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Neutron Tagging Technique in Super-Kamiokande

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Abstract: One of the physics goals in Super-Kamiokande Phase III (SK-III) is the observation of relic supernova neutrinos from the identification of their electron anti-neutrino component. Application of the delayed coincidence method benefits as a powerful tool in the selection of an electron anti-neutrino with a large background reduction. This selection is accomplished by detecting both a positron and a neutron created in the inverse beta decay. The technique of neutron tagging in Super-Kamiokande, a water Cherenkov detector, is reported with a newly designed trigger module together with the deployment of an apparatus of Am/Be-incorporated BGO crystal. Moreover, 2.4 liters acrylic vessel containing 0.2 % $GdCl_3$ solution is prepared to study the neutron tagging efficiency by Gadolinium: Am/Be-incorporated BGO crystal is installed at the center of the above vessel.

Introduction

Discovery of relic supernova neutrinos is one of the physics goals in Super-Kamiokande (SK) and search for $\bar{\nu}_e$ was conducted using its live data of 1,496 days and 791 days in the first and second phase (SK-I/SK-II), respectively. The obtained result, in particular, for SK-I is determined to be 1.2/cm^{-2}s^{-1} with 90 % confidence level [1] that is very close to the latest theoretical expectation of 1.1/cm^{-2}s^{-1} [2]. The difficulties in the current analysis reside in discriminating the irreducible background events of atmospehric ν_e as well as Michel electrons induced from invisible muons produced by incident atmospheric ν_μ on nuclei: their kinetic energy is below threshold of Cherenkov light creation. Application of the delayed coincidence method thus benefits as a powerful tool in the $\bar{\nu}_e$ selection together with the accomplishment of a large background reduction. This is achieved by detecting both a positron and a neutron created in the inverse beta decay. Therefore, detection of these neutrons is highly indispensable to realize the observation of relic supernova $\bar{\nu}_e$. In this paper, the study of neutron tagging motivated by this physics interest is presented.

Study of Neutron Tagging with Am/Be and BGO Scintillator

Free protons in water are of crucial importance for $\bar{\nu}_e$ detection in SK. The relevant reaction is the inverse β decay of $\bar{\nu}_e$ incident on one of such protons. Moreover, the observation of a neutron created in this reaction is highly motivated in order to identify $\bar{\nu}_e$ and reduce the background events. 0.2 % $GdCl_3$ dissolving into SK water is one of the methods resulting in 90 % efficiency of the thermalized neutron capturing on Gd. Hence this method is proposed [3] and currently under discussion among the SK collaboration. All the related reactions are depicted as follows:

$$\begin{aligned} \bar{\nu}_e + p &\rightarrow \underline{e^+} + n \\ n + p &\rightarrow ...(\mathrm{thermalization}) \rightarrow n + \mathrm{Gd} \\ &\rightarrow \mathrm{Gd} + \underline{\gamma(\mathrm{Totally\ 8\ MeV})}. \end{aligned}$$

The e^+ consists of the prompt signal while the delayed one is characterlized by gamma-rays yielding to the total energy of $\sim$ 8 MeV, which of these are underlined above. The γ-rays of such result from an advantage of usage of Gd with approximately 49,000 barns of the cross section against the capture of thermalized neutrons on this nucleus. These are released in 20 $\sim$ 30 μs after the inverse β decay reaction is occurred. The feasibility check with Gd solution is thus required for the study of neutron tagging. Am/Be radioactive source is used since this works as gamma and neutron emitter to experience the similar reaction of inverse β decay. The followings are the details of the relevant processes;

$$\begin{aligned} \alpha + {}^{9}\mathrm{Be} &\rightarrow {}^{12}\mathrm{C}^{*} + n \\ {}^{12}\mathrm{C}^{*} &\rightarrow {}^{12}\mathrm{C} + \underline{\gamma(4.4\,\mathrm{MeV})} \\ n + p &\rightarrow ...(\mathrm{thermalization}) \rightarrow n + \mathrm{Gd} \\ &\rightarrow \mathrm{Gd} + \underline{\gamma(\mathrm{Totally}\ 8\ \mathrm{MeV})}. \end{aligned}$$

Gammas underlined above are utilized as prompt (E_γ = 4.4 MeV) and delayed ($E_\gamma^{\mathrm{Tot}} = \sim$ 8 MeV) signals in this study. BGO scintillator, in addition, is prepared to trigger SK detector efficiently with high scintillation light induced from prompt 4.4 MeV gammas: Am/Be is embedded in the middle of BGO. The 2.4 liters of cylindrical $GdCl_3$ vessel is made of acryl with the configuration as in Figure 1. The Am/Be-incorporated BGO is placed at the center of this vessel and the whole apparatus is thus deployed at the detector center in SK.

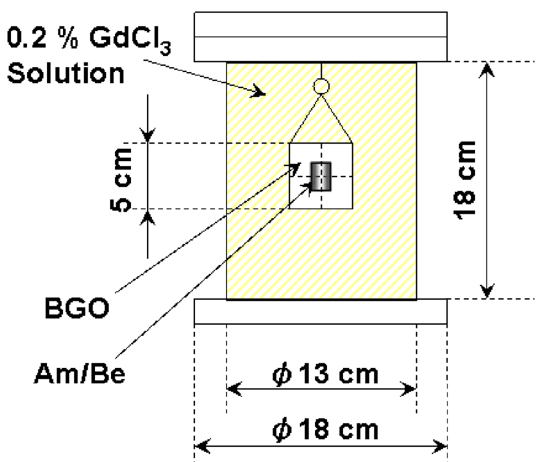

Figure 1: Configuration of the apparatus.

Forced Trigger System

1 MHz forced trigger system is introduced for this neutron tagging study. This trigger is activated once the prompt trigger is issued by the BGO scintillation light induced from 4.4 MeV γ-rays of Am/Be. The performance of the forced trigger results in the active 64 μs succeeding to the dead 64 μs and the recovery of alive 64 μs. Figure 2 indicates the schematic view of the forced trigger issue.

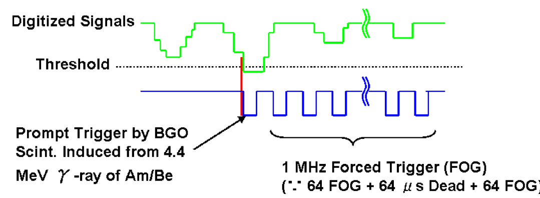

Figure 2: Schematics of forced trigger issue.

Data Analysis and Results

Experimental Mode

The BGO itself is, in fact, the combination of its 8 cubics to realize the 5 cm-in-length cubic as in Figure 1. Only one cubic with the length of 2.5 cm is also used in the experiment to understand the systematical difference in γ-ray spectrum released from Gd; this results from the shadow effect due to the different size of BGO. Both single and octal cubic cases are distinguished as different experimental modes.

Event Collection with FOG Activation

The parameter of T_{diff} is characterized as the time difference between prompt and delayed events. This parameter is studied at the first stage of the analysis to determine and extract the time activated in the forced trigger system with 100 % detection efficiency. Figure 3 is exhibited to introduce such T_{diff} regions of 100 % efficiency guaranteed. Terminology of both "On-time" and "Off-time" appeared in Figure 3 are referred to the T_{diff} regions of the signal presence and absence of gammas from Gd, respectively, to be discussed later in this section.

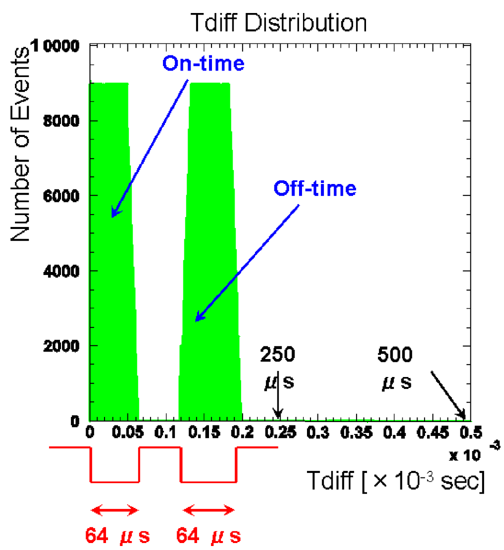

Figure 3: $T_{\rm diff}$ distribution.

Study of N10 for Signal Extract

N10 is defined as a maximum number of hit photomultipliers (PMTs) within the sliding 10 ns timing window and introduced to retrieve the contribution of gammas from Gd. The time of flight of photons is subtracted from the timing for all hit PMTs in the N10 calculation. Below are the N10 distributions only for "On-time" region (left) and "Off-time" region (right). Figure in left indicates a bump

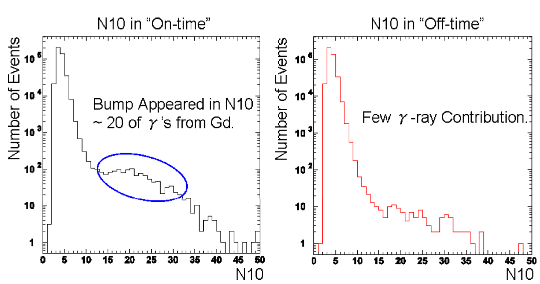

Figure 4: N10 distribution.

emerged approximately in 20 of N10 that is originated from Gd-released gammas. On the other hand, few gamma-ray contribution is observed in right so that it is found out signals are almost existed in the "On-time" region. For further analysis, the cut criteria is implemented with N10 of more than 15.

Ratio of (N300/N10) Cut for Cherenkov Event Retrieval

γ's emitted from Gd undergo to hit the deployed BGO leading to the emission of high light of scintillation. Study with the ratio of (N300/N10) helps to discriminate these from pure Cherenkov events of those gammas. N300 is analogous to N10 except the applied timing width to be 300 ns which is the decay time of BGO scintillator. Figure 5 includes the distributions of this ratio for data and MC in left and right, individually. Black-colored histograms in these panels indicate they are based on the single cubic case; while the usage of 8 cubics lead to those in red. Moreover, the cut of N10 > 15 is involved for all distributions. The shadow

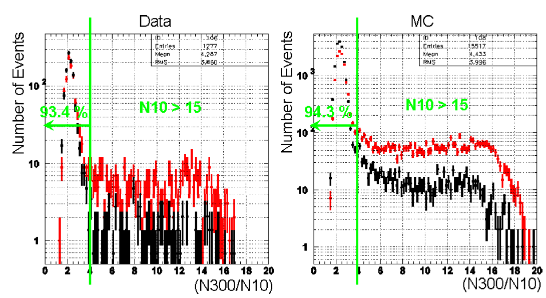

Figure 5: (N300/N10) ratio distribution.

effect resulting from the BGO volume is clearly observed in the above figures, and the ratio < 4 is determined for rejecting the scintillation events. In fact, this cut guarantees more than 90 % retrieval of Cherenkov events. This criterion is considered for later stages of the analysis.

$T_{\rm diff}$ Distribution After Data Quality Cuts

The same data quality cuts are contained in the following $T_{\rm diff}$ Distribution in Figure 6. Both are those of data in single (left) and octal (right) cubic cases. These are fitted with single exponential to retrieve the decay time of thermal neutrons, and are evaluated to be $\tau_{\rm Single}$ = 23.7 $\pm$ 1.7 μs and $\tau_{\rm Octal}$ = 30.4 $\pm$ 3.3 μs. They are consistent with the theoretically expected of $\sim$ 20 μs.

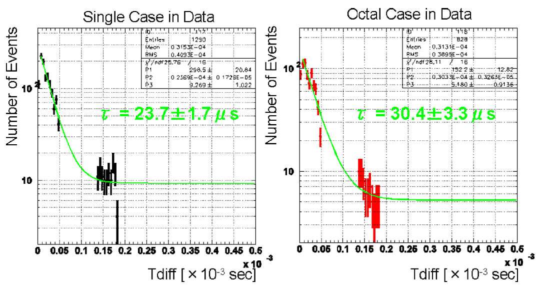

Figure 6: $T_{\rm diff}$ distribution after data quality cuts.

N50 Distribution After Data Quality Cuts

Data quality cuts discussed above are conducted for N50 distribution to make a clear observation of gammas from Gd. N50 is similar to N10 except the time width of 50 ns to be used as an energy evaluator. Two panels in Figure 7 are related to this study and all introduced are the histograms subtracted "Off-time" from "On-time" spectrum. The left incorporates two data distributions of N50 with single cubic case in black and octal case in red, in individual. Those for MC with the same color schemes are shown in right. In either case are figured out to be consistent the spectrum of the data and MC in $\sim$ 2 % in Gaussian peak.

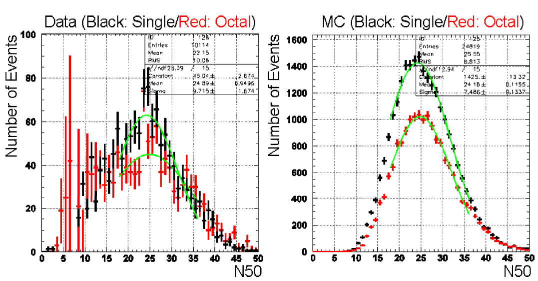

Figure 7: N50 distribution after data quality cuts.

Computation of Neutron Detection

The detection efficiency of neutrons is estimated at first in MC with the configuration of the volume of $GdCl_3$ solution to be infinity. And this study leads to 90 % efficiency realized of thermal neutrons captured on Gd. On the basis of the obtained unserstanding is motivated the experiment through the apparatus of the 2.4 liters of $GdCl_3$ solution together with the Am/Be and BGO. Considering the deployed apparatus surrounded by the water, results from data and MC are consistent each other in terms of the efficiency in 10 %: these are, in respective, 8.8 $\pm$ 0.2 % and 10.2 $\pm$ 0.1 % in the single cubic case, and the octal case gives 7.7 $\pm$ 0.3 % and 6.9 $\pm$ 0.1 %, individually. Statistical errors are only considered in the above results. Moreover, more than 90 % of neutron capture on Gd is observed in MC confining the 2.4 liters of volume. Thus, the detection efficiency of thermal neutrons in the real case of SK is confirmed to be $\sim$ 90 %.

Summary

Research and developement are performed with the apparatus of 2.4 liters of 0.2 % $GdCl_3$ solution, BGO scintillator and Am/Be radioactive source. The data analysis is then proceeded for the study of the neutron tagging using the above apparatus together with the introduction of the forced trigger system. γ-rays with $E_\gamma^{\rm Tot}$= $\sim$ 8 MeV emitted from thermal neutron capture on Gd are observed. And this result is found to be consistent with the expectation by MC in the study of the neutron decay time and the γ-ray spectrum in N50. Furthermore, the observation probability of those gammas are correspondent each other in data and MC. This is motivated from the MC study with the infinite volume of 0.2 % $GdCl_3$ giving $\sim$ 90 % detection of thermal neutron capture. Hence, a possibility of $\bar{\nu}_e$ is clarified via the developed apparatus of 2.4 liters of 0.2 % $GdCl_3$ solution.

References

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