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Development of Water-based Liquid Scintillator for neutrino experiments

By

TIANQI ZHANG
DISSERTATION

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Abstract

As the field of neutrino physics continues to evolve, new technologies for neutrino detection are in demand. The Water-based Liquid Scintillator (WbLS) is among the most promising ones. By introducing a small amount of Liquid Scintillator into water, the light yield of WbLS can be adjusted to allow the detection of particles below the Cherenkov threshold with better energy resolution than Water Cherenkov (WC) Detectors. With water as their base, WbLS detectors also inherit all the advantages from its water predecessors: low cost, capability for direction reconstruction and environmental friendliness.

The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) is a 26-ton gadolinium-doped water Cherenkov detector located 100 meters downstream in the Booster Neutrino Beam (BNB) at the Fermi National Accelerator Laboratory. While ANNIE's main physics goal is to measure neutron multiplicity of neutrino-nucleus interactions, it is also part of the ongoing effort of the development of new neutrino detection technologies. These technologies include the development of WbLS and Large Area Pico-second Photon Detectors (LAPPD). Following an overview of the current status of neutrino physics, this thesis will briefly describe the ANNIE experiment. The result of the first deployment of WbLS in ANNIE is presented, it shows a clear evidence of the capability of separating Cherenkov Radiation and scintillation. The ratio of photo-electrons collected is measured to be 1.77 ± 0.06 (stat.) ± 0.05 (syst.). The result of attenuation measurement for WbLS is shown in Chapter 2. The attenuation length

of WbLS is measured as 22.0 ± 0.5 m. This result shows a promising application of WbLS as a neutrino detecting medium in future large scale neutrino experiments.

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Chapter 1

Introduction to Neutrino Physics

Every second, about 100 trillion neutrinos pass through our bodies, yet we feel nothing. The ghostly nature of the neutrino makes it hard to detect, but also makes it a fascinating probe of our universe.

In this chapter, our journey of neutrino physics starts from its history. We will highlight some big events for the field of neutrino physics. A brief overview of the Standard Model of Particle Physics will then be presented in section 1.2. With this background knowledge in particle physics, we will discuss the properties of neutrinos and why they are interesting. Finally, we review the neutrino sources and neutrino interactions that make neutrino experiments possible.

1.1 History of The Neutrino Physics

1.1.1 The birth of the idea

The history of the neutrino starts in 1930. Theoretical physicist Wolfgang Pauli hypothesized the existence of a charge-neutral particle he called ‘neutron’. The creation of this idea was to solve a mystery in β decay. He called this hypothetical particle a ‘desperate remedy to save the ‘exchange theorem’ of statistics and the law of energy conservation’. We now know this particle as the neutrino, and while it is not responsible for the spin statistics paradox, it is responsible for the missing energy of the β decay.

1.1.1.1 The Beta decay spectrum

The history of neutrino physics begins with the study of nuclear β decay. Before the discovery of the neutrino, the nuclear β decay was understood as a two-body problem.

$${}^AZ \rightarrow {}^A(Z+1) + e^- \quad (1.1)$$

Where AZ denotes the nucleus with mass number A and atomic number Z. From this model, one would predict that the β decay spectrum is mono-energetic, just like the α decays. The reason being that the energy conservation law and the momentum conservation law together allow only a fixed energy for the emitted electron. In 1914, Chadwick first presented definitive evidence suggesting that β decay spectrum is continuous [1]. Just like many other big discoveries, several hypotheses were raised to question if the model of energy loss was

due to the experimental set up. Only 15 years after Chadwick's discovery was the issue experimentally settled: the nuclear β decay spectrum is continuous. At the time, it appeared that the law of energy conservation was being violated in order to explain this phenomenon.

1.1.1.2 Nuclear spin paradox

The other motivation of Pauli's postulate was to explain the spin statistics. We now know that this issue is caused by another charge-neutral particle, namely neutron. Back in the early 20th century, before the discovery of neutron, it had been postulated that nuclei are made of protons and electrons, for example, a ^{16}O nucleus would consist of 16 protons and 8 electrons, thus has 8 positive charges. While this seems like a straightforward model, it has several fundamental problems. One of the problems is that the spin statistics seemed to be violated. According to this model, ^{14}N is predicted to be a fermion because it consists of an odd number of fermions (14 protons and 7 electrons). But experiments showed ^{14}N behaves like a boson, thus another big tension between theory and experiments. We now understand that with the existence of neutron, ^{14}N actually consists of even number of fermions (7 protons plus 7 neutrons), so it is indeed a boson.

1.1.2 First experimental evidence

With Pauli's hypothetical particle, β decay can be described as a three body process:

$${}^AZ \rightarrow {}^A(Z+1) + e^- + \bar{\nu} \quad (1.2)$$

The new term $\bar{\nu}$ denotes the proposed particle, we now know it as electron anti-neutrino. The continuous energy is thus caused by missing energy carried by this ‘undetectable’ particle. Because this particle is charge neutral, even Pauli himself didn’t think it could be detected. In 1956, a group of scientists reported the first evidence of free neutrino near a nuclear reactor [2]. The reaction

$$\bar{\nu} + p \rightarrow e^+ + n \tag{1.3}$$

was employed wherein the intense neutrino flux from a large reactor was incident on a detector containing many target protons in a kind of liquid scintillator. The interaction was identified from a delayed pulse pair: The first pulse is due to kinetic energy plus the annihilation of the positron into a pair of 511 keV gamma rays. The later pulse is due to the capture of the moderated neutron in cadmium dissolved in the scintillator. The background signal from reactor neutrons and gamma radiation was ruled out statistically from the calculation of shielding effectiveness.

1.1.3 Experimental anomalies

As the exploration of the neutrino properties kept going, several puzzles arose. In 1968, the famous Homestake experiment (or sometimes referred to as the Davis experiment) [3] first detected neutrinos from the sun (solar neutrinos). However, the experiment found only one-third the number of solar neutrinos predicted by astrophysicist John Bahcall, leading to the “solar neutrino problem.” Later in 1985, The Kamiokande collaboration in Japan

and the IMB (Irvine, Michigan, Brookhaven) collaboration in the United States detected atmospheric neutrinos. Similar to the solar neutrino problem, the experiments found a smaller ratio of muon neutrinos to electron neutrinos than expected. This was called the “atmospheric neutrino anomaly.”

Both anomalies are the result of the neutrino oscillation. As neutrinos travel, they change their flavor. When neutrinos travel from the sun to the earth, some of the electron neutrinos oscillate to other flavors, and the Homestake experiment [4] detected only electron neutrinos with the reaction:

$$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar}^+ + e^- \quad (1.4)$$

Every week, Davis bubbled helium through the tank to collect ${}^{37}\text{Ar}$ that had formed. By detecting ${}^{37}\text{Ar}$ decays, Davis was able to determine how many neutrinos detected.

The above equation can be generalized to muon neutrinos and tau neutrinos. The generalized form can be written as:

$$\nu_l + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar}^+ + l^- \quad (1.5)$$

Where l can be electron, muon or tau. However, the Homestake experiment was not sensitive to the muon or tau version of the above interaction. The reason is that most of the solar neutrinos have energy less than 20 MeV, this is not enough energy to produce heavy leptons.

In 1998, the Super-Kamiokande (Super-K) experiment first found the evidence of the neutrino oscillation [5]. Different from the Homestake experiment, Super-K utilized the

charge current reaction:

$$\nu + N \rightarrow X + l \quad (1.6)$$

The flavor of the final state interaction is used to identify the flavor of the incoming neutrino. Thus, Super-K experiment is sensitive to all neutrino flavors. Super-K detector is a 50 k-ton water Cherenkov detector. This type of the detector is known for its sensitivity in direction reconstruction. For a detector near the surface of the earth, neutrinos generated in the atmosphere travel different distances to the detector from different zenith angles. With its sensitivity in flavor identification and direction reconstruction, Super-K found the ratio of ν_μ/ν_e is different from different zenith angle, providing the first evidence of the neutrino oscillation.

Later in 2001, SNO experiment published their result that confirmed the solar neutrino flavor change using their heavy water detector. Unlike the previous experiments, the SNO experiment was sensitive to three reactions, one reaction is sensitive to all neutrino flavors:

$$\nu_x + d \rightarrow p + n + \nu_x \quad (1.7)$$

This is called Neutral Current (NC) interaction and the sensitivity to all flavors are the same. Another reaction is called Charged Current (CC) interaction and it is only sensitive to electron neutrinos:

$$\nu_e + d \rightarrow p + p + e^- \quad (1.8)$$

And the third reaction is elastic scattering, it is sensitive to all the flavors just like the NC reaction. The difference being it has reduced sensitivity to ν_μ and ν_τ . The combined result of

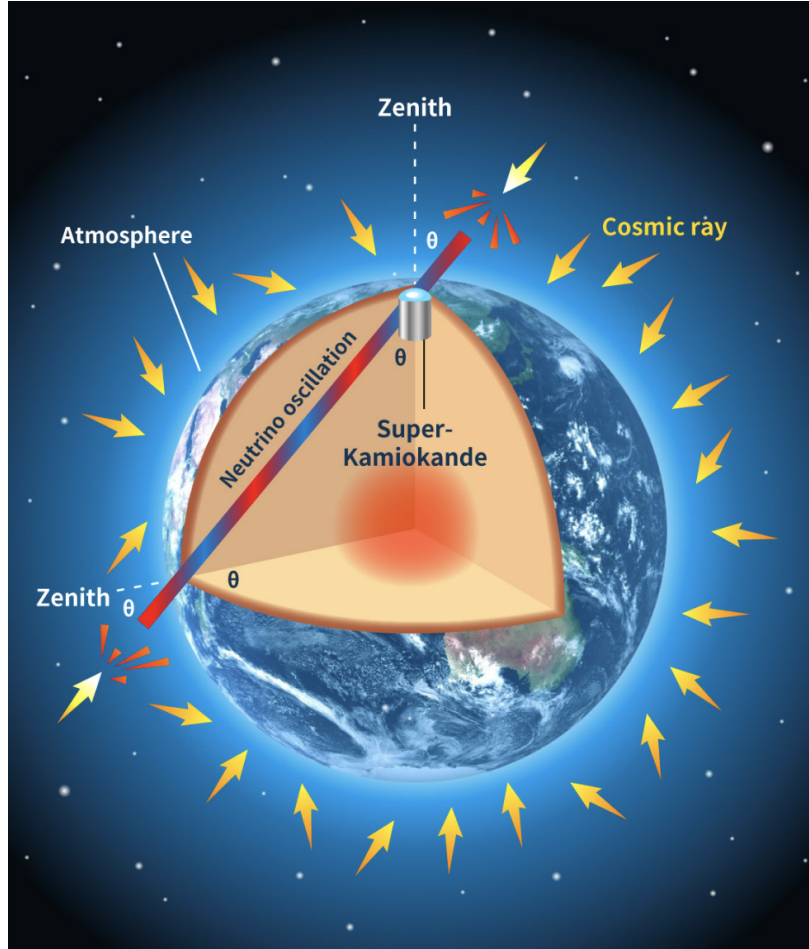


Figure 1.1: Atmospheric neutrinos travel from different zenith angle have different travel distance. Figure from [6]

the three reaction would show direct evidence of solar neutrino flavor change, see Figure 1.2.

For the sake of the brevity of this thesis, other big events in the history of the neutrino physics are not mentioned. More historical events can be found in the reference.

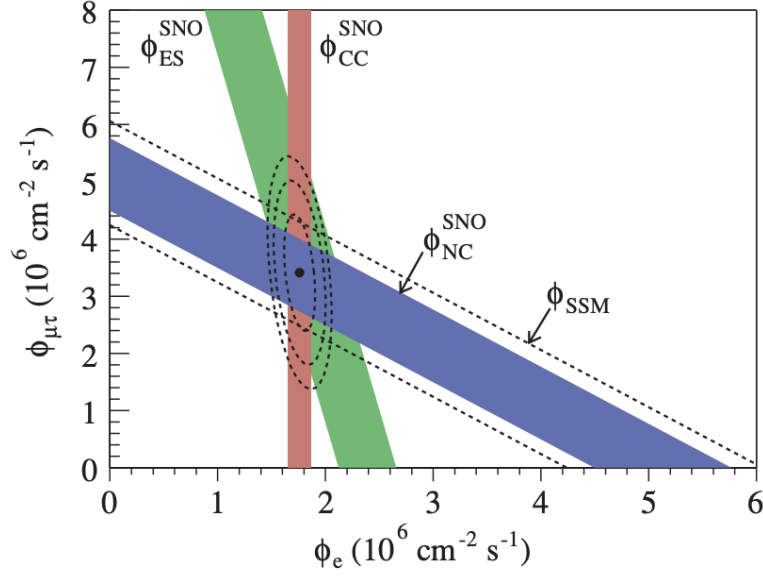


Figure 1.2: The constraints on solar neutrino flux from the SNO experiment. The blue band is from neutral current measurement. The red band is from charged current measurement and the green band is from electron scattering measurement. Figure from [7]

1.2 The Standard Model of Particle Physics

The Standard Model (SM) of Particle Physics is a model that describes three fundamental forces (electromagnetic, weak and strong interactions) and all known fundamental particles in our universe. With the Higgs Boson discovered in 2012 at the Large Hadron Collider (LHC) at CERN [8], the SM is believed to have its last piece completed. Although the SM has shown big success in providing experimental predictions, it fails to explain several physical phenomena such as dark matter, baryon asymmetry and neutrino non-zero mass that leads to neutrino oscillation.

The mathematical framework of the SM is quantum field theory, in which a Lagrangian contains all the information of kinematics and the interactions via exchange bosons. The SM Lagrangian is constructed following a set of proposed symmetry: The Poincaré symmetry and the local gauge symmetry. The Poincaré symmetry is postulated for all the relativistic quantum field theories to incorporate the theory of special relativity. The local gauge symmetry is specific to the SM and can be described by the following groups:

$$SU(3)_C \times SU(2)_W \times U(1)_Y \tag{1.9}$$

where the subscripts denote the color charge (C), weak isospin (L), and weak hypercharge (Y) gauge fields. They roughly correspond to the three fundamental forces mentioned above. The $SU(3)_C$ group describes the strong interaction. The eight generators of this group correspond to the eight bosons that mediate the strong interaction called gluons. The $SU(2)_W$ group describes interactions related to left-handed chiral fields in the context of the electroweak interaction, the three generators of the group corresponds to the three W fields. Similarly, the generator of the $U(1)_Y$ group corresponds to the B field. After spontaneous gauge symmetry breaking, the $SU(2)_W \times U(1)_Y$ group becomes the unbroken $U(1)_{EM}$ group, resulting in three massive bosons($W^\pm, Z^0$) and one massless boson γ . The corresponding fields are related to the W and B fields via:

$$\begin{aligned}
W_\mu^\mp &= \frac{1}{\sqrt{2}}(W_\mu^1 \pm iW_\mu^2) \\
Z_\mu &= W_\mu^3 \cos(\theta_W) - B_\mu \sin(\theta_W) \\
A_\mu &= B_\mu \cos(\theta_W) + W_\mu^3 \sin(\theta_W)
\end{aligned} \tag{1.10}$$

Here A_μ denotes the vector field that describes photon (γ). θ_W is the Weinberg angle.

The bosons above describe the force mediators of the SM. For example, the electromagnetic force can be described as the exchange of the massless boson (the photon). The nature of zero mass enables the range of electromagnetic force to be infinite.

There are three generation of fermions that describe the normal matter (as opposed to dark matter). For each generation of fermions, the transformation under the local gauge symmetry are:

$$\begin{aligned}
Q_L &\sim (3, 2)_{+\frac{1}{6}} \\
u_R &\sim (3, 1)_{+\frac{2}{3}} \\
d_R &\sim (3, 1)_{-\frac{1}{3}} \\
L_L &\sim (1, 2)_{-\frac{1}{2}} \\
e_R &\sim (1, 1)_{-1}
\end{aligned} \tag{1.11}$$

With Q_L stands for the left-handed quarks, u_R and d_R denote the right-handed up type quarks and down type quarks respectively. L_L denotes the left-handed leptons (consist of charged leptons and neutrinos) and e_R denotes the right-handed charged leptons. The two

numbers on the right are the representations of the $SU(3)_C$ group and the $SU(2)_W$ group respectively. The subscript is the hypercharge of the particle.

The subscripts L and R denote the left-handed and right-handed chirality. Not to be confused with helicity, which is the projection of the spin along the linear momentum of a subatomic particle, chirality is an intrinsic property of the particle. In the case of massless particles, chirality and helicity of the particle always have the same handedness.

In the SM, all the leptons transform as a singlet under the $SU(3)_C$ group. This means that the leptons are color neutral, thus do not engage in strong interactions. All the right-handed particles transform as singlet under the $SU(2)_W$ group. This means they can't interact with the charged W bosons. The right-handed neutrinos do not exist in the SM because they have never been seen in any experiments.

The masses of fermions result from the coupling of the fermion fields with the Higgs field. This is called Yukawa coupling. The Higgs field is a complex scalar doublet under $SU(2)_W$. It has four degrees of freedom. After symmetry breaking, three degrees of freedom are absorbed by the three massive W and Z bosons. The one degree of freedom left is called the Higgs boson. The Yukawa coupling takes the form:

$$\mathcal{L}_{yukawa} = -y_{ij} \overline{f_{Li}} f_{Rj} \phi + h.c. \quad (1.12)$$

the coupling constant y_{ij} is not predicted by the SM and can only be measured experimentally. Its strength is the key factor of fermion masses. Notice that Yukawa coupling

requires both left and right-handed particle, it implies that neutrino has zero mass as only left-handed neutrino has been discovered. Figure 1.3 summarizes all the particles from the SM.

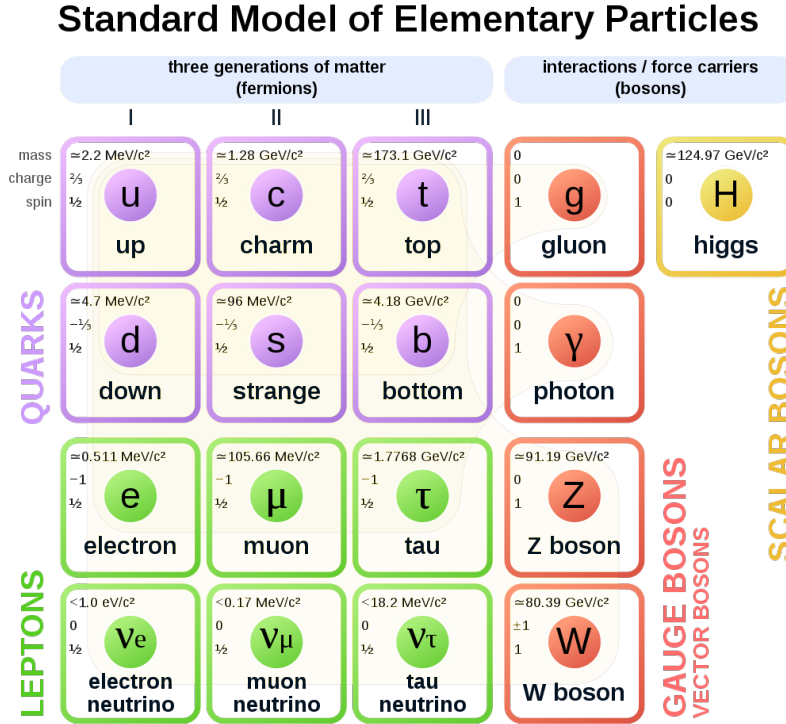


Figure 1.3: Summary of the Standard Model particles. Figure from [9]

1.3 The Properties of Neutrinos

While the SM has demonstrated some success in predicting experimental results with great precision, it is considered incomplete because it fails to explain some phenomena. As men-

tioned in Section 1.2, The SM requires neutrino to be massless. On the other hand, the observation of the neutrino oscillation requires the neutrino to be massive. The inconsistency between the experimental observation and the SM makes neutrino a good probe for physics beyond the Standard Model(BSM). Here we discuss some of the interesting neutrino properties.

1.3.1 Neutrino mass

In order to introduce mass terms to neutrino, one must extend the particle content of the SM. Here we discuss some neutrino mass terms that modify the SM with minimal extensions.

1.3.1.1 Dirac mass

We can simply add a right-handed neutrino to SM to allow the Yukawa coupling of the neutrino and the Higgs field:

$$\mathcal{L}_{yukawa} = -y_{ij}\bar{L}_{Li}\nu_{Rj}\tilde{H} + h.c. \quad (1.13)$$

In this case, the neutrino mass matrix element m_{ij} is obtained from substituting Higgs Vacuum Expectation Value (VEV):

$$\begin{aligned} \mathcal{L}_{yukawa} &\supset m_{ij}\nu_{Li}\nu_{Rj} \\ m_{ij} &= \frac{y_{ij}v}{\sqrt{2}} \end{aligned} \quad (1.14)$$

To have the neutrino mass smaller than 0.14 eV (The current cosmological observation constraint on the total neutrino mass [10]), the coupling constant needs to be on the order of 10^{-12} . Furthermore, the right-handed neutrino would transform as a singlet under all gauge transformation, causing it to have no interaction with normal matter, making it hard to produce. For these two reasons, this model is not very appealing.

1.3.1.2 Majorana mass

As neutrinos are charge neutral, they could be their own anti-particle, in other words, they can be so-called Majorana fermions. In general, the Majorana mass term is in the form:

$$m_{majorana}\bar{\psi}\psi \tag{1.15}$$

Here ψ can be a two component scalar (as opposed to the four component Dirac spinor). The Majorana mass term can be generated from either a Higgs triplet field or a nonrenormalizable operator:

$$\frac{c}{\Lambda}(L\epsilon H)^2 \tag{1.16}$$

Here c is the coupling constant and Λ is the effective scale. L represents the lepton field in the SM, ϵ is $i\sigma_2$ operator, and H is the SM Higgs field. But plugging in the Higgs VEV, one can find the Majorana mass term. One interesting property of the Majorana neutrino is that it allows the violation of lepton number conservation. This violation can be observed

through a nuclear process called the neutrinoless double beta decay ($0\nu\beta\beta$), as shown in Figure 1.4. The conventional β decay produces an electron, an antineutrino, and increases the proton number Z by one. There exist a number of elements that can decay by emitting electrons, but they cannot emit only one electron, either because the resulting nucleus has higher rest mass or the reaction is suppressed by spin statistics. Some of them can decay by emitting two electrons:

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e \quad (1.17)$$

If the nature of the neutrinos is Majorana, the above process can happen without emitting any neutrino 1.4. Experiments searching for $0\nu\beta\beta$ decay include GERDA, EXO-200, Majorana, SNO+ and KamLAND-Zen. While no experiment has discovered such decay, the current limits on the half-life $T_{1/2}^{0\nu}$ of $0\nu\beta\beta$ decay are on the order of 10^{25} years [11–15].

While a Majorana mass term doesn't require a right-handed neutrino, it has its own cons. The generation of the Majorana mass term requires either a Higgs triplet field, which requires a very small VEV to be consistent with the current Weinberg angle measurement or a non-renormalizable operator. To understand this, notice that the Higgs doublet field satisfies a larger symmetry:

$$O(4) \supset SU(2) \times SU(2) \quad (1.18)$$

We can construct the Higgs in a way that its VEV breaks this symmetry to $SU(2)_{diag}$:

$$H_{new} = (\epsilon H^*, H) \quad (1.19)$$

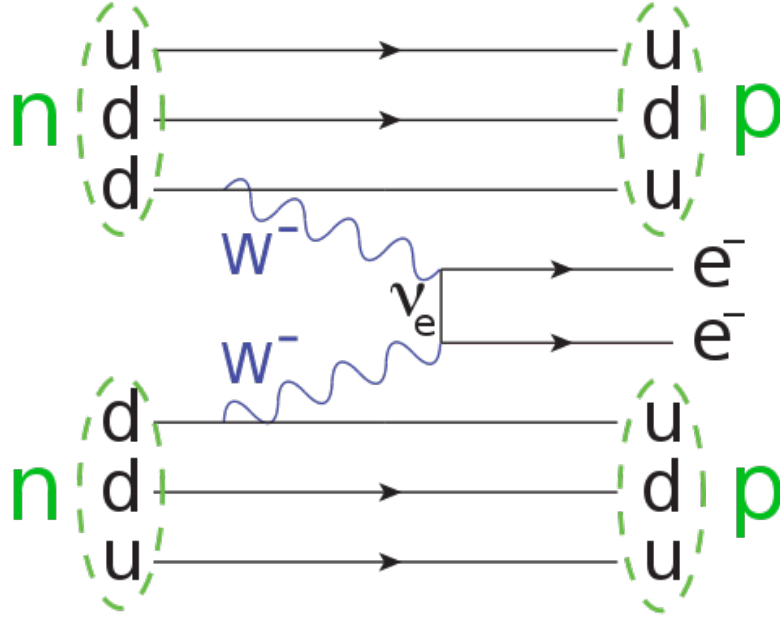


Figure 1.4: Feynman diagram for neutrinoless double beta decay. This process can be viewed as two neutrons going through beta decay simultaneously. If neutrinos are their own anti-particles, the two supposedly outgoing neutrino cancel each other, resulting in a neutrinoless double beta decay. Figure from [9]

Here H is the Higgs doublet. The three broken generators corresponds to the three massive bosons, i.e. W and Z bosons, and they form a triplet of the unbroken symmetry. The $U(1)_Y$ transformation breaks this symmetry and thus causes the mass of the W boson different from the Z boson and brings the relation:

$$M_W = M_Z \cos \Theta_W \quad (1.20)$$

This is not generally the case for other representations, thus a very small Higgs triplet VEV is needed to be consistent with the current measurement of the Weinberg angle Θ_W . The way to construct a Higgs triplet while having a large VEV is possible but beyond the scope

of this thesis. Reference [16] provides more insights.

1.3.1.3 The seesaw mechanism

The non-renormalizable operator mentioned in section 1.3.1.2 can be introduced by a renormalizable interaction called the seesaw mechanism. The idea is to combine both Dirac mass terms and Majorana mass terms. The Dirac mass terms come from the Yukawa coupling, and since the right-handed neutrinos are singlet in all SM transformation, that can have intrinsic Majorana masses:

$$\overline{(\nu_L^c, \nu_R)} \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} \quad (1.21)$$

Here the bar notation represents the conjugate $\bar{\psi} = \psi^\dagger \gamma^0$ and γ^0 is the time-like gamma matrix. For the sake of simplicity, only one generation of the neutrino is considered here. To extend the model to three generations, m_D and M become 3×3 matrices. The two eigenvalues of the mass matrix are:

$$\begin{aligned} m_1 &= \frac{1}{2}M - \frac{1}{2}\sqrt{M^2 + 4m_D^2} \\ m_2 &= \frac{1}{2}M + \frac{1}{2}\sqrt{M^2 + 4m_D^2} \end{aligned} \quad (1.22)$$

In the scenario that $m_D \ll M$, the two eigenvalue become m_D^2/M and M . The geometrical mean of the two eigenvalue is equal to m_D , so if one eigenvalue gets larger, the other one gets smaller, hence the name ‘seesaw’. The eigenvector that corresponds to m_1 largely consists of ν_L and the eigenvector of m_2 largely consists of ν_R . The Dirac mass m_D is

estimated to be comparable to a typical standard model particle, ranging from about 1 MeV to 100 GeV (from the electron to the top quark). Just as an estimate, assuming m_D to be 1 GeV, with m_1 at the order of 1 eV or smaller, m_2 would be so large (about 10^9 GeV) that it cannot be produced in any process. This naturally leads to the fact that the right-handed neutrinos are not yet discovered.

1.3.2 Neutrino Oscillation

Neutrino oscillation was first proposed by Bruno Pontecorvo in 1957, first introduced as neutrino-antineutrino oscillation. Maki, Nakagawa and Sakata then considered oscillations into different flavours in 1962 [17]. In 1967, Bruno Pontecorvo proposed the possibility of solar neutrino oscillation, followed by the discovery of the solar neutrino problem (discussed in section 1.1.3). In 1969, Pontecorvo and Gribov proposed neutrino flavour oscillations as a possible solution [18].

1.3.2.1 Lepton mixing

In analogy to the quark mixing, it's natural to assume the neutrino flavor eigenstates are not the same as their mass eigenstates. The flavor eigenstates are defined via charged current weak interactions and are labeled by the associate charged lepton: e , μ and τ . Here, we discuss the scenario that only three neutrino mass eigenstates exists. The transformation between the two spaces in the lepton sector can be described by a unitary transformation:

$$\begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} = U_L^{(E)} \begin{pmatrix} e'_L \\ \mu'_L \\ \tau'_L \end{pmatrix} ; \quad \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = U_L^{(\nu)} \begin{pmatrix} \nu'_{eL} \\ \nu'_{\mu L} \\ \nu'_{\tau L} \end{pmatrix} \quad (1.23)$$

This transformation can be used to diagonalize the mass matrix in Yukawa coupling.

With such diagonalization, the charged current interaction becomes:

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}(\overline{e_L}, \overline{\mu_L}, \overline{\tau_L})\gamma_\lambda U_L^{(E)+} U_L^{(\nu)} \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} W_\lambda^- + h.c. \quad (1.24)$$

Here the prime symbol is dropped for simplicity. Since both transformation matrices are unitary, the combined mixing matrix $V = U_L^{(E)+} U_L^{(\nu)}$ is also unitary. If neutrinos are Dirac fermions, this mixing matrix can be parameterized by four parameters: 3 rotation angles and one CP-violation phase. This is because 5 parameters can be absorbed into the lepton states by redefining their phase angles. If the neutrinos have a Majorana mass term, 6 parameters are needed (3 rotations and 3 CP phases). This is because the Majorana mass terms are not invariant under phase rotation, so there is no freedom to rotate the neutrino phases anymore. A famous parameterization of this transformation is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, in analogy to the CKM matrix in the quark sector. The PMNS matrix

takes the form:

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1.25)$$

Here c_{ij} and s_{ij} are short notation for $\cos(\theta_{ij})$ and $\sin(\theta_{ij})$ respectively. The last matrix is non-trivial only when neutrinos have a Majorana mass term.

1.3.2.2 Flavor Oscillations in vacuum

Due to the lepton mixing, neutrinos produced in a weak interaction process can oscillate to other flavors in propagation. Any weak eigenstate can be expressed as a superposition of mass eigenstates:

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i}^* |\nu_i\rangle \quad (1.26)$$

In vacuum, the mass eigenstates are also the energy eigenstates. So the time evolution operator acts on the mass eigenstates becomes a rotation of the complex phase:

$$|\nu(t)\rangle = U(t) |\nu_i\rangle = e^{-iE_i t} |\nu_i\rangle \quad (1.27)$$

We can express the probability of the neutrino oscillating from flavor α to flavor β as at a certain time t to be:

$$P(\nu_\alpha \rightarrow \nu_\beta)(t) = |\langle \nu_\beta | \nu(t) \rangle|^2 \quad (1.28)$$

With neutrino mass being tiny, neutrinos travel almost at the speed of light:

$$v_{neutrino} = c = 1 \quad (1.29)$$

After traveling a distance L , combining equation 1.26 and equation 1.27, we can find the probability of the neutrino oscillating from flavor α to flavor β to be:

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\beta)(t = L) = & \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}) \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right) \\ & + 2 \sum_{i>j} \text{Im}(U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}) \sin \left(\frac{\Delta m_{ij}^2 L}{2E} \right) \end{aligned} \quad (1.30)$$

Here, the Δm_{ij}^2 is the mass squared difference between the i^{th} and j^{th} eigenstates. The scale factor in front of L is sensitive to Δm_{ij}^2 . Neutrino oscillation experiments can measure the mass squared difference by fitting the energy spectrum. For this reason, the neutrino oscillation experiments are not sensitive to the neutrino mass ordering.

The oscillation length is defined as :

$$L_{ij} = \frac{4\pi E}{\Delta m_{ij}^2} \quad (1.31)$$

By comparing the actual distance from the neutrino source to the detector and the oscillation length, we can summarize the sensitivity of Δm_{ij}^2 from each neutrino source.

From equation 1.30, notice that if the matrix element is real, i.e. $U_{\alpha x} = U_{\alpha x}^*$, the equation is symmetric under the exchange of α and β . We can conclude that $P(\nu_\alpha \rightarrow \nu_\beta)$ is not the same as $P(\nu_\beta \rightarrow \nu_\alpha)$ only if the CP violating phase is non-zero. So in theory, by comparing the two flavor changing probability at the same distance, one could measure the CP violating

Table 1.1: Characteristic values for L and E with the corresponding range of Δm^2 in which they are most sensitive to oscillation in vacuum, table from [19]

Experiment	L (m)	E (MeV)	Δm^2 (eV ²)
Solar	10^{10}	1	10^{-10}
Atmospheric	$10^4 - 10^7$	$10^2 - 10^5$	$10^{-1} - 10^{-4}$
Reactor			
- VSBL-SBL-MBL	$10 - 10^3$	1	$1 - 10^{-3}$
- LBL	$10^4 - 10^5$	1	$10^{-4} - 10^{-5}$
Accelerator			
- SBL	10^2	$10^3 - 10^4$	> 0.1
- LBL	$10^5 - 10^6$	$10^3 - 10^4$	$10^{-2} - 10^{-3}$

phase. In practice, neutrino experiments compare $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ because producing ν_e beam is difficult.

1.4 Neutrino Sources

The weakly interacting nature makes neutrinos hard to detect, but fortunately, the amount of the neutrinos is very large. Neutrinos are produced from a variety of sources with a broad range of energy. Thanks to this, a precise measurement of the neutrino oscillation parameters is possible. Figure 1.5 shows a summary of the neutrino sources in our universe.

The current neutrino studies explore the nature of the neutrinos using sources ranging from reactor antineutrinos to accelerator neutrinos and antineutrinos. The neutrino sources that lie outside this energy range are not commonly studied for neutrino physics, but for other interesting topics. At the low energy end, the big bang relic neutrinos play an important role

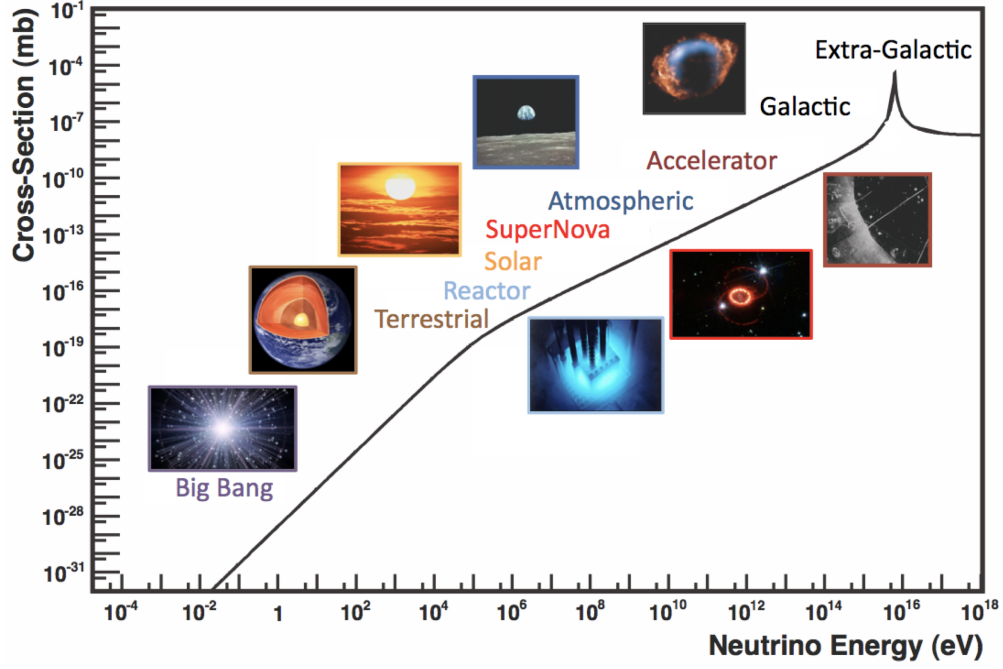


Figure 1.5: Overview of the prominent neutrino and antineutrino sources known within the universe. The desired energy range for typical neutrino physics experiments range from reactor neutrinos to accelerator neutrinos. The cross-section of the neutrino interaction is roughly proportional to its energy. Figure from [20]

in modeling the fine structure of the Cosmic Microwave Background [21]; Geoneutrinos are studied to understand the abundance of ^{238}U , ^{232}Th and ^{40}K and their spatial distribution in the Earth's crust and mantle. At the high energy end, the cosmic neutrinos are studied to understand the high energy radiation sources from the universe.

1.4.1 Solar neutrinos

Solar neutrinos are produced in the core of the Sun through various nuclear fusion reactions. There are two sets of nuclear reactions responsible for neutrino and energy productions in the Sun, the pp chain and the CNO cycle. Figure 1.6 and Figure 2.1 show these two processes respectively. The pp chain are responsible for 99% of the sun's power [22] and 91% of the solar neutrino [23]. The electron neutrinos produced in all fusion processes in the Sun form the total solar neutrino flux. Figure 1.8 shows the energy spectrum of the neutrino flux from different nuclear processes. By convention, solar neutrinos are named after their parents, for example, a pep neutrino means the neutrino is produced by the fusion process of two protons and one electron. As we can see from the figure, most of the neutrinos have energy less than 10 MeV. The flux of solar neutrinos is dominated by pp neutrinos (order of $10^{10} \text{ s}^{-1} \text{ cm}^{-2}$) having a continuous energy spectrum with a 420 keV endpoint. In the pp-chain, mono-energetic ${}^7\text{Be}$ (0.384 MeV when ${}^7\text{Li}$ is excited and 0.862 MeV when ${}^7\text{Li}$ is at ground state) and pep (1.44 MeV) neutrinos are produced, as well as ${}^8\text{B}$ neutrinos characterized by lower flux (order of $10^6 \text{ s}^{-1} \text{ cm}^{-2}$) and a continuous energy spectrum extending up to about 15 MeV. It is worth mentioning that the number of the final state particles determines if a neutrino energy spectrum is continuous or mono-energetic. For example, the pep neutrinos are mono-energetic because only two daughter particles are produced in the final state, the conservation law of energy and momentum ensures the energy of the neutrino is fixed. For the processes with continuous energy spectrum, the shapes of the energy distribution are

mainly determined by the kinematics of the nuclear reaction, with some corrections due to the Coulomb potentials of nuclei. This is because the energy of these reactions are at MeV scale, while the core temperature of the sun is at keV scale.

The most precise measurements of the pp, ${}^7\text{Be}$, and pep neutrinos are provided by Borexino experiment using highly purified liquid scintillator [24]. The precise measurement of ${}^8\text{B}$ neutrinos come from SNO [25] and Super-K [26] using ultrapure water. For the hep neutrinos, because of their very low expected flux, only upper limit were found by the SNO experiment [27]. The upper limit is still about three times higher than the expected flux. The detection of the CNO neutrinos is also not straightforward. The energy spectrum of CNO neutrinos overlaps largely with ${}^{210}\text{Bi}$ contamination and ${}^{11}\text{C}$ background caused by cosmic muons. In 2020, Borexino [28] experiment released their measurement on CNO neutrinos with 5σ C.L. using highly purified liquid scintillator with a upper constraint on the ${}^{210}\text{Bi}$ contamination.

Solar neutrinos are good source for oscillation parameters Δm_{21}^2 and θ_{12} due to its energy range and long distance from the earth. Further, a precise measurement of solar neutrino provides insight of the neutrino matter effect in the Sun and in the earth (day/night effect).

The measurement of solar neutrino interaction rate can be used to infer electron neutrino survival probability (P_{ee}) from the Sun. In the low energy region, below 1.5 MeV, the flavor conversion is dominated by oscillation in vacuum. At higher energy region, the flavor conversion is dominated by the matter effect. Figure 1.9 shows the survival probability of solar electron neutrinos from Borexino, SNO and Super-K.

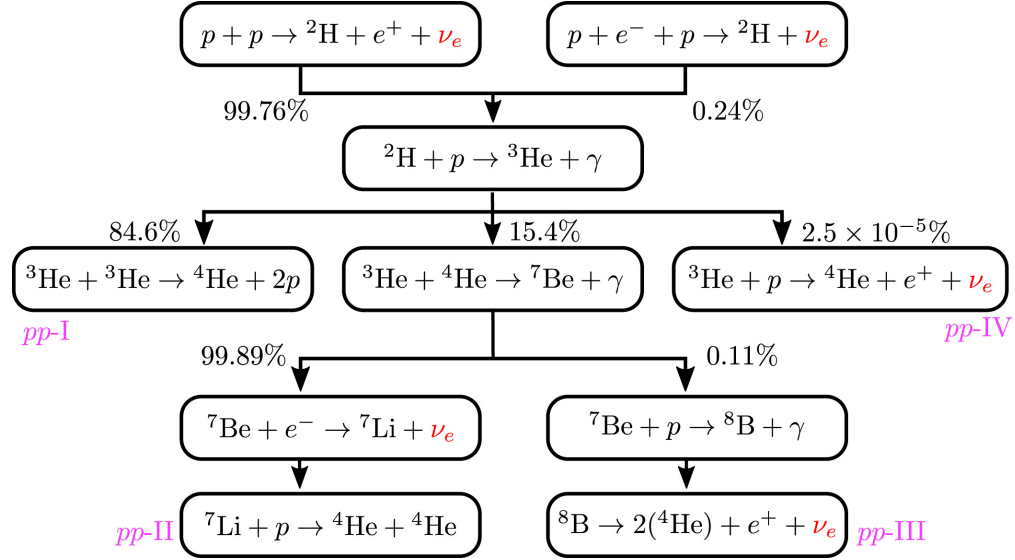


Figure 1.6: The pp chain in the solar fusion process. Two protons go through a fusion process and generate one neutrino. The daughter product ${}^2\text{H}$ can fuse to ${}^3\text{He}$. The ${}^3\text{He}$ can further fuse to ${}^7\text{Be}$ and generate neutrinos by capturing electrons. Figure from [22]

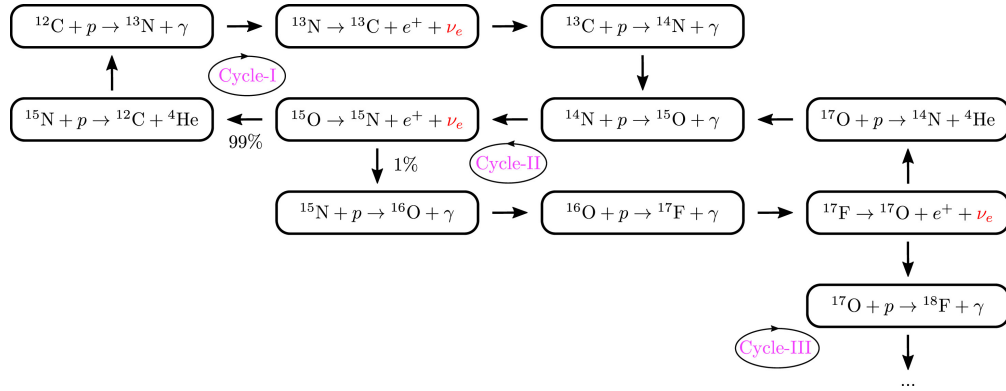


Figure 1.7: The CNO cycle in the solar fusion process. Figure from [22]

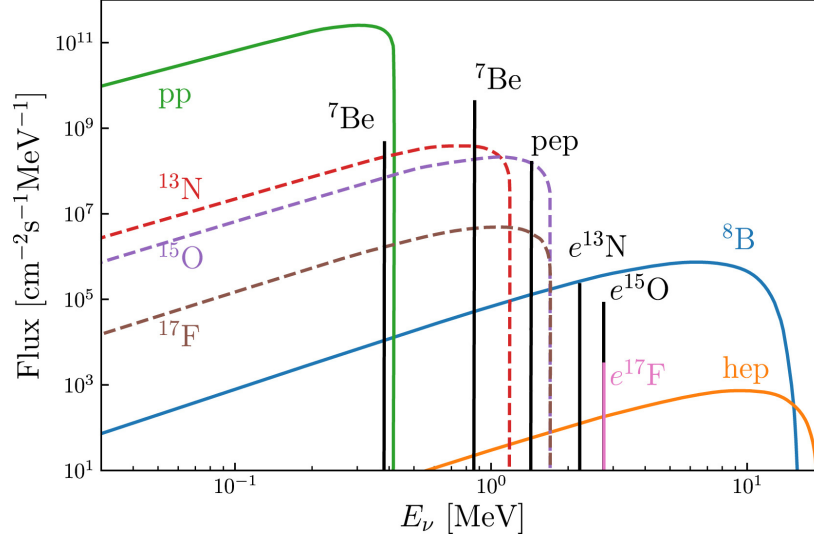
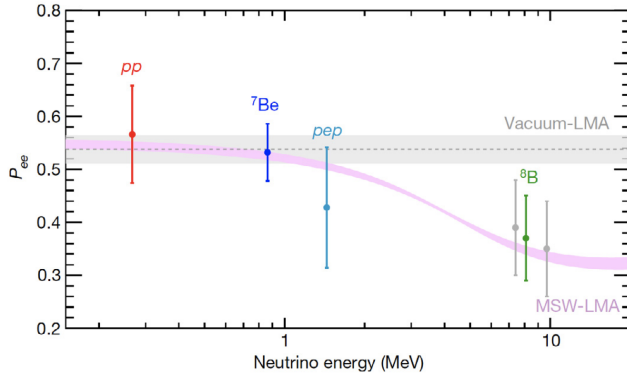


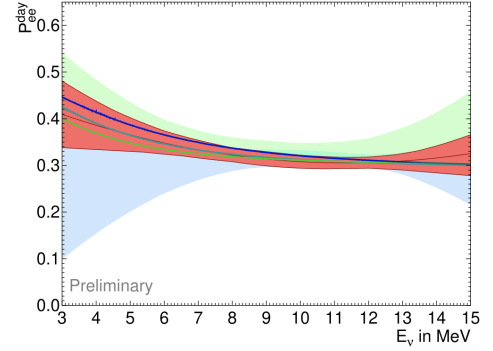
Figure 1.8: The solar neutrino flux from the most prevalent fusion processes in the Sun. The flux unit is in $cm^{-2}s^{-1}MeV^{-1}$ for continuous sources and in $cm^{-2}s^{-1}$ for mono-energetic sources. Figure from [22]

1.4.2 Reactor antineutrinos

Neutrinos produced from nuclear reactors are a good source for neutrino studies. They are produced in a large quantity, they are produced with only one flavor, and they have a fixed distance to the neutrino detectors. Nuclear reactors rely on the fission of the fuel to generate power. The fission fuel typically consists of four main isotopes: ^{235}U , ^{238}U , ^{239}Pu and ^{241}Pu . These isotopes can capture neutrons and become unstable heavier nuclei. These heavier nuclei absorb a thermal neutron and split into smaller daughter nuclei, a free neutron, and releases energy in the form of gamma radiation and kinetic energy. A portion of the free neutrons will be thermalized, and captured by another fissionable isotopes to trigger another



(a) The survival probability result from Borexio [29] for various solar neutrinos. The pink band is the 1σ prediction of the MSW effect in matter. The gray band is the Large Mixing Angle (LMA) solution for the solar neutrinos.



(b) The allowed survival probability 1σ band from SNO (blue), Super-K (green) and combined (red). The solid lines are MSW predictions from different oscillation parameters.

Figure 1.9: Electron neutrino survival probability. Taken from [30]

fission process. This is called the chain reaction.

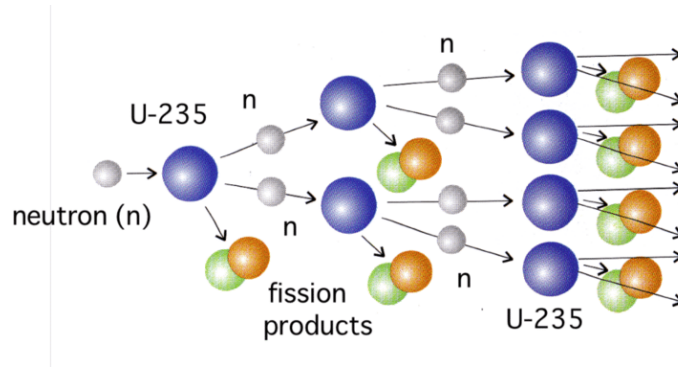


Figure 1.10: A demonstration of nuclear chain reaction. Taken from [31]. A heavy nucleus absorbs a thermalized neutron and splits into lighter fission products and two more neutrons and releases energy. The product neutrons will be thermalized and absorbed, causing the reaction to continue.

The daughter isotopes produced in the fission process are usually unstable. This is

because the heavy elements like ^{235}U usually have a higher ratio of number of neutrons over number of protons, and lighter elements tend to have a more balanced neutron proton ratio. So those isotopes will typically undergo a beta decay, transfer one or more neutrons into protons and emit electrons and electron antineutrinos. On average, about six electron antineutrinos are produced per fission [32].

So far, the best detection method for reactor antineutrino is the inverse beta decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$. This reaction has a relatively large cross-section ($\sim 6 \times 10^{-43} \text{cm}^2$). Moreover, the presence of a positron and a neutron in the final state provides a paired signal that is easy to distinguish from other radioactive backgrounds. Given the cross-section of IBD, one can calculate the expected antineutrino spectrum:

$$S(E) = N_p \cdot \epsilon_d(E_\nu) \cdot \frac{P_{\text{sur}}(L/E_\nu)}{4\pi L^2} \cdot \frac{d\Phi}{dE_\nu}(E_\nu) \cdot \sigma_{\text{IBD}}(E_\nu) \quad (1.32)$$

Where N_p is the total number of target protons, ϵ_d is the detection efficiency after all analysis cuts, and P_{sur} is the neutrino oscillation probability for a $\bar{\nu}_e$ to survive as a $\bar{\nu}_e$ after traveling a distance L from the reactor. $\frac{d\Phi}{dE_\nu}$ is the energy-dependent reactor antineutrino flux and σ_{IBD} is the inverse beta decay cross-section. For a given distance, the oscillation parameters can be extracted by fitting the energy spectrum.

The first observation of reactor neutrino oscillation was made by KamLAND [33] in 2002. It detects antineutrinos from more than 20 reactors with an average travel distance of about 180 km. The measurement from KamLAND confirmed the Large Mixing Angle (LMA) solution of the solar neutrino problem. The latest results from three-flavor neutrino oscillation

analyses with constraints from solar and short-baseline reactor neutrino experiments are [34]

$$\tan^2 \theta_{12} = 0.436^{+0.029}_{-0.025}, \quad \Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2. \quad (1.33)$$

The mass-splitting parameter Δm_{21}^2 is measured in high precision because it is independent of prior information for normalization.

There's a deficit of the measured antineutrino rate in short-baseline reactor experiments ($L < 2\text{km}$) with respect to a new set of calculations of the antineutrino flux in 2011. The difference measurement and the model don't agree at 98.6% C.L. [35]. This is called the Reactor Antineutrino Anomaly (RAA). One popular solution to this anomaly is the existence of sterile neutrino, with its corresponding mass around 1 eV or higher. A more detailed review of RAA can be found here [36].

1.4.3 Atmospheric neutrinos

High energy cosmic rays, typically consist of protons, can interact with atoms in the Earth's atmosphere and result in a cascade of particles. These particles consist of mesons, mostly pions. Pions are unstable, they will rapidly decay into muons and muon antineutrinos (or antimuons and muon neutrino):

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu \\ \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \end{aligned} \quad (1.34)$$

The charged daughter products, muons (or antimuon), are also unstable, they will decay into the corresponding muon neutrinos, electrons and corresponding electron neutrinos:

$$\begin{aligned}\mu^+ &\rightarrow \bar{\nu}_\mu + e^+ + \nu_e \\ \mu^- &\rightarrow \nu_\mu + e^- + \bar{\nu}_e\end{aligned}\tag{1.35}$$

Therefore, about two thirds of the atmospheric neutrinos are muon flavored, the remainder are electron flavored. As mentioned in section 1.1, atmospheric neutrinos provided the first evidence of the neutrino oscillation because their distance from the origin to the detector are dependent on the zenith angle. Because of their various distance and large range of energy, atmospheric neutrinos are good for measurement of θ_{23} and Δm_{23}^2 . A summary of the measurement of these two parameters can be found in table 1.2.

Experiment	$\sin^2 \theta_{23}$	$ \Delta m_{32}^2 [10^{-3} \text{ eV}^2]$
Antares [37]	$0.50^{+0.2}_{-0.19}$	$2.0^{+0.4}_{-0.3}$
IceCube [38]	$0.51^{+0.07}_{-0.13}$	$2.31^{+0.11}_{-0.09}$
Super-K [39]	$0.588^{+0.031}_{-0.064}$	$2.50^{+0.13}_{-0.20}$

Table 1.2: Measurements of $\sin^2 \theta_{23}$ and $|\Delta m_{32}^2|$ from Antares, IceCube and Super-K. Taken from [40]

1.4.4 Accelerator neutrinos

An accelerator neutrino is a human-generated neutrino from a particle accelerator. The accelerator neutrino beam typically consists of mostly muon type neutrinos. It can switch

between neutrino or antineutrino mode depend on the physics goal. Figure 1.11 shows the production scheme of muon neutrino. First, a proton beam is accelerated in a particle accelerator. The proton beam then collides with a fixed target, producing mesons like pions or kaons. This process is very similar to the production of atmospheric neutrinos mentioned in section 1.4.3. A set of magnetic horns will then be used to focus the charged mesons and select the charge. The positively charged mesons are used to produce muon neutrinos and vice versa. Then the mesons are sent to a decay channel. The length of the decay channel is designed to maximize the decay probability of mesons while minimizing the decay probability of muons in order to have a relatively high beam purity. The remaining mesons and charged leptons will be absorbed by the beam dump, while neutrinos will travel freely through the beam dump, forming a relatively pure neutrino beam. A typical neutrino beam has energy centered at a range from hundreds of MeV to hundreds of GeV. Two types of neutrino experiments can be placed at the beam downstream: short baseline experiments and long baseline experiments. These experiments benefit from the fact that the neutrino flux and energy profile are well under control and the knowledge of the neutrino incident direction facilitates the neutrino reconstruction and background discrimination. The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) is among the short baseline experiments. In Chapter 3, we will discuss how we make use of the Booster Neutrino Beam (BNB) from Fermilab to make technical development of Water-based Liquid Scintillator (WbLS).

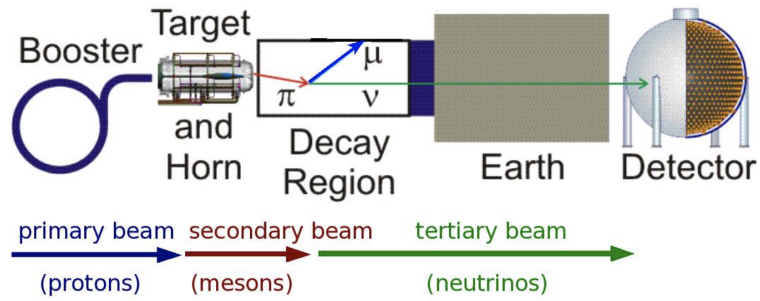


Figure 1.11: A demonstration of muon neutrino production taken from [41]. A beam of high energy proton hits the graphite target and produce mesons. The mesons are further selected by a neutrino horn. The selected mesons decay in the decay channel to generate neutrinos. Finally, the decay products other than neutrinos are dumped in the beam dump.

Chapter 2

Attenuation Coefficient Measurement of Water-based Liquid Scintillator

Recent developments in the field of liquid scintillator chemistry and fast-timing photosensors have paved the way for a new generation of large-scale detectors capable of tackling a broad range of physics issues. Water-based Liquid Scintillator (WbLS) is a promising detection medium that combines the advantages of pure water, including low attenuation, accurate direction reconstruction, and low cost, and those of liquid scintillator, including high light yield and low-threshold detection. When coupled with high efficiency, fast-timing photosensors, such as Large Area Picosecond Photo Detectors (LAPPD), WbLS exhibits an immense potential for neutrino physics and BSM searches. In this chapter, we first discuss the physics topics that would be improved with future WbLS detector, more specifically, Theia[42]. We then demonstrate the importance of attenuation measurement of WbLS in

neutrino experiments. We then give an overview of the Scattering and Attenuation Measuring Device (SAMD) system, along with validation tests of the system. This chapter ends with pure water test, WbLS result and discussion on systematic errors.

2.1 WbLS Empowered Physics Goals

WbLS is an admixture of a low percentage of liquid scintillator in water, featuring high transparency and which is an enabling medium for hybrid neutrino event detection. It enables detections such as CNO neutrinos and Diffuse Supernova Neutrino Background (DSNB).

Large Water Cherenkov (WC) detectors like Super-Kamiokande (Super-K) have faced limitations in sensitivity due to the inability to detect particles with energy below the Cherenkov threshold. For example, this limits sensitivity to the Diffuse Supernova Neutrino Background (DSNB)[43]. The main detecting reaction for DSNB is the inverse beta decay (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$. In this interaction, positron is first detected, followed by the gamma rays from neutron capture. In WC detectors, positron annihilation signal cannot be detected due to its low energy, making the prompt signal indistinguishable from electron signals, which is a common product of atmospheric neutrino CCQE interactions. Another example would be the detection of proton decay. The kaon from $p \rightarrow \bar{\nu} + K^+$ is below the Cherenkov threshold, making it invisible in a WC detector.

Organic liquid scintillators (LS) have been used to enhance sensitivity for below Cherenkov threshold particles. LS is currently being used in the KamLAND, Borexino, and SNO+ de-

tectors, and is planned for use in the JUNO detector. While LS is very effective at increasing sensitivity at low energies, it comes at the loss of the directional sensitivity and multi-track resolution that is a hallmark of WC detectors. Use of organic LS also introduces issues of high cost, short optical transmission lengths, and undesirable environmental and safety problems.

The recent development of water-based liquid scintillator (WbLS)[44] has the potential to make the best of both worlds. By adding a small amount (typically 1–10%) of liquid scintillator into water, the liquid yield can be adjusted to allow detection of particles below Cherenkov threshold while not sacrificing directional information, cost, or environmental friendliness. First developed at Brookhaven National Lab (BNL), WbLS has a great potential in neutrino experiments like ANNIE and Theia.

2.1.1 Solar neutrinos

The world-leading limit on the CNO flux comes from the Borexino experiment[29]. A primary obstacle to observation is the challenge of distinguishing the elastic scattering (ES) of CNO neutrinos from radioactive backgrounds, particularly beta decays, using only the energy spectrum. Sensitivity to event direction could substantially add to the discrimination power, as the neutrino-scattered electron direction should be strongly correlated with the direction of the Sun, whereas the background should appear isotropic. The combined detection of both Cherenkov and scintillation signals in WbLS should allow for both direction reconstruction

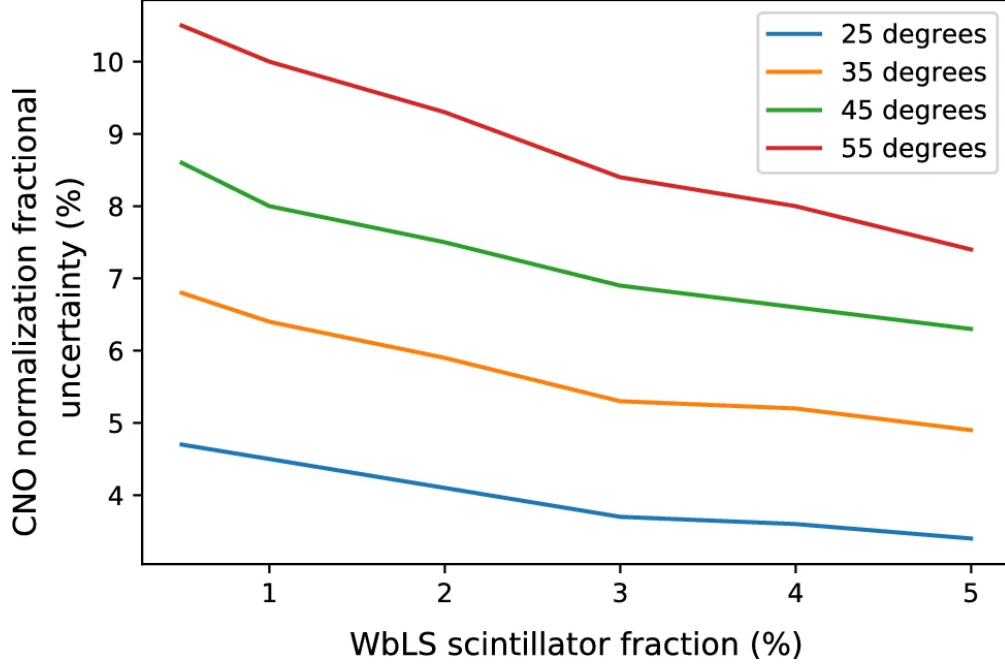


Figure 2.1: Fractional uncertainty of the CNO normalization parameter as a function of angular resolution and WbLS scintillator fraction, for Theia-100[46], by comparison, the CNO flux measured by Borexino Experiment has an uncertainty of around 43% [47].

and the required low threshold. The sensitivity of the precise measurement from CNO neutrino flux can be shown in Figure 2.1 Other exciting physics opportunities related to solar neutrinos include tests of solar luminosity through precision measurements of pep and pp neutrinos; tests of the solar temperature; and, potentially, separation of the different components of the CNO flux to probe the extent to which this cycle is in equilibrium in the Sun's core[45].

2.1.2 Diffuse Supernova Neutrino Background (DSNB)

The Diffuse Supernova Neutrino Background (DSNB) consists of neutrinos emitted by all core-collapse supernovae (SNe) throughout the Universe[48, 49]. Travelling over vast distances and red-shifted by cosmic expansion, these neutrinos constitute a faint isotropic background flux. The discovery and subsequent spectroscopy of the DSNB will provide unique information on the redshift-dependent SN rate, the relative frequency of neutron star and black hole formation and the equation of state of the emerging neutron stars (e.g. [50]).

The primary detection reaction for the component of the DSNB flux is the inverse beta decay (IBD). With an expected event rate of 0.1 per year per kiloton of detector material, overwhelming backgrounds have to be faced. IBD from reactor and atmospheric anti-neutrinos are indistinguishable backgrounds at low and high energy, limiting the effectiveness of DSNB detection in a broad energy window. A WbLS detector offers the possibility to discriminate events by the magnitude of the Cherenkov signal accompanying the scintillation light. While electron/positron signals feature a high Cherenkov-to-scintillation (C/S) ratio, that of non-relativistic nuclear recoils is practically zero. Because atm-NC events feature nuclear recoils, their C/S ratio is typically small. As demonstrated by the upper panel of Figure 2.2 that displays the C/S ratios of signal and atm-NC events as a function of visible energy, this parameter provides a powerful tool to reject atm-NC (but also fast neutron) background events. Residual atm-BG events with non-zero C/S values are due to the emission of γ -rays in nuclear de-excitations of oxygen nuclei. The bottom panel of Figure 2.2

shows the relation between signal efficiency and background reduction factor as a function of C/S threshold[51].

2.2 Attenuation Coefficient Measurement

For future large scale neutrino experiments such as Theia[42], traditional Liquid Scintillator (LS) has the disadvantage of being expensive and difficult to dispose due to environmental and fire safety concerns. WbLS is a promising replacement for several reasons: (1) WbLS consists of mostly water, making it affordable at large scale. (2) Many isotopes that are common in neutrino experiments, such as Te, can be dissolved in water but are fairly insoluble in non-polar solvent used for conventional LS. (3) WbLS can be tuned to take advantage of high light yield as well as Cherenkov directionality.

Many neutrino detectors use optical photons emitted from neutrinos interacting with detecting media. Thus, the optical transparency of the medium is an important factor in the detector efficiency. Attenuation length is the usual parameter used to quantify optical transparency. This section describes the design principle of an attenuation measurement experiment.

Scattering and Attenuation Measuring Device (SAMD) is a device built on the Davis campus to measure the attenuation length of liquid media, more specifically, WbLS, for future neutrino detectors.

For an initial intensity I_0 of an incident light at position $x=0$ propagating with a wave-

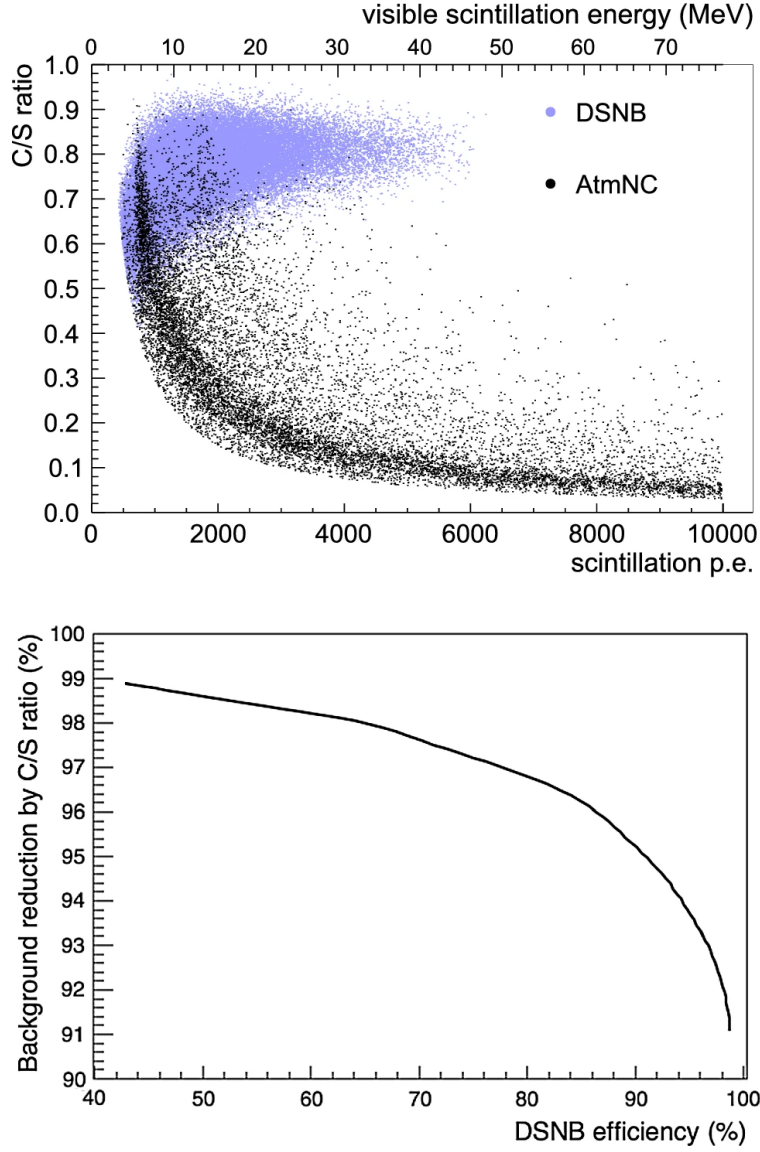


Figure 2.2: Top panel: The C/S ratio offers a powerful tool for the discrimination of positron-like DSNB (blue) and hadronic prompt events from atm-NC reactions (black). While most background events feature no Cherenkov light and, as such, a C/S ratio of 0, some final-state γ rays result in a curved band of atm-NC events that leaks slightly into the signal region. Bottom panel: atm-NC background reduction as function of the DSNB signal efficiency, figure taken from [46]

length λ in a liquid, the intensity I after propagating a distance x through the liquid can be written as follows:

$$I = I_0 \exp(-x/L(\lambda)) \quad (2.1)$$

Where L is the attenuation length which is a function of wavelength λ . Attenuation is considered a combined effect of absorption and scattering. SAMD is the device that allows the measurement of light intensity with a varying propagating distance x . The attenuation length can thus be extracted.

For absorption, most molecules and ions absorb energy in the ultraviolet or visible range, i.e., they are chromophores. The absorbed photon excites an electron in the chromophore to higher energy molecular orbitals, giving rise to an excited state. In the case of water, three types of transition that can give rise to absorption of electromagnetic radiation: (1)rotational transitions, in which the molecule gains a quantum of rotational energy. Atmospheric water vapor at ambient temperature and pressure gives rise to absorption in the far-infrared region of the spectrum, from about 200 cm^{-1} ($50 \text{ }\mu\text{m}$) to longer wavelengths towards the microwave region[52]. (2)vibrational transitions in which a molecule gains a quantum of vibrational energy. The fundamental transitions give rise to absorption in the mid-infrared in the regions around 1650 cm^{-1} (μ band, $6 \text{ }\mu\text{m}$) and 3500 cm^{-1} (so-called X band, $2.9 \text{ }\mu\text{m}$)[53]. (3)electronic transitions in which a molecule is promoted to an excited electronic state. The lowest energy transition of this type is in the vacuum ultraviolet region. The absorption of visible light in water is attributed to a sequence of overtone and combination bands. It

starts with the tail of the 3rd overtone of O-H asymmetric stretching, i.e. the frequency of this mode is 4 times the intrinsic frequency of the O-H bond oscillation. This mode has the absorption band at 698nm, thus is responsible for red light absorption and thus cause water to appear blue[54].

The scattering effect of pure water on visible light is dominated by thermal fluctuation, and this effect is described by Smoluchowski-Einstein Fluctuation Theory. Random thermal motion of molecules in a liquid causes the fluctuation in the number of molecules in a given volume element. The size of volume elements is small compared with the wavelength of light such that the light field inside the volume elements can be considered homogeneous, but big enough to contain a sufficient number of molecules for statistical thermodynamics to be applicable. The microscopic fluctuation in the number of molecules leads to microscopic fluctuation in density ρ and subsequently the microscopic fluctuation in the refractive index n that ultimately leads to the scattering of light. The volume scattering function β due to density fluctuation is[55]:

$$\beta(\theta) = \frac{\pi^2 k_B T \beta_T}{2\lambda^4} \left(\rho \frac{\partial n}{\partial \rho} \right)^2 (1 + \cos^2(\theta)) \quad (2.2)$$

where n is the index of refraction and is a function of the density ρ . k_B is Boltzmann constant, λ is the wavelength of light, β_T is the isothermal compressibility, T is absolute temperature, and θ is the scattering angle. The scattering function $\beta(\theta)$ can be thought as the probability density of a photon scattered to the angle θ by a collection of target molecules.

Water molecules are not isotropic, the anisotropic nature of water molecules further complicates the problem and affects the scattering function. After taking anisotropic effect into account, the scattering function becomes:

$$\beta(\theta) = \frac{\pi^2 k_B T \beta_T}{2\lambda^4} \left(\rho \frac{\partial n}{\partial \rho} \right)^2 \left(1 + \frac{1 - \delta}{1 + \delta} \cos^2(\theta) \right) \left(\frac{6 + 6\delta}{6 - 7\delta} \right) \quad (2.3)$$

where δ is the depolarization ratio, defined as the ratio between horizontally and vertically polarized components of the scattered light at 90 degrees with an incident, un-polarized light. The detailed derivation can be found in [55]. The scattering coefficient b can then be expressed as:

$$b = 2\pi \int_0^\pi \beta(\theta) \sin(\theta) d\theta \quad (2.4)$$

In WbLS, the two dominant scattering component are Rayleigh scattering and Mie scattering. Rayleigh scattering results from the electric polarizability of the particles. The oscillating electric field of a light wave acts on the charges within a particle, causing them to move at the same frequency. The particle, therefore, becomes a small radiating dipole whose radiation we see as scattered light. The particles may be individual atoms or molecules. Mie scattering describes the scattering of an electromagnetic plane wave by a homogeneous sphere. The "Mie scattering" formulas are most useful in situations where the size of the scattering particles is comparable to the wavelength of the light, rather than much smaller or much larger. So the micelles formed by scintillators are the dominant Mie scattering centers in WbLS.

To model both scattering and absorption of light inside a liquid, consider N different absorption and scattering species inside the liquid, each has a cross-section σ , the attenuation length can be written as :

$$1/L = n_r * \sigma_r + n_m * \sigma_m + n_a * \sigma_a \quad (2.5)$$

Where L is the attenuation length and n_r , n_m and n_a are the number densities of and Rayleigh scattering, Mie scattering and absorption centers respectively. σ_r, σ_m and σ_a are the corresponding cross-sections. The number density can be temperature dependent, its effect will be discussed later.

A direct attenuation coefficient measurement device must meet the following requirement:

- The distance scale has to be large enough to make the attenuation effect observable.
- The wavelength range should cover detector working range in a typical neutrino experiment, this is set by the spectral range of the photo sensors used by the detector.
- The data should be relative light intensity rather than absolute light intensity to counter the light loss through processes that are not of interest, for example, light loss by reflection.
- The light source should be monitored, so the scale factor I_0 is well understood, this can reduce the uncertainty caused by instability of the input laser.
- The system should have a linear response to changes in the input light intensity in the expected dynamic range.

- The system must be robust in a way that the result should not be sensitive to small changes in the system configuration. For example, PMT voltage, measuring time, etc
- The material to build the device should be chemically compatible with the liquid to be tested

2.2.1 Determination of distance scale

In order to make the attenuation effect observable, the scale of liquid capacity has to be large enough. The determination of the capacity scale depends on the attenuation length of the tested material L and the resolution of the data, which can be represented by the uncertainty σ . Consider equation 2.1 as true data, the measured data can be assumed to follow a Gaussian distribution centered at the true value:

$$I_m \sim G(I_t, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2} \left(\frac{I_m - I_t}{\sigma}\right)^2\right)$$

where I_m denotes measured signal and I_t denotes the true data. I_m and I_t both are functions of light path. σ is the standard deviation, and is governed by statistical fluctuation and systematic uncertainties. At this stage, the bias caused by any detection flaw is not considered.

An observable effect would mean the observed data at the max distance d_{max} should have a large deviation from the data at $d=0$ compared to the deviation from measured data and the true value. For a rough estimation, one standard deviation is considered here. This

means if the relative uncertainty is 2%, the true light intensity at distance d_{max} should be less than 98% of the true light intensity at distance 0. Hence:

$$0.98 = \exp(-d_{max}/L)d_{max} = -L \ln(0.98) \approx 0.02L \quad (2.6)$$

Because the distance scale is determined before any measurement of WbLS, an estimation based on water is made for two reasons: 1, As we discussed in the previous section. WbLS is a mixture of water and scintillator, so the attenuation length for WbLS should be smaller than water at the same wavelength. 2, The absorption coefficient of water is already well understood. A measurement of water can be a good validation test of the device. So it is important the device is long enough for a measurement of pure water.

As shown in Figure 2.3, the smallest absorption coefficient of water is around 0.006 m^{-1} in the region of interest, this corresponds to an absorption length of 167 m, thus a minimum distance scale of 3.34m.

2.2.2 Wavelength coverage

The wavelength coverage is determined by the spectral response of photon detectors in neutrino detectors, as well as the scintillator used.

In neutrino experiments, a typical photon detector is a Photon Multiplier Tube (PMT). The photocathode of a PMT converts photons flux into electron flux. The conversion efficiency varies with the wavelength of incident light. This relationship is called the spectral response and is typically characterized in terms of quantum efficiency or radiant sensitiv-

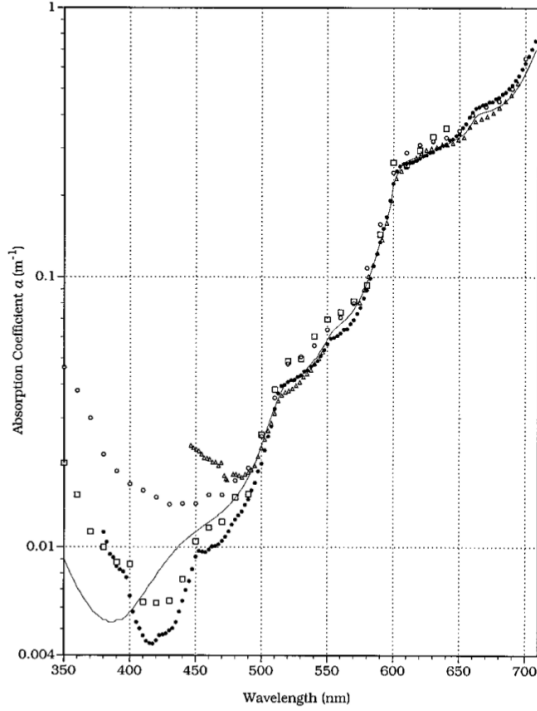


Figure 2.3: The absorption coefficient of pure water from different experiments[56][57][58][59]. Figure from [60]

ity. The long wavelength limit is determined by the photocathode material, while the short wavelength limit is determined by the window material. As shown in Figure 2.4, A typical working range of a PMT lies in the region between 300nm to 650nm.

The optical response of the scintillator component is also a factor to be considered. Because of the high light yield and reasonable price, linear alkyl benzene (LAB) is considered a good scintillator in neutrino experiments. In order to reduce the absorption of scintillation light, PPO is usually added to LAB as a wavelength shifter, Figure 2.5 shows the absorption length of LAB and PPO in JUNO and Daya Bay experiments.

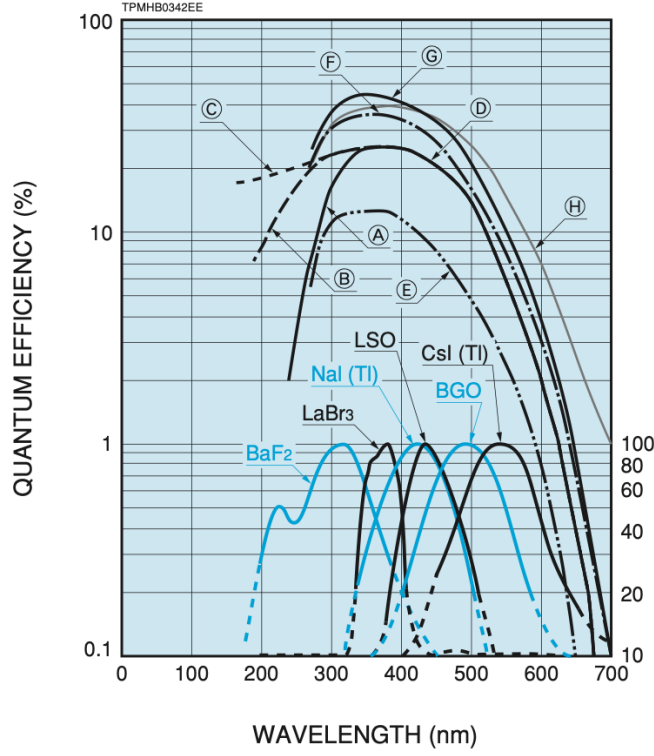


Figure 2.4: Spectral response of a typical PMT, the range of the quantum efficiency larger than 1% is between 300nm and 650nm. The characters in the plot stands for different materials, which is not of interest here. More details can be found in the original material[61]

2.2.3 Measurement strategy

As discussed in the previous section, the light intensity is a function of only the light path and attenuation length, which is a medium-related parameter. So the most straightforward way to measure attenuation length is to simply reverse equation 2.1:

$$L(\lambda) = x / (\ln(I_0) - \ln(I)) \quad (2.7)$$

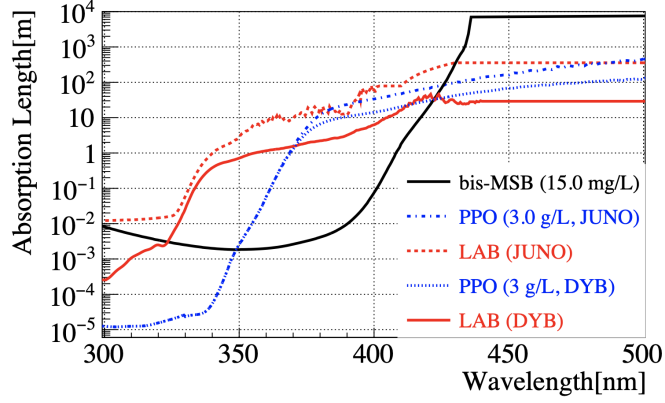


Figure 2.5: The measured absorption length of LAB and PPO in JUNO and Daya Bay experiment. The absorption length is significantly higher in the 350 nm wavelength region. Figure from [62]

But in practice this is not the case because of inevitable light loss due to optical reflection and refraction by the optical components. We can extend our model into a more practical version by adding a light loss term to equation 2.1:

$$I = \alpha I_0 \exp(-x/L(\lambda)) \quad (2.8)$$

where α denotes the overall efficiency of optical components. Notice α is not a function of x because the optical system is fixed.

Equation 2.7 thus becomes:

$$L(\lambda) = x/(\ln(\alpha) + \ln(I_0) - \ln(I)) \quad (2.9)$$

It is usually hard to determine the exact value of α , furthermore, the uncertainty of α accumulates with the number of optical components added to the system. So we need

to consider another strategy.

In the case we have multiple measurement, and each measurement is denoted a number i , we can re-write equation 2.7:

$$I_i = \alpha I_0 \exp(-x_i/L(\lambda)) \quad (2.10)$$

The ratio between two measurement is thus:

$$I_i/I_{i+1} = \exp((x_{i+1} - x_i)/L(\lambda)) = \exp(\Delta x/L(\lambda)) \quad (2.11)$$

The attenuation length L can be calculated as:

$$L(\lambda) = \Delta x / (\ln(I_{i+1}) - \ln(I_i)) \quad (2.12)$$

Equation 2.12 shows if we choose relative light intensity instead of absolute light intensity, the measured attenuation length L is independent of I_0 and α .

2.2.4 Light source monitor

In order to make relative light intensity measurement, the light source must be stable, that is to say, the input light intensity I_0 should be a constant or has relatively small fluctuation.

While the behavior of a light source is not always trustworthy, a monitoring system can serve the same purposes of canceling statistical fluctuations. A beam splitter with high pass can be used as a sampler for monitoring purpose. Assuming all the system response is linear (α is not a function of I_0), we can measure both output light intensity I and the input light intensity I_0 for each light pulse, and the ratio of the two is independent I_0 of :

$$R = I/I_0 = \alpha \exp(-x_i/L(\lambda)) \quad (2.13)$$

Thus, the ratio between the final light intensity I and initial light intensity I_0 is the quantity of interest, this will be denoted as R in the following sections.

2.3 Scattering and Attenuation Measuring Device (SAMD)

The Scattering and Attenuation Measuring Device (SAMD) is built on UC Davis campus to measure the attenuation length of neutrino detecting medium, more specifically WbLS, for future neutrino detectors. This section describes the experimental setup of SAMD.

To measure the attenuation length of the target medium, SAMD consists of three components: the optics, the DAQ system and the main attenuation arm. A schematic diagram is shown in Figure 2.6

A laser triggered by a pulse generator produces periodic laser pulses. The laser pulses are then reflected by a 45 degree mirror and passes through a neutral density filter and a polarizer and eventually is split by a beam sampler. Only one percent of the photons are reflected by the sampler and reach an integrating sphere, while the majority of the laser photons pass through the sampler and reach to the main attenuation arm. The pulse is then attenuated by the liquid held in the main attenuation arm and is captured by the PMT at

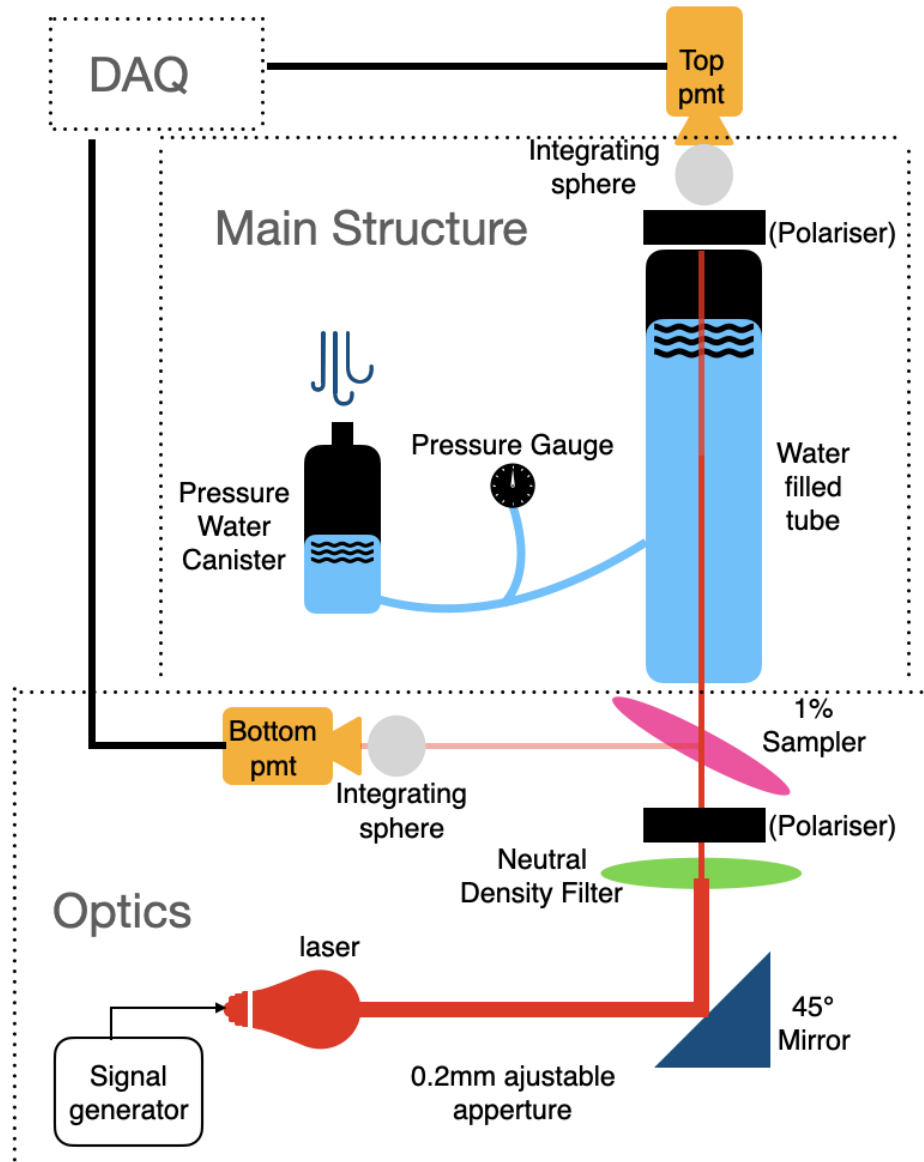


Figure 2.6: An experimental diagram of the SAMD experiment at the University of California, Davis

the top of the arm. The amount of liquid inside the arm is tuned by a pressure water canister and is precisely measured by a pressure gauge. The attenuation coefficient is then deducted by counting the total photon received by the top PMT with varying amount of absorbent inside the arm.

2.3.1 Optical components

The optical system is an essential part of SAMD. The main purpose of the optical system is to generate well monitored and fully controlled light pulse. It is located inside a dark box that is mounted on an optical table to isolate vibration from the ground and to reduce external light background. A picture of it is shown in Figure 2.8. It consists of:

- four **commercial pulsed lasers** to generate laser pulses of four different wavelengths
- **remote controllable motors** to align the direction and position of light path. Alignment of the light path is essential for the measurement, a detailed discussion will be made in the measurement and analysis section.
- a **45° mirror** to redirect laser pulses towards the attenuation arm
- a **neutral density filter** to attenuate the laser pulse, so the light intensity lies in the linear response region of PMT. A linearity test is made possible by varying the optical density of this filter
- a **beam sampler** to monitor laser pulse quality.

- an **integrating sphere** to collect light with minimum effect from small variation in the incident angle

2.3.1.1 The laser system

SAMD uses four commercial laser systems manufactured from Thorlab with different center wavelength: 401nm, 450nm, 490nm and 520nm. The spectrum of each laser is shown in Figure 2.9. The wavelength is chosen to avoid scintillator absorption spectrum below 350nm. Each laser is installed onto a motor driven rotation stage with a step size of 10^{-3} mm.

All the lasers are Thorlab NPL series. The output pulse width of the lasers is adjustable and is ranged from 5ns to 39ns. In SAMD, all the measurement has a fixed pulse width of 5ns. The lasers are triggered externally by a pulse generator at a rate of 1 kHz. The trigger rate is chosen so the PMT has enough rest time between pulse.

The optical output is a linearly polarized, free-space beam collimated by an integrated aspheric collimating lens, which is permanently fixed in a tube located behind the shutter. The lens position is factory set for a nominal divergence of about 1 mrad, which corresponds to a dot with a size of 1 cm at the top detector end (see Figure 2.7), given the distance from the laser to the light detector is about 5m.

The energy per pulse is varied for each laser and is dependent on the pulse width. The maximum pulse energy can be found in the manufacture manual, see appendix A. The single pulse energy for SAMD can thus be estimated by assuming the pulse energy is a linear function of pulse width. For example, the typical maximum energy per pulse for a 450nm

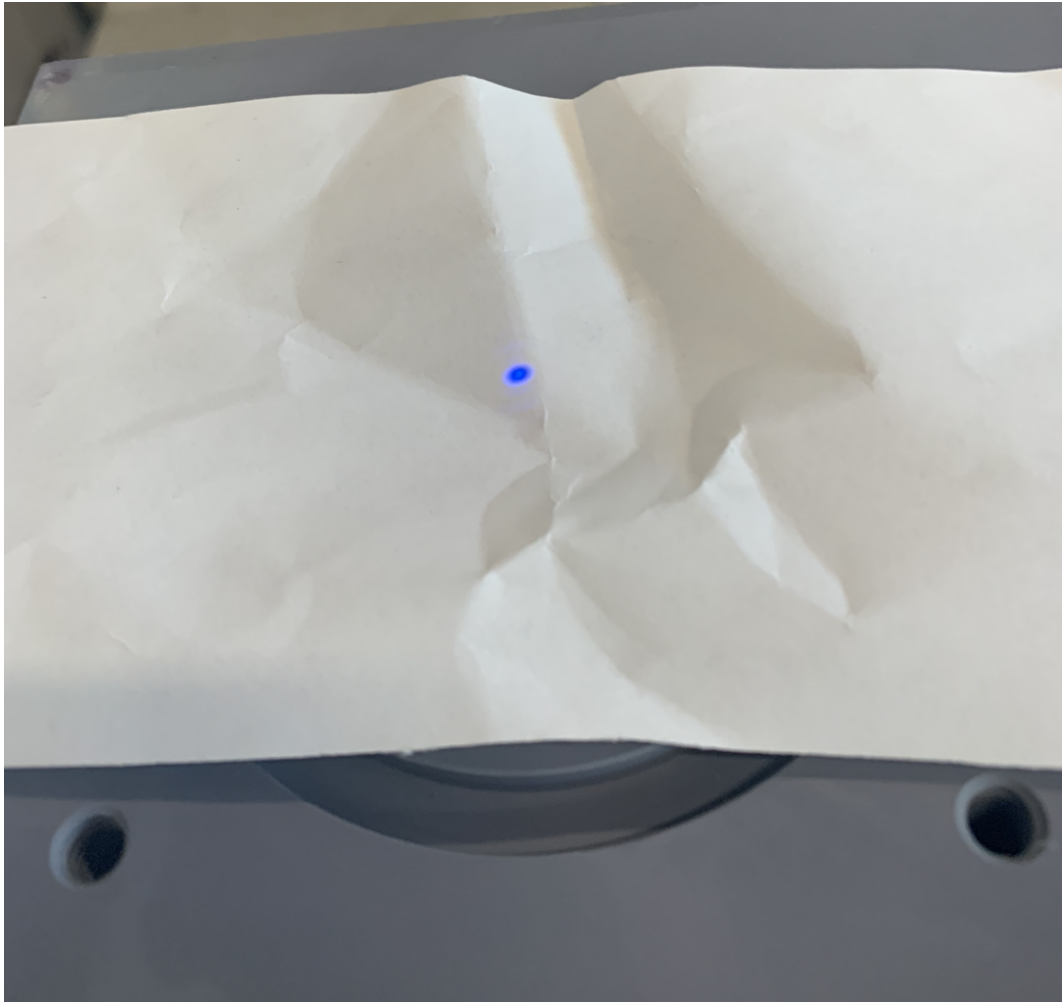


Figure 2.7: A picture of the laser dot near the top detecting plane.

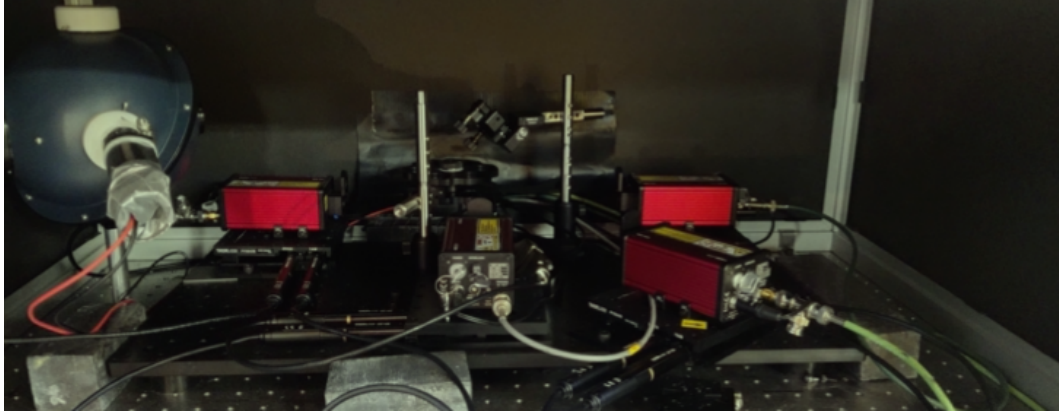


Figure 2.8: A picture of the optics system inside a dark box.

laser is 3nJ with the maximum pulse width equals 39ns. This corresponds to an energy of 0.46 nJ for a pulse with pulse width 6ns. According to Planck's Equation, 1.5×10^{10} photons are emitted per single pulse. Despite significant loss in the integrating spheres, this number of photons are too high compared to the maximum photons one PMT can handle, so a neutral density filter is mounted to reduce the light intensity for both top and bottom PMTs.

2.3.1.2 Remote Controllable Motors

All four lasers are mounted on Thorlab Motorized Pitch/Yaw Platforms, model number PY004Z8. The Platforms provide $\pm 2.5^\circ$ in pitch and $\pm 4^\circ$ in yaw. The minimum incremental movement is 7.13 arcsec for pitch and 15.17 arcsec for yaw, which corresponds to a movement of 0.2 mm and 0.4 mm for the light spot on the top optical spheres. This step size is small enough to serve the purpose of precise alignment. The remote motors

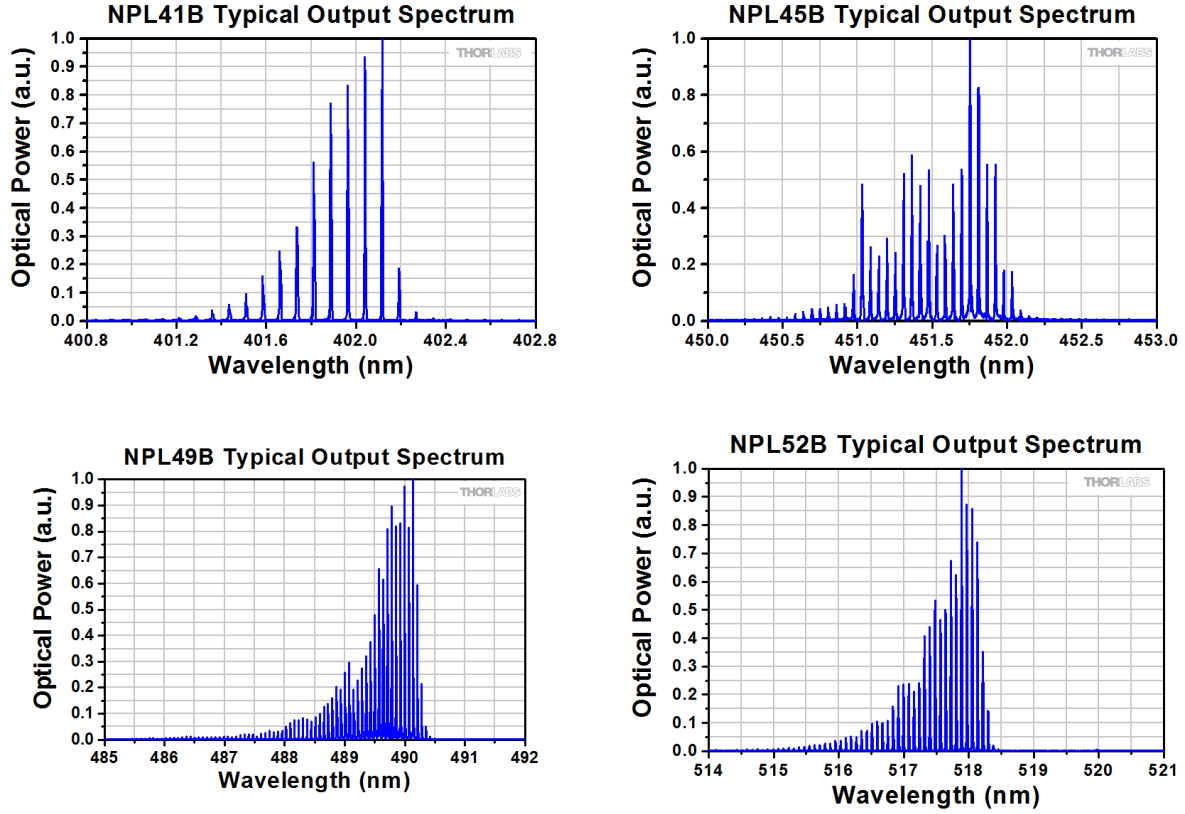


Figure 2.9: Spectrums of all four lasers in use, The lasers are considered monochromatic given the half-width of the laser output spectrum is around 2nm. The variation of attenuation length is treated as a systematic uncertainty. Figure from [63]

are controllable and programmable by both computers and Thorlab provided K-Cube DC Servo Motor Controller. During alignment, the platform scans in both pitch and yaw direction. A 45° mirror is mounted on a Thorlab motorized rotation stage, model number PRM1Z8. The stage can provide a 360° rotation for the component mounted on top of it, in this case, a 45° mirror. This mirror redirects the horizontal beam generated by lasers towards the top optical sphere. This rotation stage is also controllable remotely by com-

puter, with minimum achievable incremental motion 25 arcsec. The step size is small enough for alignment purpose. The rotation movement of this stage and the pitch movement of the Pitch/Yaw Platforms together controls the angular displacement of the beam, while the Yaw movement controls the translational displacement. Furthermore, the rotation stage makes possible changing light source without opening the dark box by facing the mirror towards different lasers.

2.3.1.3 Neutral Density Filter

Neutral Density Filters are filters that can reduce by-passing light intensity in a broadband. SAMD uses anti-reflective coated neutral density filters to reduce the laser pulse energy to a level where PMT works efficiently without saturating. These filters are also used to test the response linearity of the system. The key parameter of the neutral density filters is their Optical Density (OD), which is defined by:

$$OD = \log_{10}(-1/T) \quad (2.14)$$

where T is the transmission and is valued between 0 and 1.

SAMD utilizes 5 low OD filters and 6 high OD filters, all of them are purchased from Thorlab. The filters are mounted on a two layers rotational mirror mount that is placed horizontally (See Figure 2.10). The five low OD filters are mounted on the top layer and serve as fine-tuning, and the six high OD filters are mounted on the bottom layer. The average transmissions for filters are show in Table 2.1 [64].

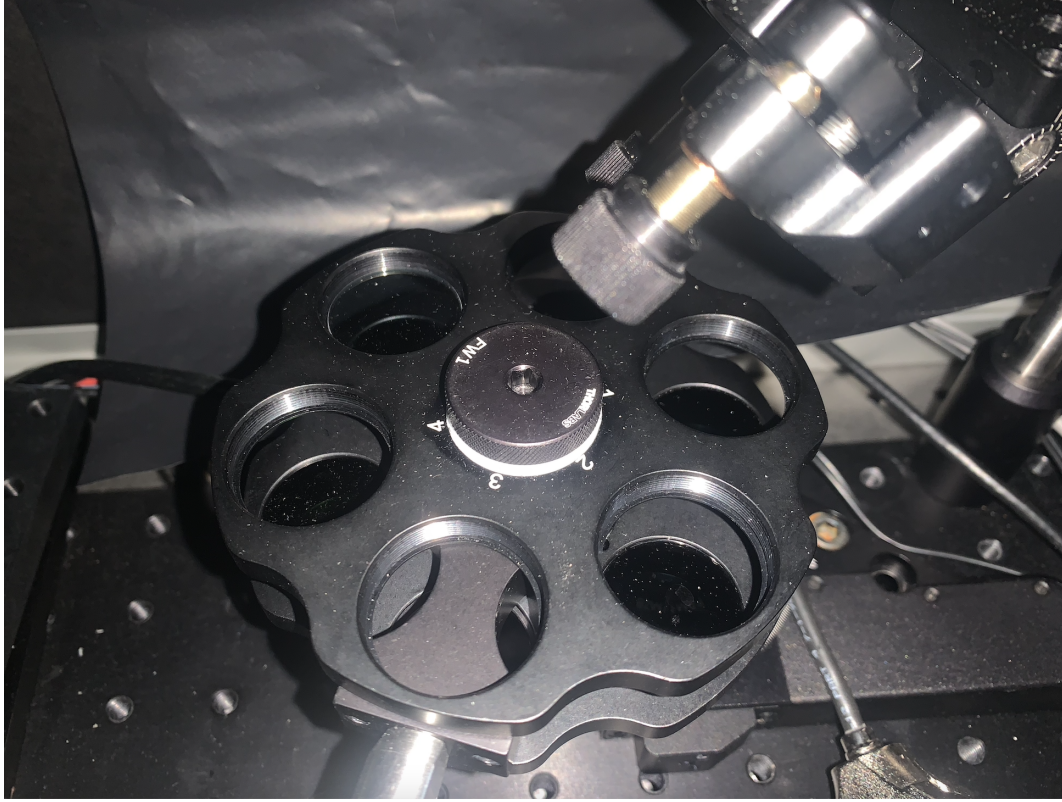


Figure 2.10: The two layers ND filter mount

Table 2.1: The transmission rate for each ND filter

Filter Type	0.2	0.3	0.4	0.5	0.6	1	2	3	4	5	6
Transmission(%)	63	50	40	32	25	10	1	0.1	0.01	0.001	0.0001

The spectral response in visible light region is shown in Figure 2.11

The transmission of each filter is also cross-checked using UV-Vis spectrometer. Each filter was placed inside the spectrometer and fully covers the reception window. Because of the AR coating, the reflection can be neglected. The spectrometer records the absorption

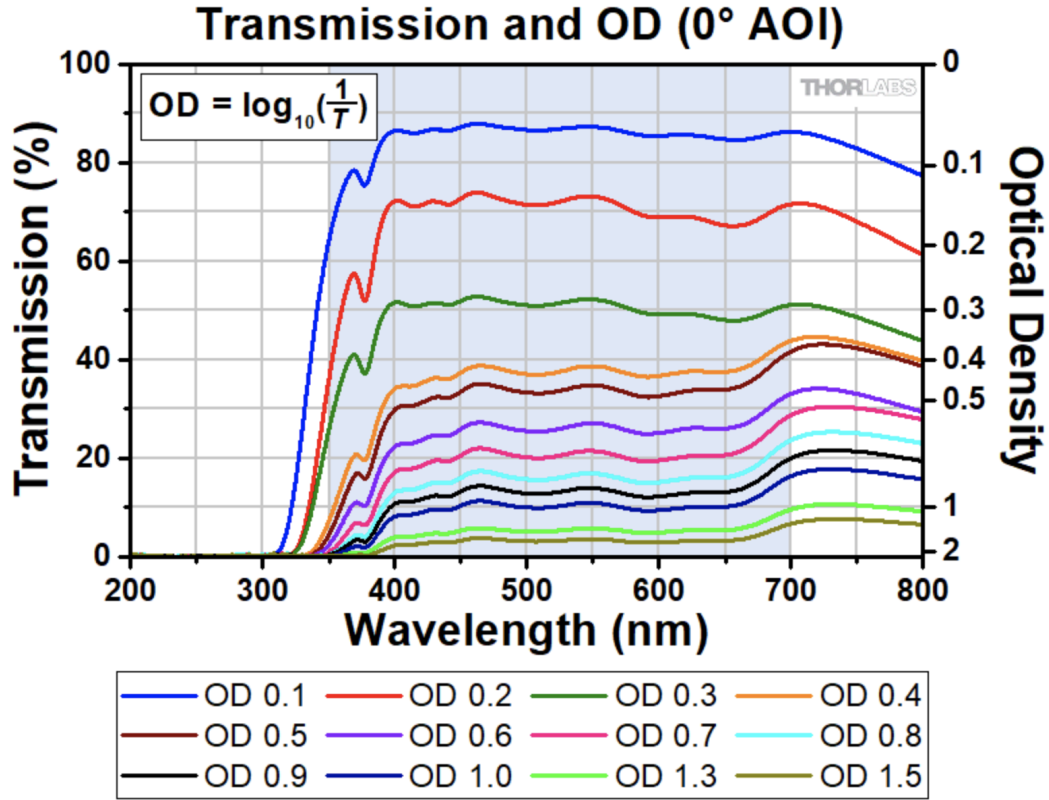


Figure 2.11: Spectral response of ND filter

rate for a range of wavelengths. The test result is shown in Figure 2.12

2.3.2 DAQ system

The photons that travel through the testing materials are taken and transformed into digital signals by the SAMD Data Acquisition (DAQ) system. The DAQ system consists of integrating spheres, Hamamatsu Photo Multiplier Tubes (PMTs) with 14.3 mm diameter, one CAEN R8033N high voltage supply and one CAEN DT5730S digitizer.

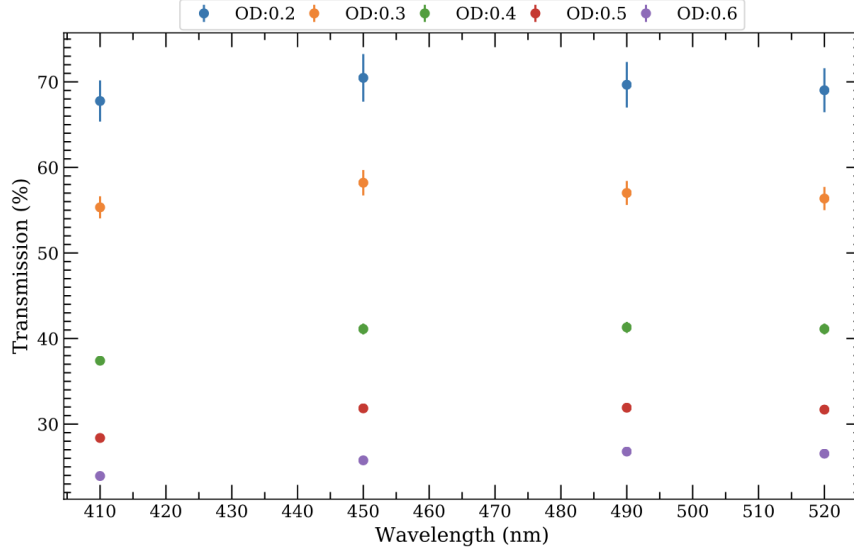


Figure 2.12: The test result of UV-Vis spectrometer for each filter at wavelengths of interest

2.3.2.1 Integrating spheres

The Newport 819C-SF-6 Integrating Sphere is a 6 inch, Spectrafect coated, 4-port integrating sphere. Its damage threshold is 1.7 J/cm^2 . Two spheres are installed as a beam receiver in SAMD: one at the top end of the test arm, one at the bottom, as demonstrated in Figure 2.4. The one-inch port at 0° is served as beam input port and the one-inch port at 90° is served as output port that feed the diffused light to the PMTs. Both spheres include a baffle between the 90° and 0° ports, which prevents direct illumination from the light source to the detector port. As shown in Figure 2.13, a collimated laser beam is fed into the input port, diffused by the inner surface of the sphere and create a evenly distributed photon field from multiple scattering with the inner coating. The reflectance of the coating is about

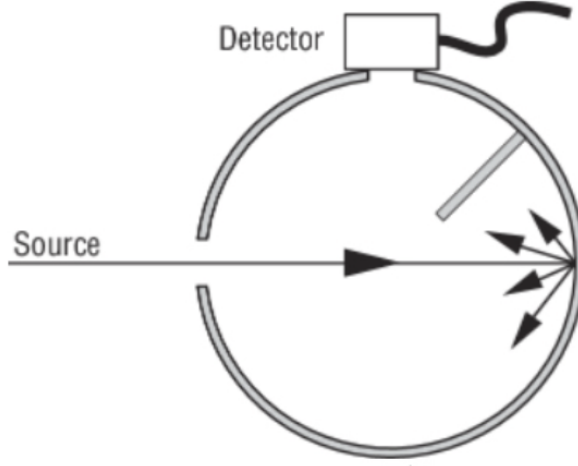


Figure 2.13: Integrating sphere operating in beam mode

98%, resulting in a minimum photon reduction. The purpose of the sphere is to increase port robustness, in SAMD case, to reduce the dependency of the angle of the incoming laser beam from data.

2.3.2.2 Photo Multiplier Tubes

One Hamamatsu PMT is mounted on the 90° position of both integrating spheres as a photon detector that transform light signals into analog signals. All PMTs are operating under high voltage at around 750V. This bias voltage is chosen such that the PMTs are not saturated under high intensity pulses while maintaining a good signal-to-noise ratio. The light pulse is converted to electrical current by the PMT and is further converted into digital signal by CAEN DT5730S digitizer. The digitized waveform is shown in Figure 2.15. At each run, about 10000 waveforms are collected. The average of all the waveforms are calculated as

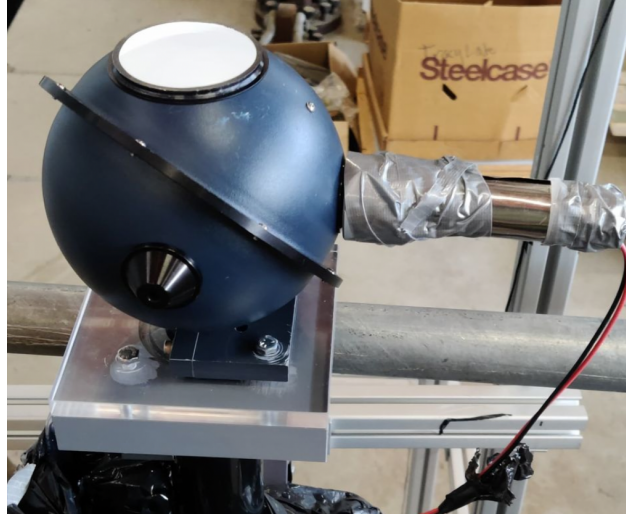


Figure 2.14: Picture of the Top PMT mounted on integrating spheres. It is covered in mu metal for magnetic field shielding

shown in Figure 2.15(b). The average incoming light intensity is then calculated over the averaged waveform. The baseline of the waveform calculated using prompt window method and then subtracted from the waveform data to remove the effect of biased voltage. The integration window of the signal is determined by setting a certain threshold on the absolute value of the data point as well as their derivatives, i.e. all the data that pass through the threshold is identified as the starting/ending point of the light signal. The determination of integration window is necessary to remove after-pulsing effect caused by residual gas ions inside PMTs. The numerical integral is then estimated from the Riemann sum of all the data points within the integration window. The numerical integral is then used as light pulse intensity because the light pulse intensity is proportional to this integral. As discussed in section 2.2.3, the proportion factor is not of interest because the relative intensity change is

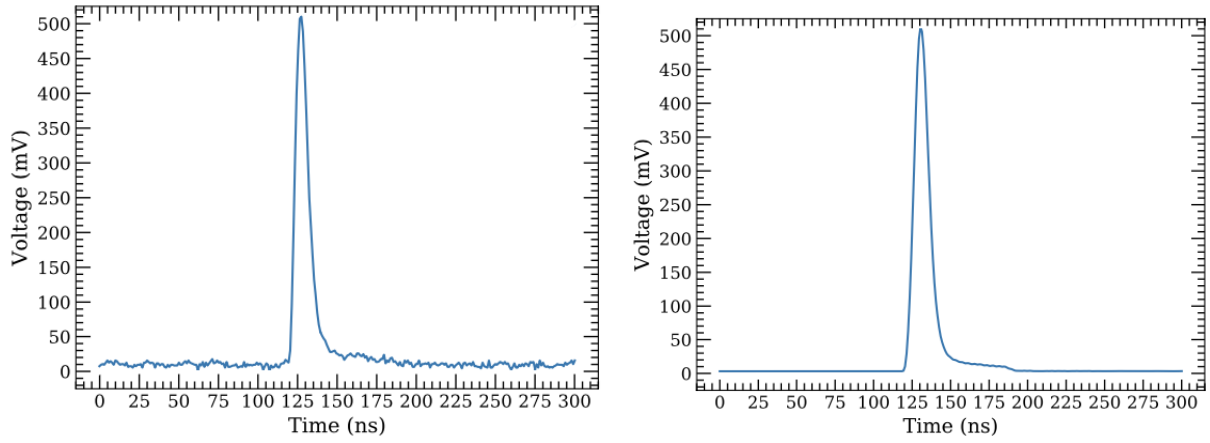


Figure 2.15: Digitized waveform captured by CAEN Digitizer. (a)Single waveform from one pulse. (b)Average waveform from a collection of 10,000 waveforms

the key of finding attenuation parameters.

2.3.3 support structure and attenuation arm

As stated in section 2.1.1, the minimum distance scale for a precise measurement should be larger than 3.34m. As a result, we chose 4m as the distance scale to allow extra space for overflow. Figure 2.16 shows the side view of the SAMD main structure. The support structure is made of T-slotted aluminum, this slotted structure allows a fine tune on the shape while remaining strong. Attached to the structure is a liquid container made of UV-resistant thick wall black PVC. The use of black PVC has several advantages:

1. The high resistance on UV light make it a perfect material to block background noise from the Sun.



(a)



(b)

Figure 2.16: (A) The side view of support structure and attenuation arm. (B) The vertical laser line for arm calibration

2. Black PVC has been tested to be compatible with the WbLS.
3. Black PVC has high absorption to visible light. This is good for reducing light reflection on the inner wall.

The black PVC tube is then covered with black plastic to further reduce external light. To ensure the tube is straight enough for the light pulse to pass through, a vertical laser leveler is used to fine tune the tube mounting points, as shown in Figure 2.16a.

The bottom of the black tube is made of a transparent acrylic plate. The fact that the refractive index of the acrylic plate is similar to water ensures a simple refraction scenario and allows better robustness for the alignment.

The optical parts are placed on the optical table right under the PVC tube. All the optical parts are covered inside a black box designed to block external light. The gap between the black box and the PVC tube is also covered with black box plus additional black plastic.

2.3.4 plumbing system

SAMD plumbing system consists of three pieces: (a)White PVC container, (b)plastic tube, (c)Pressure Gauge as shown in Figure 2.17. The white PVC container functions as a WbLS reservoir. The top of the container is an airtight lid, with two ports mounted in the middle. A nitrogen tank is connected to one port to pressurize the container and to push the testing liquid to a desire height. Nitrogen is used as a cover gas to prevent oxidation of the WbLS. A safety valve is mounted on the other port to prevent over pressurization. The height of liquid inside the tube is calculated from the pressure gauge reading:

$$H = 0.0102P + C \quad (2.15)$$

Here P denotes the pressure reading in mbar and the unit of H is m. Two capacitive sensors are mounted on the side of the attenuation arm. The alarm threshold of the sensors are set so when the water level passes the middle of the sensor, it will trigger the indicator light on it. These sensors were used to calibrate the conversion factor between pressure reading and

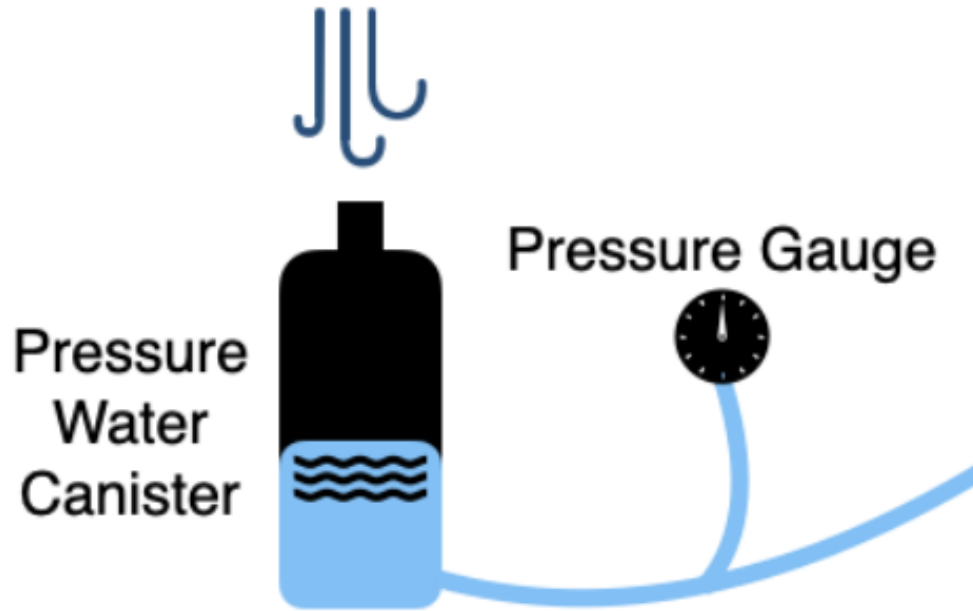


Figure 2.17: A schematic drawing of the pumping system

height of water level. Notice the constant C in equation 2.15 is not of interest because only the change of height ΔH is recorded.

2.4 System Validation

In this section, we discuss the validation procedures of the measuring device. Three tests were carried out as validation tests before any measurement to exclude experimental bias:

1. Angular dependence test. The PMT response is tested to be not sensitive to a small

variation of laser angle.

2. PMT Linearity. The PMT response is tested to be linear with the incoming light intensity.
3. PMT stability. The PMT response is tested to be stable under a long operation period.

These tests make sure that human-chosen hyperparameters does not affect the measurement. The data obtained from these tests are used for systematic uncertainty analyses. Upon passing the validation tests. A measurement of attenuation coefficient of pure water was conducted. The result agrees with the integrating cavity measurement[60], which indicates SAMD is well calibrated.

2.4.1 Angular dependence

During the construction phase, the beam direction can be controlled by observing the laser dot position on the top of the attenuation arm, as shown in Figure 2.5. But the observation of the laser dot becomes impossible during the test phase because the system is sealed in the black plastic cover. Thus, a test on angular dependence of signal intensity is required. The procedure of this test is straightforward: After alignment, scan the laser in the near area and record the signal intensity for each angle. The result for the top and the bottom PMT signal is shown in Figure.

As shown in Figure 2.18(B), the light intensity of the bottom PMT starts to decrease when θ is bigger than 1° , but the overall relative change is smaller than 1%. In addition

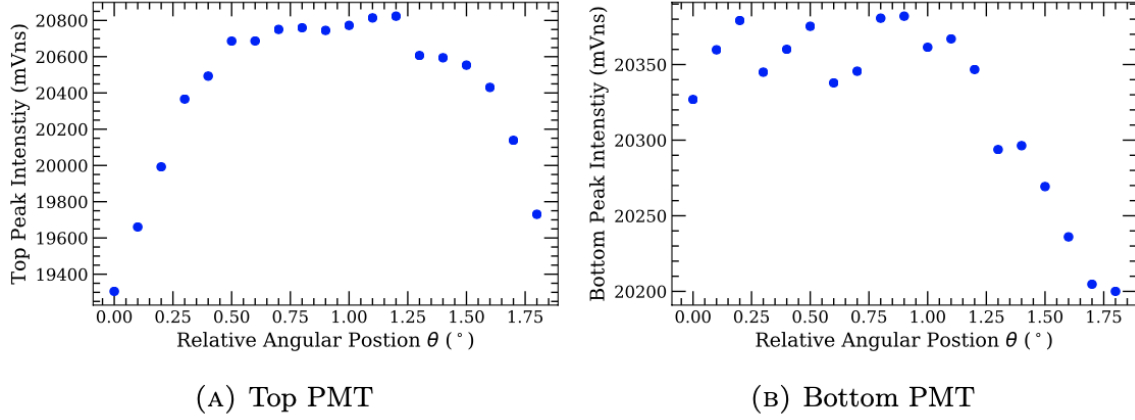


Figure 2.18: Light intensity received by the top and the bottom PMTs in a laser scan process. Notice that the scale of the bottom PMT intensity is much narrower, indicates a stable PMT readout over a large angle.

to this, the variation in the small angle region is comparable to statistical fluctuation. This means the angular dependence of the bottom PMT signal doesn't contribute to the overall I/I_0 measurement. Figure 2.18(A) shows the signal angular dependency of the top PMT. Given the fact that the top PMT locates further away from the laser system, it is expected to be more sensitive to laser angle. As expected, the top PMT has a smaller stable region with a higher variation. The data points outside the stable region indicate the start of misalignment. Upon understanding the behavior of the top and the bottom PMT. We can now choose a measurement region based on the I/I_0 plot, shown in Figure 2.19. The I/I_0 plot posses the same feature as the top PMT, this is as expected because of the low variation for the bottom PMT. In this plot, we can choose the region between 0.5 and 1.25 as the stable region, this gives us a mean of 1.02 and a Root Mean Square (RMS) error of 0.01. Notice

that the above procedure is one example of measuring I/I_0 at a certain water level. For the measurement of attenuation length, each data is measured with the laser pointing in the middle of such plot. During the attenuation measurement. We found that such alignment setting changes with water level. While it is hard to describe such effect with mathematical rigor, we can discuss the major causes are from the following facts:

1. The bottom plate is not strictly perpendicular to the light path, causing diffraction.
2. The liquid to be tested is also causing diffraction.
3. Meniscus effect on the water level causes light path to diffract.

The alignment procedure requires the laser to align in a way that it's at the middle of the stable scan region, this ensures the light path is of the minimum of all possible paths to reduce bias as much as possible.

2.4.2 Signal stability

Several external factors can have effects on the signal stability, they are considered systematic errors that are related to time. The major factors are:

1. water cleanliness
2. external light from the Sun and fluorescent lamps
3. arm shape changes due to temperature variance

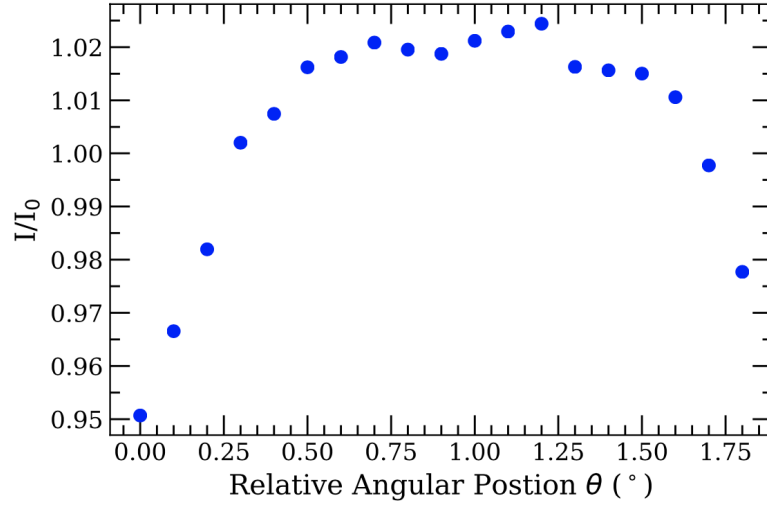


Figure 2.19: The I/I_0 ratio of a laser scan process

4. other temperature related physical constants, for example, scattering coefficient of liquid
5. PMT long-term and short-term drift of the gain

In order to measure the effect of such systematic error, data were taken continuously over the course of a 5-day period. The attenuation arm was filled with 1.69 ± 0.05 m of fresh type I water. Figure 2.21 shows the data taken over this 5-day period. Comparing the top and bottom peak intensity, it is clear that the top peak intensity varies 40% more than the bottom peak intensity. This change can not be explained by water cleanliness alone. If water quality decreased with time, the effect will be seen in the constant decrease in top peak intensity with time.

An event can be seen on day 4 and 5, the top peak intensity and I/I_0 show a sudden decrease in intensity for around 8hrs before recovering. The reason for this is due to the location of SAMD against the concrete shield of a 76-inch isochronous cyclotron in the Crocker Nuclear lab. The magnetic fields are pointed vertically. Magnetic fields can decrease the electron multiplication (gain) inside a PMT. This is why the top peak intensity has a greater decrease in intensity being located above the cyclotron and concrete shielding compared to the bottom PMT being located at the side of the cyclotron shielding. To try to counter this strong magnetic field, several layers of Mu metal were rolled around the top and the bottom PMT, as can be seen in Figure 2.14. Mu metal was chosen as a shield for its high permeability. To correctly nullify the magnetic field, coils would be needed to counter the magnetic field. This was considered as time insensitive and would still lead to complications in correctly calibrating as the cyclotron magnetic field is varied depending on use. To ensure that the magnetic field would not affect the result, data was only taken when the magnet was turned off (evenings and weekends).

Looking at data taken for a single day (8/5/22) we can see the effect of light and temperature on the ratio I/I_0 in Figure 2.20. The first (20 ± 1) ks values of I/I_0 are stable, fluctuating around 0.71. Around this time I/I_0 starts to decrease. (21 ± 1) ks roughly corresponds to 06:00 which on the 8/5/22 in Davis, California corresponds to sunrise. There is continued decrease in I/I_0 until (56 ± 1) ks (15:30) where I/I_0 begins to increase. At (73 ± 1) ks (20:30) the value I/I_0 begins to stabilize again slightly below 0.71. The decrease could be from decreasing water quality or still higher temperatures than the previous night.

The fact that the lowest I/I_0 value occurs around 15:30 indicates that this effect could be more dependent on temperature than light. The light system is secured in a light-tight box and bags, however, it is still possible that some external light could enter the system. While temperature and external light can both affect the system, it is not too important to determine which is dominant, as the variation over the course of the day will be used to calculate the systematic error for changes in I/I_0 with time. Like angular dependence, the root mean squared error is used to determine the error in I/I_0 with time. The root mean squared was found for all data taken on the 8/5/22 and was calculated to be $\delta I/I_0 = 0.02$. When different days were selected and different wavelengths were used, the relative systematic error was found to be consistently 0.02 to 1 significant figure. Data is taken within a day of opening type 1 water so any variation due to water quality is also included in this error as well as other variables such as pressure, laser and PMT stability.

2.4.3 System Linearity

As the ratio of I and I_0 is the main quantity of concern, if the system responses linearly with the incoming light intensity become the major concern. In order to verify the linearity, data was taken under different neutral density filter settings. As stated in section 2.3.1.3, the behavior of all neutral density filter is tested using UV-Vis and well understood under the wavelength of interest.

Figure 2.22 shows the top PMT response with different neutral density filter settings. The

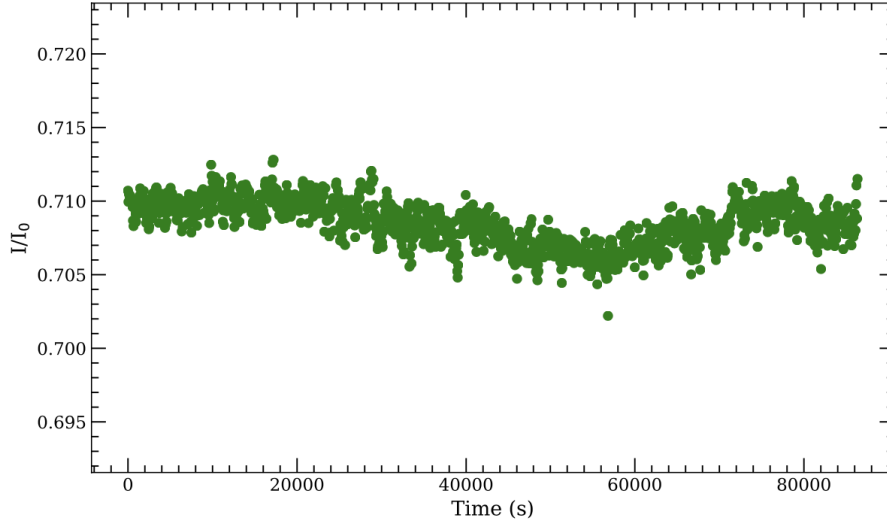


Figure 2.20: A continuous measurement of the top and the bottom PMT intensity on 8/5/22. The time is measured in seconds starting from mid-night.

main concern of non-linearity comes from signal saturation, noise and charge equilibrium of PMTs. More information on factors that affect the PMT linearity can be found here[65]. For this reason, two sets of test are compared in this plot: cold and hot PMT. Cold PMT means we start the test right after the PMT is turned on. Hot PMT means we start the test after one hour warm up after the PMT is turned on. In the warm PMT case, the accumulated charge, if there is any, reaches to an equilibrium. Another hyperparameter to be tuned is the PMT bias voltage. If the voltage is too high, signal saturation may cause non-linearity of the system. If the bias voltage is too low, the signal could be so dim and couldn't be resolved from background noise. For the measure of non-linearity, a linear regression is used to fit the I/I_0 with varying transmission rate. Figure 2.22 shows only the fit of the best

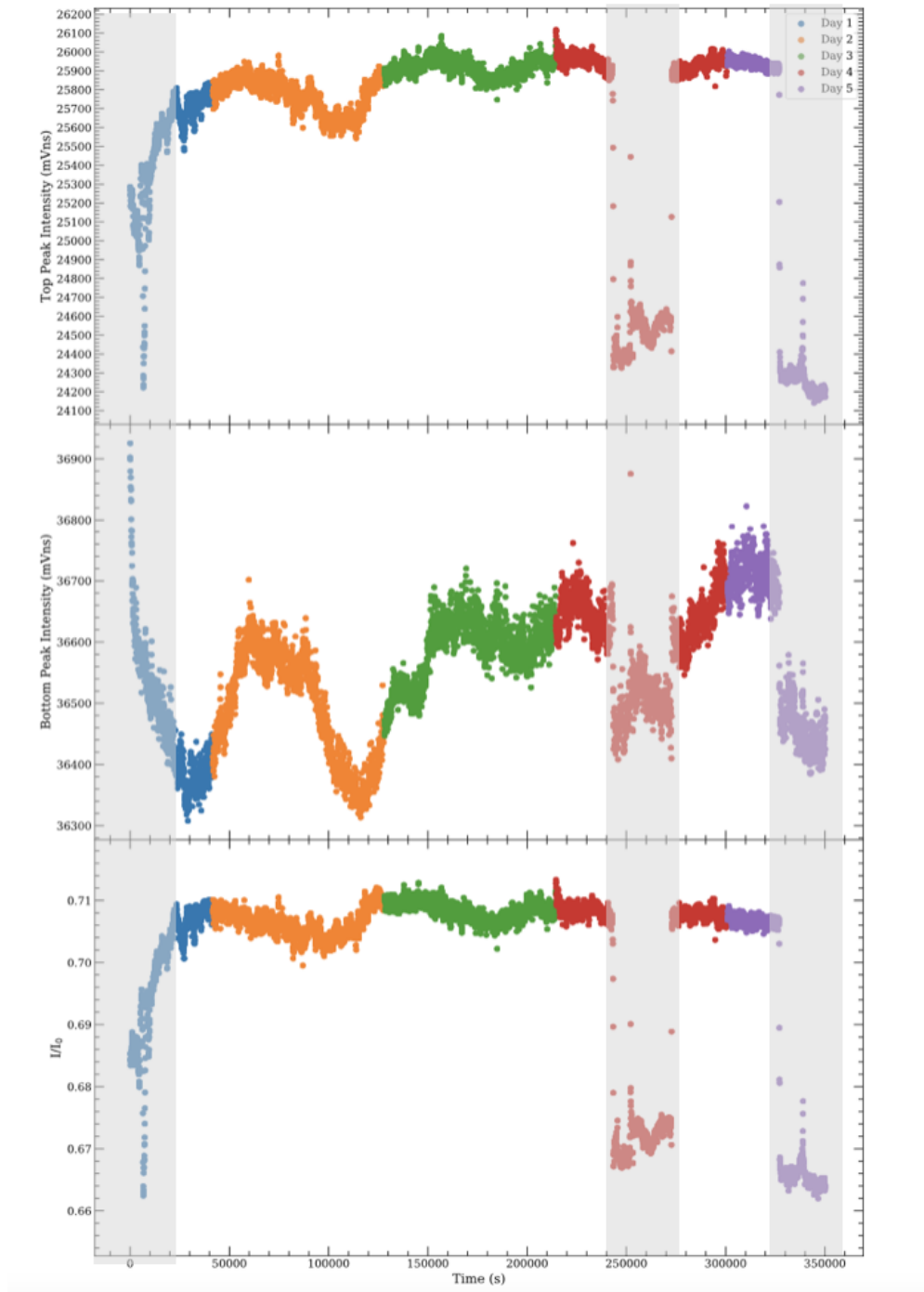


Figure 2.21: A continuous measurement of the top and the bottom PMT intensity for 5 days. The color represents a different day. The shaded region is when cyclotron is running.

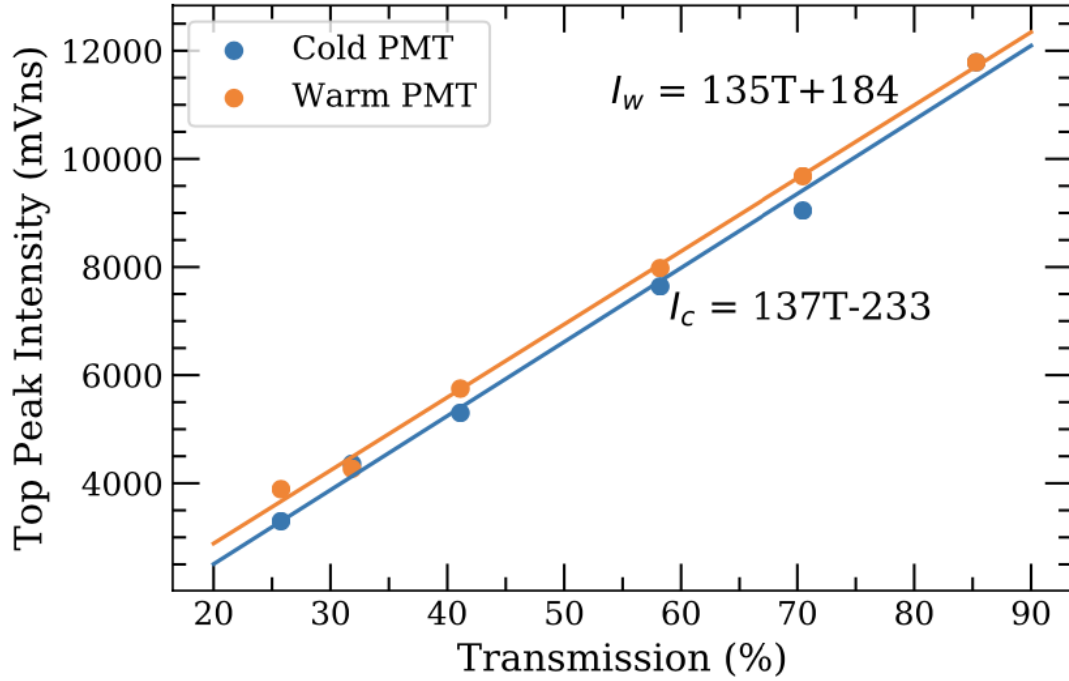


Figure 2.22: This plot shows SAMD system is working in a linear response region

choice. After choosing the best bias voltage, a reduced χ^2 test is applied as goodness of fit. Assuming the relative systematic uncertainty is not changing with the transmission rate, forcing the reduced χ^2 equals to one gives us the estimate of the associated systematic error, see Figure 2.23.

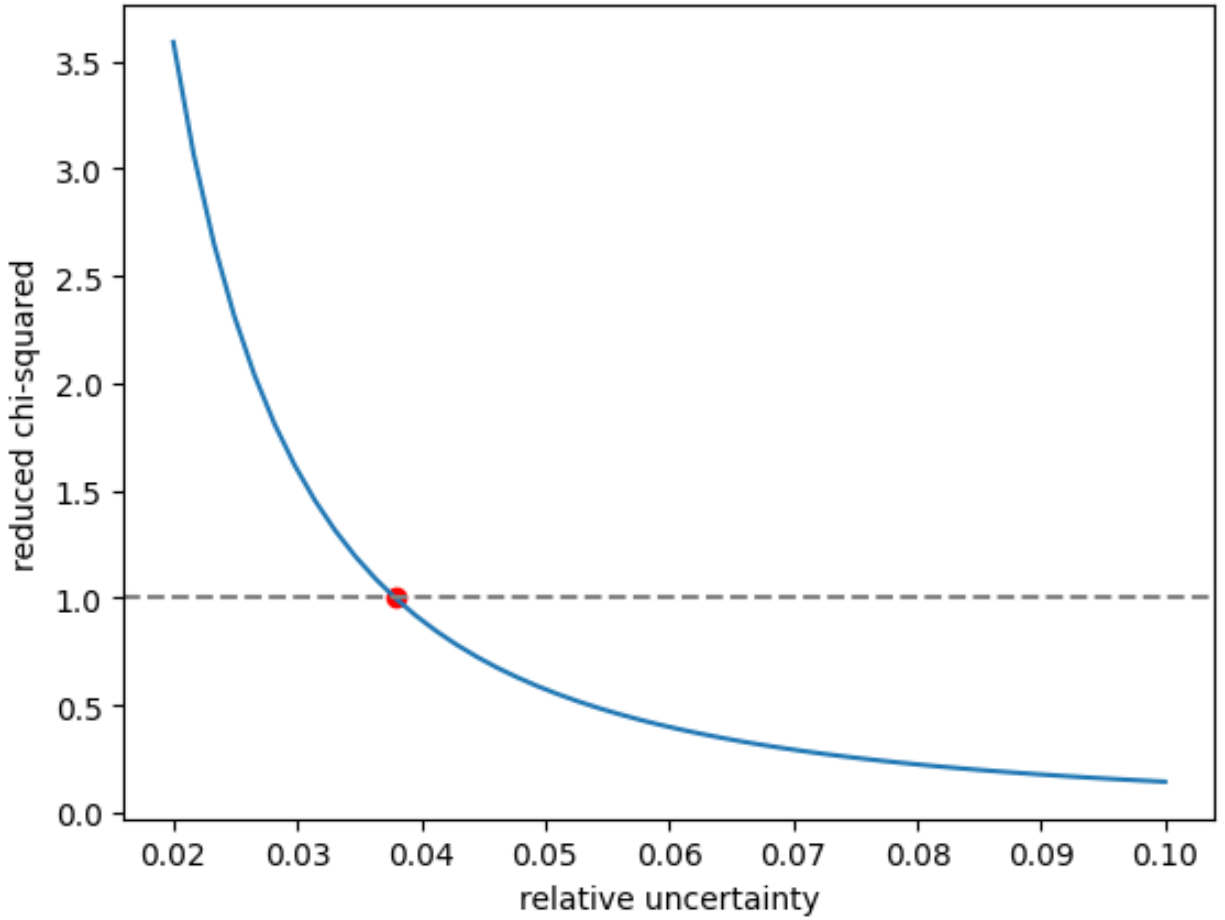


Figure 2.23: Reduced chi-squared statistics as a function of relative error.

2.4.4 Statistical and systematic errors

2.4.4.1 Statistical uncertainty

Here, we briefly discuss the method of determining the statistical uncertainty. Unlike most of the neutrino experiments, the number of events in this experiment is very large due to the fully controlled laser source. This results in a small statistical uncertainty. For each

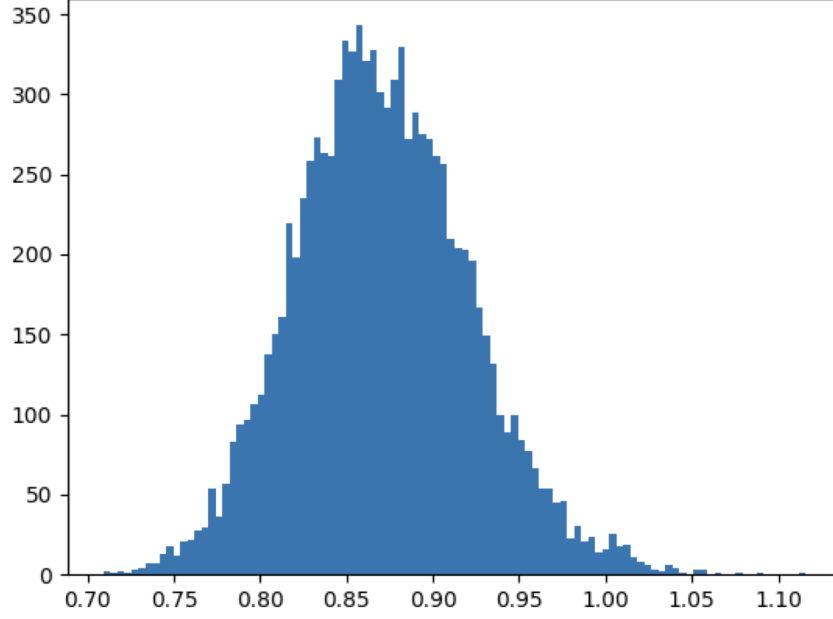


Figure 2.24: The sample distribution of I/I_0 in one measurement, the sample size is 10000. Each sample is from a laser pulse

measurement, 10000 laser pulses are injected into the testing medium and received by the PMTs. For each laser pulse, an I/I_0 is calculated. The sample distribution of I/I_0 is shown in Figure 2.24. The standard deviation is calculated from the sample distribution at around 0.11. The one sigma uncertainty of the sample mean is 0.0011 using the following relation:

$$\sigma_{\bar{x}}^2 = \frac{s^2}{n} \quad (2.16)$$

Where n is the sample size, $\sigma_{\bar{x}}^2$ is the variance of the sample mean and s^2 is the sample mean.

2.4.4.2 Systematic errors

Although a variety of systematic errors contribute to the measurement in this experiment, they can be categorized into three types: angular dependence, stability and linearity. All three types are discussed in the previous sections. While not every systematic error is quantified, the joint uncertainty of each type can be estimated by testing the statistics from the validation tests. As discussed in the previous sections, the joint systematic errors that are angular dependent and time dependent are estimated with the RMS of the corresponding test. The systematic errors associate with signal linearity are estimated using the reduced chi-squared test. Table 2.2 summarizes all the systematic errors discussed.

Table 2.2: Summary of systematic errors

source	type	relative errors(%)
bottom plate diffraction	angular dependence	2.0
liquid diffraction		
Meniscus effect		
liquid cleanliness	signal stability	2.0
external light		
arm shape change		
temperature effect		
PMT gain drift		
PMT linearity	system linearity	3.8
Integrating method		

2.5 Result for WbLS

In this section, we provide the final measurement of WbLS attenuation length. We first provide our result for the attenuation measurement of pure water. The result agrees with the Integrating Cavity Measurements of water at the wavelength of interest, thus can be used as a verification of our system. We then show the attenuation result of WbLS measurement using the same procedure of water test. Finally, we discuss the statistical and systematic error of the measurement.

2.5.1 Verification with pure water

To measure the attenuation of light in a liquid medium, the height of the liquid is increased and the decrease in the intensity recorded. At each height, a laser scan is applied to find the actual intensity with minimum error. Figure 2.25 shows the PMT intensity measurement for varying water height. Looking at the top PMT intensity, it is clear that as the water level rises, the PMT response decreases just as expected. The response behaves like a linear decrease, this is because the attenuation length of water at 520nm is around 20m, which is several times larger than our range of water level. The bottom PMT response doesn't change with water height thus behaves like a statistical fluctuation. The change in bottom intensity is less than 0.2%.

Upon getting the top and bottom PMT intensity, three photon counting methods were compared, as shown in Figure 2.26. The red curve represents a method of averaging the photon

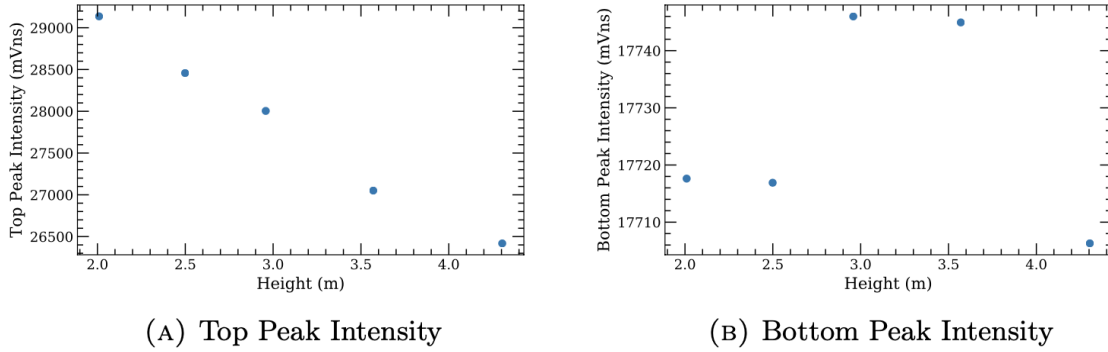


Figure 2.25: Change in light intensity of the top PMT(A) and the bottom PMT(B) with varying water level for 520nm laser.

count for each event in the 10000 events per measurement. The green curve represents the method of photon counting after averaging all the 10000 event, as discussed in section 2.3.2.2. The blue curve uses the pulse height of each pulses as an indicator of photon received. This is a valid method because the integration window is relatively stable and the proportion factor between the actual photon count and the pulse height is not of interest. Compared to the previous two methods, the peak finding method is not sensitive to PMT after pulses or any unknown waveform following the laser pulse. The resulting I/I_0 calculated from all three methods are then fitted to the Beer–Lambert law:

$$I/I_0 = \alpha e^{-H/L} \quad (2.17)$$

With H being the height of water and L being the attenuation length. As discussed in section 2.2.3, parameter A represents the optical effect caused by device reflection, light

collecting efficiency and other effects that are very hard to be determined. It is a nuisance parameter in the fitting because it is independent of the parameter of interest: the attenuation length. It is still worth noticing that the three methods results in a different fitted A . This is the result of different pulse width between bottom and top PMT pulses, as these three methods have different ratio factors dependent on the pulse width. Moreover, the method of summing over all pulses also depend on the TDC lateness: if any two pulses are off by one tick of a clock, the super position of the two pulses will have a different pulse shape. Notice that the three methods gives us the same attenuation length fit at $23\text{m}\pm 1\text{m}$. This indicates the systematic error of choosing different counting technique can be neglected. Due to the fact that the parameter α is not used in the following analysis, and it has no dependency on the fitted attenuation length, the three methods are equally valid. The method of averaging pulse integrals is selected for all analysis. The fitting method used above is orthogonal distance regression. This method minimizes the average orthogonal distance between data points and the fitted function that is weighted by x error and y error. This method better implement the error on the x component, in this case, water level, than the traditional RMS fit. As mentioned in section 2.2.4, the height of the water level is determined by pressure gauge reading alone. This means the uncertainty of water height is highly dependent on the accuracy of the pressure gauge and the variation of the air pressure in the room. Although the accuracy of the pressure gauge is provided by the manufacture at around 1mbar, we find that the actual variation is around 5mbar due to temperature and air pressure variation. This corresponds to an uncertainty in water level of around 5cm. Before the measurement

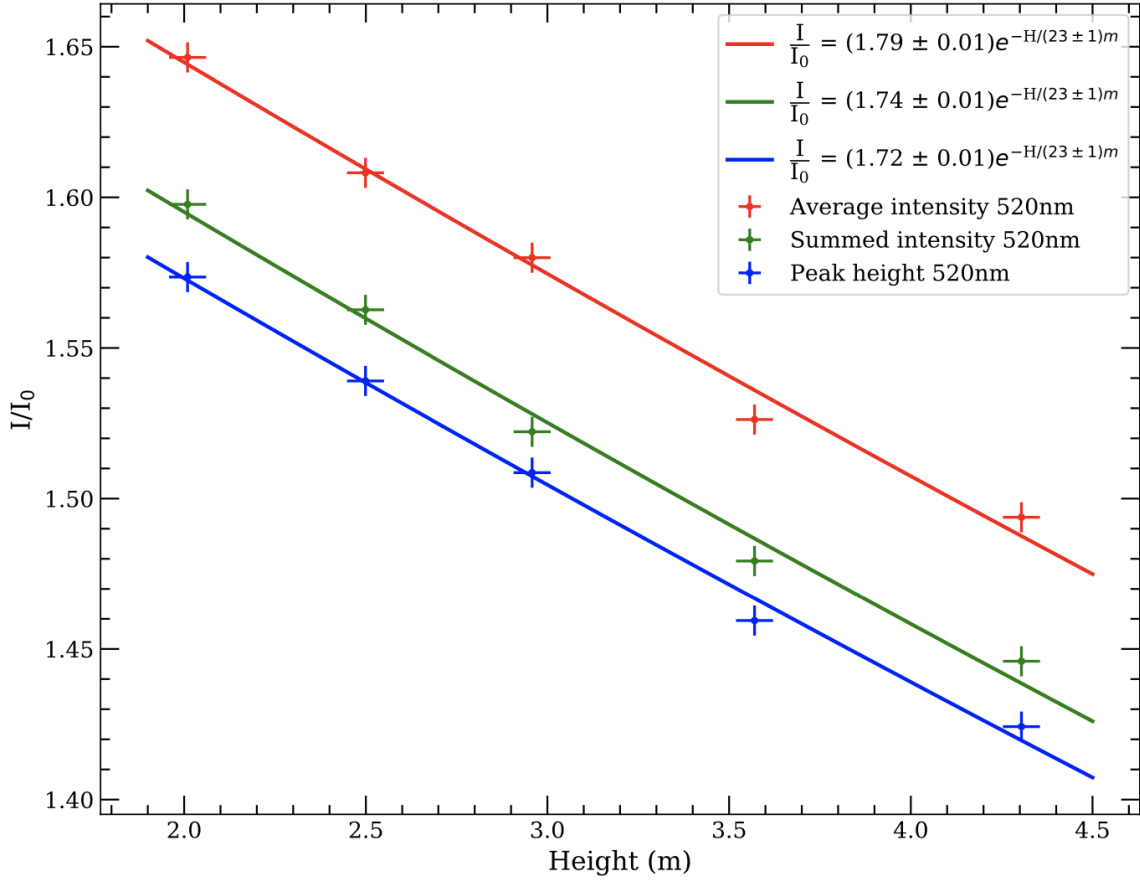
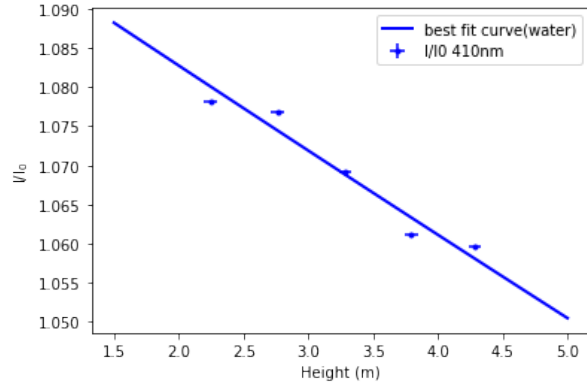
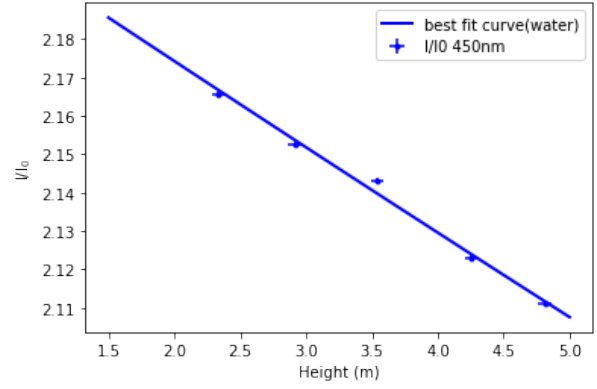


Figure 2.26: I/I_0 curve for varying liquid height and fitted using equation 2.17.

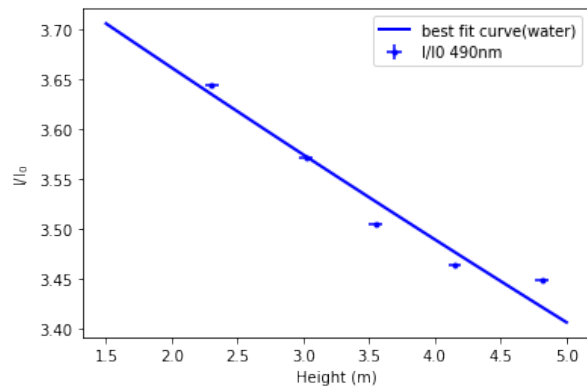
were taken, SAMD went through vigorous cleaning, as cleanliness was a leading cause of inconsistency in previous results. The PVC attenuation arm and pressurized canister was cleaned by running a solution of diluted pure ethanol through the tube, followed by a few flushes with type 1 water. All plumbing connecting the pressurized canister, pressure gauge and transmission tube was replaced with new tubing, fixtures and valves. Two separate batches of ChemWorld Type I water were measured, one in June 2022 and one in November



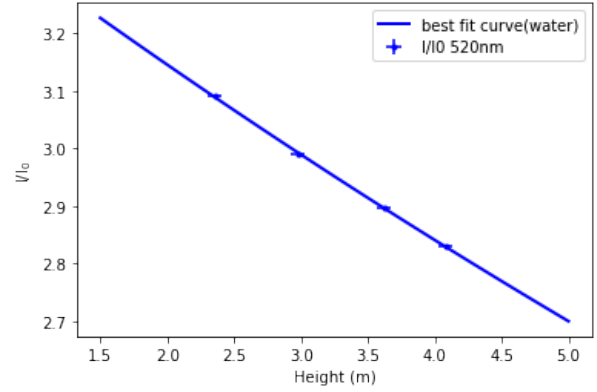
(a) Attenuation curve at 410nm



(b) Attenuation curve at 450nm



(c) Attenuation curve at 490nm



(d) Attenuation curve at 520nm

Figure 2.27: The attenuation curve in water and their best fits for four different wavelengths.

2022, both have the same result. The results are shown in table 2.3. And a comparison is made between SAMD result and results from other experiments, as shown in Figure 2.28. It is worth noticing that SAMD result is the same as Super-K result on measuring attenuation length. In the Super-K measurement, the laser was injected into a diffuser ball inside the inner detector. A CCD camera was then used to make a measurement of the intensity of light. By moving the diffuser ball in the water, it was possible to find the attenuation using a similar method as used above. A beam splitter and PMT outside the tank is used to measure the initial intensity. This method has many differences from the SAMD yet generated the same result. The result from Pope is a measurement of water absorption only. It utilizes an integrated cavity technique. The measurement is independent of scattering because the optical energy lost is proportional to the absorption due to the high reflectivity of the cavity wall. It provides an upper bound of the attenuation length because the scattering effect is pruned. The result from seawater measurement, on the other hand, provides a lower bound of this measurement, as the scattering effect of seawater is greater than pure water.

2.5.2 WbLS result

The measurement of WbLS attenuation length uses the same method as pure water test. The result can be found in Table 2.3. Figure 2.30 shows the attenuation curves for WbLS measurement for the four wavelengths. To compare with the pure water result, Figure 2.29 shows the WbLS result along with the water results. Comparing this result to water, a

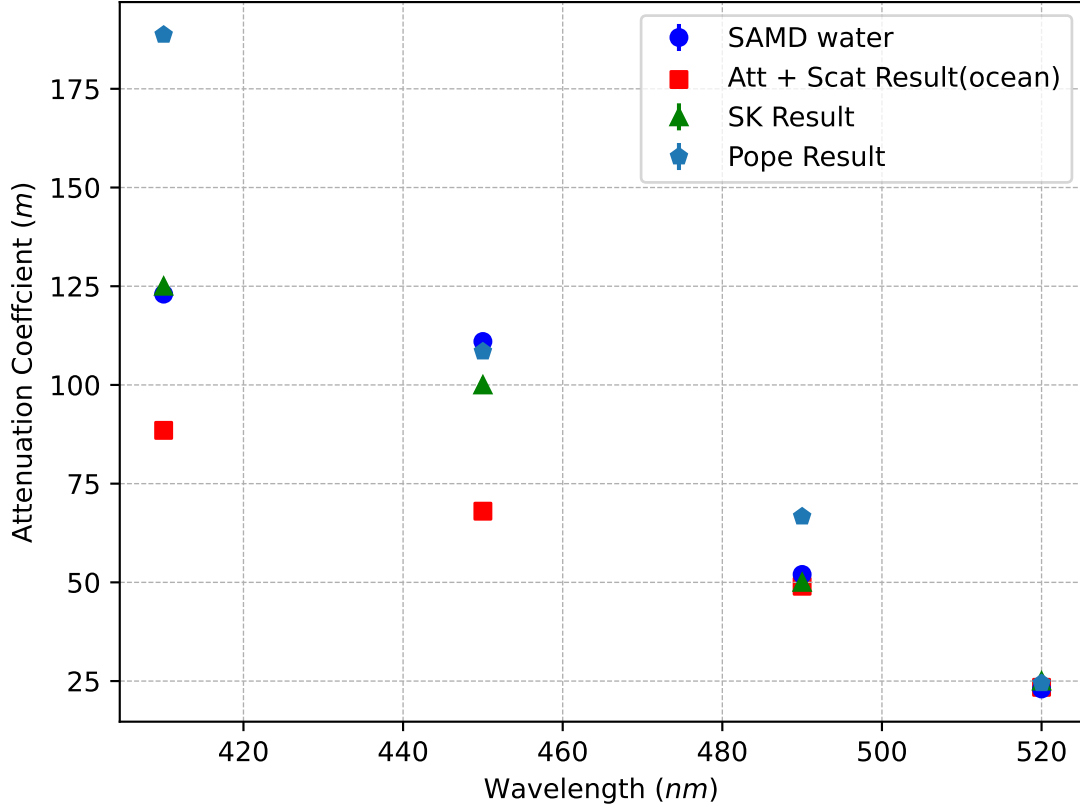


Figure 2.28: SAMD result compared to other experiments

significant reduction in attenuation length is seen. Due to the liquid scintillator absorbing and scattering the light, a reduction in the distance the light can travel decreases. The effect is more noticeable in the shorter wavelengths of light. As the higher wavelength light already has a smaller attenuation length, the effect of the increased absorption of the liquid scintillator has less of an impact than at the lower wavelengths of light. Moreover, as the wavelength of light is relatively large compared to the micelle of WbLS, the scattering

Table 2.3: The attenuation result from water testing and WbLS measurement. A is the fitted amplitude and χ^2 is for goodness of fit

Type	Wavelength (nm)	A	z (m)	χ^2
Water June 2022	410	1.051 ± 0.004	73 ± 8	0.231
Water June 2022	450	1.155 ± 0.004	65 ± 4	0.242
Water June 2022	490	0.746 ± 0.001	51 ± 2	0.061
Water June 2022	520	1.79 ± 0.01	23 ± 1	1.334
Water Nov 2022	410	1.103 ± 0.005	103 ± 14	0.213
Water Nov 2022	450	2.219 ± 0.004	97 ± 5	0.189
Water Nov 2022	490	3.83 ± 0.05	43 ± 6	1.138
Water Nov 2022	520	3.48 ± 0.01	19.6 ± 0.2	0.033
WbLS Nov 2022	410	1.182 ± 0.005	13.4 ± 0.2	0.150
WbLS Nov 2022	450	4.38 ± 0.02	22.0 ± 0.5	0.569
WbLS Nov 2022	490	4.06 ± 0.01	17.3 ± 0.2	0.158
WbLS Nov 2022	520	3.77 ± 0.01	13.3 ± 0.2	0.195

effect follows Rayleigh approximation. The scattered intensity of Rayleigh scattering is proportional to λ^{-4} , thus the lower the wavelength, the larger the scattering effect.

2.6 Conclusion

WbLS shows great application potential for solar neutrino from the Sun's CNO cycle and the diffused supernova neutrino background. With its low cost, it is a promising candidate medium for the future large neutrino detectors. One key characteristic of the detecting medium of a large detector is its photon attenuation length: As the attenuation length go larger, the light collection efficiency goes better.

This chapter shows the work on building the attenuation measurement device for WbLS.

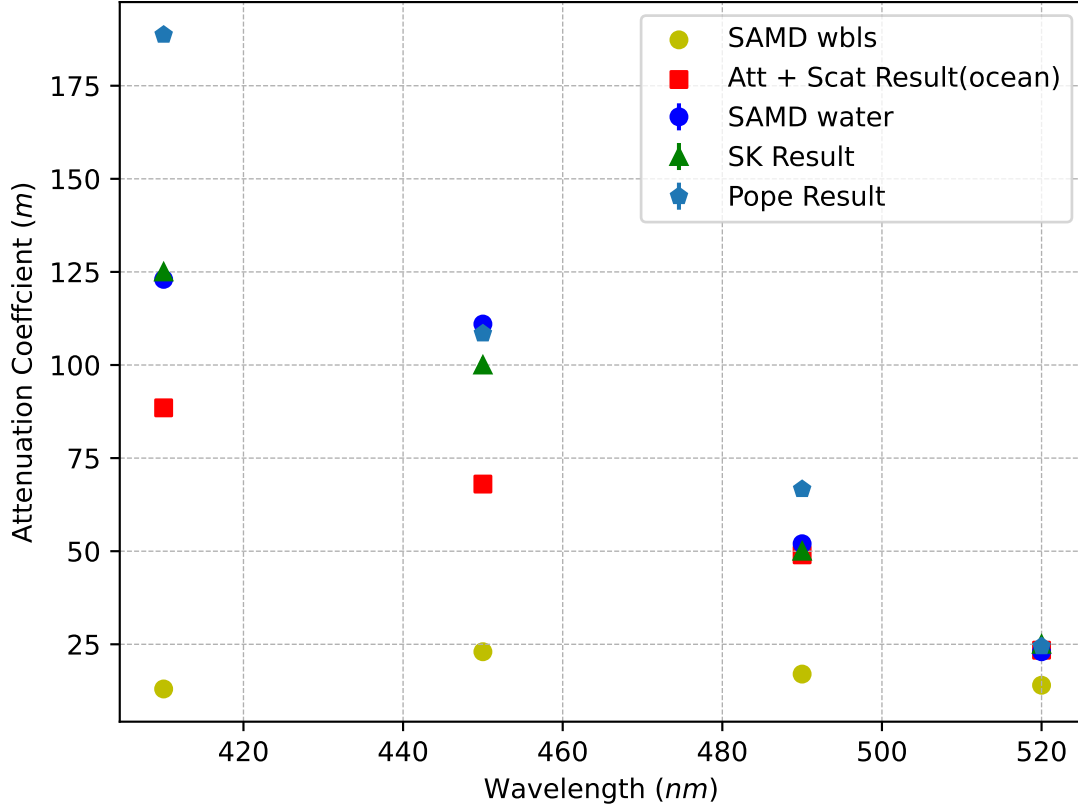
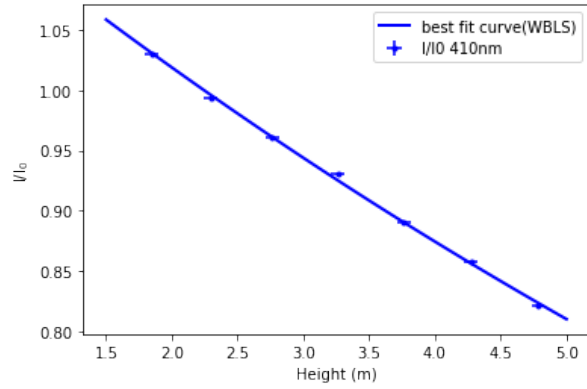
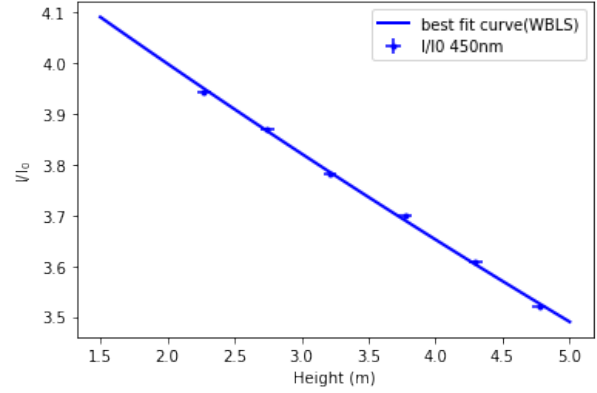


Figure 2.29: SAMD attenuation measurement for WbLS compared to pure water results

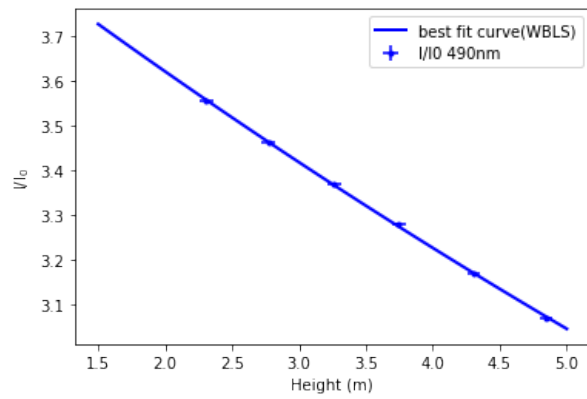
The scale of the experiment and the measurement strategy is identified first. The device is then built out of concept on the UC Davis campus. Three validation tests were conducted to ensure minimal bias: the angular dependence test, the signal stability test and the system linearity test. The angular dependence test covers the systematic errors associated with laser alignment, laser divergence and detector angular response. The lasers are scanned in both Pitch and Yaw directions in each measurement to account for the change of



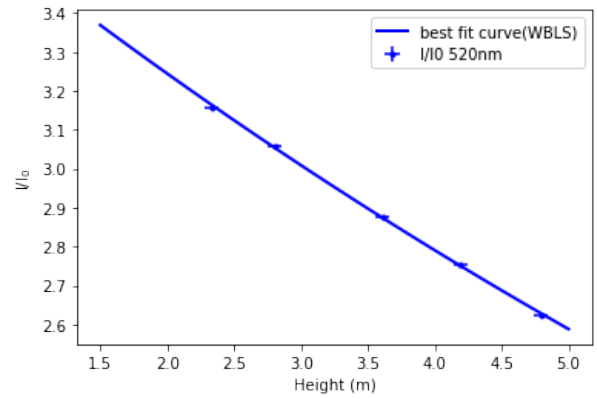
(a) Attenuation curve at 410nm



(b) Attenuation curve at 450nm



(c) Attenuation curve at 490nm



(d) Attenuation curve at 520nm

Figure 2.30: The attenuation curve in water and their best fits for four different wavelengths.

incident angle caused by diffraction. The variation of the PMT signal intensity within the selected range of angles is chosen to represent the uncertainty. The signal stability test takes a continuous measurement of the PMT intensity over several days. The variation in the continuous measurement shows both short term fluctuation and diurnal patterns. Although one measurement typically takes about one hour, a conservative uncertainty estimation is made by considering the variation of a whole day. The system linearity test covers the error caused by PMT response and integration methods. By comparing the PMT signal intensity vs pre-tested ND settings, the relative errors associated with linearity can be estimated by performing a ‘reversed’ chi-squared test. SAMD is validated by comparing its pure water results with other experiments, and the results agree.

Finally, the attenuation length of WbLS is measured to be at maximum 22.0 ± 0.5 m at 450 nm wavelength and at minimum 13.3 ± 0.2 m at 520 nm wavelength. This shows that a WbLS detector can be constructed at the order of 20 m without losing much of its photon collection efficiency.

At the short wavelength region, the Rayleigh scattering effect dominates, resulting in a shorter attenuation length. In kilo-ton scale experiments, the feasibility of using spectral photon sorting for Cherenkov-Scintillation separation may be constrained.

Chapter 3

WbLS Deployment in ANNIE

Given the success of large scale water Cherenkov and liquid scintillator detectors in the context of neutrino physics, there is currently an ongoing interest in the concept of hybrid event detection.

The aim is to combine the advantages of water Cherenkov detectors — large optical transparency, sensitivity to the particle direction, as well as particle identification through the Cherenkov ring topology — with the low-threshold calorimetric information of liquid scintillator detectors. The latter would provide better energy resolution, additional particle identification capabilities, and allow for the detection of neutral particles or particles with energies below the Cherenkov threshold. To achieve such a hybrid event detection, it is necessary to differentiate between the Cherenkov and scintillation component of the events.

For this a number of different approaches have been developed in recent years, such as spectral photon sorting [66, 67], time separation through fast photodetectors [68–70] or the

development of novel target materials, such as slow scintillators [71, 72] and WbLS. It is also possible to combine these separation approaches, such as the use of fast LAPPDs together with a WbLS medium [73]. WbLS is an admixture of a low percentage of liquid scintillator in water, featuring high transparency and which is an enabling medium for hybrid neutrino event detection. Compared to pure liquid scintillator, it has a reduced scintillation yield, which allows for easier identification of the Cherenkov light. The WbLS hence provides a larger total number of photons compared to Cherenkov light from pure water. Conceptually similar ideas have already been used successfully in LSND [74] and in MiniBooNE [75], using a diluted scintillator and mineral oil as detection media, respectively.

ANNIE is part of a wider experimental effort for the technical demonstration of the hybrid optical detection concept. This includes bench-top scale experiments such as CHESS [76, 77] and FlatDot[70] but also other mid-scale detectors setups: Eos [78], the 1-ton [79] and 30-ton purification demonstrator at Brookhaven, and NuDot [80]. Furthermore, WbLS is explored as a detection medium for the proposed Theia detector [46]. Several recent community-planning exercises have been highlighting the importance of the developments summarized above [80–82]. This chapter is a published paper[83] that presents the first result of WbLS deployment in the ANNIE detector. Section 1 describes the mechanical structure, filling and deployment procedure of the WbLS vessel. Section 2 shows the production procedure of WbLS and provides evidence of its long term stability. Section 3 shows the scintillation events alongside the Cherenkov events observed by ANNIE detector. This provides evidence on the capability of WbLS. Two methods of measuring scintillation light yield are presented

in this section, proving the detection of both scintillation and Cherenkov radiation. My work on the Michel electron selection will be presented in this section, with more details than the paper[83].

3.1 The ANNIE Detector

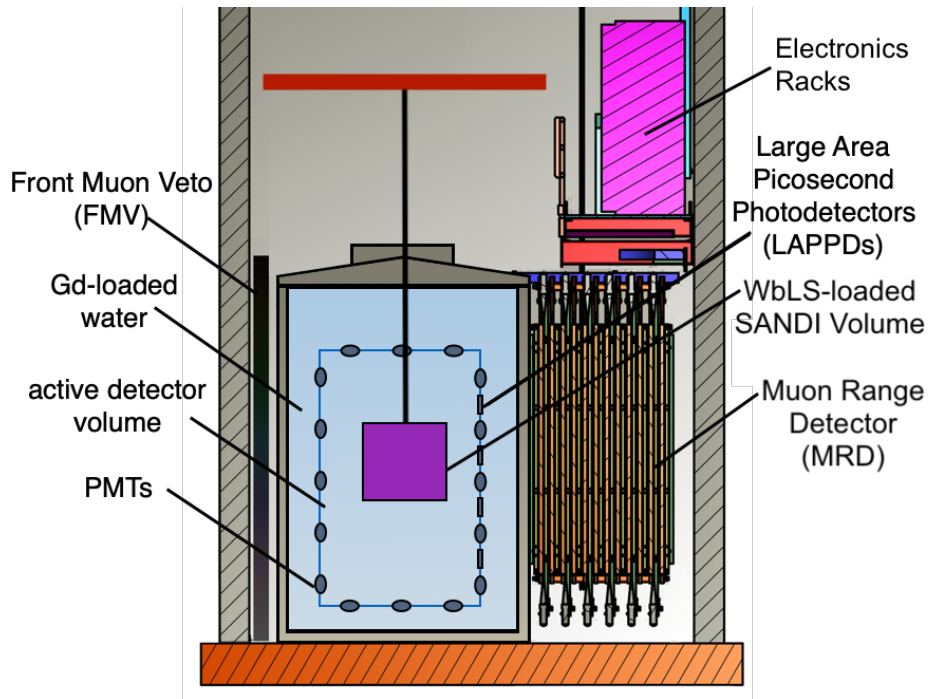


Figure 3.1: Detector schematic with the WbLS-filled vessel, called SANDI (Scintillator for ANNIE Neutrino Detection Improvement).

ANNIE consists of three separate main detector elements: (1) the front muon veto (FMV), (2) the main water Cherenkov detector, and (3) the muon range detector (MRD), as shown schematically in Fig. 3.1. The ANNIE hall [84] consists of three levels (top, middle,

and lower). The top is at ground level and is the entrance to the hall with the middle and lower levels below ground level. The middle level houses the electronics racks and has access to the lid of the ANNIE tank.

The FMV, located upstream of the main detector volume, consists of two layers of scintillating paddles. Each paddle is read out at one end by a 2-inch PMT coupled to a glass light guide. The primary purpose of the FMV is to reject events originating from an interaction in the dirt upstream of ANNIE. Only the existence of an incoming particle is relevant and not the exact position, therefore both layers are oriented horizontally. The two layers are read out on opposite ends to mitigate the impact of attenuation losses from a particle passing through the far end. The FMV was found to have a muon tagging efficiency of $(95.6 \pm 1.6) \%$ [85]. This efficiency was determined through the use of the MRD muon track reconstruction, by back-propagating found muon tracks to the position of the FMV and checking for a coincidence with an FMV paddle hit.

The MRD is placed downstream of the main detector volume, and like the FMV, consists of layers of scintillator paddles read out by 2-inch PMTs, arranged in alternating horizontal and vertical orientations. This provides the capability to determine the muon direction through the MRD.

The primary detector of ANNIE is a 26-ton, cylindrical, highly pure water volume loaded with 0.2% of gadolinium sulfate by weight. The interior of the tank is instrumented with 132 PMTs for 10% photo cathode coverage. Five Large Area Picosecond Photodetectors (LAPPDs), provided by Incom Inc., will supplement the PMTs to provide improved timing

and spatial resolution. LAPPDs are $20\text{cm} \times 20\text{cm}$ photodetectors that utilize micro-channel plates (MCPs) to achieve sub-centimeter spatial resolution and a timing resolution down to the order of tens of picoseconds [86].

The ANNIE tank has a removable top hatch measuring about 1m in diameter, which supports four PMTs. Additionally, the tank lid has several small ports where calibration sources can be lowered into the water and slots through which LAPPDs can be deployed.

ANNIE is placed 100m downstream of the BNB target. The BNB is produced by impinging 8 GeV protons onto a beryllium target. The resulting hadrons are focused by a toroidal magnetic horn that is typically pulsed to focus positive hadrons while defocusing negative ones. These hadrons, primarily pions, then decay to produce neutrinos. The associated charged leptons are stopped by an absorber 50m downstream of the target. The BNB produces a flux consisting of 93.6% ν_μ and 5.9% $\bar{\nu}_\mu$ peaked around 700MeV [87], and operates at a maximum average rate of 5Hz, delivering about 4×10^{12} protons on target (POT) over a $1.6 \mu\text{s}$ spill.

3.2 Deployment of WbLS in ANNIE

WbLS was deployed in ANNIE from March to May 2023 in a program dubbed SANDI (Scintillator for ANNIE Neutrino Detection Improvement). The SANDI vessel is a cylinder made of 2.54cm thick acrylic with an interior measuring 90cm in height and 72cm in diameter giving it a 366L capacity. The vessel is held by a stainless steel frame, which serves as a

lifting structure. Electro-polished SAE 304 stainless steel is used to ensure compatibility with the gadolinium-loaded water. With the stainless steel structure, the vessel weighs $\sim 163\text{kg}$ when empty. After fabrication, the vessel was leak tested by pressurizing it to 2psi for 24 hours, during which time the vessel maintained this pressure.

To deploy SANDI, a steel support structure was designed, fabricated, and installed by the Fermilab engineering staff. The structure consists of two 4-inch square steel support tubes with 1/4-inch thick walls. A $W8 \times 13$ steel I-beam spans the columns to support the SANDI vessel. Connected to the I-beam is an electrical winch with a teflon-wrapped stainless steel cable. The winch is on rollers and was used to lift the vessel, maneuver it into position, and lower it into the water. The vessel is shown in Figure 3.2 hanging from the deployment structure.

Filling the SANDI vessel took two days to complete. Two days prior to filling, the SANDI vessel was flushed with nitrogen to reduce the potential for biological contamination. To account for fluid displacement, Gd-water was removed from the tank, stored in two drums lined with polyethylene, and later reused after extracting SANDI. The top hatch of the ANNIE tank, along with its four PMTs, was removed and stored on the tank lid. The empty SANDI vessel was then lowered into the center of the tank, just to the point where it became buoyant. As the vessel was filled, it was lowered in steps to maintain access while limiting the additional force on the support structure.

Due to the small size of the ANNIE hall, the WbLS barrels were held outside the ANNIE hall under a tent. The WbLS was pumped from the barrels through a 0.2-micron filter and

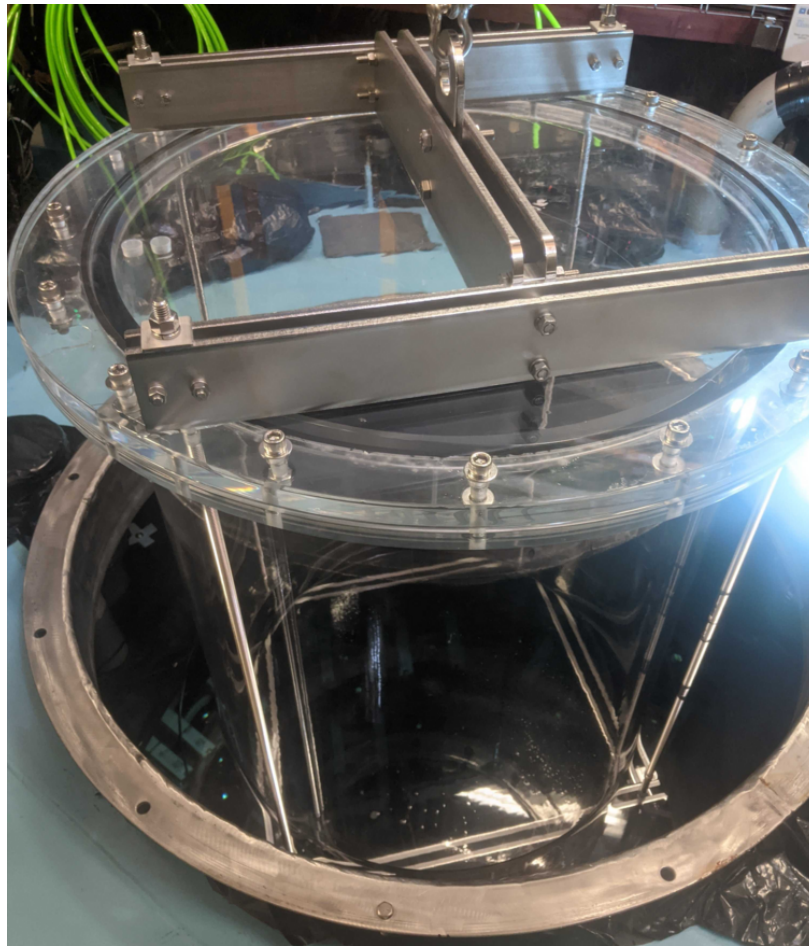


Figure 3.2: The SANDI vessel suspended from the deployment structure.

into 10L containers. The containers were then carried down to the lower level where they were emptied through a funnel connected to the inlet of the SANDI vessel. In addition to the inlet port, the SANDI vessel was also fitted with a teflon overflow tube. When the vessel was nearly full, the inlet was capped off with a stainless steel fitting, and the overflow tube was filled with about 3m of WbLS to remove the last air pocket. Once the vessel was lowered to

its final location, a temporary PVC lid with a cutout for the suspension cable and overflow tube was fitted to the ANNIE tank. The overflow tube and temporary lid were both covered with opaque plastic.

During the deployment period, water samples were extracted from the ANNIE tank for observation. The samples were analyzed with a UV-vis spectrophotometer to monitor the absorption spectrum and check for WbLS contamination. The resin filters of the ANNIE water system were expected to capture WbLS from any small leaks. Throughout the duration of the deployment, the UV-vis monitoring did not show any change in the absorption spectrum that would indicate WbLS contamination.

The extraction of the SANDI vessel proceeded much the same way as the deployment. However, in this case, we pumped directly from the vessel on the middle level of the ANNIE hall up to the WbLS storage barrels on the top level. Samples of the extracted WbLS were taken back to Brookhaven National Laboratory (BNL) for analysis.

3.3 Production and Long Term Stability of the deployed WbLS

The organic component of the WbLS used in SANDI is a mix of modified polyethylene glycol-based surfactants and a diisopropylnaphthalene (DIN) base liquid scintillator loaded with a fluor of 2,5-diphenyloxazole (PPO). All raw components were purified using vacuum

distillation and an exchange column before synthesis. To fill the SANDI tank, approximately 500L of WbLS were produced using an in-situ mixing technique [79] with a double-jacketed 90L Chemglass reaction vessel at BNL. This WbLS formula was designed to be compatible with Gadolinium loading, similar to that which was deployed in CHESSE for precision light-yield and time profile measurements [88], and at the BNL 1000L test bed for optical transparency, stability, and larger-scale testing [79]. This formulation differs from the WbLS formulation studied in [77, 89] in order to provide compatibility with Gadolinium loading, and therefore the optical parameters are expected to differ.

The reaction vessel for the production of the WbLS has several injection ports made of polytetrafluoroethylene (PTFE) to prevent any chemical complication of adding organic materials. All the tubing, filtration system, liners, and the mixing system were pre-cleaned with ethanol (Ethyl alcohol 190 proof), rinsed with ultrapure water (resistivity $18.2 \text{ M}\Omega \cdot \text{cm}$) and dried with nitrogen gas. Afterward, it was sealed in an inert environment until use. At different stages of the synthesis, 1% (mass) of purified organic materials were introduced through different ports into the reactor, where pure water (99% by mass) was pre-filled and mixed at 100rpm for four hours. Finally, the WbLS was filtered through a 0.2-micron PTFE membrane using a 316-stainless steel filtration housing and stored in 55-gal lined drums for shipment.

Each drum was outfitted with a dual polyethylene liner, each measured 5-micron in thickness, to serve as a reservoir for liquids. The maximum storage capacity of each drum was set at 180 L, equivalent to two 90 L batches from the vessel system, to facilitate handling

and prevent overflow. Further, nitrogen cover gas was introduced to the liquid to ensure its stability during transport. Three WbLS drums ($\approx 450\text{L}$) were shipped to and placed in a temperature-controlled warehouse at Fermilab in November 2022.

The performance of the WbLS used in SANDI was assessed using a Shimadzu UV-Vis spectrophotometer with a 10cm quartz cell for optical transmission and a Beckman LS6500 coincidence counter using a ^{137}Cs source for a light-yield measurement at BNL. Figure 3.3a shows the optical stability before and after the SANDI deployment. The variation in optical transmission is within the statistic uncertainty (0.0003) of the two baselines. Fig. 3.3b shows the Compton spectra induced from ^{137}Cs . This represents the light-yield stability of the WbLS before and after its deployment, as the spectra are the same within the measurement uncertainty. Together the UV and light-yield data represent the overall WbLS stability through different processes including shipment, storage, deployment, and draining over a period of nine months since production.

3.4 Detection of WbLS Scintillation in ANNIE

This section describes the detection of the WbLS scintillation light in ANNIE from the BNB muon-neutrinos. Two independent analyses are performed to estimate the effect of the WbLS-filled SANDI vessel on the number of detected photoelectrons (p.e. or charge) in ANNIE, relative to the Cherenkov light of pure water. This is done through a data-on-data comparison of throughgoing muon events and Michel electrons, which is meant to be a

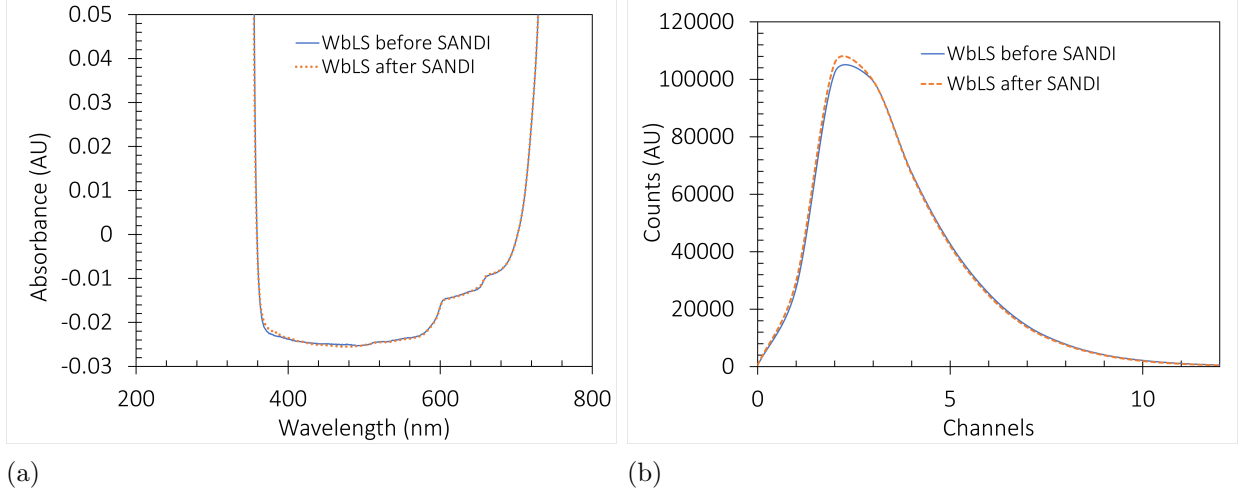


Figure 3.3: (a) The WbLS optical transparency before and after the SANDI deployment. (b) The WbLS light-yield before and after the SANDI deployment, given by the Compton spectra induced from ^{137}Cs .

principal proof for the WbLS feasibility in a neutrino beam. The two data sets used in this section are the pre-SANDI (without WbLS) data, running from December 2022 to March 2023, and the SANDI data (with WbLS), from March 2023 to May 2023.

3.4.1 Throughgoing muon analysis

Muons can be produced by the interaction of the beam ν_μ with nuclei. If such a muon is produced outside of SANDI it can cross the ANNIE detector from front to back and is called a throughgoing muon. These events are well suited to estimate the impact of the WbLS-filled SANDI vessel on the number of detected photoelectrons and the additional contribution of the scintillation. The reason for this is that these muons are minimally ionizing particles which produce a relatively well-defined photoelectron spectrum, depending on the entrance

angle and total track length in ANNIE, smeared by the detector response.

The principal event selection of neutrino-associated muon events is performed in a data acquisition window of $\Delta t = 2\mu\text{s}$ of every incoming beam trigger. First, a coincidence is required between the water tank cluster and the MRD cluster within 100 ns to select events with a muon in the final state. Here, a water tank cluster is defined as at least five tank PMT hits registered in a pre-defined time window of 50 ns and a MRD cluster is defined as at least four MRD PMT hits in a time window of 30 ns. The MRD coincidence guarantees the selection of a muon event and the MRD is sensitive to the muon track direction. Events are required to have exactly one reconstructed muon track to simplify the comparison analysis. The MRD track is then extrapolated back through the ANNIE water tank and events are then selected if the muon track intersects the SANDI volume. This is expected to provide a large number of selected events which can produce scintillation light, as they pass the SANDI volume. A similar cut on the muon tracks has been performed for the ANNIE data without the SANDI vessel, where muon tracks were required to pass through the space where SANDI would be. It has to be noted here that the MRD track angle reconstruction has an estimated uncertainty of 0.17 rad and an uncertainty on the MRD entry point of 12 cm in both the X and Y coordinates [85]. This means that not all selected events have a true intersection with the SANDI volume. Additionally, a lower limit on the detected number of photoelectrons in the water tank of 200 p.e. is selected to minimize the impact of noise.

These data sets are further split in two, depending on whether the FMV trigger is coincident with the PMT tank trigger or not. If such a coincidence between the FMV, the water

tank and the MRD occurs, then the corresponding event can be identified as a throughgoing muon. This event selection is well suited for an estimation of the impact of the additional scintillation, as the throughgoing muons provide a relatively simple event topology. Muons that go through the entire ANNIE detector provide an energy distribution that is more narrow than muons that get produced inside the tank, because the spread in track length is smaller for the throughgoing muons. If the FMV is not triggered in coincidence with the water tank and MRD, then the event is considered a neutrino candidate, i.e. the neutrino interacts inside the water tank and the associated muon is detected by the MRD.

These selection cuts provide four data sets with 1771 pre-SANDI neutrino candidate events, 1181 SANDI neutrino candidate events, 983 pre-SANDI throughgoing muon events, and 615 SANDI throughgoing muon events.

In the following, the water tank PMTs are divided into two categories: The upstream PMTs with a Z-position < 0 m and the downstream PMTs with a Z-position > 0 m, where the Z-axis is defined by the neutrino beam direction and the origin of the coordinates is the center of the water tank. For Cherenkov light, it is expected that the downstream PMTs should detect a relatively large number of photoelectrons, as it is emitted in a forward cone along the muon direction. The upstream PMTs are not able to see direct Cherenkov light, but they can detect a small fraction of the downstream p.e. coming from reflections off the ANNIE structures and downstream PMT glass. The scintillation from the WbLS vessel on the other hand is emitted isotopically. It is therefore expected that both the upstream and downstream PMTs should detect a substantial amount of direct scintillation light, while

seeing a very different amount of direct or indirect Cherenkov light. This effect can be seen for the throughgoing muon data sets in Fig. 3.4.

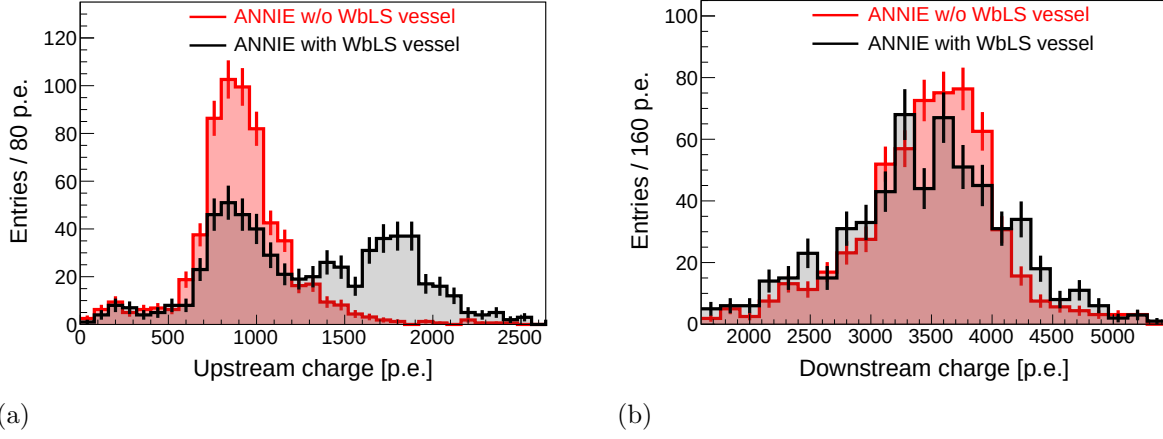


Figure 3.4: Distribution of the charge for the selected throughgoing muon events in units of the number of detected photoelectrons for (a) upstream PMTs and (b) downstream PMTs. The events are selected if they have an intersection of the reconstructed muon track of ANNIE with the WbLS vessel volume. The black distributions show the data of ANNIE with the WbLS vessel, and the red distributions show the data of ANNIE without the WbLS vessel. The latter distribution is normalized to the statistics of the black distribution of the ANNIE with WbLS events.

The left Fig. 3.4a shows the measured distribution for the total number of detected photoelectrons (charge) of all upstream PMTs for the SANDI data (ANNIE with the WbLS vessel) in black and for the pre-SANDI data (without the WbLS vessel) in red. The latter distribution is normalized in the plot to the statistic of the SANDI data for better comparison. It can be seen, that the pre-SANDI data has a charge distribution with a single peak around 900 p.e., which corresponds to the reflected Cherenkov light of muons traversing the entire tank. The upstream charge distribution of the SANDI data shows two peaks at

around 900 p.e. and 1700 p.e. These two peaks originate from the non-perfect MRD track reconstruction, which gives rise to two populations of events: (1) Those events for which the reconstructed muon track has an intersection with the WbLS vessel, while the true muon track does not intersect with the WbLS vessel. (2) Those events for which both the reconstructed and true muon track do have an intersection with the WbLS vessel. Here, a more sophisticated track direction and interaction vertex reconstruction could provide a better event selection, by using the charge and time information of the tank photodetectors. Such a technique is under development. The peak with a lower number of p.e. corresponds to events of the first type, which did not produce scintillation light, while the peak at the larger number of p.e. includes both the reflected Cherenkov light and the direct scintillation light. Therefore, Fig. 3.4a provides a qualitative demonstration of the detection of scintillation from the WbLS. It is interesting to note that the charge distribution of muons that miss the WbLS has a peak position that is comparable to that of the distribution for the pre-SANDI data events. This likely indicates that the reflection of Cherenkov light from the SANDI vessel structure is relatively small. If the SANDI vessel structure would have reflected a large fraction of the Cherenkov photons, then the average upstream charge for the muon events that miss the WbLS would have been shifted noticeably, compared to the pre-SANDI data muon events. This observation has been qualitatively confirmed by a simple simulation of the detector geometry. It indicates that the reflections off the SANDI vessel structure can only provide a few-percent level effect, relative to the detected number of downstream photons.

Figure 3.4b shows the downstream charge distribution for ANNIE without the WbLS vessel in red and for ANNIE with the WbLS vessel in black. Here both distributions have a peak around 3400 p.e., where the presence of the WbLS vessel provides a distribution that is broadened compared to the distribution for pure Cherenkov light. This can be seen by comparing the root-mean-square of the two histograms, which is around 590 p.e. for the pre-SANDI data and around 710 p.e. for the SANDI data. As expected, the number of detected photoelectrons for the downstream PMTs is larger than for the upstream PMTs due to the directionality of the Cherenkov light from the selected muons. The effect of the broadening for ANNIE with the WbLS vessel can be explained by the two event populations described previously. Those muon tracks that are mis-reconstructed such that the true muon track does not intersect the WbLS vessel do not produce scintillation light. At the same time their Cherenkov photons can still traverse the WbLS, which has a lower transparency than the pure water, and therefore these events are shifted to a lower average number of downstream p.e., compared to the events for ANNIE without the WbLS. Those events for which the muon tracks do have an intersection with the WbLS vessel produce both scintillation and Cherenkov light, which shifts the downstream p.e. distribution to higher values compared to ANNIE without the WbLS. This is assumed to provide a broader downstream charge distribution for the SANDI data, as the contribution of the scintillation is not large enough compared to the direct Cherenkov hits to produce two distinctly separate peaks.

A supplementary investigation for the principal detection of the WbLS scintillation is shown in Fig. 3.5. Here all throughgoing muons are selected, not only those which have a

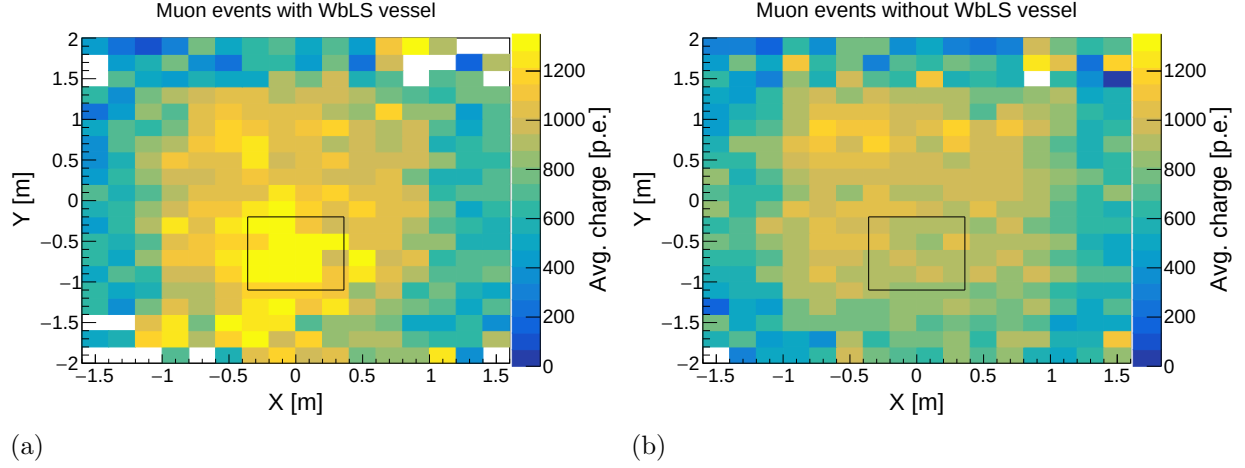


Figure 3.5: The average number of detected upstream photoelectrons plotted against the intersection of the reconstructed muon track with the X-Y-plane for $Z = 0$. The black outline shows the position and dimensions of the WbLS vessel. (a) For throughgoing muon events of ANNIE with the WbLS vessel. (b) For throughgoing muon events of ANNIE without the WbLS vessel.

reconstructed track that intersects the WbLS volume. The plots show the number of detected upstream photoelectrons, averaged for each position bin, plotted against the intersection of the reconstructed muon track with the X-Y-plane for the center of the water tank ($Z = 0$). The WbLS volume, centered at $X = 0$ m and $Y = -0.65$ m, is shown as a black frame. For the SANDI data in the left Fig. 3.5a the events with the highest average number of detected upstream photoelectrons correspond largely to the position of the WbLS-filled SANDI vessel, smeared by the resolution of the track reconstruction. The comparison with the pre-SANDI data in the right Fig. 3.5b shows the absence of this feature for the same volume without the WbLS. This shows that the WbLS-filled SANDI vessel is responsible for the increase in the detected number of upstream photoelectrons, which meets the expectations of the isotropic

WbLS scintillation.

Figure 3.4 makes it possible to provide a rough estimate of the increased light output due to the WbLS, using an analytical fit of the p.e. distributions. For the SANDI data, two bi-Gaussian fits are performed on the upstream and downstream p.e. distributions. The same events that have a clear scintillation contribution in the upstream p.e. distribution must also provide scintillation to the downstream p.e. Therefore, the upstream p.e. distribution can be used to estimate the number of events with and without a scintillation contribution, which can then be fixed for the fit of the downstream p.e. distribution. The bi-Gaussian fit on the number of photoelectrons Q is defined as follows:

$$f(Q) = C + \frac{A_W}{\sqrt{2\pi Q}\sigma_W} \exp\left\{\left(-\frac{1}{2} \left(\frac{Q - \mu_W}{\sigma_W\sqrt{Q}}\right)^2\right)\right\} + \frac{A_S}{\sqrt{2\pi Q}\sigma_S} \exp\left\{\left(-\frac{1}{2} \left(\frac{Q - \mu_S}{\sigma_S\sqrt{Q}}\right)^2\right)\right\} \quad (3.1)$$

Here C is a constant offset, A_W , A_S are the amplitudes, μ_W , μ_S are the mean values, and σ_W , σ_S are the standard deviations for the two different event populations, where S denotes those events that go through the WbLS vessel and produce scintillation and W denotes those events that do not. The additional term of $\sqrt{Q}$ takes into account the impact on the p.e. distribution smearing due to the Poissonian nature of the number of photoelectrons. Here the fit parameters of interest are the mean p.e. values of the two event populations: The number of upstream p.e. $\mu_W^U = (880 \pm 20)$ p.e. and the number of downstream p.e. $\mu_W^D = (3056 \pm 59)$ p.e. for those muon events that do not cross SANDI and the corresponding

values $\mu_S^U = (1713 \pm 34) \text{ p.e.}$, $\mu_S^D = (3637 \pm 51) \text{ p.e.}$ for those muon events that do cross SANDI and produce scintillation light. The estimated ratio of the muon tracks that go through SANDI relative to all selected events is 0.44 ± 0.07 , corresponding to about 270 events. The best fit results are also illustrated in Fig. 3.6 for the SANDI data. Here the black histogram shows the data, the red line shows the best fit distribution, and the blue and green lines show the charge distributions of the fit corresponding to the two event populations for illustration purposes. The pre-SANDI data is fitted with a single Gaussian, resulting in $\mu_{\text{pre-SANDI}}^U = (887 \pm 9) \text{ p.e.}$, $\mu_{\text{pre-SANDI}}^D = (3473 \pm 25) \text{ p.e.}$

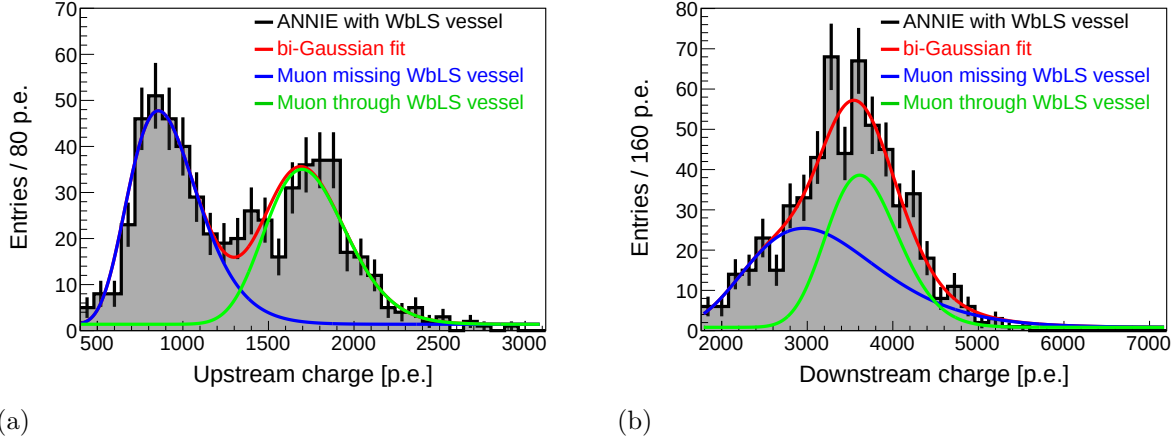


Figure 3.6: Illustration of the bi-Gaussian charge fit. The data with the WbLS vessel is shown in black, the full fit is shown in red and the two event populations of muons passing through the WbLS vessel or missing it are shown in green and blue, respectively.

The muons that cross the WbLS vessel are not fully contained inside it, and the above fit values include a large fraction of Cherenkov light from pure water as well as scintillation and Cherenkov light from the WbLS vessel. Additionally, the WbLS can absorb Cherenkov

light, without re-emitting scintillation, and the SANDI structure can also have a shadowing effect. It is possible to use the above p.e. mean values and the MRD reconstructed muon tracks to correct for the muon track length through the WbLS vessel and estimate the loss of Cherenkov light due to SANDI. For this purpose, a simple toy-MC simulation has been used to estimate the average true track length L of the muons, given the reconstructed MRD tracks and their uncertainties. The estimated value for the average track length through the entire ANNIE water tank is $l_{\text{ANNIE}} = (2.951 \pm 0.012) \text{ m}$. A small selection effect has been observed on this value for the two event populations, where the muon tracks missing the WbLS vessel give a value of $l_{\text{W}} = (2.896 \pm 0.012) \text{ m}$ and the events crossing it give $l_{\text{S}} = (3.019 \pm 0.011) \text{ m}$. The reason for this effect is the cylindrical shape of the water tank, where muon tracks that miss the WbLS vessel tend to intersect the tank more often at off-center positions. The average track length of the muons through the WbLS vessel is $l_{\text{WbLS}} = (0.597 \pm 0.007) \text{ m}$. The toy-MC has also been used to estimate the average track length of the Cherenkov photons through the WbLS vessel, which are emitted along the muon tracks, as $l_{\text{che}} = (0.463 \pm 0.010) \text{ m}$. The average fraction of the Cherenkov photons that pass through the WbLS vessel is estimated likewise as $r_{\text{che}} = 0.123 \pm 0.003$. In the following we define q_{W} [p.e./m] as the estimated number of detected Cherenkov photoelectrons per meter of muon track in pure water, q_{S} [p.e./m] as the estimated number of Cherenkov and scintillation photoelectrons from the WbLS, and A_{eff} as the effective absorption of the Cherenkov light by the SANDI vessel, its steel holding structure and the WbLS itself. The following equations can be used to estimate these parameters, assuming that the total number

of detected photoelectrons is simply proportional to the track length of the muon through the medium, with q_W , q_S as the relevant proportionality constants:

$$\begin{aligned}\mu_{\text{pre-SANDI}}^U + \mu_{\text{pre-SANDI}}^D &= q_W \cdot l_{\text{ANNIE}} \\ \mu_W^U + \mu_W^D &= q_W \cdot l_W \cdot (1 - A_{\text{eff}}) \\ \mu_S^U + \mu_S^D &= q_W \cdot l_S \cdot (1 - A_{\text{eff}}) + q_S \cdot l_{\text{WbLS}}\end{aligned}\tag{3.2}$$

Solving the above equations results in $q_W = (1395 \pm 10) \text{ p.e./m}$ and $q_{\text{SANDI}} = (2159 \pm 154) \text{ p.e./m}$, where the errors have been added in quadrature. Therefore, the ratio for the estimated number of photoelectrons per meter of muon track length from the WbLS compared to the number of photoelectron from pure water is $\frac{q_S}{q_W} = 1.42 \pm 0.13$. Additionally, the equations allow for an estimation of the total absorption of Cherenkov light. The absorption parameter A_{eff} is an effective parameter, which includes all possible sources of the Cherenkov absorption due to the deployment of SANDI, such as the acrylic SANDI vessel, its steel holding structure and the WbLS attenuation of the Cherenkov light. This value is estimated as $A_{\text{eff}} = 0.08 \pm 0.03$, meaning that roughly 8% of the Cherenkov light is missing due to the WbLS-filled SANDI vessel, compared to the normal configuration of the ANNIE water tank.

A number of potential sources of systematic uncertainty have been investigated for the above calculations. First, the position of SANDI inside the ANNIE water tank is known only with a certain precision. The SANDI position has been estimated through the bi-Gaussian fit of Eq. 3.1 and the comparison of the relative contribution of true scintillation events A_S/A_W

for different assumed positions of SANDI. The corresponding SANDI position uncertainty has been estimated conservatively as ± 0.1 m. Re-performing the calculations again for different assumed SANDI positions results in a systematic uncertainty of $\Delta \frac{q_S}{q_W} = \pm 0.16$. Second, the analytical fit has also been re-performed with some variations, such as leaving out the sliding standard deviation term $\sqrt{Q}$, without the constant C , and within different fit ranges. The corresponding systematic uncertainty is estimated as $\Delta \frac{q_S}{q_W} = \pm 0.07$. Adding these uncertainties in quadrature results in a ratio of $\frac{q_S}{q_W} = 1.42 \pm 0.13$ (stat.) ± 0.18 (syst.) = 1.42 ± 0.23 (stat. + syst.).

It has to be noted here that the above value is a simple measurement of the expected number of photoelectrons with and without the WbLS-filled SANDI vessel, given the selected throughgoing muons events. This is not a measurement of the WbLS scintillation light-yield, whose in-situ measurement necessitates a dedicated, full Monte Carlo based analysis, which takes into account the full detector response and geometry, as well as all interactions of the photons with the different detector media.

3.4.2 Neutrino candidate events

The next part of this section shows WbLS scintillation light for neutrino candidate events in ANNIE. These beam neutrino events have been selected in the same way as the throughgoing muon events, with the difference that now the FMV is required to have not seen a signal in coincidence with the tank PMTs and the MRD. This selects muon events that have

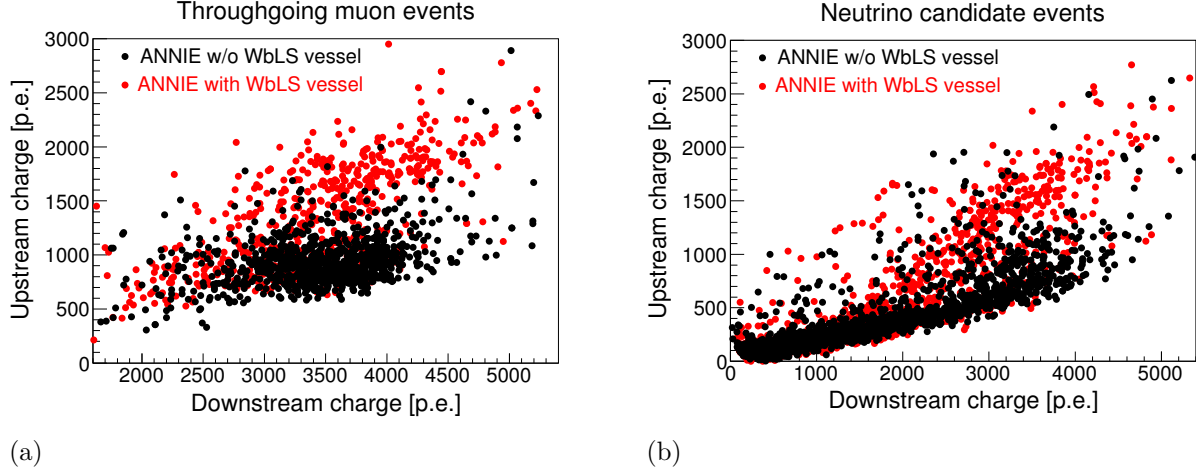


Figure 3.7: Scatter plots of the number of detected photoelectrons for the downstream PMTs vs. the upstream PMTs for the selected events of ANNIE without the WbLS vessel in black and for the events of ANNIE with the WbLS vessel in red. (a) Throughgoing muon events, which required a coincident FMV trigger. (b) Neutrino candidate events, which required the absence of a coincident FMV trigger.

been produced through neutrino interactions inside the ANNIE tank. Here again the MRD reconstructed muon track is required to intersect the WbLS vessel.

Figure 3.7 shows scatter plots of the number of detected photoelectrons for the downstream PMTs against the upstream PMTs, where the pre-SANDI data without the WbLS vessel is shown in black while SANDI data with the WbLS vessel is shown in red. Throughgoing muon events are shown on the left in Fig. 3.7a. The same features described in Fig. 3.4 are also visible here. There are again two populations of events for the SANDI data, where the mis-reconstructed muon track events without scintillation are hidden in the plot behind the black points. The events with scintillation show stronger linear dependency between the upstream and downstream photoelectrons compared to the Cherenkov light from ANNIE

without WbLS, as is expected from the isotropy of scintillation.

Figure 3.7b shows the neutrino candidate events, i.e. neutrino interactions which produce muons inside the water tank, as selected by the FMV. Below a downstream photoelectron number of around 1500 p.e. there is no clear difference between the pre-SANDI and SANDI data events. As the number of downstream photoelectrons is proportional to the muon path length through the water tank, this likely means that these muons are produced in neutrino interactions behind the WbLS vessel. For larger numbers of downstream photoelectrons, the SANDI data shows again two event populations, as described previously. The events which produce scintillation light have a distribution which is well distinguishable from the events of ANNIE without the WbLS. This scatter plot therefore provides a qualitative proof that WbLS produces a larger amount of light than pure water for accelerator neutrino events in an operating large scale neutrino detector.

3.4.3 Michel electron analysis

Michel electrons, produced by decaying muons, follow a well known spectrum that can be used as a standard candle for the comparison of the detected number of photoelectrons in water and in the WbLS. The total energy spectrum of Michel electrons in vacuum can be described as follows [90]:

$$N(E) = 3 \left(\frac{E}{E_{\max}} \right)^2 - 2 \left(\frac{E}{E_{\max}} \right)^3, \quad (3.3)$$

where E is the energy of the electron and $E_{\text{max}} \approx 53 \text{ MeV}$ is the maximal possible electron energy in the decay.

The contribution of anti-muons from the decay of anti-muon neutrinos is considered negligible for the following selection of Michel electrons. A coincident event pair is required for the Michel electron selection: A prompt event caused by a muon, followed by a second event caused by the Michel electron. The prompt event is selected by several cuts to exclude most of the background: First, the prompt event is required to be triggered within the $2 \mu\text{s}$ acquisition window, and it is required to be the brightest signal among all the signals within a time window of the corresponding BNB trigger. Second, an FMV hit is required to be in coincidence with the muon candidate event to enforce that the muon source is located outside the ANNIE detector. Furthermore, a prompt event is required to have a bary-center located in the downstream part of the detector and the event time is required to have no MRD signal within a 50 ns time window. This cut enforces the selection of muons stopping in the tank. Finally, a photoelectron range of $[1000, 4000] \text{ p.e.}$ is required to further exclude muon candidates that are falsely tagged as stopping muons to compensate for the MRD inefficiency. In the case that an event passes all the cuts mentioned above, all subsequent clusters within a time window of $\Delta t \in [1000, 6000] \mu\text{s}$ are tagged as Michel electron candidate events. A charge balance cut of $q_{\text{cb}} < 0.2$ is applied to the Michel electron candidate events to further reduce background caused by a large, single PMT signal. The charge balance

parameter q_{cb} is defined using the following equation:

$$q_{cb} = \sqrt{\frac{\sum Q_i^2}{Q_{\text{sum}}^2} - \frac{1}{N}}, \quad (3.4)$$

where Q_{sum} represents the total number of observed photoelectrons in the cluster, Q_i references the number of photoelectrons that have been observed by PMT_i , and N is the number of PMTs involved in the cluster. Charge balance values close to 1 indicate that most of the charge has been seen by a single PMT, indicating that the cluster was probably a noise event.

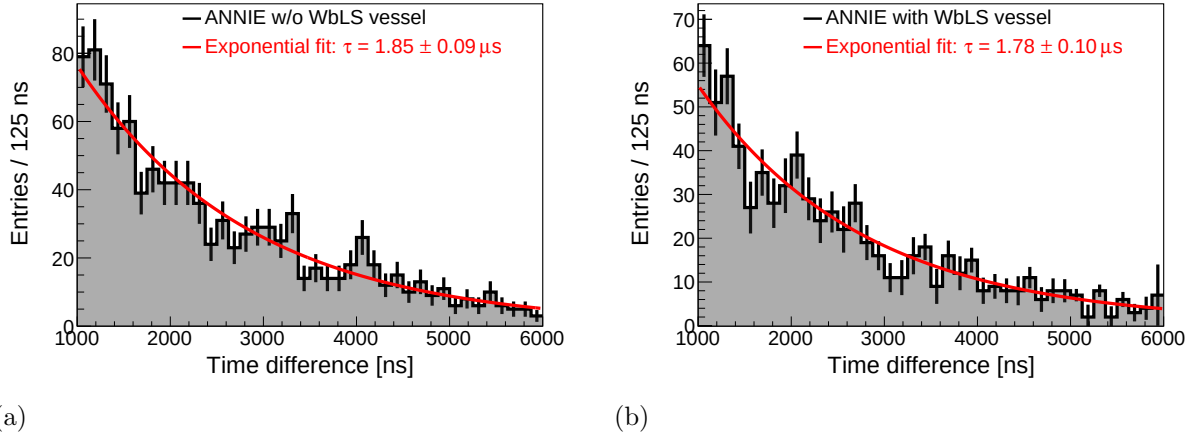


Figure 3.8: Histograms for the timing distribution between Michel electron events and the preceding muon events, which follows the exponential decay rule for (a) the data without the WbLS vessel and (b) the data with the WbLS vessel.

A good comparison of the number of photoelectrons produced by Michel electrons in pure water and in the SANDI vessel requires a pure sample with minimum background. As a measure of sample purity, the time distribution of the selected Michel electron events is

shown in Fig. 3.8. Here the pre-SANDI data is shown on the left and the SANDI data is shown on the right. The timing spectrum is fitted by a function of an exponential decay plus noise that is assumed to be a constant:

$$A = A_0 e^{\frac{-t}{\tau}} + C, \quad (3.5)$$

where A_0 denotes the initial amplitude at $t = 0$, τ is the decay constant and C denotes the noise. The fitted decay constants are $\tau = (1.78 \pm 0.10) \mu s$ for the SANDI data and $\tau = (1.85 \pm 0.09) \mu s$ for the pre-SANDI data. The expected muon lifetime is calculated using the following equation:

$$\frac{1}{\tau_{\text{tot}}} = R_{\text{tot}} = R_{\text{vac}} + R_{\text{oxy}}, \quad (3.6)$$

where R_{tot} denotes the total muon decay rate, R_{vac} and R_{oxy} denote the muon decay rate in vacuum and the capture rate in pure oxygen, respectively. τ_{tot} is the overall lifetime of the muon. From the experimental results of [91], the expected muon lifetime τ_{tot} is $(1.788 \pm 0.002) \mu s$, which is well in agreement with the results of both event selections. Here the effect of muon capture on hydrogen is ignored.

Now let's take a look at the charge property of selected michel electrons, as shown in Fig 3.9. This is a scatter plot of number of PMT hits versus the total charge of michel electron events. The total charge of an event is a good indicator of energy deposited in the tank, as most of the energy deposit through Cherenkov radiation and scintillation. All the michel events in the plot can be roughly categorized into two groups, as indicated by the red lines. The main difference between these two groups is the charge to hits ratio. This is a

clear evidence indicating the ANNIE tank is capable of distinguishing Cherenkov radiation and scintillation. The group with lower charge to hits ratio corresponds to the scintillation light because of its isotropic nature. The wider the radiation angle, the more PMT hits.

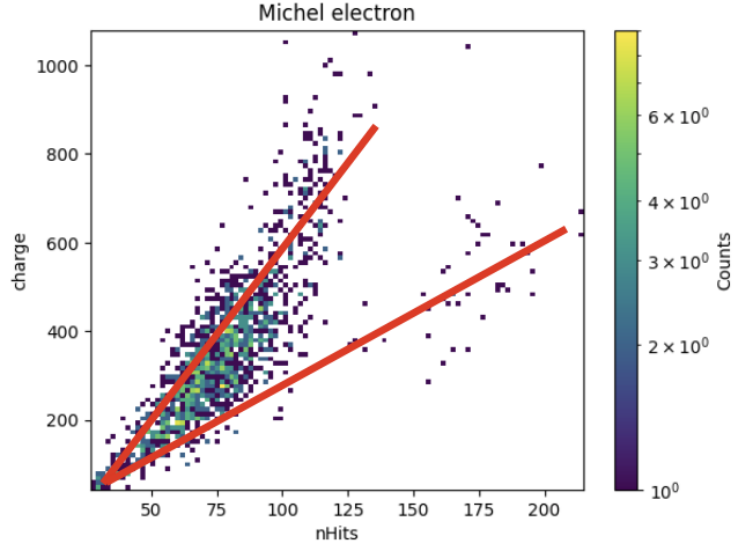


Figure 3.9: The scattering plot of michel electron events. x component is the number of PMTs triggered by the event, y component is the total charge of the event.

The stopping muon events, on the other hand, doesn't resemble this behavior. Fig 3.10 shows the scatter plot of muon events. The difference is due to the long trajectory of muon travelling inside the ANNIE tank. Most of the stopping muons are produced by the interaction of the beam μ_{nu} with dirt outside the ANNIE hall. The average travel length of these muons are thus half the size of ANNIE tank, which is around 2 meters. Electrons, on the other hand, are scattered by the target medium due to their high charge to mass ratio.

For this reason, the electron's travel distance is typically several centimeters. The Cherenkov radiation produced by muon is roughly proportional to its travel length, resulting in a higher charge collected by PMTs for Cherenkov radiation. In a detector filled with WbLS only, scintillation light would also be increased and the charge versus hits ratio should remain unchanged. In this setup of WbLS deployment, the SANDI vessel is only 72 cm in diameter, which is too small to fully make use of the long travel length of muon. For this reason, the muon cluster is dominated by Cherenkov radiation.

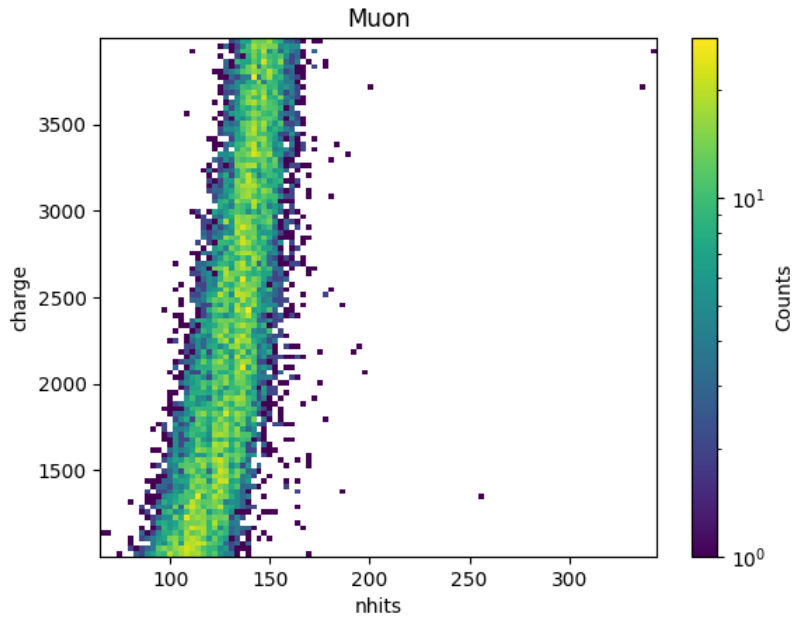


Figure 3.10: The scattering plot of muon events. x component is the number of PMTs triggered by the event, y component is the total charge of the event.

Figure 3.11a shows the charge distribution of the selected Michel electron events for the pre-SANDI data in red and for the SANDI data in black. It can be seen, that the selected

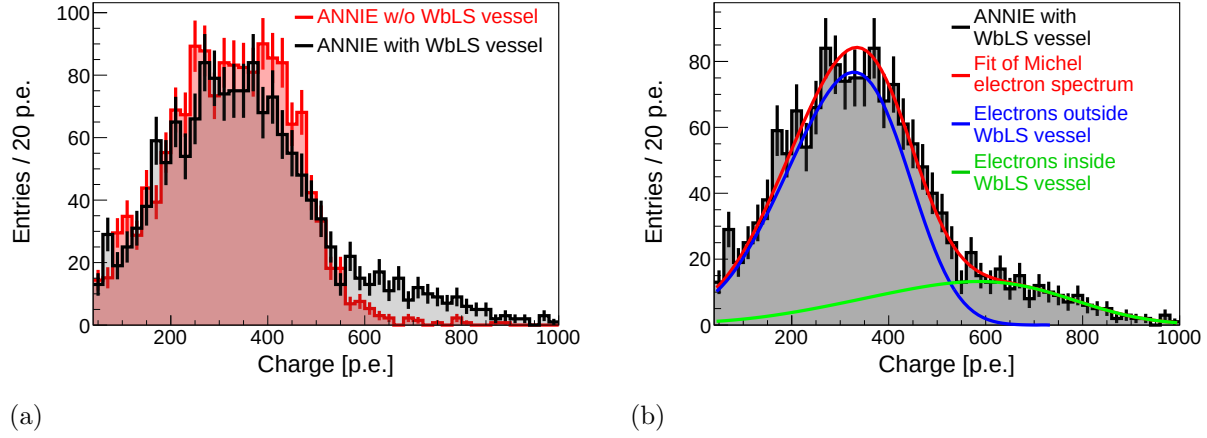


Figure 3.11: Histograms of the Michel electron charge distribution collected by PMTs inside the ANNIE tank. (a) The data of ANNIE without the WbLS vessel in red and for ANNIE with the WbLS in black. The ANNIE without WbLS data is normalized to the statistics of ANNIE with the WbLS vessel for better comparison. (b) The fit of the Michel electron data for ANNIE with the WbLS vessel. This is a combination of events inside and outside the WbLS vessel, estimated by the fit and shown in blue and green respectively.

Michel electrons fall into two categories: Those electron events for which the parent muon decayed within the SANDI vessel and those electron samples for which the parent muon decayed outside the SANDI vessel. For those Michel electrons that have been generated outside of SANDI, the source of the detected photoelectrons is from Cherenkov radiation, while for the ones generated inside SANDI, the source is a combination of both Cherenkov radiation and WbLS scintillation. The latter event category can be seen in comparison with the pre-SANDI Michel electron charge distribution above ~ 600 p.e.

The comparison of the mean values of these two event populations of the SANDI Michel electrons can provide an estimation of the additional number of photoelectrons provided by

the deployment of the WbLS-filled vessel. A Gaussian smeared Michel spectrum is used to describe the total number of photoelectrons collected by the PMTs inside ANNIE tank Q . The spectrum is described by the following equation:

$$g(Q) = \int_0^{E_m} A \cdot f(E) \cdot G(Q, \mu(E), \sigma) dE, \quad (3.7)$$

where $f(E) \propto N(E)$ is defined in equation (3.3) as the Michel electron energy spectrum, $G(Q, \mu(E), \sigma)$ is the Gaussian distribution, $\mu(E) = kE$ is the mean number of photoelectrons as a function of energy and is naively assumed to be proportional to the energy deposited inside the ANNIE tank. σ is the energy resolution of the detector and follows the square root relation: $\sigma = \sigma_0 \sqrt{E}$.

Equation (3.7) is then used to fit the photoelectron distribution in Fig. 3.11b. Here the charge distribution of the SANDI data is a combination of the two event populations described above, each with a unique mean value for the number of detected photoelectrons. The parameter of interest is the proportionality factor k of the photoelectron mean value for the two distributions: $k_{\text{SANDI}} = (14.44 \pm 0.87) \text{ p.e./MeV}$ and $k_{\text{Water}} = (8.17 \pm 0.14) \text{ p.e./MeV}$. The correlation coefficient of these parameters given by the fit is 0.0073. The ratio of $k_{\text{SANDI}}/k_{\text{Water}} = 1.77 \pm 0.06$ can be used to estimate the relative increase of the detected number of photoelectrons in ANNIE due to the WbLS-filled SANDI vessel, compared to pure water. Like with the previous analysis of throughgoing muons, the systematic uncertainty here has been estimated by varying the analytical fit function; with and without a sliding

standard deviation $\sigma = \sigma_0 \sqrt{E}$. The corresponding uncertainty is $\Delta \frac{k_{\text{SANDI}}}{k_{\text{Water}}} = \pm 0.05$, resulting in $\frac{k_{\text{SANDI}}}{k_{\text{Water}}} = 1.77 \pm 0.06 \text{ (stat.)} \pm 0.05 \text{ (syst.)} = 1.77 \pm 0.08 \text{ (stat.+syst.)}$.

3.5 Conclusion

WbLS is a novel target material which allows for the simultaneous detection of Cherenkov radiation and scintillation. Cherenkov radiation provides sensitivity to the particle direction and track reconstruction, as well as allowing for particle identification through the Cherenkov ring topology. The addition of scintillation improves the energy resolution and allows for the detection of particles below the Cherenkov threshold.

The work described in this chapter is part of the ongoing technical demonstration and experimental validation of the hybrid detection concept, which is important for future, large scale, advanced optical neutrino detectors such as Theia [46].

SANDI (Scintillator for ANNIE Neutrino Detection Improvement), a cylindrical vessel with a diameter of 72 cm and 90 cm height, was successfully filled with WbLS and deployed in the ANNIE water tank for about two months. Samples of the WbLS have been measured at Brookhaven National Laboratory before and after the SANDI deployment. No deterioration of optical transparency or light-yield have been found, which indicates a long term stability of the WbLS under real deployment and beam measurement conditions.

The WbLS scintillation signal can be quantified by the comparison of the ANNIE data with the WbLS vessel and of ANNIE data without the SANDI vessel. The scintillation has

been observed for throughgoing muons, Michel electrons from muon decays inside ANNIE, as well as beam neutrino interactions inside ANNIE. Two independent estimations of the increase of the detected number of photoelectrons due to the deployment of the WbLS vessel have been performed, one with throughgoing muons and one with Michel electron events. These analyses have been performed through analytical fits on the distributions of the detected number of photoelectrons. The analyses results are expressed as a ratio of the number of detected photoelectrons for events that deposit energy within the WbLS-filled SANDI vessel and the detected number of photoelectrons for events outside the SANDI vessel. These ratios are $q_{\text{SANDI}}/q_{\text{Water}} = 1.42 \pm 0.23$ (stat.+syst.) for the throughgoing muons and $k_{\text{SANDI}}/k_{\text{Water}} = 1.77 \pm 0.08$ (stat.+syst.) for the Michel electrons.

The observed increase in the detected number of photoelectrons is clearly caused by the additional scintillation of the WbLS and the order of magnitude of this detected increase is in agreement with the expectations given by bench-top experiments [88]. Nonetheless, it has to be noted that above results cannot be directly interpreted as a measurement of the intrinsic scintillation light-yield of the WbLS. They rather express the increase in the number of detected photoelectrons with and without the deployment of the WbLS-filled SANDI vessel.

For future light-yield studies, Michel electrons show great potentials. Due to its fixed energy spectrum and sharp ending point, Michel electron directly associate particle energy with number of photon electrons produced. It is also a good source for calibration purpose and estimation of energy resolution. The prompt and delayed signal pair allows a pure

sample selection, resulting in a low uncertainty caused by background events.

An in-situ measurement of the intrinsic WbLS light-yield requires a detailed Monte Carlo model of the full ANNIE detector response that includes the effects of the SANDI vessel structure and the absorption, re-emission and scattering of light in the WbLS, as well as the full ANNIE detector response. The work of producing such a Monte Carlo model is currently underway.

The results presented here will form the basis for the further development of hybrid event detection in the GeV energy range in ANNIE. Future reconstruction and particle identification algorithms will make use of both the Cherenkov light and the WbLS scintillation. These algorithms are expected to depend on critical parameters of the WbLS, such as its attenuation length and scintillation light-yield.

Using the upgraded reconstruction techniques, the planned follow-up analyses on the collected WbLS data regard the detection of neutron captures on hydrogen, the search for neutral current events, as well as the investigation of the hadronic scintillation component, all within the WbLS vessel. Further plans include the re-deployment of SANDI with gadolinium-loaded WbLS to study the enhanced neutron detection, and potentially filling the entire ANNIE tank with WbLS to permit a better assessment of the performance of hybrid event reconstruction in a future large-scale experiment.

Chapter 4

Conclusion

Since its first postulation, neutrino has resolved many mysteries in the field of physics. It is still a powerful probe to the unknowns of our universe. New technologies are being developed to improve our resolution of neutrino detection. Among them, water-based Liquid Scintillator possesses a great potential for future neutrino physics as it combines the advantages of already mature Water Cherenkov detector and liquid scintillator detector.

As part of the development process of the WbLS, this thesis discusses two important factors that are of interest: the preliminary study of Cherenkov radiation/scintillation separation and the photon attenuation length measurement. We conclude in Chapter 3 that the WbLS developed by Brookhaven National Lab is capable of generate both Cherenkov radiation and scintillation, which meets its physics goal. A preliminary analysis on its light yield was performed in the ANNIE detector using three different approaches, all the approaches lead to the same result: a ratio of 1.77 of scintillation versus Cherenkov light.

The results presented will form the basis for the further development of hybrid event detection in the GeV energy range in ANNIE. Future reconstruction and particle identification algorithms will make use of both the Cherenkov light and the WbLS scintillation.

The Scattering and Attenuation Measuring Device(SAMD) is discussed in Chapter 2. This device is validated by several tests. Its pure water result agrees with the result in literature, this further proves the accuracy of the measurement. The final result of photon attenuation length in WbLS is presented in this chapter, concluding that WbLS is transparent enough for future large neutrino detectors.

Attenuation length and light-yield are both critical parameters, and they play important roles in Monte Carlo algorithms and reconstruction algorithms

As photon scattering is also an important factor for signal reconstruction, as the name SAMD suggested, a future update will be performed on SAMD allowing it to perform photon scattering measurement.

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