DOCTORAL DISSERTATION

Measurement of Neutrino and Antineutrino Neutral-Current Quasielastic-like Interactions and Applications to Supernova Relic Neutrino Searches

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ABSTRACT

MEASUREMENT OF NEUTRINO AND ANTINEUTRINO NEUTRAL-CURRENT QUASIELASTIC-LIKE INTERACTIONS AND APPLICATIONS TO SUPERNOVA RELIC NEUTRINO SEARCHES

Neutrinos are a key messenger that carry valuable information about the supernova explosion. In particular, discovery of supernova relic neutrinos (SRNs) would open up many paths to precise studies of the supernova explosion mechanism. A barrier for the discovery of SRNs is that one of the main backgrounds, atmospheric neutrino neutral-current quasielastic-like (NCQE-like) interactions, is not precisely measured nor predicted. In this thesis, a measurement of this channel using Super-Kamiokande data in the T2K experiment is presented. Signal event candidates were selected based on nuclear de-excitation γ -rays. An application of the measured results to the background estimation in an SRN search at Super-Kamiokande is also reported.

T2K has accumulated 14.94×10^{20} and 16.35×10^{20} protons-on-target exposures of the neutrino and antineutrino beams, respectively. The measured flux-averaged NCQE-like cross sections are:

$$\langle \sigma_{\nu\text{-NCQE}} \rangle = 1.70 \pm 0.17 (\text{stat.})^{+0.51}_{-0.38} (\text{syst.}) \times 10^{-38} \text{ cm}^2/\text{oxygen},$$

 $\langle \sigma_{\bar{\nu}\text{-NCQE}} \rangle = 0.98 \pm 0.16 (\text{stat.})^{+0.26}_{-0.19} (\text{syst.}) \times 10^{-38} \text{ cm}^2/\text{oxygen},$

at flux-averaged energies of 0.82 GeV and 0.68 GeV for neutrinos and antineutrinos, respectively. These are the world's most precise measurement results to date, and the antineutrino result is the first measurement of this channel. Distributions in the kinematic regions of interest for SRN searches are also studied for the first time.

The largest uncertainty in the NCQE-like measurement comes from modeling of the γ -rays emitted from neutron-oxygen reactions. In order to provide experimental data, a measurement of γ -ray production via neutron-oxygen reactions with an 80 MeV neutron beam was performed. Several γ -rays of various energies were observed and their production cross sections were measured to $\sim 20\%$ precision.

An SRN search was performed with a new estimation of the NCQE-like background based on these T2K results and using a 2970.1-day data set from Super-Kamiokande. The new estimation reduces the uncertainty from 100% to 60%. This improves the search sensitivity by 12% compared to an analysis with a 100% uncertainty on the NCQE-like background. No significant excess over the prediction was observed in the data spectrum, and an upper limit on the $\bar{\nu}_e$ flux was placed. The result is the world's most stringent above 13.3 MeV in neutrino energy and a factor 3 to 30 above model predictions. The methods presented in this thesis are applicable to SRN searches at other water Cherenkov detectors, such as SK-Gd and Hyper-Kamiokande, and may help a future discovery of the SRN flux.

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Part I Introduction

Chapter 1

Introduction

Supernova explosions are one of the most dynamic phenomena in the universe and have been playing important roles in terms of physics and astrophysics. It is particularly important to study the supernova via neutrino detections. In this chapter, first, supernovae and their relations with neutrinos are described, and followed by the descriptions on supernova relic neutrinos, which are neutrinos from all past supernovae. After describing the physics background, experimental searches for supernova relic neutrinos are explained, focusing on an importance of the neutrino neutral-current quasielastic interaction, which is the main subject of this thesis.

1.1 Supernova Explosion

A star, whose mass is more than about eight times heavier than the Sun, ends its life by an explosion, a kinetic energy of which reaches $\sim 10^{51}$ erg. This is one of the most energetic phenomena in the universe, known as a supernova. It is estimated that supernovae occur a few times a century in a galaxy [1,2]. Many have been observed via optical surveys in many galaxies over centuries. Figure 1.1 gives an image of the Crab Nebula, which was observed in 1054 as a Type-II supernova. Despite these observations there remain many unknowns about supernovae and their explosion mechanisms.



Figure 1.1: An image of the Crab Nebula taken by NASA's Hubble Space Telescope [3].

1.1.1 Supernova Types

Supernovae are classified by their spectral characteristics: Ia, Ib, Ic, and II, as shown in Figure 1.2. A supernova whose spectrum without hydrogen lines (the Balmer series) is classified as Type-I, and that with those lines as Type-II. Type-I supernovae with intense silicon lines are classified as Type-Ia. Among the other Type-I supernovae, those with and without helium lines are Type-Ib and Type-Ic, respectively. Type-Ia supernovae are typically observed in older elliptical galaxies that do not contain young stars, while the other types are observed only in the region where star formations occur actively. This indicates that Type-Ia supernovae can originate from long-lived stars unlike the other types. The reason for this difference is related to the explosion mechanisms as explained below.



Figure 1.2: Classification of supernovae based on their spectral properties and explosion mechanisms.

The kinetic energy of supernovae reaches $\sim 10^{51}$ erg. Possible sources for such large energy are the nuclear energy and the gravitational energy [4]. First, the explosion with release of the nuclear energy is explained. Assuming that drastic nuclear fusion reactions happen in a star whose mass is similar to the Sun, the released energy (E) is:

$$E \sim 3 \times 10^{51} \left(\frac{M}{M_{\rm sun}}\right) \,\,\mathrm{erg},$$
(1.1)

where $M_{\rm sun} = 1.989 \times 10^{30}$ kg is the solar mass and M is the mass of the star. Here the fusion reactions from carbon to iron are assumed. This energy size is comparable to the scale of energies of Type-Ia supernovae. This drastic fusion happens in a star which is supported by pressures of the Fermi gas degenerate electrons such as white dwarfs. This type of explosions is

called "thermonuclear supernovae". Second, the explosion based on release of the gravitational energy is possible. When a star collapses by the gravity to leave a compact object with a mass similar to the Sun, the released energy is:

$$E \sim 3 \times 10^{53} \left(\frac{M}{M_{\rm sun}}\right)^2 \left(\frac{R}{10 \text{ km}}\right)^{-1} \text{ erg},\qquad(1.2)$$

where R is the radius after the collapse and 10 km is a typical size of the neutron star. This gives enough energy to explain the scale of the supernova explosion when ~1% of the total released energy is used as kinetic energy. This type is called "core-collapse supernovae", 99% of whose energy is carried by neutrinos. The collapse by the gravitation is inevitable for the star which is more massive than ~10 $M_{\rm sun}$ and the lifetime of those stars is typically $\leq 10^7$ years. This is short compared to a typical lifetime of ~10¹⁰ years for a star with ~1 $M_{\rm sun}$. The fact that only Type-Ia supernovae are observed in elliptical galaxies indicate that these are the thermonuclear supernovae, while the other types (Ib, Ic, and II) are the core-collapse supernovae. Though both types of supernovae accompany the neutrino burst, much more neutrinos are emitted from the core-collapse supernovae. Therefore this thesis focuses on the core-collapse type.

1.1.2 Galactic Evolution

Supernovae are important phenomena that drive both the chemical and physical evolution of the universe [5–7]. The explosion rate, properties of the stars that cause supernovae, and the explosion properties are important to unravel the history of the universe and help to predict its future evolution.

In the early phase, the universe was composed of only hydrogen and helium. On the other hand, the present universe is enriched with heavier elements. Explosive phenomena such as supernovae are an important source for synthesizing heavy elements via two possible paths. Since the star makes elements via its nuclear fusion inside itself, the explosion disperses elements heavier than hydrogen and helium into the universe. This process, however, can produce elements only up to iron, because the binding energy per nucleon takes its maximum at iron nuclei. Another important process is the r-process [8,9], in which neutrons are captured by light elements during the explosion leading to beta decay to produce heavier elements than iron. The r-process requires a neutron-dominant environment, which is represented by the electron-to-proton ratio (Y_e) to be $Y_e < 0.5$. In supernovae, $Y_e = 0.3 \sim 0.45$ is expected ¹.

1.1.3 Insights into Fundamental Physics

All four forces (electromagnetic force, strong force, weak force, and gravitation) are involved in the supernova dynamics, and all of them are essential. Therefore, to study the explosion mechanism leads to validation of the fundamental forces in the Standard Model of particle physics. Currently the theoretical simulations do not perfectly succeed in modeling these explosions. It has been argued that some fundamental theory might be insufficient and hence some physics beyond the Standard Model (BSM) could be required.

¹Some studies disfavor the r-process in supernovae because the neutron amount near the core decreases due to inverse beta decay. Instead neutron star mergers are another favorable sites for the r-process since they satisfy the neutron rich condition ($Y_e \sim 0.1$) while their rate is lower than supernovae.

1.1.4 Relation to Other Astronomical Objects

Supernovae are thought to be strongly related to other astronomical phenomena. Among them, γ -ray bursts (GRBs) are of particular interest. A GRB is considered to be a highly relativistic jet, and its energy reaches 10^{54} erg, making it the most luminous event in the universe. It is thought that some supernovae produce GRBs, and there have been some coincident observations of a supernova and a GRB, such as SN1998bw+GRB980425 [10] and SN2001ke+GRB011121 [11]. Since the rate of GRBs is ~10 times less than supernovae, it is important to study supernovae in detail for the GRB research. Other related objects are, for example, black holes and pulsars (neutron stars rotating with a high frequency). Both of them are often made from supernova explosions.

1.2 Neutrinos from Core-Collapse Supernovae

Neutrinos are elementary particles with spin 1/2 and no electric charge, and have three flavors: electron, muon, and tau corresponding to their charged lepton partners. They interact with materials only via weak forces (and gravity). It is thought that neutrinos play an essential role in the supernova explosion and are an important messenger that carry different information about the supernova than electromagnetic radiation. In this section, the neutrino oscillation is described first as an important property of neutrinos, and followed by the descriptions on the explosion mechanism of the core-collapse supernova.

1.2.1 Neutrino Oscillations

It was believed that neutrinos are massless. However, the observation of neutrino oscillations [12,13] contradicts this, indicating that neutrinos have small but nonzero masses (<1 eV). When neutrinos have mass, their flavor eigenstates, $|\nu_{\alpha}\rangle$ ($\alpha = e, \mu, \tau$), are expressed as superposition of their mass eigenstates, $|\nu_{i}\rangle$ (i = 1, 2, 3):

$$|\nu_{\alpha}\rangle = \sum_{i} U_{\alpha i} |\nu_{i}\rangle, \qquad (1.3)$$

where U is a 3×3 unitary matrix, referred to as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [14,15]. This matrix is expressed by four independent parameters, which are three mixing angles (θ_{12} , θ_{23} , and θ_{13}) and one complex phase (δ_{CP}):

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ = \begin{pmatrix} c_{12}s_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & c_{13}c_{23} \end{pmatrix},$$
(1.4)

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$. In case of $\sin \delta_{CP} \neq 0$, the PMNS matrix contains imaginary parts, which cause CP violation. In vacuum, the evolution of a mass eigenstate $|\nu_i\rangle$ after a traveling time t is derived from the Schrödinger equation:

$$i\frac{d}{dt}|\nu_i(t)\rangle = \mathcal{H}|\nu_i(t)\rangle = E_i|\nu_i(t)\rangle, \qquad (1.5)$$

$$|\nu_i(t)\rangle = \exp(-iE_it)|\nu_i\rangle, \qquad (1.6)$$

where \mathcal{H} represents the Hamiltonian and E_i is the energy of the mass eigenstate. The flavor eigenstate $|\nu_{\alpha}\rangle$ at a time t can be written as:

$$|\nu_{\alpha}(t)\rangle = \sum_{i} U_{\alpha i} \exp(-iE_{i}t)|\nu_{i}\rangle.$$
(1.7)

Since the masses of neutrinos are small, an approximation, $E_i = \sqrt{p_i^2 + m_i^2} \simeq p_i + \frac{m_i^2}{2p_i} \simeq p + \frac{m_i^2}{2E}$, where p_i and m_i are the momentum and mass of the mass eigenstate respectively $(p_i \sim p \text{ and } E_i \sim E)$, can be used:

$$|\nu_{\alpha}(t)\rangle = \sum_{i} U_{\alpha i} \exp(-ipt) \exp\left(-\frac{im_{i}^{2}t}{2E}\right) |\nu_{i}\rangle$$
$$= \sum_{i,\beta} U_{\alpha i} \exp(-ipt) \exp\left(-\frac{im_{i}^{2}t}{2E}\right) U_{\beta i}^{\dagger} |\nu_{\beta}\rangle.$$
(1.8)

Then the $\nu_{\alpha} \rightarrow \nu_{\beta}$ transition probability is calculated as:

$$P(\nu_{\alpha} \rightarrow \nu_{\beta}) = |\langle \nu_{\beta} | \nu_{\alpha}(t) \rangle|^{2}$$

$$= \left| \sum_{i,\beta} U_{\alpha i} \exp(-ipt) \exp\left(-\frac{im_{i}^{2}t}{2E}\right) U_{\beta i}^{\dagger} \right|^{2}$$

$$= \sum_{i,j} U_{\alpha i}^{\dagger} U_{\beta i} U_{\alpha j} U_{\beta j}^{\dagger} \exp\left(-\frac{i(m_{i}^{2} - m_{j}^{2})t}{2E}\right)$$

$$= \sum_{i,j} U_{\alpha i}^{\dagger} U_{\beta i} U_{\alpha j} U_{\beta j}^{\dagger} \exp\left(-\frac{i\Delta m_{ij}^{2}L}{2E}\right)$$

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \operatorname{Re}(U_{\alpha i}^{\dagger} U_{\beta i} U_{\alpha j} U_{\beta j}^{\dagger}) \sin^{2}\left(\frac{\Delta m_{ij}^{2}L}{4E}\right)$$

$$+ 2 \sum_{i>j} \operatorname{Im}(U_{\alpha i}^{\dagger} U_{\beta i} U_{\alpha j} U_{\beta j}^{\dagger}) \sin\left(\frac{\Delta m_{ij}^{2}L}{2E}\right), \qquad (1.9)$$

where $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ is a mass-squared difference, t is replaced with a travel distance L = ct (neutrinos are relativistic), and the unitary condition $(\sum_i U_{\alpha i}^{\dagger} U_{\beta i} = \delta_{\alpha\beta})$ had been used. According to this equation, neutrino oscillation occurs only when at least two masses are not

degenerate $(m_i \neq m_j)$ and there is nonzero mixing $(U \neq I)$. Neutrino oscillations in vacuum are parametrized by three mixing angles $(\theta_{12}, \theta_{23}, \text{ and } \theta_{13})$, two mass-squared differences $(\Delta m_{21}^2$ and $\Delta m_{32}^2)^{-2}$, and a CP phase (δ_{CP}) . The formalism needs to be modified for the case of oscillations in matter [16, 17]. Over the past 20 years, the neutrino oscillation parameters have been measured with various sources: atmospheric, solar, reactor, and beam neutrinos. The order of the mass eigenstates, $\Delta m_{32}^2 > 0$ or $\Delta m_{32}^2 < 0$, has not been determined. The former is called the normal hierarchy (NH) and the latter the inverted hierarchy (IH). The NH is slightly favored by some experiments including T2K and Super-Kamiokande [18–20]. The CP phase is not observed yet, though a recent T2K result excludes sin $\delta_{CP} = 0$ with more than 2σ confidence [21]. Table 1.1 summarizes the most precise results of the oscillation parameters as of 2018 [22].

Oscillation parameter	Best-fit value
$\sin^2 \theta_{12}$	0.307 ± 0.013
$\sin^2 \theta_{23}$ (NH, Octant I)	$0.417_{-0.028}^{+0.025}$
$\sin^2 \theta_{23}$ (NH, Octant II)	$0.597_{-0.030}^{+0.024}$
$\sin^2 \theta_{23}$ (IH, Octant I)	$0.421^{+0.033}_{-0.025}$
$\sin^2 \theta_{23}$ (IH, Octant II)	$0.592_{-0.030}^{+0.023}$
$\sin^2 \theta_{13}$	$(2.12 \pm 0.08) \times 10^{-2}$
Δm_{12}^2	$(7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2$
Δm_{32}^2 (NH)	$(2.51 \pm 0.05) \times 10^{-3} \text{ eV}^2$
Δm^2_{32} (IH)	$(-2.56 \pm 0.04) \times 10^{-3} \text{ eV}^2$

Table 1.1: Best-fit values of the neutrino oscillation parameters from PDG2018 [22]. NH and IH represent the normal and inverted neutrino mass hierarchy, respectively.

1.2.2 Core-Collapse Supernovae and Neutrino Emission

In this section, the explosion mechanism of the core-collapse supernova (CCSN) is explained. The neutrino-heating mechanism [4,23] is described here because it is widely accepted although the mechanism is not completely confirmed and still being actively studied. Figure 1.3 shows a schematic view of the mechanism for explanation below.

(Steps 1-3) A star initially supports itself against the gravity with pressure produced by nuclear fusion. The process begins with the hydrogen burning into helium (1). The temperature and density increase due to nuclear fusion until it is high enough for helium fusion to occur. Since hydrogen remains in the outer parts of the star avoiding the fusion, the star becomes layered (2). Once the helium in the core is exhausted, the star contracts again, until the temperature and density of the core become sufficiently high for the fusion of more massive nuclei. This sequence continues until the silicon burning in the core and the star structure becomes multi-layered (3). The silicon burning produces nickel and iron group nuclei. Since iron nuclei have the largest binding energy, nuclear fusion stops.

(Steps 4-7) As iron accumulates in the core of the star, the density and temperature of the core become higher, increasing the Fermi energy of electrons therein. It promotes the electron capture reaction $(e^- + p \rightarrow \nu_e + n)$ mainly on protons in iron. This causes lack of the degenerate pressure. In addition, at temperatures above $\sim 5 \times 10^9$ K, photodisintegration of iron nuclei

 ${}^{2}\Delta m_{21}^{2} + \Delta m_{32}^{2} + \Delta m_{13}^{2} = 0$


Figure 1.3: Schematic illustration of the explosion mechanism of core-collapse supernovae assuming a neutrino-heating mechanism. Descriptions of each part with numbers in the parentheses are given in the text.

 $(\gamma + {}^{56}\text{Fe} \rightarrow 13\alpha + 4n - 124.4 \text{ MeV})$ occurs. Since this is an endothermic reaction, the core pressure does not increase enough. These processes make the core unstable and become triggers of the gravitational collapse of the core (4). In this phase, the mean free path for neutrinos is determined by the interaction with nuclei, $\sim 10^9$ cm, which is larger than the size of the iron core. Therefore, the ν_e 's produced from electron capture can initially escape from the core. The surface where the neutrino is scattered last is called the "neutrinosphere", which is represented as dashed blue circles in Figure 1.3. The inner part of the core ("inner core") falls with a velocity proportional approximately to the radius, while the outer part ("outer core") falls quasi-free with a velocity proportional to the inverse square of the radius. When the density of the inner core reaches $\sim 10^{11}$ g/cm³, the neutrinosphere becomes as large as the inner core. Then electron neutrinos produced from electron capture are trapped (5). The collapse continues until the inner core reaches nuclear density ($\sim 10^{14}$ g/cm³). At that point, repulsive nuclear forces halt the collapse and the core bounces. A shock wave (yellow waved circles in Figure 1.3) is launched at the boundary between the two parts of the core. The shock wave propagates outwards and interact with surrounding matter. Neutrinos are produced through the chargedcurrent interactions; however, these neutrinos are not emitted since they are trapped in the neutrinosphere. In the most inner part, a proto neutron star (PNS) is formed (6). Once the shock wave arrives at the neutrinosphere, the emission of neutrinos begins (7), and this emission ("neutronization burst") continues until the shock wave arrives in the region with low matter density. The duration of the neutronization burst is ≤ 10 ms.

(Steps 8–12) After the passage of the shock wave, matter (nucleons, electrons, and positrons) falls on to the PNS. PNS is then heated to produce neutrinos. The falling matter is represented by black arrows in panel (8). In this phase ("accretion phase"), neutrinos of all flavors are produced via electron and positron capture $(e^- + p \rightarrow \nu_e + n, e^+ + n \rightarrow \bar{\nu}_e + p)$ and pair production $(e^- + e^+ \rightarrow \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau})$. These are called the thermal neutrinos. The shock wave stalls by losing its energy due to the pressure from the accretion materials, photodisintegration, and neutrino emission (9). In order for the star to explode, revival of the shock wave is required. The revival is believed to be caused by neutrino-heating ³. In this mechanism, matter behind the shock wave is heated by absorption of neutrinos emitted from the PNS region and the shock wave regains energy. If the shock wave has enough energy to blow off the outer layer of matter, an explosion happens. If not, the matter accretion to the PNS and neutrino emission continue until a black hole is formed. In the case of an explosion, the PNS cools by emitting neutrinos and becomes a neutron star or a black hole depending on the mass and the initial metallicity of the progenitor.

The energy of emitted neutrinos depends on the flavor. Neutrinos emitted from a deeper layer whose temperature is higher are likely to have higher energy. Since $\bar{\nu}_x$'s experience only neutral-current interactions, the corresponding neutrinosphere is smaller than those of ν_e 's and $\bar{\nu}_e$'s. Due to the neutron-rich environment in the PNS, the radius of $\bar{\nu}_e$'s neutrinosphere is smaller than the ν_e 's one. A smaller neutrinosphere indicates that the corresponding neutrinos have higher energy. Figure 1.4 shows the time evolution of the neutrino luminosity and the average energy for different flavors obtained in a numerical simulation [24]. The sharp peak in the ν_e plot in the figure corresponds to the neutronization burst. The order of average energies is $E_{\nu_e} < E_{\bar{\nu}_e} < E_{\bar{\nu}_x}$ as expected.

³Other scenarios include the shock revival caused by magnetic fields or convection.



Figure 1.4: Time evolution of the neutrino luminosity (top) and average energy (bottom) for each neutrino flavor in a numerical simulation [24]. Note that $\nu_x = \frac{1}{4}(\nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau)$.

1.2.3 Observation of Neutrinos from SN1987A

There has only been one observation of neutrinos from a supernova so far. On February 23rd, 1987, the Kamiokande-II, IMB, and Baksan experiments observed neutrino emission from SN1987A in the Large Magellanic Cloud [25–27]. Figure 1.5 shows the distribution of the energy and time of neutrinos in the Kamiokande-II and IMB detectors. This event verifies the fundamental mechanism of the CCSNe while its power to constrain models is not strong due to small statistics. The total energy derived from SN1987A is consistent with the expectation in Equation 1.2 [28,29]. In order to learn more about the supernova mechanism, detectors around the world, including Super-Kamiokande, are watching the next supernova burst.

1.3 Supernova Relic Neutrinos

As mentioned above, the supernova explosion rate is rare (a few per century per galaxy); however, neutrinos emitted from all past CCSNe are accumulated and form an integrated flux. This flux is called the supernova relic neutrinos (SRNs) or diffuse supernova neutrino background (DSNB). Detection of SRNs would provide valuable information on the supernova rate and physics of the neutrino emission process. In this section, the theoretical prediction of the SRN flux is reviewed based on Refs. [31, 32].

The number density of SRNs which were emitted at redshifts $z \sim z + dz$ and whose energies at emission were $E'_{\nu} \sim E'_{\nu} + dE'_{\nu}$ is expressed as:



Figure 1.5: Distribution of time and energy of the neutrinos from SN1987A, observed in the Kamiokande-II (12 events) and IMB (8 events) experiments. The figure is taken from Ref. [30].

$$dn'(E'_{\nu}) = R_{\rm CCSN}(z)(1+z)^3 \frac{dt}{dz} dz \frac{dN(E'_{\nu})}{dE'_{\nu}} dE'_{\nu}, \qquad (1.10)$$

where $R_{\text{CCSN}}(z)$ represents the CCSN rate in a unit comoving volume at redshift z and t is time and the quantities at the neutrino emission time is attached with the superscript prime sign. The factor $(1 + z)^3$ is multiplied to express the volume at the CCSN and $dN(E'_{\nu})/dE'_{\nu}$ is the neutrino number spectrum from each CCSN. The SRN number density at present is:

$$dn(E'_{\nu}) = \frac{dn'(E'_{\nu})}{(1+z)^3}.$$
(1.11)

The energy is also redshifted to $E'_{\nu} = (1+z)E_{\nu}$. Then the number density of SRNs that were emitted at redshifts $z \sim z + dz$ and have energies $E_{\nu} \sim E_{\nu} + dE_{\nu}$ at present is written as:

$$dn(E_{\nu}) = R_{\rm CCSN}(z) \frac{dt}{dz} dz \frac{dN(E'_{\nu})}{dE'_{\nu}} (1+z) dE_{\nu}.$$
 (1.12)

The relation between the redshift z and the time t is given by the Friedmann equation as:

$$\frac{dt}{dz} = \frac{1}{H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}},$$
(1.13)

where H_0 is the Hubble constant, and Ω_m and Ω_Λ are the matter density and the cosmological constant, respectively. The SRN flux is then expressed using the relation $d\Phi(E_{\nu})/dE_{\nu} = c \cdot dn(E_{\nu})/dE_{\nu}$, where c is the speed of light, as:

$$\frac{d\Phi(E_{\nu})}{dE_{\nu}} = c \int_0^\infty \frac{dz}{H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} R_{\rm CCSN}(z) \frac{dN(E_{\nu}')}{dE_{\nu}'}.$$
(1.14)

The number spectrum can be a function of the initial mass M and the metallicity Z of the progenitor. In this case, the initial mass function $\Psi_{IMF}(M)$ and the metallicity distribution function $\Psi_{ZF}(z, Z)$ of the progenitor are used:

$$\frac{d\Phi(E_{\nu})}{dE_{\nu}} = c \int_{0}^{\infty} \frac{dz}{H_{0}\sqrt{\Omega_{m}(1+z)^{3}+\Omega_{\Lambda}}} \times \left[R_{\text{CCSN}}(z) \int_{0}^{Z_{\text{max}}} \Psi_{\text{ZF}}(z,Z) \left\{ \int_{M_{\text{min}}}^{M_{\text{max}}} \Psi_{\text{IMF}}(M) \frac{dN(M,Z,E_{\nu}')}{dE_{\nu}'} dM \right\} dZ \right].$$
(1.15)

There are various factors that affect the SRN flux. Hereafter only electron antineutrinos are considered since the signal in experimental searches is usually inverse beta decay as described later.

1.3.1 Neutrino Oscillation Effects

The number spectrum of $\bar{\nu}_e$ is a mixture of spectra of all flavor neutrinos:

$$\frac{dN_{\bar{\nu}_e}}{dE_{\nu}} = \bar{P}_{ee} \frac{dN_{\bar{\nu}_e}^0}{dE_{\nu}} + \bar{P}_{\mu e} \frac{dN_{\bar{\nu}_{\mu}}^0}{dE_{\nu}} + \bar{P}_{\tau e} \frac{dN_{\bar{\nu}_{\tau}}^0}{dE_{\nu}}$$
(1.16)

$$= \bar{P}_{ee} \frac{dN_{\bar{\nu}_e}^0}{dE_{\nu}} + (1 - \bar{P}_{ee}) \frac{dN_{\bar{\nu}_x}^0}{dE_{\nu}}, \qquad (1.17)$$

where $\bar{P}_{\alpha e}$ ($\alpha = e, \mu, \tau$) ($\sum_{\alpha} \bar{P}_{\alpha e} = 1$) is the transition probability from $\bar{\nu}_{\alpha}$ to $\bar{\nu}_{e}$ after the travel through stellar envelopes and space. The superscript "0" represents the number spectrum at the initial neutrino emission. With the PMNS matrix in Equation 1.4 and oscillation parameters in Table 1.1, this equation is transformed into:

$$\frac{dN_{\bar{\nu}_e}}{dE_{\nu}} = |U_{e1}|^2 \frac{dN_{\bar{\nu}_1}}{dE_{\nu}} + |U_{e2}|^2 \frac{dN_{\bar{\nu}_2}}{dE_{\nu}} + |U_{e3}|^2 \frac{dN_{\bar{\nu}_3}}{dE_{\nu}}$$
(1.18)

$$= \cos^2 \theta_{12} \cos^2 \theta_{13} \frac{dN_{\bar{\nu}_1}}{dE_{\nu}} + \sin^2 \theta_{12} \cos^2 \theta_{13} \frac{dN_{\bar{\nu}_2}}{dE_{\nu}} + \sin^2 \theta_{13} \frac{dN_{\bar{\nu}_3}}{dE_{\nu}}$$
(1.19)

$$\sim \quad 0.68 \cdot \frac{dN_{\bar{\nu}_1}}{dE_{\nu}} + 0.30 \cdot \frac{dN_{\bar{\nu}_2}}{dE_{\nu}} + 0.02 \cdot \frac{dN_{\bar{\nu}_3}}{dE_{\nu}}, \tag{1.20}$$

Under the normal mass hierarchy, $dN_{\bar{\nu}_1}/dE_{\nu} \sim dN_{\bar{\nu}_e}^0/dE_{\nu}$, $dN_{\bar{\nu}_2}/dE_{\nu} \sim dN_{\bar{\nu}_x}^0/dE_{\nu}$, and $dN_{\bar{\nu}_3}/dE_{\nu} \sim dN_{\bar{\nu}_x}^0/dE_{\nu}$, then:

$$\frac{dN_{\bar{\nu}_e}}{dE_{\nu}} \sim 0.68 \cdot \frac{dN_{\bar{\nu}_e}^0}{dE_{\nu}} + 0.32 \cdot \frac{dN_{\bar{\nu}_x}^0}{dE_{\nu}}.$$
(1.21)

In contrast, under the inverted mass hierarchy, $dN_{\bar{\nu}_3}/dE_{\nu} \sim dN_{\bar{\nu}_e}^0/dE_{\nu}$, $dN_{\bar{\nu}_1}/dE_{\nu} \sim dN_{\bar{\nu}_x}^0/dE_{\nu}$, and $dN_{\bar{\nu}_2}/dE_{\nu} \sim dN_{\bar{\nu}_x}^0/dE_{\nu}$, then:

$$\frac{dN_{\bar{\nu}_e}}{dE_{\nu}} \sim \frac{dN_{\bar{\nu}_x}^0}{dE_{\nu}}.$$
(1.22)

As described above, the emission rate and average energy of the supernova neutrino depend on the flavor. Since the electron flavor neutrino has relatively lower energy than the muon and tau flavor neutrinos as described above, the SRN flux becomes harder in the inverted hierarchy.

1.3.2 Galaxy Evolution

The supernova rate $R_{\text{CCSN}}(z)$ can be expressed by the cosmic star formation rate density (CSFRD) $\dot{\rho}_*(z)$, mass of the stars produced in a unit time and a unit comoving volume, and the initial mass function $\Psi_{\text{IMF}}(M)$ as:

$$R_{\rm CCSN}(z) = \zeta_{\rm CCSN} \dot{\rho}_*(z), \qquad (1.23)$$

$$\zeta_{\text{CCSN}} = \frac{\int_{M_{\min}}^{M_{\max}} \Psi_{\text{IMF}}(M) dM}{\int_{0.1M_{\min}}^{100M_{\text{sun}}} M \Psi_{\text{IMF}}(M) dM},$$
(1.24)

where $M_{\rm min}$ and $M_{\rm max}$ are the minimum and maximum masses of the progenitor which produce the SRN, respectively. For $M_{\rm max}$, $100M_{\rm sun}$ is frequently used. In Figure 1.6, CSFRD and IMF predictions from different models are shown. For CSFRD, model difference gets larger for z > 0.5, and this leads to a difference in the low energy SRN flux as larger redshifts correspond to lower energies. The IMF directly relates to the rate of heavy progenitors which cause supernovae. Models which have a higher probability in the low mass, such as "Chabrier" in the right panel of Figure 1.6, give the larger SRN flux. It is widely believed that stars heavier than $10M_{\rm sun}$ always cause CCSNe. However, it depends on models for the region $8-10M_{\rm sun}$. The minimum mass in the integration in Equation 1.23 affects the SRN flux prediction. As expected, the lower minimum mass provides larger flux over energies. The combinations of these three show about 3 times difference in the number of events at most [31–33].

1.3.3 Contributions from Failed Supernovae

Some stars fail in the explosion to become black holes ("failed supernovae"). In this case, since the accretion phase continues until black hole formation, more energetic neutrinos are emitted in general. Therefore, the rate of progenitors that would become black holes affects the SRN flux. The galactic metallicity evolution is strongly related to the black hole formation. Another important factor is the equation-of-state (EOS) of the neutron star. It takes more time for the PNS, whose EOS is stiffer, to become the black hole, then accordingly the neutrino emission amount is larger.



Figure 1.6: The CSFRD as a function of redshift, $\dot{\rho}_*(z)$ (left), and the mass distribution, $M\Psi_{\rm IMF}(M)/\int_{0.1M_{\rm sun}}^{100M_{\rm sun}} M\Psi_{\rm IMF}(M) dM$ (right), for different models [31, 32].

1.3.4 Shock Revival Time

As explained in the section for the CCSN mechanism, the shock wave stalls once and revives via neutrino-heating. The time between the stall and revival is used as a parameter in the supernova study ("shock revival time"). Apparently the longer revival time leads to more neutrinos because more matter falls on to the PNS. This effect appears in the high energy region of the SRN flux due to the high temperature of the PNS. The typical value of the revival time is considered O(100) ms. For instance, Ref. [34] suggests 100-200 ms deduced from the mass distribution of neutron stars and black holes, Ref. [35] suggests 300-400 ms based on simulations, and there exists some studies suggesting even longer than 500 ms.

1.3.5 SRN Flux Predictions

Many models have been proposed to predict the SRN flux. Some of them are briefly reviewed below and their $\bar{\nu}_e$ flux predictions are shown in Figure 1.7. There is nearly an order of magnitude difference in the flux depending on the model.

- Horiuchi+18 [36]: This model studies the effect of the progenitor conditions on the explosion, especially focusing on the critical compactness, which determines if the star becomes a black hole or not. In Figure 1.7, the results with two values (0.1 and 0.5) are shown. The smaller critical compactness corresponds to more black hole formation.
- Nakazato+15 [31, 37]: This model considers the redshift dependence of black hole formation and investigates the effects of various effects on the SRN flux, such as neutrino oscillations, the star formation rate, the initial mass function, EOS of the neutron star, and the shock revival time. Two cases providing the largest and smallest fluxes are shown in Figure 1.7.
- Horiuchi+09 [38]: In this calculation, the CCSN rate is derived from the cosmic star formation history based on data [39]. The $\bar{\nu}_e$ spectrum per explosion is approximated with a Fermi-Dirac distribution. In Figure 1.7, the effective neutrino temperature is assumed to be 6 MeV.

- Lunardini09 [40]: This model considers failed supernovae which form black holes, separately from the explosions that form neutron stars. The explosion resulting in the black hole contributes to the higher energy SRN fluxes.
- Ando+09 [41]: This is the first model that takes into account neutrino oscillations. The normal mass hierarchy and oscillations in vacuum are assumed.
- Malaney97 [42]: This model considers the redshift evolution of the cosmic gas, as determined from observations of absorption lines in quasi-stellar objects.
- Hartmann+97 [43]: This model calculates the flux using the chemical evolution of the universe. The information on the galactic halo and chemical evolution are obtained from observations of the Damped Ly α system.



Figure 1.7: SRN $\bar{\nu}_e$ fluxes from various theoretical models [31, 36, 38, 40–43].

1.4 Status of SRN Searches

As explained in the previous section, there are many theoretical predictions of the SRN flux. Observation of SRNs would provide constraints on theoretical uncertainties. So far the SRN signature has never been detected despite enormous experimental efforts towards the discovery. Almost all experimental searches are performed using inverse beta decay (IBD) of electron antineutrinos $(\bar{\nu}_e + p \rightarrow e^+ + n)$, since its cross section is the largest as explained in Chapter 10.

The world's most sensitive searches have been performed in the Super-Kamiokande (SK) water Cherenkov detector and the KamLAND liquid scintillation detector. At SK the first search was conducted with 1496 live days and spectrum fitting with various backgrounds was performed. It placed an upper limit on the SRN $\bar{\nu}_e$ flux in the energy region of $E_{\nu} > 19.3$ MeV [44]. This search was updated with a higher statistics 2853-day data set and improved analysis techniques. Here the analysis threshold was lowered to $E_{\nu} > 17.3$ MeV [45]. As described in Chapter 4, an electronics upgrade made it possible to record more data after a primary trigger. This makes it possible to tag a neutron from IBD. This can reduce a large amount of backgrounds, especially muon spallation events dominating the energy region $E_{\nu} < 17.3$ MeV, and then the search with the lower energy threshold has been achieved. In contrast to the spectrum analysis, the neutron tagging analysis suffers from lower statistics because of the low tagging efficiency in SK (about 20%). The first analysis with the neutron tagging technique using 960 day of data showed comparable or better results compared to the KamLAND experiment in the region below 16 MeV while the result above 16 MeV is still worse than the SK spectrum analysis [46]. KamLAND is tuned to measure the IBD signal using delayed coincidence, which requires the signal be paired with a 2.2 MeV γ -ray from the neutron capture on hydrogen. Since the neutron tagging efficiency is almost 100% in KamLAND and the energy threshold is lower, the search sensitivity is competitive in the lower energy region though the detector size is 20 times smaller than SK [47]. The upper limits on the $\bar{\nu}_e$ flux from both experiments are shown in Figure 1.8.



Figure 1.8: Upper limits on the $\bar{\nu}_e$ obtained from searches in the Super-Kamiokande and the KamLAND experiments. The black solid lines correspond to the maximum and minimum predictions in Nakazato model [31]. The figure is taken from Ref. [31].

This thesis focuses on the search at SK, especially with the neutron tagging analysis. Among several background sources, the atmospheric neutrino interactions are dominant in the region $E_{\nu} > 14$ MeV. Above ~20 MeV the charged-current neutrino interaction, where the charged lepton is produced in the final state, is the main background. This channel is measured in many neutrino experiments because it is the signal in the neutrino oscillation analysis. Then the interaction models are studied with many experimental data. Prior to the work in this thesis, data on the neutral-current interaction, which dominates as the main background source around 14-20 MeV, was not sufficient. This thesis focuses on the neutral-current interaction, especially the quasielastic channel (called "NCQE"), to improve the SRN search sensitivity. More details on the neutrino interaction are given in the next section.

1.5 Neutrino-Oxygen NCQE Interactions

1.5.1 Neutrino-Nucleus Interactions

Neutrinos interact with materials via weak boson exchanges ("weak interaction"). Depending on the weak boson type, W^{\pm} or Z^0 , the interaction is referred to as charged-current (CC) or neutral-current (NC), respectively. In the energy region from sub-GeV up to 10 GeV, neutrinos interact with nucleons inside nuclei. From an experimental point of view, since the detector material is not usually free protons, nuclear effects inside nuclei are important. Neutrinonucleus interactions are classified into several types as explained below. Feynman diagrams for the neutrino-nucleus interactions are shown in Figure 1.9.

(Quasi)elastic scattering

The main channel below ~ 1 GeV is (quasi)elastic scattering with a nucleon:

$$\nu_l + N \rightarrow l + N', \tag{1.25}$$

$$\nu_l + N \rightarrow \nu_l + N,$$
 (1.26)

where l is the charged lepton and ν_l is the counterpart neutrino, and N is the nucleon. In the CC channel (Equation 1.25), the nucleon type (neutron or proton) is flipped. In case of CC the channel is called CC quasielastic (CCQE) since the interaction is not truly "elastic" due to momentum transfer for the charged lepton production. Interactions of this type without a charged lepton (Equation 1.26) are termed NC elastic.

Multi-nucleon scattering via meson exchange currents

Nucleons inside the nucleus are correlated to each other via meson exchange currents. More than one nucleon could take part in the interaction. In this case multiple nucleons are scattered. The leading term is the case two nucleons are involved and is referred to as the two-particle-two-hole (2p2h) interaction.

Resonant meson production

Nucleons can be excited to the baryon resonance. These would then decay into combinations of nucleons and meson(s). The dominant intermediate resonant state

in a few GeV region is $\Delta(1232)$, and this state decays mainly into a nucleon and a pion:

$$\nu_l + N \rightarrow l + \Delta(1232) \rightarrow l + N' + \pi, \qquad (1.27)$$

$$\nu_l + N \rightarrow \nu_l + \Delta(1232) \rightarrow \nu_l + N' + \pi.$$
 (1.28)

Other baryon resonance states give different final states which can be composed of multiple mesons or a radiative photon.

Coherent pion production

When neutrinos interact with entire nuclei (A) coherently and nuclei are virtually excited, pions are produced from decays of the nuclei. The remaining nuclei are in their ground states:

$$\nu_l + A \quad \to \quad l + A + \pi^{\pm}, \tag{1.29}$$

$$\nu_l + A \quad \to \quad \nu_l + A + \pi^0. \tag{1.30}$$

Deep inelastic scattering

In higher energy region (>5 GeV), neutrinos are likely to directly hit quarks inside nucleons and this is referred to as deep inelastic scattering (DIS). The final state from DIS usually contains hadrons:

$$\nu_l + N \rightarrow l + N' + \text{hadrons},$$
 (1.31)

$$\nu_l + N \rightarrow \nu_l + N' + \text{hadrons.}$$
 (1.32)

1.5.2 NCQE Interactions

Hereafter water is assumed as a target material since the detector used in this thesis is Super-Kamiokande. At $E_{\nu} \gtrsim 200$ MeV, the NC quasielastic nucleon knock-out (NCQE) process,

$$\nu(\bar{\nu}) + {}^{16}\text{O} \rightarrow \nu(\bar{\nu}) + n + {}^{15}\text{O}^*,$$
 (1.33)

$$\nu(\bar{\nu}) + {}^{16}\text{O} \rightarrow \nu(\bar{\nu}) + p + {}^{15}\text{N}^*,$$
 (1.34)



Figure 1.9: Feynman diagrams for neutrino-nucleus interactions [48]: (a) CC quasielastic scattering, (b) CC resonant single pion production, (c) CC coherent pion production, and (d) CC deep inelastic scattering.

becomes dominant over the NC inelastic process without nucleon emission $(\nu(\bar{\nu}) + {}^{16}\text{O} \rightarrow \nu(\bar{\nu}) + {}^{16}\text{O}^*) {}^4$ [49]. The residual nuclei then de-excite to the ground state with the emission of γ -rays ⁵. The out-going nucleons, especially neutrons, further interact with water inside the detector, which produce γ -rays and additional neutrons in some cases. These neutrons are then captured by hydrogen, emitting 2.2 MeV γ -rays. Pairs of the primary signal and the 2.2 MeV γ mimic the SRN signal, as schematically shown in Figure 1.10. In the figure, the case for Gd-doped water is shown together, because SK has its upgrade plan to dope Gd as mentioned in Chapter 8. In the SK-I/II/III analysis [45], a 100% uncertainty was assigned to this channel ⁶ because of little data on the NCQE channel. Hence, measuring the NCQE interaction with high accuracy is essential to understand the background to the SRN search. There is a measurement of this channel by atmospheric neutrinos in SK [50]. However, it is difficult to make a feedback to the cross section model because the uncertainty is too large and the atmospheric neutrinos contain both neutrinos and antineutrinos. In addition, the analysis should contain the SRN contributions.

An artificial neutrino beam used in the T2K experiment has its peak around 600 MeV as shown in Chapter 3, and this is similar to the spectrum of atmospheric neutrinos. Measurements with the T2K beam can provide constraints on the NCQE background estimation in the SRN search at water Cherenkov detectors.

 $^{^{4}}$ This terminology is a nuclear physicist's manner. In neutrino physics, these two are both called the NC elastic interaction.

⁵Since there is no branching fraction for hydrogen to emitting γ -rays with this interaction, only oxygen is considered here.

 $^{^{6}\}mathrm{In}$ the SK-IV analysis, only the accidental background was considered.



Figure 1.10: Schematic drawings for the $\bar{\nu}_e$'s inverse beta decay by SRNs (top) and the NCQE interaction by atmospheric neutrinos (bottom) in a pure or Gd-doped water Cherenkov detector.

1.5.3 Previous NCQE Measurement in T2K

In the T2K experiment, the neutron-oxygen NCQE interaction cross section was measured to be $1.55^{+0.71}_{-0.35}$ (stat. \oplus syst.) $\times 10^{-38}$ cm²/oxygen with data from a 3.01×10^{20} protons-on-target exposure in the neutrino beam mode [51], as shown in Figure 1.11. In the measurement, the γ -ray signal from the NCQE interaction was successfully selected and the basic analysis method was established. However, the measurement has large statistical and systematic uncertainties. Another problem is that the systematic uncertainty regarding modeling of the γ -rays produced in neutron-oxygen reactions is estimated based only on theoretical models because there is limited experimental data in the energy of interest here. This may be highly model-dependent and dangerous. In addition, there is no measurement of the antineutrino NCQE cross section, while both are present in similar proportions in the atmospheric neutrino flux. In order to estimate the atmospheric neutrino NCQE interaction precisely, both neutrino and antineutrino interactions should be separately measured.



Figure 1.11: Flux-averaged neutrino-oxygen NCQE cross section measured in T2K with a 3.01×10^{20} protons-on-target data. The black points correspond to the measured value, with vertical and horizontal bars being the measured uncertainty and the width of the neutrino flux, respectively. The red line corresponds to the theoretical prediction. The figure is taken from Ref. [51].

1.6 Outline of This Thesis

In this thesis, a measurement of neutrino- and antineutrino-oxygen NCQE-like interactions in the T2K experiment and its applications to the background estimation in an SRN search at Super-Kamiokande are presented. The NCQE-like cross section results are the world's most precise measurements. The antineutrino result is the first measurement of this channel to date. In addition, distributions in the kinematic regions of interest for SRN searches are studied for the first time. The background estimation method demonstrated in this thesis is the first application of experimental data. With the T2K results, the uncertainties on the NCQE background are reduced, and a better sensitivity in the SRN search is achieved. The obtained upper limit on the $\bar{\nu}_e$ flux is the most stringent result to date. These are applicable for the future water Cherenkov experiments as well. The thesis hereafter is organized as follows.

Part II describes a measurement of neutrino and antineutrino NCQE-like interactions on oxygen in the T2K experiment. Chapter 2 gives an overview of the analysis. Chapters 3 and 4 explain the T2K experiment and the Super-Kamiokande detector, respectively. In Chapter 3, beam monitoring with the muon monitor is highlighted, which is essential to stable data taking. Details of the Monte Carlo simulation is explained in Chapter 5. The event selection for the NCQE signal is described in Chapter 6 and followed by the estimation of uncertainties in Chapter 7. Cross section results and discussions are given in Chapter 8.

In Part III (Chapter 9), studies for improvements of the modeling of γ -ray emission from the neutron-oxygen reaction are presented. This interaction is important to reduce the largest uncertainty in the NCQE-like interaction measurement.

Part IV is tailored to the analysis of a search for supernova relic neutrinos with a 2970.1day data set from Super-Kamiokande. The signal and background and their simulations are overviewed in Chapter 10, and the data reduction is explained in Chapter 11. Chapter 12 describes the background estimation in detail. Here the T2K results are applied to the NCQE background estimation. The final search result is shown in Chapter 13.

The thesis is concluded in Chapter 14 with a summary of the obtained results presented in Parts II, III, and IV.

Part II

Measurement of Neutrino- and Antineutrino-Oxygen Neutral-Current Quasielastic-like Interactions

Chapter 2

Measurement Overview

2.1 Measurement Motivation

Precise measurement of the neutrino-oxygen NCQE interaction in the sub-GeV region benefits a variety of physics studies. As explained in Chapter 1, this interaction forms the main background in SRN searches at water Cherenkov detectors. Currently the search sensitivity is limited by the large uncertainty of this interaction especially in the low energy region where the SRN flux is expected to be high. Measuring the NCQE interaction with the T2K beam would improve the situation since the T2K energy region is similar to that of atmospheric neutrinos. When searching for dark matter in accelerator-produced neutrino experiments, as proposed in Refs. [52, 53], the NC interaction rate should be estimated precisely since it is the main background. Another motivation arises in the sterile neutrino search in accelerator neutrino experiments [54–56]. The fact that the NC interaction is flavor-independent makes it possible to search for a deficit in the NC event rate, which could be interpreted as transitions from active to sterile neutrinos. Furthermore, the NC measurement is important to understand the neutrino-nucleus interaction, from a standpoint different from the CC measurements, such as strange quark contributions inside the nucleus, which is visible only in the NC interaction [57–60]. The initial state of nucleons inside nuclei could be addressed through the NC-induced γ -ray measurements.

2.2 Neutral-Current Quasielastic Interactions

The differential cross section of the neutral-current (NC) elastic interaction of a neutrino (an antineutrino) on a free nucleon can be written as follows [61]:

$$\frac{d\sigma^{\nu(\bar{\nu})}}{dq^2} = \frac{M^2 G_F^2}{8\pi E_{\nu}^2} \left\{ A(q^2) \pm B(q^2) \frac{s-u}{M^2} + c(q^2) \frac{(s-u)^2}{M^4} \right\},\tag{2.1}$$

where E_{ν} denotes the initial (anti)neutrino energy, M = 0.938 GeV is the nucleon mass, $G_{\rm F}$ is the Fermi coupling constant, $q = p_{\nu} - p'_{\nu}$ is the four momentum transfer (p_{ν} and p'_{ν} are four momenta of in-coming and out-going (anti)neutrinos respectively), and s and u are the Mandelstam variables ($s - u = 4ME_{\nu} + q^2$, assuming $m_{\nu} = 0$). The upper (lower) sign corresponds to the neutrino (antineutrino) interaction. The factors A, B, and C are written by using $\tau = -q^2/4M^2$ as below:

$$A(\tau) = \left(4\tau + \frac{m^2}{M^2}\right) \left[(1+\tau)|\tilde{F}_A|^2 - (1-\tau)|\tilde{F}_V^1|^2 + \tau(1-\tau)|\tilde{F}_V^2|^2 + 4\tau \tilde{F}_V^1 \tilde{F}_V^2 - \frac{m^2}{4M^2} \{(\tilde{F}_V^1 + \tilde{F}_V^2)^2 + |\tilde{F}_A|^2 + 4\tilde{F}_A \tilde{F}_p - 4\tau |\tilde{F}_p|^2\}\right],$$

$$(2.2)$$

$$B(\tau) = 4\tau \tilde{F}_{A}(\tilde{F}_{V}^{1} + \tilde{F}_{V}^{2}), \qquad (2.3)$$

$$C(\tau) = \frac{1}{4} (|\tilde{F}_A|^2 + |\tilde{F}_V^1|^2 + \tau |\tilde{F}_V^2|^2).$$
(2.4)

Here the form factors \tilde{F}_V^i (i = 1, 2), \tilde{F}_A , and \tilde{F}_p are specific to NC interactions and are described by the form factors for the charged-current (CC) interactions $(F_V^i, F_A, \text{ and } F_p)$:

$$\tilde{F}_{V}^{1,N} = \pm \frac{1}{2} F_{V}^{1} - 2\sin^{2}\theta_{W} \cdot F_{N}^{1}, \qquad (2.5)$$

$$\tilde{F}_{V}^{2,N} = \pm \frac{1}{2} F_{V}^{2} - 2\sin^{2}\theta_{W} \cdot F_{N}^{2}, \qquad (2.6)$$

$$\tilde{F}_A = \frac{1}{2} (F_A^s \pm F_A) = \frac{1}{2} (\Delta s \pm g_A) \left(1 - \frac{q^2}{M_A^2} \right)^{-2}, \qquad (2.7)$$

$$\tilde{F}_{p} = \frac{2M^{2}\tilde{F}_{A}}{m_{\pi}^{2} - q^{2}},$$
(2.8)

where N = p and n correspond to proton and neutron with upper and lower signs respectively, $\theta_{\rm W}$ is the Weinberg angle ($\sin^2 \theta_{\rm W} = 0.23117$ in the present work), and $m_{\pi} = 0.13957$ GeV is the charged pion mass. The axial-vector interaction part is described by the axial-vector mass (M_A) and the axial-vector weak coupling constant (g_A). The strange quark contribution, $\Delta s = F_A^s (1 - q^2/M_A^2)^2$, appears in the NC interaction and this effect differs between protons and neutrons. Furthermore F_V^i and F_N^i can be written by using the electric and magnetic form factors (G_E^V, G_M^V, G_E^N , and G_M^N):

$$F_V^1 = \frac{G_E^V + \tau G_M^V}{1 + \tau},$$
 (2.9)

$$F_V^2 = \frac{G_M^V - G_E^V}{1 + \tau},$$
(2.10)

$$F_N^1 = \frac{G_E^N + \tau G_M^N}{1 + \tau},$$
 (2.11)

$$F_N^2 = \frac{G_M^N - G_E^N}{1 + \tau}.$$
 (2.12)

These electric and magnetic form factors are parametrized often in the dipole and BBBA05 methods [62]. In the neutrino-nucleus scattering, nuclear effects such as the nucleon motion

and its binding inside the nucleus should be considered. Further details about neutrino-nucleus scattering theories can be found in Refs. [57, 63].

At $E_{\nu} \gtrsim 200$ MeV in neutrino-oxygen interactions, nucleons are likely to be knocked-out off nuclei. This interaction is especially termed NC quasielastic (NCQE). After the neutrino-oxygen NCQE interaction, the remaining nucleus is usually in its excited state:

$$\nu(\bar{\nu}) + {}^{16}\text{O} \rightarrow \nu(\bar{\nu}) + n + {}^{15}\text{O}^*,$$
 (2.13)

$$\nu(\bar{\nu}) + {}^{16}\text{O} \rightarrow \nu(\bar{\nu}) + p + {}^{15}\text{N}^*,$$
 (2.14)

These nuclei promptly relax to the ground state by emitting γ -rays in some cases, such as ${}^{15}\text{O}^* \rightarrow {}^{15}\text{O} + \gamma$ and ${}^{15}\text{N}^* \rightarrow {}^{15}\text{N} + \gamma$. These γ -rays are available as a probe to measure the NCQE interaction, as is done in the present work.

. . .

2.3 Signal Definition

In the present work, the neutrino- and antineutrino-oxygen flux-averaged cross sections are measured using nuclear de-excitation γ -rays as a signal with the T2K beams. In this work, the signal is termed "NCQE-like" because the event selection may contain contributions from NC two-particle-two-hole (2p2h) interactions, in which two nucleons are involved in the interaction via meson exchange currents. Previous studies [50,51] may have also included such contributions although the fact was not specifically addressed. Note that the measurement of this inclusive process is still beneficial in terms of the motivations explained in the beginning of this chapter.

Chapter 3

T2K Experiment

In this chapter, components of the T2K experiment and data taking history are described.

3.1 Overview of T2K

The T2K experiment [64] has been designed for the precise measurement of neutrino oscillations. T2K provides a variety of physics programs as well, including the neutrino cross section measurement which is the main focus of this thesis. In the experiment, neutrino and antineutrino beams are produced by the J-PARC accelerator and directed towards the Super-Kamiokande (SK) detector. The near detectors are placed to measure (anti)neutrinos before their oscillations. The cross sectional schematic illustration of T2K is given in Figure 3.1. T2K has been running since 2009 and its physics run is divided into nine periods (Runs 1–9).



Figure 3.1: Schematic view of the T2K experiment.

3.2 J-PARC Accelerator and Neutrino Beamline

Prior to the neutrino beamline

Figure 3.2 gives an aerial view of J-PARC. Neutrinos or antineutrinos are produced from proton beams. Protons are accelerated step-by-step in three accelerators at J-PARC: the linear accelerator (LINAC) up to 400 MeV/c, the rapid cycling synchrotron (RCS) up to 3 GeV/c, and the main ring synchrotron (MR) up to 30 GeV/c.



Figure 3.2: Aerial view of the J-PARC. Note that "50 GeV" for MR is the original design value, but the actual operation is with a 30 GeV setting.

Primary neutrino beamline

Beams are extracted from the MR and passed to the neutrino beamline. Here proton beams are bundled into eight bunches (six in T2K Run 1), each being approximately 58 ns wide and separated by about 580 ns. The eight bunches are referred to as a spill. Each beam spill is delivered with a repetition cycle of ~ 3 sec. (2.48 sec. in the recent operation). The beam structure is schematically viewed in Figure 3.3.



Figure 3.3: Schematic view of the J-PARC proton beam structure [48].

The neutrino beamline is composed of the 54 m long preparation section, the 147 m long arc section, and the 37 m long final focusing section, as shown in Figure 3.4.



Figure 3.4: Schematic view of the T2K neutrino beamline [65].

There are various proton beam monitors equipped in the primary beamline. They are explained briefly in the following.

- CT (current transformer): A CT is a 50-turn toroidal coil around a cylindrical ferromagnetic core. Five CTs are equipped to monitor the proton beam intensity.
- ESM (electro-static monitor): An ESM is composed of four segmented cylindrical electrodes, measuring the beam position with the beam-induced current in the top-bottom and left-right sides. There are 21 ESMs equipped in total.
- SSEM (segmented secondary emission monitor): An SSEM is made of two 50 μ m thick titanium foils stripped in horizontal and vertical directions. Nineteen SSEMs measure the beam position and width at each position in the primary beamline. In the physics data taking, only the most downstream SSEM is used to minimize the beam loss.
- BLM (beam loss monitor): A BLM is a wire proportional counter filled with an Ar-CO₂ gas mixture. Fifty BLMs are installed to monitor the beam loss.

Secondary neutrino beamline

Experimental components after the primary beamline are shown in Figure 3.5. After the final focusing part, a baffle is placed as a collimator for the beam. The proton beam is injected onto a graphite target. The optical transition radiation (OTR) monitor [66], an imaging detector made of a foil and a camera, is located just upstream of the target and used to measure the beam position and width. Charged hadrons, such as pions and kaons, are produced from the proton-target reactions, and then focused by magnetic fields generated by three electromagnetic horns [67,68]. Each horn is made of an aluminum conductor and produces a toroidal magnetic

field inside the conductor. The applied current to the horns is 250 kA. Some hadrons will decay into pairs of a muon (anti)neutrino and a muon in the 96 m long decay volume lying after the target. The polarity of the horn current can be changed, allowing selection of the beam property, which is either neutrino-dominant or antineutrino-dominant in its composition. The former setting is referred to as forward horn current (FHC) mode and the latter as reverse horn current (RHC) mode. The muon monitor (MUMON) [69] is placed at the downstream of the beam dump to measure the >5 GeV muons, which are outcomes of the pion and kaon decays. MUMON gives the neutrino beam profile indirectly on a bunch-by-bunch basis and plays an indispensable role for the experimental operation. Further details about MUMON are given later in this chapter.



Figure 3.5: Experimental components after the primary neutrino beamline, including the secondary neutrino beamline, the near detectors, and the far detector [70].

3.3 Near and Far Detectors

In T2K, the far detector, Super-Kamiokande, is placed at 2.5° off-axis with respect to the proton beam direction at the graphite target. This provides a narrow-band flux and adjusts a flux peak being at the maximum oscillation probability, as shown in Figure 3.6.

At 280 m away from the graphite target, two near detectors are placed at on-axis and 2.5° off-axis, INGRID [71] and ND280 [72, 73], respectively. INGRID is composed of the fourteen identical modules aligned in a cross formation: seven being laid horizontally and another seven vertically, as shown in Figure 3.7, and measures a neutrino beam profile. Each module is made of plastic scintillators and iron plates. The beam profile measured by INGRID is shown in Figure 3.8. The other near detector, ND280, is a complex of several components as shown in Figure 3.9, and measures neutrino event rate and spectrum before oscillations. The Super-Kamiokande detector, a large water Cherenkov detector, is located 295 km away. Since it is the main detector for the analyses in this thesis, it is described in detail in Chapter 4. Beam timing information is shared between the beamline and the far detector via the GPS system.



Figure 3.6: The $\nu_{\mu} \rightarrow \nu_{\mu}$ and $\nu_{\mu} \rightarrow \nu_{e}$ probabilities as a function of neutrino energy (top two), and the neutrino flux in different off-axis (OA) angle configurations (bottom).



Figure 3.7: Schematic illustration of INGRID. The whole structure is shown in the left panel and each module is shown in the right panel. Each module consists of the iron target plates and the tracking scintillator planes and is surrounded by the veto scintillator planes.



Figure 3.8: A neutrino beam profile measured by INGRID. The left and right panels correspond to the horizontal and vertical directions, respectively.



Figure 3.9: Schematic illustration of ND280. The neutrino beam is incident from the left side in the figure.

3.4 Beam Monitoring with MUMON

In addition to the beam measurements by proton monitors and INGRID, MUMON is used to monitor the muon beam intensity and direction. Only MUMON can monitor the beam on a bunch-by-bunch basis at downstream of the graphite target, and then its stable operation and quick trouble shooting are essential to stable data taking.

MUMON consists of two arrays of detectors, silicon PIN photodiodes (Si; Hamamatsu S3590-08) and ionization chambers (IC; $Ar+N_2$ or $He+N_2$) [69], and the Si array lies upstream of the IC array. The schematic view is given in Figure 3.10. Each array covers a 150×150 cm² region by 7×7 channels with a 25 cm interval between each. The sensor waveforms are sampled with a 65 MHz Flash-ADC. The current MUMON has been running since the beginning of the T2K operation [74]. By May of 2019, T2K has accumulated data with 1.51×10^{21} POT in the FHC mode and 1.65×10^{21} POT in the RHC mode. J-PARC has been increasing its beam power throughout the experimental operation, as shown in Figure 3.11.



Figure 3.10: Schematic illustration of the T2K muon monitor.

Figure 3.12 shows the beam measurement results by MUMON and INGRID over the T2K operation periods until May of 2019. The beam direction is stable within a 0.3 mrad requirement [74]. Figures 3.13 and 3.14 give the measured muon beam center and width by MUMON for each MR operation period. The beam width is smaller in RHC than FHC due to difference in the kinematics of the parent hadrons. MUMON is also essential to understand the beam properties such as relationships of muon beams with proton beams and horn conditions. These measurements have been performed, contributing to the operation. The results can be found in Appendix A. The current MUMON detectors have several issues with their performances under the high intensity beam irradiation and these are investigated. In addition, a new detector based on an electron-multiplier tube is studied for the future operation with further high power beams [75, 76]. These studies are described in Appendix B.



Figure 3.11: History of the accumulated POT and the J-PARC beam power over the T2K Run 1-9 operation period.



Figure 3.12: INGRID and MUMON beam measurements of the event rate and beam directions over the T2K Run 1–9 operation period.



Figure 3.13: Muon beam center in horizontal (top) and vertical (bottom) directions measured by MUMON Si and IC in each J-PARC MR run. T2K was operated with no horn current application in MR Run 41, showing the large error.



Figure 3.14: Muon beam width in horizontal (top) and vertical (bottom) directions measured by MUMON Si and IC in each J-PARC MR run. T2K was operated with no horn current application in MR Run 41, showing the narrow beam. The beam width in RHC is smaller than that in FHC, which is attributed to difference in the momentum of the parent hadrons. Since the parent hadrons are produced by protons, the number of particles are likely to be larger when the negative hadrons, which are the parents of antineutrinos, are made. Therefore, the momentum of each particle, including the negative hadron, is likely to be smaller and accordingly those hadrons are easier to focus in RHC, contributing to the narrower beam.

3.5 Data Set

In the analysis, data from T2K Runs 1-9 with 14.94×10^{20} POT in the FHC mode and 16.35×10^{20} POT in the RHC mode, which have passed the quality check based on the beam and detector conditions, are used. The detailed information of each run is summarized in Table 3.1 with the operation period, the operation mode (FHC or RHC), and the accumulated POT.

Table 3.1: Summary on the T2K runs with the operation period, the operation mode, and the accumulated POT for the good spills used in the analysis.

T2K Run#	Operation Mode	Start Date	End Date	POT [×10 ¹⁹]	
1	FHC	23rd, Jan., 2010	26th, Jun., 2010	3.26	
2	FHC	18th, Nov., 2010	11th, Mar., 2011	11.22	
3b	FHC	8th, Mar., 2012	22nd, Mar., 2012	2.17	
3c	FHC	8th, Apr., 2012	9th, Jun., 2012	13.82	
4	FHC	19th, Oct., 2012	8th, May., 2013	35.97	
5a	FHC	21st, May., 2014	29th, May., 2014	0.66	
5b	FHC	29th, May., 2014	3rd, Jun., 2014	1.78	
		24th, Jun., 2014	26th, Jun., 2014		
5c	RHC	4th, Jun., 2014	24th, Jun., 2014	5.12	
6a	FHC	2nd, Nov., 2014	4th, Nov., 2014		
		12th, Jan., 2015	16th, Jan., 2015	1.03	
		25th, Feb., 2015	27th, Feb., 2015		
6b	RHC	4th, Nov., 2014	25th, Nov., 2014	12.04	
		29th, Nov., 2014	22nd, Dec., 2014	10.04	
6c	RHC	27th, Feb., 2015	12th, Mar., 2015	5.25	
6d	RHC	12th, Mar., 2015	1st, Apr., 2015	7.89	
60	RHC	8th, May., 2015	20th, May., 2015	0.20	
oe		22nd, May., 2015	1st, Jun., 2015	9.29	
6f	FHC	1st, Jun., 2015	3rd, Jun., 2015	0.89	
7a	FHC	1st, Feb., 2016	3rd. Feb., 2016	0.89	
7b	RHC	3rd, Feb., 2016	18th, May., 2016	34.99	
7c	FHC	19th, May., 2016	27th, May., 2016	3.96	
8	FHC	27th, Oct., 2016	12th, Apr., 2017	71.70	
9a	FHC	17th, Oct., 2017	22nd, Oct., 2017	2.04	
9b	RHC	22nd, Oct., 2017	6th, Dec., 2017	26.53	
9c	RHC	6th, Dec., 2017	22nd, Dec., 2017	10.25	
9d	RHC	9th, Mar., 2018	31st, May., 2018	51.10	
Total	FHC	-		149.38	
Total	RHC			163.46	

Chapter 4

Super-Kamiokande

In this chapter, the Super-Kamiokande detector, the detector simulation, the event reconstruction, and the detector calibrations are described. Descriptions in this chapter are important also for the SRN analysis in Part IV.

4.1 Overview of Super-Kamiokande

Super-Kamiokande (SK) is a cylindrical water Cherenkov detector, a schematic view of which is shown in Figure 4.1, and is located 1,000 m under Mt. Ikeno in Kamioka, Gifu of Japan. This location provides an environment with a depth of 2700 m-water-equivalent (m.w.e.), where only cosmic-ray muons with energies above 1.3 TeV can reach the detector. The cosmic-ray muon flux as a function of depth is shown in Figure 4.2. At SK, the muon rate is about 2 Hz.







Figure 4.2: Cosmic-ray muon flux as a function of depth [77]. The unit 10^3 hg/cm² is equivalent to km.w.e. The depth of SK is 2700 m.w.e.

CHAPTER 4. SUPER-KAMIOKANDE

The detector structure is separated into two regions, the inner detector (ID) and the outer detector (OD). The 20 inch and 8 inch photomultiplier-tubes (PMTs) are implemented to detect Cherenkov light from charged particles in each region, respectively. The whole detector is filled with 50 kton ultra pure water. A variety of physics programs are provided in SK: neutrino oscillation measurements with atmospheric neutrinos, solar neutrinos, and accelerator neutrino beams, searches for physical phenomena beyond the Standard Model such as proton decay and dark matter, and astronomical object studies via detections of neutrinos, for example, from supernovae and the Sun.

SK started its operation in April 1996 and has been running in five separate run periods so far. The operation period for the first five years until July of 2001 is called "SK-I", and some bad PMTs were replaced with new ones during the shutdown after this period. It was followed by the accident that nearly half of PMTs had been broken due to a chain reaction of shock wave. The operation was restarted as "SK-II" with approximately 5,000 ID PMTs. Each PMT is protected by a fiber reinforced plastic cover to avoid further destructions. These new PMTs were installed and data taking was resumed and continued until September of 2008. This operation period is referred to as "SK-III". The fourth stage of the SK operation, "SK-IV", started with the new electronics which enables to store data longer after a primary event and then activates the neutron tagging analysis, as described later. In 2018, the SK tank underwent the refurbishment. After the tank refurbishment work, the operation started and has been running as of January 2020, which is termed as "SK-V". The properties in each operation period are summarized in Table 4.1. In the analyses in this thesis, data from SK-IV are used, therefore the descriptions in the following part focus on the system in SK-IV.

Phase	SK-I	SK-II	SK-III	SK-IV	SK-V
Start	Apr., 1996	Oct., 2002	Jul., 2006	Sep., 2008	Jan., 2019
End	Jul., 2001	Oct., 2005	Aug., 2008	May., 2018	(running)
Live time [days]	1496	791	548	2970	-
Number of ID PMTs	11,146	5,182	11,129	11,129	11,129
ID PMT coverage	40%	19%	40%	40%	40%
Number of OD PMTs	1,885	1,885	1,885	1,885	1,885
PMT protection	No	Yes	Yes	Yes	Yes
Neutron tagging	No	No	No	Yes	Yes
Threshold [MeV]	4.5	6.5	4.0	3.5	3.5

Table 4.1: Properties of the five SK operation periods.

4.2 Detection Principle

Observable in SK is Cherenkov light emitted from the charged particle passing through the detector at a speed faster than the speed of light in water. The momentum threshold for the Cherenkov radiation depends on the particle type, for example, 0.57 MeV/c for electrons, 118 MeV/c for muons, 156 MeV/c for charged pions, and 1051 MeV/c for protons. Cherenkov photons are emitted in a cone shape with a half opening angle (θ), referred to as Cherenkov opening angle which is related to the speed of the particle ($\beta = v/c$; v and c are the speeds of the charged particle and light, respectively) and the refractive index (n) as $\cos \theta = 1/n\beta$. In water ($n \sim 1.33$) the Cherenkov angle is $\theta \sim 42^{\circ}$ for sufficiently relativistic particles ($\beta \sim 1$).

The Cherenkov photons then reach the wall and are detected by the PMTs, forming ring patterns. The ring pattern looks different by the particle type, the particle momentum, the multiplicity, and so on. For example, the electron-induced ring is likely to be fuzzier than the muon-induced ring because of electromagnetic cascades. Figure 4.3 gives an example of the Cherenkov ring observed in SK.



Figure 4.3: An example of the Cherenkov ring pattern in SK. Each pixel corresponds to the PMT and the color scale denotes the detected charge amount.

4.3 Detector Components

4.3.1 Water Tank

The SK detector is subdivided into the ID and OD parts with a support structure between them, which is shown in Figure 4.4. The ID measures 33.8 m in diameter and 36.2 m in height, containing 32 kton water, and is instrumented with 11,129 20 inch PMTs on the wall supported by the structure in Figure 4.4. The PMT coverage in the ID is about 40%. The OD region is about 2 m thick between the support structure and the tank surface. There are 1,885 8 inch outward-facing PMTs equipped on the back side of the ID wall. The OD is used to issue a veto for the cosmic-ray muon events.

4.3.2 Photomultiplier Tubes

The 20 inch PMTs (R3600) were produced by Hamamatsu Photonics K.K. and optimized for the experiment [77,78]. The schematic view of the PMT is given in Figure 4.5. The photocathode is made of bialkali (Sb-K-Cs) and the dynode is the 11-stage Venetian blind type. With a high voltage application of ~2000 V, the gain is about 10^7 . The quantum efficiency is wavelength-dependent as shown in Figure 4.6, being the most sensitive to around 360 nm (~21%). The single photoelectron (p.e.) distribution is clearly seen, as shown in the left panel of Figure 4.7.



Figure 4.4: Schematic illustration of the PMT support structure in SK [77].



Figure 4.5: Schematic cross sectional view of the SK 20 inch PMT (Hamamatsu R3600) [77].
The transit time spreads by about 2.2 ns, as shown in the right panel of the same figure. After the accident in 2001, the fiber reinforced plastic (FRP) cover was installed to each ID PMT. The acrylic surface of the cover is more than 96% transparent to light with wavelength above 350 nm.

The 8 inch PMTs are used in the OD. There are two types: 591 R1408 PMTs from the IMB experiment [79] and 1,293 R5912 PMTs that were newly installed after the accident in 2001.



Figure 4.6: Quantum efficiency of the SK 20 inch PMT as a function of wavelength [77].



Figure 4.7: Distribution of single photoelectron pulse height (left) and relative transit time with 410 nm wavelength light at the single p.e. level (right) for the SK 20 inch PMT [77].

4.3.3 Helmholtz Coils

To reduce the effect of the geomagnetic field on the collection of photoelectrons in PMTs, 26 sets of Helmholtz coils are installed, around the water tank [80]. The currents of the Helmholtz coils are monitored real time. The original magnetic field, which was measured before SK-I, was \sim 450 mG while the average field with the coil operation is 32 mG.

4.3.4 Water and Air Systems

Water is one of the most essential parts in the experiment because the water quality affects the Cherenkov photon propagation. Water is originally taken from the two streams in the Kamioka mine and then purified and circulated by a dedicated system. The purified water is circulated with a flow rate of 60 ton/hour. The left panel of Figure 4.8 shows a schematic diagram of the water circulation system. With this system water is supplied in the bottom region and drained in the top region. Usually water is well convecting below the vertical position of -11 m (the ID center is set to the origin of the coordinate). In this region the temperature is then uniform; however, it rises gradually above this level, as shown in the right panel of Figure 4.8. This variance results in a 5% difference in the water transparency over the ID detector.



Figure 4.8: Schematic diagram of the water circulation system in SK-IV (left) and the water temperature as a function of the ID vertical position (right) [80].

In the low energy analysis, including the works reported in this thesis, reducing radioactive impurities in the water, especially radon, is important. The radon concentration in the supply water is reduced by the water purification system down to 1.83 ± 0.31 mBq/m³. In addition, the air purification system is being operated to prevent radon dissolving into the purified water [81].

4.4 Data Acquisition System in SK-IV

As mentioned before, the front-end electronics was upgraded in SK-IV to QTC-Based Electronics with Ethernet (QBEE) [82]. Since then the SK has been operated with QBEE.

4.4.1 Front-End Electronics: QBEE

The main parts of the QBEE module are the QTC (charge-to-time converter) and TDC (time-to-digital converter). Eight QTCs are put on each QBEE board and each QTC processes data from three PMTs. The charge dynamic range is from 0.2 to 2500 pC, and each channel has three different gains, the relative ratios of which are 1 : 1/7 : 1/49, corresponding to the large, medium, and small gains, respectively. Figure 4.9 shows a block diagram of the QTC for the

PMT signal readout and its surroundings. The block diagram for one QTC channel is shown in Figure 4.10.



Figure 4.9: Block diagram of the QTC and its surrounding parts [82].



Figure 4.10: Block diagram of one QTC channel [82].

The timing chart in the QTC operation is shown in Figure 4.11. After the QTC is triggered by the discriminator, it opens a charge gate spanning 400 ns, and is followed by a discharge gate with a 350 ns window. The time consumed for processing one signal is about 900 ns in total.



Figure 4.11: Timing chart for the QTC operation [82].

4.4.2 Triggers

A variety of triggers are prepared in SK-IV, depending on the number of hit PMTs within a 200 ns time window, defined as N_{200} , and other special conditions. The trigger types are the super-low energy (SLE), low energy (LE), high energy (HE), super-high energy (SHE), outer detector (OD), after-window (AFT), and T2K triggers. When N_{200} exceeds pre-determined thresholds, which are summarized in Table 4.2, the corresponding trigger is issued. Depending on the trigger type, a data taking window is different. For example, the SHE trigger opens a 40 μ s window (5 μ s before and 35 μ s after the trigger timing, respectively) to store data. The similar counting is conducted for the OD PMTs and the OD trigger is issued if N_{200} for the OD PMTs exceeds 22. The AFT trigger is specially tailored to the neutron tagging and produced when the SHE trigger is issued but the OD trigger is not, extending the data storing window up to 535 μ s from the SHE trigger point. The T2K triggers are used for the NCQE-like measurement and data with the SHE+AFT triggers are used for the SRN search.

¹Even when the beam is off, the T2K trigger is sometimes issued to take data for the neutron tagging analysis as explained later in Chapter 10.

Trigger Type	Threshold	Time Window $[\mu s]$
SLE	$34 \rightarrow 31$ (after May of 2015)	[-1.5, +1.0]
LE	47	[-5, +35]
HE	50	[-5, +35]
SHE	$70 \rightarrow 58$ (after September of 2011)	[-5, +35]
OD	22 (in OD)	[-5, +35]
AFT	SHE + no OD	[+35, +535]
T2K	Beam on	[-500, +535]

Table 4.2: Summary of the SK triggers. The numbers in the second column are the number of hit PMTs within a 200 ns window (N_{200}) .

4.5 Detector Simulation

Interactions and transport of particles, generation and propagation of Cherenkov photons in water, and the PMT and electronics responses are simulated by a dedicated Monte Carlo (MC) package. Details can be found in Ref. [83].

The physics process is based on GEANT3 ver. 3.21 [84]. As mentioned in Chapter 9, hadronic interactions are simulated by GCALOR [85,86]. For the low momentum (<500 MeV/c) pion interaction, a custom model [87] based on experimental data of the π -¹⁶O interaction [88] and the π -*p* interaction [89] is implemented.

For the charged particles, Cherenkov photons are generated following the equation below:

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha}{n\lambda^2} \left(1 - \frac{1}{n^2\beta^2}\right),\tag{4.1}$$

where N represents the number of generated Cherenkov photons, λ is wavelength of the photon, n is the refractive index, α is the fine structure constant, β is the velocity of the charged particle in water in a unit of the speed of light in vacuum, and x is the traveling length. Since n depends on various environmental factors, such as the wavelength, the water temperature, and the water pressure, their measurement results are used in the simulation. Here only photons whose wavelengths are between 300 and 700 nm (the PMT sensitive range) are generated. The generated Cherenkov photons are then transported in water with the effects of scattering and absorption. The probability for each process is implemented depending on the water transparency. The Rayleigh and Mie scatterings are taken into account here. At the wall of the tank, the reflection of Cherenkov photons is implemented. Further details can be found in Ref. [81].

The charge and timing responses of PMTs and the electronics are also simulated so that the MC provides the same data structure as the observed data. This enables to compare the MC outputs directly to the observed data.

4.6 Low Energy Event Reconstruction

There are various types of reconstruction tools for the SK analysis. For the reconstruction of low energy events ($\leq 80 \text{ MeV}$), a dedicated tool is used ².

4.6.1 Vertex and Direction Reconstructions

The vertex position is reconstructed using the timing information of hit PMTs. Since low energy electrons and positrons travel only a short distance, for example, ~10 cm at 20 MeV, the tracks are treated as point-like sources. The timing residual of each hit PMT is defined as $t - t_{\text{tof}} - t_0$, where t is the hit timing, t_{tof} is the time-of-flight (TOF) from the vertex position to the hit PMT, and t_0 is the time of the interaction which is treated as a free parameter. The likelihood function is defined as:

$$\mathcal{L}(\mathbf{x}, t_0) = \sum_{i=1}^{N_{\text{hit}}} \log P(t - t_{\text{tof}} - t_0), \qquad (4.2)$$

where **x** represents the testing vertex position and $P(t - t_{tof} - t_0)$ is the probability density function of the timing residual for a single photoelectron signal which is extracted from the LINAC calibration, as shown in Figure 4.12. With the maximum likelihood fitting based on this, the vertex position and t_0 are determined. The vertex resolution, a 1σ difference between the true and reconstructed positions, as a function of electron energy is shown in Figure 4.13.



Figure 4.12: Probability density function for the timing residual $(t - t_{tof} - t_0)$ obtained by the LINAC calibration. Peaks at around 40 ns and 110 ns are the PMT after-pulses.

The event direction is reconstructed using information on the Cherenkov ring pattern. This is performed by maximizing the following likelihood:

 $^{^{2}}$ Another tool made for proton decay and atmospheric neutrino analyses also treat events below 80 MeV.



Figure 4.13: Vertex resolution as a function of electron energy in SK-IV. The figure is taken from Ref. [81].

$$\mathcal{L}(\mathbf{d}) = \sum_{i=1}^{N_{20}} \log f(\cos \theta_i, E) \times \frac{\cos \theta_i}{a(\theta_i)}, \tag{4.3}$$

where N_{20} is the number of hit PMTs within a 20 ns timing window around $t - t_{tof} - t_0 = 0$, d is the event direction, $f(\cos \theta_i, E)$ is the expected distribution of the opening angle between the true event direction and the observed direction where E is the event energy, θ_i is the reconstructed event direction, and $a(\theta_i)$ is the correction for the PMT acceptance. The angular resolution is 25° for the 10 MeV electrons.

With reconstructed event vertex and direction, two parameters which are used in the analysis are defined, *dwall* and *effwall*: *dwall* represents the distance from the reconstructed vertex to the closest ID wall and *effwall* is the distance from the reconstructed vertex to the ID wall as measured backward along the reconstructed direction. Schematic illustration for these two parameters is given in Figure 4.14.

The fit quality parameters, g_{vtx} and g_{dir} , are obtained and used in the analysis. The vertex quality parameter, g_{vtx} , is defined as:

$$g_{\rm vtx} = \frac{\sum_{i} w_i e^{-\frac{1}{2} \left(\frac{\Delta t_i}{\sigma}\right)^2}}{\sum_{i} w_i} \quad \text{with} \quad w_i = -\frac{1}{2} \left(\frac{\Delta t_i}{\omega}\right)^2, \tag{4.4}$$

where $\Delta t_i = t_{\text{res},i} - t_0$ ($t_{\text{res},i}$: the timing residual of an event for the *i*-th hit PMT, t_0 : the fit value minimizing all $t_{\text{res},i}$), and w_i is the weight for the *i*-th hit PMT to reduce the dark noise. The ω and σ are set to 60 ns and 5 ns, respectively. The summation above is conducted over all hit PMTs, satisfying $|\Delta t_i| < 50$ ns for the numerator and $|\Delta t_i| < 360$ ns for the denominator.



Figure 4.14: Schematic illustration for definitions of *dwall* and *effwall*.

The angular quality parameter, g_{dir} , is evaluated by using the spatial uniformity of hit PMTs based on the Kolmogorov-Smirnov test:

$$g_{\rm dir} = \frac{\max_i \{ \angle_{\rm uni}(i) - \angle_{\rm data}(i) \} - \min_i \{ \angle_{\rm uni}(i) - \angle_{\rm data}(i) \}}{2\pi},\tag{4.5}$$

where $\angle_{\text{data}}(i)$ is the azimuthal angle of the *i*-th hit PMT in data which is included in the sliding 50 ns window (N_{50}) and $\angle_{\text{uni}}(i) = 2\pi i/N_{50}$ is the azimuthal angle of the *i*-th hit PMT in the toy simulation when the uniform distribution is assumed. The g_{vtx} value increases as the timing distribution becomes sharper, while g_{dir} decreases as the space distribution becomes more uniform. With these two parameters, a new quality parameter (ovaQ) is defined as $ovaQ = g_{\text{vtx}}^2 - g_{\text{dir}}^2$. The larger ovaQ corresponds to sharper in time and more uniform in space for an event. This is used to discriminate the low energy background.

4.6.2 Energy Reconstruction

For the energy reconstruction, the effective number of hits (N_{eff}) , which is defined below, is used.

$$N_{\rm eff} = \sum_{i=1}^{N_{50}} \left[(X_i + \epsilon_{\rm tail} - \epsilon_{\rm dark}) \times \frac{N_{\rm all}}{N_{\rm normal}} \times \frac{R_{\rm cover}}{S(\theta_i, \phi_i)} \times \exp\left(\frac{r_i}{\lambda_{\rm run}}\right) \times \frac{1}{QE_i} \right].$$
(4.6)

Here N_{50} is the number of hit PMTs within a 50 ns timing window. Other parameters are explained in the following.

• Occupancy (X_i) : The energy reconstruction is conducted assuming the number of hits in one PMT is single in the low energy region. This assumption breaks down at higher energies. When a PMT detects multiple photons, the surrounding PMTs are likely to have hits. The term X_i is used for estimating the multiple photoelectron effect for the *i*-th PMT, defined as:

$$X_i = \begin{cases} \log\left(\frac{1}{1-x_i}\right) & (x_i < 1)\\ 3.0 & (x_i = 1) \end{cases}$$

$$(4.7)$$

where x_i represents the ratio of the number of hit PMTs to the total number of PMTs in a 3×3 patch around the *i*-th hit PMT.

- Late hits (ϵ_{tail}): Some Cherenkov photons arrive late due to scattering and reflection and then are not detected during the 50 ns window. This is corrected by the term ϵ_{tail} .
- Dark noise (ϵ_{dark}) : The dark noise contribution is subtracted from the occupancy.
- Correction for the dead PMTs $(N_{\rm all}/N_{\rm normal})$: Some PMTs may not be working properly depending on the period. This is corrected by the term $N_{\rm all}/N_{\rm normal}$, where $N_{\rm all}$ and $N_{\rm normal}$ are the numbers of all and properly working PMTs, respectively.
- Correction for the PMT coverage $(R_{\text{cover}}/S(\theta_i, \phi_i))$: The effective photocathode area is represented by $S(\theta_i, \phi_i)$ (θ_i : the incident angle, ϕ_i : the azimuth angle), and the acceptance of the PMT is corrected by R_{cover} .
- Correction for the water transparency (r_i/λ_{run}) : The correction about the water transparency (λ_{run}) is added for the event located at distance r_i from the *i*-th PMT to the vertex.
- Correction for the PMT quantum efficiency $(1/QE_i)$: The last correction term is about the quantum efficiency of PMTs.

The relation between the effective number of hits and the reconstructed visible energy is shown in Figure 4.15. A linearity better than $\pm 0.5\%$ is achieved in the energy region 0–80 MeV. In the analyses in this thesis, the effect of the PMT gain shift over the SK-IV period (shown in Chapter 7) is not corrected, but the systematic error regarding this is estimated.

4.6.3 Cherenkov Angle Reconstruction

A Cherenkov opening angle ($\theta_{\rm C}$) for each event is reconstructed as the most frequently occurring value in the distribution of opening angles by all three-hit (triplet) combinations of the hit PMTs within a 15 ns timing window. The distributions of angles formed by the triplet hits are shown in Figure 4.16 for typical events. The Cherenkov angle is characterized by the event topology and then used to identify the particle type. The electron and single γ -ray events tend to have $\theta_{\rm C} \sim 42^{\circ}$, while the multiple- γ events have higher angles. In the current low energy region, muons are not so relativistic as to have 42° but instead show lower angles.



Figure 4.15: Relation between the number of effective hits (N_{eff}) and the reconstructed visible energy (E_{rec}) for generated electrons in MC and the linear fitting result (top) and the ratio of the MC and the fit values (bottom).



Figure 4.16: Distributions of opening angles by all three-hit combinations of the hit PMTs for the e-like (left), μ -like (middle), and multiple- γ -like (right) event, respectively. The blue lines and numbers indicate the most frequent values which are taken as the reconstructed Cherenkov angles.

4.7 Detector Calibration

SK is calibrated in various ways. Here they are overviewed, and more details can be found in Refs. [77, 80, 90, 91].

4.7.1 PMT Calibration

The absolute gain is applied to all PMTs in common to convert the number of photoelectrons into the charge. The applied high-voltages to PMTs were determined at the beginning of the SK-III using a Xe light source. A Ni-Cf source is used for the calibration. The absolute gain is determined from the distribution of the average charge of single photoelectron to be 2.645 pC/p.e. in SK-IV.

The relative gains are measured using high and low intensity lights. The charge detected by the *i*-th PMT (Q_{obs}^i) in the high intensity measurement is expressed as:

$$Q_{\rm obs}^i \propto I_{\rm high}^i \times QE^i \times G^i, \tag{4.8}$$

where I_{high}^{i} is the light intensity seen from the *i*-th PMT, and QE^{i} and G^{i} are the quantum efficiency and the relative gain of the *i*-th PMT, respectively. In the low intensity measurement, the number of observed hits (N_{obs}) is expressed as:

$$N_{\rm obs}^i \propto I_{\rm low}^i \times QE^i, \tag{4.9}$$

where I_{low}^i is the light intensity seen from the *i*-th PMT. Using Equations 4.8 and 4.9:

$$G^{i} = \frac{Q^{i}_{\text{obs}}}{N^{i}_{\text{obs}}} \times \frac{I^{i}_{\text{low}}}{I^{i}_{\text{high}}}.$$
(4.10)

Here the light attenuation and geometric effects are all cancelled out. The measured relative PMT gains fluctuate within 6%.

The relative timings of the PMTs are measured using a laser. A N_2 laser beam is injected from the center of the ID tank, as shown in the left panel of Figure 4.17. In the same figure, the two-dimensional plot of the timing versus charge is shown.

4.7.2 Water Transparency Measurement

The water transparency is measured in two ways. The absorption and scattering parameters are independently measured using the N_2 laser, and the effective attenuation length is measured using the decay electrons from cosmic-ray muons. The measured effective attenuation length of photons in the water is around 140 m and is stable within 15% in SK-IV.



Figure 4.17: Schematic illustration for the timing calibration (left) and the 2D distribution of the charge and timing (right). The QBin in the lower horizontal axis of the right panel is defined as: QBin = 5Q (0 < Q < 10) or QBin = $50 \cdot \log_{10} Q$ (10 < Q < 3981). The figures are taken from Ref. [80].

4.7.3 Energy Calibration

The energy scale calibration is performed in three independent ways: LINAC [90], DT generator [91], and decay electrons.

An electron linear accelerator (LINAC) is equipped on the top of the SK tank. It injects downward-going mono-energetic electron beams into the SK tank. The electron energy is available up to ~ 19 MeV and is measured within a ± 20 keV precision by a germanium detector. Several positions are taken as injection points to study the position dependence. Figure 4.18 shows comparison of the LINAC data with the corresponding MC. The absolute energy is determined by LINAC with an accuracy better than 1%.



Figure 4.18: Distributions of reconstructed energies for the different energy settings in the LINAC 2010 data. The figure is taken from Ref. [92].

A deuterium-tritium (DT) neutron generator is used to provide a cross check in the energy scale calibration. The 6.1 MeV γ -rays are isotropically emitted and used as a calibration point. This is conducted every a few months. In the DT calibration, the direction dependence is also measured and it is found that a directional bias is less than 1%. Another calibration source is decay electrons from cosmic-ray muons. With this sample, the energy scale up to ~60 MeV can be calibrated.

Through the calibrations explained above, the absolute energy scale had been monitored and found to be stable better than 1% in the SK-IV period, as shown in Figure 4.19. Note that the PMT gain shift effect is corrected here. This causes an additional a few % error on the energy scale, as is explained in Chapter 7.



Figure 4.19: The N_{eff} distribution as a function of time in the SK-IV period measured using the decay electron sample. The blue and red dashed lines indicate the average and $\pm 0.5\%$ deviated values, respectively. Here the effect of the PMT gain shift is corrected.

Chapter 5

Event Simulation

The MC simulation is essential to determine the selection criteria and to estimate the uncertainties. The simulation in this analysis considers the models of neutrino flux, neutrino interaction, γ -ray emission, and detector response.

5.1 Neutrino Flux

As described in Chapter 3, the neutrino beam is produced from the proton reactions on the graphite target, and this is simulated by FLUKA ver. 2011.2c.6 [93]. Here the proton beam properties, such as energy, position, and width, reflect the measurement results by the ESM, SSEM, and OTR. The hadron interaction cross sections are renormalized using data from the NA61/SHINE experiment [94–98], where the protons with the same energy are incident on the graphite target and the kinematics of the out-going hadrons is measured. The experiments were conducted with different graphite target configurations: thin targets and the T2K replica target. In the present work, both data are used for the renormalization. Transport and decay of the particles are simulated by GEANT3 [84]. Figure 5.1 shows the flux predictions at SK without neutrino oscillations.



Figure 5.1: T2K neutrino flux predictions at SK in the FHC (left) and RHC (right) modes. Here the neutrino oscillations are not considered.

5.2 Neutrino Interaction

The neutrino-nucleus interaction and the final state interaction inside the nucleus are simulated by the neutrino event generator NEUT ver. 5.3.3 [99]. For the NCQE interaction, the spectral function model by Benhar et al. [100, 101] is used as the nucleon momentum distribution inside the nucleus, while the relativistic Fermi gas model by Smith-Moniz [102] is used for the CCQE interaction. CC 2p2h interactions are simulated based on the model by Nieves et al. [103], but the NC counterpart is not simulated since there is no calculation available in the literature. To describe the vector form factor and the axial-vector form factor, BBBA05 and dipole parametrizations [62, 104] are used, respectively. For the single pion production via baryon resonance, the Rein-Schgal model [105] with some modifications is used. Deep inelastic scattering is simulated using the GRV98 parton distribution [106] corrected by Bodek and Yang [107]. The nominal NEUT settings about neutrino interaction parameters in this analysis are summarized in Table 5.1. Here the errors of each interaction parameter, which are used later in the systematic error estimation, are also shown. Figure 5.2 gives the NCQE cross section in NEUT for neutrinos and antineutrinos. The final state interactions are simulated with a cascade model [18,99]. Further details about the neutrino-nucleus interaction simulation are given in Ref. [18].

Table 5	5.1: Neutri	no interaction	parameter	settings in	NEUT fo	or the n	ominal N	AC pro	duction.
Errors	of each par	ameter are also	shown. N	ote that the	e definitio	n of "NO	C other"	here is o	different
from "I	NC-other"	elsewhere in the	his thesis.						

Parameter	Mean value	Error
Axial vector mass in QE (M_A^{QE})	$1.21 { m ~GeV/c^2}$	$0.18 { m ~GeV/c^2}$
Fermi momentum for oxygen $(p_{\rm F} {\rm O})$	$225.0 \ \mathrm{MeV/c}$	$31.0 \ \mathrm{MeV/c}$
2p2h normalization for ν	1.0	1.0
2p2h normalization for $\bar{\nu}$	1.0	1.0
2p2h normalization carbon to oxygen	1.0	0.2
2p2h shape for oxygen	0.0	0.0
Form factor parameter in single pion production $(C_5^{\rm A}(0))$	1.01	0.15
Axial vector mass in resonance interaction $(M_{\rm A}^{\rm RES})$	$0.95 \ \mathrm{GeV/c^2}$	0.15 GeV/c^2
Non-resonant (Isospin = $\frac{1}{2}$) background normalization	1.30	0.40
ν_e/ν_μ	1.0	0.028284
$\bar{ u}_e/\bar{ u}_\mu$	1.0	0.028284
CC DIS normalization	0.0	0.4
CC coherent normalization for oxygen	1.0	0.3
NC coherent normalization	1.0	0.3
$NC1\gamma$ normalization	1.0	1.0
NC other normalization for far detector	1.0	0.3
BeRPA parameter A	0.59	0.118
BeRPA parameter B	1.05	0.21
BeRPA parameter D	1.13	0.1695
BeRPA parameter E	0.88	0.352
BeRPA parameter U	1.20	0.1



Figure 5.2: NCQE cross sections by NEUT for neutrinos (left) and antineutrinos (right) on all neutrons, all protons, and all nucleons inside oxygen.

5.3 Nuclear De-excitation γ -rays and Detector Response

The nuclear de-excitation γ -rays are simulated separately for the primary γ -rays from neutrinonucleus interactions and the secondary γ -rays from nucleon-nucleus interactions. The processes are schematically shown in Figure 5.3. More details can be found in Ref. [104].



Figure 5.3: Schematic drawing of the primary and the secondary γ -rays in the NCQE interaction.

After the neutrino-oxygen interaction, one of excited states is selected based on probabilities calculated by Ankowski et al. [49]. The possible states are categorized into four: $(p_{1/2})^{-1}$, $(p_{3/2})^{-1}$, $(s_{1/2})^{-1}$, and others. According to the simple nuclear shell model, nucleons inside ¹⁶O belong to either of $p_{1/2}$, $p_{3/2}$, or $s_{1/2}$. The states of $(p_{1/2})^{-1}$, $(p_{3/2})^{-1}$, and $(s_{1/2})^{-1}$ are the situation that a nucleon occupying either of $p_{1/2}$, $p_{3/2}$, or $s_{1/2}$ is removed from the nucleus, respectively. Probabilities for each state to be produced are summarized in Table 5.2. The treatment of the others state is explained below.

	$(p_{1/2})^{-1}$	$(p_{3/2})^{-1}$	$(s_{1/2})^{-1}$	others
Simple shell model	0.25	0.50	0.25	0
Ankowski et al. [49]	0.158	0.3515	0.1055	0.385
This analysis	0.158	0.3515	0.4905	-

Table 5.2: Probabilities of a remaining nucleus belonging to each excited state, $(p_{1/2})^{-1}$, $(p_{3/2})^{-1}$, $(s_{1/2})^{-1}$, and *others*, after the neutrino interaction.

The $(p_{1/2})^{-1}$ state corresponds to the ground state of ¹⁵O (¹⁵N) after a neutron (proton) knock-out, and therefore does not lead to any γ -ray emission.

The possible excited states and γ -ray emission modes for the $(p_{3/2})^{-1}$ state are summarized in Table 5.3. Here E_{ex} represents the excited energy level, J^{π} is the spin and parity of the residual nucleus, E_{γ} and E_p are energies of the emitted γ -ray and proton respectively, R_{γ} is the probability of the residual nucleus to emit the γ -ray at each excited state, and Br(X^{*} \rightarrow Y + γ) is the branching ratio for the residual nucleus (X = ¹⁵N or ¹⁵O) to de-excite to the ground state of Y. The most likely modes are the emission of the 6.32 MeV γ -ray from ¹⁵N or the 6.18 MeV γ -ray from ¹⁵O.

Table 5.3: Excited states and γ -ray emission modes of ¹⁶O proton hole $(p_{3/2})_p^{-1}$ and neutron hole $(p_{3/2})_n^{-1}$.

Residual nucleus	$E_{\rm ex} [{\rm MeV}]$	J^{π}	$E_{\gamma} [{\rm MeV}]$	$E_p \; [\mathrm{MeV}]$	R_{γ} [%]	$Br(X^* \to Y + \gamma) ~[\%]$
$^{15}\mathrm{N}$	6.32	$\left(\frac{3}{2}\right)^{-}$	6.32	-	100	86.2
	9.93	$\left(\frac{3}{2}\right)^{-}$	5.30	-	15.3	1.1
			6.32	-	4.9	0.3
			7.30	-	2.1	0.1
			9.93	-	77.6	5.4
	10.70	$\left(\frac{3}{2}\right)^{-}$	-	0.5	-	6.9
¹⁵ O	6.18	$\left(\frac{3}{2}\right)^{-}$	6.18	-	100	100

There are more fractions to the emission of γ -rays with energies of >3 MeV from the $(s_{1/2})^{-1}$ state. For the proton knock-out case, excited states and their branching ratios of the γ -ray emission are measured or calculated as summarized in Table 5.4. From the analogy, the neutron knock-out case is set to be identical in the nominal MC.

The others state includes all the other states whose excited energies are higher than any of the three states above or which are affected by other nuclear effects such as short-range correlation between nucleons. Since there is no data nor theoretical calculation on the γ -ray emission from the others state, this state is integrated into $(s_{1/2})^{-1}$ at the nominal MC production. The systematic uncertainty regarding this treatment is estimated later.

The interactions of particles produced in the neutrino interaction, the Cherenkov light emission, and the PMT responses are simulated by the GEANT3-based dedicated package, which is described in Chapter 4. Important for this analysis is the hadronic interaction parts, especially the models of neutron reactions on oxygen. The hadronic interactions are based on GCALOR [85,86]. This implements MICAP for neutrons below 20 MeV and NMTC above 20 MeV, respectively. MICAP reads experimental cross sections from ENDF/B-V, while NMTC is based on the intra-nuclear cascade model. Details about these models can be found in Refs. [85, 86] and references therein.

Residual nucleus	$E_{\rm ex}$ [MeV]	J^{π}	$E_{\gamma} [{\rm MeV}]$	R_{γ} [%]	$Br(^{15}N^* \to Y + \gamma) \ [\%]$
$^{13}\mathrm{C}$	3.09	$\left(\frac{1}{2}\right)^+$	3.09	100	3.0
	3.68	$\left(\frac{3}{2}\right)^+$	3.68	99.3	4.2
	3.85	$\left(\frac{1}{2}\right)^+$	3.09	1.20	< 0.1
$^{12}\mathrm{C}$	4.44	2+	4.44	100	5.8
^{14}N	g.s.	2^{+}	-	-	6.7
	4.92	0^{-}	4.92	97	5.0
	5.11	2^{-}	5.11	79.9	< 0.1
	5.69	1^{-}	3.38	63.9	2.9
			5.69	36.1	1.6
	5.83	3^{-}	5.11	62.9	0.3
			5.83	21.3	0.1
	6.20	1^{+}	3.89	76.9	< 0.1
			6.20	23.1	< 0.1
	6.45	3^{+}	5.11	8.1	0.2
			6.44	70.1	2.0
	7.03	2^{+}	7.03	98.6	(6.6)
$^{14}\mathrm{C}$	g.s.	2^{+}	-	-	1.1
	6.09	1^{-}	6.09	100	< 0.1
	6.59	0^{+}	6.09	98.9	< 0.1
	6.73	3^{-}	6.09	3.6	< 0.1
			6.73	96.4	0.4
	6.90	0^{-}	6.09	100	< 0.1
	7.01	2^{+}	6.09	1.4	< 0.1
			7.01	98.6	(6.6)
	7.34	2^{-}	6.09	49.0	2.8
			6.73	34.3	2.0
			7.34	16.7	1.0

Table 5.4: Excited states and γ -ray emission modes of the proton hole $(s_{1/2})_p^{-1}$ in ¹⁶O. The g.s. represents the ground state.

5.4 Neutrino Oscillation Effect

Unlike the NC interaction, the cross section and the final state of the CC interaction depend on the neutrino flavor, then neutrino oscillation effects need to be considered. At the stage of event selection described in Chapter 6, this effect is corrected as shown in Figure 5.4, where the oscillation probability at true neutrino energy is multiplied as weight to each MC event. Although the oscillation probabilities of $\nu_{\mu} \rightarrow \nu_{\tau}$ and $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\tau}$ are high, the CC cross sections of ν_{τ} ($\bar{\nu}_{\tau}$) are negligible in the T2K energy region because the tau lepton mass is higher. Therefore, contributions from tau (anti)neutrinos are negligible. The $\nu_{\mu} \rightarrow \nu_{\mu}$ and $\nu_{\mu} \rightarrow \nu_{e}$ oscillation probabilities are written as follows:



Figure 5.4: Schematic drawing for the correction of oscillation effects.

$$P(\nu_{\mu} \to \nu_{\mu}; E_{\nu}) \simeq 1 - (\cos^{4} \theta_{13} \cdot \sin^{2} 2\theta_{23} + \sin^{2} 2\theta_{13} \cdot \sin^{2} \theta_{23}) \cdot \sin^{2} \left(1.267 \cdot \frac{\Delta m_{32}^{2} [eV^{2}] \cdot L[km]}{E_{\nu} [GeV]} \right),$$
(5.1)

$$P(\nu_{\mu} \to \nu_{e}; E_{\nu}) \simeq \sin^{2} 2\theta_{13} \cdot \sin^{2} \theta_{23} \cdot \sin^{2} \left(1.267 \cdot \frac{\Delta m_{32}^{2} [eV^{2}] \cdot L[km]}{E_{\nu} [GeV]} \right)$$

$$\mp \frac{\Delta m_{21}^{2} [eV^{2}] \cdot L[km]}{4E_{\nu} [GeV]} \cdot J_{CP} \cdot \sin \delta_{CP} \cdot \sin^{2} \left(1.267 \cdot \frac{\Delta m_{32}^{2} [eV^{2}] \cdot L[km]}{E_{\nu} [GeV]} \right), \quad (5.2)$$

$$J_{CP} = \frac{1}{8} \cos \theta_{13} \cdot \sin 2\theta_{12} \cdot \sin 2\theta_{23} \cdot \sin 2\theta_{13} \cdot \sin \delta_{CP}, \quad (5.3)$$

where L denotes the experimental baseline, 295 km, and E_{ν} represents the neutrino energy. In Equation 5.2, an upper and a lower sign corresponds to neutrino and antineutrino oscillations, respectively. In the correction, the CC cross sections of ν_{μ} ($\bar{\nu}_{\mu}$) and ν_{e} ($\bar{\nu}_{e}$) are assumed to be the same, and later the systematic error of this assumption is evaluated. In addition, the kinematics difference between the final state electron and muon is not considered, because this effect is expected to be small. By using the equations above, the weight factor (wgt_{osc}) multiplied to each MC event is obtained as follows:

$$wgt_{\rm osc}(E_{\nu}) = P(\nu_{\mu} \to \nu_{\mu}; E_{\nu}) + P(\nu_{\mu} \to \nu_{e}; E_{\nu}) \cdot \frac{\sigma_{\rm CC}(\nu_{e}; E_{\nu})}{\sigma_{\rm CC}(\nu_{\mu}; E_{\nu})}$$
$$\simeq P(\nu_{\mu} \to \nu_{\mu}; E_{\nu}) + P(\nu_{\mu} \to \nu_{e}; E_{\nu})$$
$$= 1 - \cos^{4}\theta_{13} \cdot \sin^{2} 2\theta_{23} \cdot \sin^{2} \left(1.267 \cdot \frac{\Delta m_{32}^{2}[eV^{2}] \cdot L[km]}{E_{\nu}[GeV]}\right).$$
(5.4)

The same oscillation probability is assumed for muon antineutrinos and so does the weight factor. Oscillation parameters used in the analysis are taken from the recent T2K result [108], as summarized in Table 5.5.

Table 5.5: Neutrino oscillation parameters and their errors used in this analysis. These are taken from the recent T2K result [108].

Parameter	Nominal	Error
$\sin^2 \theta_{13}$	0.0211	± 0.0008
$\sin^2 \theta_{23}$	0.541	+0.027/-0.037
$\Delta m_{32}^2 [\times 10^{-3} \mathrm{eV^2}]$	2.469	+0.073/-0.071

Chapter 6

Event Selection

6.1 Selection Criteria

In the analysis, events are categorized into five: neutrino and antineutrino NCQE interactions (" ν -NCQE" and " $\bar{\nu}$ -NCQE" respectively), all the other NC interactions ("NC-other"), CC interactions, and beam-unrelated accidental backgrounds. Both NC-other and CC include neutrino and antineutrino interactions. Note that this categorization is based on the primary neutrino interaction type (before the final state interactions), that is, for example, an NC pion production event where a pion is absorbed in the nucleus is categorized as the NC-other interaction. The first four are simulated and the beam-unrelated events are estimated using the off-timing data, as described later. The cuts described in this chapter effectively select the signal-like events and reduce the other events. Table 6.1 summarizes the type of event selections and their application targets (data and/or MC).

No.	Selection	Application target
0	Energy window	Data & MC
1	Good spill selection	Data
2	Timing cut	Data
3	Decay- e cut	Data
4	Fiducial volume cut	Data & MC
5	Low energy background cut	Data & MC
6	CC interaction cut	Data & MC

Table 6.1: Type of the NCQE event selections and their application targets.

Energy window

In this analysis, the energy window is set to 3.49-29.49 MeV in visible energy. The lower edge is determined by the SK energy threshold. The higher edge is settled because the Michel electron background from the ν_{μ} and $\bar{\nu}_{\mu}$ CC interactions increase while the NCQE signal decreases above 30 MeV.

Good spill selection

Each spill is judged whether good for physics analysis or not based on the beam and SK detector conditions. Only good spill data are used in the analysis.

Timing cut

In order to select beam-induced events, the reconstructed event timing is required to be within ± 100 ns with respect to the expected timing of each bunch ("on-timing"). Beam-unrelated events are selected by applying the same energy and quality cuts but a different timing cut with a window $[-500, -5] \mu s$ with respect to the beam spill ("off-timing").

Decay electron cut

Since the signal events do not accompany a muon nor a pion, tagging these particles would be a powerful cut. Here an electron or a positron from muon decay is focused. The required minimum energy, $E_{\rm th}$, for a charged particle, whose mass is m, to emit Cherenkov light in a medium with a refractive index of n can be written as follows:

$$E_{\rm th} = \frac{nmc^2}{\sqrt{n^2 - 1}}.$$
 (6.1)

In water, n being 1.33, this "Cherenkov threshold" is 158.7 MeV for muons and 209.7 MeV for pions while 0.768 MeV for electrons and positrons. Therefore, in case that the energy of an out-going muon or pion is smaller while its decay product, an electron or a positron, has larger energy than its Cherenkov threshold, SK detects signature of only these decay electrons or positrons (referred to as the "decay-e" events).

It is possible that the selected event is the decay-e from a preceding muon, then the preactivity is searched before the event. Here a 30 ns wide window is slid between 0.2 and 20 μs before the event, and the number of hit PMTs within 30 ns (N_{30}) is counted. Then, the event whose maximum N_{30} is greater than 22 is rejected. This pre-activity cut is applied only for data, because these events do not exist in the MC sample. The effect on the signal efficiency by the pre-activity cut is negligible.

The other possibility that the decay-*e* comes after the selected event is also checked, but the signal-to-background ratio is not improved much, then the cut on this post-activity is not considered here.

Fiducial volume (FV) cut

There are lots of background events due to radioactive impurities in the detector material. Since these backgrounds are expected to come mainly from the ID wall, *dwall* is required to be larger than 200 cm. This FV cut is usually applied in the SK analysis. Below 6 MeV these backgrounds increase considerably even after the FV cut, and then tighter cuts are required, as described next.

Low energy background cut

Cuts in the energy region below 6 MeV are tuned using three variables, dwall, effwall, and ovaQ. Cuts on these variables are optimized in five energy regions between 3.49 MeV and 5.99 MeV with a 0.5 MeV bin and the optimization is performed separately for different T2K run periods because the beam power and the detector condition differ from run to run. A figure-of-merit (FOM) to be maximized for the cut optimization is defined as:

$$FOM = \frac{N_{sig}}{\sqrt{N_{sig} + N_{bkg}}} \quad (N_{bkg} = N_{bkg}^{MC} + N_{bkg}^{beam-unrelated}), \tag{6.2}$$

where $N_{\rm sig}$ represents the number of signal events by MC (ν -NCQE for FHC and $\bar{\nu}$ -NCQE for RHC respectively), while $N_{\rm bkg}$ represents the number of background events composed of the beam neutrino background $(N_{\rm bkg}^{\rm MC})$ and the beam-unrelated background $(N_{\rm bkg}^{\rm beam-unrelated})$. The FOM is calculated for each set of $\{dwall, effwall, ovaQ\}$ independently in the five lowest energy regions, 3.49-3.99, 3.99-4.49, 4.49-4.99, 4.99-5.49, and 5.49-5.99 MeV. By scanning the multiple parameter sets, the optimized one is selected which maximizes the FOM. In the scan a temporary cut of $\theta_{\rm C} \geq 34^{\circ}$ is applied to reduce CC events, while the cut for the CC events will be optimized later¹. Table 6.2 summarizes the scan regions and intervals of each parameter.

Parameter	\min	max	interval
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Table 6.2: Scan regions and intervals of each parameter.

After calculating FOMs for each energy region in each run, distributions of the best cut values of dwall, effwall, and ovaQ, as a function of energy are obtained. Results from Run 8 are shown in Figure 6.1 as an example. The results for the other runs are given in Appendix C. Each distribution is fit by a linear function. As for the *dwall* and *effwall* distributions, if the optimized value is 200 cm (the FV cut criterion) in two successive bins, the region after the second 200 cm bin is rejected from the fitting area. The fitting results are also shown in Figure 6.1. In the end, each parameter is required to be larger than the fit line, that is, the events in the upper right portion in the figure are selected. Figure 6.2 gives the ovaQ distributions after the energy cut, the good spill cut, the on-timing cut, the FV cut, the dwall cut, and the effwall cut. Clear separations between signal and background events are seen.

Parameter	min	max	interval
dwall [cm]	200	320	10
effwall [cm]	200	1200	10
ovaQ	0.20	0.30	0.01

¹The effect of this temporary treatment on the optimization is small.



Figure 6.1: Optimized cut values for dwall (top), effwall (middle), and ovaQ (bottom), as a function of reconstructed energy for Run 8. Vertical bars represent the bin width in the parameter scans. Red lines represent linear fits to each distribution and used as cut criteria. The fitting regions for dwall and effwall are explained in the text.



Figure 6.2: Distributions of ovaQ in FHC (left) and RHC (right) after the energy cut, the good spill cut, the on-timing cut, the FV cut, the *dwall* cut, and the *effwall* cut.

CC interaction cut

A single charged particle with momentum large compared to its mass tends to have a Cherenkov opening angle of $\sim 42^{\circ}$ because it is almost relativistic. On the other hand, if the particle momentum is lower, for example, ≤ 250 MeV for muons, the reconstructed Cherenkov angle decreases. In this analysis, the low energy muons from the CC interaction still above the Cherenkov threshold distribute below $\sim 35^{\circ}$, whereas their decay-e's have $\sim 42^{\circ}$. These are seen in Figures 6.3 and 6.4 for FHC and RHC, respectively. To reduce the CC interaction events, the cut criteria are tuned in the 2D $E_{\rm rec} - \theta_{\rm C}$ plane. The two parameters ($a_{\rm opt}$ and $b_{\rm opt}$) of a linear function, $\theta_{\rm C} = a_{\rm opt} \times E_{\rm rec} + b_{\rm opt}$, are determined by maximizing FOM. The definition of FOM is the same as Equation 6.2. Here the selection is done by requiring an event fulfilling $\theta_{\rm C} \geq a \times E_{\rm rec} + b$, and the combination of a and b which maximizes FOM is taken as an optimized one. The cut criteria are also shown in the figures. The large part of the NCQE events locates above the functions, while the CC events are below them. Some CC events remain after the cut and these could be due to, for example, multiple γ -rays via neutron production, and similar population is seen also in the NC-other distribution. With the optimized cut, the signal efficiency is 99% (99%) while 63% (58%) of the CC events are removed in the FHC (RHC) sample.



Figure 6.3: Two-dimensional $E_{\rm rec} - \theta_{\rm C}$ distributions of each interaction mode and the beamunrelated events before the CC interaction cut together with the optimized cut function ($\theta_{\rm C} = 1.68 \times E_{\rm rec} + 17.73$) in FHC.



Figure 6.4: Two-dimensional $E_{\rm rec} - \theta_{\rm C}$ distributions of each interaction mode and the beamunrelated events before the CC interaction cut together with the optimized cut function ($\theta_{\rm C} = 1.57 \times E_{\rm rec} + 17.73$) in RHC.

6.2 Selected Samples

Figure 6.5 shows the reconstructed energy distributions of the MC beam neutrino events and the beam-unrelated events both before and after the cuts. The numbers of each interaction and the beam-unrelated events are summarized in Tables 6.3 and 6.4, for the FHC and RHC mode, respectively. After the cuts, the signal efficiency is more than 90%, while the background is reduced by more than two orders of magnitude, and 204 events remain in the FHC sample and 97 events remain in the RHC sample. The FHC sample has a high signal purity, while the neutrino NCQE interaction forms $\sim 20\%$ of the RHC sample because of the cross section difference between neutrinos and antineutrinos. The observed and predicted numbers of selected events agree well to each other both in the FHC and RHC modes at every selection stage.

Table 6.3: Number of events after each cut in data and MC in FHC. Before the timing cut, only the beam quality and detector condition cuts are applied. In the column with "Total", the sum of the ν -NCQE, $\bar{\nu}$ -NCQE, NC-other, CC, and beam-unrelated events is shown.

	Observation		Prediction							
	On-timing	Total	ν -NCQE	$\bar{\nu}$ -NCQE	NC-other	CC	Beam-unrelated			
Timing cut	4595	-	-	-	-	-	4357.5			
Decay-e cut	4553	-	-	-	-	-	4350.8			
FV cut	831	896.8	190.7	5.2	52.1	24.9	623.9			
$dwall \operatorname{cut}$	735	791.4	190.0	5.2	51.9	24.8	519.5			
$e\!f\!fwall \operatorname{cut}$	442	492.7	185.6	5.0	51.4	24.6	226.1			
ovaQ cut	220	263.9	181.0	4.9	50.2	24.1	3.7			
CC cut	204	238.4	178.6	4.8	42.5	8.9	3.6			

Table 6.4: Number of events after each cut in data and MC in RHC. Before the timing cut, only the beam quality and detector condition cuts are applied. In the column with "Total", the sum of the ν -NCQE, $\bar{\nu}$ -NCQE, NC-other, CC, and beam-unrelated events is shown.

	Observation			Pr	ediction		
	On-timing	Total	ν -NCQE	$\bar{\nu}$ -NCQE	NC-other	CC	Beam-unrelated
Timing cut	3626	-	-	-	-	-	3746.9
Decay-e cut	3597	-	-	-	-	-	3470.0
FV cut	613	606.0	19.6	60.7	19.6	5.7	500.4
$dwall \operatorname{cut}$	535	524.1	19.5	60.5	19.5	5.7	418.9
effwall cut	282	279.4	19.1	58.7	19.3	5.6	176.7
$ovaQ \operatorname{cut}$	101	101.8	18.5	57.0	18.7	5.5	2.1
CC cut	97	94.3	17.9	56.5	15.5	2.3	2.1



Figure 6.5: The $E_{\rm rec}$ distribution of the MC beam neutrino and the beam-unrelated events before the FV cut and after all cuts for the FHC (left) and RHC (right) modes. The beamunrelated backgrounds are reduced dramatically after the cuts both in FHC and RHC.

The data quality of the selected events is checked by seeing if there is no bias in the distributions of the event vertex and timing and the event rate. The vertex distributions in the X-Y and R^2-Z coordinates, where X and Y correspond to the horizontal plane ($R^2 = X^2 + Y^2$) and Z corresponds to the vertical direction, for the FHC sample are shown in Figure 6.6. The selected events distribute uniformly in both the horizontal and vertical coordinates. In the figure, the beam direction is represented by a red arrow, and no bias on the event vertex with respect to the beam direction is observed. The event timing and the residual timing from the expected beam timing of the FHC sample are shown in Figure 6.7. The numbers of selected events in eight bunches are comparable to each other and most events come within 50 ns from the expected beam timing. Figure 6.8 shows event rates in each FHC run in comparison to the overall average rate of $1.37/10^{19}$ -POT. The event rate of each run is consistent with the overall average. Corresponding data quality checks for the RHC sample are shown in Figures 6.9, 6.10, and 6.11. The averaged event rate over the all RHC runs is $0.59/10^{19}$ -POT. No bias are seen in the position, timing, and event rate distributions.

Figures 6.12 and 6.13 show distributions of the reconstructed energy and Cherenkov angle and their 2D scatter plots for the FHC and RHC samples, respectively. The observed $E_{\rm rec}$ distributions agree well with the predictions and clear contributions from ~6 MeV γ -rays are observed in both FHC and RHC modes. In the $\theta_{\rm C}$ distribution of the FHC sample, the observed data at high angles is below the expectation, while no such excess in the expectation is seen in the RHC distribution. A similar tendency was also observed in the previous analysis [51], while the statistical uncertainty was large. The high angle region is dominated by the multiple- γ events, as explained in Chapter 4. These are caused mainly by fast neutron reactions on nuclei inside the detector. The excess in the FHC sample may then be attributed to inaccurate modeling of fast neutron reactions and the subsequent γ -ray emissions (secondary- γ). The fact that the excess is seen in FHC while not in RHC, may be understood by difference in the kinematics of out-going nucleons between neutrino and antineutrino interactions. Helicity conservation produces more forward-going leptons in the final state and accordingly lower



Figure 6.6: Vertex distributions for the selected events in FHC: X-Y (left) and R^2-Z (right). Area filled with transparent gray and blue represent the ID and FV regions, respectively. The red arrow in the left panel represents the beam direction.



Figure 6.7: Distributions of the event timing (left) and its residual time from the spill timing (right) for the selected events in FHC.



Figure 6.8: Observed event rate in each FHC run.



Figure 6.9: Vertex distributions for the selected events in RHC: X-Y (left) and R^2-Z (right). Area filled with transparent gray and blue represent the ID and FV regions, respectively. The red arrow in the left panel represents the beam direction.



Figure 6.10: Distributions of the event timing (left) and its residual time from the spill timing (right) for the selected events in RHC.



Figure 6.11: Observed event rate in each RHC run.



Figure 6.12: Distributions of $E_{\rm rec}$ (top) and $\theta_{\rm C}$ (middle), and their 2D scatter plot (bottom) in the FHC sample. In the 2D plot, magenta dots represent the observed events.



Figure 6.13: Distributions of $E_{\rm rec}$ (top) and $\theta_{\rm C}$ (middle), and their 2D scatter plot (bottom) in the RHC sample. In the 2D plot, magenta dots represent the observed events.

momentum nucleons in the antineutrino interaction than the neutrino interaction, as shown in Figure 6.14. The lower momentum nucleons will undergo fewer nuclear reactions inside the water to produce secondary γ -rays. Comparison of the ratio of the single- γ peak around 42° to the multiple- γ peak around 90° of the MC in Figures 6.12 and 6.13 shows that there are relatively fewer events at high angles in the RHC sample. Figure 6.15 shows the 2D distributions of the energy of neutrons from the (anti)neutrino NCQE interactions and $\theta_{\rm C}$ obtained by MC. The large contribution at high angles from the higher momentum neutrons is seen in the FHC ν -NCQE distribution, while this is weaker in the RHC $\bar{\nu}$ -NCQE distribution. The observation and prediction agree well to each other in the 2D scatter plots in Figures 6.12 and 6.13.



Figure 6.14: Kinetic energies of neutrons from the neutrino and antineutrino NCQE interactions in RHC obtained by MC.



Figure 6.15: The 2D distributions of the energy of neutrons from the ν -NCQE interaction in FHC (left) and the $\bar{\nu}$ -NCQE interaction in RHC (right) and $\theta_{\rm C}$ obtained by MC.

Chapter 7

Uncertainty Estimates

Statistical errors on the observed events are calculated to be $\sqrt{204/204} = 7.0\%$ for the FHC sample and $\sqrt{97}/97 = 10.2\%$ for the RHC sample, respectively.

Systematic error in this analysis is composed of six parts: neutrino flux prediction, neutrino interaction model, primary- γ emission model, secondary- γ emission model, oscillation parameters, and detector response. For the beam-unrelated events, only statistical errors are considered as 3.0% in FHC and 3.9% in RHC. This is because they are part of the observed data and then respond to detector uncertainties in the same way.

7.1 Neutrino Flux

Flux uncertainties are estimated for each neutrino flavor, operation mode, and neutrino energy bin. Figure 7.1 shows the total and each source uncertainties of the flux prediction at SK as a function of neutrino energy for different neutrino flavors in both FHC and RHC modes [109]. The flux uncertainty is composed of hadronic interaction model, proton beam and neutrino beam measurements, and horn and magnetic field measurements. The hadronic interaction model is the dominant uncertainty. The hadronic interaction cross section is tuned by data from the NA61/SHINE experiment, as mentioned in Chapter 5, and the replica target data is used in this analysis in addition to the thin target data. This has improved the uncertainty mainly at around the flux peak. The MC neutrino event is renormalized by the error size at its flavor and energy, and the change in the number of selected events relative to the nominal case is taken as the systematic error. Here the energy bins are treated as fully correlated. The results are summarized in Table 7.1.

Table 7.1: Uncertainties on the observed event rate in percent for each sample component due to the systematic errors on neutrino flux prediction.

	ν -NCQE	$\bar{\nu}$ -NCQE	NC-other	CC
FHC	6.7	8.6	7.3	6.4
RHC	7.0	6.4	7.0	6.5



Figure 7.1: Total and each source uncertainties of the flux prediction at SK as a function of neutrino energy for different neutrino flavors in both FHC and RHC modes. The solid line indicates the current uncertainty, while the dashed line corresponds to the uncertainty in the tuning only with the thin target data.
7.2 Neutrino Interaction

The cross section model uncertainties are estimated by changing model parameters by their 1σ errors as summarized in Table 5.1. In addition, systematic uncertainties of nuclear effects are evaluated by replacing the Fermi gas model with the spectral function model. The resulting errors are shown as "Cross section model" in Table 7.2. Here the model uncertainty is not considered for the NCQE interaction, because the γ -ray is emitted isotropically and the detector is 4π efficient therefore the signal efficiency is unaffected by the cross section model uncertainty. In contrast, the detector such as ND280 does not 4π acceptance, therefore, for example, the change in Q^2 due to the cross section model uncertainty, which affects the out-going lepton direction, clearly changes the number of selected events. Figure 7.2 shows the Q^2 distributions of the signal in FHC and RHC at each selection stage, in which no significant change is seen throughout all stages. This supports that the NCQE signal is not affected by the interaction model uncertainty.

Table 7.2: Uncertainties on the observed event rate in percent for each sample component due to the systematic errors on neutrino interaction model.

		ν -NCQE	$\bar{\nu}$ -NCQE	NC-other	CC
FHC	Cross section model	-	-	8.2	16.5
	NC inelastic	3.0	3.0	-	-
	Total	3.0	3.0	8.2	16.5
RHC	Cross section model model	-	-	10.8	38.2
	NC inelastic	3.0	3.0	-	-
	Total	3.0	3.0	10.8	38.2



Figure 7.2: The Q^2 distributions of ν -NCQE in FHC (left) and $\bar{\nu}$ -NCQE in RHC (right) at each selection stage.

The NC inelastic interaction without nucleon knock-out, ν ($\bar{\nu}$) + ¹⁶O $\rightarrow \nu$ ($\bar{\nu}$) + ¹⁶O^{*}, is not simulated in this analysis. However, the present selection may contain contributions from this process. Figure 7.3 shows the neutrino-oxygen NC cross sections leading to the ground state (¹⁵O, ¹⁵N) and the excited state (¹⁵O^{*}, ¹⁵N^{*}) calculated in Ref. [110]. Note that these nuclei are produced by decay from the excited ¹⁶O^{*} after the NC inelastic scattering with no nucleon emission. This shows the sum of cross sections leading to ${}^{15}O^*$ and ${}^{15}N^*$ after the $^{16}O(\nu,\nu')$ interaction is increased from 6.7×10^{-42} cm² at $E_{\nu} = 50$ MeV to 481×10^{-42} cm² at $E_{\nu} = 500$ MeV while are saturated above $E_{\nu} \sim 200$ MeV. On the other hand, Figure 7.4 shows the NCQE cross sections calculated in Ref. [49]. Comparing these two, the QE process is dominant than the inelastic process without nucleon knock-out above $E_{\nu} \sim 200$ MeV as mentioned in Chapter 2. The former cross section is ~ 40 times larger than the latter at 500 MeV, and is expected to be more in the higher energy region. In the T2K measurement, the dominant contributions come from neutrinos with >500 MeV (see Figure 5.1). With assumption that the detectable γ -ray emission rate from excited states after the inelastic interaction without nucleon emission is comparable to that after the QE, a conservative $3\% (\gtrsim 1/40)$ error is assigned. Similar is expected for the antineutrino case, so the same size error is assigned. It is also possible that γ -rays are produced by the proton secondary reactions after the NC interactions on hydrogen, $\nu(\bar{\nu}) + {}^{1}H \rightarrow \nu(\bar{\nu}) + {}^{1}H$, though this process is not simulated in the current analysis. The contributions from the proton-induced secondary- γ 's in the NCQE interaction with oxygen are estimated and compared with the total, which result in $\leq 9\%$. Since the composition of hydrogen in water is 1/9, the contribution size is $\leq 1\%$ (negligible).



Figure 7.3: (See only the lower part) Total and partial cross sections leading to the ground state (¹⁵O and ¹⁵N) and the excited state (¹⁵O^{*} and ¹⁵N^{*}) after the ¹⁶O(ν, ν') interactions [110].

7.3 Primary- γ Production

Primary- γ production is determined based on the spectroscopic strengths of the excited states, therefore the uncertainties on these strengths may affect the observed event rate. The results are summarized in Table 7.3.

The calculation of the $p_{3/2}$ strength is accomplished with a precision of 5.4% according to Ankowski et al. [49]. To estimate the effect of the $p_{3/2}$ state, the spectroscopic strength of this state is increased by 5.4% with the changed amount absorbed by decrease of the strength of



Figure 7.4: Neutrino- and antineutrino-oxygen NCQE interaction cross sections and those with γ -ray emission [49].

the $p_{1/2}$ state, which gives $(p_{1/2}, p_{3/2}, s_{1/2}) = (0.139, 0.3705, 0.4905)$. The uncertainty size due to this change is different between ν -NCQE and $\bar{\nu}$ -NCQE because the rate of out-going neutrons is changed and accordingly the secondary- γ emission is affected. This is more visible in the FHC sample since the out-going neutron has larger effect as explained in the previous chapter. The error of the $s_{1/2}$ state is included in that of the *others* state as explained below. Note that an even conservative size change of this state does not produce any comparable error ¹.

As mentioned in Chapter 5, there is no data nor theories on the γ -ray emission from the *others* state. At the nominal MC production, this state is integrated into the $(s_{1/2})^{-1}$ state. The error on this treatment is estimated by comparing the nominal case to an extreme case. Since no significant deviation on the strength of $p_{3/2}$ from the calculated strength is observed in the (e, e'p) and (p, 2p) scattering experiments [49,111], the *others* state cannot be integrated into the $(p_{3/2})^{-1}$ state. In contrast, it is possible for the *others* state to behave like the ground state, $(p_{1/2})^{-1}$, because no signal is produced from the ground state and then such situation does not contradict any experiments. As an extreme case, the integration of *others* into $(p_{1/2})^{-1}$ is selected as $(p_{1/2}, p_{3/2}, s_{1/2}) = (0.543, 0.3515, 0.1055)$. The different treatment shows the dominant error in this source.

Table 7.3: Uncertainties on the observed event rate in percent for each sample component due to the systematic errors on primary- γ emission model.

		ν -NCQE	$\bar{\nu}$ -NCQE	NC-other	CC
	$p_{3/2}$ changed	0.1	3.3	3.1	5.6
FHC	others integrated into $(p_{1/2})^{-1}$	11.0	10.1	5.1	3.4
	Total	11.0	10.6	6.0	6.6
	$p_{3/2}$ changed	0.8	1.8	2.6	< 0.1
RHC	others integrated into $(p_{1/2})^{-1}$	12.2	11.3	2.3	0.5
	Total	12.2	11.4	3.5	0.5

¹This is clear that the different treatment of the *others* state changes the nominal $s_{1/2}$ strength by about 80% which produces the error of 5–10% level.

7.4 Secondary- γ Production

Uncertainties regarding the secondary nuclear interaction and subsequent γ -ray emission are considered. Contributions from the secondary γ -ray production are made mainly by neutrons (and some protons). In the previous analysis, the systematic error was estimated by replacing part of GCALOR with the NEUT γ -ray emission model (Ankowski et al. [49]) [51, 104]. The neutron energy boundary, where the neutron interaction changes from non-QE to QE (without and with a nucleon knock-out respectively), was assumed to be 30 MeV. However, the recent measurement, which is reported in Part III, shows that QE is not dominant even at 80 MeV. Accordingly it may be dangerous to place such a boundary at the moment.

In this analysis, only the number of emitted Cherenkov photons is focused to estimate the uncertainty about the secondary- γ production. First, the probability (P_{selected}) of an event being reconstructed in the 3.49–29.49 MeV energy region as a function of the number of emitted Cherenkov photons is calculated using the MC samples. Calculated probabilities for the FHC and RHC samples are shown in Figure 7.5. In both cases, events with Cherenkov photons between 1000 and 5000 are likely to be reconstructed in the selected region.



Figure 7.5: Probabilities of an event being reconstructed in the current analysis window of 3.49-29.49 MeV as a function of the number of Cherenkov photons ($N_{\rm C}$) in FHC and RHC.

The number of emitted Cherenkov photons $(N_{\rm C})$ is composed of mainly three parts:

$$N_{\rm C} \simeq N_{\rm C}^{\rm primary-\nu} + N_{\rm C}^{\rm secondary-n} + N_{\rm C}^{\rm secondary-p}.$$
(7.1)

Here $N_{\rm C}^{\rm primary-\nu}$ denotes contributions from the primary neutrino interaction while $N_{\rm C}^{\rm secondary-n}$ and $N_{\rm C}^{\rm secondary-p}$ are from the secondary neutron and proton reactions, respectively. The $N_{\rm C}^{\rm secondary-n}$ and $N_{\rm C}^{\rm secondary-p}$ are varied and the number of selected events are recalculated by using the probability distribution in Figure 7.5. The maximum fractional difference between the nominal and changed settings is taken as the systematic uncertainty. The variation size is described in what follows. The secondary- γ emission consists of two processes: the nucleon-¹⁶O reaction and the emission of nuclear de-excitation γ -rays. In Ref. [112], the proton-¹²C data is fit to obtain constraints on the nucleon-nucleus scattering. As a result of the fitting, a factor of 1.229 ± 0.075 is obtained for scaling the intra-nuclear cascade cross section. To cover the whole region of the original and corrected cross sections, Ref. [113] assigns a 30% error on the secondary interaction cross section. Because different nucleon and nucleus types are considered here, while the basic picture is expected to be similar and the effect of the target difference in the neutrino-nucleus interaction is measured to be less than 5% in Ref. [114], a conservative 40% error is assigned for the nucleon-¹⁶O reaction in this analysis.

In order to estimate the impact of γ -ray emission from fast neutron reactions on oxygen, a muon-induced spallation study in SK [115] is used. Since the selected sample therein should contain contributions from such neutron reactions, and the measured energy distribution does not differ by more than 50% from the MC prediction, this number is taken as the error estimate.

In total, a 65% (~ 40% \oplus 50%) error is used to change the number of Cherenkov photons made by secondary nuclear interactions, that is, factors of 1.65 or 0.35 are multiplied to $N_{\rm C}^{{\rm secondary}-n}$ and $N_{\rm C}^{{\rm secondary}-p}$. For further safety, the larger one of the two cases (±65%) is taken as the systematic error. The resulting errors are shown in Table 7.4. The error sizes are similar between FHC and RHC in NC while the error size in RHC is larger in CC. This is considered due to the fact that the antineutrino CC interaction is likely to involve a neutron in the final state. The larger uncertainty for the NC-other interaction than that for the NCQE interaction may be understood by that the NC-other interaction has more neutrons in the final state, for example, via pion production, and consequently the secondary- γ effect is larger.

It should be noted that the current method considers only Cherenkov photons, therefore the model dependence has been reduced from the previous analysis [51, 104]. The secondary- γ model remains the dominant uncertainty source in this analysis.

The final state interaction (FSI) of nucleons may affect the secondary γ -ray production. Thus, the FSI cross section is changed by 30% in NEUT following Refs. [113, 116]. This produces no more than a few % change to the selected number of events, so a 3.0% error is assigned conservatively to all the interaction types in both modes.

		ν -NCQE	$\bar{\nu}$ -NCQE	NC-other	CC
FHC	Secondary Cherenkov photons	13.2	13.1	19.3	17.3
	Nucleon FSI	3.0	3.0	3.0	3.0
	Total	13.5	13.4	19.5	17.6
	Secondary Cherenkov photons	13.3	12.8	19.1	21.2
RHC	Nucleon FSI	3.0	3.0	3.0	3.0
	Total	13.6	13.1	19.3	21.4

Table 7.4: Uncertainties on the observed event rate in percent for each sample component due to the systematic errors on secondary- γ emission model.

7.5 Oscillation Parameters

As described in Chapter 5, the event rate of the CC interaction is corrected for neutrino oscillations. Then the effect of uncertainties on the oscillation parameters, θ_{13} , θ_{23} , and Δm_{32}^2 , as summarized in Table 5.5, are considered. First, the two combinations which maximize and minimize the oscillation probability are taken as $(\sin^2 \theta_{13}, \sin^2 \theta_{23}, \Delta m_{32}^2) = (0.0219, 0.504, 2.543 \times 10^{-3} \text{ eV}^2)$ and $(0.0203, 0.568, 2.398 \times 10^{-3} \text{ eV}^2)$, respectively. These produce errors of +3.7/-1.6% for FHC and +2.9/-2.1% for RHC. Second, the assumption of the same cross sections for ν_{μ} and ν_e ($\bar{\nu}_{\mu}$ and $\bar{\nu}_e$) could produce an error. To estimate this error, the CC cross section ratio of ν_{μ} and ν_e ($\bar{\nu}_{\mu}$ and $\bar{\nu}_e$) is obtained at each energy bin and multiplied to each MC event. The change from the nominal setting is taken as the systematic error. Event increases by 1.7% and 1.1% are obtained for FHC and RHC, respectively. In general, the CC cross section of ν_e ($\bar{\nu}_e$) is higher than that of ν_{μ} ($\bar{\nu}_{\mu}$) especially in a lower energy region due to difference in the lepton mass. Totally 4.1% and 3.1% errors assigned for the CC event rate in FHC and RHC, respectively.

7.6 Detector Response

Errors of each reduction parameter and cut criterion may change the observed event rate. The estimation results are 3.4%, 3.4%, 2.0%, and 5.2% for ν -NCQE, $\bar{\nu}$ -NCQE, NC-other, and CC, respectively. Details of each item are explained below.

Energy

The error on the absolute scale of the reconstructed energy is evaluated to be 1.5% (Figure 7 in Ref. [117]) by the LINAC [90] and DT [91] calibrations. To estimate an uncertainty coming from the absolute error, $E_{\rm rec}$ is shifted by its error size, and a less than 1% change is seen in the selected number of events. The resolution error is also evaluated by the calibrations to be 1.6%. This does not produce any sizable error. In total, a 1% error is assigned.

Vertex position and direction

The vertex position precision is estimated to be 5 cm in Ref. [117]. This may affect the *dwall* cut. A 5 cm change in *dwall* does not produce a more than 1% error in every interaction mode. Since the effect of the position resolution error is considered to be negligible, a 1% uncertainty is assigned to the *dwall* cut.

As for the *effwall* case, not only position error but also direction error needs to be considered. Even a conservatively large error of the angular precision (3°) does not lead to an error of larger than 50 cm. A 50 cm change in *effwall* produces a less than 1% error in the final event number. Neither does resolution error arise a more than 1% error. Thus, 1% is used as the systematic uncertainty regarding the *effwall* cut.

Fit quality

Ref. [81] shows an estimation of the ovaQ error to be 1.5%. This causes a negligible size of error in the end. The effect of the ovaQ resolution error on the final result is also negligible.

Cherenkov opening angle

A 2° change of $\theta_{\rm C}$ is applied and the difference from the nominal is checked. This can cover both absolute and resolution error effects. As a result, a smaller than 0.5% change is seen for NCQE, while a 1% change for NC-other and a 4% change for CC are seen. This is reasonable because the CC events lie close to the CC interaction cut criteria in the $E_{\rm rec}-\theta_{\rm C}$ plane, as shown in Figures 6.3 and 6.4.

PMT gain shift

Over the T2K operation period (SK-IV), the SK PMT gain has been increasing continuously, as shown in Figure 7.6. This affects the effective number of hit PMTs, and accordingly changes the reconstructed energy. The size of such effect on the reconstructed energy is at most a few percent. Then, this effect is taken into account as the systematic error, with a change of $E_{\rm rec}$ by 5%. As a result, changes of 2% for ν -NCQE, 2% for $\bar{\nu}$ -NCQE, 0.5% for NC-other, and 3% for CC are found. The fact that a smaller change is seen in NC-other can be understood by that NC-other events distribute almost uniformly in energy while NCQE events locate mainly in a lower energy side where the PMT gain shift effect is more critical. As for the other reconstructed parameters such as vertex and Cherenkov opening angle, the gain shift effect is expected to be negligible.



Figure 7.6: SK PMT relative gain with respect to April 2009 as a function of time. Different colors correspond to the PMT types with different production periods. Clear gain shift is observed over the operation period in every PMT type.

Accidental coincidence events

The accidental events due to the cosmic-ray muons would potentially affect the selection. This effect is checked by the SK trigger rate and found to be negligible.

7.7 Summary of Systematic Uncertainties

Table 7.5 summarizes the systematic uncertainties as well as the event composition fraction of each interaction mode. The dominant errors come from the primary- and secondary- γ emission models. The total uncertainties on the NCQE signal are ~20% in both FHC and RHC.

Table 7.5: Summary of systematic uncertainties on the observed event rate in percent for the FHC and RHC sample components. The fraction of each component, listed as "Event fraction", is shown together in percent. For the beam-unrelated events, the total uncertainty entry represents the statistical uncertainty.

		ν -NCQE	$\bar{\nu}$ -NCQE	NC-other	CC	Beam-unrelated
	Event fraction	75.0	2.0	17.8	3.7	1.5
	Neutrino flux	6.7	8.6	7.3	6.4	-
	Neutrino interaction	3.0	3.0	8.2	16.5	-
FUC	Primary- γ production	11.0	10.6	6.0	6.6	-
FIIC	Secondary- γ production	13.5	13.4	19.5	17.6	-
	Oscillation parameter	-	-	-	4.1	-
	Detector response	3.4	3.4	2.0	5.2	-
	Total error	19.2	19.7	23.3	26.7	3.0
	Event fraction	19.0	59.9	16.5	2.5	2.1
	Neutrino flux	7.0	6.4	7.0	6.5	-
	Neutrino interaction	3.0	3.0	10.8	38.2	-
RHC	Primary- γ production	12.2	11.4	3.5	0.5	-
	Secondary- γ production	13.6	13.1	19.3	21.4	-
	Oscillation parameter	-	-	-	3.1	-
	Detector response	3.4	3.4	2.0	5.2	-
	Total error	20.1	19.0	23.4	44.7	3.9

Chapter 8

Cross Section Results

8.1 Cross Section Extraction

The number of observed events in the FHC and RHC samples $(D_{obs}^{FHC} \text{ and } D_{obs}^{RHC})$ are expressed as follows:

$$D_{\rm obs}^{\rm mode} = f_{\nu-\rm NCQE} M_{\nu-\rm NCQE}^{\rm mode} + f_{\bar{\nu}-\rm NCQE} M_{\bar{\nu}-\rm NCQE}^{\rm mode} + M_{\rm NC-other}^{\rm mode} + M_{\rm CC}^{\rm mode} + D_{\rm beam-unrelated}^{\rm mode}, \quad (8.1)$$

where mode = FHC or RHC, $M_{\nu\text{-NCQE}}^{\text{mode}}$ and $M_{\bar{\nu}\text{-NCQE}}^{\text{mode}}$ represent the number of neutrino and antineutrino NCQE interactions respectively, and $M_{\text{NC-other}}^{\text{mode}}$, $M_{\text{CC}}^{\text{mode}}$, and $D_{\text{beam-unrelated}}^{\text{mode}}$ are those of the NC-other interaction, the CC interaction, and the beam-unrelated events, respectively. Here quantities from data are written with a capital D, while those from MC with a capital M. The factors $f_{\nu\text{-NCQE}}$ and $f_{\bar{\nu}\text{-NCQE}}$ are the measured quantities and serve to scale the NCQE cross section predictions. The number of events by neutrino and antineutrino interactions are calculated as below:

$$M_{\nu-\text{NCQE}}^{\text{mode}} = \sum_{\nu=\nu_{\mu},\nu_{e}} \int \sigma_{\nu-\text{NCQE}}^{\text{NEUT}}(E_{\nu}) \phi_{\nu}^{\text{mode}}(E_{\nu}) \epsilon_{\nu-\text{NCQE}}^{\text{mode}}(E_{\nu}) T dE_{\nu}, \qquad (8.2)$$

$$M_{\bar{\nu}\text{-NCQE}}^{\text{mode}} = \sum_{\nu=\bar{\nu}_{\mu},\bar{\nu}_{e}} \int \sigma_{\bar{\nu}\text{-NCQE}}^{\text{NEUT}}(E_{\nu}) \phi_{\nu}^{\text{mode}}(E_{\nu}) \epsilon_{\nu\text{-NCQE}}^{\text{mode}}(E_{\nu}) T dE_{\nu}, \qquad (8.3)$$

$$M_{\text{NC-other}}^{\text{mode}} = \sum_{\nu=\nu_{\mu},\nu_{e},\bar{\nu}_{\mu},\bar{\nu}_{e}} \int \sigma_{\nu-\text{NC-other}}^{\text{NEUT}}(E_{\nu})\phi_{\nu}^{\text{mode}}(E_{\nu})\epsilon_{\nu-\text{NC-other}}^{\text{mode}}(E_{\nu})TdE_{\nu}, \quad (8.4)$$

$$M_{\rm CC}^{\rm mode} = \sum_{\nu=\nu_{\mu},\nu_{e},\bar{\nu}_{\mu},\bar{\nu}_{e}} \int \sigma_{\nu-\rm CC}^{\rm NEUT}(E_{\nu})\phi_{\nu}^{\rm mode}(E_{\nu})\epsilon_{\nu-\rm CC}^{\rm mode}(E_{\nu})TdE_{\nu}.$$
(8.5)

Here σ^{NEUT} expresses the NEUT cross section, ϕ is the flux, ϵ is the selection efficiency, T is the number of target nucleons, and E_{ν} is the neutrino energy. From Equation 8.1, the relations below are obtained for each operation mode:

$$D_{\rm obs}^{\rm FHC} - M_{\rm NC-other}^{\rm FHC} - M_{\rm CC}^{\rm FHC} - D_{\rm beam-unrelated}^{\rm FHC} = f_{\nu-\rm NCQE} M_{\nu-\rm NCQE}^{\rm FHC} + f_{\bar{\nu}-\rm NCQE} M_{\bar{\nu}-\rm NCQE}^{\rm FHC}, (8.6)$$
$$D_{\rm obs}^{\rm RHC} - M_{\rm NC-other}^{\rm RHC} - M_{\rm CC}^{\rm RHC} - D_{\rm beam-unrelated}^{\rm RHC} = f_{\nu-\rm NCQE} M_{\nu-\rm NCQE}^{\rm RHC} + f_{\bar{\nu}-\rm NCQE} M_{\bar{\nu}-\rm NCQE}^{\rm RHC}. (8.7)$$

By transforming these, $f_{\nu-\text{NCQE}}$ and $f_{\bar{\nu}-\text{NCQE}}$ can be written as below:

$$f_{\nu-\text{NCQE}} = \frac{XM_{\bar{\nu}-\text{NCQE}}^{\text{RHC}} - YM_{\bar{\nu}-\text{NCQE}}^{\text{FHC}}}{M_{\nu-\text{NCQE}}^{\text{FHC}}M_{\bar{\nu}-\text{NCQE}}^{\text{RHC}} - M_{\nu-\text{NCQE}}^{\text{RHC}}M_{\bar{\nu}-\text{NCQE}}^{\text{FHC}}},$$
(8.8)

$$f_{\bar{\nu}\text{-NCQE}} = \frac{XM_{\nu\text{-NCQE}}^{\text{RHC}} - YM_{\nu\text{-NCQE}}^{\text{FHC}}}{M_{\bar{\nu}\text{-NCQE}}^{\text{FHC}}M_{\nu\text{-NCQE}}^{\text{RHC}} - M_{\bar{\nu}\text{-NCQE}}^{\text{RHC}}M_{\nu\text{-NCQE}}^{\text{FHC}}},$$
(8.9)

$$X = D_{\rm obs}^{\rm FHC} - M_{\rm NC-other}^{\rm FHC} - M_{\rm CC}^{\rm FHC} - D_{\rm beam-unrelated}^{\rm FHC}, \qquad (8.10)$$

$$Y = D_{\rm obs}^{\rm RHC} - M_{\rm NC-other}^{\rm RHC} - M_{\rm CC}^{\rm RHC} - D_{\rm beam-unrelated}^{\rm RHC}.$$
 (8.11)

Based on the number of the observed events, 204 in FHC and 97 in RHC, the scale factors are calculated to be $f_{\nu-\text{NCQE}} = 0.80$ and $f_{\bar{\nu}-\text{NCQE}} = 1.11$. Errors of these factors are evaluated by pseudo experiments generated according to random variations of the statistical and systematic uncertainties described in Chapter 7. Here statistical uncertainties are considered for $D_{\rm obs}^{\rm mode}$ (the effect of the statistical uncertainty for $D_{\text{beam-unrelated}}^{\text{mode}}$ is negligible), and systematic uncer-tainties are considered for $M_{\nu-\text{NCQE}}^{\text{mode}}$, $M_{\overline{\nu}-\text{NCQE}}^{\text{mode}}$, $M_{\text{NC-other}}^{\text{mode}}$, and $M_{\text{CC}}^{\text{mode}}$. The pseudo experiments are generated assuming Gaussian distributed errors, with means and variations as shown in Tables 6.3, 6.4, and 7.5. All the errors are uncorrelated except for the primary- and secondary- γ uncertainties ¹. The primary- γ production error is considered to be fully correlated among different interaction types and operation modes. The secondary- γ production error is treated in the same way. This is because the changes in γ -ray production rates are common for all the neutrino interaction types and T2K operation modes. Note that the primary- γ and secondary- γ production uncertainties are uncorrelated. Distributions of the calculated scale factors for one million pseudo experiments are shown in Figures 8.1 and 8.2, for the statistical and systematic variation cases, respectively. The dominant error is the uncertainty of the secondary- γ emission model. The scale factors have a weak negative correlation for variations of the statistical uncertainties but a strong positive correlation under the influence of the systematic uncertainties. In the end, the scale factors are measured as follows:

$$f_{\nu-\text{NCQE}} = 0.80 \pm 0.08 (\text{stat.})^{+0.24}_{-0.18} (\text{syst.}),$$
 (8.12)

$$f_{\bar{\nu}\text{-NCQE}} = 1.11 \pm 0.18 (\text{stat.})^{+0.29}_{-0.22} (\text{syst.}).$$
 (8.13)

¹Correlations from the flux and cross section parameters have a negligible impact on the final result and have therefore been omitted here.



Figure 8.1: Results of the pseudo experiments on the scale factors when the numbers of the observed events are varied based on the statistical uncertainties: $f_{\nu-\text{NCQE}} = 0.80 \pm 0.08$ and $f_{\bar{\nu}-\text{NCQE}} = 1.11 \pm 0.18$.



Figure 8.2: Results of the pseudo experiments on the scale factors when the numbers of the predicted events are varied based on the systematic uncertainties: $f_{\nu-\text{NCQE}} = 0.80^{+0.24}_{-0.18}$ and $f_{\bar{\nu}-\text{NCQE}} = 1.11^{+0.29}_{-0.22}$. The dominant uncertainty source is the secondary- γ emission model.

8.2 Flux-averaged NCQE-like Cross Sections

The predictions of the flux-averaged cross sections by NEUT for the neutrino and antineutrino NCQE interactions ($\langle \sigma_{\nu-\text{NCQE}}^{\text{NEUT}} \rangle$ and $\langle \sigma_{\overline{\nu}-\text{NCQE}}^{\text{NEUT}} \rangle$) are calculated as below:

$$\langle \sigma_{\nu\text{-NCQE}}^{\text{NEUT}} \rangle = \frac{\sum_{\nu=\nu_{\mu},\nu_{e}} \int \sigma_{\nu\text{-NCQE}}^{\text{NEUT}}(E_{\nu})\phi_{\nu}(E_{\nu})dE_{\nu}}{\sum_{\nu=\nu_{\mu},\nu_{e}} \int \phi_{\nu}(E_{\nu})dE_{\nu}} = 2.13 \times 10^{-38} \text{ cm}^{2}/\text{oxygen}, \quad (8.14)$$

$$\langle \sigma_{\bar{\nu}\text{-NCQE}}^{\text{NEUT}} \rangle = \frac{\sum_{\nu = \bar{\nu}_{\mu}, \bar{\nu}_{e}} \int \sigma_{\bar{\nu}\text{-NCQE}}^{\text{NEUT}}(E_{\nu}) \phi_{\nu}(E_{\nu}) dE_{\nu}}{\sum_{\nu = \bar{\nu}_{\mu}, \bar{\nu}_{e}} \int \phi_{\nu}(E_{\nu}) dE_{\nu}} = 0.88 \times 10^{-38} \text{ cm}^{2}/\text{oxygen.} \quad (8.15)$$

The nominal fluxes, $\phi_{\nu} = \phi_{\nu}^{\text{FHC}}$ and $\phi_{\bar{\nu}} = \phi_{\bar{\nu}}^{\text{RHC}}$, are used for neutrinos and antineutrinos in the calculations above. Note that summation over muon and electron (anti)neutrinos means for the unoscillated fluxes in Figure 5.1, while the actual flux contains tau (anti)neutrinos which appear due to the neutrino oscillation. This treatment is justified because the NCQE interaction is flavor-independent. Here the integrations are conducted up to 10 GeV and the effect from the region above is negligible. The observed flux-averaged NCQE-like cross sections are obtained by multiplying the scale factors to each of the NEUT cross sections:

$$\langle \sigma_{\nu\text{-NCQE}} \rangle = f_{\nu\text{-NCQE}} \cdot \langle \sigma_{\nu\text{-NCQE}}^{\text{NEUT}} \rangle = 1.70 \pm 0.17 (\text{stat.})^{+0.51}_{-0.38} (\text{syst.}) \times 10^{-38} \text{ cm}^2/\text{oxygen},$$
(8.16)

$$\langle \sigma_{\bar{\nu}\text{-NCQE}} \rangle = f_{\bar{\nu}\text{-NCQE}} \cdot \langle \sigma_{\bar{\nu}\text{-NCQE}}^{\text{NEUT}} \rangle = 0.98 \pm 0.16 (\text{stat.})^{+0.26}_{-0.19} (\text{syst.}) \times 10^{-38} \text{ cm}^2 / \text{oxygen.}$$

$$(8.17)$$

The measured NCQE-like cross sections are shown together with the predictions on NCQE from NEUT in Figure 8.3. The measurement on neutrinos improves over the previous result with the FHC Run 1–3 data, $\langle \sigma_{\nu\text{-NCQE}} \rangle = 1.55^{+0.71}_{-0.35}(\text{stat.} \oplus \text{syst.}) \times 10^{-38} \text{ cm}^2/\text{oxygen}$ [51]. The result on antineutrinos is the first measurement of this channel to date. Covariance matrices of the neutrino and antineutrino NCQE-like cross sections are calculated for both variations of the statistical and systematic uncertainties as shown in Table 8.1.

Table 8.1: Covariance of the neutrino and antineutrino cross sections for the statistical (systematic) error case. The unit of numbers is $(10^{-38} \text{ cm}^2/\text{oxygen})^2$.

	$\sigma_{ u\text{-NCQE}}$	$\sigma_{ar{ u} ext{-NCQE}}$
$\sigma_{\nu-\mathrm{NCQE}}$	$0.030 \ (0.227)$	$-0.005\ (0.095)$
$\sigma_{\bar{\nu}\text{-NCQE}}$	-0.005 (0.095)	$0.025\ (0.058)$



Figure 8.3: The measured neutrino- (left) and antineutrino- (right) oxygen NCQE-like cross sections in comparison with the NCQE cross sections predicted by NEUT. The points are placed at the flux mean values, 0.82 GeV for neutrinos and 0.68 GeV for antineutrinos, respectively. The vertical bars represent the statistical errors (shorter) and the quadratic sums of the statistical and systematic errors (longer). The horizontal bars represent the upper and lower 1σ ranges of the fluxes. The T2K fluxes for each neutrino beam mode are also shown together in an arbitrary normalization.

8.3 Discussion

8.3.1 NC 2p2h Interactions

Currently, there are no theoretical models nor experimental results available in the literature about the NC 2p2h interaction, so this channel is not simulated in this analysis. Since the NC 2p2h interaction involves the multi-nucleon knock-out, not only multiple γ -rays but also the secondary γ -rays from the recoil nucleons are expected. Therefore, if this process exists then the selection in this analysis likely to include such events. However, if the ratio of NC 2p2h to NCQE cross sections is similar to the corresponding CC ratio, roughly 5–10% [103], the present measurement is not sensitive to these events.

8.3.2 Comparison with Theoretical Models

The measured NCQE-like cross sections are tied to NEUT as the underlying model about signal and background, but it is interesting to compare these results with other theoretical predictions. Five models from Ref. [118] are referred in comparison.

- Spectral Function (SF) [100, 101]: The SF describes a distribution of the momentum and removal energy of nucleons inside the nucleus, which provides a different initial momentum distribution of nucleons from the relativistic Fermi gas model [102].
- Relativistic Mean Field (RMF) [119–122]: The RMF makes use of the relativistic distorted waves to describe the knocked-out particle.

- Superscaling (SuSA) [123, 124]: In the SuSA approach, the measured electron-nucleus cross sections are used to predict the neutrino-nucleus cross sections.
- Relativistic Green's Function (RGF) [122,125–127]: In this approach, the final state interactions are included using the relativistic Green's function and a complex optical potential. Here two parametrizations, EDAI and "democratic", are considered for the optical potential.
- Relativistic Plane Wave Impulse Approximation (RPWIA) [122]: In the RPWIA, the final state interactions between nucleons is neglected and the knocked-out particle is described by the relativistic plane wave.

The predictions of these models are shown in Figure 8.4. Due to difference in the available energy range of the calculation values, the cross sections of some models are not shown in the full range. The flux-averaged cross sections are calculated using each model prediction, and the results are shown in Figure 8.5, together with the measurement results. Here the integration ranges are different following the cross section available range of each model but this effect is expected to be small since all the models are calculated up to at least 2 GeV where the T2K flux gets attenuated enough. The measured result on neutrinos is consistent with all of the models within the 1σ error, but the SF, RMF, and SuSA models lie outside the 1σ region for antineutrinos. However, it should be noted that each model has its uncertainties and none of these models contains the NC 2p2h process.



Figure 8.4: Neutrino (left) and antineutrino (right) NCQE cross sections on all nucleons in oxygen as a function of neutrino energy for six theoretical predictions.



Figure 8.5: Comparison of the flux-averaged NCQE-like cross sections by T2K and the fluxaveraged NCQE cross sections by various models for neutrinos (left) and antineutrinos (right). Solid line and transparent area represent the measured mean values and their 1σ uncertainties including both statistical and systematic ones, respectively.

8.3.3 Impact on Supernova Relic Neutrino Searches

The present work can be used to estimate the NCQE-like background by atmospheric neutrinos in the SRN search, which is the main motivation of this thesis. The cross section results can be used directly, as is demonstrated in Part IV. However, this suffers from large uncertainties from the neutron multiplicity and γ -ray emissions that affect the Cherenkov angle distribution, as described in Chapter 12. If instead the number of events in the expected SRN signal region is used, most errors can be avoided. In the following, the current analysis samples are projected onto the 2D $E_{\rm rec} - \theta_{\rm C}$ plane, which is used in the SK SRN search. This is divided into four regions: (1) $E_{\rm rec} \in [3.49, 7.49]$ MeV and $\theta_{\rm C} \in [38, 50]$ degrees, (2) $E_{\rm rec} \in [7.49, 29.49]$ MeV and $\theta_{\rm C} \in [38, 50]$ degrees (3) $E_{\rm rec} \in [3.49, 7.49]$ MeV and $\theta_{\rm C} \in [78, 90]$ degrees, and (4) $E_{\rm rec} \in [7.49, 29.49]$ MeV and $\theta_{\rm C} \in [78, 90]$ degrees. The signal window of the SK SRN analysis corresponds to region 2. Figure 8.6 gives the $E_{\rm rec} - \theta_{\rm C}$ distributions from the FHC and RHC samples before the CC interaction cut and after all of the preceding cuts. Table 8.2 summarizes the numbers of observed and predicted events in each region calculated from Figure 8.6. The difference between the observation and prediction in regions 3 and 4 in the FHC sample may be attributed to the inaccurate modeling of the secondary- γ emission as explained in Chapter 6. The $E_{\rm rec}$ distributions for $\theta_{\rm C} \in [38, 50]$ degrees and $\theta_{\rm C} \in [78, 90]$ degrees for the FHC and RHC samples are shown in the top four panels of Figure 8.7. Similarly, the $\theta_{\rm C}$ distributions for $E_{\rm rec} \in [3.49, 7.49]$ MeV and $E_{\rm rec} \in [7.49, 29.49]$ MeV are shown in the bottom four panels of the same figure. Here also the FHC distributions from observation and prediction show discrepancies, which may be attributed to the modeling of the secondary- γ emission. These distributions can be used to estimate the NCQE-like background to the SRN search by suitable weighting of the prediction to observation. This is more realistic with much larger statistics realized in Hyper-Kamiokande and with high power beams in the upgraded J-PARC, which could provide the NCQE-like background estimation better than a 10% precision as is explained later.



Figure 8.6: Two-dimensional $E_{\rm rec} - \theta_{\rm C}$ distributions for FHC (left) and RHC (right) respectively before the CC interaction cut and after all of the preceding cuts described in Chapter 6. Magenta dots correspond to the observed data.

FHC	Region 1	Region 2	Region 3	Region 4
Observation	47	16	18	40
Prediction (total)	41.1	20.4	30.8	73.8
ν -NCQE	34.8	10.7	24.4	49.6
$\bar{\nu}$ -NCQE	1.1	0.3	0.6	1.3
NC-other	3.4	5.7	4.6	19.3
CC	0.8	3.6	0.7	3.6
Beam-unrelated	1.0	0.1	0.5	0.0
RHC	Region 1	Region 2	Region 3	Region 4
Observation	19	12	14	21
Prediction (total)	18.6	7.3	11.9	27.0
ν -NCQE	3.2	1.1	2.2	5.7
$\bar{\nu}$ -NCQE	13.4	3.4	7.5	13.1
NC-other	1.2	2.1	1.7	7.2
CC	0.1	0.7	0.2	1.0

Table 8.2: Numbers of observed and predicted events for each region defined in the text.



Figure 8.7: The $E_{\rm rec}$ distributions for $\theta_{\rm C} \in [38, 50]$ degrees and $\theta_{\rm C} \in [78, 90]$ degrees (top four) and the $\theta_{\rm C}$ distributions for $E_{\rm rec} \in [3.49, 7.49]$ MeV and $E_{\rm rec} \in [7.49, 29.49]$ MeV (bottom four). All are before the CC interaction cut and after all of the preceding cuts described in Chapter 6.

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8.4 Future Prospects

Secondary- γ emission model

The current largest error source is the modeling of the secondary γ -ray emission. This could be improved by incorporating experimental data on γ -rays from the neutron-oxygen reactions, which is described in Part III. As is explained in the next chapter, the experiment using an 80 MeV neutron beam achieved a 20% precision on the γ -ray production cross section. If enough data points with similar sized errors are accumulated at different neutron energies, the secondary γ -ray uncertainty in the NCQE-like measurement can be reduced to less than 5%.

SK-Gd

SK has an upgrade plan to SK-Gd, which dissolves gadolinium-sulfate $(Gd_2(SO_4)_3)$ to enhance the sensitivity to the neutron signal [128] utilizing the large neutron capture cross section of gadolinium (49.7 kb)². Figure 8.8 shows neutron capture efficiencies as a function of the Gd doping rate in SK. With a 0.2% doping of $Gd_2(SO_4)_3$ (corresponding to a 0.1% doping of Gd), a ~90% capture efficiency is achieved. Since the Gd emits a few γ -rays whose energy sum is ~8 MeV (7.9 MeV with 80.5% and 8.5 MeV with 19.3% as branching fractions), the detection efficiency is almost 100%, resulting in the 90% neutron tagging efficiency at a 0.1% Gd doping.



Figure 8.8: Neutron capture efficiency as a function of Gd doping rate in SK.

There are many possible studies about the NCQE sample using neutron information. This would help to study the relationship of neutrons, their transport in water, and the secondary- γ production. Information on the neutron capture vertex would further constrain the kinetic

²The neutron capture cross section of hydrogen is 0.33 b and that of oxygen is 0.19 mb.

energy of neutrons from the NCQE interactions, by measuring the neutron flight length from the primary interaction vertex. Neutron information would also allow for the differential cross section measurement by reconstructing Q^2 as well as the Δs measurement if the proton and neutron in the final state are discriminated. Finally, it may be possible to identify the NCQE interaction resulting in the ground state by requiring no activity by the primary γ -ray. This would reduce uncertainties on the initial state of nucleons inside the nucleus, which could improve the sensitivity of searches for proton decay via $p \to \nu K^+$ [129].

Hyper-Kamiokande

Hyper-Kamiokande (HK) is a successor of SK with a fiducial volume of ~190 kton (~8.4 times larger than SK) [130,131], as schematically illustrated in Figure 8.9. In HK, the photosensor is expected to improve much over the SK one, then the higher neutron tagging efficiency (~40%) is expected. In the era of HK, J-PARC will be upgraded to serve a 1.3 MW proton beam (from the current 500 kW) as well as the magnetic horn current will increase to 320 kA (from the current 250 kA) [76], yielding a ~3 times more intense neutrino beam. HK is planned to be constructed at 2.5° off-axis with respect to the J-PARC proton beam direction.



Figure 8.9: Schematic illustration of the Hyper-Kamiokande detector.

Since the off-axis angle is the same, a measurement similar to the current work but with ~ 25 times higher statistics is possible. With this condition, $\gtrsim 100$ times larger data sets both on the FHC and RHC samples are obtained after the 5-year operation, which provides about 1000 events with the neutron tagging in the SRN signal region (region 2 in the previous section). In the SRN background estimation, as described in Chapter 12, the atmospheric neutrino flux uncertainty needs to be considered, which is currently about 15%. This will be improved by a new hadron interaction experiment (EMPHATIC) [132] down to as large as 5%. In the end, the NCQE-like background would be estimated with a $\sim 10\%$ accuracy. In addition, the neutron kinematics after the NCQE interaction can be investigated with high statistics.

Part III

Studies towards Improvements of γ -ray Emission Model

Chapter 9

RCNP-E487 Experiment

9.1 Experimental Motivation and Overview

As described in Part II, in addition to γ -rays produced from the neutrino-oxygen interaction, γ -rays are emitted from the reactions by nucleons, mostly neutrons, knocked-out by the NCQE interaction. Since the emission of these secondary γ -rays is isolated from the primary γ -ray emission due to the neutrino interaction by only less than O(100) ns, the primary- and secondary- γ 's are reconstructed in the same event in SK. In the previous analysis, the uncertainty on the secondary- γ emission rate was estimated by comparing two models, GCALOR [85,86] and the γ emission model in NEUT [49]. In the estimation, the boundary between inelastic interactions without nucleon knock-out and quasielastic nucleon knock-out interactions by neutrons was set to 30 MeV in the neutron energy. The GCALOR was replaced with the latter model for neutrons with energies above 30 MeV, and variance was taken as a systematic error; however, setting such boundary is highly model-dependent. This has been improved in the present work, as explained in Chapter 7, but there still remains a large uncertainty about the secondary- γ model. Within GCALOR, the ENDF/B-V library [133] is used for simulating neutron reactions below 20 MeV and an intra-nuclear cascade model is used for energies above 20 MeV. The latest update in the ENDF/B library, ENDF/B-VIII, includes new data from experiments, but data on neutron reactions above 20 MeV is limited. The intra-nuclear cascade model is considered to be insufficient for energies between 20 and 200 MeV, while it describes interactions above 200 MeV well [134, 135]. Furthermore, there is little data on the γ -ray production from neutron-oxygen reactions. Therefore, providing experimental data on γ -ray production via neutron reactions on oxygen is beneficial for the study of neutrino-oxygen NCQE interactions.

Basic concept of the experiment is to measure the γ -rays emitted from neutron reactions on oxygen using neutron beams, a water target, and γ -ray detectors. Since data especially above neutron energy of 20 MeV is insufficient and the neutron energy from the NCQE interaction ranges up to several hundred MeV as shown in Figure 6.14, three energies (30, 80, and 250 MeV) were selected as the experimental points. The experiments are conducted at Osaka University's Research Center for Nuclear Physics (RCNP) [136–138] in Japan. The experiment with an 80 MeV beam is numbered as "E487" and that with 30 and 250 MeV beams as "E525" at RCNP. In this thesis, results from the E487 experiment are presented ¹.

¹Data taking of the E525 experiment was finished, and the analysis is now on-going.

9.2 Experimental Setup

The experiment was conducted in a 100 m long neutron beamline. A schematic drawing of the neutron beamline and the experimental setup is shown in Figure 9.1. Protons were accelerated to a kinetic energy of 80 MeV by two cyclotrons, the K140 AVF cyclotron and the K400 ring cyclotron. The proton beam was then injected onto a 10 mm thick lithium target, which is a compound of 92.5% ^{nat}Li and 7.5% ⁶Li, producing a neutron beam via the $^{7}\text{Li}(p, n)^{7}\text{Be}$ reaction. The proton beam size perpendicular to the beam direction was tuned to be smaller than the lithium target size then almost all the protons hit on the target. During the beam test, the energy of protons was kept to be 80 ± 0.6 MeV. The proton beam was accelerated in 200 ps wide bunches, each being separated by 62.5 ns, and a chopper was set to pass one in nine bunches to the lithium target. The beam current was tuned to be between a few and ~ 100 nA after the chopper. At downstream of the lithium target, a magnetic field bends charged particles, which are produced from the proton-lithium reactions, towards a beam dump. The beams are then composed almost only of neutral particles, which are neutrons and photons at the current energy. A Faraday cup was placed at the beam dump and measured the proton beam current throughout the beam time. A few particles that are not fully bent are stopped by an iron and concrete collimator which is placed 4.5 m away from the target. The depth of the collimator is 1.5 m and its aperture is 10×12 cm².



Figure 9.1: Schematic drawing of the RCNP facility and its neutron beamline. The dotted magenta box represents a magnified experimental setup.

A cylindrical acrylic vessel, which is 20.0 cm in diameter and 26.5 cm in height, was placed on the beam axis as a target. This container is 0.5 cm thick along its barrel and 1.0 cm thick at its ends. Measurements were performed in both water-filled and empty conditions.

A Saint-Gobain B380 lanthanum bromide scintillator (LaBr₃(Ce)) was used to detect γ rays. The crystal is cylindrical shape with 4.5 cm diameter and length. The LaBr₃(Ce) was optically coupled to a Hamamatsu H6410 photomultiplier tube (PMT). The charge and time data were read out by a VME 12-bit CAEN V792N QDC and a VME 12-bit CAEN V775N TDC, respectively. The scintillator was placed upstream of the acrylic container to reduce backgrounds from the neutrons that are scattered off materials, and shielded with lead bricks on all sides except for the surface facing the acrylic target to lower backgrounds from the irradiated surrounding materials. Another γ -ray detector, an ORTEC GEM 20180-P highpurity germanium (HPGe) detector, was placed in a similar position to the LaBr₃(Ce) detector. The detector uses a cylindrical coaxial crystal with a 55 mm (44 mm) in diameter (length) with a hole diameter (depth) of 9.2 mm (33.4 mm). The pulse height data from the HPGe detector was read out by an MCA Kromek K102. No time data was recorded, hence, the HPGe was used as a reference detector with a better energy resolution. The HPGe detector was covered with lead bricks similarly to the LaBr₃(Ce) detector. A photograph of the setup for the γ -ray measurement is given in Figure 9.2.



Figure 9.2: Photograph of the setup for the γ -ray and fast neutron background measurements with a water-filled target.



Figure 9.3: Photograph of the setup for the neutron flux measurement.

Apart from the γ -ray measurements, dedicated measurements of the neutron beam and the background arising from fast neutrons were conducted. For the neutron beam measurement, the acrylic target was replaced by an organic liquid scintillator, Saint-Gobain BC-501A 20LA32, with coupled to a Hamamatsu H6527 PMT. The scintillator is a 5 inch diameter and a 8 inch long cylindrical shape and was read out by the same QDC and TDC as the LaBr₃(Ce) detector. The setup photograph is shown in Figure 9.3. Backgrounds at the LaBr₃(Ce) position from fast neutron hits were measured by an OKEN CsI(Tl) scintillator. The CsI(Tl) is cubic with a size of $3.5 \times 3.5 \times 3.5 \times 3.5 \text{ cm}^3$ and was coupled to a H6410 PMT. It was placed near the LaBr₃(Ce) and covered with the lead bricks similarly. The waveform data were recorded by a 14-bit 250 MHz CAEN DT5725 digitizer. Scattered neutron measurements were performed in parallel to the main measurements with both water-filled and empty configurations, as shown in Figure 9.2.

In all measurements, the proton beam current was monitored by the Faraday cup and used for the normalization in the analysis.

9.3 Detector Calibration

Energy calibrations of the LaBr₃(Ce), HPGe, and CsI(Tl) detectors were conducted using the photoelectric-absorption peaks of the γ -rays from several isotopes: ¹³⁷Cs, ⁶⁰Co, ²⁴¹Am/Be, ⁵⁷Fe, and so on. These cover the energy range up to 8 MeV. The energy spectra taken with the LaBr₃(Ce) are shown in Figure 9.4. The detector gains were monitored throughout the beam time and no significant variations were observed.



Figure 9.4: The LaBr₃(Ce) energy spectra in QDC channel with various radioactive sources: 0.662 MeV from ¹³⁷Cs, 1.17 and 1.33 MeV from ⁶⁰Co, 1.46 MeV from ⁴⁰K, 2.22 MeV from ²H, 2.61 MeV from ²⁰⁸Tl, 4.44 MeV from ¹²C, and 7.65 MeV from ⁵⁷Fe. The S.E. and D.E. represent the single and double escape peaks of the corresponding photoelectric-absorption peak, respectively. Different colors correspond to different measurements.

For the BC-501A energy calibration, recoil electrons from Compton-scattered γ -rays by a ²²Na source were used. The Compton-scattered γ -rays were tagged by the LaBr₃(Ce) detector with different geometrical settings, which allows for selection of the energy of recoil electrons depending on the angles made by the BC-501A and LaBr₃(Ce) detectors and the ²²Na source. The largest error on the energy scale comes from the geometrical uncertainty, but this results in less than a 0.1% systematic uncertainty in the neutron flux measurement as described in the next section.

In order to identify neutron events separately from γ -rays in the BC-501A and CsI(Tl) detectors, pulse shape information is utilized. Separation capability in the BC-501A was checked by an ²⁴¹Am/Be neutron source. As for the CsI(Tl) detector, the separation performance was tested with a 70 MeV fast neutron beam at Tohoku University's Cyclotron and Radioisotope Center [139].

9.4 Neutron Beam

In order to measure the γ -ray production cross section, a measurement of the neutron flux is necessary. In the analysis, first, neutron-like events are selected using the pulse shape discrimination (PSD) technique in the BC-501A detector. Second, the kinetic energies of neutron-like events are inferred from their time-of-flight (TOF) between the lithium target and the detector. Third, the kinetic energy distribution is converted into the flux by applying the neutron detection efficiency calculated using the Monte Carlo code, SCINFUL-QMD [140,141]. The neutron beam profile was also estimated with data from similar measurements at different positions.

9.4.1 PSD and TOF Analyses

For events whose energy is within the QDC dynamic range, a PSD parameter is defined as:

$$PSD \text{ parameter} = \frac{Q_{\text{tail}} - Q_{\text{ped}}}{Q_{\text{total}} - Q_{\text{ped}}},\tag{9.1}$$

where Q_{tail} is the integrated charge of the waveform for a pre-determined late-time window and Q_{total} is the charge of the entire waveform. The PSD parameter is larger for particles having larger dE/dx, such as protons excited by neutrons, in the BC-501A [142]. The Q_{ped} represents an offset of the QDC module, which differs channel to channel. The late-time window was optimized by calibration data with neutrons from an ²⁴¹Am/Be source. The PSD parameter larger and smaller than 0.24 are treated as neutrons and γ -rays, respectively. The neutron inefficiency by this selection was checked to be negligible by an ²⁴¹Am/Be calibration. Protons and heavier particles, such as deuterons and alphas, induced by neutron reactions in the scintillator, are observed in the large PSD parameter region. Figure 9.6 shows distributions of the deposited energy in the BC-501A broken down by the neutron-like and γ -like events after PSD. Events with energy beyond the QDC dynamic range (~4000 ch corresponding to ~6.5 MeV) are selected as neutrons from γ -rays in this energy region is small.

The TOF distributions of neutron-like and γ -like events are reconstructed using TDC data. Time-walk corrections are applied for both neutron-like and γ -like events separately when the events are within the QDC dynamic range. A common correction is applied at high energies above the dynamic range, where this effect is expected to be small. Figure 9.7 shows TOF



Figure 9.5: PSD parameter as a function of Q_{total} value in QDC channel. The blue line represents the neutron selection criterion.



Figure 9.6: Deposited energy in QDC channel in the BC-501A detector for all (black), neutronlike (blue), and γ -like (red) events.

distributions for the neutron-like and γ -like events after the time-walk corrections. The sharp peak around 3350 ch corresponds to γ -rays emitted from the initial proton-lithium interaction (called the flash γ -rays). The small amount of neutron-like contamination in the flash- γ peak indicates that PSD is effective. Neutron kinetic energies are reconstructed using their time difference to the flash γ -ray peak and the distance between the lithium target and the BC-501A. The result of the kinetic energy reconstruction is shown in Figure 9.8. The peak is seen at 77 MeV and is consistent with the expectation from the beam setting.



Figure 9.7: TOF distributions of all (black), neutron-like (blue), and γ -like (red) events classified by PSD. The sharp peak around 3350 ch is due to the flash γ -rays.

9.4.2 Detection Efficiency

The neutron detection efficiency of the BC-501A scintillator was calculated with a dedicated Monte Carlo code, SCINFUL-QMD [140,141], for each neutron energy bin. In the simulation, geometry, the energy threshold, the light attenuation inside the detector, and the PMT response are set. The first four are taken from the geometrical survey, calibration data, and the previous study with the same detector [143]. The PMT response is based on models in Refs. [144–146]. In the simulation 100,000 neutrons are generated in each of one hundred energies spanning from 0.1 MeV to 99 MeV, with a 1 MeV binning above 1 MeV. Figure 9.9 shows the estimated neutron detection efficiencies with the nominal setting.

9.4.3 Neutron Flux Estimation

The neutron flux is obtained from the kinetic energy distribution divided by the detection efficiency, as shown in Figure 9.10. The distribution is normalized by the detector solid angle from the lithium target and the incident protons. The neutron flux in the peak region between 72 and 82 MeV is $1.71 \times 10^{10} \, [/sr/\mu C]$. This region is used for the cross section analysis later.



Figure 9.8: Kinetic energy distribution of the neutron-like events reconstructed from the TOF distribution.



Figure 9.9: Neutron detection efficiencies of the BC-501A calculated with SCINFUL-QMD. The attenuation factor of 0.008 cm^{-1} from the previous study [143] and the PMT light output function from Satoh et al. [144] are used. The bump around 20 MeV is due to an open of new reaction channels by carbon.



Figure 9.10: Neutron flux normalized by the detector covering solid angle and the incident protons. The red bars indicate the peak region (72-82 MeV) used for the cross section analysis.

9.4.4 Flux Uncertainties

Table 9.1 summarizes the statistical and systematic uncertainties on the neutron flux in the 72-82 MeV region. The statistical uncertainty is less than 0.5%. Systematic uncertainties are described in the following part.

Table 9.1: Statistical and systematic uncertainties on the neutron flux in the energy region of 72-82 MeV.

Error source	Size [%]
Statistical	0.5
Beam stability	1.4
Neutron selection	2.2
Detection efficiency by SCINFUL-QMD	10.0
Former bunch and environmental contamination	1.0
Kinetic energy reconstruction	1.0
Total	10.4

Beam stability

The flux measurement was conducted three times at the beginning, the middle, and the end of the beam test. Over the three measurements the flux was stable within a 1.4% fluctuation. This is incorporated as a systematic error.

Neutron selection

The uncertainty of the neutron selection is estimated using the contamination of neutron-like events in the flash- γ peak in Figure 9.7. The flux is varied by the rate of remaining neutron-

like events to the total events in the flash- γ peak after PSD, and the difference is taken as a systematic error, resulting in 2.0%. In addition, the contamination of γ -ray events in the higher energy data is extrapolated to the QDC overflow region using the distribution in Figure 9.6, yielding a 0.8% contamination. In the end, the neutron selection error is taken to be the sum in a quadrature of these two components, 2.2% in total.

Detection efficiency by SCINFUL-QMD

Physics modeling of SCINFUL-QMD is based on experimental data [140, 141], and a 10% uncertainty is estimated for the region below 80 MeV in the previous studies [143]. Other errors such as the energy calibration uncertainty and the PMT response model are checked to be negligible. In total, a 10.0% uncertainty is assigned.

Other systematic errors

Systematic errors in the TOF measurement can result in uncertainties in the reconstructed kinetic energy and accordingly flux due to efficiency differences between energy bins. The time-walk correction error is found to have a negligible impact on the result. The TDC calibration uncertainty leads to a 0.4 ns uncertainty in the TOF measurement. Uncertainties of the detector alignment produce a 0.3 ns error, and the width of flash- γ peak incurs a further 1.1 ns. In total a 1.2 ns error is assigned to the TOF measurement. This corresponds to a 1 MeV uncertainty in the kinetic energy reconstruction and a 1% uncertainty in the flux.

Contaminations from the former beam bunches or environmental neutrons are estimated to be less than 1% by comparing the event rate in the region between the flash- γ peak and the neutron peak in Figure 9.7.

9.4.5 Neutron Beam Profile

In order to reduce neutron backgrounds in the γ -ray detectors due to direct exposure to the neutron beam, a profile measurement was conducted ahead of the γ -ray measurements. In the profile measurement, the BC-501A scintillator was shifted from the center to 20 cm perpendicularly off-axis in steps of 4 cm. The flux at each position was measured with the same method as described above. The measurement results are shown in Figure 9.11. The flux at 20 cm away from the beam center is smaller than that at the beam center by more than two orders of magnitude. This position is outside of the expected beam profile as determined by the collimator (10 cm from the beam center), the γ -ray detectors were placed at 20 cm away from the beam center. The neutron background at the position was measured with the CsI(Tl) scintillator as explained later.



Figure 9.11: Neutron beam profile measured by the BC-501A detector. The result is for the peak region (72-82 MeV).

9.4.6 TOF Measurements in the Lanthanum-Bromide Scintillator

To infer kinetic energies of neutrons which produce γ -rays observed in the LaBr₃(Ce) scintillator, its timing information is used to perform a TOF analysis similarly to the BC-501A. The γ ray event timing is corrected for the time-walk effect and the distance between the detector and the acrylic target is considered in the reconstruction. Figure 9.12 shows both TOF and reconstructed kinetic energy distributions. The flux peak and width are consistent with the result from the BC-501A detector.



Figure 9.12: Distributions of TOF (left) and the inferred kinetic energy (right) in the LaBr₃(Ce) detector. In the left panel, the on-timing (corresponding to 72-82 MeV in the kinetic energy) and off-timing regions are indicated by the solid and dashed bars, respectively. In the right panel, the red bars indicate the neutron energy region used for the cross section analysis.

9.5 De-excitation γ -rays from Neutron-Oxygen Reactions

Figures 9.13 and 9.14 show the observed energy spectra without the TOF cut by the HPGe and $LaBr_3(Ce)$ detectors, respectively. In both figures, the red and blue spectra correspond to the results with a water-filled and an empty target, respectively. The vertical axes are normalized with the solid angle covered by the acrylic vessel from the lithium target and the incident protons. Several energy peaks are observed in both detectors. The $LaBr_3(Ce)$ spectra with the TOF cut are shown in Figure 9.15. Here three spectra are shown: one with a water-filled target and the on-timing cut applied, one with an empty target and the on-timing cut applied, and one with a water-filled target and the off-timing cut applied. Note that the off-timing spectrum is normalized to the length of the on-timing window.



Figure 9.13: Energy spectra of the HPGe detector with and without water. The spectra in the bottom panel focus on the region between 3 and 8 MeV.

Table 9.2 summarizes energies of the γ -rays of primary interest to the present measurement, their parent nuclei with excited states, and the physics processes that produce them. Parent nuclei are identified by the peak energy and the peak width. The γ -rays from nuclei with



Figure 9.14: Energy spectra of the $LaBr_3(Ce)$ scintillator with and without water without the TOF cut.



Figure 9.15: Energy spectra of the $LaBr_3(Ce)$ scintillator with and without water with the TOF cut selecting the on-timing and off-timing regions defined in Figure 9.12.

Energy	Parent (J^{π})	Physics process
7.12 MeV	$^{16}O(1^{-})$	${}^{16}\mathrm{O}(n,n'){}^{16}\mathrm{O}^*$
$6.92 { m MeV}$	$^{16}O(2^+)$	${ m ^{16}O(n,n')^{16}O^{*}}$
$6.32 { m MeV}$	$^{15}N(\frac{3}{2})$	${ m ^{16}O}(n,np){ m ^{15}N^*}$
$6.13~{\rm MeV}$	$^{16}O(3^{-})$	${ m ^{16}O(n,n')^{16}O^{*}}$
$5.27 { m MeV}$	$^{15}N(\frac{5}{2}^+)$	${}^{16}O(n,n'){}^{16}O^*$ then ${}^{16}O^* \to {}^{15}N^* + p$, or ${}^{16}O(n,np){}^{15}N^*$
$4.44~{\rm MeV}$	${}^{12}C(2^+)$	${}^{16}O(n,n'){}^{16}O^*$ then ${}^{16}O^* \to {}^{12}C^* + \alpha$, or ${}^{16}O(n,n\alpha){}^{12}C^*$
$3.68 { m MeV}$	${}^{13}C(\frac{3}{2})$	${ m ^{16}O}(n, lpha){ m ^{13}C^{*}}$
$2.31~{\rm MeV}$	$^{14}N(0^+)$	$^{16}{ m O}(n,2np)^{14}{ m N}^{*}$
$2.30~{\rm MeV}$	${}^{15}\mathrm{N}(\frac{7}{2}^+)$	${ m ^{16}O}(n,np){ m ^{15}N^*}$

Table 9.2: Energies, parent nuclei with their spin (J) and parity (π) , and physics processes of the observed γ -ray peaks.

shorter lifetime than the duration of motion after hits by incident particles are Doppler shifted then the peak width of those γ 's becomes larger.

The 6.13 MeV γ -ray from the excited state of ¹⁶O are clearly seen in both the HPGe and LaBr₃(Ce) spectra. Inelastic scattering, (n, n'), is expected to produce this excited state. The observed peak appears stronger in the spectrum without the TOF cut in Figures 9.13 and 9.14, as there is a large contribution to this process from lower energy neutrons. On the other hand, the peak intensity is reduced relative to others in the spectrum with the on-timing TOF cut, as shown with the red spectrum in Figure 9.15. Although clear peaks are not observed, there seen some contributions above 6.5 MeV. Among possible peaks after neutron reactions on oxygen, the 6.92 MeV and 7.12 MeV γ -rays from ¹⁶O after the (n, n') scattering may be more likely to be emitted, because they are from the excited states next and next-next to the 6.13 MeV state, respectively. These peaks are added in the spectrum fitting as explained later.

The large bump around 5.8 MeV seen in the LaBr₃(Ce) spectrum with the on-timing cut in Figure 9.15 is difficult to explain only by the Compton edge of the 6.13 MeV γ -ray. It is considered due to the 6.32 MeV γ -ray from ¹⁵N. This peak is thought to come from the direct knock-out process, (n, np), because it is emitted dominantly when ¹⁵N is created through this process according to Refs. [111,147]. This is not seen clearly in the spectra without the TOF cut in Figures 9.13 and 9.14 because other components from interactions of lower energy neutrons which are likely to produce the 6.13 MeV γ 's may dominate. A similar process, (n, 2n), exists; however, γ -rays from the state after this process are not observed clearly in this experiment. The reason for this may be that a neutron is more likely to be paired with a proton inside the nucleus therefore the (n, np) process is more probable than the (n, 2n) process.

In the HPGe spectrum (Figure 9.13), the 5.27 MeV γ -rays from ${}^{15}N(\frac{5}{2}^+)$ are observed clearly. It is less visible in the LaBr₃(Ce) spectrum without the TOF cut (Figure 9.14) because of the worse energy resolution. With the on-timing TOF cut, the 5.27 MeV γ peak, especially the S.E. peak, is visible in Figure 9.15. Possible processes which produce this γ -ray are nucleon knock-out, ${}^{16}O(n, np)$, deuteron flipping, ${}^{16}O(n, d)$, and nuclear decay from an excited state of ${}^{16}O$ with proton emission after the inelastic process, ${}^{16}O^* \rightarrow {}^{15}N^* + p$. The present work does not have an ability to distinguish the production processes, then an inclusive measurement is performed. It is worth noting that the ${}^{16}O(n, np)$ cross section is predicted to be small at 60.7 MeV in a calculation [148] and the 6.32 MeV γ is the most likely if this direct process happens as described above. Therefore, the 5.27 MeV γ -rays in this analysis might come from the (n, n') process followed by decay with proton emission. The 4.44 MeV peak from ${}^{12}C(2^+)$
is also observed. Here the alpha knock-out, ${}^{16}O(n, n\alpha)$ or decay of ${}^{16}O$ with alpha emission $({}^{16}O^* \rightarrow {}^{12}C^* + \alpha)$ (c.f. Ref. [148]) are potential processes contributing to this peak. As in the 5.27 MeV case, these processes cannot be separated, thus an inclusive measurement is conducted. In similar processes but with neutron emission, the 5.18 MeV γ -ray from ${}^{15}O(\frac{1}{2}^+)$ is expected, but was not observed in this experiment. This could be understood by the fact that the minimum excitation energy required for decay with neutron emission (15.66 MeV) is higher than those for decay with proton emission (12.13 MeV) and decay with alpha emission (7.16 MeV).

The 3.68 MeV γ -rays are observed by both the HPGe and LaBr₃(Ce) detectors. This is considered to come from ¹³C generated by (n, α) reactions with ¹⁶O. Another peak observed clearly is the one around 2.30 MeV. This is not so visible in the spectra without the TOF cut due to the strong peak by 2.22 MeV γ -rays produced from thermal neutron capture. These thermal neutron induced events can be removed by the off-timing data, as explained in the next section. There are two possibilities: the 2.30 MeV γ from ¹⁵N($\frac{7}{2}^+$) and the 2.31 MeV γ from ¹⁴N(0⁺). These two cannot be separated by the LaBr₃(Ce) due to insufficient energy resolution.

Many peaks that are not from the fast neutron reactions on oxygen are also observed. These are explained below though are not of high interest for the purpose in this thesis. The 3.84 MeV γ -rays seen in Figure 9.13 from ¹⁷O are thought to arise from thermal neutron capture on ¹⁶O. In addition, there are several other peaks that cannot be attributed to neutron-oxygen reactions. For instance, the 2.22 MeV and 7.63 MeV peaks are likely due to neutron capture on ¹H and ⁵⁶Fe, respectively. Other peaks such as the 1.46 MeV γ -ray from ⁴⁰K and the 2.61 MeV γ -ray from ²⁰⁸Tl can be made by a number of reactions with neutrons and materials in the beamline.

In this work, the production cross sections for nine peaks in Table 9.2 are measured with a spectrum analysis, which is explained later in this chapter. For the 2.30 MeV and 2.31 MeV peaks, an inclusive cross section is measured. The spectrum analysis is performed for the peak neutron energy region, then the LaBr₃(Ce) spectra with the on-timing cut in Figure 9.15 are used.

9.6 Background Estimation

Backgrounds are sorted into four: (1) fast neutron hits, (2) non-water backgrounds, (3) γ -rays from thermal neutron capture and β 's, and (4) γ -rays from scattered fast neutron reactions. Each background is explained in the following part.

Fast neutron hits

Neutrons reacting with the LaBr₃(Ce) are a potential background, which are either scattered off the acrylic target or incident off-axis. The CsI(Tl) scintillator was used to measure this background with its PSD capability. For this measurement, the PSD integration region was optimized with figure-of-merit laid out in Ref. [139]. The same neutron energy region as the cross section analysis, 72–82 MeV, is selected in the CsI(Tl) time data. The result is shown in Figure 9.16, where three populations are seen: (a) γ -rays, (b) neutrons, and (c) pile-up events. The latter is due to events having multiple signals within one Flash-ADC time window. The amount of such pile-up events is negligible compared to that of the γ -ray events. The fast neutron background is estimated in each energy region between 1 and 8 MeV. Here the result with an empty target is subtracted from that with a water-filled target. The resulting contamination of neutrons is smaller than 1% in all energy regions. This is negligible compared to the total systematic error. Even if the material difference between CsI(Tl) and $LaBr_3(Ce)$ is considered, the fast neutron contamination rate is still negligible.



Figure 9.16: Distribution of the ratio of the integrated tail part to the total in the CsI(Tl) waveform as a function of energy. The populations (a), (b), and (c) correspond to the γ -like, neutron-like, and pile-up events, respectively.

Non-water background

Backgrounds arising from neutron reactions on other objects than water are estimated using data with an empty target. They are seen as the blue spectrum in Figure 9.15 and subtracted from the measurement with water in the acrylic vessel which is the red spectrum in the same figure.

γ -rays from thermal neutron capture and β 's

The γ -rays emitted from thermal neutron capture and the electrons or positrons from beta decay have much longer time scale than the beam repetition cycle (~560 ns) and hence are expected to distribute uniformly in time. The contributions from these can then be subtracted using data in the off-timing region which is shown as the magenta spectrum in Figure 9.15. The energy spectrum in the off-timing region is subtracted from that in the on-timing region with normalization based on length of the time window in the left panel of Figure 9.12.

γ -rays from scattered fast neutron reactions

After subtraction of the non-water background and the off-timing background, continuous components remain in the spectrum. This is considered due to the γ -ray events that are produced by scattered neutron reactions with the surrounding materials, as depicted in Figure 9.17. If this assumption is right, the continuous component is smaller in the spectrum with the TOF cut selecting faster neutrons, because it takes time for the γ -ray to reach the detector from the emission point. To check this, the spectra from the different timing regions, corresponding to 72-77 MeV and 77-82 MeV in neutron kinetic energy, are compared as shown in the left panel of Figure 9.18. Clear shape difference between the two spectra is seen. To further check the assumption, the spectrum with an empty target and the on-timing TOF cut is compared with the difference between the 72-77 MeV and 77-82 MeV spectra. Here the 77-82 MeV spectrum is subtracted from the 72-77 MeV spectrum with an arbitrary scaling. The result is given in the right panel of Figure 9.18. The shape of the two look similar. These make the assumption that the continuous background is made by the scattered neutrons reacting with the surrounding materials plausible. The non-water spectrum with the on-timing cut is used for the spectrum fitting later.



Figure 9.17: Schematic illustration of the continuous background caused by γ -rays from scattered fast neutron reactions with the surrounding materials for a water-filled target (left) and an empty target (right).



Figure 9.18: Comparison of the spectra for the neutron energy region 72-77 MeV and 77-82 MeV (left) and comparison between the shape difference of these two and the non-water spectrum for the 72-82 MeV region (right).

9.7 Spectrum Analysis

In the previous section, the non-water and off-timing backgrounds are subtracted. Now the observed spectrum is composed of signals (the γ -rays from neutron-oxygen reactions) and the continuous background. With signal and background templates, the observed data is fit to extract the γ -ray production cross sections. The signal template is made by the simulation based on a GEANT4 package [149], and the continuous background template is obtained from the on-timing non-water data.

9.7.1 Signal Templates

In the GEANT4 simulation, the $LaBr_3(Ce)$ detector and the acrylic target filled with water are set, and γ -rays are generated randomly and isotropically in the water. The γ -rays are then detected by the $LaBr_3(Ce)$. The obtained spectrum is smeared with the detector resolution which is obtained from the resolution curve below. The Gaussian fitting was conducted for several peaks, which are not Doppler shifted, and the resulting width (σ_E) is plotted as a function of energy (E [MeV]) in Figure 9.19. The data points are then fit to obtain a resolution curve. The Doppler shift effect should be considered for some peaks. It is known that its effect size is $\sim 1\%$. The 4.44 MeV peak is known to be Doppler shifted and its resolution obtained from the Gaussian fitting to data, $1.09 \pm 0.08\%$, is consistent with the calculated resolution from the resolution curve in Figure 9.19 and the Doppler effect, $1.14 \pm 0.10\%$. Therefore, a 1% is added to the resolution obtained by the curve in Figure 9.19 for the Doppler shifted peaks, 7.12, 6.92, 6.32, 4.44, 3.68, and 2.30 or 2.31 MeV. Note that the 2.30 MeV spectrum is used for the 2.30 MeV and 2.31 MeV peaks since they are not discriminated in the $LaBr_3(Ce)$. The resulting signal templates are shown in Figure 9.20. Here the spectra with better and worse resolutions by 1σ uncertainties of the resolution curve are shown together. For the peaks with no Doppler shift, the effect of this resolution uncertainty is large.



Figure 9.19: Energy resolution as a function of the deposited energy in the LaBr₃(Ce). The black points are data and the red line is the fitting to those data points. The resolution curve function is: $\sigma_E/E = p0 + p1/\sqrt{E} + p2/E$ (E [MeV]), where $p0 = (-1.89 \pm 0.81) \times 10^{-3}$, $p1 = (1.68 \pm 0.17) \times 10^{-2}$, and $p2 = (-2.47 \pm 0.91) \times 10^{-3}$.



Figure 9.20: Signal templates for each γ -ray peak in the LaBr₃(Ce) simulated by GEANT4. The spectra smeared with the nominal and $\pm 1\sigma$ resolutions by the resolution curve are shown.

9.7.2 Continuous Background Template

As described in the previous section, γ -rays from the scattered neutron reactions on the surrounding materials form the continuous background. The shape of this background is obtained from the on-timing data with an empty target. In order to obtain a smooth shape template, the on-timing non-water spectrum is fit. Here the spectrum should contain some signal components such as the 6.13 MeV and 4.44 MeV γ -rays due to the acrylic vessel, then the region between 3 and 6.5 MeV is removed in the fitting. The spectrum is well fit with an exponential function, as shown in Figure 9.21. This fitting function is used as the continuous background template.



Figure 9.21: An exponential fitting to the on-timing non-water spectrum for the continuous background template. The region 3-6.5 MeV is removed in the fitting to avoid the signal components.

9.7.3 Fitting Results

The fitting to the observed spectrum with the continuous background template and the eight signal templates is performed. The χ^2 is calculated by comparing the observed and predicted (= signal + background) spectra as below:

$$\chi^2 = \sum_i \chi_i^2 = \sum_i \left(\frac{N_i^{\text{obs}} - N_i^{\text{pred}}}{\sigma_i}\right)^2,\tag{9.2}$$

$$N_i^{\text{pred}} = f_0 \cdot N_i^{\text{bkg}} + \sum_j f_j \cdot N_i^{\text{sig},j}, \qquad (9.3)$$

where N_i^{obs} and N_i^{pred} represent the numbers of observed and predicted events in the *i*-th energy bin, N_i^{pred} being the sum of background and signal events multiplied with the scale factors f_j $(j = 0, 1, \dots, 8, 0$: background, 1–8: signal). The error for the *i*-th energy bin (σ_i) considers the statistical uncertainties of data and MC, the MC modeling error, and the energy resolution error. The MC modeling is checked by γ -ray sources and the absolute difference in the number of detected events between data and MC is found to be 3.4%, and this is taken as a systematic error. The energy resolution error is taken as the maximum difference in the number of events in the bin between the nominal and either $\pm 1\sigma$ as shown in Figure 9.20. The scale factors, f_j , are determined by minimizing the χ^2 value. The fitting is performed in two steps. First, only the high energy region, 5.5–7.3 MeV is fit, with the background and the 7.12 MeV, 6.92 MeV, 6.32 MeV, and 6.13 MeV signal spectra. In the second fitting, the scale for these four signals are fixed while that for the background is varied in the best-fit $\pm 2\sigma$ region. The second fitting is performed for the region including the low energy side, 2.2–7.3 MeV. The fitting results are summarized in Table 9.3. The best-fit spectrum is shown together with the observed data in Figure 9.22. The best-fit spectrum agree well with the observation in general, though there seen some discrepancies around the 6.13 MeV and 5.27 MeV peaks. This is considered due to large resolution uncertainties of these two peaks as seen in Figure 9.20. The effect on the cross section of these deviations is smaller than the currently assigned systematic uncertainties.

-			
1st fitting		2nd fitting	
χ^2/ndf	$138.33/51 \sim 2.71$	χ^2/ndf	$414.53/162 \sim 2.56$
f_0	0.055 ± 0.007	f_0	0.049 ± 0.001
f_1	0.16 ± 0.02	f_5	0.72 ± 0.03
f_2	0.19 ± 0.02	f_6	0.60 ± 0.02
f_3	0.90 ± 0.05	f_7	0.14 ± 0.02
f_4	0.78 ± 0.09	f_8	0.19 ± 0.02

Table 9.3: Results of the first and second spectrum fittings.

9.7.4 Cross Section Results

The γ -ray production cross section (σ_{γ}^{j}) for the *j*-th signal is calculated as:

$$\sigma_{\gamma}^{j} = \frac{N_{\text{fit}}^{j}}{\epsilon_{\gamma}^{j} \cdot \phi_{n} \cdot T} = f_{j} \times \frac{N_{\text{MC,generated}}}{\phi_{n} \cdot T}, \qquad (9.4)$$

$$N_{\rm fit}^j = f_j \cdot N_{\rm MC, detected}^j, \tag{9.5}$$

$$\epsilon_{\gamma}^{j} = \frac{N_{\rm MC,detected}^{j}}{N_{\rm MC,generated}},\tag{9.6}$$

where ϕ_n denotes the neutron flux [/sr/ μ C], T is the number of target oxygen nuclei per area [/cm²], ϵ_{γ} is the γ -ray detection efficiency, and $N_{\text{MC,generated}}$ ($N_{\text{MC,detected}}$) is the number of generated (detected) events in the GEANT4 simulation. The generated events are 10⁸ for every peak and the number of the target oxygen is estimated to be 8.52×10^{23} /cm². The mean free path for 77 MeV neutrons is about 30 cm estimated from the total neutron-water cross section of ~1 b [133]. This is longer than the target length of 24.5 cm then whole part of the target effectively functions, requiring no correction.

The systematic uncertainty on the cross section is composed of errors regarding the spectrum fitting, neutron flux, and target. The first two are given in the previous sections. For the 6.13 MeV and 5.27 MeV peaks, the fitting uncertainties are larger due to larger resolution



Figure 9.22: Energy spectrum of the $LaBr_3(Ce)$ scintillator after the TOF cut and subtractions of the non-water spectrum and the off-peak spectrum in a linear (top) and a log (bottom) vertical scale. Different color spectra correspond to signal and background: 7.12 MeV (gray), 6.92 MeV (brown), 6.32 MeV (magenta), 6.13 MeV (orange), 5.27 MeV (cyan), 4.44 MeV (green), 3.68 MeV (yellow), 2.30 MeV (violet), and continuous background (blue).

errors, as explained above. In the water-filled measurement, $\sim 56\%$ of neutrons do not reach the back-face of the acrylic vessel, which is estimated from the mean free path and the target length. This may lead to overestimate of the non-water background, since there is little neutron deficit at the back-face in the non-water measurement. Since the back-face volume rate to the toal vessel is $\sim 23\%$ and the neutron flux at the center is ~ 1.7 times larger than the barrel position from Figure 9.11, the effective contributions from the back-face to the total non-water background is $\sim 29\%$. Contributions from the spectrum without water to that with water are at most 50% in Figure 9.15. Therefore, the effect of the back-face is estimated to be 8.1% (= $56\% \times 29\% \times 50\%$).

The cross sections for each γ -ray are summarized in Table 9.4. The result for the 2.30 MeV and 2.31 MeV peaks is an inclusive cross section. In general, the measurement is performed with better than 20% precisions. As explained above, the 7.12 MeV, 6.92 MeV, and 6.13 MeV γ -rays originate from the inelastic scattering without nucleon knock-out. In addition, the 5.27 MeV and 4.44 MeV γ -rays might come from the same process followed by proton and alpha emission, respectively. In contrast, the 6.32 MeV γ -ray is likely to be from the direct knock-out (quasielastic) process. Then the current results indicate that the inelastic process without nucleon knock-out exceeds the quasielastic nucleon knock-out process at 80 MeV.

γ -ray energy [MeV]	cross section [mb]
7.12	1.1 ± 0.1 (fitting) ± 0.1 (flux) ± 0.1 (target)
6.92	1.3 ± 0.1 (fitting) ± 0.1 (flux) ± 0.1 (target)
6.32	6.2 ± 0.3 (fitting) ± 0.6 (flux) ± 0.5 (target)
6.13	5.4 ± 0.6 (fitting) ± 0.6 (flux) ± 0.4 (target)
5.27	4.9 ± 0.2 (fitting) ± 0.5 (flux) ± 0.4 (target)
4.44	4.1 ± 0.1 (fitting) ± 0.4 (flux) ± 0.4 (target)
3.68	1.0 ± 0.1 (fitting) ± 0.1 (flux) ± 0.1 (target)
2.30 + 2.31	1.3 ± 0.1 (fitting) ± 0.1 (flux) ± 0.1 (target)

Table 9.4: Results of the γ -ray production cross sections.

9.8 Summary and Prospects

In the E487 experiment at RCNP, several γ -ray peaks emitted from the neutron-oxygen reactions are observed, and their production cross sections are measured. The results indicate that the inelastic process without nucleon knock-out may be dominant over the quasielastic nucleon knock-out process at 80 MeV. This contradicts the assumption that boundary of the transition between these two interactions is 30 MeV used in the previous NCQE measurement [51]. Therefore, in this thesis, another method is used instead, as explained in Chapter 7. Furthermore, the current ~13% uncertainty in the NCQE measurement, as shown in Chapter 7, would be reduced down to less than 5%, if the precision comparable to the E487 experiment ($\leq 20\%$) is achieved at several energy points and those results are suitably incorporated in the simulation.

The measurement was improved with a HPGe detector by storing its time data in the E525 experiment. Similar spectrum analysis is performed to extract production cross sections at neutron energies of 30 and 250 MeV. In the E525 experiment, better precision results are expected thanks to higher energy resolution in the HPGe detector. Together with the results from the current work in this thesis, these cross section results will be implemented in the SK

simulation, and would help improve the systematic uncertainty in the NCQE-like measurement. This improvements would also be valuable for the analysis utilizing the neutron information especially in SK-Gd, including the SRN search reported in Part IV. The improved simulation would be useful also in the future water Cherenkov experiments such as Hyper-Kamiokande.

Part IV

Search for Supernova Relic Neutrinos

Chapter 10

Signal and Background

In this part, a search for supernova relic neutrinos using an SK-IV 2970.1-day data set is reported. In the analysis, the NCQE-like cross section results from T2K are applied to the atmospheric neutrino background estimation, as described in Chapter 12.

In this chapter, the SRN signal and the background sources in the search are overviewed and their MC simulations are explained.

10.1 Signal

All three flavor neutrinos are emitted from supernovae as explained in Chapter 1, but the dominant interaction in SK is inverse beta decay (IBD) of electron antineutrinos ($\bar{\nu}_e + p \rightarrow e^+ + n$) in the energy region of the analysis (<30 MeV). Figure 10.1 shows effective neutrino cross sections, which are cross sections including the energy resolution and detector threshold effects, of various interaction channels as a function of neutrino energy. The second largest cross section is smaller than IBD by more than two orders of magnitude, therefore only IBD is considered. In the analysis, pairs of a positron and a 2.2 MeV γ -ray from neutron capture on hydrogen are searched.



Figure 10.1: Effective neutrino interaction cross sections as a function of neutrino energy [150].

In the simulation, events are produced uniformly in the positron energy, and the actual spectra are obtained with renormalization by the parent $\bar{\nu}_e$ flux. In total nine SRN $\bar{\nu}_e$ fluxes from seven models are referred, which are shown in Figure 1.7 in Chapter 1. IBD cross sections are taken from Ref. [151] and shown in Figure 10.2.



Figure 10.2: IBD cross section on a free proton as a function of $\bar{\nu}_e$ energy as calculated by Strumia and Vissani [151].

10.2 Background

Background sources are categorized into four: (1) atmospheric neutrino interactions, (2) muon spallation, (3) reactor neutrino events, and (4) accidental background events.

10.2.1 Atmospheric Neutrinos

Atmospheric neutrinos are a major background in the search. The MC production of atmospheric neutrino events are based on flux prediction by the HKKM2011 model [152, 153] and the neutrino interaction by NEUT ver. 5.3.6. The fluxes used in the analysis are shown in Figure 10.3. In the figure, neutrino oscillations are not considered, but such effect is applied later. The neutrino interaction model is the same as the one used in the NCQE-like measurement described in Chapter 5. However, the setting of spectroscopic factors is different; The *others* state is integrated into $(p_{1/2})^{-1}$ here, while it is integrated into $(s_{1/2})^{-1}$ in the NCQE-like analysis. The systematic error of this treatment is evaluated in the NCQE-like measurement in Chapter 7.

10.2.2 Muon Spallation and Lithium-9

SK is exposed to ~ 2 Hz cosmic-ray muons, and high energetic muons break up oxygen nuclei in water ("muon spallation"), producing electromagnetic and hadronic particles such as photons, neutrons, and pions. These will subsequently undergo reactions with other nuclei via several channels. Eventually the nuclei are in their excited states, which decay via many channels.



Figure 10.3: Atmospheric neutrino flux at Kamioka from the HKKM2011 calculation: the vertical axis shown in linear (left) and log (right). Here the neutrino oscillation is not taken into account.

Energies of β 's and γ 's resulting from the decays range in the current analysis window. Some decays form a combination of " $\beta+n$ " which is the same as the $\bar{\nu}_e$ signal. Possible isotopes and their visibilities in water are studied with the FLUKA simulation [93] in Refs. [154–156], and summarized in Table 10.1. The table categorizes isotopes into three: neutrons (the 1st row), isotopes whose decay contain a β (the 2nd–19th rows), and isotopes which are not likely backgrounds standalone because they are stable, have very long lifetime, or decay without a β (the 20th–33rd rows). Even if the final state is not a " $\beta+n$ " combination, when a β or γ forms a coincidental pair with a neutron or fake hits, due to PMT noise or radioactive materials, this becomes a background to the search. Therefore, the muon spallation should be reduced. Since the spallation endpoint in the energy is 20.6 MeV from the ¹⁴B and ¹¹Li, the cut should be tuned up to the periphery. In the analysis, the cuts are prepared for the region up to 19.49 MeV. Details about the spallation cut are given in Chapter 11.

The $\beta+n$ decay events are an irreducible background in the analysis. Among such isotopes listed in the table, the ⁹Li isotope is the most likely background due to its yield, lifetime, and energy. The ⁹Li decays into a $\beta+n$ pair with a branching ratio of 50.8%, as shown in the left panel of Figure 10.4. This is almost identical to the $\bar{\nu}_e$'s IBD event except that the β from ⁹Li is an electron and the neutron energy is higher than that from IBD. SK is not sensitive to these differences, then the MC event production is performed by renormalizing the $\beta+n$ event made for the $\bar{\nu}_e$ signal. Potential systematic errors due to difference in the neutron energy is covered by the Am/Be calibration since neutrons from the source have similar energies to those from ⁹Li. The β spectra from ⁹Li for different decay modes are shown in the right panel of Figure 10.4. The previous SK measurement result [115] is used as the ⁹Li production rate: $0.86 \pm 0.12(\text{stat.}) \pm 0.15(\text{syst.}) \text{ kton}^{-1}\text{day}^{-1}$.

Isotope	Half-life	Decay mode	Yield	Primary process
	[sec.]		$[\times 10^{-7} \text{muon}^{-1} \text{g}^{-1} \text{cm}^2]$	
\overline{n}			2030	
¹⁸ N	0.624	β^{-}	0.02	$^{18}\mathrm{O}(n,p)$
$^{17}\mathrm{N}$	4.173	$\beta^- n$	0.59	${}^{18}\mathrm{O}(n, n+p)$
^{16}N	7.13	$\beta^{-}\gamma$ (66%), β^{-} (28%)	18	(n,p)
$^{16}\mathrm{C}$	0.747	$\beta^- n$	0.02	(π^-, np)
$^{15}\mathrm{C}$	2.449	$\beta^-\gamma~(63\%),~\beta^-~(37\%)$	0.82	(n, 2p)
$^{14}\mathrm{B}$	0.0138	$eta^-\gamma$	0.02	(n, 3p)
$^{13}\mathrm{O}$	0.0086	β^+	0.26	$(\mu^{-}, p + 2n + \mu^{-} + \pi^{-})$
$^{13}\mathrm{B}$	0.0174	β^{-}	1.9	$(\pi^{-}, 2p + n)$
$^{12}\mathrm{N}$	0.0110	β^+	1.3	$(\pi^+, 2p + 2n)$
$^{12}\mathrm{B}$	0.0202	β^{-}	12	$(n, \alpha + p)$
$^{12}\mathrm{Be}$	0.0236	β^{-}	0.10	$(\pi^-, \alpha + p + n)$
$^{11}\mathrm{Be}$	13.8	$\beta^{-}~(55\%),~\beta^{-}\gamma~(31\%)$	0.81	$(n, \alpha + 2p)$
11 Li	0.0085	$\beta^- n$	0.01	$(\pi^+, 5p + \pi^+ + \pi^0)$
$^{9}\mathrm{C}$	0.127	β^+	0.89	$(n, \alpha + 4n)$
⁹ Li	0.178	$\beta^{-}n$ (51%), β^{-} (49%)	1.9	$(\pi^-, \alpha + 2p + n)$
$^{8}\mathrm{B}$	0.77	β^+	5.8	$(\pi^+, \alpha + 2p + 2n)$
⁸ Li	0.838	β^{-}	13	$(\pi^-, \alpha + {}^2\mathbf{H} + p + n)$
⁸ He	0.119	$\beta^{-}\gamma$ (84%), $\beta^{-}n$ (16%)	0.23	$(\pi^-, {}^3\mathrm{H} + 4p + n)$
$^{15}\mathrm{O}$			351	(γ, n)
^{15}N			773	(γ, p)
$^{14}\mathrm{O}$			13	(n,3n)
^{14}N			295	$(\gamma, n+p)$
$^{14}\mathrm{C}$			64	(n, n+2p)
^{13}N			19	$(\gamma, {}^{3}\mathrm{H})$
$^{13}\mathrm{C}$			225	$(n, {}^{2}\mathrm{H} + p + n)$
$^{12}\mathrm{C}$			792	$(\gamma, lpha)$
$^{11}\mathrm{C}$			105	$(n, \alpha + 2n)$
$^{11}\mathrm{B}$			174	$(n, \alpha + p + n)$
$^{10}\mathrm{C}$			7.6	$(n, \alpha + 3n)$
$^{10}\mathrm{B}$			77	$(n, \alpha + p + 2n)$
$^{10}\mathrm{Be}$			24	$(n, \alpha + 2p + n)$
⁹ Be			38	(n,2lpha)
sum			3015	

Table 10.1: List of isotopes produced in the muon spallation at SK calculated by FLUKA [154]. The primary process is with ^{16}O except for the first three rows.



Figure 10.4: Decay scheme of ⁹Li (left) and β spectra from its decay with a neutron emission (right). In the right panel, black one represents the total spectrum and the other color ones correspond to decay modes from different excited states, and K_n represents the emitted neutron kinetic energy.

10.2.3 Reactor Neutrinos

Reactor neutrinos are the electron antineutrinos and then an irreducible background in the analysis. Their contamination in the analysis is limited to the lowest energy bin. Reactor neutrino flux is calculated using the database on Power Reactor Information System (PRIS) from IAEA [157] with neutrino oscillations [158], and the event production is done with renormalization of the $\bar{\nu}_e$ signal MC. Figure 10.5 shows the reactor $\bar{\nu}_e$ flux at SK. It should be noted that the reactors in Japan were off in large part of the SK-IV period.



Figure 10.5: Reactor neutrino flux at SK for the SK-IV operation period.

10.2.4 Accidental Background Events

There are two types of accidental background events. First one is made by the combination of a low energy event and a true neutron which is mainly produced from muon spallation. This is referred to as the "accidental true background". The other is the combination of a low energy event and a fake event, such as PMT dark noise and radioactive events, which mimics neutrons. This is referred to as the "accidental fake background". It is difficult to remove the former background in the current analysis, then the strict spallation cut is applied as explained in the next chapter. The latter can be separated from the signal (the true neutron) by applying the neutron tagging as explained in Chapter 11.

10.3 Energy Window

The energy window in the analysis is set to 7.49-29.49 MeV, which is separated into four regions as 7.49-9.49, 9.49-11.49, 11.49-19.49, and 19.49-29.49 MeV. This is determined by the detector threshold and background types. As is explained in the next chapter, the SK energy threshold was lowered from 9.49 MeV to 7.49 MeV by the SHE trigger improvement. The lowest two bins (7.49-9.49 MeV and 9.49-11.49 MeV) are dominated by the muon spallation backgrounds (9 Li) and the accidental fake background. The NCQE interaction becomes large in the region 11.49-19.49 MeV, and the other interactions of atmospheric neutrinos are dominant in the highest energy region.

Chapter 11

Data Reduction

11.1 Data Set

All data taken with the SHE+AFT trigger in the SK-IV period (see Chapter 4) are used for the search. After rejection of suspicious periods or runs in terms of data quality, live time of the data set is 2970.1 days. The analysis energy ($E_{\rm rec}$) window is determined depending on the SHE trigger threshold, which was changed once from the 70 hits to the 58 hits. The former and latter correspond to the 9.49 MeV and 7.49 MeV analysis thresholds, respectively. Neutrons are searched in the window spanning from 2 μ s after the SHE trigger until the end of the AFT trigger time window. The AFT window length is different depending on the operation period. The trigger conditions in different periods are summarized in Table 11.1.

Start Date	End Date	Live time	SHE threshold	AFT window length
6th, Oct., 2008	22nd, Nov., 2008	25.0 days	70 hits	$350 \ \mu s$
22nd, Nov., 2008	9th, Sep., 2011	$869.8 \mathrm{~days}$	70 hits	$500 \ \mu s$
9th, Sep., 2011	31st, May., 2018	$2075.3 \mathrm{~days}$	58 hits	$500 \ \mu s$

Table 11.1: Summary on the period and live time for different SHE and AFT trigger conditions.

Data reduction is performed in four steps: the first reduction removes trash data, the second reduction focuses on removal of muon spallation events, the third reduction targets are mainly the atmospheric neutrino backgrounds, and the fourth reduction is the neutron tagging to remove the large accidental fake background.

11.2 First Reduction

Non-physics data cut

The normal runs, which are not test nor calibration runs, are used for physics analyses. Such normal runs are further reduced either if the run time is shorter than 5 minutes, the run started less than 15 minutes after the high-voltage recovery, any hardware problem is reported, or event distribution is strange due to detector problems. Some calibrations are not labeled as test runs since they are conducted with periodical triggers during normal runs. Such calibration events are removed from the analysis sample. The number of hits due to PMT noise is expected to be smaller than that due to physical events. To eliminate PMT noise induced events, $N(Q < 0.5 \text{ p.e.})/N_{\text{all}} < 0.55$, where N(Q < 0.5 p.e.) and N_{all} represent the number of hit PMTs with a charge larger than 0.5 p.e. and the number of all PMTs, is required. During the T2K operation, a special trigger is issued every 2.48 sec. and its time window is $[-500, +535] \mu$ s. This region is removed from the sample.

Cosmic-ray muon cut

Cosmic-ray muon events happen ~ 2 Hz at SK. In many cases such events are expected to leave signs in the OD, then the events are removed if the OD trigger is issued. Even if the OD trigger is not issued, events with more than nineteen OD PMTs hit are removed. Some muons decay into electrons to leave hits inside the ID. To eliminate this, events within 50 μ s after muons are removed. Spallation events caused by muons will be treated later.

Fiducial volume cut

There are many background events coming from the wall. To remove these, the fiducial volume (FV) cut is applied, which selects only events more than 200 cm away from the ID wall.

Fit quality cut

Some events are poorly reconstructed, which occurs more often for background events. These events are removed with goodness-of-fit parameters, $g_{\rm vtx}$ and ovaQ. Figure 11.1 shows $E_{\rm rec}-g_{\rm vtx}$ distributions for the $\bar{\nu}_e$ signal MC and data after the non-physics run cut, the FV cut, and the OD cut. Events with $g_{\rm vtx} < 0.5$ are rejected with keeping the signal efficiency >99.9%. Figure 11.2 shows similar distributions for ovaQ after the $g_{\rm vtx}$ cut. Events with ovaQ < 0.25 are removed and the signal efficiency is >99.9%.



Figure 11.1: The $E_{\rm rec}-g_{\rm vtx}$ distributions for the $\bar{\nu}_e$ signal MC (left) and data (right). Dashed green lines indicate the cut criteria, and events with $g_{\rm vtx} > 0.5$ are selected.



Figure 11.2: The $E_{\rm rec}$ -ovaQ distributions for the $\bar{\nu}_e$ signal MC (left) and data (right). Dashed green lines indicate the cut criteria, and events with ovaQ > 0.25 are selected.

11.3 Second Reduction: Spallation Cut

After the first reduction, the dominant background is cosmic-ray muon spallation. Since there is no reliable MC simulation that treats all spallation isotopes ¹, a data-driven method is taken in this analysis. Note that the ⁹Li events are simulated, as explained in the previous chapter; however, this MC does not contain the spallation production process therefore the efficiency needs to be estimated. This is achieved by the data-driven method here. The basic idea is to investigate the events that are likely to be caused by the preceding muons.



Figure 11.3: Two sample regions for the spallation cut.

In order to study the correlation between the muon and the signal candidate (the SHEtriggered event), muon-like events are collected. The OD and HE triggers are required to identify the muon, and its information, including the track, the number of tracks, and the deposit energy along the track (dE/dx), are extracted by the muon fitter. Details about the

¹There is the FLUKA package, but systematic uncertainties are not estimated well.

muon fitter can be found in Refs. [159–161]. For each SHE event, correlations with the muons that come within ± 30 sec. from the SHE event are studied. Hereafter the region [-30, 0] sec. is termed the pre region and the region [0, +30] sec. is termed the post region, which are schematically shown in Figure 11.3. Then the muons in these two regions are compiled for all SHE events to produce the pre and post samples, respectively.

The muon fitter classifies the muon type into six; The single through-going muons are the ones with a single track that passes through the detector. These dominate the muon events (83.8%); When a single muon stops inside the detector, this is categorized as the stopping muons (4.7%); There are two categories for the multiple track muons, the event with one of the tracks being fit properly (4.6%) and the event with more than one tracks being fit properly (2.5%). In this analysis, both are treated together as the multiple muons; The muons whose track length is less than 7 m, usually traveling close to the edge of the ID, are called the corner-clipping muons (4.1%); The track information is not extracted properly due to the fitting failure for the misfit muons (0.3%). The goodness-of-fit parameter is calculated, and the muons with this goodness smaller than 0.4 are treated as the poorly-fit muons in this analysis. Figure 11.4 shows a 2D distribution of the muon type and the goodness obtained from the muon fitting to the current 2970.1-day data set.



Figure 11.4: Muon types categorized by the muon fitter and their goodness. Variable types which are used for the spallation likelihood calculation are shown in each region. In the analysis, the corner-clipping muons are considered not to cause spallation.

Several variables for finding muon spallation events are calculated for the pre and post samples: dt, L_{tran} , L_{long} , Q_{peak} , Q_{μ} , and N_{track} . The variable dt represents the time difference

between the SHE event and the muon. There are two variables regarding the geometrical information; L_{tran} is the distance between the SHE event vertex and the muon track, and L_{long} is the distance from the point where the SHE event vertex is projected onto the track to the place where dE/dx peaks along the muon track, as schematically shown in Figure 11.5. The Q_{peak} is the maximum dE/dx value in the track, Q_{μ} is the total deposit charge by the muon, and N_{track} is the number of muon tracks. Distributions of these variables are made for the combinations of different conditions on the muon type (single through-going, stopping, multiple, corner-clipping, and missfit or poorly-fit), the SHE event energy region (7.49 $< E_{\rm rec} <$ 9.49 MeV, 9.49 $< E_{\rm rec} < 11.49$ MeV, and $11.49 < E_{\rm rec} < 19.49$ MeV), and the dt region |0| < |dt| < 0.05 sec., 0.05 < |dt| < 0.5 sec., and 0.5 < |dt| < 30 sec.). The results for the single through-going muons, $7.49 < E_{\rm rec} < 9.49$ MeV, and 0 < |dt| < 0.05 sec. are shown in Figure 11.6. Clear contributions from the spallation are seen as an excess in the pre sample than the post sample in every distribution. The spallation events are more likely to populate near the SHE event both in time and space and to be produced from the muons depositing much energy in the detector. The distributions for other conditions are given in Appendix D. The corner-clipping muons are judged not to produce spallation since no significant excess is seen in the pre sample.



Figure 11.5: Schematic of the variables, L_{tran} and L_{long} , for the spallation cut. The cylindrical shape represents the SK detector.

In order to discriminate the spallation events from the random events more effectively, likelihood is calculated from these variables. For this, two probability density functions (PDFs), the spallation PDF (PDFⁱ_{spall}) and the random PDF (PDFⁱ_{random}), are prepared for each discriminating variable *i*. The post sample distribution is subtracted from the pre sample distribution and the resulting distribution is area-normalized to produce the spallation PDF. For making the random PDF, two dedicated samples are made, the "shuffled" post sample and the toy MC sample. The shuffled post sample is obtained by shuffling L_{tran} and L_{long} among the muons of each SHE event in the post region to achieve randomness. Since the other three variables



Figure 11.6: Distributions of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), and Q_{μ} (bottom) for the single through-going muons and 7.49 $< E_{\text{rec}} < 9.49$ MeV. For variables except for dt, the distributions are for 0 < |dt| < 0.05 sec. The smoothing over the bins is performed for some distributions to mitigate the statistical fluctuation.

 $(Q_{\text{peak}}, Q_{\mu}, N_{\text{track}})$ are the muon properties, the random distributions are made by a toy MC based on the muon measurements. Taking L_{tran} and L_{long} from the shuffled post sample and $Q_{\text{peak}}, Q_{\mu}, N_{\text{track}}$ from the toy MC sample and combining these two, the random sample is produced. Then each distribution is area-normalized to serve as the random PDF. The ratios of PDFⁱ_{spall} to PDFⁱ_{random} are multiplied to each other to make spallation likelihood (L_{spall}) as:

$$L_{\text{spall}} = \log\left(\prod_{i} \frac{\text{PDF}_{\text{spall}}^{i}}{\text{PDF}_{\text{random}}^{i}}\right).$$
(11.1)

For the misfit and poorly-fit muons, only dt is used to calculate the spallation likelihood since the other variables are not reliable. For the multiple muons, the muon fit results only from the first track are used, and the number of tracks is used. These are also summarized in Figure 11.4. The PDF distributions for the single through-going muons, $7.49 < E_{\rm rec} < 9.49$ MeV, and 0 < |dt| < 0.05 sec. are shown in Figure 11.7. The spallation likelihoods for the different muon types and $7.49 < E_{\rm rec} < 9.49$ MeV are shown in Figure 11.8. In all distributions, the contributions from spallation are clearly observed as an excess at high values of the spallation likelihood in the pre sample. The cut criteria are determined separately for the muon types and represented with dashed green lines in the figure. The SHE events with at least one muon in their pre region having likelihood larger than the threshold which is represented by the green lines in the figure are removed. The distributions for other conditions are given in Appendix D.

The random and spallation event efficiencies in the spallation cut are estimated as follows. The random event efficiency is estimated by calculating the spallation likelihood for the events in the toy MC sample and applying the cut criteria determined above. Since the data sample at this stage is dominated by the spallation and solar neutrino events, the spallation efficiency is estimated based on data by separating the solar events. This is performed in the $\cos \theta_{\rm sun}$ distribution, where $\theta_{\rm sun}$ is defined as the angle between the event direction and the direction pointing to the Sun at the event timing as schematically shown in Figure 11.9. In this distribution, the event is categorized into two as the solar and non-solar events. The numbers of each event are represented as $N_{\rm sol}$ and $N_{\rm nonsol}$, respectively. The solar events populate in the region close to $\cos \theta_{\rm sun} = 1$, while the non-solar events distribute uniformly. Therefore, the number of non-solar events are composed of the spallation and the atmospheric neutrino events. The contribution of the atmospheric neutrinos is negligible in the region $E_{\rm rec} < 11.49$ MeV but visible above. The spallation efficiency ($\epsilon_{\rm spall}$) is calculated as:

$$\epsilon_{\rm spall} = \frac{N_{\rm nonsol}^{\rm after} - N_{\rm atm}^{\rm after}}{N_{\rm nonsol}^{\rm before} - N_{\rm atm}^{\rm before}},\tag{11.2}$$

$$N_{\rm atm}^{\rm after} = N_{\rm atm}^{\rm before} \times \epsilon_{\rm random}, \tag{11.3}$$

where $N_{\text{nonsol}}^{\text{before}}$ ($N_{\text{atm}}^{\text{after}}$) and $N_{\text{nonsol}}^{\text{after}}$ ($N_{\text{atm}}^{\text{after}}$) represent the numbers of non-solar (atmospheric neutrino) events before and after the spallation cut, respectively. The atmospheric neutrino events are obtained by MC. Since the atmospheric neutrino events occur independent of the muons, $N_{\text{atm}}^{\text{after}}$ is obtained by multiplying the random efficiency to $N_{\text{atm}}^{\text{before}}$. The resulting efficiencies are summarized in Table 11.2. The random efficiency above 11.49 MeV is more than 80% while that below is about half.



Figure 11.7: The spallation and random PDFs of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), and Q_{μ} (bottom) for the single through-going muons and 7.49 $< E_{\text{rec}} < 9.49$ MeV. For variables except for dt, the distributions are for 0 < |dt| < 0.05 sec.



Figure 11.8: Distributions of the spallation likelihood for each muon type in the 7.49–9.49 MeV energy region. Dashed green lines represent the cut criteria. Events in the right side of the lines are removed.

Table 11.2: Random and spallation event efficiencies by the present spallation cut for each $E_{\rm rec}$ region. The uncertainties come mainly from the statistics of the samples.

$E_{\rm rec}$ region [MeV]	$\epsilon_{\mathrm{random}}$	$\epsilon_{ m spall}$
7.49 - 9.49	$0.478 {\pm} 0.014$	0.077 ± 0.001
9.49 - 11.49	$0.549{\pm}0.016$	$0.098 {\pm} 0.001$
11.49 - 19.49	$0.827 {\pm} 0.010$	$0.101 {\pm} 0.001$



Figure 11.9: Schematic drawings of the definition of θ_{sun} and the $\cos \theta_{sun}$ distribution.

11.4 Third Reduction

Wall-originated event cut

In order to remove backgrounds coming from the wall further, the cut based on *effwall* is applied. Figure 11.10 shows the *effwall* distributions for the $\bar{\nu}_e$ signal MC and data after the spallation cut. Since the signal-to-background ratio becomes worse below 500 cm, the events with *effwall* < 500 cm are removed. Signal efficiencies with this cut are about 92% in all $E_{\rm rec}$ regions.



Figure 11.10: The *effwall* distributions for the $\bar{\nu}_e$ signal MC (left) and data (right) after the spallation cut.

Pre-activity cut

When a decay electron from the muon makes the SHE event and the primary signature, such as γ -rays by the neutrino interaction, is not high energetic enough to be triggered, this forms a background in the search. In order to remove this background, the pre-activity is searched in the time range $[-5, 0] \mu$ s with respect to the SHE trigger by a 15 ns long timing window. The maximum number of hits in this time window is required to be less than 12. This cut is applied only to data since these pre-activity events do not exist in MC. The efficiency loss for the signal by this cut is small (<0.1%).

Post-activity cut

There is another case that the triggered events may accompany decay-e's. The post-activity is searched similarly to the pre-activity search. Figure 11.11 shows the number of decay-e's $(N_{\text{decay-e}})$ with all the preceding cuts in the atmospheric neutrino MC sample. Events with $N_{\text{decay-e}} \ge 1$ are rejected. Many CCQE-like events are removed by this cut. The signal efficiency loss is negligible.



Figure 11.11: Number of decay electrons after the pre-activity cut in the atmospheric neutrino MC sample from the 7.49 $< E_{\rm rec} < 29.49$ MeV region. Different colors correspond to the neutrino interaction types.

Pion and γ -ray cut

Fuzziness of the Cherenkov ring is characterized by the *pilike* parameter, which is defined as follows using the triplet PMT distribution (see Figure 4.16):

$$pilike = \frac{N(\text{peak} \pm 3^{\circ})}{N(\text{peak} \pm 10^{\circ})},$$
(11.4)

where $N(\text{peak} \pm 3^{\circ})$ and $N(\text{peak} \pm 10^{\circ})$ are the numbers of entries in the region of the peak value ± 3 and ± 10 degrees in the triplet PMT distribution, respectively. Some pions are quickly captured by oxygen while electrons are likely to travel and scatter more, which leads to fuzzier

ring patterns. Another target here is the multiple- γ events mainly by the NC interactions. Figure 11.12 shows the *pilike* distributions from the $\bar{\nu}_e$ signal and atmospheric neutrino MC samples with all the preceding cuts. The events with *pilike* > 0.36 are removed with the signal efficiency of ~98%. Pion production events and NCQE events are removed effectively.



Figure 11.12: The *pilike* distributions for the $\bar{\nu}_e$ signal (left) and atmospheric neutrino (right) MC samples after the post-activity cut. Both samples are from the 7.49 < $E_{\rm rec}$ < 29.49 MeV region.

Charge/Hit cut

The total charge stored in all PMTs of an event, Q_{50} , is calculated with a 50 ns time window. The ratio of Q_{50} to the total number of hit PMTs, N_{50} , which is calculated with the same time window, represents how concentrated the hits are then corresponds to fuzziness of the Cherenkov ring ². Figure 11.13 shows the Q_{50}/N_{50} distributions of the $\bar{\nu}_e$ signal and atmospheric neutrino MC samples after all the preceding cuts. The events with $Q_{50}/N_{50} > 2$ are removed with the signal efficiency of ~99%.

Cherenkov angle cut

Electron events tend to be reconstructed at $\theta_{\rm C} \sim 42^{\circ}$ and mainly NC events are likely to distribute at higher angles. Figure 11.14 shows the $\theta_{\rm C}$ distributions from the $\bar{\nu}_e$ signal and atmospheric neutrino MC samples after all the preceding cuts. Less event above 85 degrees is mainly due to the *pilike* cut. Events are required to satisfy $38^{\circ} < \theta_{\rm C} < 50^{\circ}$. The signal efficiency depends on the energy since lower energy events are more likely to have the wide $\theta_{\rm C}$ distribution due to more scatterings and then be removed. This cut accompanies a large uncertainty in the atmospheric NCQE-like background estimation, as described in the next chapter.

In the third reduction, the atmospheric neutrino events are reduced to less than 15% while the $\bar{\nu}_e$ signal is kept with more than the 80–90% efficiency depending on the $E_{\rm rec}$ region.

²The ratio Q_{50}/N_{50} has correlation with *pilike*.



Figure 11.13: The Q_{50}/N_{50} distributions for the $\bar{\nu}_e$ signal (left) and atmospheric neutrino (right) MC samples after the *pilike* cut. Both samples are from the 7.49 < $E_{\rm rec}$ < 29.49 MeV region.



Figure 11.14: The Cherenkov angle distributions for the $\bar{\nu}_e$ signal (left) and atmospheric neutrino (right) MC samples after the Q_{50}/N_{50} cut. Both samples are from the 7.49 $< E_{\rm rec} <$ 29.49 MeV region.

11.5 Fourth Reduction: Neutron Tagging

Tagging neutrons from the $\bar{\nu}_e$'s IBD is a powerful technique to select signal. The idea is to search for a 2.2 MeV γ -ray from neutron capture on hydrogen, whose typical time-scale is ~200 μs , by investigating the later window. Because the amount of backgrounds, such as PMT dark noise and radioactive events, is too many below 3.5 MeV, separating the 2.2 MeV signal from these backgrounds relies on the neural network technique, based on the boosted decision tree (BDT) [162]. In this section, the procedure and performance are explained briefly. Basic descriptions about the neutron tagging method in SK can be found in Refs. [92, 163, 164].

Procedure

The primary events are simulated in MC as described in Chapter 10. For the neutron tagging study, information about later hits are necessary. The PMT dark noise is simulated and convoluted in the region between the primary event timing and 18 μs later. The region after 18 μs and up to 535 μs (385 μs for some periods) reflects hits from the dummy spill data, which are taken with the T2K trigger when the beam is off. Since the PMT gain shift is observed, as described in Chapter 7, the dummy spill data are taken from 10 different periods over SK-IV, and the systematic error is estimated later. These extensions are added to both the $\bar{\nu}_e$ signal and atmospheric neutrino MCs. The tagging procedure is separated in two steps: the pre-selection and the BDT selection.

First, a 10 ns sliding time window is used to look for a hit cluster in the region $[+2, +535] \mu s$ (or $[+2, +385] \mu s$). If the number of hit PMTs in this 10 ns window (N_{10}) exceeds seven, $N_{10} > 7$, the cluster is kept as a 2.2 MeV γ -ray candidate. Figure 11.15 shows the N_{10} distributions of the neutron signal and background. To avoid a multiple counting of the same 2.2 MeV γ event, an additional search until 20 ns later is conducted, and additional clusters in this window, are treated as the same event.



Figure 11.15: Number of hit PMTs in a 10 ns sliding time window for the neutron signal and background in the region $[+2, +535] \mu s$. The blue line and arrow indicate the pre-selection criterion.

After the pre-selection based on N_{10} , a multivariate analysis based on the BDT is performed. In this analysis 22 variables are used: N_{10} , seven geometrical variables, seven PMT noise related variables, and seven fitter related variables. They are described in more detail in Refs. [92, 165, 166]. The BDT is trained with both the neutron signal and the dummy trigger background samples.

Performance

The performance is evaluated using the MC sample that contains the neutron signals and does not contain them. Figure 11.16 shows a relation of the signal efficiency and the mis-tag probability for the different operation periods. The efficiencies in the current working points are summarized in Table 11.3. The neutron tagging removes the accidental fake background effectively with keeping the signal efficiency as O(10)%.



Figure 11.16: The signal efficiency and the mis-tag probability for the different ten operation periods. Different colors correspond to the results from the different data taking periods.

Table 11.3: The signal efficiency and the mis-tag probability in the current working points.

Energy region	Signal efficiency	Mis-tag probability
7.49–9.49 MeV	0.129	2.08×10^{-4}
$9.49{-}11.49 { m MeV}$	0.151	4.06×10^{-4}
$11.49 - 19.49 { m MeV}$	0.146	3.51×10^{-4}
$19.49{-}29.49~{\rm MeV}$	0.241	5.27×10^{-3}

Calibration with an Americium-Beryllium source

In order to check the neutron tagging method, calibrations with an Am/Be neutron source are performed, following the procedure in Refs. [46, 163, 166]. The source is embedded in a 5 cm

cubic bismuth germanate oxide (BGO) scintillator, as shown in Figure 11.17. Alpha decay happens in an 241 Am, and is followed by a reaction of an alpha with a 9 Be, producing an excited carbon and a neutron. The carbon then de-excites with emission of a 4.44 MeV γ -ray:

$$\alpha + {}^{9}\text{Be} \rightarrow {}^{12}\text{C}^* + n, \qquad (11.5)$$

$$^{12}C^* \rightarrow ^{12}C + \gamma \text{ (prompt)}, \qquad (11.6)$$

$$n + p \rightarrow d + \gamma$$
 (delayed). (11.7)

The γ -ray from carbon decay is the prompt signal and the γ -ray from neutron capture is the delayed signal in this calibration. The calibration is conducted twice in 2009 and 2016 and at different positions inside the ID, A: (35.3, -70.7, 0.0) cm, B: (35.3, -1201.9, 0.0) cm, and C: (35.3, -70.7, 1500.0) cm in the coordinate where the ID center position is set to (0, 0, 0). The measurements are compared with the MC expectations and the results are summarized in Table 11.4. The observed efficiencies show good agreements in general with the predicted efficiencies. The largest discrepancy between the data and MC results, 21% in 2009 at the position A, is taken as a systematic uncertainty on the neutron tagging efficiency.



Figure 11.17: Photograph of the Am/Be source embedded in the BGO scintillator.

Table 11.4: Neutron tagging efficiencies in percent estimated by the Am/Be calibration both in data and MC.

Year	Position	Data	MC
	А	20.7 ± 0.4	16.3 ± 0.1
2009	В	23.2 ± 0.5	21.1 ± 0.1
	\mathbf{C}	25.9 ± 0.6	24.1 ± 0.2
	А	18.1 ± 0.3	15.2 ± 0.1
2016	В	23.9 ± 0.5	19.3 ± 0.1
	С	25.6 ± 0.6	23.3 ± 0.2

11.6 Reduction Summary

The numbers of observed events in four $E_{\rm rec}$ regions after each reduction are summarized in Table 11.5. Most events are reduced by the neutron tagging because of the very low probability of the accidental fake coincidence, as shown in Table 11.3. The reduction efficiencies are summarized in Table 11.6 for these energy regions. Total efficiencies are also shown with products of each selection efficiency. Here the multiplication starts after the FV cut.

Energy region [MeV]	7.49-9.49	9.49-11.49	11.49 - 19.49	19.49 - 29.49
fit quality cut	864437	400598	145226	609
spallation cut	69362	42420	17374	609
effwall cut	54966	35433	14776	551
pre-activity cut	54956	35422	14750	497
post-activity cut	54956	35420	14743	479
$pilike { m cut}$	49877	32750	14150	292
charge/hit cut	49377	32557	14077	255
Cherenkov angle cut	23677	19767	11401	132
neutron tagging	8	17	12	11

Table 11.5: Number of observed events after each cut in different $E_{\rm rec}$ regions.

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Energy region [MeV]	7.49 - 9.49	9.49 - 11.49	11.49 - 19.49	19.49 - 29.49
fit quality cut	>0.999	>0.999	>0.999	>0.999
spallation cut	0.478	0.549	0.827	1
effwall cut	0.924	0.921	0.920	0.918
pre-activity cut	>0.999	>0.999	>0.999	>0.999
post-activity cut	>0.999	>0.999	>0.999	>0.999
$pilike \ { m cut}$	0.974	0.978	0.982	0.980
charge/hit cut	0.999	0.998	0.995	0.989
Cherenkov angle cut	0.793	0.852	0.909	0.952
neutron tagging	0.129	0.151	0.146	0.241
Total	0.043	0.064	0.099	0.204

Chapter 12

Background Estimation

As overviewed in Chapter 10, the background is sorted into four types. The background estimates are summarized in Table 12.1 and the spectrum is shown in Figure 12.1. In the lower two energy bins, the main background sources are the ⁹Li and accidental fake events, while the atmospheric neutrino events become large in the upper two energy bins.

Energy [MeV]	7.49 - 9.49	9.49 - 11.49	11.49 - 19.49	19.49 - 29.49
Atmospheric- ν (ν -NCQE)	1.2 ± 0.9	$1.3{\pm}1.0$	$2.2{\pm}1.3$	$0.5 {\pm} 0.5$
Atmospheric- ν ($\bar{\nu}$ -NCQE)	$0.6 {\pm} 0.4$	$0.9{\pm}0.7$	$1.2 {\pm} 0.7$	$0.3 {\pm} 0.3$
Atmospheric- ν (non-NCQE)	0.2 ± 0.1	$0.2{\pm}0.1$	$1.1{\pm}0.3$	5.1 ± 1.2
⁹ Li	7.6 ± 3.5	5.5 ± 3.1	$2.8{\pm}1.8$	0
Reactor- ν	$2.0{\pm}2.0$	$0.1{\pm}0.1$	0	0
Accidental fake coincidence	$4.9 {\pm} 2.0$	$8.0 {\pm} 3.0$	4.0 ± 1.5	$0.7 {\pm} 0.2$
Total	16.5 ± 4.6	16.0 ± 4.5	11.3 ± 2.8	6.6 ± 1.3

Table 12.1: Summary of the background estimates in the SRN search.



Figure 12.1: Background energy spectrum after all the reductions. Different colors correspond to each background source. Shaded bars represent the total systematic error of the background.
12.1 Atmospheric Neutrinos

Backgrounds from the atmospheric neutrino interactions are estimated by MC, which is described in Chapter 10. This background is categorized into two: NCQE-like and the others. Estimation of each is explained in the following part.

12.1.1 NCQE-like Interaction

Below 19.49 MeV, the dominant atmospheric neutrino background is made by the NCQE-like interactions. To estimate this background, the measurement in Part II is used. The MC predictions of neutrino and antineutrino NCQE-like interactions are renormalized by multiplying the scale factors in Equation 8.12. This provides an inclusive estimation of the NCQE and NC 2p2h interactions. The errors of these factors are taken as cross section uncertainties.

There are two uncertainties about neutrino flux: the atmospheric neutrino flux uncertainty and the uncertainty due to the flux difference between the T2K and atmospheric neutrinos. A 15% is taken as the former error from Refs. [152, 167]. The latter one arises from the fact that the scale factors above are measured in the T2K fluxes while the current focus is the atmospheric neutrino flux and then the effect of cross section model uncertainties is different. To estimate this uncertainty, the ratios of flux-averaged events in the T2K beam and atmospheric neutrino fluxes for different cross section models are calculated. The ratios, R^i_{ν} and $R^i_{\bar{\nu}}$ for model *i* from Figure 8.4 in Chapter 8, are defined as follows:

$$R^{i}_{\nu} = \frac{\int \phi^{\text{T2K}}_{\nu} \sigma^{i}_{\nu-\text{NCQE}} dE_{\nu}}{\int \phi^{\text{TTM}}_{\nu} \sigma^{i}_{\nu-\text{NCQE}} dE_{\nu}},\tag{12.1}$$

$$R^{i}_{\bar{\nu}} = \frac{\int \phi^{\text{T2K}}_{\bar{\nu}} \sigma^{i}_{\bar{\nu}-\text{NCQE}} dE_{\bar{\nu}}}{\int \phi^{\text{ATM}}_{\bar{\nu}} \sigma^{i}_{\bar{\nu}-\text{NCQE}} dE_{\bar{\nu}}},\tag{12.2}$$

where ϕ^{T2K} and ϕ^{ATM} represent the T2K and atmospheric neutrino fluxes respectively, and $\sigma^i_{\nu\text{-NCQE}}$ and $\sigma^i_{\bar{\nu}\text{-NCQE}}$ correspond to neutrino and antineutrino NCQE cross sections on oxygen from model *i* respectively. Table 12.2 summarizes the relative ratios to R^{NEUT}_{ν} and $R^{\text{NEUT}}_{\bar{\nu}}$. The maximum differences are taken as systematic errors, 5% for neutrinos and 7% for antineutrinos.

Model (i)	$R^i_{ u}/R^{ m NEUT}_{ u}$	$R^i_{\bar{\nu}}/R^{\rm NEUT}_{\nu}$
NEUT	1	1
\mathbf{SF}	1.03	1.03
RMF	1.05	1.07
SuSA	0.96	0.98
RGF, EDAI	1.04	1.04
RGF, Democratic	1.05	1.06
RPWIA	0.98	0.96

Table 12.2: Relative ratios of the flux-averaged events from the T2K flux to the atmospheric neutrino flux from six models in Figure 8.4 to NEUT (the nominal model in the analysis).

Uncertainties of the random event efficiencies in the spallation cut affect the estimation of the NCQE-like events. The errors are 3% for 7.49–9.49 MeV, 3% for 9.49–11.49 MeV, and 1% for 11.49–19.49 MeV as shown in Table 11.2.

Since the Cherenkov angle distribution for the NCQE events is highly dependent on models of the neutrino interaction and the following secondary interaction, the uncertainty regarding the Cherenkov angle cut needs to be considered. Figure 12.2 shows $E_{\rm rec}$ distributions for the $\theta_{\rm C}$ region between 38 and 50 degrees obtained from the T2K FHC and RHC samples. The numbers of observed and predicted events are compared in each energy region. Since the statistics is limited, two samples are combined here. This treatment also gives similar proportions of the atmospheric neutrino and antineutrino NCQE interactions and hence is justified. The resulting differences are 42% for 7.49–9.49 MeV, 50% for 9.49–11.49 MeV, 18% for 11.49–19.49 MeV, and 84% for 19.49–29.49 MeV. These are taken as systematic uncertainties. Systematic errors about the other third reduction cuts are estimated similarly to the NCQE-like cross section analysis, as described in Chapter 7, and found to be as small as a few percent in total.



Figure 12.2: The $E_{\rm rec}$ distributions for the $\theta_{\rm C}$ region between 38 and 50 degrees obtained from the T2K FHC (left) and RHC (right) samples. These are before the CC interaction cut described in Chapter 6.

There are two systematic error sources in the neutron tagging: tagging efficiency and neutron multiplicity. As for uncertainty on the tagging efficiency, 21% is employed in this analysis as the maximum difference between the measured and predicted efficiencies in the Am/Be calibration, as shown in Chapter 11. In this analysis, the number of neutrons is required to be one, therefore the model uncertainty affecting the neutron multiplicity has to be estimated. Here the recent T2K measurement of the neutron multiplicity after neutrino interactions with the CC-dominant samples at Super-Kamiokande are used [116]. Figure 12.3 shows the average of the number of tagged neutrons as a function of reconstructed Q^2 . The ratios of the number of the observation to that of the prediction in Figure 12.3 are calculated for each Q^2 region. Here the sum of the numbers from the FHC and RHC samples is used. The results are summarized in Table 12.3. The numbers of tagged neutrons (N_{tagged}) for these Q^2 regions in the atmospheric neutrino MC sample are shown in Figure 12.4. The number of events in the $N_{tagged} = 1$ bin is varied so that the average of the number of tagged neutrons becomes the product of its original value

and the factors in Table 12.3. Here the events with $Q^2 > 3 \text{ GeV}^2$ are treated together with the events with $0.75 < Q^2 < 3 \text{ GeV}^2$ because the number of events in $Q^2 > 3 \text{ GeV}^2$ is small. The ratio of the number of events in the $N_{\text{tagged}} = 1$ bin after the variation to that before the variation is multiplied to each event depending on its Q^2 . Then the variance in the number of selected events is evaluated. The resulting variances are approximately 40% for both neutrinos and antineutrinos in every E_{rec} region.



Figure 12.3: Average of the number of tagged neutrons in the neutrino event as a function of reconstructed Q^2 in the T2K Run 1–9 FHC (left) and RHC (right) samples [116].

Table 12.3: Ratios of the number of the observation to that of the prediction in each Q^2 region calculated from Figure 12.3. The number of the observation is the sum of those from the FHC and RHC samples, and this is the same for the prediction as well $(N_{\rm obs} = N_{\rm obs}^{\rm FHC} + N_{\rm obs}^{\rm RHC})$ and $N_{\rm pred} = N_{\rm pred}^{\rm FHC} + N_{\rm pred}^{\rm RHC}$.

Q^2 region	$N_{\rm obs}/N_{\rm pred}$
$0.00 - 0.25 \text{ GeV}^2$	0.65
$0.25 - 0.50 \ { m GeV^2}$	0.72
$0.50 - 0.75 \ { m GeV^2}$	0.51
$0.75 - 3.00 \text{ GeV}^2$	0.82

Uncertainties on the NCQE-like background estimation is summarized in Table 12.4 for neutrinos and antineutrinos in different $E_{\rm rec}$ regions. The largest uncertainty comes from the Cherenkov angle cut and the neutron multiplicity. The uncertainties are improved for the region below 19.49 MeV from the previous 100% to 60-70%.



Figure 12.4: Number of tagged neutrons in the atmospheric neutrino MC sample for each Q^2 region. Top and bottom four correspond to neutrinos and antineutrinos, respectively.

Energy [MeV]	7.49 - 9.49	9.49 - 11.49	11.49 - 19.49	19.49 - 29.49
T2K cross section (in this thesis)		+32/-25	5(+31/-25)	
Atmospheric- ν flux		15	5(15)	
Flux difference		Ę	5(7)	
Spallation cut	3 (3)	3(3)	1 (1)	0 (0)
Cherenkov angle cut	42 (42)	50(50)	18 (18)	84 (84)
Other third reduction	3 (3)	3(3)	3(3)	3(3)
Neutron tagging efficiency		21	L (21)	
Neutron multiplicity	40 (39)	41 (40)	40 (40)	41 (42)
Total (neutrino)	+72/-69	+77/-74	+60/-57	+102/-100
Total (antineutrino)	+71/-68	+76/-74	+60/-57	+102/-101

Table 12.4: Summary of the NCQE background uncertainties for neutrinos and antineutrinos for each energy region. The numbers are shown in percent. The numbers for antineutrinos are shown in parenthes.

12.1.2 CCQE-like Interaction and Pion Production

The other atmospheric neutrino backgrounds are dominated by the events with decay-e's. The Michel spectrum is well-known, hence the MC spectrum in the 29.49–79.49 MeV region is fit by the observed spectrum in the same region. The fitting is done for the spectrum with the neutron tagging ¹. First, the spectrum shape is changed by smearing the spectrum, and this effect is found to be negligible. Second, the overall scaling of the spectrum is considered. In the fitting, χ^2 is calculated for each energy bin between 29.49 and 79.49 MeV. The fitting is done separately for different neutron tagging criteria (BDT cut score) used in each $E_{\rm rec}$ region, that is, the scale factors are obtained for each $E_{\rm rec}$ region. The results are summarized in Table 12.5. This includes all uncertainties about the flux model, the cross section model, and selection cuts. The results are consistent with each other among the different $E_{\rm rec}$ regions and accordingly the BDT scores as well. The reason for much smaller values than the nominal is that the current model may be inappropriate and this is consistent with the neutron multiplicity results from T2K shown in Figure 12.3 where the number of tagged neutrons in data is much lower than that in MC [116]. Figure 12.5 shows the result from the fitting for the neutron tagging condition in the 19.49–29.49 MeV region.

Table 12.5: Results of the Michel spectrum fitting for the neutron tagging conditions in each energy region.

Energy region	Scaling factor
7.49-9.49 MeV	$0.383 {\pm} 0.138$
$9.49 - 11.49 { m MeV}$	$0.377 {\pm} 0.122$
$11.49 - 19.49 { m MeV}$	$0.388 {\pm} 0.125$
$19.49{-}29.49~{\rm MeV}$	$0.361{\pm}0.084$

¹The fitting before the neutron tagging gives a better precision, but instead the large neutron tagging errors should be considered as shown in the NCQE-like background estimation.



Figure 12.5: The $E_{\rm rec}$ distributions in the 29.49–79.49 MeV region for data, the atmospheric neutrino MC, and the scaled MC with the neutron tagging condition in the 19.49–29.49 region.

12.2 Lithium-9

The ⁹Li background is simulated using the $\bar{\nu}_e$ signal MC as described in Chapter 10. Systematic uncertainty sources are separated into five: the production rate and the first to fourth reductions. In the analysis, the result in Ref. [115] is used as the production rate, which is $0.86 \pm 0.12(\text{stat.}) \pm 0.15(\text{syst.}) \text{ kton}^{-1}\text{day}^{-1}$ (a 22% uncertainty in total). The uncertainty in the first reduction is negligible. The second reduction error is explained below, and the third reduction error is a few percent as described in the NCQE-like part. As the neutron tagging uncertainty, 21% is taken from the Am/Be calibration.

The ⁹Li efficiency in the spallation cut is estimated as follows. First, the spallation likelihood is calculated in the same way as described in Chapter 11 for the pre and post samples, though here dt is replaced with random numbers following the exp $(-dt/\tau)$ where $\tau = 0.26$ sec. (Li9 lifetime). The resulting likelihood distributions for the 7.49–9.49 MeV region are shown in Figure 12.6. Then the selection efficiencies for each muon type are averaged with weights based on its fraction to the total muons to obtain "weighted efficiency". The outcomes are the efficiencies for one pair of an SHE event and a muon, then the random event efficiencies in Table 11.2 are multiplied to reflect all the pairs. The resulting ⁹Li efficiencies are 3.1% for 7.49–9.49 MeV, 4.1% for 9.49–11.49 MeV, and 13.1% for 11.49–19.49 MeV. Uncertainties come from the statistical error of the sample and the random event efficiency. Table 12.6 summarizes the efficiency in each muon type and the efficiencies.

In total, systematic errors on the ⁹Li background are 46% for 7.49–9.49 MeV, 56% for 9.49-11.49 MeV, and 64% for 11.49–19.49 MeV, respectively. There is no ⁹Li event in the region above 19.49 MeV.



Figure 12.6: Distributions of the spallation likelihood in the 9 Li sample for each muon type in the 7.49–9.49 MeV region. Dashed green lines represent the cut criteria, the right side of which is removed.

Table 12.6: Summary of the 9 Li efficiency in the spallation cut. The 9 Li efficiency is the product of the weighted efficiency and the random event efficiency.

$E_{\rm rec}$ region [MeV]	7.49 - 9.49	9.49 - 11.49	11.49 - 19.49
misfit or poorly-fit muons	0	$0.025 {\pm} 0.002$	$0.068 {\pm} 0.005$
single though-going muons	$0.059 {\pm} 0.027$	$0.059 {\pm} 0.039$	$0.135 {\pm} 0.064$
stopping muons	$0.170 {\pm} 0.126$	$0.468 {\pm} 0.253$	$0.758 {\pm} 1.471$
multiple muons	$0.106 {\pm} 0.011$	$0.037 {\pm} 0.012$	$0.112 {\pm} 0.027$
corner-clipping muons	0	0	0
Weighted efficiency muons	$0.065 {\pm} 0.023$	$0.074{\pm}0.035$	$0.158 {\pm} 0.088$
Random event efficiency	$0.478 {\pm} 0.014$	$0.549 {\pm} 0.016$	$0.827 {\pm} 0.010$
⁹ Li efficiency	$0.031{\pm}0.011$	$0.041{\pm}0.019$	$0.131 {\pm} 0.073$

12.3 Reactor Neutrino Background

Reactor neutrino background is estimated by renormalizing the $\bar{\nu}_e$ signal MC as described in Chapter 10. The reactor neutrino events populate only in the lowest energy bin. In this analysis, a conservative 100% uncertainty is assigned for the reactor neutrino events. The effect of this conservative error on the sensitivity is limited because the reactor neutrino background rate is small.

12.4 Accidental Fake Coincidences

The accidental fake background spectrum is obtained by multiplying the mis-tag probabilities in Table 11.3 to the observed spectrum before the neutron tagging. Since the estimation uses data, only statistical uncertainties should be considered except for uncertainties on the mis-tag probability. The statistical error is less than 1% for the region below 19.49 MeV and 9% for 19.49–29.49 MeV. The time variation in the PMT gain has a critical impact on the mis-tag probability ². Figure 11.16 shows the mis-tag probability as a function of the signal efficiency for ten different periods that cover the whole period of SK-IV. The errors due to this time variation are 41% for 7.49–9.49 MeV, 37% for 9.49–11.49 MeV, 38% for 11.49–19.49 MeV, and 26% for 19.49–29.49 MeV.

²This has no sizable impact on the signal efficiency in the neutron tagging because the signal has more hits.

Chapter 13

Results

13.1 Selected Events

The observed spectrum and the estimated background spectrum are shown in Figure 13.1. No significant excess is observed in data over the background prediction in every energy region.



Figure 13.1: Energy spectra of the observation and background prediction after all the reductions. Different colors correspond to each background source. Shaded bars represent the total systematic error of the background.

13.2 Model-independent $\bar{\nu}_e$ Flux Upper Limit

Since no significant excess is observed in the data spectrum, an upper limit on the $\bar{\nu}_e$ flux is calculated using pseudo experiments as follows. The number of signal events, N_{sig} , is calculated by the numbers of the observation and background (N_{obs} and N_{bkg} respectively) as $N_{\text{sig}} = N_{\text{obs}} - N_{\text{bkg}}$ with random variations of the statistical and systematic uncertainties on N_{obs} and

 $N_{\rm bkg}$. The pseudo experiments are generated assuming Gaussian-shape errors with means and variances summarized in Table 12.1, and performed separately for four $E_{\rm rec}$ regions. Figure 13.2 shows the result on the 7.49–9.49 MeV region.



Figure 13.2: Result of the pseudo experiments on the number of signal events with statistical and systematic variances for the 7.49–9.49 MeV region.

The 90% C.L. upper bound on the number of signal (N_{10}^{limit}) is calculated as the number, the integration between zero and which contains 90% of the integration above zero, as shown in Figure 13.2. Then the 90% C.L. upper limit on the $\bar{\nu}_e$ flux is calculated as:

$$\phi_{90}^{\text{limit}} = \frac{N_{90}^{\text{limit}}}{t \cdot N_p \cdot \bar{\sigma}_{\text{IBD}} \cdot \epsilon_{\text{sig}}},\tag{13.1}$$

where t is the live time [sec.], N_p is the number of free protons, $\bar{\sigma}_{\text{IBD}}$ is the IBD cross section $[10^{-41} \text{ cm}^2]$ at a mean neutrino energy in the corresponding region (\bar{E}_{ν}) , and ϵ_{sig} is the signal efficiency. Note that the neutrino energy is obtained as $E_{\nu} = E_{\text{rec}} + 1.8$ MeV in IBD. The results are shown in Table 13.1. For the sensitivity, a similar procedure is taken but by replacing the number of observed event (N_{obs}) with the number of nominal background events which is shown in Table 12.1. In the pseudo experiments here, statistical uncertainties on the background are considered. The sensitivity results are also shown in the same table. In the table, the sensitivity and upper limit per MeV are also shown. These are shown and compared with the previous searches in Figure 13.3. The present analysis places the world's most stringent upper limits in the region above 12 MeV.



Figure 13.3: Model-independent $\bar{\nu}_e$ flux upper limit at 90% C.L. with a 2970.1-day data set from SK-IV. The sensitivity in the current work is also shown. For comparisons, the upper limits by the KamLAND 2343 days [47], the SK-I/II/III spectrum analysis with 2853 days [45], and the SK-IV neutron tagging analysis with 960 days [46] and 2778 days [166] are shown together.

$E_{\rm rec}$ region [MeV]	7.49 - 9.49	9.49 - 11.49	11.49 - 19.49	19.49 - 29.49
$E_{\nu}(=E_{\rm rec}+1.8)$ region [MeV]	9.29-11.29	11.29 - 13.29	13.29 - 21.29	21.29 - 31.29
$t \times 10^8 \text{ sec.}] ([\text{days}])$	1.79(2075.3)		2.57(2970.1)	
N_p		$1.5 \times 10^{33} (22)$	2.5 kton FV	
$\bar{\sigma}_{\rm IBD} \; [\times 10^{-41} \; {\rm cm}^2] \; (\bar{E}_{\nu} \; [{\rm MeV}])$	0.72(10.29)	1.05(12.29)	2.17(17.29)	4.92(26.29)
$\epsilon_{ m sig}$	0.043	0.064	0.099	0.204
$N_{90}^{\text{sensitivity}}$	9.1	8.8	6.4	4.4
$\phi_{90}^{\text{sensitivity}} \ [/\text{cm}^2/\text{sec.}]$	109.2	34.1	7.8	1.1
$d\phi_{90}^{\text{sensitivity}}/dE_{\nu} \ [/\text{cm}^2/\text{sec.}/\text{MeV}]$	54.6	17.1	1.0	0.1
N_{90}^{limit}	5.2	10.5	7.8	9.2
$\phi_{90}^{\text{limit}} \ [/\text{cm}^2/\text{sec.}]$	62.1	40.8	9.4	2.4
$d\phi_{90}^{\text{limit}}/dE_{\nu} \ [/\text{cm}^2/\text{sec.}/\text{MeV}]$	31.0	20.4	1.2	0.2

Table 13.1: Summary of the 90% C.L. sensitivities and upper limits on the electron antineutrino flux in each energy region. \bar{E}_{ν} represents the mean neutrino energy in the region.

13.3 Discussion

13.3.1 Comparison with Theoretical Predictions

The 90% C.L. upper limits in this analysis are compared with theoretical predictions in Table 13.2. The current limits in the region above 13.29 MeV are a factor 3 to 30 above model predictions, while those in the lower energy regions are even farther.

Table 13.2: Comparison of the 90% C.L. upper limit on the $\bar{\nu}_e$ flux with the SRN theoretical predictions.

$E_{\nu} [{\rm MeV}]$	9.29-11.29	11.29-13.29	13.29-21.29	21.29-31.29
This work $[/cm^2/sec.]$	62.1	40.8	9.4	2.4
Horiuchi $+18$ [36] [/cm ² /sec.]				
$\xi_{2.5, ext{crit}} = 0.1$	1.47	1.22	1.82	0.49
$\xi_{2.5, \rm crit} = 0.5$	1.44	1.07	1.23	0.18
Nakazato $+15 [31, 37] [/cm^2/sec.]$				
Maximum, Inverted hierarchy	0.95	0.60	0.91	0.21
Minimum, Normal hierarchy	0.41	0.26	0.38	0.07
Horiuchi $+09$ [38] [/cm ² /sec.]	2.23	1.61	2.94	0.80
Lunardini09 [40] $[/cm^2/sec.]$	1.01	0.79	1.18	0.27
Ando $+09 \ [41] \ [/cm^2/sec.]$	1.11	0.74	1.18	0.27
Malaney97 [42] $[/cm^2/sec.]$	0.52	0.34	0.53	0.10
Hartmann+97 [43] $[/cm^2/sec.]$	0.95	0.65	1.09	0.25

13.3.2 Benefits of the T2K NCQE-like Results

In this work, the NCQE-like background is estimated using the T2K results for the first time, as demonstrated in Chapter 12. This provides more reliable estimation of this background than the

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previous analyses that are based on the theoretical predictions. The uncertainty size is reduced from 100% to 60–70% as shown in Table 12.4. With the T2K results, the search sensitivity (the upper limit) has been improved by 3% (2%) for the region $9.29 < E_{\nu} < 13.29$ MeV and by 12% (10%) for the region $13.29 < E_{\nu} < 21.29$ MeV in comparison to an analysis with a 100% uncertainty.

The estimation with the T2K measurements is promising in terms of its possible improvements. As mentioned in Chapter 8, precisions of the NCQE cross section will be improved with the RCNP results presented in Part III, more precise flux prediction, and larger statistics. Furthermore, the neutron tagging will be applicable to the NCQE sample and this would avoid large uncertainty from the neutron multiplicity which is explained in Chapter 12. This is more feasible in SK-Gd because of the higher neutron tagging efficiency. In the era of Hyper-Kamiokande, thanks to its ~8.4 times larger fiducial mass and the upgrade of J-PARC and the neutrino beamline as mentioned in Chapter 8, ~1000 events are expected in the SRN signal region in the $E_{\rm rec}-\theta_{\rm C}$ phase space with the neutron tagging. This could provide the NCQE background estimation with a precision better than 10%, avoiding large uncertainties due to neutron multiplicity and Cherenkov angle cut.

13.3.3 Future Prospects

The 3σ sensitivities at SK-Gd and HK are evaluated with the same procedure as explained above for the 90% C.L. sensitivities. In SK-Gd, since the γ -ray energy is ~8 MeV, the search is free of the accidental fake background. Other than the accidental background, the same background sources with the current systematic uncertainties are assumed and the absolute amount of each background is scaled by live time. A 90% neutron tagging efficiency is assumed for SK-Gd. For HK, the neutron tagging efficiencies twice better than those in SK with the same mis-tag probabilities, shown in Table 11.3, are assumed, because the γ -ray energy is 2.2 MeV and then HK also suffers from the large background by PMT dark noise and radioactive sources. Here the other backgrounds than the accidental coincidences are scaled by live time and detector mass and the same error sizes as the current analysis are assumed.

The results for SK-Gd are shown in Figure 13.4. Here the results only for the region $E_{\nu} > 13.29$ MeV are presented, because the lower region is less promising. Models by Horiuchi+18 and Horiuchi+09 can be tested after 5–10 years of operation. The reach after the 10-year operation is comparable or a bit worse compared to predictions by Lunardini09, Ando+09, and Hartmann+97. However, the sensitivity is not enough to reach the predictions by Nakazato+15 and Malaney97. Note that the evaluations are based on the current background composition and systematic uncertainties, but it is highly probable that the ⁹Li background will be reduced with improvements on the spallation cut and use of various neutron information, or understood well through the spallation measurement as demonstrated in Ref. [115]. This would help to achieve the better sensitivity and then test more models.

The results for HK are shown in Figure 13.5 also only for the region above 13.29 MeV in neutrino energy. According to the results, HK can test most models except for the minimum flux prediction by Nakazato+15, while it is not so far. Again note that if the ⁹Li background is reduced or estimated more precisely, it is probable to test the whole region of the Nakazato+15 prediction.

As mentioned above, the situation about the ⁹Li background will improve by using neutron information. Once the ⁹Li background uncertainty and its rate are reduced, the improved measurements of the NCQE-like interactions in SK-Gd and HK would be much more beneficial. Figure 13.6 shows the 3σ sensitivities in SK-Gd with a 0.1% Gd doping for different conditions



Figure 13.4: The 3σ sensitivity for the $\bar{\nu}_e$ flux as a function of SK-Gd operation period with a 0.1% Gd doping for the neutrino energy region 13.29 $< E_{\nu} <$ 21.29 MeV (left) and 21.29 $< E_{\nu} <$ 31.29 MeV (right). The predictions from the models explained in Chapter 1 are also shown.



Figure 13.5: The 3σ sensitivity for the $\bar{\nu}_e$ flux as a function of Hyper-Kamiokande operation period for the neutrino energy region $13.29 < E_{\nu} < 21.29$ MeV (left) and $21.29 < E_{\nu} < 31.29$ MeV (right). The predictions from the models explained in Chapter 1 are also shown.

on the NCQE-like background. Here the non-NCQE background is scaled by live time with the same systematic error as the analysis in this thesis and the amount of ⁹Li background is reduced to 1/5 from the simple scaling by live time with a 10% uncertainty. The treatments of the reactor and accidental backgrounds are the same as above for SK-Gd. Three conditions for the NCQE-like background are considered: the absolute amount scaled by live time with 100% and 60% uncertainties, and the absolute amount reduced by 30% (×0.7) from the simple scaling with a 40% uncertainty. The 100% and 60% error cases correspond to the previous and current situations. Since the number of neutrons from atmospheric neutrinos seems smaller than the MC prediction as shown in Chapter 12, the absolute background amount may be reduced in the future, then the third case assumes the reduced NCQE-like background. With an improved estimation of the NCQE-like background, models by Horiuchi+18, Lunardini09, Ando+09, and Hartmann+97 can be tested in the 13.29-21.29 MeV region, while the reach with a 100% error is not enough for these models. The benefits of improvements on the NCQE-like background estimation are limited for the region above 21.29 MeV. The Michel spectrum fitting will be improved with higher statistics in the future, providing prediction on the CCQE-like event rate with better precision. All these improvements would help a future discovery of the SRN flux. Further sensitivity results are given in Appendix E.



Figure 13.6: The 3σ sensitivity for the $\bar{\nu}_e$ flux as a function of SK-Gd operation period with a 0.1% Gd doping for the neutrino energy region 13.29 $< E_{\nu} <$ 21.29 MeV (left) and 21.29 $< E_{\nu} <$ 31.29 MeV (right) for different NCQE-like background conditions. Note that assumptions on the background are different from those in Figure 13.4 as explained in the text. The predictions from the models explained in Chapter 1 are also shown.

Part V Summary

Chapter 14

Conclusion

Supernova explosions are among the most powerful and complex phenomena in the universe, and unraveling the details of the explosion and properties of the supernova itself would help solve various mysteries in particle physics, nuclear physics, and astrophysics. There have been frequent observations of supernovae in optical surveys, though the observation via neutrinos is limited to SN1987A. Supernova relic neutrinos (SRNs), if detected, would provide valuable information about the supernova explosion mechanism as well as star formation history. The atmospheric neutrino neutral-current quasielastic-like (NCQE-like) interactions are among the dominant background in SRN searches at water Cherenkov detectors. In this thesis, a measurement of the NCQE-like interaction with T2K neutrino and antineutrino beams based on nuclear de-excitation γ -rays was presented, and its application to an SRN search at Super-Kamiokande was also reported.

Beam monitoring with the muon monitor is essential to stable data taking in T2K, and this has been achieved through various investigations. It helped T2K accumulate data with 14.94×10^{20} and 16.35×10^{20} protons-on-target exposures of the neutrino and antineutrino beams, respectively. With these data sets, the flux-averaged NCQE-like cross sections were measured as:

> $\langle \sigma_{\nu\text{-NCQE}} \rangle = 1.70 \pm 0.17 (\text{stat.})^{+0.51}_{-0.38} (\text{syst.}) \times 10^{-38} \text{ cm}^2/\text{oxygen},$ $\langle \sigma_{\bar{\nu}\text{-NCQE}} \rangle = 0.98 \pm 0.16 (\text{stat.})^{+0.26}_{-0.19} (\text{syst.}) \times 10^{-38} \text{ cm}^2/\text{oxygen},$

at flux-averaged energies of 0.82 GeV and 0.68 GeV for neutrinos and antineutrinos, respectively. Simultaneous treatment of both FHC and RHC data has resulted in similar sized errors for the neutrino and antineutrino results. These are the world's most precise measurement results to date, and the antineutrino result is the first measurement of this channel. The obtained results were found to be consistent with currently available models within the precisions. Based on distributions from the FHC and RHC samples, properties of γ -rays emitted from the secondary nuclear reactions were investigated. In addition, distributions in the kinematic regions of interest for SRN searches were studied for the first time in this thesis. This has suggested an importance of understanding the secondary- γ emission. Possible updates to the measurement utilizing the neutron information were also discussed.

The largest uncertainty in the NCQE-like measurement comes from the modeling of γ -rays emitted from neutron-oxygen reactions. Prior to the work in this thesis there was little data on this interaction. In order to provide experimental data, a measurement of γ -ray production via neutron-oxygen reactions with an 80 MeV neutron beam was performed at RCNP. In the experiment, several γ -rays of various energies thought to come from neutron-oxygen reactions were observed and their production cross sections were measured to ~20% precision. The results indicate that the current models used in the NCQE-like measurement are incomplete. This experiment established the basic measurement method and suggests there is the potential to reduce the secondary- γ uncertainty from 13% to less than 5% if similar measurements are made with different neutron energies. Additional measurements at neutron energies of 30 and 250 MeV were performed in the same facility and the data analysis is on-going towards the model improvements together with the results obtained in this thesis.

An SRN search was performed using a 2970.1-day data set from Super-Kamiokande IV. In order to remove a large amount of muon spallation background, a data-driven method was developed. The neutron tagging method was tuned based on the boosted decision tree technique and has removed huge accidental backgrounds. In the estimation of the atmospheric NCQElike background, the T2K results are used. This new estimation has reduced the uncertainty from 100% to 60%, improving the search sensitivity by 12% compared to an analysis with a 100% uncertainty on the NCQE-like background. No significant excess over the prediction was observed in the data spectrum, and an upper limit on the $\bar{\nu}_e$ flux was placed. The result is the world's most stringent above 13.3 MeV in neutrino energy, which is a factor 3 to 30 above model predictions. In future water Cherenkov detectors, such as SK-Gd and Hyper-Kamiokande, which will have better background rejection power or a larger fiducial mass, the NCQE-like background will become more important. The search sensitivities and the potential to make constraints on SRN models at these detectors were also discussed. The methods presented in this thesis are applicable to SRN searches at these detectors, and may help a future discovery of the SRN flux.

Appendices

Appendix A

Beam Studies with MUMON

A.1 Correlation between Proton and Muon Beams

Muon beams are affected by proton beam properties such as intensity, position, and width. These are studied and some of them are shown in Appendix B.

A.2 Correlation between Horn Current and Muon Beam

The horn current affects the magnetic field and accordingly the muon beam. This effect is corrected in the measurement. In order to obtain the correction functions, the horn current scans are performed both in FHC and RHC modes. The horn current is measured by two horn power supplies (HPS1 and HPS2). The HPS1 measures the current for the horn-1, while the HPS2 measures the current for the horns-2 and 3 (the current is separated into two). The scan points are shown in Figure A.1. The results in the FHC and RHC modes are shown Figures A.2 and A.3, respectively.



Figure A.1: Horn scan points in FHC (left) and RHC (right) in the 2D HPS1-HPS2 plane. Magenta boxes represent the points used for obtaining the correction functions. The other points are used for the cross check after the correction.



Figure A.2: Horn scan results in the FHC mode for the HPS1 (top) and HPS2 (bottom) scans. The left and right panels give the results from Si and IC, respectively.



Figure A.3: Horn scan results in the RHC mode for the HPS1 (top) and HPS2 (bottom) scans. The left and right panels give the results from Si and IC, respectively.

Appendix B

Electron-Multiplier Tubes for MUMON

B.1 Concerns for the Current MUMON Detectors

In the near future, J-PARC will strengthen its beam power up to 1.3 MW from the current 485 kW. In addition, the electromagnetic horn current is increased from 250 kA to 320 kA. These will provide nearly tripled power beams. The current MUMON detectors are expected to suffer from issues in such situation, which are observed even at present.

For Si sensors, the yield degradation is observed and this is considered due to radiation damage. Figure B.1 shows a history of ratio of the average Si yield to the average IC (Ar) yield over the T2K operation. It is found that the Si yield has been continuously degraded over the period. Note that Si sensors were replaced twice so far; the whole of 49 ch was replaced with new ones (2nd generation) after MR Run 49, and the 24 ch were changed to the new ones (3rd generation) after MR Run 74 (the remaining 25 ch are the 2nd generation). The ratios of the yield sum of these 25 ch to that of 24 ch before and after the second replacement are shown in Figures B.2 and B.3. Just after the replacement, the new sensors show their yield decrease in a short period. This was reported from the studies in the first replacement. After the 3rd generation sensor yield gets stable, the degradation rate of the 2nd generation is found to be faster than that of the 3rd generation.

For IC, the signal linearity is broken at high intensity due to the space charge effect that the electric field inside the detector is distorted by lots of accumulated ions. This effect is more visible in the latter bunches because more ions are accumulated from the former bunches. Figure B.4 shows that linearity response of IC (Ar) is broken above 400 kW. The feature for the bunches 1 to 7, seen in the right panel of the figure, is attributed to the fact that the Si detectors have longer decay time as shown later. The drop in the 8th bunch is due to the space charge effect of IC (Ar). One solution to this issue would be change of the gas since ligher ions will be sweeped faster and then no accumulation causing the space charge effect happens. However, the pileup becomes a problem instead when He gas is used, as shown in Figure B.5. This is because contributions to signal not only from electrons but also from ions are visible. Such pileup clearly affects the bunch-by-bunch beam monitoring.



Figure B.1: Ratio of the average signal yield of Si to that of IC (Ar) over the T2K operation. Si sensors are replaced twice so far and the second replacement was conducted for only half of 49 sensors.



Figure B.2: Ratio of the average yield of odd-numbered Si sensors to that of even-numbered Si sensors in certain periods in T2K Run 8. All sensors are the 2nd generation ones.



Figure B.3: Ratio of the average yield of odd-numbered Si sensors to that of even-numbered Si sensors in certain periods in T2K Run 9. The odd-numbered sensors are the 3rd generation and the even-numbered ones are the 2nd generation.



Figure B.4: IC (Ar) yield for the 8th bunch at several beam intensities under a +250 kA horn operation (left) and the ratio of the IC (Ar) to the Si center channels for each bunch at 460 kW and +250 kA horn current (right).



Figure B.5: IC (He) signal waveform at 340 kW and +250 kA horn current, equivalent to 2.5×10^6 /cm² per 80 ns (left), and IC (Ar) signal waveform at 480 kW and -250 kA horn current, equivalent to 2.3×10^6 /cm² per 80 ns (right).

B.2 Electron-Multiplier Tubes

For the reasons described above, a new detector for the muon monitoring is desired under the future high intensity operation. Electron-multiplier tubes (EMTs) are one candidate as a new detector. Secondary electron emission (SEM) monitors are usually radiation tolerant and their response is fast, which are important for the muon monitor. Photomultiplier tubes (PMTs) are one of the SEM detectors; however, the photocathode is not necessary for the muon detection. Replacing the photocathode with another material, in the present work with aluminum, EMTs are considered as a candidate. Indeed, PMTs are also tested but showed worse performance than EMTs about their linearity and stability, as explained later in this chapter. The schematic illustration of the signal multiplication is shown in Figure B.6. Secondary electrons are emitted either at the aluminum cathode or at the dynodes when a muon passes through the detector. Those secondary electrons are then accelerated and hit the downstream dynodes to produce further secondary electrons.



Figure B.6: Schematic illustration of the signal multiplication in EMTs.

The secondary emission efficiency is expressed by the number of emitted electrons over that of incident particles and is specific to the type of material and the properties of incident particles such as particle type and energy. In Figure B.6, Δ and δ represent the secondary emission efficiencies for aluminum and dynodes, respectively. Here a subscript "e" is used for electrons and a subscript " μ " is used for muons as incident particles. The subscripts of δ represent the dynode numbers. The product of the secondary emission efficiencies of all dynodes gives the gain of the PMT:

$$G = \delta_{e,1} \times \delta_{e,2} \times \dots \times \delta_{e,n} = \prod_{i=1}^{n} \delta_{e,i}.$$
 (B.1)

For the muon monitor, the signal is generated mainly by muons and electrons (δ -rays) produced by muon hits. The energy of δ -rays is up to several hundred MeV according to the beamline simulation [74]. The muons and δ -rays penetrate the EMT, while most secondary emission electrons stop at the dynodes. The final output signal (Q) is expressed as follows:

$$Q = Q_{\mu} + Q_e, \tag{B.2}$$

$$Q_{\mu} = e \cdot \phi_{\mu} \cdot \left\{ A_{\text{sur}} \cdot \Delta_{\mu,\text{Al}} \cdot \prod_{i=1}^{n} \delta_{e,i} + \sum_{i=1}^{n-1} \left(A_{i} \cdot \delta_{\mu,i} \cdot \prod_{j=i+1}^{n} \delta_{e,j} \right) \right\},$$
(B.3)

$$Q_e = e \cdot \phi_e \cdot \left\{ A_{\text{sur}} \cdot \Delta_{e,\text{Al}} \cdot \prod_{i=1}^n \delta_{e,i} + \sum_{i=1}^{n-1} \left(A_i \cdot \delta_{e,i} \cdot \prod_{j=i+1}^n \delta_{e,j} \right) \right\},\tag{B.4}$$

where e represents the elementary electric charge (1.6×10^{-19} C), A_{sur} and A_i are the area of the aluminum cathode surface and each dynode surface [cm²] respectively, and ϕ_{μ} and ϕ_{e} are the muon and δ -ray fluxes [/cm²]. The first terms in Eqs. B.3 and B.4 correspond to the secondary electrons at the aluminum cathode, and the second terms correspond to those at the *i*-th dynode.

B.3 First Prototype Detectors

Two EMTs were made based on HAMAMATSU[®] PMT R9880 by depositing aluminum on the cathode, termed as EMTC3 and EMTC4. The reason why R9880 was selected is that it is short enough for the installation space. Figure B.7 shows a picture of the EMTC3 sensor and Figure B.8 shows the divider curcuit diagram for EMTs. In the figure, the resistances R_1-R_{10} are set to 330 k Ω and R_{11} is set to 160 k Ω . This setting gives uniform voltage differences between the dynodes. The capacitors, C_1-C_{11} , are put to compensate for the charge used on the dynodes in the multiplication. To maintain linearity of the EMT response, sufficient charge (usually 100–1000 times the consumed charge) should be stored in the capacitors. The 51 Ω damping resistances (R_{12} and R_{13} in the figure) are inserted to reduce waveform ringing, but these are not used this time so that the charged consumed in the earlier bunches can be compensated for quickly from the capacitors.

In the present work, two divider curcuits are made (C3 and C4). Table B.1 summarizes the capacitances and stored charges in each capacitor in C3 and C4 when a negative bias -500 V is



Figure B.7: A photograph of EMTC3. The monitor radius is 8 mm.



Figure B.8: Schematic diagram of the divider circuit of the prototype EMT. "K", "P", "DY" and "GND" represent the cathode, anode, dynode, and ground, respectively. The resistances R_1-R_{10} are 330 k Ω , and R_{11} is 160 k Ω . The capacitances are given in Table B.1.

Table B.1: Capacitances and stored charges for EMTC3 and EMTC4 when -500 V is applied.

	EMTC	C3	EMTC	C4
	capacitance (nF)	charge (μC)	capacitance (nF)	charge (μC)
K-DY1 (C_1)	-		-	
DY1-2 (C_2)	-		-	
DY2-3 (C_3)	-		-	
DY3-4 (C_4)	-		-	
DY4-5 (C_5)	-		-	
DY5-6 (C_6)	-		100	4.8
DY6-7 (C_7)	-		100	4.8
DY7-8 (C_8)	10	0.48	100	4.8
DY8-9 (C_9)	10	0.48	330	15.7
DY9-10 (C_{10})	10	0.48	330	15.7
DY10-GND (C_{11})	15	0.35	330	7.6

applied. Only C_8 to C_{11} were used for EMTC3 and C_6 to C_{11} for EMTC4, and other capacitors were removed (represented as "-" in the table).

Both EMTs were installed at the downstream of the IC. The installation positions are shown in Figure B.9. The signal and high-voltage cables for the EMTs are the same ones as those for the Si and IC sensors. The readout electronics is also the same but the attenuator module is not used for the EMTs.



Figure B.9: Installation positions of the prototype EMTs overlaid with the IC sensor positions (left) and a zoom version focusing around the EMTs (right). Green squares in the left panel indicate the 49 ch of the IC and solid magenta square corresponds to the center channel.

Output charge

The expected charge for the prototype detectors can be calculated by using Eqns ??. To simplify the case contributions from δ -rays are ignored and the area of each aluminum and dynode surface is assumed to be the same (A). The radius is 8 mm then the surface area is $A = 2.01 \text{ cm}^2$. It is assumed that particles are incident on the EMT perpendicular to the surface and then the effective surface area is not changed. In addition, the secondary emission efficiencies for electrons of all dynodes $(\delta_{e,i})$ are assumed to be equal (δ_e) . At -500 V the typical gain of R9880 is 5×10^3 and the number of dynodes is n = 10. Therefore the gain per dynode is calculated to be $\delta_e \sim 2.35$. The secondary emission efficiencies for several GeV muons, $\Delta_{\mu,\text{Al}}$ and $\delta_{\mu,i}$, are assumed to be 0.08. The normalied muon flux under the +250 kA horn operation is $\phi_{\mu}^{\text{normalized}} = 1.09 \times 10^5 \text{ /cm}^2/10^{12}$ POT. At the proton beam power of 460 kW, the number of protons is $N = 3.0 \times 10^{13}$ POT/bunch. The muon flux can be calculated as $\phi_{\mu} = \phi_{\mu}^{\text{normalized}} \cdot N$. With assumptions above the expected EMT charge is calculated to be 730 pC/bunch at 460 kW beam power and +250 kA horn current. This power is corresponding to a muon flux of 3.3×10^6 /cm² per 80 ns beam bunch. The measured charge outputs per beam bunch for EMTC3 and C4 when -500 V was applied are shown in Table B.2. The measurement result is found to be in a good agreement with the expectation. The difference in the output charge between C3 and C4 is compatible with the expected difference between individual PMTs.

Table B.2: EMT output signal size per bunch at 460 kW beam intensity and +250 kA horn current (muon flux of 3.3×10^6 /cm² per 80 ns beam bunch) with applied voltage of -500 V. The expected charge is 730 pC/bunch.

Bunch#	EMTC3 charge [pC]	EMTC4 charge [pC]
1	873.1	784.9
2	870.7	787.3
3	866.9	788.6
4	855.9	787.9
5	860.4	797.0
6	850.6	795.5
7	847.8	798.5
8	854.1	797.7
Average	859.9	792.2

Time response

Figure B.10 shows EMTC3 and EMTC4 waveform examples. The signal has a tail component due to both the detector intrinsic property and reflections from cables and electronics modules. These tails could affect the performance of bunch-by-bunch basis beam monitoring. The ratio of the integration of the tail region to the integration of the 1st bunch region is calculated to evaluate the tail component fraction. This is done for two tail regions as shown in Figure B.10; Tail-1 as earlier and Tail-2 as later tail parts. The tail sizes of the Si center channel, the IC center channel, EMTC3, and EMTC4 are shown in Figure B.11. Here the beam intensity is 450 kW and the horn current setting is +250 kA. The EMTs show smaller tail sizes ($\sim 1\%$) than the Si and IC sensors (a few %). This indicates that EMTs perform better than the current detectors in terms of signal response.



Figure B.10: Examples of the EMTC3 (left) and C4 (right) waveform. Two tail parts (Tail-1 and Tail-2) are shown together in shaded bands.

Intensity resolution

Figure B.12 shows signal sizes normalized with the proton beam power for beam spill, from the Si center channel, the IC center channel, EMTC3, and EMTC4. The proton beam power and the horn current are 450 kW and +250 kA, respectively. The intensity resolutions of C3 and



Figure B.11: Relative sizes of Tail-1 (left) and Tail-2 (right) to the 1st bunch signals. The proton beam power and the horn current setting are 450 kW and +250 kA respectively, corresponding to a muon flux of 3.2×10^6 /cm² per 80 ns beam bunch.

C4 are 0.34% and 0.41% respectively. These of Si and IC are better than the EMTs (0.25% and 0.24% respectively). Each detector resolution is summarized in Table B.3, including both for the 1st bunch only and for the spill. The statistical fluctuation effect on each value is less than 0.01%. The effect of noise due to the readout system such as cables and electronics modules is evaluated by integrating the baseline before the beam spill to be less than 0.1%. The EMTs show a bit worse resolution than the current detectors. However, a 1% uncertainty on the intensity measurement for each of 49 ch sensors leads to an 0.06 mrad uncertainty in the beam direction measurement, which is much smaller than the total precision of 0.28 mrad. The current intensity measurement precision is limited by the readout system calibration (a few %), therefore the intensity resolution of the EMTs fulfills the requirements for the muon monitor.

Table B.3: Intensity resolution of each detector for spill and the first bunch only. The proton beam intensity is 450 kW and the horn current is +250 kA.

Detector	Spill (8 bunch sum)	First bunch
EMTC3	0.34%	0.73%
EMTC4	0.41%	0.78%
Si center	0.25%	0.37%
IC (Ar) center	0.24%	0.33%

Linearity performance

Beam intensity scans were carried out to test the linearity response of the EMTs. In the scans, the beam power was tuned to be 13 kW, 50 kW, 150 kW, 260 kW, 340 kW, 400 kW, 460 kW, and 500 kW, and the horn current was set to +250 kA. For the EMTs two different voltages, -500 V and -450 V, were applied to study the space charge effect. This occurs when the number of produced electrons is large, which causes the electric field distortion and accordingly signal degradation. The scan conditions are summarized in Table B.4.

The signal yields are corrected for the horn current effect (see Ref. ?? for details about the relationship between the muon flux and the horn current). In the intensity scans, the proton



Figure B.12: The normalized signal sizes of EMTC3 (left top), EMTC4 (right top), Si (left bottom), and IC with Ar gas (right bottom) under the 450 kW beam power and the +250 kA horn current.

beam position was kept within ± 0.5 cm, monitored by SSEM19 and SSEM18. The effect of this fluctuation on the muon flux is less than 1%. The proton beam width changes as the beam power changes, from 2 mm (1.5 mm) at the lowest power to 4.8 mm (4 mm) at the highest power in the horizontal (vertical) direction. The effect of this change on the muon flux is corrected using MC simulation. For various conditions on the beam width, the muon flux at the EMT position is simulated. The simulation result is shown in Figure B.13. The measured yield is corrected by the ratio of the yield at the measured beam width to that at the nominal condition of 4 mm in both horizontal and vertical directions. During the scans the beam width was taken from SSEM18, since SSEM19 had some unreliable points at very low beam intensities. The beam width was too narrow for the monitor sensitivity and beam profile reconstruction was therefore not reliable at those points. The consistency between SSEM19

Table B.4: Proton bea	m powers	and applied vo	oltages to	the EM7	Is in the bea	am intensity	scans.
The number of proton	s per kW	at a repetition	cycle of 2	2.48 sec is	s 5.3×10^{11}	protons/spil	l/kW.
:	Scan	Ream nower	[kW]	Applied 1	HV [V]		

Scan	Beam power [kW]	Applied HV [V]
Ι	150, 260, 340, 400, 460	-500
II	260, 340, 400, 460	-450
III	13, 50	-500, -450
IV	500	-500

and SSEM18 was confirmed by other reliable points. In order to validate the width correction, two different beam widths, 2.6 mm (2.2 mm) and 4.2 mm (3.2 mm) for the horizontal (vertical) direction, were tried at 150 kW ($\sim 80 \times 10^{12}$ protons/spill) in Scan I.



Figure B.13: Ratio of the muon flux at the EMT position for various proton beam widths to that at beam width = (4, 4) mm obtained by the simulation.

Figure B.14 shows the results from the Si center channel. The left panel shows the result before the beam width correction and the right panel shows that after the correction. The horn current effect is corrected in both results. At low intensities the plots are more scattered due to a poor signal-to-noise ratio. This figure shows the beam width correction works properly. It is more visible looking at the points at 150 kW in Scan I. The signal linearity is kept within $\pm 1\%$ above 100 kW up to 4500 kW.



Figure B.14: Beam intensity scan results for the Si center channel before (left) and after (right) the beam width effect correction. Different colors represent different scans, each of which is summarized in Table B.4.

The scan results for EMTC3 and EMTC4 are shown in in Figures B.15 and B.16, respectively. The results are after the horn current and beam width corrections. In the figures, both cases with -500 V and -450 V applied as high-voltage are shown. EMTC4 shows better linearity performance than EMTC3, because the capacitance used in the divider circuit for C4 was improved. Results with lowe voltage show better linearity, which indicates that the space charge effect is more visible under the -500 V application. EMTC4 with -450 V applied shows

as good linearity as Si up to 460 kW (muon flux of 3.3×10^6 /cm² per 80 ns beam spill). To further improve linearity response, the different divider ratio can be changed.



Figure B.15: Beam intensity scan results for EMTC3 with -500 V (left) and -450 V (right) applied.



Figure B.16: Beam intensity scan results for EMTC4 with -500 V (left) and -450 V (right) applied.

Yield stability

Signal stability <3% is required for the muon monitor. The prototype EMTs were exposed to the muon beam over the five data taking periods, as summarized in Table B.5. EMTC3 was installed before Period I. Since several tests including high-voltage and attenuation level tunings were performed, therefore the stability before Period I is not shown here. EMT4 was installed before Period II. There is about half a year beam off period between Periods II and III, during which the EMT high-voltages were turned off. In the middle of Period V, a short turn off of the high-voltage was conducted for one day.

Figures B.17, B.18, B.19 and B.20 show the yields as a function of time for the Si center channel, the IC center channel, EMTC3, and EMTC4. The horn current correction is applied. The yield jumps are observed twice in EMTC3, the cause of which is still unknown, but these appear as synchronized with unrelated IC calibration work. Both EMTC3 and C4 show drifts in their yields in the initial high-voltage applications in Periods I and III for EMTC3 and Periods II and III for EMTC4, respectively. This drift is considered due to the stabilization of the dynode materials such as alkali metals and antimony (Sb). PMTs usually require "warming-up" by irradiation with light for the initial stabilization; however, this is not possible for EMTS
Period	Horn current [kA]	HV [V]	POT $[\times 10^{18}]$
I (23, Feb., $2017 \sim 30$, Mar., 2017)	+250	-500	224.1
II (31, Mar., 2017 ~ 12, Apr., 2017)	+250	-500	76.8
III (16, Oct., 2017 \sim 22, Oct., 2017)	+250	-505	20.5
IV (22, Oct., 2017 \sim 2, Nov., 2017)	-250	-505	59.4
V (2, Nov., 2017 ~ 22, Dec., 2017)	-250	-450	305.8

Table B.5: Beam conditions and high-voltages for EMTC3 and EMTC4 during each beam exposure period.

since they do not have a photocathode. The recommended warm-up output charge is several μ A for several minutes, which is equivalent to several mC. Table B.6 shows the integrated charge before the EMT signal gets stable. The yields seem reasonable compared to the expected charge for the PMT warming-up. For later irradiations both C3 and C4 stabilized after fewer incident protons. This is thought to be due to stabilization of the dynode materials to some level by the former irradiation. After the initial drift period, the yield is stable within $\pm 1\%$ excluding some periods where the yield fluctuated due to changes in the EMT high-voltage and the proton beam conditions. EMTs usually satisfies the requirement of <3% signal fluctuation.

Table B.6: Total charge integration prior to EMT signal yield stabilization. The calculations for Period III assume the charge per PMT is larger by 10% since a bit higher-voltage (-505 V) was used.

EMT number	Period	POT amount $[\times 10^{18}]$	Integrated charge [mC]
C3	Ι	~ 70	~ 2.0
	III	~ 13	~ 0.4
C4	II	~ 50	~1.3
	III	~ 13	~ 0.4



Figure B.17: Signal yield of the Si center channel as a function of time.



Figure B.18: Signal yield of the IC (Ar) center channel as a function of time. The yield jumps seen in Period III and IV, marked with magenta circles, are due to calibration work where the entire IC system is moved (see Ref. [74] for the calibration method).



Figure B.19: Signal yield of EMTC3 as a function of time. Two yield jumps are seen and seem to be synchronized with IC calibration work, although the cause is not fully understood. After a short HV-off period during Period V, the yield changed.



Figure B.20: Signal yield of EMTC4 as a function of time. Other than the short periods just after the HV is turned on, C4 shows stable performance.

B.4 Further Tests and Prospects

B.4.1 New Divider Circuits

Since better linearity was observed with the lower voltage (-450 V) than the higher voltage (-500 V) in the first prototypes. Since this is considered due to the space charge effect by electron cloud, can be avoided if one uses another type of the divider circuit which provides different voltage fractions among dynodes and then possibly better linearity. Instead the gain will be lowered and signal size becomes small.

This was in fact purchased from Hamamatsu and the new prototypes were made and installed in the muon monitor place together with C3 and C4. However, since the operation mode after the installation was RHC and then muon flux is approximately 66% of that in FHC, the linearity check up to the high intensity could not checked. This work is now left for the future.

B.4.2 Test of PMTs

The second prototype detectors contained PMTs with new divider circuits as mentioned above. The pictures of the PMT and the divider circuit are shown in Figure B.21. Installed PMTs are two: one with warming-up and the other without warming-up.



Figure B.21: Pictures of the PMT and the divider circuit.

The example waveforms for one of the PMTs (the one with warming-up) are shown in Figure B.22. Two pictures correspond to different conditions (beam power and applied high-

voltage): (470 kW,-250 kA) and (40 kW,-500 V). The horn current is the same for two as -250 kA. Although two cases should see similar sizes of output signal calculated from the beam power and the gain, the waveform from the (470 kW,-250 kA) case observes saturated signal but the other case does not. This is considered due to the cathode linearity condition. When the in-coming yield is large and the resistivity is high, the voltage induced by the input is large, which leads to worse yield efficiency. In case of EMTs, since the alminum whose resistivity is sufficiently low, such saturation was not observed. This saturation was observed in the other PMT (without warming-up) and then not related to the warming-up. Figure B.23 shows the yield stability of the PMTs. Different signal sizes are because of many different high-voltage trials. Regardless of the high-voltage values, the yields are continuously decreased in both. This is considered due to the damage of the photo-cathode. In conclusion, PMTs are found not suitable for the muon monitor detector.



Figure B.22: Example waveforms of one of the installed PMTs. The condition in the left panel is 470 kW power, -250 kA horn current and -350 V applied, and that in the right panel is 40 kW, -250 kA, and -500 V.



Figure B.23: Yield stability of the PMT with (left) and without (right) warming-up.

B.4.3 EMTs without Alkali/Sb

Usually alkali metals and Sb are put on the surface of dynodes to obtain high gain, but these materials are potentially sensitive to the radiation damage. Therefore EMTs without alkali/Sb on the dynode surface are prepared and tested. Unfortunately the signal was not observed because of the low gain ($\sim O(10)$). This may be useful under the future intensity. In addition, it needs to be done to change the current equipment that allows the voltage application only up to 500 V, while the maximum voltage that can be applied to EMTs is 1000 V. This would help the situation further.

B.4.4 Prospects

From the studies with the prototype detectors, EMTs are found to be a promising candidate for the future MUMON. Before the actual installation, further tests of linearity and stability performances need to be done. An electron beam test at Tohoku University's Research Center for Electron Photon Science was carried out to test EMTs towards the future installation. It will be determined whether install EMTs as MUMON or not by seeing the results from the beam test.

Appendix C

Supplements for the NCQE-like Analysis

C.1 Low Energy Background Cut Criteria

The optimized cut functions for three parameters, dwall, effwall, and ovaQ, are shown in Table C.1 for each T2K run. For the parameter param (: dwall, effwall, and ovaQ), the linear function $param = p_{param}[0] + p_{param}[1] \times E_{rec}$ is used for the cut.

Run#	$p_{\rm dwall}[0]$	$p_{\text{dwall}}[1]$	$p_{\text{effwall}}[0]$	$p_{\text{effwall}}[1]$	$p_{\rm ovaQ}[0]$	$p_{\rm ovaQ}[1]$
1	523.5	-70.0	2087.7	-332.0	0.3831	-0.042
2	477.7	-60.0	1934.0	-300.0	0.4095	-0.048
3b	389.6	-40.0	2154.5	-352.0	0.3641	-0.038
3c	386.3	-40.0	2154.5	-352.0	0.3811	-0.042
4	539.2	-80.0	2035.7	-332.0	0.3506	-0.036
5a	539.2	-80.0	2131.0	-350.0	0.3866	-0.044
5b	539.2	-80.0	2131.0	-350.0	0.3866	-0.044
5c	539.2	-80.0	1939.0	-296.0	0.3906	-0.044
6a	539.2	-80.0	2100.6	-344.0	0.3277	-0.032
6b	624.0	-100.0	2579.5	-452.0	0.3726	-0.036
6c	624.0	-100.0	2579.5	-452.0	0.3726	-0.036
6d	624.0	-100.0	2579.5	-452.0	0.3726	-0.036
6e	624.0	-100.0	2579.5	-452.0	0.3726	-0.036
6f	539.2	-80.0	2134.5	-352.0	0.3277	-0.032
7a	539.2	-80.0	1972.3	-322.0	0.3401	-0.038
7b	539.2	-80.0	1840.2	-290.0	0.3457	-0.032
7c	539.2	-80.0	1972.3	-322.0	0.3401	-0.038
8	539.2	-80.0	1668.8	-266.0	0.3771	-0.042
9a	539.2	-80.0	1793.1	-288.0	0.3895	-0.048
9b	539.2	-80.0	1837.6	-294.0	0.3911	-0.042
9c	539.2	-80.0	1837.6	-294.0	0.3911	-0.042
9d	539.2	-80.0	1837.6	-294.0	0.3911	-0.042

Table C.1: Summary on the cut function parameters for dwall, effwall and ovaQ in each run.

C.2 Study of Post-activity Cut

As described in Chapter 6, only the pre-activity cut is applied for the decay-*e* events. The results on the post-activity is shown in Figures C.1 and C.2 for the FHC and RHC samples, respectively. With the post-activity cut removing events with $N_{\text{decay-e}} > 0$, the CC events are reduced by nealy 10% and the NC1 π and NC-other events are reduced by 5%, while the efficiency loss for the NCQE events is small.

C.3 Distributions at Each Selection Stage

Distributions from the FHC and RHC samples after each selection cut are shown in the following pages.



Figure C.1: Distributions of the number of decay-e after the candidate event for FHC events: NC (left) and CC(right).



Figure C.2: Distributions of the number of decay-e after the candidate event for RHC events: NC (left) and CC(right).



Figure C.3: Distributions of $E_{\rm rec}$, $\theta_{\rm C}$, dwall, effwall, ovaQ, and $\cos \theta_{\rm beam}$ after the FV cut in FHC.



Figure C.4: Distributions of $E_{\rm rec}$, $\theta_{\rm C}$, dwall, effwall, ovaQ, and $\cos \theta_{\rm beam}$ after the dwall cut in FHC.



Figure C.5: Distributions of $E_{\rm rec}$, $\theta_{\rm C}$, dwall, effwall, ovaQ, and $\cos \theta_{\rm beam}$ after the effwall cut in FHC.



Figure C.6: Distributions of $E_{\rm rec}$, $\theta_{\rm C}$, dwall, effwall, ovaQ, and $\cos \theta_{\rm beam}$ after the ovaQ cut in FHC.



Figure C.7: Distributions of $E_{\rm rec}$, $\theta_{\rm C}$, dwall, effwall, ovaQ, and $\cos \theta_{\rm beam}$ after the CC interaction cut in FHC.



Figure C.8: Distributions of $E_{\rm rec}$, $\theta_{\rm C}$, dwall, effwall, ovaQ, and $\cos \theta_{\rm beam}$ after the FV cut in RHC.



Figure C.9: Distributions of $E_{\rm rec}$, $\theta_{\rm C}$, dwall, effwall, ovaQ, and $\cos \theta_{\rm beam}$ after the dwall cut in RHC.



Figure C.10: Distributions of $E_{\rm rec}$, $\theta_{\rm C}$, dwall, effwall, ovaQ, and $\cos \theta_{\rm beam}$ after the effwall cut in RHC.



Figure C.11: Distributions of $E_{\rm rec}$, $\theta_{\rm C}$, dwall, effwall, ovaQ, and $\cos \theta_{\rm beam}$ after the ovaQ cut in RHC.



Figure C.12: Distributions of E_{rec} , θ_{C} , dwall, effwall, ovaQ, and $\cos \theta_{\text{beam}}$ after the CC interaction cut in RHC.



Figure C.13: Distribution of true E_{ν} for each neutrino interaction (left) and the one focusing on CCQE and CC 2p2h (right) in FHC.



Figure C.14: Distribution of true E_{ν} for each neutrino interaction (left) and the one focusing on CCQE and CC 2p2h (right) in RHC.

C.4 Primary- and Secondary- γ Distributions

The neutrino and antineutrino NCQE events are broken down into the events with the primary- γ only, secondary- γ only, and both γ -rays. The resulting $E_{\rm rec}$ and $\theta_{\rm C}$ distributions for FHC and RHC are shown in Figures C.15 and C.16. It is found from these that the secondary- γ events contribute to the region with higher energy and Cherenkov opening angle.



Figure C.15: The $E_{\rm rec}$ distributions for the NCQE events broken down by the γ -ray type in FHC (left) and RHC (right).



Figure C.16: The $\theta_{\rm C}$ distributions for the NCQE events broken down by the γ -ray type in FHC (left) and RHC (right).

C.5 Properties of Nucleons in the NCQE Interaction



Figure C.17: Nucleon kinetic energy after NCQE in FHC: neutron (left) and proton (right). Each of them is area normalized.



Figure C.18: Nucleon kinetic energy after NCQE in RHC: neutron (left) and proton (right). Each of them is area normalized.



Figure C.19: The 2D distributions of neutron energy and Cherenkov angle for neutrino (left) and antineutrino (right) NCQE interactions in FHC.



Figure C.20: The 2D distributions of proton energy and Cherenkov angle for neutrino (left) and antineutrino (right) NCQE interactions in FHC.



Figure C.21: The 2D distributions of neutron energy and Cherenkov angle for neutrino (left) and antineutrino (right) NCQE interactions in RHC.



Figure C.22: The 2D distributions of proton energy and Cherenkov angle for neutrino (left) and antineutrino (right) NCQE interactions in RHC.



Figure C.23: The $E_{\rm rec}$ (left) and $\theta_{\rm C}$ (right) distributions for neutrino-proton and neutrinoneutron NCQE interactions in FHC. The numbers of selected events for protons and neutrons are 76.4 and 102.2, respectively.



Figure C.24: The $E_{\rm rec}$ (left) and $\theta_{\rm C}$ (right) distributions for antineutrino-proton and antineutrino-neutron NCQE interactions in RHC. The numbers of selected events for protons and neutrons are 25.6 and 30.8, respectively.

Appendix D Distributions for the Spallation Cut

Some histograms, PDFs, and likelihoods for the SRN spallation cut are shown in the following pages. Figures D.17, D.18, and D.19 show the spallation likelihood of the ⁹Li sample.



Figure D.1: The dt distributions of the missfit or poorly-fit muons for pre and post samples and different energy regions.



Figure D.2: Distributions of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), and Q_{μ} (bottom) of the single through-going muons for 7.49 $< E_{\text{rec}} < 9.49$ MeV. For variables except for dt, the distributions are for 0 < |dt| < 0.05 sec.



Figure D.3: Distributions of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), and Q_{μ} (bottom) of the single through-going muons for 7.49 $< E_{\text{rec}} < 9.49$ MeV. For variables except for dt, the distributions are for 0.05 < |dt| < 0.5 sec.



Figure D.4: Distributions of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), and Q_{μ} (bottom) of the single through-going muons for 7.49 $< E_{\text{rec}} < 9.49$ MeV. For variables except for dt, the distributions are for 0.5 < |dt| < 30 sec.



Figure D.5: Distributions of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), and Q_{μ} (bottom) of the stopping muons for 7.49 $< E_{\text{rec}} < 9.49$ MeV. For variables except for dt, the distributions are for 0 < |dt| < 0.05 sec.



Figure D.6: Distributions of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), Q_{μ} (bottom), and N_{track} of the multiple muons for 7.49 $< E_{\text{rec}} < 9.49$ MeV. For variables except for dt, the distributions are for 0 < |dt| < 0.05 sec.



Figure D.7: Distributions of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), Q_{μ} (bottom), and N_{track} of the multiple muons for 7.49 $< E_{\text{rec}} < 9.49$ MeV. For variables except for dt, the distributions are for 0.05 < |dt| < 0.5 sec.



Figure D.8: Distributions of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), Q_{μ} (bottom), and N_{track} of the multiple muons for 7.49 $< E_{\text{rec}} < 9.49$ MeV. For variables except for dt, the distributions are for 0.5 < |dt| < 30 sec.


Figure D.9: Distributions of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), and Q_{μ} (bottom) of the corner-clipping muons for 7.49 $< E_{\text{rec}} < 9.49$ MeV. For variables except for dt, the distributions are for 0 < |dt| < 0.05 sec.



Figure D.10: Distributions of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), and Q_{μ} (bottom) of the single through-going muons for $9.49 < E_{\text{rec}} < 11.49$ MeV. For variables except for dt, the distributions are for 0 < |dt| < 0.05 sec.



Figure D.11: Distributions of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), and Q_{μ} (bottom) of the single through-going muons for $11.49 < E_{\text{rec}} < 19.49$ MeV. For variables except for dt, the distributions are for 0 < |dt| < 0.05 sec.



Figure D.12: PDF distributions of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), and Q_{μ} (bottom) of the single through-going muons for 7.49 $< E_{\text{rec}} < 9.49$ MeV. For variables except for dt, the distributions are for 0 < |dt| < 0.05 sec.



Figure D.13: PDF distributions of dt (top left), L_{tran} (top right), L_{long} (middle left), Q_{peak} (middle right), Q_{μ} (bottom), and N_{track} of the multiple muons for 7.49 $< E_{\text{rec}} < 9.49$ MeV. For variables except for dt, the distributions are for 0 < |dt| < 0.05 sec.



Figure D.14: Distributions of the spallation likelihood for each muon type in the 7.49–9.49 MeV energy region. Dashed green lines represent the cut criteria. Events in the right side of the lines are removed.



Figure D.15: Distributions of the spallation likelihood for each muon type in the 9.49–11.49 MeV energy region. Dashed green lines represent the cut criteria. Events in the right side of the lines are removed.



Figure D.16: Distributions of the spallation likelihood for each muon type in the 11.49–19.49 MeV energy region. Dashed green lines represent the cut criteria. Events in the right side of the lines are removed.



Figure D.17: Distributions of the spallation likelihood in the ${}^{9}Li$ sample for each muon type in the 7.49–9.49 MeV region. Dashed green lines represent the cut criteria, the right side of which is removed.



Figure D.18: Distributions of the spallation likelihood in the ${}^{9}Li$ sample for each muon type in the 9.49–11.49 MeV region. Dashed green lines represent the cut criteria, the right side of which is removed.



Figure D.19: Distributions of the spallation likelihood in the ${}^{9}\text{Li}$ sample for each muon type in the 11.49–19.49 MeV region. Dashed green lines represent the cut criteria, the right side of which is removed.

Appendix E

Future SRN Search Sensitivities

Figure E.1 gives results for SK-Gd with a 0.1% Gd doping. Here the same systematic errors as the analysis in this thesis are assumed for the backgrounds except for the accidental background. Since the γ -ray energy is ~8 MeV, SK-Gd is free of the accidental background. The absolute amounts of the other backgrounds are scaled from the current analysis by live time. As mentioned in Chapter 13, models by Horiuchi+18 and Horiuchi+09 can be tested and the reach after the 10-year operation is comparable or a bit worse compared to predictions by Lunardini09, Ando+09, and Hartmann+97.

Figure E.2 gives results for Hyper-Kamiokande. The same systematic errors as the analysis in this thesis are assumed; however, the twice better neutron tagging efficiencies with the same mis-tag probabilities are considered. Here the absolute background amount is obtained with scaling from the current analysis by live time and detector mass. Most models except for the minimum flux prediction by Nakazato+15 can be tested.

The case for Hyper-Kamiokande with a 0.1% Gd doping (called "HK-Gd" in this thesis) is also considered. The amount of the NCQE-like background is considered to be 70% of the nominal prediction by the MC multiplied with the scale factors from T2K. This is due to that the current model may be inappropriate about the neutron multiplicity as shown in Chapter 12 and it seems that the number of neutrons is smaller than the prediction. A 10% systematic error is assumed for the NCQE-like background. For the non-NCQE background, a 10% systematic error is considered because the Michel spectrum fitting is expected to be performed more precisely with higher statistics. The amount of the ⁹Li background is assumed to be scaled by the statistics from the current analysis, while the systematic error is assumed to be 10%. There is no accidental background in HK-Gd. The results are shown in Figure E.3. All the models can be tested by HK-Gd and advanced studies such as the spectrum measurement are expected.

In order to see the benefits of the NCQE-like measurement, the sensitivities in SK-Gd with different NCQE-like conditions are evaluated as shown in Figure E.4. In this estimation, the amount of the ⁹Li background is assumed to be 1/5 of the analysis in this thesis with scaling by live time. This is because the better spallation cut is expected in SK-Gd. Three conditions for the NCQE-like background are considered: the absolute amount scaled by live time with 100% and 60% uncertainties, and the absolute amount reduced by 30% (×0.7) from the simple scaling with a 40% uncertainty. With an improved estimation of the NCQE-like background, models by Horiuchi+18, Lunardini09, Ando+09, and Hartmann+97 can be tested in the 13.29–21.29 MeV region, while the reach with a 100% error is not enough for these models.



Figure E.1: The 3σ sensitivity for the $\bar{\nu}_e$ flux as a function of SK-Gd operation period with a 0.1% Gd doping for the neutrino energy region $9.29 < E_{\nu} < 11.29$ MeV (top left), $11.29 < E_{\nu} < 13.29$ MeV (top right), $13.29 < E_{\nu} < 21.29$ MeV (bottom left), and $21.29 < E_{\nu} < 31.29$ MeV (bottom right). The predictions from the models explained in Chapter 1 are also shown.



Figure E.2: The 3σ sensitivity for the $\bar{\nu}_e$ flux as a function of Hyper-Kamiokande operation period for the neutrino energy region $9.29 < E_{\nu} < 11.29$ MeV (top left), $11.29 < E_{\nu} < 13.29$ MeV (top right), $13.29 < E_{\nu} < 21.29$ MeV (bottom left), and $21.29 < E_{\nu} < 31.29$ MeV (bottom right). The predictions from the models explained in Chapter 1 are also shown.



Figure E.3: The 3σ sensitivity for the $\bar{\nu}_e$ flux as a function of HK-Gd operation period with a 0.1% Gd doping for the neutrino energy region $9.29 < E_{\nu} < 11.29$ MeV (top left), $11.29 < E_{\nu} < 13.29$ MeV (top right), $13.29 < E_{\nu} < 21.29$ MeV (bottom left), and $21.29 < E_{\nu} < 31.29$ MeV (bottom right). The predictions from the models explained in Chapter 1 are also shown.



Figure E.4: The 3σ sensitivity for the $\bar{\nu}_e$ flux as a function of SK-Gd operation period with a 0.1% Gd doping for the neutrino energy region 9.29 $< E_{\nu} < 11.29$ MeV (top left), $11.29 < E_{\nu} < 13.29$ MeV (top right), $13.29 < E_{\nu} < 21.29$ MeV (bottom left), and $21.29 < E_{\nu} < 31.29$ MeV (bottom right) for different NCQE-like background conditions. Note that assumptions on the background are different from those in Figure E.1 as explained in the text. The predictions from the models explained in Chapter 1 are also shown.

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