



Neutron Tagging Technique in Super-Kamiokande

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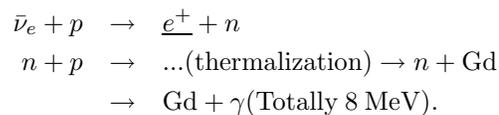
Abstract: One of the physics goals in SK-III is the observation of relic supernova neutrinos from the identification of their electron anti-neutrino component. Application of the delayed coincidence method benefits as a powerful tool in the selection of an electron anti-neutrino with largely reduced background. 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 % GdCl₃ 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 $1.2/\text{cm}^{-2}\text{s}^{-1}$ with 90 % confidence level [3] that is very close to the latest theoretical expectation of $1.1/\text{cm}^{-2}\text{s}^{-1}$ [1]. The difficulties in the current analysis reside in discriminating the irreducible background events of atmospheric 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.

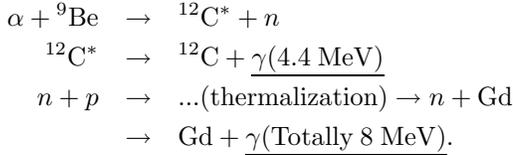
Study of Neutron Tagging with Am/Be and BGO Scintillator

Free protons in water are of crucial importance for $\bar{\nu}_e$ detection in SK. The relevant reaction is the quasielastic neutrino scattering, or 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 % GdCl₃ 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 [2] and currently under discussion among the SK collaboration. All the related reactions are depicted as follows:



The e^+ consists of the prompt signal while the delayed one is characterized by gamma-rays yielding to the total energy of ~ 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 $20 \sim 30 \mu\text{s}$ 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;



Gammas underlined above are utilized as prompt ($E_\gamma = 4.4\text{ MeV}$) and delayed ($E_\gamma^{\text{Tot}} = \sim 8\text{ MeV}$) 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 GdCl₃ 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.

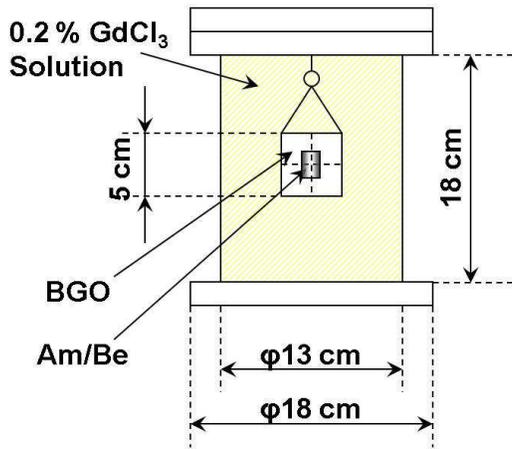


Figure 1: Configuration of the apparatus.

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.

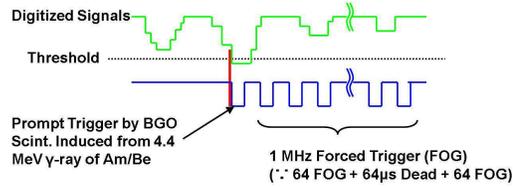


Figure 2: Schematics of forced trigger issue.

Data Analysis and Results

T_{diff} Distribution

The parameter of T_{diff} is defined 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.

N10 Distribution for Signal Extract

N10 is defined as a maximum number of hit photomultipliers (PMTs) within 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 PMT timing when N10 is counted. Below are the N10 distributions only for “On-time” region (left) and “Off-time” region (right). Figure in left indicates a bump emerged approximately in 20 of N10 that is originated from Gd-released gammas. On the other hand, few gamma-ray contribution is observed in

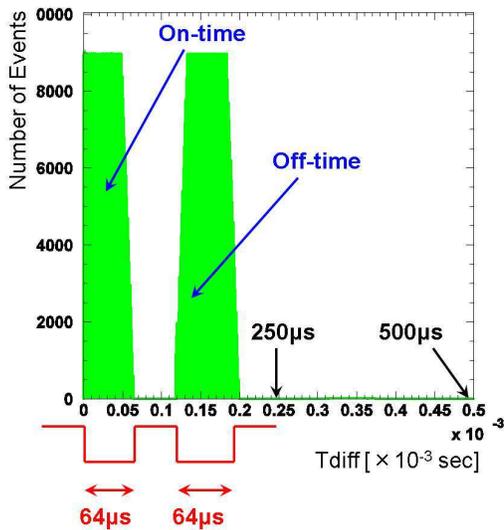


Figure 3: T_{diff} distribution.

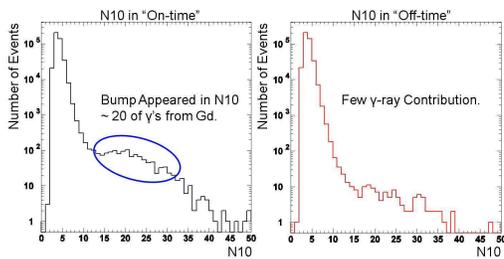


Figure 4: N10 distribution.

right so that it is found out signals are almost existed in the “On-time” region. For further analysis, the cut criteria is conducted with N10 of more than 15.

Rejection of Scintillation Events

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. In MC, the BGO placement is not considered to investigate the behavior of the ratio only based upon the Cherenkov events from gammas. Moreover, the cut of $N10 > 15$ is involved for both distributions. Hence, the ra-

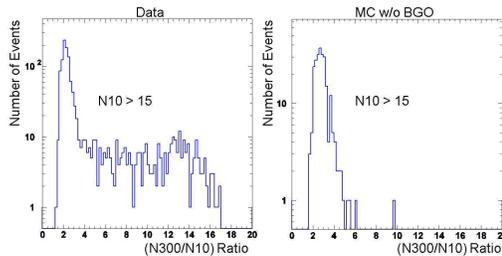


Figure 5: $(N300/N10)$ ratio distribution.

tio < 4 is accounted for rejecting the scintillation events and this cut is conducted for further analysis. In fact, cherenkov events are mostly observed with the contribution of scintillation less than 25 %.

N50 Distribution with Data Quality Cuts

Data quality cuts discussed above are performed for N50 distribution to make a clear observation of gammas from Gd. N50 is similar to N10 but the time width of 50 ns to be used as an energy evaluator. As in Figure 6, the subtracted N50 histogram in green obtained from the black colored one in “On-time” and the “Off-time” histogram in

red. The appeared bump is consistent in $N50 \sim 23$ with the expectation from MC in blue.

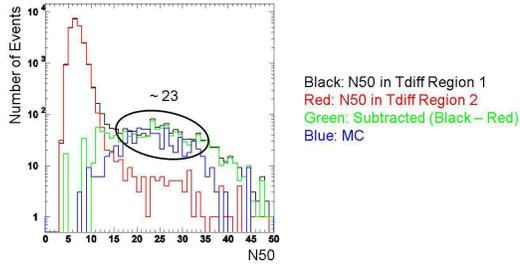


Figure 6: N50 distribution with data quality cuts.

T_{diff} Distribution with Data Quality Cuts

The same data quality cuts are included in the following T_{diff} Distribution in Figure 7. Both histograms are those for data and MC in left and right, respectively, fitted with exponential to retrieve the decay time of thermal neutrons. These are evaluated to be consistent each other with $\tau_{\text{Data}} = 40.7 \pm 4.7 \mu\text{s}$ and $\tau_{\text{MC}} = 31.7 \pm 3.0 \mu\text{s}$.

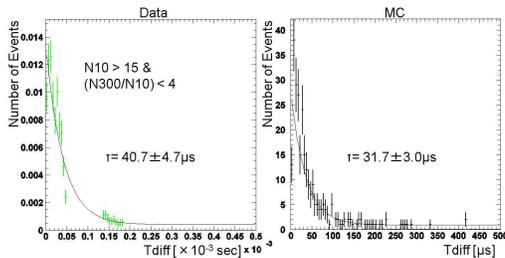


Figure 7: T_{diff} distribution with data quality cuts.

Computation of Neutron Detection

The detection efficiency of neutrons is estimated 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 understanding 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 of $9.3 \pm 0.3 \%$ and $9.8 \pm 4.3 \%$ in this apparatus. Moreover, more than 90 % of neutron capture on Gd is observed in MC confining the 2.4 liters of volume. So that the detection efficiency of thermal neutrons is confirmed to be $\sim 90 \%$.

Summary

Research and development 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 $E_{\gamma}^{\text{Tot}} = \sim 8 \text{ MeV}$ emitted from thermal neutron capture on Gd are observed and this result is found to be consistent with the expectation by MC: Decay time of capturing of such neutrons are $\tau_{\text{Data}} = 40.7 \pm 4.7 \mu\text{s}$ and $\tau_{\text{MC}} = 31.7 \pm 3.0 \mu\text{s}$ based on the T_{diff} as in the time difference between prompt and delayed signals. 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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- [2] J. F. Beacom and M. R. Vagins. *Phys. Rev. Lett.*, 93:171101, 2004.
- [3] M. Malek *et al.* *Phys. Rev. Lett.*, 90:061101, 2003.