Development of A Gadolinium-doped Water Cherenkov Detector for The Observation of Supernova Relic Neutrinos

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Abstract

Supernova relic neutrinos (SRN) are the neutrinos which are produced from all the past supernova explosions and are supposed to be flowing in the universe. No experiments have succeeded in detecting SRN yet. Super-Kamiokande (SK) is a 50-kton water Cherenkov detector which has the best sensitivity to SRN. A study of $\gamma$-rays produced in neutral-current neutrino-oxygen quasi-elastic interaction and in the pion absorption by oxygen nucleus was essential for the background estimation to SRN. This study has played a significant role in the result of SRN search in SK.

Although SK reaches an SRN flux approximately within a factor 2 above the theoretical expectations by detecting positron via inverse beta decay (IBD) interaction ($\bar{\nu}_e + p \rightarrow e^+ + n$), the present search is limited by the systematic error due to much background. In order to observe SRN by reducing background, a GADZOOKS! project is proposed. By dissolving gadolinium sulfate ($\text{Gd}_2(\text{SO}_4)_3$) into the SK pure water in the future, SK will be able to tag the neutron in coincidence of the positron and separate IBD from background events which associate no neutrons in most cases. A dedicated 200-ton detector, which is named EGADS, has been built to prove the feasibility of a realistic Gd-doped water Cherenkov detector.

In this thesis, the construction, the operation, and the initial performance of EGADS will be described. The delayed $\gamma$-ray signal from Gd neutron capture has been measured using an Am/Be neutron source at 115 and 230 ppm concentrations of $\text{Gd}_2(\text{SO}_4)_3$ in EGADS. The $\gamma$-ray energy, the position and the time of $\gamma$-ray production from Gd neutron capture are measured. The detection efficiency is defined as "neutron capture efficiency" times "reconstruction efficiency". The detection efficiencies for 115 ppm and 230 ppm concentrations of $\text{Gd}_2(\text{SO}_4)_3$ were measured to be $22.7 \pm 0.7\%$ and $35.2 \pm 1.0\%$, respectively. The background efficiencies for a 400 $\mu$sec time window were also measured to be $1.2 \pm 0.3\%$ and $1.1 \pm 0.3\%$ for each concentration. These results are found to be consistent with Monte Carlo simulation. We expect that the higher concentration provides the better performance since the neutron capture efficiency is linearly proportional to the detection efficiency.

Further, in order to evaluate the performance of the neutron capture in the SK detector, the $\gamma$-ray events from Gd neutron capture are observed in the SK detector by using the Am/Be neutron source and a 2-litter vessel filled with $\text{Gd}_2(\text{SO}_4)_3$ solution. The reconstruction efficiency of $\gamma$-ray from Gd neutron capture and the background efficiency for a 35 $\mu$sec time window were estimated to be $88.0 \pm 2.0\%$, and $(8 \pm 2) \times 10^{-3}\%$, respectively. We also estimated the performance of the Gd-doped SK detector. About 16 - 30 SRN events are expected for 10 years of measurement , and the cosmic-ray accidental background is expected to be negligible.
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Chapter 1

Physics Background

On the 23rd of February, 1987, the Kamiokande, IBM, and BAKSAN observed a neutrino burst from SN 1987A (Figure 1.1). The SN 1987A occurred at a distance of about 51.4 kpc from Earth, the three neutrino detectors detect the neutrino bursts approximately three hours earlier than the measurement by the optical detectors. Kamiokande detected 11 neutrinos, IBM detected 8 neutrinos, and BAKSAN detected 5 neutrinos. This was the first detection of a neutrino bursts from supernova explosion in history, and it introduced a new field of research: neutrino astronomy. This detection proved that the fundamental model of core collapse supernova was correct.

Figure 1.1: Supernova 1987A.

1.1 Supernova Explosion

The mechanism of supernova explosion is explained in this section. Supernova explosions occur at the final stages of the evolution of massive stars. As shown in Figure 1.2, supernovae are categorized into different types based on their spectroscopic characteristics and properties of the light curve. Supernovae can also be divided into two categories according to the mechanism of explosion. Type Ia supernovae are believed due to the thermonuclear disruption of white dwarfs, and they are discovered in galaxies containing very old stars. Type Ib, Ic and II supernovae are generated by the core collapse of massive
stars (M $> 8M_\odot$). From the point of view of neutrino physics, core-collapse supernovae are the most interesting, because they releases all types of enormous neutrinos.

1.1.1 Type II Supernova

Type II supernova is caused by the core collapse of the star whose mass is more than $8M_\odot$, where $M_\odot$ is solar mass. These star forms the iron core and burns the silicon at $T \simeq 3.4 \times 10^9$K. If the mass of the iron core exceeds the Chandrasekhar mass limit ($1.4M_\odot$), the gravitational core collapse and photodisintegration are caused within a 10 sec. If the neutron star is left, the released energy from the Type II supernova is calculated as

$$\Delta E = \left(-GM^2\right)_{GS} - \left(-GM^2\right)_{NS}$$

(1.1)

$$= 2.7 \times 10^{53} \left(\frac{M}{M_\odot}\right)^2 \left(\frac{R}{10km}\right)^{-1} \text{[erg]},$$

(1.2)

where GS and NS stand for a giant star and a neutron star, and the first term is almost negligible. On the other hand, the energy from the photodisintegration is estimated $1.4M_\odot \times 6 \times 10^{23} \times 3.2\text{MeV} \simeq 1 \times 10^{51}\text{erg}$. The kinetic energy for the ejecta mass of $M_{ej} = 10M_\odot$ is on the order of $E_{kin} = 1/2M_{ej} \times v^2 \simeq 10^{51}\text{erg}$, assuming $v \sim 2000\text{km/s}$. In short, neutrino emission from a core collapse carries 99 % of the released energy. The total energy obtained by SN 1987A is consistent with the calculation by Eq. 1.2.

Time evolution of type II supernova

1. Photodisintegration and neutronization

At the last stage of massive star evolution, the gravitational force is balanced by the pressure of degenerate relativistic electrons. In the core where the temperature and density are high, the photodisintegration of iron nuclei occurs in the interaction,

$$\gamma + ^{56}\text{Fe} \rightarrow 13\alpha + 4n - 124.4\text{ MeV},$$

(1.3)
and the electron capture also occurs.

\[ e^- + N(Z, A) \rightarrow N(Z-1, A + \nu_e) + \nu_e \]  

(1.4)

These lead to the reduction of the pressure support by the electrons and the trigger of a rapid core collapse. In this step, only electron-neutrinos are released freely from the core, because their mean free path is much longer than the radius of the core. However, the amount of released neutrinos is quite smaller than the one in the third step.

2. Neutrino trapping

The collapse in the inner part of the core is homologous. On the other hand, the material outside a certain value of radius collapses supersonically in quasi-free fall, and its velocity is proportional to the inverse square of the radius. Electron-neutrinos begins to be trapped via coherent scattering off nuclei in the core when the density of the inner core exceeds the $10^{11}$ – $10^{12}$ g/cm$^3$. The radius of this characteristic surface is calculated by the coherent scattering cross section and the density at

\[ R_\nu \approx 1.0 \times 10^7 cm \left( \frac{E_\nu}{10 MeV} \right). \]  

(1.5)

This surface is called a neutrinosphere. Neutrinos generated outside of the neutrinosphere can be released from the core. However, neutrinos generated inside can be diffused out like the photons from the photosphere of normal stars.

Figure 1.3: Time evolution of stellar shell for the selected mass points with the numerical supernova model from [2]. Mass 1.665 \( M_\odot \) is the first mass point. Solid lines are drawn for every fifth mass point. The dashed lines are for two succeeding mass points (108 \( M_\odot \) and 109 \( M_\odot \)) near the edge of the nascent neutron star and ejected matter.
3. **Core bounce and neutrino emission**

The homologous collapse continues until the density of the inner core reaches at the nuclear density $\sim 10^{14} \text{g/cm}^3$. Figure 1.3 shows the time evolution of stellar shell. The repulsive nuclear force stops the collapse, and drives the shock wave towards to the outer core. As the propagation of shock wave toward to outer core dissociating nuclei into free proton and neutron, enormous electron neutrinos are produced via electron capture.

$$e^- + p \rightarrow n + \nu_e$$  \hspace{1cm} (1.6)

The cross section of coherent scattering is proportional to the square of nuclear mass ($A$), which leads to the decouple of the previously trapped anti-electron neutrinos from the matter. This sudden release of electron-neutrinos is called prompt electron-neutrino burst or neutronization burst. The peak of neutrino luminosity exceeds $10^{53} \text{erg/s}$. However, due to the short time scale (a few msec scale), the total energy of the emitted neutrino is about $10^{51} \text{erg}$. Simultaneously, all types of neutrinos ($\nu_e, \nu_\mu, \nu_{\tau}$) are produced thermally in the hit post-bound region via following interactions, electron-positron annihilation,

$$e^- + e^+ \rightarrow \nu + \bar{\nu}$$  \hspace{1cm} (1.7)

and nucleon-nucleon bremsstrahlung.

$$N + N \rightarrow N + N + \nu + \bar{\nu}$$  \hspace{1cm} (1.8)

And, electron-neutrinos and anti electron-neutrinos are produced by charged-current interactions,

$$e^- + p \rightarrow n + \nu_e, \hspace{1cm} (1.9)$$

$$e^+ + n \rightarrow p + \nu_e. \hspace{1cm} (1.10)$$

4. **Delayed explosion**

Shock wave loses the energy by photodissociation of nuclei ($\sim 1.7 \times 10^{51}$ erg to disintegrate 0.1 $M_\odot$ iron) and by emission of neutrinos behind the shock front.

5. **Remnant of the star**

Time scale of thermal neutrino emission is 10 seconds. Finally, the protonneutron star cools and turns into a neutron star or black hole, which is determined by the its mass and initial metallicity.

**General description of type II supernova**

Hydrodynamic calculation with neutrino transport is used to obtain the neutrino flux from the Type II. The core density is $> 10^{13} \text{g/cm}^3$, so the core is opaque to neutrino transport. The effective temperature of the core surface is estimated by the radiation law as

$$T_{\text{eff}} = \left[ \frac{\Delta E}{4\pi\sigma R^2_{\text{eff}} 1/4 (7/8)g_{\nu}} \right]^{1/4}, \hspace{1cm} (1.11)$$

where $\sigma$ is Stefan-Boltzmann constant, $g_{\nu}$ is the number of neutrino species, $R$ is few 10 km, and $\tau$ is the cooling time of the core whose order is 5-10 sec. The effective temperature is obtained $\simeq$ 4 MeV and average neutrino energy $\bar{\epsilon}_\nu \equiv 3.15 T_{\text{eff}} \simeq 10 \text{MeV}$. The total neutrino flux is $\Phi_\nu = \Delta E / \bar{\epsilon}_\nu \simeq 2 \times 10^{58}$. The neutrino flux from the supernova at the center of the galaxy is obtained by

$$\phi_\nu = \frac{\Phi_\nu}{4\pi d^2} \simeq 1.6 \times 10^{12} \text{cm}^{-2} \text{[s/\nu cm}^2]. \hspace{1cm} (1.12)$$
Figure 1.4: Time evolution of neutrino luminosity and averaged energy from [2]. Dashed line is $\nu_e$, solid line is $\bar{\nu}_e$ and bold solid line is $\nu_x$ ($\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$).

From this flux, we expect the following events in a 1-kt water Cherenkov detector for a supernova at galactic center ($\sim 10$ kpc): 170 events ($\bar{\nu}_e + p \rightarrow e^+ + n$), 8 events ($\nu_e + e \rightarrow \nu_e + e^-$).

Figure 1.4 indicates the hierarchy of neutrino energies as follows:

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

The neutrino energy reflects the temperature of matter surrounding the neutrino sphere. Inside of the neutrinosphere, thermal equilibrium is established. The neutrinos emitted from the deeper and hotter part have the higher energy. The neutrinosphere for $\nu_x$ ($x = \mu, \tau$) and $\bar{\nu}_x$ is the smallest among all neutrino flavors, and the $\nu_x$’s interacts only via neutral current interactions. The neutrinosphere for $\bar{\nu}_e$ is smaller than that for $\nu_e$ because the proto-neutron star is neutron rich.

The current supernova models expect energy hierarchy shown in Eq. (1.13). However, it is not easy to derive the time integrated average energy without detailed calculation. As shown in Figure 1.5, the average energies for all neutrino flavors are estimated roughly in [2, 3] as follows:

$$\langle E_{\nu_e} \rangle \approx 13MeV$$
$$\langle E_{\bar{\nu}_e} \rangle \approx 16MeV$$
$$\langle E_{\nu_x} \rangle \approx 23MeV$$

Energy spectrum of supernova neutrinos is usually estimated by the Fermi-Dirac (FD) distribution with the zero potential [4].

$$\frac{dN}{dE} = \frac{L}{7\pi^2} \frac{120}{T^4} \frac{E^2}{e^{E/T} - 1}$$

where $T$ is the effective neutrino temperature ($T \approx (E)/3.1514$) and $L$ is the total neutrino luminosity. Figure 1.6 shows the energy spectrum is anti-electron neutrino calculated by supernova simulation [2].
The suppression at the low and high energy region compared with FD distribution can be seen, which is due to compensation by using a “pinched” FD distribution [6, 7].

\[
d\frac{dN}{dE} = L \frac{1}{F(\eta)} \frac{E^2}{T^4} \frac{1}{e^{E/T-\mu} + 1} \tag{1.18}
\]

where \( \eta \) is a pinching parameter and \( F(\eta) = dx^3/(e^x-\eta + 1) \) is a normalization factor. In this case, the average energy depends on both \( T \) and \( \eta \), and up to second order, \( \langle E/T \rangle \sim 3.1514+0.1250\eta+0.0429\eta^2 \).

1.2 Supernova Relic Neutrinos

Enormous numbers of supernovae have exploded since the beginning of the universe. There are about \( 10^{21} \) stars, and \( 10^{17} \) stars have a mass greater than 8 M\(_{\odot}\), and they are expected to finish as a supernova explosion. The neutrinos emitted from all such supernova explosions constitute the Supernova Relic Neutrino (SRN) flux. Measuring the overall flux and energy spectrum of SRN will enable us to investigate the history of past supernova explosions. For example, the flux of SRN can provide information on the star formation rate and supernova rate in galaxies.

1.2.1 Supernova Relic Neutrino Flux

The origin of Supernova Relic Neutrinos (SRN) is all supernovae from the big bang to the present day. Since SRN is the superposition of all supernova neutrinos, its spectrum is calculated by

\[
F_\nu(E_\nu) = c \int_0^{Z_{max}} R_{SN}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu} \left| \frac{dt}{dz} \right| dz, \tag{1.19}
\]

where \( c \) is light speed, \( R_{SN} \) is the supernova rate depending on the red shift parameter, \( E_\nu \) is detected neutrino energy, and \( E'_\nu = E_\nu(1+z) \) is the neutrino energy initially emitted. The relation between the cosmic time \( t \) and red shift \( z \) is calculated by Friedmann equation as

\[
\frac{dz}{dt} = -H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}, \tag{1.20}
\]

Figure 1.5: Energy spectra of neutrinos from [3]. Solid, dashed, and long-dashed lines correspond to \( \nu_e \), \( \bar{\nu}_e \), and \( \nu_x \), respectively.
Figure 1.6: Energy spectrum of $\bar{\nu}_e$ from the theoretical model from [2]. The chemical potential is set to zero for the FD distribution.

where $H_0$ is Hubble constant value, and $\Omega_m$ and $\Omega_\Lambda$ are the fraction of the cosmic energy density in matter and dark energy respectively.

There are many theoretical models estimating the SRN flux in a similar assumption. Even before the 1987A, SRN had been predicted, and its flux was calculated assuming the constant SFR without experimental data. After the 1987A, SRN flux is calculated more precisely. Figure 1.7 shows the theoretical SRN spectrum from [9]. The expected SRN spectrum peaks in $<10$ MeV region due to the red shift.

Rate of Supernova

The supernova rate is considered to be proportional to the star formation rate (SFR), because the lifetime of a massive star is much shorter than the lifetime of the universe.

The SFR is usually obtained by measurement of living massive stars [8]. In order to estimate the SFR from the observables, distribution of stellar masses at formation has to be considered as initial mass function. Figure 1.8 shows the SFR as a function of red shift. These results indicate that SFR increases with the red shift $z$ for $0 - 1$ region. It means that supernova explosion occurred more frequently in the early universe. For $z \leq 1$, $R_{SN}$ can be described as

$$R_{SN}(z) \equiv R_{SN}(0)(1 + z)^\beta,$$

(1.21)

where, $R_{SN}(0)$ is a normalization factor, and the best fit value for $\beta$ is 3.28 up to the red shift $z \sim 1$ [9].

1.2.2 SRN Search Experiment

The SRN search has been performed at several detectors in the world (Kamiokande[35], Mont Blanc[36], SNO[37], and KamLAND[38]). However, still SRN has not yet been discovered. The upper limits on SRN $\bar{\nu}_e$ flux by these experiments are shown in Table 1.1. SK currently has the best sensitivity to the SRN signal in the world. The advantage of the scintillation detectors is the lower background by neutron tagging, while a water Cherenkov detector is capable of large size detector because of cheap material.
Figure 1.7: Theoretical spectrum for SRN from [17].

Figure 1.8: Recent measurement of core-collapse supernova as the function of red shift, with the expectation from star formation rate data [5].


<table>
<thead>
<tr>
<th>Experiment</th>
<th>channel</th>
<th>Energy window [MeV]</th>
<th>Flux [cm$^{-2}$/sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kamiokande</td>
<td>$\bar{\nu}_e$</td>
<td>8-14</td>
<td>$\sim 10^2$</td>
</tr>
<tr>
<td>Super-Kamiokande</td>
<td>$\bar{\nu}_e$</td>
<td>16-30</td>
<td>2.8-3.0</td>
</tr>
<tr>
<td>Mont Blanc</td>
<td>$\nu_e$</td>
<td>20-50</td>
<td>$8.2 \times 10^3$</td>
</tr>
<tr>
<td>SNO</td>
<td>$\nu_e$</td>
<td>22.9-36.9</td>
<td>72</td>
</tr>
<tr>
<td>KamLAND</td>
<td>$\bar{\nu}_e$</td>
<td>$&gt;19$</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 1.1: Flux upper limit for each experiment.

**SNO**

Sudbury Neutrino Observatory (SNO) is a Cherenkov detector in Canada, and is consisted of 1 kton heavy water and 10,000 PMTs. From 1999 Nov. 2 until 2001 May 28 (306.4 days) corresponding to an exposure of 0.65 kton yr. SNO searches $\nu_e$ of SRN primarily through

$$\nu_e + d \rightarrow p + p + e^-$$ (1.22)

SNO obtained that upper limit of SRN $\bar{\nu}_e$ flux is 70 cm$^{-2}$s$^{-1}$ at the 90% confidence level in the energy range 22.9-36.9 MeV.

**Mont Blanc**

This is 90 tons liquid scintillation detector, which has been operating since 1985 at the Mont Blanc Laboratory. Mont Blanc obtained the $\bar{\nu}_e$ limit flux of $8.2 \times 10^3$cm$^{-2}$sec$^{-1}$ at the 90% confidence level by IBD search. LSD search $\nu_e$ and $\bar{\nu}_e$ signal via the following process.

$$\nu_e + ^{12}C \rightarrow ^{12}N + e^-$$ (1.23)

$$^{12}N \rightarrow ^{12}C + e^+$$ (1.24)

and

$$\bar{\nu}_e + ^{12}C \rightarrow ^{12}B + e^+$$ (1.25)

$$^{12}B \rightarrow ^{12}C + e^-$$ (1.26)

**KamLAND**

KamLAND is 1 kton single volume liquid scintillation detector in the Kamioka mine, and detecting anti-electron neutrino from the sun and other sources via inverse beta decay (IBD) interaction. This flux limit was applied for the SRN flux, result in SRN is found to be 139 cm$^{-2}$s$^{-1}$, assuming LMA model [15]. The main background in the scintillation detector is $^9$Li produced by cosmic muons, reactor neutrinos, and critical one is the atmospheric neutrinos.

**Borexino**

Borexino is 300 tons single volume liquid scintillation detector in Italy, and detecting anti-electron neutrino from the sun and other sources via IBD interaction. The specification of this detector is a low energy threshold: 60 keV, good energy resolution:4.5% at 1 MeV.
1.3 Supernova Relic Neutrino Search at Super-Kamiokande

The world’s best limit on the SRN flux comes from Super-Kamiokande (SK), a large water Cherenkov detector located in the Kamioka mine in Japan [18]. SK searches for SRN events via a positron signal produced by the inverse beta decay interaction, since its cross section is by far the largest of the possible supernova neutrino interactions with water.

\[ \bar{\nu}_e + p \rightarrow e^+ + n \] (1.27)

The cross section of neutrino interactions in 0 - 60 MeV range is shown in Figure 1.9. While SK does have the world’s best limit, its current search for SRN is strongly constrained by background; the search region for SRN \( \bar{\nu}_e \) has been confined to 16 - 30 MeV.

![Figure 1.9: Cross section for the water target, which includes the response of the SK detector like energy resolution and trigger effect. Figure is from [20].](image)

The most important sources of background are atmospheric \( \nu_\mu \) and \( \nu_e \) charged current interactions and \( \gamma \) rays produced by neutral-current neutrino-Oxygen interactions. Figure 1.10 shows the visible energy spectrum in the final data samples for each Cherenkov angle region, and fitting result of the LMA model is overlaid. Figures 1.11 and 1.12 show the exclusion contour.

1.3.1 Background

After all cuts for the SRN search are applied, remaining backgrounds are from atmospheric neutrino interaction. The energy spectrum of these remaining background is shown in Figure 1.13. These backgrounds are categorized into four interactions as follows:

- **Decay electron from invisible muon**
  This is the largest remaining background. Atmospheric muon-neutrinos interact in the SK detector and induce the muon via charged current interaction. This muon is low energy, often below Cherenkov threshold, in which case its decay electron cannot be removed, because the muon is invisible. This background’s energy spectrum is well known Michel spectrum.
Figure 1.10: SK-I/III final sample and LMA model best fit result for each Cherenkov angle region [18]. The SRN signal region is determined to be 38-50 degree region.

Figure 1.11: Exclusion contour showing the SRN event rate vs. neutrino temperature [18]. The red region is corresponding the 90% CL result of SK. CGI is Cosmic Gas Infall model [12], HMA is Heavy Metal Abundance model [13], CE is Chemical Evolution model [14]. LMA is Large Mixing Angle model [15]. FS is Failed Supernova model [16], and the 4 and 6 MeV are estimation of neutrino temperature from [17].
• **Atmospheric neutrino** ($\nu_e, \bar{\nu}_e$)

  Atmospheric neutrinos interact with proton or neutron as

  \[
  \begin{align*}
  \nu_e + n & \rightarrow e^- + p, \\
  \bar{\nu}_e + p & \rightarrow e^+ + n.
  \end{align*}
  \]

  Since SK cannot distinguish the electron and position signal, atmospheric $\nu_e$ cannot be separated from SRN $\bar{\nu}_e$ signals.

• **Neutral-current neutrino-oxygen quasi-elastic interaction (NC QE)**

  This is quasi-elastic scattering on an oxygen nucleus, which residual nucleus becomes excited, and can give off de-excitation $\gamma$ rays, or cause other nuclear reactions. This background have an energy spectrum that rises sharply at our lower energy bound, similar to SRNs. Most of them are removed by Cherenkov angle reconstruction, but some still leak into our final sample and must be modeled. With the lowering of the energy threshold from 18 MeV to 16 MeV, this background has become especially relevant.

• **Heavy particle production from atmospheric neutrino events**

  This background is a grouping of two different things, both heavier particles. First NC interactions generate charged pion (only $\pi^+ > 200$ MeV are generated here). The pion events $> 200$ MeV mostly deposit energy in the detector through Cherenkov radiation from the accelerated pion. As the energy reconstruction assumes these are electrons, the reconstructed energy varies largely and is roughly flat.

  Included with them, since the spectrum and Cherenkov angle distribution are relatively similar, are surviving muons (from muon-neutrino interactions) above Cherenkov threshold.
Backgrounds were modeled using SKDETSIM which is the official SK MC using GEANT 3.21 for particle tracking, and NEUT [21] to model neutrino interactions. The $\gamma$-ray production in neutrino-Oxygen NCQE interaction and pion absorption was re-evaluated and was contributed to the SRN search in SK.

1.3.2 Study of $\gamma$-ray Production in Neutral-Current Neutrino-Oxygen Interaction

The $\gamma$-ray production from neutral-current neutrino-Oxygen quasi-elastic (NC QE) interaction, one of remaining background, is very important, and has to be understood because its spectrum is similar to the SRN spectrum. Recently, the calculation of cross section of $\gamma$-ray production was performed [22, 23, 24].

The cross section of $\gamma$-ray production following a NC QE interaction, $\sigma_\gamma$, is written in the form

$$\sigma_\gamma = \sigma(\nu + ^{16}\text{O} \rightarrow \nu + \gamma + Y + N)$$

$$= \sum_\alpha \sigma(\nu + ^{16}\text{O} \rightarrow \nu + X_\alpha + N) \times Br(X_\alpha \rightarrow \gamma + Y),$$

(1.30)

(1.31)

where N is knocked out nucleon, $X_\alpha$ is the residual nucleus in the state $\alpha$, and Y is the system resulting from the electromagnetic decay in the state $X_\alpha$, e.g., $^{15}_8\text{O}$, $^{15}_7\text{N}$, $^{14}_7\text{O} + n$, $^{15}_6\text{C} + p$.

The cross section NC QE is calculated by

$$\frac{d\sigma_{\nu A}}{d\Omega dE_\nu'} = \sum_{N=p,n} \int d^3p dE P_N(p,E) \frac{M}{E_N} \frac{d\sigma_{\nu N}}{d\Omega dE_\nu}$$

(1.32)

where $E_N = \sqrt{M^2 - \mathbf{p}^2}$, M being is nucleon mass, $d\sigma_{\nu N}/d\Omega dE_\nu$ is elementary neutrino-nucleon cross section, $P_N(p,E)$ is the spectrum function that is the probability of removing nucleon of momentum $\mathbf{p}$ from the target leaving the residual nucleus with energy $E + E_0 - M$, $E_0$ being the target ground-state energy.

According to the shell model, nuclear dynamics can be described by a mean field. In the simplest implementation of this model, protons in the $^{16}\text{O}$ nucleus occupy three states, $1p_{1/2}$, $1p_{3/2}$, and $1s_{1/2}$.
with removal energy 12.1, 18.4, and 42 MeV, respectively [25, 26, 27]. The $p_{1/2}$, $p_{3/2}$, and $s_{1/2}$ spectroscopic strengths ($S_{\alpha}$) have been computed by integrating the oxygen spectral function over the energy ranges $11.0 \leq E \leq 14.0$ MeV, $17.25 \leq E \leq 22.75$ MeV, and $22.75 \leq E \leq 62.25$ MeV, respectively.

Dividing these numbers by the degeneracy of the shell-model states, one obtains the quantities listed in Table 1.2. The same spectroscopic strengths have been used for protons and neutrons.

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$p_{1/2}$</th>
<th>$p_{3/2}$</th>
<th>$s_{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{\alpha}$</td>
<td>0.632</td>
<td>0.703</td>
<td>0.422</td>
</tr>
<tr>
<td>Br($X_\alpha \rightarrow \gamma+Y$)</td>
<td>0%</td>
<td>100%</td>
<td>16 ± 1%</td>
</tr>
</tbody>
</table>

Table 1.2: Spectroscopic strength of the $^{16}$O hole states ($S_{\alpha}$) and their branching ratios for de-excitation by the $E_\gamma > 6$MeV photon emission [23].

The branching ratios $Br(X_\alpha \rightarrow \gamma + Y)$, necessary to calculate the cross section ($\sigma_\gamma$), are also given in Table 1.2. In the case of the $p_{1/2}$-proton (neutron) knockout, the residual nucleus is $^{15}$N ($^{15}$O) ground state. Hence, no $\gamma$ rays are produced. As the $p_{3/2}$-proton (neutron) hole lies below the nucleon-emission threshold, 10.2 MeV (7.30 MeV), they always de-excites to the ground state by the emission of 6.2 or 6.3 MeV $\gamma$ rays. When a proton (neutron) is knocked out from the deepest $s_{1/2}$ shell, the excitation energy is high enough for many de-excitation channels to open, of which only two, $^{14}$C + p and $^{14}$N + n ($^{14}$C + p and $^{14}$C + $\alpha$), yield photons of energy higher than 6 MeV. The theoretical estimate of the branching ratio for these processes [23, 28, 29], being in total 16%, turns out to be in good agreement with the value $15.6\pm 1.3\%^{\pm0.6}$% measured by the $^{16}$O(p, 2p)$^{15}$N experiment (E148) carried out at the Research Center for Nuclear Physics of the Osaka University [30].

Recently, T2K experiment measured the cross section of $\nu_{\mu} + O \rightarrow \nu_{\mu} + X + \gamma$, for the first time [22].
1.3.3 The $\gamma$-ray Production in Pion Absorption

The re-evaluation of the $\gamma$-ray background by pion absorption in NEUT was one of the key points to the publication of SK SRN result \[18\]. NC interactions generate pion ($\nu + ^{16}\text{O} \rightarrow \nu + ^{16}\text{O} + \pi$). The pion interaction above 100 MeV is dominated by $\pi^+ + ^{16}\text{O} \rightarrow \Delta$. On the other hand, the pion interaction below 100 MeV is dominated by pion absorption in Oxygen. The $\gamma$-ray produced by

$$\pi^\pm + ^{16}\text{O} \rightarrow X + \gamma.$$  \hspace{1cm} (1.33)

The branching ratio of $\gamma$-ray emission in NEUT is not based on the experimental data. By referring to the existing experimental data of $^{16}\text{O}$(\pi+, 2p)$^{14}\text{N}$ at the 115 MeV with 0 to 20 MeV excitation energy in the residual nucleus $^{14}\text{N}$ \[31\], the $\gamma$-ray emission process was checked. The first experiment measured the scattering angle of both scattered protons. Figure 1.15 shows the angular correlation of two protons. Since a peak was observed, the dominant interaction in $E_\pi < 200$ MeV is the two nucleon emission. The three or four nucleon emissions are also existing, but its cross section is very small, hence de-excitation $\gamma$ rays comes mainly from $^{14}\text{N}$. The $\gamma$-ray emission, electromagnetic interaction, has to be dominant below the proton separation energy $S_p = 7.55$ MeV (neutron separation energy $S_n = 10.55$ MeV). So, pion absorption $\gamma$-ray background can be removed from the SRN background.

In order to estimate specification of $\gamma$-ray emission, the second experiment $^{16}\text{O}(\pi^-, 2n)^{14}\text{N}$ data \[34\] was referred. This experiment measured branching ratio of $\text{Br}(3.945 \text{ MeV} \rightarrow 2.313 \text{ MeV}) = 4.8\%$, $\text{Br}(5.106 \text{ MeV} \rightarrow 2.313 \text{ MeV}) = 0.2\%$. According to Table of Isotope, 2.313 MeV excited state of $^{14}\text{N}$ emits $\gamma$-ray with 100% probability. This measurement obtained $\text{Br}(2.313 \text{ MeV})=5.3\%$; hence, the probability of single 2.313 MeV $\gamma$-ray can be calculated, $5.3\%-(0.2+4.8)=0.3\%$. Table 1.3 shows the implemented table of $\gamma$-ray branching ratio in NEUT.
<table>
<thead>
<tr>
<th>the number of $\gamma$</th>
<th>Energy [MeV]</th>
<th>Ratio [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.795, 2.313</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>1.64, 2.313</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>0.717</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>2.313</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>3.684</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>3.865</td>
<td>1.0</td>
</tr>
<tr>
<td>1</td>
<td>4.44</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>5.106</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>5.27</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>6.131</td>
<td>1.7</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>83.6</td>
</tr>
</tbody>
</table>

Table 1.3: Branching ratio of $\gamma$ ray emission in pion absorption in NEUT.

1.4 Super-Kamiokande Experiment

Super-Kamiokande (SK) is the water Cherenkov detector for the neutrino observation. SK has achieved several physics discoveries: evidence of first neutrino oscillations through atmospheric neutrinos [39], observation of solar neutrino oscillation [40],[41], first indication of terrestrial matter effect (day/night effect) of solar neutrino [41], confirmation of atmospheric neutrino result as a far detector of long baseline experiment (K2K experiment)[43],[44],[45]. And SK has found the lower lifetime limit of proton decay [46].

SK is located 1000 m depth underground in order to reduce cosmic ray muon background. Construction of the detector is started from 1991 and completed in 1995. SK is made up of a cylindrical stainless water tank, 39 m radius and 41.4 m height, filled with 50 ktons of pure water. The SK tank is a double structure of Inner detector (ID) and outer detector (OD). ID is the cylindrical water tank, 33.8 m radius and 36.2 m height, filled with 32.5 ktons of pure water. The purpose of OD is follows:

- The veto counter for the cosmic ray background.
- The shields for the background such as $\gamma$ rays by the radioactive source from the surround rock

ID and OD is separated by the structure called super module which supports the twelve 20-inch PMTs for ID and two 8-inch PMTs for OD. The surface coverage of PMTs is approximately 42%, which coverage is called photo coverage.

Detection of neutrinos

Neutrinos do not have the electric charge and through matter, so, it is difficult to detect them. However, neutrinos occasionally interact with matter and a charged particle is generated. The charged particle is detected by the Cherenkov light. Cherenkov light is emitted when the speed of a charged particle exceeds the speed of the light.

$$E_{\text{thr}} = \frac{nm}{\sqrt{n^2 - 1}}$$

(1.34)

where $n$ is reflective index ($n=1.34$), and $m$ is the mass of a charged particle. Cherenkov photons are emitted in a cone with opening angle defined by

$$\cos \theta = \frac{1}{n\beta}.$$  

(1.35)
The number of photons emitted per unit wavelength per unit length of radiator is given by

\[
\frac{d^2N}{d\lambda dx} = \frac{2\pi z^2 \alpha}{\lambda^2} \left( 1 - \frac{1}{\beta^2 n^2(\lambda)} \right),
\]

(1.36)

where \( z \) is particle charge in unit of e, \( \alpha \) is the fine structure constant, and \( \beta \) is the velocity of electron in unit of light speed in vacuum.

### 1.4.1 Phase of Super-Kamiokande

The operation of the detector is separated into 4 phases from SK-I to SK-IV. Table 1.4 shows the summary of feature of each SK phase. The first operation from 1996, SK-I, began with 11,146 ID PMTs and 1,885 OD PMTs. SK-I was operated for years to April 2001 stably, but it was suspended for the trouble and the reconstruction of the detector. SK-II has started after partial reconstruction, at the condition with reduced PMTs (5,182 ID PMTs and 1,885 OD PMTs). After full reconstruction, SK begun the operation, as the SK-III. To avoid to repeat the trouble about the PMTs, the fiber reinforced plastic and acrylic case was attached to PMTs in the full reconstruction. SK-IV is the phase for upgraded DAQ and electronics which is explained in Sec. 1.4.5.

### 1.4.2 20-inch Photo-Multiplier

Cherenkov light is detected by PMTs. The 20-inch PMT was originally developed by Hamamatsu photonics in cooperating with Kamiokande collaboration [47]. The photo-cathode of PMT is coated with Bialkali so that the sensitive region is 300 - 600 nm and quantum efficiency is maximum at 390 nm (Figure 1.19). The dynode structure was optimized to achieve high collection efficiency which results in a good 1 p.e. distribution and timing resolution. The specification of 20-inch PMTs is summarized in the Table.1.5.

The inside of the PMTs is vacuum for preventing discharging and accelerating photo-electronics effectively. Then, if the glass tube is broken, it causes a strong shock wave. In order to avoid cascading
Figure 1.17: PMT support frame called super module for the top, barrel and bottom PMTs.
Figures 1.18, 1.20: Schematic view of the 20-inch PMT.

<table>
<thead>
<tr>
<th>Phase</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of ID PMTs</td>
<td>11,146</td>
<td>5,182</td>
<td>11,129</td>
<td>11,129</td>
</tr>
<tr>
<td>Number of OD PMTs</td>
<td>1,885</td>
<td>1,885</td>
<td>1,885</td>
<td>1,885</td>
</tr>
<tr>
<td>Photo-cathode Coverage</td>
<td>40%</td>
<td>19%</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>Front-End Electronics</td>
<td>ATM</td>
<td>ATM</td>
<td>ATM</td>
<td>QBEE</td>
</tr>
<tr>
<td>Trigger Type</td>
<td>Hardware</td>
<td>Hardware</td>
<td>Hardware</td>
<td>Software</td>
</tr>
</tbody>
</table>

Table 1.4: Feature of each SK-phase.

of the implosions of PMTs in the detector, all of the ID PMT are covered by acrylic covers and fiber reinforced plastic cases (Figure 1.20).

1.4.3 Water Purification System

The 50 kton of pure water used in SK are taken from underground water in Kamioka mine. The impurities like small dust, ions, and bacteria not only shorten the light attenuation length, but also can be a background source for low energy neutrino observation. Therefore, it is crucial to remove impurities from the water as much as possible before filling the detector.

1. 1 μm Water filter: This filter removes the garbage of more than 1 μm in pure water. Furthermore, the radio active source attached to that garbage.

2. Heat Exchanger: This device keeps water temperature around 13 degrees. The circulation pump and PMTs mounted inside detector heats the water. Heated water induced the dark noise of PMTs, convection in the detector and bacteria in the pure water. It is important to manage the water temperature.

3. Ion Exchanger: This device removes the iron ions in the pure water such as Fe$^{2+}$, Ni$^{2+}$, Co$^{2+}$, and $^{222}$R and its Daughter nuclide $^{218}$Po ions. CO$_2$ is also removed in this step because CO$_2$ is dissolved in the pure water as CO$_2$ + H$_2$O $\rightarrow$ 2H$^+$ + CO$_2$.  

19
Figure 1.19: Cherenkov light spectrum and quantum efficiency of the PMT are plotted as the function of wavelength.

Figure 1.20: The FRP and acrylic case to prevent the shock wave.
<table>
<thead>
<tr>
<th>Product name</th>
<th>R3600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photocathode area</td>
<td>50 cm diameter</td>
</tr>
<tr>
<td>Photocathode material</td>
<td>Bialkali(Sb-K-Cs)</td>
</tr>
<tr>
<td>Collection efficiency</td>
<td>70 %</td>
</tr>
<tr>
<td>Dynode</td>
<td>11 stage Venetian bind type</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>about 21 % (360-400nm)</td>
</tr>
<tr>
<td>Gain</td>
<td>$10^7$ (1700-2000V)</td>
</tr>
<tr>
<td>Dark noise rate</td>
<td>4.5 kHz</td>
</tr>
<tr>
<td>Timing resolution</td>
<td>2.2 ns RMS (1 p.e.)</td>
</tr>
<tr>
<td>Drift time</td>
<td>~100 ns</td>
</tr>
<tr>
<td>Weight</td>
<td>13 kg</td>
</tr>
<tr>
<td>Pressure tolerance</td>
<td>6kg/cm$^2$ water proof</td>
</tr>
</tbody>
</table>

Table 1.5: Specification of 20-inch PMTs.

4. **UV sterilizer**: The bacteria in the pure water is removed by irradiation of ultraviolet rays.

5. **Rn less air dissolving system**: Dissolve the Rn less air into the pure water to improve the removal efficiency of the Rn air in the step of vacuum degasfilter system.

6. **Reverse Osmosis Filter**: Remove the an organic compound with more than 100 atomic number.

7. **Vacuum Degasfilter system**: Removing the gas in the water. Main target is Rn gas which is removed with efficiency of $\sim 96\%$. Oxygen is also removed about $\sim 99\%$.

8. **Cartridge Ion Exchanger**: This is resin for high molecular. This removes the ions such as Na$^+$, Cl$^-$, Ca$^{2+}$ and others.

9. **Ultra Filter**: Remove small particles down to the 10 nm size.

10. **Membrane Degasfilter**: Remove the radon gas with efficiency of $\sim 83\%$.
The concentration of the Rn in the pure water is suppressed less than $10^{-3}\text{Bq/m}^3$ through this system. Furthermore, transparency of pure water exceeds 130 m.

### 1.4.4 Air Purification

The ambient air in the mine contains a rich Rn gas emitted from the rock. The concentration of Rn gas in the mine is $\sim 1500\text{ Bq/m}^3$ and $\sim 30\text{ Bq/m}^3$ during summer and winter seasons respectively. In order to send fresh air into SK experimental area, the air purification system was installed at the entrance of the mine, which is consisted of air blower, air filters and a heat exchanger. As a result, Rn concentration in experimental area is kept at 20-30 mBq/m$^3$. [48]

![SUPER-KAMIOOKANDE AIR PURIFICATION SYSTEM](image)

Figure 1.22: Overview of the Rn reduced air system.

### 1.4.5 Data Acquisition System in SK-IV

The data acquisition system in SK-IV phase is explained here. As explained in Section 1.4.1, front-end electronics were replaced to QBEE [49] from beginning of the SK-IV phase. Figure 1.23 shows the DAQ block diagram for SK-IV. The data from the QBEE is sent to the front-end PCs as TCP packets, and sorted in time order. The merger PCs are merges and sorts the data sent from the front-end PCs via 10-Gigabit Ethernet, and scans the data by software trigger. Triggered events are sent to the Organizer PCs and are sorted in time order again, and stored in the disk for further analysis.

SK has multiple trigger types. High energy (HE) trigger is for the high energy events like atmospheric neutrinos. Low energy (LE) trigger is for low energy events like supernova relic neutrinos and solar neutrinos. Special high energy (SHE) trigger is issued when PMT hits exceeds the 70 hits which corresponds to $\sim 10\text{ MeV}$. After (AFT) trigger is issued after SHE trigger, and it requires that OD trigger is not issued. Super low energy (SLE) was introduced to take events for more low energy solar neutrinos. Summary of trigger configuration in SK-IV is shown in Table 1.6.
Figure 1.23: Block diagram of DAQ in SK-IV phase.

<table>
<thead>
<tr>
<th>SK-IV Triggers</th>
<th>Hits/200nsec threshold</th>
<th>Gate width (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>SLE</td>
<td>34</td>
<td>-0.5 → 1.0</td>
</tr>
<tr>
<td>LE</td>
<td>47</td>
<td>-5 → 35</td>
</tr>
<tr>
<td>HE</td>
<td>50</td>
<td>-5 → 35</td>
</tr>
<tr>
<td>SHE</td>
<td>70 - 58</td>
<td>-5 → 35</td>
</tr>
<tr>
<td>AFT</td>
<td>SHE, no OD</td>
<td>35 → 535</td>
</tr>
</tbody>
</table>

Table 1.6: Trigger configuration in SK-IV phase.
Chapter 2

GADZOOKS!

2.1 Neutron Tagging using Gadolinium

GADZOOKS! [Gadolinium Anti-neutrino Detector Zealously Outperforming Old Kamiokande, Super!], a Gadolinium-doped water Cherenkov detector, has previously been proposed [50]. The addition of 0.1% gadolinium (Gd) to the SK water is the key to reducing the SRN background, which should allow the first detection of SRN. Neutrons produced by inverse beta decay (IBD) are thermalized in about 1 µsec and captured by Gd.

\[ n + Gd \rightarrow Gd + \gamma's \quad (8MeV) \quad (2.1) \]

Figure 2.1 shows the principle idea behind GADZOOKS!. Neutron capture on Gd emits about 3 - 4 γ-rays with a total energy of 8 MeV. The coincident detection of the prompt positron and the delayed γ-ray cascade makes it possible to uniquely identify anti-neutrino events and to lower the energy threshold for the SRN search down to 10 MeV, where more SRN events are expected (see Figure 1.7). Given the predicted rates, this widening of the energy window should lead us to the first observation of SRN using SK. With its large thermal neutron capture cross section (49000 barn), 0.1% Gd solution results in about 90% efficiency in neutron capture (Figure 2.2); the remaining 10% are captured by protons in the water (p + n → d + γ(2.2 MeV)).

Figure 2.1: The principle of delayed coincidence detection.
The SRN search is affected by background like spallation and solar neutrinos in the low energy region. Figure 2.3 shows the event rate in the 22.5 kton fiducial volume in SK-IV after event selection. Its origin is spallation events induced by cosmic rays, which remains after the present spallation cut. The colored line is the expectation of the theoretical model of SRN in SK. The current background rate in final sample is about 8 events per day. On the other hand, from theoretical models, the expected rate for $\bar{\nu}_e$ is 0.7 - 1.1 events per year. To reach SRN signals, the background rate must be suppressed by $2 \times 10^{-4}$ times from the current level.
2.2 Benefit of Neutron Tagging in Super-Kamiokande

The ability to identify anti-electron neutrinos using IBD will provide extra benefits to the SK analysis. They are explained here.

Neutron tagging using GADZOOKS! improves the SK’s ability to measure the directionality of supernova detection. A supernova explosion emits both neutrinos and anti-neutrinos which have different energy spectra and the time profiles. The discrimination of these neutrinos will improve the investigation of the explosion mechanism. Using the electron scattering ($\nu + e^-$), the current SK can determine the supernova direction with an uncertainty of $\sim 5$ degrees. (SK is the only neutrino detector capable of measuring supernova directionality in the world.) By neutron tagging, SK can discriminate between electron scattering and IBD interactions, and improve the accuracy to $\sim 3$ degrees as shown in Figure 2.4. In addition, the $\gamma$ rays and/or neutrons from neutral-current $\nu$-Oxygen events would be much better identified. This is of key importance in measuring the $\nu_\mu/\nu_\tau$ temperature [52].

If supernova is big and close to Earth. GADZOOKS! has a chance to detect neutrinos from supernova even before the core collapse. Some candidates are Antares (170 pc), Betelgeuse (200 pc) and Gamma Velorum (340 pc). About a week before an explosion, during the Si-burning phase, anti-electron neutrinos are produced via electron-positron annihilations in the core. Although the luminosity of neutrinos is quite low compared to the forthcoming core collapse ($10^{-8}$ order), while the latter lasts just a few seconds, the Si burning phase lasts several days. The mean energy of neutrinos from Si burning is about 1 MeV. Most of anti-neutrinos are invisible in SK, but the total 8 MeV $\gamma$ ray from a Gd neutron capture detected and it results in the sudden and monotonical increase in single rate of PMT as shown in Figure 2.5. Table 2.1 shows the expected number of pre-supernova neutrinos in the current SK and GADZOOKS!. It is

Figure 2.4: Simulation of angular distribution without neutron tagging (left) and with neutron tagging (right). Neutrino flux and spectrum from Livermore simulation [2].

 identified. This is of key importance in measuring the $\nu_\mu/\nu_\tau$ temperature [52].
important to observe pre-supernova neutrinos, since we can study the mechanism of stellar evolution at the Si-burning stage before the core collapse begins. In addition, the increase in the event rate is obviously an indication of the beginning of a supernova explosion, and it can be used as alarm before supernova neutrino bursts occur.

Figure 2.5: The number of IBD events from Betelgeuse before the day when the core collapse [53].

<table>
<thead>
<tr>
<th>Detector</th>
<th>Target mass</th>
<th>Min. pre-collapse</th>
<th>Ev. 24-0h pre-collapse</th>
<th>Ev. 3-0h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borexino</td>
<td>0.3 kt</td>
<td>2 MeV</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>KamLAND</td>
<td>1 kt</td>
<td>2 MeV</td>
<td>108</td>
<td>65</td>
</tr>
<tr>
<td>Super-K</td>
<td>32 kt</td>
<td>5 MeV</td>
<td>173</td>
<td>158</td>
</tr>
<tr>
<td>GADZOOKS!</td>
<td>22.5kt</td>
<td>3.8 (1.8) MeV</td>
<td>442 (1883)</td>
<td>345 (1130)</td>
</tr>
</tbody>
</table>

Table 2.1: Estimation of the number of detectable events by SK and GADZOOKS! from pre-supernova candidate Betelgiuse, assuming it is 0.13 kpc away [54]. The number in parentheses is only neutron signals in IBD interaction.

GADZOOKS! can suppress the background in the energy range below 10 MeV for reactor neutrino observations. If all reactors in Japan are activated, GADZOOKS! can detect the reactor neutrinos at same event rate as KamLAND. Neutron tagging can help in discriminating between neutrinos and anti-neutrinos in the GeV scale energy region for atmospheric neutrino physics. Neutron tagging also reduces the background in proton decay searches by requiring final states with no neutrons.

2.3 Gadolinium

There are 7 isotopes of Gd in the natural world. The abundance ratio and cross section for neutron capture of these isotopes are shown in Table 2.2. $^{155}$Gd and $^{157}$Gd have a resonance state in the thermal energy region in the neutron capture reaction. A neutron captured Gd is excited and returns to the ground state, then approximately 3 - 5 $\gamma$ rays are emitted. The $\gamma$ ray energy can be calculated by using
mass difference. For example, $^{155}$Gd neutron captured emits the $\gamma$ rays through the following process:

$$n + ^{155}Gd \rightarrow ^{156}Gd^* \rightarrow ^{156}Gd + \gamma's \quad (2.2)$$

Then, the total energy of emitted $\gamma$ rays is

$$E_\gamma = M(^{155}Gd) + M_n - M(^{156}Gd) = 8.54[MeV], \quad (2.3)$$

where $M(^{155}Gd)$ and $M(^{156}Gd)$ are the mass of $^{155}$Gd and $^{156}$Gd respectively, $M_n$ is the mass of neutron.

In the same way, the energy of the $\gamma$ ray from the $^{157}$Gd neutron capture is obtained as 7.94 MeV. SK in SK-IV phase searches for SRN by using the 2.2 MeV $\gamma$ ray from neutron capture on proton.

$$n + p \rightarrow d + \gamma (2.2MeV) \quad (2.4)$$

<table>
<thead>
<tr>
<th>Atomic number</th>
<th>Abundance ratio [%]</th>
<th>Cross section [barn]</th>
</tr>
</thead>
<tbody>
<tr>
<td>152</td>
<td>0.2</td>
<td>735</td>
</tr>
<tr>
<td>154</td>
<td>2.18</td>
<td>85</td>
</tr>
<tr>
<td>155</td>
<td>14.80</td>
<td>60,900</td>
</tr>
<tr>
<td>156</td>
<td>20.47</td>
<td>1.8</td>
</tr>
<tr>
<td>157</td>
<td>15.65</td>
<td>254,000</td>
</tr>
<tr>
<td>158</td>
<td>24.84</td>
<td>2.2</td>
</tr>
<tr>
<td>160</td>
<td>21.86</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Table 2.2: Cross section and abundance ratio of each Gd isotope.
The detection efficiency for 2.2 MeV $\gamma$ rays is 17.74\% and the accidental background probability is 1.06\% per 500 $\mu$sec \[19\]. If a Gd-doped SK is realized, the higher efficiency for 8 MeV $\gamma$-ray energy of Gd potentially enables us to obtain the first detection of SRN in SK.

### 2.3.1 Gd Compound and Material Soak Test

At the first, a Gd compound which is dissolved in the SK water had to be determined. To be a good candidate for GADZOOKS!, the compound must be water soluble, relatively transparent to Cherenkov light, and not be too difficult to handle in large quantities, as about 100 tons (roughly half of which is Gd) would be required for a 50 kton detector. We considered three easily dissolved candidate Gd compounds, GdCl$_3$, Gd(NO$_3$)$_3$, Gd$_2$(SO$_4$)$_3$. However, we discovered that the chlorine in GdCl$_3$ caused unwanted corrosion, and strong light absorption by nitrate in Gd(NO$_3$)$_3$ was found below 350 nm, cutting off a significant part of the Cherenkov light spectrum. Consequently, Gd$_2$(SO$_4$)$_3$ remained as the best candidate. 0.2\% Gd$_2$(SO$_4$)$_3$ solution corresponds to about 0.1\% Gd solution in terms of mass of Gd.

**Soak test**

Soak tests for all 32 component materials of the SK detector were conducted to evaluate any potential corrosion and/or deterioration \[56\]. Each sample piece was placed into a polypropylene bottle filled either with 0.2\% Gd$_2$(SO$_4$)$_3$ solution or pure water and stored at a variety of controlled temperatures. The transparencies of the solutions were investigated using JASCO V-550 spectrophotometer. The only material that made transparency worse was found to be a rubber, which is used for the PMT supporter in SK. The measured transparency is shown in Figure 2.7. This study, however, concluded that the effect of Gd-loading on the SK detector materials is expected to be negligible and that water transparency will remain high if the water temperature is kept at 15°C. This corresponds to the temperature of the surrounding rock at the underground SK site.

![Figure 2.7](image-url) Measured transparency as the function of the wavelength. The dip in transparency of Gd solution around 250 nm is absorption by Gd. The 20-inch PMT is sensitive in 300 - 600 nm wavelength as shown in Figure 1.19.
An estimation of the effect is explained here. The absorbance is defined by

\[ A = -\ln(T/T_0), \]  

(2.5)

where \( T \) is the measured transparency of 0.2% \( \text{Gd}_2(\text{SO}_4)_3 \) solution with a sample and \( T_0 \) is pure water without a sample. The effective transparency (\( \mu_{eff} \)) which includes the quantum efficiency (QE) of PMT is calculated by

\[ \mu_{eff} = \frac{\int \frac{1}{\lambda} \text{QE}(\lambda) \mu(\lambda) d\lambda}{\int \frac{1}{\lambda} \text{QE}(\lambda) d\lambda}, \]  

(2.6)

where \( \mu \) is the transparency, and \( \lambda \) is wavelength. This \( \mu \) is obtained using

\[ \mu(\lambda) = \frac{A(\lambda)}{0.02} \times \frac{1}{R}, \]  

(2.7)

where 0.02 m is the length of our quartz capsule, and \( R \) is the accelerated factor of this soak test compared with the SK water. The pure water in the SK detector is circulated within one month. Meanwhile, the duration of this soak test was 3 months, and the amount of the water and the surface area of the rubber was taken into account (Table 2.3). So, \( R \) is given as \( R = 3 \times 5.08/(5.25 \times 10^{-3}) = 2900 \). The attenuation length can be calculated using \( L_\lambda = \mu^{-1} \), and so

\[ L_{eff} = \frac{1}{\mu_{eff}} = \sim 100[m]. \]  

(2.8)

This is almost the same level as the current SK water. The effect of \( \text{Gd}_2(\text{SO}_4)_3 \) in SK is estimated to be small. The final evaluation will be performed by using a dedicated R&D system (EGADS) which is explained in the next chapter.

<table>
<thead>
<tr>
<th>Amount of water [g]</th>
<th>Surface area of the rubber [mm$^2$]</th>
<th>Ratio [mm$^2$/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soak test 5 \times 10^2</td>
<td>2.54 \times 10^3</td>
<td>5.08</td>
</tr>
<tr>
<td>SK 5 \times 10^10</td>
<td>2.63 \times 10^8</td>
<td>5.25 \times 10^{-3}</td>
</tr>
</tbody>
</table>

Table 2.3: Condition of the soak test and SK.
Chapter 3

R&D Detector for a Gd-doped Water Cherenkov Detector: EGADS

3.1 EGADS Experiment

The new experimental hall near the SK detector in the Kamioka mine was excavated and a dedicated R&D facility was constructed in the hall in order to demonstrate the principle of GADZOOKS! (Figure 3.1). This facility is named EGADS [Evaluation Gadolinium’s Action on Detector Systems]. As shown in Figure 3.1, the EGADS facility consists of a 200-ton water Cherenkov detector with the same 20-inch PMT as used for SK, a pre-treatment system for dissolving Gd sulfate (Gd₂(SO₄)₃·H₂O) into the water in the 15 ton tank, a main Gd-doped water circulation system, and a water transparency measurement device (UDEAL). The following items are being tested with this facility:

- Transparency of the Gd-doped water. As in SK, it is important to keep the transparency high to enable various physics analyses.
- Since current SK water system removes ions, it must be modified to purify without throwing the
Figure 3.2: The schematic view of the R&D detector for Gd-doped water Cherenkov detector.

Gd sulfate out.

- Effect of Gd on detector materials. We are looking for any Gd-related corrosion and/or deterioration of SK materials.

- Behavior and handling of Gd sulfate in the water. Gd sulfate should be uniformly distributed in the detector, and should be able to be removed quickly, economically, and completely whenever desired.

- Ambient neutron level in the tank. We need to check how Gd $\gamma$-ray events from non-IBD neutrons may affect the solar neutrino measurements in the SK detector.

- Demonstration of delayed coincidence detection by the 200-ton detector,

3.1.1 Progress of the R&D Experiment

The general progress of EGADS is explained here.

- Step1

  Before mounting PMTs in the 200-ton tank, the water purification system was checked with the pure water for 6 months to check for any effect on the stainless steel tank. The water transparency was evaluated by UDEAL, and it achieved the same level of clean water as the SK water.

- Step2

  We next tested and succeed in the dissolution of Gd sulfate in the pre-treatment system. In 2011-2012, we first operated the circulation system with Gd-doped water and worked to achieve the best possible efficiency of Gd recovery while maintaining good transparency of the Gd-doped
water. Gd recovery was determined to be above 99.9% for each pass. The Gd sulfate concentration was periodically measured with an atomic absorption spectrometer, and stayed constant even after many cycles.

Figure 3.4 shows the attenuation length of the pure water and Gd-doped water as a function of the light wavelength. The Gd-doped water quality was investigated using not only the UDEAL measurement and its linear extrapolation but also a commercial JASCO V-550 spectrophotometer. This spectrophotometer can continuously measure the attenuation length in steps of 0.1 nm, even for wavelengths below 337 nm, thus extending our transparency measurements beyond UDEAL’s sensitivity region. Figure 3.5 shows the Cherenkov spectrum after passing through 15 meters. This was calculated using \((\text{Cherenkov spectrum}) \times (\text{Attenuation length of water/Gd}) \times \text{(Quantum efficiency of PMT)}\). The length of 15 m was determined from the average path length between the positions where the Cherenkov light was generated and the position where the light was detected by PMTs in the SK detector. The Cherenkov light left (called LL15 hereafter) was 70.2% for the EGADS Gd-doped water compared with the no water. This value was 86.2% of the Cherenkov light left for the SK pure water. This transparency is sufficient to perform all the usual physics (plus the new physics enabled by neutron tagging) in a Gd-doped SK detector.

- **Step 3**
  
  For the total evaluation of the Gd-doped water Cherenkov detector, the PMTs were mounted in the 200-ton tank. (see Sec. 3.2).

- **Step 4**
  
  After PMT mounting, the pure water was circulated through the detector, and we confirmed that transparency was as good as before the PMT mounting. During the circulation with pure water, the detector calibration was conducted (see Sec. 4).

- **Step 5**
Figure 3.4: Attenuation length of pure water and Gd-doped water circulated thorough EGADS system before PMT mounting.

Figure 3.5: The expectation of detected Cherenkov light spectrum.
After approximately half a year circulation with pure water, the dissolution of the Gd compound was started with the 30 kg of Gd sulfate. However, after the second batch of 30 kg of Gd sulfate, the transparency became far worse compared with the transparency during Step 2. This indicated that some material related to the PMTs affected the transparency. In fact, the rusty wire was found in the detector, which is used to support the black sheet. Unfortunately, this wire does not comprise SUS304 which is the material used in the SK detector. Therefore, we had to remove this material and clean the inside of the detector. In this thesis, the data for two batches of 30 kg of Gd sulfate are analyzed. This corresponds to Gd sulfate concentrations of 115 ppm and 230 ppm (see Sec. 6).

### 3.2 200-ton Water Cherenkov Detector

The Gd-doped water was circulated through the EGADS detector and its transparency was evaluated.

The diameter and height of the inner volume of the detector are 541.7 cm and 494.9 cm, respectively (Figure 3.6). There are five ports on the top of the detector for the detector calibration. The same 20 inch-PMTs as used for SK were mounted in the detector. These PMTs were previously used in K2K 1 kton detector. Of the 227 PMTs, about 151 PMTs were bare, but the other 76 PMTs were equipped with blast-resistant FRP and acrylic cases (Figure 1.20). As shown in Figure 3.7, these shielded PMTs were uniformly mounted in the detector, as we want to test different configurations to evaluate the effect of Gd. Beside the SK PMTs, 8 5-cm hybrid photodetectors (HPD) and 5 20-inch high quantum efficiency PMTs (HQE PMT) were installed [58]. They are developed for the Hyper-Kamiokande [59]. The active photocathode coverage is about 40%, which is the same as for SK. As in the SK detector, opaque polyethylene telephthalate sheets were installed to cover the gaps between the PMTs. It suppresses low energy-radioactivity events behind the PMTs and reflection on the wall of the detector.

This detector can work as a supernova neutrino detector. If a supernova occurs near Earth, a lot of neutrino events are expected (Betelgeuse:~90,000 events, Galactic Center:~40 events).

Figure 3.6: (left) The side view of 200-tank. (right) Floor of 200-ton tank and the PMT support frame. 168 (24×7) PMTs are mounted to wall, 36 PMTs are mounted to top and floor respectively.
PMT mounting

The PMT mounting work was performed in the summer of 2013. An overview of the PMT mounting work is shown in Figure 3.8. In advance of the mounting work, 240 70-m cables were placed between the detector and front-end electronics.

The PMTs selected by pre-calibration (Section 4.1) were carried into the EGADS experimental room and checked one by one in terms of the dark rate, signal shape, and photocathode flaws. Only good PMTs were attached the support frame as shown in Figure 3.9. They were brought into the detector and mounted to the support beam. A 70-m cable and PMT are connected, and the connection part is attached to a heat shrink tube for the waterproofing. For this work, about 8 people joined per a day, and it took one and a half months for all the PMTs.

Compensation coil

Since a large PMT is even affected by the terrestrial magnetic field (∼0.4 Gauss), the magnetic field in the detector has to be compensated. The magnetic field transverse to PMT \( B_0 \) is especially critical, and it is calculated as

\[
B_0 = \begin{cases} 
\sqrt{B_x^2 + B_y^2}, & \text{(Top/Bottom PMTs)} \\
\sqrt{(-B_x \sin \theta + B_y \cos \theta)^2 + B_z^2}, & \text{(Barrel PMTs)}. 
\end{cases}
\]  

(3.1)

where the definition of \( \theta \) is shown in Figure 3.10.

In order to reduce the effect of the terrestrial magnetic field, a network of compensation coils surrounds the entire detector volume (the coil is attached to the tank wall). The alignment of this compensation coil was designed with a magnetic field simulation. After the construction of the 200-ton tank, the coil current was tuned to compensate the magnetic field effectively. A comparison of the magnetic field is shown in Figure 3.11. About 20% of the usual uncompensated values are sufficient for the R&D.
Figure 3.8: The picture of PMT mounting work.

Figure 3.9: The support frame for the PMT for (left) barrel position, (right) top and bottom position.
Figure 3.10: (left) Measurement height for barrel PTMs. (right) Gauss meter used for the measurement.

Figure 3.11: (left) Terrestrial magnetic field at the position of barrel PMTs with and without the compensation coil. (right) Magnetic field at the positions of the bottom PMTs.
Dark rate

After the adjustment of the high voltage for all PMTs (Sec. 4.2), the dark signals for each PMT was measured. As shown in Figure 3.12, the dark rate of PMT attached FRP cover was relatively higher because of light emission from the FRP. According to the investigation at SK, this light emission is considered to be due to the chemiluminescence. However, this level of dark noise does not affect on our measurements using the calibration source.

![Figure 3.12: The distribution of dark rate for all PMTs. (upper) bare PMTs. (bottom) PMTs with FRP case.](image)

Cosmic muon measurement

The first EGADS measurement was the cosmic muon rate. Cosmic muon was observed by the self trigger mode, and the muon candidates were selected using following procedure.

- Select the events with more than 50 hit PMTs in order to remove low energy background events. The muon energy is enough so that almost all PMTs observe the Cherenkov lights from the muon.
- Checked the hit pattern with the event display to remove the flasher events from PMT. Figure 3.13 shows the typical cosmic ray event.

We obtained the muon rate as $0.041 \pm 0.003$ Hz, and the validity was confirmed by comparing with the SK measurement. The flux of cosmic rays at the EGADS detector was assumed to be $1.54 \times 10^{-7}$ s$^{-1}$ cm$^{-2}$, which was measured by SK. The cosmic muon rate is 1.8 Hz at SK. 1.38 Hz of them comes through the top side of the SK detector and 0.42 Hz comes from the side of the SK detector, then

- The muon rate from the top of the detector was estimated to be $0.035$ Hz by using SK’s value and the ratio of the surface area between the SK and EGADS detector (0.257%).
For muons coming from the side of the detector, the rate was estimated using $0.035 \times R_{\text{barrel/top}} \times R'_{\text{Egads/Sk}} = 0.07 \text{ Hz}$, where $R_{\text{barrel/top}}$ is the surface area ratio of the top and side (0.23), and $R'_{\text{Egads/Sk}}$ is the ratio of the top/side between SK and EGADS (0.83).

Finally, the total muon rate was estimated to be 0.0425 Hz. The calculated and estimated rate differs by approximately 3.5% and agrees well within the error.

3.3 DAQ System

The data acquisition (DAQ) and high voltage (HV) systems were installed in the control room near the EGADS water circulation system. A schematic view of the DAQ system is shown in Figure 3.14. The EGADS DAQ system was constructed by reusing old SK front-end electronics (the so-called ATMs [Analog Timing Modules]) [57], and equivalent in performance to SK-I/III’s original DAQ system. The ATM was developed based on the TKO (Tristan KEK Online) standard for SK. Integrated charges and the time information for each PMT are recorded and digitized by the ATM module with a 12-bit ADC (Analog to Digital Converter). One ATM board can treat 12 PMT signals, and thus 20 ATMs were used for the normal PMTs.

Signals from 12 PMTs are fed to an ATM module to be processed. Every 16 events, the digitized data in the ATMs are sent to VME memory modules called SMP (Super Memory Partner), with a typical data transfer speed of $\sim 2 \text{ MB/sec}$. The TRG module records the trigger types and trigger generation timings with a 50 MHz clock, counts an event number with a 16-bit counter, and generates a global trigger signal when any one of the trigger signals is issued.

The data stream in the online PC is described in the Figure 3.15. Data collected by ATM are stored in the SMP and TRG module respectively. These data were read by a front-end Linux PC via the VME control module Bit3. Three processes were running on the front-end PCs. These are called the collector, sorter, and sender respectively. The collector process monitors the number of the events in the SMP module. If the number exceeds the pre-fixed value, the collector process reads the data from the SMP.
and saves it in the shared memory. The sorter process reads the data in the shared memory and sorts the events in order of the event number and save it in the shared memory again. The sender process sends the data to the back-end PC after receiving requests from the event builder process. The event builder process merges the data from the front-end PCs of both the SMP and TRG side. After the merger of the event information, it is saved in a file with a binary format.

The offline process checks the data file and flag file for the DAQ process. If the offline process finds the flag file of the stop or start of DAQ, the data file is sent to a computer building outside of the mine.

Figure 3.14: Schematic diagram of the EGADS DAQ system.

Figure 3.15: Schematic diagram view of the read-out system.
HV

CAEN SY1527LC and AP1932 were used for all PMTs. This setup is managed by Linux PC via a TCP/IP connection. The specifications are shown in Table 3.1, and the performance is equivalent to SK’s system.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output outrage</td>
<td>3 kV</td>
</tr>
<tr>
<td>Max output channel current</td>
<td>0.5 mA</td>
</tr>
<tr>
<td>Voltage ripple</td>
<td>&lt; 39 mV pp</td>
</tr>
<tr>
<td>Voltage-output drop</td>
<td>100-900 V</td>
</tr>
</tbody>
</table>

Table 3.1: Specification of the HV system.

ATM calibration

To convert the ATM response into real information from the PMT, the calibration of the ATM was performed for all channels of the ATM. The CTG module (Charge Timing Module) was used for the ADC calibration of ATM, which emits the signal like typical shape from the PMTs. The signal from CTG was sent to the backplane of the TKO crate via the 70-m cables, which is the same length as the cables connected to the PMTs. The TDC tester was used to perform timing calibration of the ATM. Figure 3.16 shows the obtained data for all ATM channel and its buffers. These were implemented in the offline program.

Figure 3.16: The overlay of the ATM calibration data (left) ADC, and (right) TDC for all ATM channels. Since ATM has the two buffers, calibration data was taken for both buffers, which are shown by the red and blue color line respectively.
**Trigger system**

An overview of the trigger system is shown in Figure 3.17. If the input signal into the ATM exceeds the threshold level, the signal (200 nsec width and -15 mV height) called HITSUM is emitted from the front panel of the ATM. The HITSUM signal was used to produce a trigger signal for DAQ. The HITSUM signal from all ATM boards was summed up and, summed signal was sent to the discriminator module. If this summed up HITSUM signal exceeds the threshold level, the trigger signal of DAQ is generated.

![Figure 3.17: Trigger system.](image)

**3.4 15-ton Tank and Pre-Treatment System**

A schematic view of the 15-ton tank and pre-treatment system are shown in Figure 3.18. Gd sulfate powder was dissolved into water in the 15-ton tank to produce a 0.2% Gd sulfate solution. The built-in stirrer in the 15-ton tank helps to dissolve the Gd sulfate powder completely and quickly.

The pre-treatment system is equipped with microfilters, a UV lamp to kill bacteria, and a special resin (AJ4400) which passes Gd but removes uranium and thorium with more than 99% efficiency. The water was then injected from the pre-treatment system into the main circulation system and sent to the 200-ton tank.
Figure 3.18: Schematic view of 15-ton ton tank and pre-treatment system.

Figure 3.19: The uranium concentration measurement with ICP/MS after the resin, which was initially 10 ppt.
3.5 Water Circulation System

The light attenuation length in water must be kept long for various physics goals in SK when Gd is loaded. The main EGADS water system was named “selective filtration”, because multivalent ions such as Gd$^{3+}$ and (SO$_4$)$^{2−}$ are selected out. A schematic view of this system is shown in Figure 3.20. The membrane pore size of the nanofilters (NF) is smaller than Gd and SO$_4$ ions, and so such multivalent ions are selected out at the NF. The Gd-rejected water is then sent through reverse osmosis (RO), where only H$_2$O molecules can pass through the membrane. Pure water and Gd sulfate are reunited in the collection buffer tank and sent back to the 200-ton detector.

An ion exchange resin is used in the Gd removal system currently installed in the EGADS experimental hall. The Gd is removed by this system with an efficiency of more than 99%. In the near future, a more economical removal system, likely employing a mechanical filter press and/or cascade filtration, will be installed. This new system is currently in development at the University of California, Irvine, USA.

![Figure 3.20: The schematic view of "selective filtration" water circulation system.]

3.6 Water Transparency Measurement Device

To monitor the quality of the water in the EGADS system, we used a custom-built water transparency measurement device called UDEAL [Underground Device Evaluating Attenuation Length], shown schematically in Figure 3.21. The main pipe is 8.6 meters tall. The light intensity is measured as a function of the light travel distance by changing the water level from empty to full in the main pipe. The UDEAL monitors the light attenuation with the several wave length, which is relevant to Cherenkov
region, (337, 375, 405, 445, 473, 532, and 595 nm). Light pulses from the lasers to each 30-cm integrating sphere are collected by UV enhanced silicon photodiodes, and the ratio of the integrated intensity is taken as the measured value. The precision of the UDEAL measurement is about 1%, even for hard-to-measure attenuation lengths above 100 meters. The water used for the measurement is obtained from the top, middle, and bottom of the 200-ton tank in order to evaluate uniformity of the transparency in the detector volume. Each position is measured daily to check the quality of water along with the status of the circulation system.

![Figure 3.21: The schematic view of the water transparency measurement device: UDEAL.](image)

### 3.7 Measurement of Gadolinium Concentration

Gd concentration was monitored by the Atomic Absorption Spectrometer (AAS). Its schematic view is shown in Figure 3.22.

Water samples are collected from 3 points in the detector by using the same pipe as UDEAL sampling. By measuring the concentration at 3 different height positions, the homogeneity in the detector can be investigated. Figure 3.23 shows the monitoring of the Gd sulfate concentration in the detector. The injection of Gd can be seen as jumps in the concentration. Since the load water is injected from the bottom of the tank, there is the delayed increase in the concentration of the center and top position. We can now calculate the total uncertainty to be a precision of 0.05%.
Figure 3.22: Schematic view of AAS measurement system.

Figure 3.23: Monitoring of Gd sulfate concentration in the detector by the AAS measurement before the PMT mounting.
3.8 Radioactive Contamination of Gd sulfate

It is important to keep radioactive contamination in the detector as low as possible. Measurement of radioactive contamination in the Gd sulfate itself has been conducted with the Ge detectors at Canfranc Underground Laboratory, Spain. The measurement results are shown in Table 3.2. Taking into account the dilution of the Gd sulfate in the SK detector and the removal of uranium by the AJ4400 resin, the background is estimated to be $< 3 \times 10^{-2}$ events/year at SK. The solar neutrino flux at SK is $\sim 10$ events/day for the three lowest energy bins (kinetic energy range from 3.5 MeV to 5 MeV), whereas the radioactive background coming mainly from $^{208}$Tl $\beta$-decay is estimated to be $\sim 5 \times 10^3$ events/day/kton. Several purification processes and analysis methods are being studied to reduce this background.

<table>
<thead>
<tr>
<th>chain</th>
<th>sub-chain</th>
<th>Typical rad. [mBq/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>238U</td>
<td>238 U</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>336Ra</td>
<td>5</td>
</tr>
<tr>
<td>238U</td>
<td>238 U</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>336Ra</td>
<td>100</td>
</tr>
<tr>
<td>238U</td>
<td>238 U</td>
<td>$&lt; 30$</td>
</tr>
<tr>
<td></td>
<td>336Ra</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 3.2: Typical values of radioactive contamination in the Gd sulfate.
Chapter 4

Detector Calibration

The EGADS calibration is explained in this chapter. It is important to understand the detector performance in order to identify the $\gamma$ ray from Gd neutron capture both precisely and reliably. The detector calibration was finished during pure water circulation, and this calibration followed the well established SK calibration [60].

The output charge of the $i$-th PMT ($Q_{\text{obs}}$) is defined as

$$Q_{\text{obs}} \propto N_{\text{photon}} \times \text{QE}_i \times \text{Gain}_i \quad (i = 0 - 227),$$

where $N_{\text{photon}}$ is the number of photons which hit the photo-cathode, and QE (quantum efficiency) is the probability of photo-electron emission when a photon hits the photo-cathode. In our definition, QE includes the probability that a photo-electron reaches the dynode (the collection efficiency). All PMTs should have a uniform response in order to achieve good precise energy reconstruction, and this can be done by the adjustment of HV value. The gain is the amplification factor at the PMT dynode, which is calculated as

$$\text{Gain} \propto \alpha \times \text{HV}^\beta,$$

where $\alpha$ and $\beta$ are the parameters for each PMT, and HV is the high voltage applied to each PMT.

Pre-calibration was conducted before mounting PMTs in the detector. After PMT installation, we performed HV determination and measured the gain and QE, and calibrated the timing for each PMT.

4.1 Pre-calibration and PMT Selection

Before the PMT mounting, pre-calibration was conducted for 250 PMTs in order to measure the following properties of each PMT and to select 227 good PMTs to be used for EGADS.

- Measure $\alpha$ and $\beta$ for all PMTs, and adjust the HV value to obtain uniform response for all PMTs. After PMT mounting, this HV value will be the standard value, and $\beta$ is used for further adjustment.

- Evaluate the quality of all PMTs in terms of the dark rate and 1 photo-electron (p.e.) sensitivity, because our 250 20-inch PMTs have been left unused for 7 years. It is necessary to evaluate the sensitivity of each PMT to a single p.e. since signals between one and a few p.e. are expected in each PMT from $\gamma$-rays generated by Gd neutron capture in the EGADS detector.

Pre-calibration work was conducted in about 10 days $^1$.

---

$^1$2011/7/9 - 2011/7/20
Setup

In order to reduce the effect of the cosmic rays and measure the performance of the PMTs precisely, the pre-calibration was performed at a laboratory inside the Kamioka mine. Two light sources (Xe lamp and LED) were used.

- The Xe lamp was used for measurement of multiple p.e. in order to adjust the response of the PMTs. The Xe lamp is suitable for checking individual PMT because the light intensity of the Xe lamp is very stable in the long term.
- The LED was used for measurement of 1 p.e. It enables us to conduct high event rate measurements. The occupancy of the PMT for 1 p.e. is very low, and so a high event rate measurement is needed.

The setup for pre-calibration is shown in Figure 4.1. The PMTs were installed in the $\mu$-metal box one by one to suppress the effect of a magnetic field. The magnetic field inside the $\mu$-metal box was less than 40 mGauss.

A Xe lamp was placed inside the black box. Light from the lamp first went through a UV filter to obtain only UV region light since the scintillation ball is only sensitive to the only 275 - 400 nm region. After the UV filter, light is divided and sent to the scintillation ball and the APD. For uniform light emission, the scintillation ball consisted of 15 ppm of POPOP and 200 ppm of MgO. The APD was used for the trigger signal of DAQ and for monitoring of the light intensity of the Xe lamp.

The LED installed in the $\mu$-metal box flashed in synch with the trigger signal.

![Figure 4.1: The schematic view of the pre-calibration setup.](image)

HV Determination

At the beginning of pre-calibration, we had to determine the target value of the PMT response. At first, 7 PMTs were randomly selected from our 250 PMTs, and were used as standard PMTs during pre-calibration. The response of standard PMTs was measured by supplying HV used in the previous experiment (K2K 1-kton detector). This HV value was set to gain of $1.2 \times 10^7$. The obtained average value of standard PMTs was used as the target value of pre-calibration. The determination of the operational HV value is based on the previous operational HV value ($H_0$). By taking output charge data at four HV values around the $H_0$, the target value can be calculated by fitting the four data points using an analytical formula $y = \alpha x^\beta$, where $\alpha$ and $\beta$ are constants for each PMT. An additional measurement was conducted to confirm the result. This procedure was repeated to achieve 1% of the target value.

Figure 4.2 shows the distribution of the ratio of the target value and the response of all PMTs. Using this calibration, the initial variance of 13% (RMS) was improved to 0.8% (RMS).
Selection of PMTs

We selected 227 PMTs to be mounted in the detector using following properties.

- **Dark rate**
  After the HV adjustment, the dark rate count at the 0.5-p.e. threshold was measured. Figure 4.3 shows the distribution of the measured dark rate.

- **1 p.e. sensitivity**
  The parameter of sensitivity to the 1 p.e., Peak-to-valley (PV), was measured for each PMT. This was obtained from the ratio of the number of events at the 1 p.e. peak and the dip between 0 p.e. and 1 p.e., as shown in the left of Figure 4.4.

Finally, 227 PMTs with the better PV values and low dark rates were selected from 250 PMTs as candidates for PMTs to be mounted in the detector.
4.2 HV Determination in the EGADS Detector

After the PMT installation, the uniform response of each PMT was checked with the HV value obtained during pre-calibration, and further adjustment of HV was done using the Xe lamp.

Setup

The setup of the Xe lamp was almost the same as that for pre-calibration. However, this calibration data was taken by the EGADS as shown in Figure 4.5.

Analysis

All PMTs were divided into groups such that the distance from the scintillation ball to each PMT were the same, as shown in Figure 4.6. The target response of PMTs was defined by taking the average of each group with the HV value obtained during pre-calibration.

The measurements were conducted three times by rotating the scintillation ball to cancel the azimuthal asymmetry of the scintillation ball. After taking the average of three measurements, the HV value for all

---

Figure 4.4: (left) The 1 p.e. distribution and the fitting result of double-gaussian. The PV is the ratio of $h_p$ and $h_v$. (right) The distribution of the PV value of 250 PMTs.

Figure 4.5: The schematic view the Xe measurement setup.

Figure 4.6: The schematic view the Xe measurement setup.
PMTs was re-calculated to reduce the variations from the target value of each group. After re-adjustment of the HV value, a uniformity of 0.36% RMS was obtained as shown in Figure 4.7. PMTs with an acrylic cover were also adjusted to same target response as bare PMTs since the attenuation of light by the acrylic case was small (1 - 2%).

![Figure 4.6: The definition of group of PMTs for (left) the barrel PMTs (right) the top and bottom PMTs.](image)

![Figure 4.7: The ratio of PMT response to the mean value of each PMT group.](image)

### 4.3 Gain Measurement

The measurement of the gain of all PMTs is explained here. The gain can be expressed as the product of the global gain of the detector and the relative gain of each PMT.

\[
\text{Gain}_i = (\text{Global Gain}) \times (\text{Relative Gain}_i), \quad (i = 1 - 227)
\]  

(4.3)
The global gain is the absolute amplification factor of all PMTs, and the relative gain is distributed at the standard value 1.0. The global gain and relative gain were measured independently.

### 4.3.1 Global Gain Measurement

The absolute gain is the factor for converting the charge to the number of p.e. This value is obtained by calculating the mean value of the 1 p.e. charge distribution. The setup is shown in Figure 4.8, and the LED light source was used as well as for pre-calibration.

Since the ATM ADC modules takes signal above ATM threshold (0.25 p.e.) and can not measure the 0 p.e. contribution completely, the absolute gain was obtained with the procedure used in SK calibration. The left of Figure 4.9 shows the sum of the distribution of all PMT charges. In order to remove the dark rate, this distribution was selected by the "on-time" 100 nsec time window and subtraction of the 100 nsec "off-time" event. On-time and off-time are defined as (-50)-50 nsec and (-400)-(-300) nsec in the T-TOF distribution (the right of Figure 4.9).

Since contributions bellow the ATM threshold (1 mV) have to be taken into account, the distribution obtained with half ATM threshold (50 mV) and double-gain HV was used. Furthermore, we used a straight line extrapolation into this low-charge region because it is impossible to obtain data in the

---

**Figure 4.8**: The schematic view of the LED calibration setup.

**Figure 4.9**: (left) The T-TOF distribution of the LED data. (right) The 1 p.e. distribution of the LED.
region lower than 0.3 pC. These compensations near the ATM threshold are shown in Figure 4.10. The average of the charge distribution was obtained as 2.43 pC/p.e.

![Figure 4.10: The charge distribution near ATM threshold. The half threshold data and linear fitting compensates below the ATM threshold.](image)

### 4.3.2 Relative Gain Measurement

The relative gain was measured with two sets of laser diode calibration data (Figure 4.11, the setup is explained in Section 4.5). One had a high light output (∼50 p.e./PMT) and other had a 1 p.e. level in each PMT. From Eq.(4.1), the relative gain of the i-th PMT is calculated using

\[
\frac{Q_{\text{obs}}(i)}{N_{\text{hit}}(i)} \propto \text{Relative gain}_i, \quad (i = 1-227) \tag{4.4}
\]

By taking the ratio of these data, the relative gain was obtained. Using exactly same setup except light intensity and taking ratio, this method is independent from the water transparency, geomagnetic field, and so on. The distribution of the obtained relative gain is shown in Figure 4.12.

### 4.4 Quantum Efficiency Measurement

As explained in the beginning of this chapter, all PMT has the quantum efficiency (QE), it means that all photons hitting the surface of PMT are not converted to the p.e.. It is important for EGADS observing very low amount of light to evaluate the individual difference of QE precisely because the energy reconstruction of EGADS needs the number of hit PMTs.

From Eq. 4.1, the number of hits in each PMT is given as

\[
N_{\text{hit}}(i) \propto N_{\text{photon}} \times QE_i \tag{4.5}
\]

The relative QE can be obtained by counting the number of hit for each PMT.
Figure 4.11: The schematic view of the LD calibration setup.

Figure 4.12: The relative gain distribution.
Ni source

Ideally, the 1 p.e. events had to be used in this calibration. The $\gamma$ rays from a Ni ball and a $^{252}$Cf source were used. The radioactive element $^{252}$Cf source was contained in a brass rod and it was installed at the center of the Ni ball, which consisted of 25% NiO$_2$ and 65% polythene. A picture of the setup is shown in Figure 4.13. The $^{252}$Cf source decays through $\alpha$ decay (~96.9%) and spontaneous fission (~3.1%) with a multiplicity of 3.8 neutrons. The Ni source emits the $\sim$9 MeV $\gamma$ rays through the reaction Ni(n,$\gamma$)Ni. This setup was also used for the QE calibration for SK. The Cherenkov light from the Ni $\gamma$ rays reaches the 1 p.e. level for each PMT in the SK detector. The EGADS detector detected the signal of 2 p.e. level due to the much smaller detector size. However, we used the Ni source which produces Cherenkov light because QE depends on the wavelength of the incident photon.

Analysis

The relative QE for each PMT was estimated by comparing the number of detected photons with the MC simulation having a uniform QE. The hit rate ratio between the data and MC is defined as the relative QE.

To remove hits due to dark noise and only count hits from the Ni, on-time hits were subtracted by off-time hits as well as the LED calibration (Section 4.3.1). The relative QE distribution is shown in Figure 4.14. The relative QE was implemented on a database of the Monte Carlo simulation.

4.5 Timing Calibration

Timing calibration was carried out using a two dimensional TQ (Timing versus charge) distributions. This timing calibration is essential for vertex reconstruction. Ideally, the timing response of each PMT should be the same after subtracting the time-of-flight from the vertex position to each PMT which a photon hits. However, there are differences in PMT responses due to the difference in the length of signal cables and the response of electronics (The time-walk effect (Figure 4.15)). The timing information has to be corrected, and thus the TQ distribution was made for each ATM channel.
Figure 4.14: The QE distribution.

Figure 4.15: The schematic diagram of the time-walk. A higher charge signal is triggered earlier than a lower charge signal even if the peak position is same.
**Setup**

The setup is shown in Figure 4.11. The laser diode (LD) module emits the light with a wavelength of 410 nm. The emitted light from the LD module is injected into the diffuser ball installed at the center of the detector. The diffuser ball contained 1500 ppm light MgO of 5.8 µm diameter, such that the light scattering length was about 1 cm. For the constant trigger signal, the NIM signal from the LD module was used, which was emitted simultaneously with light emission.

**Analysis**

The laser hits of each readout channel are divided into 150 bins of charge, called Qbin. Figure 4.16 shows the TQ distribution without any corrections. The timing distribution in each Qbin is fitted by a Gaussian to minimize statistical fluctuations. Since there is a contribution of both direct and indirect light, the timing distribution in each Qbin is slightly asymmetric and is not Gaussian. In order to take into account these contributions together, the timing distribution in each Qbin was fitted using an asymmetric Gaussian, which provides the peak timing and standard deviations. The peak timing and standard deviations for each Qbin were fitted using polynomial functions as a function of Qbin.

\[
polN(x) \equiv p_0 + p_1 x + p_2 x^2 + \cdots + p_N x^N, \quad (4.6)
\]

\[
Qbin \leq 10 : F_1(x) \equiv \pol3(x), \quad (4.7)
\]

\[
Qbin \leq 50 : F_2(x) \equiv F_1(10) + (x - 10) \cdot \pol4(x - 10), \quad (4.8)
\]

\[
Qbin > 50 : F_3(x) \equiv F_2(50) + (x - 50) \cdot \pol6(x - 50). \quad (4.9)
\]

The \(p_i\) value from the fitting was used for the correction of the timing information for each PMT. Figure 4.17 shows the TQ distribution after the correction. Figure 4.18 shows the timing resolution of EGADS, which corresponds to the standard deviation of the timing peak at each Qbin as a function of the charge.

---

Figure 4.16: Timing distribution as the function of the Qbin before the correlation by TQ distribution. Qbin is defined in linear-scale from 0 to 10 pC (Q/0.2 pC) and in log-scale from 10 to 3981 pC (50log(Q)/pC).
Figure 4.17: Timing distribution as the function of the Qbin after the correlation by TQ distribution.

Figure 4.18: Timing resolution as the function of charge of signal.
4.6 Auto-Xe Calibration

In order to check the detector stability and the water quality after the dilution of Gd, the auto-Xe calibration system was operated continuously except during the calibration run. The calibration setup is the same as for the Xe flash lamp calibration, but the scintillation ball was installed at a non-centered calibration hole so that the scintillation ball was never touched. Auto-calibration was operated from the period of pure water circulation, and it achieved a stability of 1%. Figure 4.19 shows the transition of the total charge of PMTs mounted at each one of three height positions. This system can measure the water effect with good precision.

Figure 4.19: The transition of the total charge of PMTs mounted at barrel, top and bottom position. By monitoring the fluctuation of the observed charge, the tendency can be checked for each of the positions and the PMT configuration.
Chapter 5

Software Tool

In this chapter, the reconstruction method and simulation tool are explained. The reconstruction tool for vertex and energy was imported from at the SK. The geometric value in this analysis can be seen in Figure 5.1. The Z-axis was defined to run vertically with its zero being the center of the SK tank. The X-axis and Y-axis were perpendicular to each other and to the Z-axis.

![Diagram showing the definition of basic variables.]

**Figure 5.1:** The definition of basic variables.

5.1 Vertex Reconstruction

The vertex position where a particle interacts with another particle is reconstructed from the timing when PMTs detected the light and its the PMT positions. The particle resulting from an interaction flies, but its position is able to be treated as a point because the flight distance is short (∼10 cm for a 20 MeV electron). The likelihood function is used to obtain the vertex position by using the likelihood $\Delta t_i$. $\Delta t_i$ is calculated as

$$
\Delta t_i = t_i - \frac{n}{c} \sqrt{(x-x_i)^2 + (y-y_i)^2} - t_0
$$

(5.1)
\[ t_i = t_i - tof - t_0, \]  

(5.2)

where \( tof \) is the time-of-light from the vertex position to the hit PMTs, and \( t_0 \) is the mean value of the

Figure 5.2: Likelihood function of BONSAI vertex fitter from Ni calibration data. The peaks around the 40 nsec and 110 nsec are caused by the after pulses.

\[ Likelihood = \sum_{i=1}^{N_{hit}} \log P(\Delta t_i(\vec{x})), \]  

(5.3)

where \( P(\Delta t_i(\vec{x})) \) is the probability density function of \( t_i(\vec{x}) - tof - t_0 \) that can be seen in Figure 5.2. This fitter is called BONSAI (Branch Optimization Navigating Successive Annealing Iteration)[61]. Sometimes dark noise hits and/or reflection light produces the local maxima of a likelihood. To avoid such mis-reconstructions, the likelihood is maximized from the vertex search by the combination of all four PMTs. Each of the four PMT combinations provides a unique vertex candidate from their timing constraints. Thus, events with more than four hit PMTs are reconstructed. This is iterated to obtain a good vertex position with a larger and more stable likelihood value.

Figure 5.3 shows the reconstructed vertex position from the Ni source position: \( R^2 = x^2 + y^2 + z^2 \).

The vertex resolution was evaluated by the electron simulation, which can be seen in Figure 5.4.

5.2 Energy Reconstruction

The reconstruction of particle energy is explained here. The particle energy affects the intensity of Cherenkov light. Therefore, by counting the number of hit PMTs, the particle energy can be investigated. The reason why is the number of hits is used instead of the observed total charge is because it is unrelated to the PMT gain. The energy reconstruction has to be done while suppressing the effect from several factors such as dark noise. The parameter defined by the following equation is used and is called the
Figure 5.3: Reconstructed vertex distribution of the Ni data and MC.

Figure 5.4: The vertex distribution as a function of electron energy. Color corresponds to each fiducial volume cut. This cut removes the events which reconstructed within 0, 50, and 100 cm from the wall of the detector.
effective PMT hit \( N_{\text{eff}} \).

\[
\text{Likelihood} = \sum_{i=1}^{N_{50}} \left[ (X_i - \epsilon_{\text{dark}} + \epsilon_{\text{tail}}) \times \frac{N_{\text{all}}}{N_{\text{alive}}} \times S(\theta_i, \phi_i) \times \exp\left(\frac{r_i}{\lambda}\right) \times G_i \right] \tag{5.4}
\]

- \( N_{50} \)
  This is defined as the maximum number of hits found by sliding a 50 nsec time window in the T\(T\)of distribution.

- \( X_i \): **Multiple photo electron hit correction**
  This is a correction to compensate for the effect of multiple p.e. in the \( i \)-th hit PMT due to the fact that if an event occurs near the detector wall and is directed towards the same wall, and the Cherenkov cone does not have much distance to expand then the observed number of hits becomes smaller. The \( X_i \) is defined as

\[
X_i = \begin{cases} 
\frac{\log \frac{1}{x_i - 1}}{1} / x_i & x_i < 1, \\
3.0 & x_i = 1,
\end{cases}
\tag{5.5}
\]

where \( x_i \) is the ratio of hit PMTs in a the \( 3 \times 3 \) PMTs surrounding the \( i \)-th PMT to the total number of live PMTs in the same area. The \( \log(\frac{1}{x_i - 1}) \) term is then the estimated number of photons per one PMT in that area and is determined from Poisson statistics.

- \( \epsilon_{\text{dark}} \): **Dark noise correction**
  The dark noise hit is estimated using

\[
\epsilon_{\text{dark}} = \frac{50\text{nsec} \times N_{\text{alive}} \times R_{\text{dark}}}{N_{50}}, \tag{5.6}
\]

where \( N_{\text{alive}} \) is the number of all live PMTs and \( R_{\text{dark}} \) is the measured dark rate.

- \( \epsilon_{\text{tail}} \): **Correction for late hit**
  Reflected Cherenkov light arrives late to PMTs. It performs a late hit outside of a 50 nsec window. To correct for such an effect, \( \epsilon_{\text{tail}} \) is calculated using

\[
\epsilon_{\text{tail}} = N_{100} - N_{50} - \frac{N_{\text{alive}} \times R_{\text{dark}} \times 50\text{nsec}}{N_{50}}, \tag{5.7}
\]

where \( N_{100} \) is the maximum number of hits found in a 100 nsec time window.

- \( \frac{N_{\text{all}}}{N_{\text{alive}}} \): **Correction for Dead PMT**
  \( N_{\text{all}} \) is the total number of PMTs.

- \( \frac{1}{S(\theta, \phi)} \): **Correction for photo-cathode coverage**
  This correction is for the direction-dependent photo-cathode coverage. It is the effective photo-cathode area as a function of the incident angle \((\theta_i, \phi_i)\). Figure 5.5 shows the \( S(\theta_i, \phi_i) \) and the definition of the angle \((\theta_i, \phi_i)\).

- \( \exp\left(\frac{r_i}{\lambda}\right) \): **Correction for water transparency**
  This is a correction is for the water transparency effect. However, this correction is negligible for EGADS data. \( r_i \) is the distance from the vertex position to a hit PMTi, \( \lambda \) is the water transparency.

- \( G_i \): **Correction for PMT gain**
  This factor is used to adjust the relative gain of the PMTs for a single p.e.
Figure 5.5: The definition of the incident angle to PMT. Correction function of the photon incident angle obtained from MC simulation.

After the determination, and event’s energy in term of MeV can be calculated as the function of $N_{eff}$. The relation between $N_{eff}$ and MeV is obtained by electron simulation, because the calibration apparatus such as LINAC cannot be installed in the EGADS detector. Figure 5.6 shows the $N_{eff}$ by the 1-9 MeV electron simulation.

Figure 5.6: (left) $N_{eff}$ distribution of 1-9 MeV electron simulation. (right) The mean $N_{eff}$ obtained by Gaussian fit as the function of electron energy. Each color line corresponds to the each vertex cut.
5.3 Detector Simulation

The EGADS simulation tool was constructed based on the Geant4 toolkit\[62\], and is named EGSIM. The dataset versions used in this thesis are shown in Table 5.1. EGSIM uses the default of physics process of

<table>
<thead>
<tr>
<th>GEANT4</th>
<th>Geant4.9.6.p02</th>
</tr>
</thead>
<tbody>
<tr>
<td>G4LEDMEDIA</td>
<td>G4EMLOW6.32</td>
</tr>
<tr>
<td>G4LEVELGAMMA</td>
<td>PhotonEvaporation2.3</td>
</tr>
<tr>
<td>G4NEUTRONXS</td>
<td>G4NEUTRONXS1.2</td>
</tr>
<tr>
<td>G4PIIDATA</td>
<td>G4PII1.3</td>
</tr>
<tr>
<td>G4RADIOACTIVE</td>
<td>RadioactiveDecay3.6</td>
</tr>
<tr>
<td>G4REALSURFACE</td>
<td>RealSurface1.0</td>
</tr>
<tr>
<td>G4SAIDXSDATA</td>
<td>G4SAIDDATA1.1</td>
</tr>
</tbody>
</table>

Table 5.1: Data set of Geant4 for EGSIM.

Geant4 for the production of Cherenkov light in the detector, and it provides the Cherenkov angle, and wavelength, etc. For the refractive index related to Cherenkov generation which EGSIM uses is the same as those of SK. The interaction length of absorption, Mie, and Rayleigh scattering also comes from the pure water models used in SK. The event simulation in Gd-doped water was conducted using the same water parameter as that of pure water, because the calibration data in a small detector such as EGADS has to be free from the water effect.

Figure 5.7 shows simulated Gd neutron capture events in the detector. The shape of photocathode of a 20-inch PMT installed in EGSIM is substantially hemispherical. The output file of EGSIM has the same format as the output file of the actual EGADS. Therefore, it is possible to use the same analysis process.

![Figure 5.7](image)

Figure 5.7: The EGADS detector simulation based on the GEANT4, which shows a Gd γ ray event.
Detector Response

When a photon reaches the PMT surface, the response of the detector is simulated. In short, the i-th PMT’s probability \( P_i(\lambda, \theta) \) of the production of a p.e. from the photon arriving at each PMT surface is estimated by

\[
P_i(\lambda, \theta) = QE(\lambda) \times F(\theta) \times \text{COREPMT} \times \text{relative QE}(i), \quad (i = 1 - 227),
\]

where \( QE(\lambda) \) is the quantum efficiency depending on the wavelength \( \lambda \) of the incident photon, which is the typical value measured by HAMAMATSU (Figure 1.19). \( F(\theta) \) is the correction factor of the incident angle \( \theta \) which is imported from SK calibration, and COREPMT is determined from the \( N_{\text{eff}} \) distribution of Ni data in Figure 5.8. The relative \( \text{QE}(i) \) is also obtained from Ni calibration (Section 4.4). In order to reduce the calculation time, the number of generated Cherenkov lights is suppressed by a factor of \( QE(\lambda)/0.75 \), therefore, including the 0.75, this factor is compensated by \( \text{QE} \).

![Figure 5.8: \( N_{\text{eff}} \) distribution. The black dot is Ni events after the subtraction of background events.](image)

1 photo electron distribution and ATM threshold

1 photo electron distribution implemented in EGSIM is obtained from LED measurement (Section 4.3). The ATM threshold effect was estimated by using the double gain and half threshold measurement.

Timing resolution

The timing resolution in the MC is the result obtained from the TQ calibration, which is explained in Section 4.5.

After-pulse and pre-pulse

The characteristic peaks in the PMT hit timing distribution after the main peak is called the after-pulse. A possible explanation of the cause of the after-pulse is that if a p.e. is back scattered at the first dynode,
it takes some time before it loses its velocity against the electric field, and comes back to the first dynode, thus producing a delayed hit.

The dark noise coming from the PMT was also generated in simulations; however, it is assumed to be the same rate for all PMTs and was adjusted to be 8 Hz (this is higher than SK’s value: \(\sim 5 \text{ kHz}\)).

5.4 Gd Simulation

For the Gd\((n,\gamma)\) reaction, EGSIM uses the default model of Geant4 and the model provided by the GLG4SIM library. GLG4SIM was originally developed for the scintillation detector experiment, and it treats the discrete \(\gamma\)-ray emission process [63]. The default Geant4 model takes it into account the nucleus recoil. Meanwhile, GLG4SIM does not take into account it.

![Figure 5.9](image)

Figure 5.9: (left) The comparison of the total \(\gamma\)-ray energy (right) and the number of \(\gamma\) rays from the neutron capture Gd.

![Figure 5.10](image)

Figure 5.10: The comparison of \(N_{\text{eff}}\) distribution of Gd \(\gamma\) ray events.
Chapter 6

Detection and Analysis of $\gamma$ rays from Gadolinium Neutron Capture

After the pure water circulation, Gd sulfate was dissolved into the water circulation system and injected into the detector in 2014. In this chapter, the first detection of $\gamma$ ray from Gd neutron capture was demonstrated and the evaluation of its performance are explained. In addition, the performance of Gd neutron capture in the SK detector is also estimated from the test data taken in SK detector.

6.1 Measurement and Setup

The Gd $\gamma$-ray measurement was performed by using a neutron source. We adopted an Am/Be source which emits the 4.43 MeV $\gamma$ ray and neutron. The Am/Be source is attached to a piece of BGO crystal. It emits scintillation light with the 4.4 MeV prompt $\gamma$ ray. This setup mimics the IBD signal as shown in Figure 6.1. In this section, the Am/Be source and related apparatus for measurements are explained.

Figure 6.1: The schematic view of the Am/Be source and a BGO scintillator, which generates the a prompt scintillation light and a neutron.
6.1.1 Am/Be Source

The Am/Be source is made up of three layers. The thin layer of Am was sandwiched between the 0.1 mm thick Be film. The Am/Be source was placed inside a 1.2 cm×1.2 cm×1.2 cm stainless steel case. Neutron emission occurs through the following interactions: an α particle from Am decay interacts with Be, and a neutron and carbon are produced. When the excited carbon decays to the ground state, the γ rays depending on the excited state are emitted. We found that 4.43 MeV γ ray and neutron were emitted at the 87 Hz and that no γ ray were emitted at 76 Hz (Figure 6.2). The 76 Hz of neutron emission does not make a prompt trigger, and so it is treated as background events originating from the Am/Be source (see Sec. 6.2). This is called the source background in this thesis.

\[
\begin{align*}
^{241}\text{Am} & \rightarrow ^{237}\text{Np} + \alpha \ (7.78\text{MeV}) \\
\alpha + \text{Be} & \rightarrow ^{12}\text{C}^* + n, ^{12}\text{C} + n \\
^{12}\text{C}^* & \rightarrow ^{12}\text{C} + \gamma \ (4.43\text{MeV})
\end{align*}
\]

Neutron energy spectrum

The neutron energy from the Am/Be source depends on excited levels of \(^{12}\text{C}\) and the neutron scattering angle, we used measured spectrum continuous energy spectrum in the MC simulation. Figure 6.3 shows the neutron energy spectrum from [65].

γ-ray energy spectrum

Figure 6.4 shows the measured γ-ray energy spectrum by a Ge detector. The peak near 4.5 MeV is the full energy deposited by a 4.43 MeV γ ray. The peak of a single escape and double escape can be seen at 3.92 MeV \((4.43 - m_e c^2)\) and 3.51 MeV \((4.43 - 2 \times m_e c^2)\) respectively, where \(m_e\) is the electron mass.
Figure 6.3: The energy spectrum of neutrons from the Am/Be source [65].

Figure 6.4: The $\gamma$-ray energy spectrum measured by a Ge detector. The red line is measurement of the Am/Be. The black line is the background measurement.
6.1.2 BGO Scintillator

The BGO scintillator described by Bi$_4$Ge$_3$O$_{12}$ is the crystal having the large cross section for the $\gamma$-ray capture. The characteristics of this crystal is shown in Table 6.1. It is very dense, low afterglow, low hygroscopicity, has good position resolution, and is easy to forming. Therefore, the BGO scintillator is used in many fields: medicine, nuclear physics and high energy physics, etc.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Density</td>
<td>7.13 [g/cm$^3$]</td>
</tr>
<tr>
<td>Decay constant</td>
<td>300 [nsec]</td>
</tr>
<tr>
<td>Wavelength</td>
<td>480 [um]</td>
</tr>
<tr>
<td>Refractive index</td>
<td>2.15</td>
</tr>
</tbody>
</table>

Table 6.1: Characteristics of the BGO scintillator

The configuration of the Am/Be source and BGO crystal is shown in the left of Figure 6.5. The probability that the 4.43 MeV $\gamma$ ray interacts with the BGO scintillator was estimated by Geant4 simulation to be approximately 12%. The energy deposited in the BGO scintillator by a 4.43 MeV $\gamma$ ray is shown on the right of Figure 6.5. The energy of the recoil electron ($T$) through Compton scattering is calculated using the relation

$$T = \frac{E_\gamma m_c}{m_e^2} (1 - \cos \theta) \frac{E_\gamma}{m_e^2} (1 - \cos \theta)$$

where $m$ is electron mass, $E_\gamma$ is the incident $\gamma$ ray energy, and $\theta$ is the scattering angle.

6.1.3 Measurement

Before injection of Gd-doped water into the EGADS detector, several preparations were done. In order to measure $\gamma$ rays from Gd neutron capture, a dedicated trigger system was built. When the scintillation light induced by the 4.43 MeV $\gamma$ ray is detected as the prompt signal, a 500 $\mu$sec gate is opened to...
search for the delayed low-energy signal. A schematic view is shown in Figure 6.6. Since the prompt scintillation lights induced by the 4.43 MeV $\gamma$ ray was too bright in the EGADS detector, the delayed events were affected by the prompt signal (afterglow and after pulse). In order to reduce the effect, we assembled a BGO scintillator in the following way. The BGO scintillator was covered by a black sheet, and the Am/Be source was attached on the black sheet. A few holes was made in the black sheet, which is designed to reduce the intensity of the prompt scintillation light. The contribution of the black sheet is shown in Figure 6.8. With a black sheet, the number of hit PMTs induced by the prompt signal is reduced to be around 100. The unwanted afterglow hits without a black sheet in the delayed trigger (seen in about 60 hits) disappeared with a block sheet and only noise hits are seen.

The distribution of the time difference between the prompt and delayed events is shown in the right figure of Figure 6.9. Although afterglow is still observed in first few $\mu$sec, the distribution is flat and no disturbing events are observed.

After the injection of Gd-doped water into the detector, the Am/Be measurement was performed in concentration of 115 ppm and 230 ppm of Gd sulfate as shown in the Figure 6.10. After the injection of Gd-doped water into the detector, it takes a few days for the Gd concentration to become homogeneous.
Figure 6.8: The number of hit PMTs. Upper figure: the prompt events. Bottom figure: the delayed events.

Figure 6.9: The difference of trigger time between the prompt and delayed events.
in the detector. We analyzed Am/Be data which were taken at a date when the Gd sulfate concentrations measured at 3 positions (top, center and bottom) agreed with each other. Therefore, position dependence of the neutron capture was not considered.

Figure 6.10: Gd concentration monitored by AAS after the PMT mounting. Upward arrow indicates the dates when the Am/Be data were taken.

As mentioned in Section 3.1.1, the water transparency deteriorated after the injection of Gd-doped water. However, the effect on the data due to water transparency was very small in a small detector such as EGADS. Actually, the effect is negligible in Figure 6.11 which shows the $N_{eff}$ distribution of the Ni data. The Am/Be data taken when the LL15 is 40 - 50% should be free from the water transparency effect. In this thesis, 33,729 and 43,887 prompt trigger events of Am/Be data were taken and analyzed for concentration of 115 ppm and 230 ppm, respectively. The background events were taken by a periodic trigger in normal Run mode which has the 400 nsec time window. 97,163 and 6,413 triggers are generated and analyzed for concentration of 115 ppm and 230 ppm respectively.

6.1.4 Neutron-Nucleus Interactions at low energy region

Here is the summary of the low energy neutron-nucleus interactions.

1. **Elastic scattering** $(n,n)$: The incident neutron energy is divided to the neutron and nucleus, but the nucleus is not excited.

2. **Inelastic scattering** $(n,n)$, $(n,n\gamma)$, $(n,2n)$: $(n,2n)$ is dominant in more than 10 MeV region.

3. **Neutron capture** $(n,\gamma)$: This interaction is the most general because thermal neutron (0.025 eV) is captured by almost all nuclei. This interaction is caused at specific energy in the epithermal neutron region for each nucleus. It is called a resonance capture.
4. **Emission of charged particles** (e.g. \((n,p), (n,d), (n,\alpha), (n,t), (n,\alpha p)\)): With the exception of some thermal neutron case, this reaction is likely to occur if the light elements or fast neutron.

5. **Nuclear fission** \((n,f)\): This is a phenomenon that the composite nucleus is split into two fission products and one or several neutrons. Fission occurs by fast neutrons in many heavy nuclides. For \(^{235}\text{U}, ^{239}\text{Pu}\) and \(^{233}\text{U}\), the fission occurs mainly with thermal neutrons.

The neutrons from the Am/Be source interact with hydrogen in water approximately by 30 times. They are thermalized and captured by Gd.

### 6.2 Analysis of \(\gamma\) rays from Gd neutron capture

In this section, the analysis of Am/Be data is explained. First, the prompt 4.43 MeV \(\gamma\)-ray events have to be selected. As shown in Figure 6.8, the prompt scintillation event induced by a 4.43 MeV \(\gamma\) ray produces 80 - 140 PMT hits. By requiring 80 - 140 hits for the prompt event, the background events can be suppressed.

The selection criteria for the delayed events are as follows:

- **Vertex position cut**: The delayed events by a Gd \(\gamma\) ray should be reconstructed around the Am/Be neutron source. So, only the events reconstructed at \(R^2 < 2m^2\) are selected. Figure 6.13 shows \(R^2 = x^2 + y^2 + z^2\) distributions of the reconstructed vertex.

- **\(\Delta T\) cut**: The neutron capture time \((\Delta T)\) has to be exponentially distributed. On the other hand, the background events have to be distributed uniformly in \(\Delta T\). Events with \(\Delta T < 400\mu\text{sec}\) were selected.
• Vertex fit goodness: Vertex fit goodness is the parameter of the quality of vertex reconstruction. For example, an unwanted event produced by flasher light from PMTs is reconstructed with goodness<0.3. The good events were selected by requiring the goodness>0.3.

• DirKS cut: DirKS was a parameter obtained Kolmogorov-Smirnov (KS) test for azimuthal angular. The well-reconstructed events can be selected by DirKS<0.4. This parameter indicates that hit PMTs are distributed uniformly around the reconstructed particle direction.

• Energy cut: Remove the low energy background by E<2 [MeV].

Figure 6.12: Reconstructed vertex position from the source position : \( R^2 = x^2 + y^2 + z^2 \) [m^2] (left) 115 ppm, and (right) 230 ppm Gd sulfate concentrations.

Figure 6.13 shows the energy spectrum of the delayed events after event selection. The source background is explained in the next sub-sub-section. The mean reconstructed energy from Gd \( \gamma \) rays was measured to be 4.2 MeV by the Gaussian fit using the MC spectrum. This value is less than 8 MeV estimated by Q value (Eq.(2.3)). In Gd neutron capture, 3 - 4 \( \gamma \) rays are emitted with a total energy of 8 MeV. However, \( \gamma \) rays below 1 MeV are invisible since only a \( \gamma \) ray above 1 MeV produce a Cherenkov light in a water Cherenkov detector. The event display of the delayed events is shown in Figure 6.15.

Figure 6.14 shows the \( \Delta T \) distribution and an exponential fitting result, which gives the mean capture time for each concentration as follows:

\[
\Delta T = \begin{cases} 
184.6 \pm 4.8 \mu s ec & (115 ppm) \\
151.3 \pm 2.6 \mu s ec & (230 ppm) 
\end{cases}
\] (6.5)

From these result, the neutron tagging by Gd have been demonstrated. Compared with the 2.2 MeV \( \gamma \) ray from neutron capture on proton, the Gd neutron capture occurs near the source position with a shorter \( \Delta T \), and 8 MeV \( \gamma \) ray cascade is sufficiently high. So, it must provide better performance to the SK detector.
Figure 6.13: Reconstructed energy distribution after event selection. (left) 115 ppm, (right) 230 ppm Gd sulfate concentration. Horizontal axis is normalized by the number of prompt trigger (neutron).

Figure 6.14: The $\Delta T$ distribution of the data and MC (left) 115 ppm and (right) 230 ppm Gd sulfate concentration. The data points indicates the component of only $\gamma$ rays from Gd neutron capture. The background data and the source background and the 2.2 MeV $\gamma$ rays are already subtracted in this figures.
Figure 6.15: The event displays of delayed events of Am/Be data.
To analyze the Am/Be data correctly, background events originating from the Am/Be source have to be considered. These are two types of such background. The first type, denoted BG1 in Figure 6.16, is the event which is a 4.43 MeV \( \gamma \) ray and the delayed neutron events accidentally detected in the delayed gate. Time integration from 0 to \( T_{\text{max}} \) (gate length of 400 \( \mu \text{sec} \)) provides the probability as

\[
P_{\text{detect}} = \int_0^{T_{\text{max}}} dt \left( P_\gamma(t) \cdot R_\gamma \cdot I_\gamma + (P_p(t) + P_{\text{Gd}}(t)) \cdot I_n \right), \tag{6.6}
\]

where \( P_\gamma, P_p \) and \( P_{\text{Gd}} \) are the detection probability of the 4.43 MeV \( \gamma \) ray from the \( \gamma \) ray from neutron captured proton and Gd, respectively, \( R_\gamma \) is the probability that the 4.43 MeV \( \gamma \) ray does not interact with the BGO scintillator, and \( I_\gamma, I_n \) is the intensity of the 4.43 MeV \( \gamma \) ray and the neutron emission, respectively.

The second type of the source background, denoted BG2 in Figure 6.16, is the delayed neutron events occurring together with the scintillation light in the delayed gate. This scintillation event is not a prompt event but is an accidental event in the delayed gate. Since this event is identified by the off-line event selection, the only neutron event remains. The event probability can be obtained by

\[
P_{\text{detect}} = \int_0^{T_{\text{max}}} d\tau \int_{T_0}^{T_{\text{max}}} dt \left( P_{\text{Gd}}(t - \tau) + P_p(t - \tau) \right) \times (1 - R_\gamma) \times I_n, \tag{6.7}
\]

where \( \tau \) is the time of the scintillation event detected in the delayed gate.

Since the probability of the first type is higher than that of the second type, it is important to check the 4.43 MeV \( \gamma \)-ray events. Figure 6.17 shows the \( N_{\text{eff}} \) and vertex distribution of a 4.43 MeV \( \gamma \) ray. This was taken in the pure water by the Am/Be source without the BGO scintillator.

**MC model dependence**

Figure 6.18 shows the energy distribution of the delayed events for the data and two MC models. As discussed in Section 5.4, the GLG4sim model gives a lower energy peak than Geant4+G4NDL4.2. From this comparison, it is difficult to say which model has to be used. In this thesis, this discrepancy between the data and MC is treated as a systematic error.

### 6.3 Evaluation of Detector Performance

The performance of the detector: the signal detection efficiency and background efficiency were evaluated. The signal detection efficiency is defined by "neutron capture efficiency" \( \times \) "reconstruction efficiency". These efficiencies were independently evaluated by Am/Be data. The background efficiency is defined as the ratio of the number of the reconstructed events to the number of prompt triggers.

#### 6.3.1 Neutron Capture Efficiency

It is important to measure the neutron capture efficiency because it directly affects on the detection efficiency. By counting the number of remaining events of the Am/Be data after event selection, the capture efficiency was calculated. The event selection criteria are as follows:

- Vertex cut: \( R^2 < 2 \text{m}^2 \)
- \( \Delta T < 450 \mu\text{sec} \)
Figure 6.16: The schematic diagram of the source background. The source background is the event originates from Am/Be source, and is accidentally detected in the 500 µsec delayed gate. The source background consists of the γ-rays from neutron capture on Gd and proton, and the 4.43 MeV γ ray.
Figure 6.17: (left) The $N_{\text{eff}}$ distribution of the 4.43 MeV $\gamma$ rays. (right) The vertex distribution of the 4.43 MeV $\gamma$ rays.

Figure 6.18: The comparison of the energy distribution between the data and MC simulations. (left) 115 ppm, and (right) 230 ppm.
• Vertex fit goodness $> 0.4$
• DirKS $< 0.4$
• $N_{\text{eff}} > 25$

The energy cut ($N_{\text{eff}} > 25$) removes most of the 2.2 MeV $\gamma$-ray event due to neutron capture on proton. Consequently, the capture efficiency due to Gd can be simply obtained. We defined $\text{Hitrate}$ as

$$\text{Hitrate} = \frac{N'}{N_{\text{Trg}}},$$

(6.8)

where $N_{\text{trg}}$ is the number of prompt triggers, and $N'$ is the number of remaining Am/Be events after event selection. Using the MC simulation, the cut efficiency of the Gd $\gamma$ ray was also estimated as

$$\text{Eff}_{\text{Cut Gd}\gamma} = \frac{N'_{\text{Gd}}}{N_{\text{Gd}\gamma}},$$

(6.9)

where $N_{\text{Gd}}$ is the number of Gd $\gamma$ ray events, and $N'_{\text{Gd}}$ is after the all event selection. The $N_{\text{eff}}$

![Figure 6.19: The $N_{\text{eff}}$ distribution of the Am/Be data.](image)

distribution after the event selection is shown on the right of Figure 6.19. Even after the event selection, the source background events still remain. So $\text{Hitrate}$ can be calculated not only from the Gd $\gamma$ ray but also from the source background component ($N_{\text{SBG}}$).

$$\text{Hitrate} = \frac{N_{\text{trg}} \times \text{Eff}_{\text{capture}} \times \text{Eff}_{\text{Gd}\gamma} + N_{\text{SBG}}}{N_{\text{trg}}}$$

(6.10)

where $\text{Eff}_{\text{capture}}$ is the capture efficiency by Gd, $N_{\text{SBG}}$ is the number of the source background. Since the source background contains the Gd $\gamma$-ray events, $N_{\text{SBG}}$ depends on the capture efficiency and is wrote in the form

$$N_{\text{SBG}} = N_{\text{SBG}}^{\text{Gd}} + N_{\text{SBG}}^{\gamma}$$

(6.11)

$$= N_{\text{trg}} \times \text{Eff}_{\text{capture}} \times \text{Eff}_{\text{SBG}}^{\text{Gd}} + N_{\text{trg}} \times \text{Eff}_{\text{SBG}}^{\gamma},$$

(6.12)
where $Eff_{Gd}^{SBG}$ and $Eff_{SBG}^{\gamma}$ is the detection efficiency of the source background of the Gd $\gamma$ ray and the 4.43 MeV $\gamma$ ray, respectively. These are also evaluated by the MC. Finally, the capture efficiency can be calculated as

$$Eff_{\text{capture}} = \frac{\text{Hitrate} - Eff_{\gamma}^{SBG}}{Eff_{\text{cut}}^{Gd} + Eff_{SBG}^{Gd}}. \hspace{1cm} (6.13)$$

Table 6.2 shows the measured capture efficiency and efficiency expected by the MC. To compensate the discrepancy between the data and MC, the MC variables were shifted to data as shown in Figure 6.20. Using the shifted MC variables, the cut efficiencies ($Eff_{SBG}^{Gd}$, $Eff_{\text{cut}}^{Gd}$, $Eff_{SBG}^{Gd}$) were re-evaluated, and the capture efficiency was recalculated as shown in Table 6.2. The differences in these estimations are taken into account as a systematic error.

<table>
<thead>
<tr>
<th></th>
<th>0.0115%</th>
<th>0.0230%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>shifted MC</td>
<td>shifted MC</td>
</tr>
<tr>
<td>Hit rate</td>
<td>0.0708</td>
<td>0.110</td>
</tr>
<tr>
<td>$Eff_{\text{cut}}^{Gd}$</td>
<td>0.223</td>
<td>0.223</td>
</tr>
<tr>
<td>$Eff_{SBG}^{\gamma}$</td>
<td>0.0019</td>
<td>0.0019</td>
</tr>
<tr>
<td>$Eff_{SBG}^{Gd}$</td>
<td>0.0124</td>
<td>0.0125</td>
</tr>
<tr>
<td>Capture Eff.</td>
<td>29.2%</td>
<td>46.1%</td>
</tr>
<tr>
<td>Result</td>
<td>$29.2 \pm 0.5_{\text{Stat}} \pm 0.3_{\text{Sys}}%$</td>
<td>$46.1 \pm 0.7_{\text{Stat}} \pm 0.5_{\text{Sys}}%$</td>
</tr>
<tr>
<td>MC</td>
<td>32.1%</td>
<td>47.4%</td>
</tr>
</tbody>
</table>

Table 6.2: Calculation of neutron capture efficiency.
6.3.2 Analysis of Reconstruction Efficiency

The signal efficiency has to be kept high. On the other hand, the background has to be suppressed as much as possible. The reconstruction efficiency of the Gd $\gamma$-ray signal and background efficiency were measured using the following steps:

1. **Pre-cut**: Remove the clear background events and the poorly reconstruction events.
2. **Likelihood cut**: Using the likelihood, the signal and background events are separated efficiently.

**Pre-cut**

In the pre-cut selection, the loss of the signal has to be minimized, and unnecessary events such as the prompt events have to be discarded. The pre-cut criteria is as follows:

- **Volume cut**: remove the events reconstructed outside of the detector.
- $\Delta T < 400$ $\mu$sec
- $N_{\text{eff}} > 5$

As described in the previous section, the Am/Be data consist of the Gd $\gamma$ ray and the background events. Therefore, the efficiency of Gd $\gamma$ rays can be calculated using

$$\text{Eff}_{\text{pre}} = \frac{(N_{\text{Gd}})_{\text{pre-cut}}}{N_{\text{Gd}}}$$

$$(6.14)$$

where $N_{\text{Data}}$ is the number of Am/Be events after the pre-cut, and $N_{\text{BG+SBG}}$ is the number of background, the source background and 2.2 MeV $\gamma$ ray events, $N_{\text{Trg}}$ is the number of prompt triggers, and $\text{Eff}_{\text{capture}}$ is the capture efficiency by Gd. Figure 6.21 shows the $N_{\text{eff}}$ distribution after the pre-cut. The pre-cut efficiencies for each Gd concentration were obtained as shown in Table 6.3.

<table>
<thead>
<tr>
<th>Concentration</th>
<th>$N_{\text{Data}}[1/N_{\text{Gd}}]$</th>
<th>$N_{\text{BG+SBG}}[1/N_{\text{Gd}}]$</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>115 ppm</td>
<td>2.817</td>
<td>2.002</td>
<td>81.6±0.9$\text{Stat.}$</td>
</tr>
<tr>
<td>230 ppm</td>
<td>2.023</td>
<td>1.221</td>
<td>80.2±0.6$\text{Stat.}$</td>
</tr>
</tbody>
</table>

Table 6.3: Calculation of pre-cut efficiency of signal. $N_{\text{Data}}$ and $N_{\text{BG+SBG}}$ are given in unit of $N_{\text{Gd}}$.

The background efficiencies are calculated using $\text{Eff}_{\text{pre,BG}} = N'_{\text{BG}}/N_{\text{Trg,BG}}$, where $N_{\text{Trg,BG}}$ is the number of prompt triggers for the background events and $N'_{\text{BG}}$ is the number of background events after the pre-cut. The following is then obtained.

$$\text{Eff}_{\text{pre,BG}} = \begin{cases} 39.0 \pm 0.2_{\text{Stat.}} \text{%} & (115 \text{ppm}) \\ 38.5 \pm 0.8_{\text{Stat.}} \text{%} & (230 \text{ppm}) \end{cases}$$

$$(6.16)$$

**Likelihood cut**

As the next step, the likelihood analysis was applied to the remaining events after the pre-cut. The root-TMVA program [67] was used to fit the distributions of the variables and to compute the likelihood distribution ($\mathcal{L}$) in the form

$$\mathcal{L}_{S(i)} = \prod_{k=1}^{n_{\text{var}}} P_{S(i),k}(x_k(i)),$$

$$(6.17)$$
Figure 6.21: The N_{eff} distribution after the pre-cut. Black histogram is the Am/Be data, red histogram is merged one of the MC and the background, green histogram is the background. Gd \gamma-ray signal is estimated by subtraction of the background events (2.2 MeV \gamma ray, source background and background) which corresponds to blue histogram.

where S (B) denotes the Signal (Background), and P(x_k(i)) are PDFs of the variables x_k(i). The likelihood response (y_{x}) for each event (i) is

\[
y_x(i) = \frac{L_S(i)}{L_S(i) + L_B(i)}.
\]  

(6.18)

By inputting the variables, Eq.(6.18) provides the optimal good separation between the signal and the background. The likelihood functions for the 115 ppm and 230 ppm concentrations were produced in the following situation

- **Signal**: The MC of a Gd \gamma ray.
- **Background**: The background data taken periodic trigger in the normal run mode.

For making the likelihood function, we used six variables (x_k)_{k=1,6} (Vertex position, N_{eff}, \Delta T, goodness, DirKS, and \beta_{14}).

These are shown in Figure 6.3.2 and 6.24, and its correlation is shown in Figure 6.22.  

\[\beta_{14} \] is the parameter for the event isotropy.

\[
\beta_l = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} P_l(\cos \theta_{ij}),
\]  

(6.19)

where N is the number of hit PMTs, \theta is the angle between i-th and j-th PMT, and P_l is the l-th Legendre polynomials. In the case of \beta \sim 0, \theta distributes uniformly. On the contrary, \beta \sim \pm 1 means that \theta distributes locally. Gd emits 3 - 4 \gamma rays isotropically, and so \beta_{14} = \beta_1 + 4\beta_4 can be used to separate background events such as radioactivity background emitting a single particle. This was originally developed by the SNO experiment [68].

Correlation coefficient showing the correlation between two random variables X and Y is defined by

\[
\rho(X,Y) = \frac{\text{cov}(X,Y)}{\sigma_X \sigma_Y}.
\]  

(6.20)

The correlation coefficient is symmetric in X and Y, lies within the interval [-1,1], and quantifies by definition a linear relationship. Thus \rho = 0 holds for independent variables, but the reverse is not true in general.
Figure 6.25 shows the response of the likelihood ($y_L$) of the remaining events of the Am/Be data after the pre-cut. The MC distribution, which is normalized by the number of neutrons, reproduces the Am/Be data. As shown in Figure 6.26, the component of the Gd γ-ray events is obtained from the Am/Be data by subtraction of the background (2.2 MeV γ ray, source background, and background events). Figure 6.27 shows the signal efficiency and background efficiency as a function of the cut value of likelihood response. In this analysis, the signal and background events are selected by choosing a cut value such that the significance is maximized (Significance = $S / \sqrt{S + B}$, where S and B are the number of events of the signal and background respectively).

![Correlation Matrix (signal)](image1)

![Correlation Matrix (background)](image2)

Figure 6.22: Correlation matrix of used variables of signal (left) and background (right).

The efficiencies of the signal and background are shown in Table 6.4. The detection efficiency can be obtained as (Pre-cut) × (Likelihood cut). The detection efficiency takes into account the neutron capture, and it calculated as (reconstruction efficiency) × (capture efficiency). A summary of the efficiency is shown in Figure 6.28. The 115 ppm and 230 ppm data were analyzed, and data points at 0.2% Gd sulfate concentration were evaluated by the MC and background data in 230 ppm. So, the 0.2% Gd sulfate concentration results depends on the background data in a 0.2% Gd sulfate concentration situation; however, a higher concentration of Gd would provide not only better capture efficiency but also better separation between the signal and the background because of a shorter $\Delta T$. Table 6.5 gives a comparison of the detection efficiency of the data and MC, and a consistent result was obtained. The

<table>
<thead>
<tr>
<th>Concentration</th>
<th>Likelihood Cut value</th>
<th>Likelihood Eff. [%]</th>
<th>pre-cut × Likelihood [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0115%</td>
<td>Signal</td>
<td>0.27</td>
<td>95.4 ±0.5 Stat.</td>
</tr>
<tr>
<td></td>
<td>Background</td>
<td></td>
<td>3.2±0.1 Stat.</td>
</tr>
<tr>
<td>0.0230%</td>
<td>Signal</td>
<td>0.41</td>
<td>95.1±0.4 Stat.</td>
</tr>
<tr>
<td></td>
<td>Background</td>
<td></td>
<td>2.9±0.4 Stat.</td>
</tr>
</tbody>
</table>

Table 6.4: The likelihood cut and reconstruction efficiencies for signal and background event for a 400 $\mu$sec time window.
Figure 6.23: Used variables for the 115 ppm concentration. (red) Gd γ-ray MC, (blue) Background data.

Figure 6.24: Used variables for the 230 ppm concentration. (red) Gd γ-ray MC, (blue) Background data.
Figure 6.25: The distribution of likelihood response ($y_L$).

Figure 6.26: The distribution of the likelihood response of the Gd $\gamma$ ray events and MC and background data. Gd $\gamma$ events was obtained by subtraction of the background from the Am/Be data.
Figure 6.27: The cut efficiencies as the function of the cut point of the likelihood response.

Figure 6.28: The efficiency of signal and background as the function of the Gd concentration.
error estimations will be discussed in the next section.

<table>
<thead>
<tr>
<th>Concentration</th>
<th>Data</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>115 ppm</td>
<td>$22.7 \pm 0.3_{\text{Stat}} \pm 0.7_{\text{Sys}} %$</td>
<td>24.1%</td>
</tr>
<tr>
<td>230 ppm</td>
<td>$35.2 \pm 0.4_{\text{Stat}} \pm 0.9_{\text{Sys}} %$</td>
<td>36.2%</td>
</tr>
</tbody>
</table>

Table 6.5: The comparison of detection efficiency between the measured and expected value. The systematic errors are explained in Sec. 6.3.3.

### 6.3.3 Systematic Error

The systematic errors in the reconstruction efficiency are explained here. First, the systematic error in the pre-cut for the background efficiency was evaluated. From Figure 6.29, we see that the neutron signal is dominant near the source position. By comparing the number of events of the Am/Be data and the background data in the region $R^2 > 3.1\text{m}^2$, the systematic error in the background data was calculated from $Err_{BG} = (N_{data} - N_{MC})/N_{BG} - 1$, where $N_{data}$ is the number of Am/Be events, $N_{BG}$ is the number of background events and $N_{MC}$ is the number of source events of MC. On the other hand, the systematic error in the MC was estimated in the region $R^2 < 3.1\text{m}^2$. This region ($R^2 < 3.1\text{m}^2$) was determined so that significance ($S/\sqrt{S+B}$) was a maximum. Since the signal efficiency was obtained by Eq. (6.15), the total systematic error due to this cut was evaluated by the systematic error of the MC, the background, and the capture efficiency as

$$Err_{\text{Sig}} = \sqrt{\left(\frac{N_{\text{Data}}}{N_{\text{Trg}} \times \text{Eff}_{\text{capture}}} \times Err_{\text{capture}}\right)^2 + Err_{BG}^2 + Err_{MC}^2}.$$ (6.21)

Next, the systematic error in the likelihood cut is explained. This takes into account the uncertainties of the variables and the Gd concentration. Figure 6.30 shows the distribution of the six variables used for the likelihood analysis. After the correcting for the discrepancy between the data and the MC by
shifting the MC variables, the PDFs were re-generated, and the efficiencies were re-evaluated by same method. The uncertainty of the AAS measurement was also taken into account (±5 ppm). Using the MC of +5 ppm concentration, the Gd γ signal was extracted from the Am/Be data. The efficiency for +5 ppm concentration was evaluated using the PDFs of the normal concentration (115/230 ppm). This is the reason why the systematic error of the background efficiency is negligible. The systematic error estimation is summarized in Table 6.6.

<table>
<thead>
<tr>
<th>Variables</th>
<th>115 ppm</th>
<th>230 ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Signal</td>
<td>Background</td>
</tr>
<tr>
<td>MC error</td>
<td>1.6%</td>
<td>-</td>
</tr>
<tr>
<td>Background error</td>
<td>0.8%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Capture efficiency error</td>
<td>0.3%</td>
<td>-</td>
</tr>
<tr>
<td>pre-cut</td>
<td>1.9%</td>
<td>0.8%</td>
</tr>
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<td>Variables error</td>
<td>1.0%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Gd concentration</td>
<td>1.5%</td>
<td>-</td>
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<tr>
<td>Likelihood cut</td>
<td>1.8%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>2.1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Detection</td>
<td>0.7%</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.6: The summary of systematic errors.
Figure 6.30: The distribution of six variables $(x_k)_{k=1,6}$ used in likelihood analysis. Black histogram is the Am/Be data. Red histogram is merged histogram of the MC and background data. Light blue histogram is the background. Green histogram is the merged histogram whose the shifted MC histogram to be consistent with the black histogram.
6.4 Evaluation of the Performance in the Super-Kamiokande Detector

In order to estimate the performance of the delayed coincidence detection in the SK detector, we used a 2-litter vessel filled with 0.2% Gd sulfate solution (Figure 6.31) and observed the Gd γ-ray signal in SK. The first such measurement was performed in the SK-III phase, and its analysis has been published [66]. At the time, GdCl$_3$ was a leading candidate as a Gd compound, and the data was taken by old electronics.

6.4.1 Measurement and Setup

An Am/Be source and the Gd sulfate solution vessel were installed at (x,y,z) = (35 cm, -71 cm, 0 cm) using a pulley and lifter with an accuracy of 1mm. Figure 6.32 shows a schematic view of the setup. Since the SK detector is much bigger than the EGADS detector, the black sheet for the BGO scintillator was not used for the light intensity adjustment.

Figure 6.31: Picture of a 2-litter vessel filled with 0.2% Gd sulfate solution and an Am/Be source.

Figure 6.32: Schematic view of Gd vessel measurement in the SK detector.
The trigger setup is explained in Figure 6.33. The prompt scintillation event was detected by the SHE trigger. The threshold of the SHE is 70 hits in 200 nsec. After the SHE trigger, a 40 μsec time window was opened and the events with 29 hits in 200 nsec were recorded as the SHE sub events. After 35 μsec from the SHE trigger, a 500 μsec gate was opened and recorded the events with 20 hits. These events are called AFT events.

When Merger Process on the online machine receives an AFT event, the merger process doesn’t receive the next AFT events for 1 sec. Thus, it is a dead time and results in a 36% loss of AFT events. Basically, future GADZOOKS! is free from this effect.

The background events were taken by a periodic trigger in normal Run mode which has a 1 msec time window, so 11069 msec of equivalent data was analyzed.

![Figure 6.33: The schematic diagram of the trigger system of data taking in the SK detector. The prompt scintillation event is detected by the SHE trigger. The delayed Gd γ-ray event is detected as the SHE sub event and AFT events.](image)

6.4.2 Simulation

Simulation of this measurement was performed by two simulation tools: EGSIM and the official SK MC called SKDETSIM. EGSIM simulated the neutron capture process by Gd and protons inside/outside of the vessel. SKDETSIM treated the propagation of particles in the detector and the response of the detector. The SK group developed SKDETSIM based on GEANT 3.21 to understand the process in the SK detector based on the calibration data, and tuned the following factors.

Production of Cherenkov photons

The number of Cherenkov photons (dN) emitted by an electron per wavelength interval (dλ) per track length (dx) is given by

\[
dN = 2\pi\alpha \left( 1 - \frac{1}{n^2\beta^2} \right) \frac{1}{\lambda^2} dx d\lambda, \tag{6.22}
\]
where \( n \) is the refractive index of water (\( n = 1.334 \)), \( \alpha \) is the fine structure constant, and \( \beta \) is the velocity of the electron in units of the velocity of light in a vacuum. The opening angle \( \theta \) of Cherenkov photons is given by \( \cos \theta = 1/(n\beta) \).

**Propagation of photon in water**

The velocity of Cherenkov photons depends on its wavelength and it is given as a group velocity \( (v_g) \) of the wave packet by

\[
v_g = \frac{c}{n(\lambda) - \lambda \frac{dn(\lambda)}{d\lambda}},
\]

where \( n(\lambda) \) is the refractive index of pure water as a function of the wavelength such as

\[
n(\lambda) = \sqrt{\frac{a_1}{\lambda^2} + a_2 + a_3\lambda^2 + a_4\lambda^3 + a_5\lambda^6}
\]

(6.24)

The parameters are

\[
\begin{align*}
\lambda_0^2 &= 0.018085, & \alpha_1 &= 5.7473534 \times 10^{-3}, \\
\alpha_2 &= 1.769238, & \alpha_3 &= 2.797222 \times 10^{-2}, \\
\alpha_4 &= 8.715348 \times 10^{-3}, & \alpha_5 &= 1.413942 \times 10^{-3},
\end{align*}
\]

(6.25) (6.26) (6.27)

in units of \( \mu \)m. There are three processes: Rayleigh scattering, Mie scattering, and absorption are taken into account in photon propagation. The attenuation length \( (L_{\text{attn.}}) \) of light in water is then described by

\[
L_{\text{attn.}} = \frac{1}{\alpha_{\text{abs}}(\lambda) + \alpha_{\text{Ray}}(\lambda) + \alpha_{\text{Mie}}(\lambda)},
\]

(6.28)

where \( \alpha_{\text{abs}}(\lambda) \), \( \alpha_{\text{Ray}}(\lambda) \) and \( \alpha_{\text{Mie}}(\lambda) \) are coefficients for the absorption, Rayleigh scattering, and Mie scattering, respectively, as \( \alpha \) function of the wavelength of photons \( (\lambda) \). The fraction of these processes depends on the wavelength and the purity of water which is given by

\[
\begin{align*}
\alpha_{\text{abs}}(\lambda) &= \begin{cases} 
\frac{A_1}{\lambda^4} + A_2(\frac{\lambda}{A_3})A_4, & (\lambda \leq 350nm) \\
\frac{A_1}{\lambda^4} + f(\lambda), & (350nm < \lambda \leq 415nm) \\
\frac{A_1}{\lambda^4}, & (415nm < \lambda)
\end{cases} \\
\alpha_{\text{Ray}}(\lambda) &= \frac{R_1}{\lambda^4} \times \left(1 + \frac{R_2}{\lambda^2}\right), \\
\alpha_{\text{Mie}}(\lambda) &= \frac{M_1}{\lambda^4},
\end{align*}
\]

(6.29) (6.30) (6.31)

where \( A_x, R_x \) and \( M_x \) are tuned parameters, and \( f(\lambda) \) is obtained from [69]. The measurement was performed by periodic laser injection calibration. When a photon arrives at the detector wall (the acrylic cover, the PMT surface or the black sheet), reflection, absorption, and transmission are considered.

### 6.4.3 Measurement of Energy Spectrum of Gd \( \gamma \) ray

The prompt event of interest is that generated by a 4.43 MeV \( \gamma \) ray. The prompt events were selected using the following criteria:

- Total charge selection to select 4.4 MeV \( \gamma \) ray. The peak around 1000 p.e. corresponds to the 4.43 MeV \( \gamma \) ray.
- Vertex cut: \( R^2 < 2m^2 \)
• Time difference from last trigger > 1 ms (remove the effect of the previous event)

Figure 6.34 shows the total charge distribution of a prompt event before and after event selection. From this selection, the loss fraction of AFT events becomes 30%. The delayed events selection:

![Histogram showing total charge distribution](image)

Figure 6.34: The total charge of the prompt event. Red histogram corresponds to the events used in this analysis.

• ∆T Cut > 1.7 µsec to remove the after-pulse from PMTs
• Vertex cut : $R^2 < 2m^2$
• Vertex fit goodness > 0.4
• DirKS < 0.4
• N200 > 20

Figure 6.35-6.37 shows the distribution of the ∆T, the vertex position, and the energy spectrum for AFT and SHE trigger events after event selection. In the same way as the EGADS analysis, the source background was taken into account. The peak of the reconstructed Gd $\gamma$ ray energy was around 4 MeV as seen in EGADS data. Figure 6.38 shows the event display of Gd $\gamma$-ray events in SK.
Figure 6.35: The time difference between prompt and delayed trigger. At the $\Delta T=35$ $\mu$sec, trigger type is separated (SHE trigger: <35$\mu$sec, AFT trigger: >35$\mu$sec). Horizontal axis is normalized by the number of AFT trigger.

Figure 6.36: The $R^2$ distribution (left) SHE sub events, (right) AFT events.
Figure 6.37: Energy spectrum (left) SHE sub event, (right) AFT event.

Figure 6.38: Event display of Gd $\gamma$ ray event.
6.4.4 Evaluation of the Performance

Capture efficiency

The capture efficiency was estimated for SK-Gd data in the same way as for EGADS analysis (Eq. (6.13)). Results are given in Table 6.7. Then, it is possible to measure the position dependence of the neutron capture efficiency due to the non-uniformity of Gd concentration in the SK detector. A neutron travels about 15cm in the Gd solution. Thus, most neutrons leak from the 2-litter vessel.

<table>
<thead>
<tr>
<th>SHE sub</th>
<th>AFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hit rate</td>
<td>0.0645</td>
</tr>
<tr>
<td>Eff\textsubscript{Gd}\textsuperscript{Cut}</td>
<td>0.4790</td>
</tr>
<tr>
<td>Eff\textsubscript{SBG}</td>
<td>0.0006</td>
</tr>
<tr>
<td>Eff\textsubscript{Gd}\textsubscript{SBG}</td>
<td>0.0023</td>
</tr>
<tr>
<td>Capture Eff.</td>
<td>13.3%</td>
</tr>
<tr>
<td>Result</td>
<td>$13.3 \pm 0.4_{\text{Stat}} \pm 0.8_{\text{Sys}}%$</td>
</tr>
<tr>
<td>MC</td>
<td>12.9%</td>
</tr>
</tbody>
</table>

Table 6.7: Summary of calculation of capture efficiencies for each of the trigger events.

Reconstruction efficiency

The reconstruction efficiency of the delayed neutron signal and background efficiency were estimated in the same way as for the EGADS analysis. Likelihood analysis was applied after the pre-cut. The followings shows the selection criteria for the pre-cut:

- Vertex cut : $R^2 < 5[m^2]$
- $\Delta T$ Cut
  - $1.7 \mu sec < \Delta T < 35 \mu sec$ (SHE sub events)
  - $35 \mu sec < \Delta T < 535 \mu sec$ (AFT events)
- $N_{200} > 20$ : $N_{200}$ is the maximum number of hits in a 200 nsec time window.

The $N_{\text{eff}}$ distribution is seen in Figure 6.39, and the signal efficiencies of the pre-cut can be obtained using Eq.(6.15). The results are summarized in Table 6.8. The background efficiencies are calculated by

<table>
<thead>
<tr>
<th>Trigger</th>
<th>$N_{\text{Data}}[1/\text{NGd}]$</th>
<th>$N_{\text{BG+SBG}}[1/\text{NGd}]$</th>
<th>pre-cut Efficiency[$%$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHE sub</td>
<td>1.093</td>
<td>0.181</td>
<td>91.1$\pm 2.0_{\text{Stat}}$</td>
</tr>
<tr>
<td>AFT</td>
<td>2.629</td>
<td>1.705</td>
<td>92.4$\pm 2.8_{\text{Stat}}$</td>
</tr>
</tbody>
</table>

Table 6.8: Calculation of pre-cut efficiency of signal.

$\text{Eff}_{\text{pre,BG}} = N'_{\text{BG}}/N_{\text{BG}}$, where $N_{\text{BG}}$ is the number of SHE triggers, and $N'_{\text{BG}}$ is the number of background events after the pre-cut in each trigger. Then, the following is obtained.

$$\text{Eff}_{\text{pre,BG}} = \begin{cases} 0.22 \pm 0.04_{\text{Stat}}\% & \text{(SHE sub)} \\ 2.58 \pm 0.15_{\text{Stat}}\% & \text{(AFT)} \end{cases} \quad (6.32)$$
Figure 6.39: The energy distribution after the pre-cut. The Gd γ-ray signal is estimated by subtraction of background events (2.2 MeV γ ray, source background and background) which corresponds to the entries of blue histogram.

For the likelihood analysis, the same variables were used as for the EGADS analysis, PDFs were generated by using the MC of Gd γ-ray and background data. Figure 6.40, 6.41 shows the distribution of the variables for each of the trigger events.

Figure 6.42 and 6.43 show the likelihood response ($y_L$) and the efficiencies as a function of the cut value of the likelihood responses. As for the EGADS analysis, the efficiencies were evaluated at the maximum significance. These efficiencies are summarized in Table. 6.9.

<table>
<thead>
<tr>
<th>Event type</th>
<th>Likelihood cut value</th>
<th>Likelihood Eff. [%]</th>
<th>Precut × Likelihood [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHE sub</td>
<td>Signal</td>
<td>$0.101$</td>
<td>$96.6 ± 2.2_{\text{Stat}}$</td>
</tr>
<tr>
<td></td>
<td>Background</td>
<td></td>
<td>$3.6 ± 0.4_{\text{Stat}}$</td>
</tr>
<tr>
<td>AFT</td>
<td>Signal</td>
<td>$0.176$</td>
<td>$98.4 ± 3.0_{\text{Stat}}$</td>
</tr>
<tr>
<td></td>
<td>Background</td>
<td></td>
<td>$3.3 ± 0.4_{\text{Stat}}$</td>
</tr>
</tbody>
</table>

Table 6.9: The likelihood cut efficiency and reconstruction efficiency.

The expected values for the reconstruction efficiency are 88.4% and 89.4% for the SHE sub and AFT events. Then, the consistent results were obtained from the Am/Be data.

The better performance was obtained than that for the EGADS data. This comes mainly from the lower background and lower mis-reconstruction probability in the SK detector. BONSAI uses the number of PMT hits for vertex reconstruction. SK can provide more PMT hits than EGADS due to the large detector size.

**Systematic error**

Since the background events in the SHE sub and AFT triggers are intrinsically common, the systematic error in the pre-cut efficiency for the background was evaluated by comparing the SHE sub events and
Figure 6.40: Used variables for SHE sub event. (Blue) Gd $\gamma$ MC, (Red) Background data.

Figure 6.41: Used variables for AFT event. (Blue) Gd $\gamma$ MC, (Red) Background data.
Figure 6.42: The distribution of likelihood response ($y_L$).

Figure 6.43: The cut efficiencies as the function of the cut point of the likelihood response for (left) SHE sub and (right) AFT events.
the AFT events. In other words, the efficiency of both events are consistent for the pre-cut selection, except for the $\Delta T$ selection. After the correcting for the time window of each event ($\text{Eff}_{\text{AFT}} = \text{Eff}_{\text{SHE}} \times (500\mu\text{sec}/35\mu\text{sec})$), the difference between them was treated as the systematic error.

The systematic error in the pre-cut for the signal was evaluated by same method as for EGADS analysis; the number of remaining event after the pre-cut was compared with the MC, and the systematic error was evaluated. Figure 6.4.4 shows the vertex distribution after pre-cut selection.

The systematic error of the likelihood cut was evaluated by the shifted MC variables shown in Figure 6.45, and these are summarized in Table 6.10. In this analysis, the Gd concentration uncertainty was not considered, since the Gd concentration was well measured.

<table>
<thead>
<tr>
<th></th>
<th>SHE sub</th>
<th>AFT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Signal</td>
<td>Background</td>
</tr>
<tr>
<td>MC error</td>
<td>0.9%</td>
<td>-</td>
</tr>
<tr>
<td>Background error</td>
<td>0.04%</td>
<td>0.04%</td>
</tr>
<tr>
<td>Capture efficiency error</td>
<td>0.8%</td>
<td>-</td>
</tr>
<tr>
<td>Pre-cut</td>
<td>0.6%</td>
<td>0.04%</td>
</tr>
<tr>
<td>Variables error</td>
<td>0.1%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Gd concentration error</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Likelihood cut</td>
<td>0.1%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>0.6%</td>
<td>0.002%</td>
</tr>
</tbody>
</table>

Table 6.10: Systematic error estimation of likelihood analysis.
Figure 6.45: The variables used in the likelihood analysis for the SHE sub event of the SK+Gd vessel data. Black histogram is the Am/Be data. Red histogram is merged histogram of the MC and background data. Light blue histogram is the background. Green histogram is the merged histogram whose shifted MC histogram to be consistent with the black histogram.
Estimation of performance

In this thesis, the Am/Be data was analyzed, and this gave a consistent result with the MC for both EGADS (full Gd-doped water Cherenkov detector) and SK (the detector for GADZOOKS!). Therefore, using the MC simulation, the performance of GADZOOKS! was evaluated in the situation that neutrons are generated from the center of the detector. In order to compensate for the small statistics of background data, the efficiency was evaluated as follows:

• Applied the pre-cut and evaluate the efficiency. However, $\Delta T$ cut was not applied, and the fiducial cut (22.5kton) was applied instead of the $R^2$ cut for the background events.

• For background events, the $\Delta T$ cut of a 100 $\mu$sec time window and the $R^2 < 3m^2$ cut efficiencies can be calculated by scaling: $100\mu$sec/1msec $\times \left(\frac{4}{3} \pi 3^3\right)/22.5kton$.

• Evaluated the likelihood cut efficiency. To suppress the background efficiency as much as possible, the events were selected out of a 0.9 likelihood response as shown in Figure 6.46.

![Figure 6.46: The distribution of the likelihood response ($y_x$).](image)

Finally, the detection efficiency and background efficiency were obtained as 73.9% and $1.4 \times 10^{-4}\%$ respectively for a 100 $\mu$sec time window and the 2.5 MeV threshold using a 90% neutron capture efficiency on 0.2% Gd sulfate solution. A previous study [66] evaluated the detection and background efficiencies as 66.7% and $2 \times 10^{-2}\%$ for the 3.0 MeV threshold and a 60 $\mu$sec window (for 2.5 MeV threshold, the background efficiency was $1 \times 10^{-1}\%$). The estimated performance has been greatly improved by this study with the likelihood analysis.

Figure 6.47 shows the expected SRN spectrum for 10 years of measurements in GADZOOKS! using the obtained signal and background efficiencies. The expected number of SRN signals is approximately 16.5, 18.2, 30.1, and 36.2 events in the case of an effective neutrino temperature of 4 MeV, 6 MeV, 8 MeV, and 1987a of the SRN model [17], respectively, and the accidental background is negligible. Since the expected atmospheric neutrino background is approximately 18.1 events, approximately 5 $\sigma$ level observations are expected, and this provides enough statistics to discuss the differences in the SRN models.
Figure 6.47: Expected SRN spectrum and background for 10 years observation in the Gd-doped SK detector for each neutrino temperature (T). (upper:right) T=4 MeV, (upper:left) T=6 MeV, (bottom:right) T=8 MeV, (bottom:left) T=SN1987a from [17]. Green line is the expected accidental background. The atmospheric neutrino background events were selected by requiring that one neutron is captured by Gd through the interaction process.
Chapter 7

Conclusion and Future Prospects

In this thesis, the delayed coincident detection in a Gd-doped water Cherenkov detector has been demonstrated.

The delayed $\gamma$-ray signal from Gd neutron capture has been measured using an Am/Be neutron source at 115 and 230 ppm concentrations of Gd$_2$(SO$_4$)$_3$ in EGADS. The $\gamma$-ray energy, the position and the time of $\gamma$-ray production from Gd neutron capture are measured. The detection efficiencies for 115 ppm and 230 ppm concentrations of Gd$_2$(SO$_4$)$_3$ were measured to be 22.7±0.7% and 35.2±1.0%, respectively. The background efficiencies for a 400 $\mu$sec time window were also measured to be 1.2±0.3% and 1.1±0.3% for each concentration. For the SK detector, the signal reconstruction efficiency and background efficiency were evaluated to be 88.0±2.0% and $(8 \pm 2) \times 10^{-3}$% (SHE sub events) by using the 2-litter vessel filled with 0.2% Gd$_2$(SO$_4$)$_3$ solution. The measured values were consistent with MC predictions. Finally, this study has shown that Gd should give the sufficiently high detection efficiency of the delayed event and accidental background can be also sufficiently suppressed compared with the search of 2.2 MeV $\gamma$ ray from neutron capture on protons for the observation of SRN.

After refurbishing and cleaning inside the detector, the EGADS experiment resumed the circulation with Gd-doped water. It will complete the study of the water transparency of Gd-doped water in near future (in 2015). The Am/Be measurement will be also resumed, and Gd $\gamma$-ray data up to 0.2% Gd$_2$(SO$_4$)$_3$ concentration will be checked.

In the world, the big projects are processing to search for the SRN signals (Hyper-Kamiokande, SNO+, LENA etc.). Any one of these would be a spectacular device for detecting SRN, but it will still take a decade until the SRN observation. However, GADZOOKS! may start the SRN observation by using the existing SK detector, and a Gd-doped SK detector has a better chance for the first detection of the SRN signals.

The other type of backgrounds has to be studied more carefully. In order to suppress the radioactivity in Gd compound, the Rn measurement setup is being prepared in the EGADS experimental room, and several membranes will be tested by this setup. The measurement technique of Rn concentration in pure water has been established by SK, but the measurement for Gd-doped water is the first trial. Although the theoretical calculation of $\gamma$ ray production is explained in this thesis, better understanding on NC QE $\gamma$ ray is also necessary. At the present time, some experiments have started investigating it (T2K NC QE $\gamma$ ray measurement [71], and Research Center for Nuclear Physics E398 [72]).

In parallel, EGADS will be converted to an advanced-technology supernova neutrino detector by replacing its front-end electronics with QBEE suitable for the very high data rates expected in the case for a nearby supernova explosion. Such an explosion will overwhelm SK’s ability to record all events. In
addition, a GPS time stamping and a real-time intelligent trigger system comprised of custom hardware and software will be added, and they are designed to extract the most detailed, accurate supernova neutrino data possible as rapidly as possible. Then, EGADS will be the only neutrino detector that has the direction sensitivity and neutrino-antineutrino flavor sensitivity until realization of the Gd-doped SK detector.
Bibliography


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