficiency, two kinds of source configure which are ”1BGO” and ”8BGO” were used. While the 8BGO structure is that source is fully surrounded by eight BGO crystals, the structure of the 1BGO configuration is that source is installed with one BGO. The picture of Am/Be source and BGO crystals are shown in Figure 2. In addition, to evaluate the effect of the source position, data takings were performed at nine points among the SK-Gd detector.

3. Analysis

The neutron tagging efficiency ϵ_n is evaluated by this formula

$$\epsilon_n = \frac{(\text{Number of tagged neutrons}) - (\text{Number of estimated background})}{(\text{Number of prompt events})} \tag{1}$$

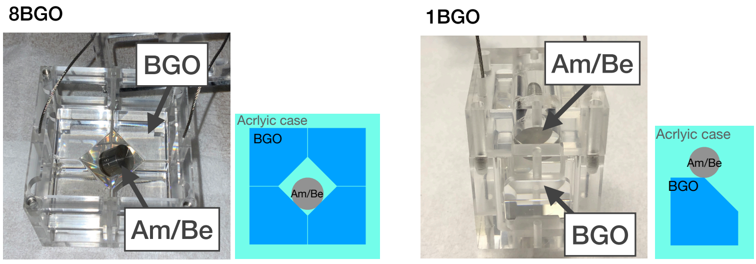

Figure 2: Appearance of the source set up for 8BGO and 1BGO structure.

For selecting a prompt event induced by our Am/Be+BGO source, the integrated charge of the inner detector (ID) within 1.3 μs around the trigger is used. Figure 3 is the observed charge distribution of the events. All hits within 535 μs after these events are recorded and analyzed for neutron search later. The events with its charge around 1000 p.e. are selected as the prompt event for the following analysis.

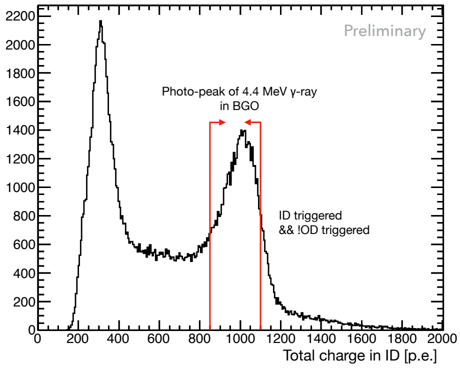

Figure 3: Distribution of the integrated charge for the inner detector of the prompt event. The peak which is seen around 1000 p.e. represents the photo peak of the 4.4 MeV gamma ray on the BGO scintillator.

Delayed neutron signals are searched in the time range of 4 μs and below 535 μs after the prompt event. Neutron candidates are selected by scanning with a 200 ns window and a threshold of 25 hits. Neutron signals are classified using four cut criteria about event reconstruction for each candidate. Figure 4 shows the distribution of cut variables and cut criteria. Filled histograms show the neutron signal computed by the Monte-Carlo simulation (MC). A fiducial volume cut which removes events within the 2 m from the tank wall, is already applied.

The time difference distribution between the prompt event and the delayed event of the tagged neutron is shown on the left side of Figure 5. The time constant τ was obtained by fitting this distribution and the result is consistent with the expected value. The number of background candidates is evaluated from the same fit of timing distribution.

The correlation between the tagging efficiency and the number of surrounding BGO is evaluated by the data at the detector center (Figure 5). The neutron tagging efficiency in the case without any BGO is estimated to be 40.5 ± 0.1(stat.)+1.0 (sys.)%, by MC simulation. The value obtained by data tends to be smaller than the MC estimate. The relative difference is -5.1% (-8.5%) in the case of 1BGO (8BGO). We concluded that the remaining $\sim$ 5% of discrepancy inevitably comes from

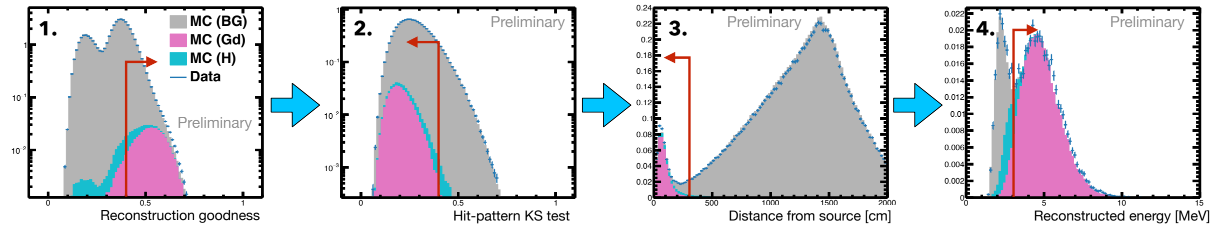

Figure 4: Distributions of the cut variables for delayed events. 1. Reconstruction goodness, 2. Hit-pattern KS test, 3. Distance from the source, and 4. Reconstructed energy. The red arrows show the cut criteria. These plots already applied the cut of former numbers.

the unknown effect of BGO and the detailed difference in data structure between actual data and MC. This discrepancy is considered as the systematic uncertainty for our evaluation of the tagging efficiency. Our systematic error estimation includes the uncertainty of Am/Be source properties, MC conditions, the cut criteria, and dependence on the source position.

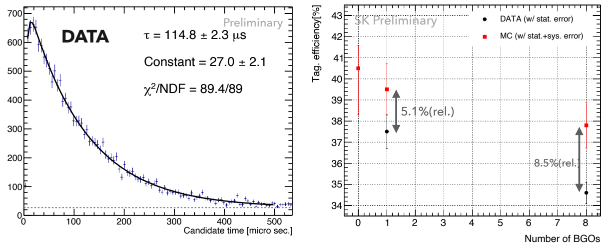

Figure 5: Time difference distribution from the prompt event of neutron events for 8BGO data (left), and the correlation between the number of BGOs and neutron tagging efficiency for the center position data (right). The dashed line shown in the left plot represents the number of background candidates evaluated by fitting to distribution.

4. Conclusion

We reported the first evaluation of the neutron tagging efficiency in SK-Gd. As a result, the efficiency without materials relevant to our source is estimated to be $40.5 \pm 0.1(\text{stat.})^{+1.0}_{-2.1}(\text{sys.})\%$ by extrapolating one and eight BGO result. We confirmed that the neutron tagging efficiency improved about twice from the pure-water period. The efficiency is roughly twice and the systematic uncertainty is relatively about half of the pure-water case [1] owing to our effort of understanding the source and BGO. The remaining difference between data and MC probably comes from the evaluation of background candidates and understanding of BGO characteristics. Furthermore, the probability of misidentification of noise event is 0.18%, which is comparable with the typical value of the pure-water period for the 20% of tagging efficiency.

References

[1] K.Abe et al., *PhysRevD.*, **104**,122002 (2021).

[2] K.Abe et al., *Nucl. Instrum. Meth.*, **1027**,166248 (2022).