Simulation Studies of the Directivity in Detection of Solar Neutrinos Using Deep Sea Water

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Abstract

The Cerenkov detector has a distinct advantage in constructing the reaction vertex and incident direction of energetic particles, enabling the identification of emission sources. We propose a novel approach to measure neutrino sources by employing a modular photomultiplier tube (PMT) array, utilizing clean and transparent deep sea water as the sensitive medium. The feasibility of detecting solar neutrinos is demonstrated through extensive simulations using the Geant4 package. These simulations incorporate the production and transport of Cerenkov photons generated by electron scattering, with the Hough transform method applied to enhance the accuracy of vertex and direction reconstruction, particularly in the presence of noisy or incomplete data. The dominant background from γ-radiation due to 40K in seawater can be suppressed by a factor of 10^7 by introducing a threshold on the number of triggered PMTs. The total reconstruction efficiency increases with incident energy, achieving 25% for 6 MeV neutrinos and 52% for 10 MeV neutrinos, respectively. For source localization, a sufficient number of neutrino events must be detected, depending on background intensity above the threshold. The Hough transform is also applied to manage high noise levels during this process. The simulation results confirm the feasibility of detecting solar neutrinos using deep sea water, paving the way for future underwater neutrino detection systems.

Full Text

Simulation Studies of Directivity in Solar Neutrino Detection Using Deep Sea Water*

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Čerenkov detectors offer distinct advantages for reconstructing reaction vertices and incident directions of energetic particles, enabling the identification of emission sources. We propose a novel approach to measure neutrino sources using a modular photomultiplier tube (PMT) array with clean, transparent deep sea water as the sensitive medium. Through extensive Geant4 simulations, we demonstrate the feasibility of detecting solar neutrinos. These simulations incorporate the production and transport of Čerenkov photons generated by electron scattering, with the Hough transform method applied to enhance vertex and direction reconstruction accuracy, particularly in the presence of noisy or incomplete data.

The dominant background from γ-radiation due to ^{40}K in seawater can be suppressed by a factor of 10^7 by introducing a threshold on the number of triggered PMTs. The total reconstruction efficiency increases with incident energy, achieving 25% for 6 MeV neutrinos and 52% for 10 MeV neutrinos. For source localization, a sufficient number of neutrino events must be detected, depending on the background intensity above threshold. The Hough transform is also applied to manage high noise levels during this process. Our simulation results confirm the feasibility of detecting solar neutrinos using deep sea water, paving the way for future underwater neutrino detection systems.

Keywords: neutrino, Čerenkov, Geant4, Energy Resolution, Direction Reconstruction, Hough Transform

INTRODUCTION

Neutrinos with energies of a few MeV or higher are major products of nuclear reactions, originating from the Sun (e) or terrestrial nuclear reactors (¯e). Detecting these neutrinos from the Sun provides a critical test of the Standard Solar Model (SSM) and led to the discovery of neutrino oscillations [1–3]. Conversely, detecting anti-electron neutrinos helps monitor nuclear reactor operations [4–12] and constrain the oscillation angle 13 between the first and third generation neutrinos [13, 14]. Despite their importance, detecting neutrinos is extremely challenging due to their weak interaction and small cross-sections. Nevertheless, numerous neutrino detectors have been developed since the first direct detection of neutrino events [15–20]. While the inverse beta decay (IBD) method is widely used for detecting ¯e, e detection can be achieved through e-e$^-$ elastic scattering. A key advantage of this scattering process is that the direction of the recoil electron closely aligns with the incident neutrino direction, depending on the neutrino energy [21, 22].

The water Čerenkov detector is a widely utilized neutrino detection technique. For example, the Super-Kamiokande detector (Super-K) employs approximately 40 kT of pure water to successfully detect solar neutrinos, supernova neutrinos, and cosmic ray neutrinos [23]. In this setup, when a recoil electron gains sufficient kinetic energy to move faster than the speed of light in water, it emits Čerenkov radiation at a specific angle, which is then detected by photomultiplier tubes (PMTs) with high timing resolution. By reconstructing the vertex and trajectory of the recoil electron, the direction of the incident neutrino can be inferred [24].

However, increasing the detector volume to improve event rates becomes technically challenging in land-based laboratories. To achieve the mega-scale detection volumes required for detecting e-e$^-$ scattering events, it has been proposed to use clean seawater or ice at the South Pole as the target material [25, 26]. This approach has been successfully implemented for detecting extremely high-energy neutrinos in various experiments [27–32]. Extending this method to lower energy domains remains challenging due to intense background radiation from natural sources such as ^{40}K and ^{208}Tl [33], as well as other radioactive isotopes produced by cosmic ray interactions. In order to understand how feasible it is to detect low-energy neutrinos using seawater, extensive simulation studies are essential.

This paper investigates the feasibility of detecting solar neutrinos using seawater as the target material through Monte Carlo simulations. The study focuses on reconstructing the incident direction of neutrinos using faint Čerenkov light signals and suppressing intense radiation backgrounds. The paper is organized as follows: Section II introduces the software, detection array construction, and optical process modeling. Section III presents the event reconstruction method, taking into account the influence and suppression of background radiation in seawater. Section IV describes the positioning of the neutrino source, and specifically discusses the physical effects of using clean seawater. Section V provides a summary.

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II. SIMULATION SOFTWARE

The simulations are carried out using the WCSim framework [34], a comprehensive simulation environment also used by the Super-K collaboration based on the Geant4 toolkit. This framework provides a complete set of functionalities, including detector geometry modeling, particle transportation from neutrino interactions in water, Čerenkov light generation and propagation, as well as PMT response modeling. This section outlines the simulation workflow.

A. Detector Construction

In the current application, water is defined as the absorbing material. The PMTs are distributed in a specific configuration to detect the Čerenkov light emitted by high-speed electrons produced in neutrino-induced reactions. For simplicity in this startup simulation, a spherical distribution of the PMTs is adopted in water. This configuration is chosen to ensure isotropic detection capabilities, which is essential for locating an unknown source. The radius of the sphere, measured at the front surface of the PMTs, is set to R = 5 m.

This value is both reasonable and feasible for constructing a demonstrator, while also providing a sufficiently large fiducial volume. Given the lack of an analytical solution for a series of points uniformly distributed on a sphere, the setup employs an approximate solution based on the Fibonacci grid [35]. The spherical coordinate angles and of the i-th PMT are shown in Eq. (1): cos = 1 - (2i - 1)/N = iπ(1 + $\sqrt{5}$)/2 (i [1, N])

Each PMT's symmetrical axis is aligned to the center of the sphere. The diameter of the sensitive area of each PMT is = 8 inches. Assuming a 30% coverage of the entire sphere surface, which represents a moderate and achievable value, a total of 2906 PMTs are constructed. The physical construction of each PMT is simplified as a glass bulb containing a vacuum. The remaining area of the sphere is covered with black sheets to minimize internal reflections, with surface reflectivity manually adjusted to 95% from the inner to outer space. To mitigate residual radiation from the PMT materials, the fiducial volume is defined by a sphere with a radius of R_{fd} = 4.5 m. Fig. 1 presents the schematic view of the PMT sphere. The distance between neighboring PMTs is maintained at 30–40 cm.

B. Simulation of the Optical Process

The simulated event begins with the generation of a charged particle in a neutrino-induced reaction. This process is enforced due to the low cross-section of weak interactions, which makes it challenging to achieve sufficient statistics using conventional sampling techniques. The charged particle loses energy in water and emits Čerenkov light if its velocity exceeds the threshold. The simulation tracks all secondary particles until they are stopped or absorbed. Čerenkov photons in water undergo scattering and absorption according to the optical parameters of the medium. If a photon reaches the PMT surface, it can generate a certain number of photoelectrons (PEs), producing a signal based on the PMT response parameters. Alternatively, photons may be absorbed if they strike the black surface outside the PMT's acceptance range.

In this study, the PMT response settings are identical to those of the Super-K experiment [36]. If more than 10 PMTs are triggered within 50 ns (representing the time it takes for light to traverse the entire detector), a trigger signal is generated, and the data are stored for further analysis. Therefore, the transport and absorption of Čerenkov photons are critical processes in the detection mechanism. The detection process is governed by several optical parameters for the medium and surfaces, including the absorption length, refractive index, and scattering length. These parameters depend on the photon wavelength. For simplicity at the beginning, the parameter set of water is adopted from Super-K [36], which is suitable for pure water but may not be ideal for seawater. The effect of seawater will be discussed in Section IV.

The attenuation length is shown in Fig. 2(a), where the value in the blue wavelength band is about 100 m, the refractive index is 1.334. Additionally, the refractive index for glass is set to 1.6, and the absorption length for a black sheet is set to 10^{-11} m. The surfaces defined are the interfaces between these media. The reflectivity between water and black sheet is set to 0.05. The quantum efficiency of the PMTs is a function of photon wavelength, as shown in Fig. 2(b). The maximum efficiency is 21.1% at $\lambda = 400$ nm.

Fig. 1 [Figure 1: see original paper]. (Color online) Schematic view of PMTs distributed on a sphere filled with water.

Fig. 2 [Figure 2: see original paper]. Parameters used in the simulation package. Data is taken from [34]. (a) Attenuation length as a function of photon wavelength. (b) PMT quantum efficiency as a function of photon wavelength.

Fig. 3 illustrates an event display of the optical process resulting from a 6 MeV electron neutrino-induced reaction. The incident direction is randomly distributed over a 4π solid angle, with the vertex fixed at the center. The red lines represent the tracks of Čerenkov photons, while the dashed arrow indicates the direction of the recoil electron, which is expected to be reconstructed from the PMTs triggered by the photons.

Photons absorbed by the water or the sphere surface are lost and excluded from the analysis.

Fig. 4 [Figure 4: see original paper]. (Color online) Correlation between the number of emitted Čerenkov photons and detected photons.

Fig. 3 [Figure 3: see original paper]. (Color online) Event display induced by a 6 MeV electron neutrino. The red lines are the tracks of Čerenkov photons and the thick dashed black arrow denotes the recoil electron in e-e^- scattering.

Fig. 5 [Figure 5: see original paper]. (Color online) Projection diagram of fired PMTs relative to the recoil electron direction. (a) Integration over 10^5 events. (b) and (c) Fired PMT distributions in two single events.

The correlation between the number of photons triggering PMTs and the total number of photons produced in each neutrino-induced reaction is illustrated in Fig. 4. The simulation incorporates dark noise at 4.2 kHz, which is typical in PMTs, and may result in 1–2 additional signals per event.

The overall efficiency of PMT triggering is approximately 20%. Considering the geometric coverage of about 30%, it is inferred that roughly 40% of the photons are lost during transport to the PMTs due to scattering or absorption.

The limited distribution of Čerenkov photons is crucial for event reconstruction at the event-by-event level. The distribution of Čerenkov photons in a polar coordinate system vs. is shown in Fig. 5. Here, is the angle between the direction of the recoil electron and the vector from the reaction vertex to the triggered PMT, while is the azimuthal angle of the Čerenkov photon. Fig. 5(a) displays the cumulative vs. plot for 10^5 events, with the electron's incident direction pointing to the pole (= 0°) by definition. The Čerenkov circle is clearly visible with its center at = 0°. However, for individual events, as shown in Fig. 5(b) and 5(c), the triggered PMTs are distributed in a scattered manner, making the circular pattern invisible to the eye. This necessitates a sophisticated algorithm to reconstruct the direction of the incident electron.

C. Discussion of the Seawater Environment

The Tropical Deep-sea Neutrino Telescope (TRIDENT) collaboration [37] measured an attenuation length of 20 m in the blue wavelength band at a depth of 3.5 km. This is considerably shorter than the 100 m reference value used in Fig. 2(a). For a typical photon travel distance of 5 m, the survival probability in seawater compared to the one in pure water is = e^(-5m/20m) / e^(-5m/100m) = 82%. Although this corresponds to an 18% reduction in photon yield, the current PMT threshold M_{pmt} $\geq$ 20 (see Section III.D) effectively rejects ^{40}K backgrounds, so the overall conclusions remain unaffected.

Impurity ions in seawater can induce background reactions, such as e + ^{37}Cl $\rightarrow$ e$^-$ + ^{37}Ar, with a cross-section of *σ{Cl} = 1.14 × 10^{-42} cm^2 [38]. Given a chloride concentration of 0.546 mol/L and an isotopic abundance of ^{37}Cl ($_{37}$ = 24.23%), the additional background-to-signal ratio is estimated to be approximately 0.5% via Eq. (2): ratio =* $_{37}$ {Cl} σ_{Cl} / (_e σ_e) = 0.5% This value is negligible; however, future studies should consider uncertainties in these parameters.

For biofouling mitigation, PMTs are oriented inward within a light-shielded detector design, which minimizes exposure to external biofouling-induced light. Since biofouling emissions are omnidirectional, unlike the directional Čerenkov radiation generated by neutrino-related signal events, this difference enables effective discrimination. Consequently, biofouling does not impose a significant challenge to the current feasibility simulations.

It is noted that the ansatz in Eq. (4) without the exponential term resembles a conventional ^{2} value. The inclusion of the exponential term is motivated by the fact that some Čerenkov photons may undergo multiple reflections before reaching a PMT, causing the actual firing time to differ significantly from the value predicted by Eq. (3). This exponential term reduces the sensitivity of the fit to such outliers, enabling a more robust reconstruction of the vertex based on event-by-event logic.

III. EVENT RECONSTRUCTION

This section presents a detailed description of the reconstruction procedure for the e-e$^-$ scattering process. The primary objective of this reconstruction is to accurately determine the timing and vertex of the scattering event based on the detected Čerenkov photons in the detector [39–43].

A. Vertex Reconstruction

The study focuses solely on the e-e^- elastic scattering process. The determination of the vertex position depends on the timing information from the fired PMTs. Consequently, the time resolution is a critical performance parameter. For neutrinos with a few MeV of kinetic energy, the recoil electron rapidly loses all its kinetic energy, resulting in a negligible track length. Therefore, all Čerenkov photons are assumed to originate from a single point, denoted as (x_0, y_0, z_0, t_0).

Given the exact position (x , y , z) of each fired PMT, the expected arrival time t of the Čerenkov photon at the i-th PMT can be calculated as: t $= t_0 +$ |r (x , y , z) - $r_0(x_0, y_0, z_0)$| $\times$ n/c where c is the speed of light in vacuum, and n is the refractive index of water.

If the reconstructed vertex coincides with the true vertex, the difference between the recorded firing time and the expected time (from Eq. (3)) for all fired PMTs should yield a sharp peak centered at zero. However, if the reconstructed vertex deviates from the true position, the calculated time distribution exhibits a broader and distorted distribution with large timing residuals.

To address this, one should select the vertex parameters that maximize the consistency between the measured and expected times, thereby yielding the final reconstructed vertex. Specifically, the strategy is to minimize the function defined in Eq. (4) [45]: exp(- $^2/\sigma^2$) where = t - t represents the deviation of the measured time t from the expected time t , and σ corresponds to the PMT time resolution (σ = 50 ns).

B. Direction Reconstruction

The Čerenkov light generally forms a cone with a semi-apex angle satisfying sin $\alpha = (n\beta)^{-1}$, where β = v/c and v is the particle's velocity. For electrons with energies of several MeV, the distance traveled before slowing down to the threshold is short (about 1 cm). As a result, the emitted Čerenkov light can be approximated to have a fixed emission angle from the reaction vertex, given by α_c arcsin(n^{-1}).

However, secondary scattering of electrons in the medium causes a broadening in the angular distribution, as shown in Fig. 6. This distribution will be used as the probability distribution function (PDF) in the Hough transform.

Fig. 6 [Figure 6: see original paper]. Angular distribution of Čerenkov light with respect to the electron flying direction.

The Hough transform (HT) method [22, 46–49] is applied to determine the direction of the recoil electron in e-e^- scattering using data recorded by the PMTs. Fig. 7 illustrates an example of the HT method applied to the event shown in Fig. 5(b). Once a vertex is reconstructed, each fired PMT defines a direction vector characterized by the polar angle and azimuth . To simplify the explanation, consider the fixed Čerenkov angle (α_c) first. For each PMT, the data point generates a circle on the - plane at the given polar angle α_c, with the longitudinal axis aligned from the vertex to the fired PMT, as shown in Fig. 7(a) by red cross symbols. This circle represents a probability distribution in the parameter space of the electron direction, characterized by $_0$ and $_0$. As shown in Fig. 7(b), summing the transformed probability distributions weighted by the number of PEs from all fired PMT data points yields the probability distribution of the high-speed electron in the - parameter space. The most probable point in this distribution corresponds to the reconstructed direction of the electron. In real calculations, due to the scattering of Čerenkov photons, the PDF of the Čerenkov angle from Fig. 6 is used instead of a fixed α_c. Following the same procedure, with the circle replaced by the continuous distribution for each transformation, the real probability distribution of the direction in the - parameter space is obtained. The most probable point $_0$- $_0$ is situated at the point with the highest probability, as depicted by the red cross marker in Fig. 7(c).

Fig. 7 [Figure 7: see original paper]. (Color online) Schematic elucidation of the Hough Transform method. (a) The fired PMTs on - plane, the circles near the red cross markers are the possibility distribution to find the electrons, assuming a constant Čerenkov angle. (b) All the possibility distributions are summed up for all fired PMTs with the number of PE as the weight. (c) The real possibility distribution of finding the electron in - parameter space, using the PDF shown in Fig. 6. The red cross marker represents the recognized direction of the electron.

C. Results from Neutrino Events

In the simulations of neutrino-induced reactions, the issue of insufficient statistics due to the small cross-section is addressed by forcing the reaction to occur when injecting a neutrino. The distribution of recoil electrons is sampled using Eq. (5) [50]: dσ/dcos (E_ ^{2} cos / (M^2 - E_ ^{2} cos^2)^2) $\times$ (M^2 - E_ ^{2} + (1/4)(M^2 - E_ ^{2} cos^2)(1 + $g_2{}^2$ - $g_1 g_2$)) where T represents the kinetic energy of the recoil electron, M = m + E_ , and the constants g_1 and g_2 characterize the coupling strength of left-handed and right-handed components in weak interactions and are dependent on the flavor of the neutrino. For solar neutrinos e, the corresponding distribution is shown in Fig. 8.

Fig. 8 [Figure 8: see original paper]. (Color online) Angular distribution of the recoil electron in e-e$^-$ scattering with respect to the incident direction of the neutrino at different E_ .

The simulation process proceeds as follows: a random point within the fiducial volume of the detector setup is selected as the reaction vertex. A scattering angle is then randomly sampled from Eq. (5) for a given neutrino energy, and the electron momentum is calculated using energy-momentum conservation. The vertex and momentum together define the recoil electron as a neutrino event.

Subsequently, Čerenkov light is generated based on the velocity of the recoil electron and transported to the PMTs, where the emitted PEs are recorded. The HT method is then applied to reconstruct the incident direction of the recoil electron and the position of the reaction vertex.

The results of the reconstruction are presented in Fig. 9. For each energy point, 10^5 events are simulated. Fig. 9(a) shows the distribution of α, defined as the angle between the reconstructed and genuine directions of the recoil electron. As the incident neutrino energy increases, the energy of the recoil electron also increases, and the distribution exhibits a more pronounced peak at $\cos(\alpha) = 1$, indicating higher reconstruction success. The efficiency increases from 0.66% at E_ = 2 MeV to 66% at E_ = 10 MeV. Fig. 9(b) displays the mean value $\cos(\alpha)$ as a function of the incident neutrino energy. At the high-energy end near 10 MeV, $\cos(\alpha)$ = 0.76, suggesting a good determination of the electron's direction. Fig. 9(c) presents the distance ΔR between the genuine and reconstructed reaction vertices. The deviation of the reconstructed vertex decreases slightly as a function of the incident neutrino energy E_ .

Fig. 9 [Figure 9: see original paper]. (Color online) (a) Distributions for angle reconstruction with their efficiency. (b) and (c) show the mean value of $\cos(\alpha)$ and the error of the constructed vertex as a function of the neutrino energy.

D. Influence of Background Events

Careful treatment is required to suppress events caused by intense background sources, including seawater radioactivity, cosmic-ray muons, and faint light emitted by bioluminescent plankton near the detector volume [51].

In principle, the muon background can be efficiently rejected using a veto detector mounted above the main detector or by applying an energy cut. This is because the Čerenkov photons produced by energetic muons penetrating the thick seawater are abundant. Additionally, the light from bioluminescent plankton induces signals on PMTs with distinct rising times and amplitudes, allowing for identification and rejection. However, seawater radioactivity is the primary concern, as the intensity of γ-radiation from radioactive isotopes is high, and their γ energy is comparable to the recoil electron energy in e-e$^-$ scattering, making it the dominant background noise.

The primary radioactive isotope in seawater is ^{40}K [52–54]. The mass fraction of potassium in seawater is _K = 380 mg/L, and the isotopic abundance of ^{40}K is $_{40}$ = 0.0117%. The decay lifetime of ^{40}K is $\tau = 5.692 \times 10^{16}$ s. Using Eq. (7), the event rate for ^{40}K is calculated: Rate = $_{40}$ · _K · N_A / (M_K · τ) = 12.03 L^{-1}s^{-1} where N_A is Avogadro's constant and M_K is the molar mass of potassium. The calculated event rate is significant, necessitating a detailed simulation of this background.

^{40}K has multiple decay channels, as shown in Fig. 10. Specifically, 89.25% of its decays are β^- decays to the ^{40}Ca ground state, and 10.55% are electron capture transitions to the 1460 keV level of ^{40}Ar. To model the ^{40}K process, a combination of 10.55% of 1.46 MeV γ-ray events and 89.25% of decayed e^{-} events with random positions and directions is simulated. The e^{-} energy is derived from Eq. (8): dN/dE (E_{max} - E)^{2} √(E^{2} + 2m E) with a maximum energy E_{max} = 1.311 MeV.

Since γ-rays can travel a distance before being absorbed, decay events are generated in an extended volume with a radius R = 6 m, exceeding the fiducial volume.

Fig. 10 [Figure 10: see original paper]. (Color online) The decay scheme of ^{40}K [55].

Fig. 11(a-c) illustrate the effects of the ^{40}K background. Fig. 11(a) shows the distribution of cos(α), where α is the angle between the reconstructed electron and the initial radiation from the source. A forward-peaking feature is evident. Fig. 11(b) displays the displacement between the real and reconstructed vertices. Fig. 11(c) presents the distribution of the number of fired PMTs M_{pmt} caused by ^{40}K events.

Another major radioactive source in seawater arises from the decay chain of ^{232}Th and ^{238}U. The most energetic γ-ray in this chain is the 2.6 MeV γ-ray from ^{208}Tl. To be conservative, the study simulates the background using 2.6 MeV γ-radiation. The results are shown in Fig. 11(d-f). The features of the 2.6 MeV γ-rays are similar to those of the ^{40}K decay, except that the multiplicity of fired PMTs M_{pmt} is slightly higher for the 2.6 MeV γ-rays, as seen in the peak positions.

Fig. 11 [Figure 11: see original paper]. (Color online) Left: The distribution of the angle between real and constructed direction of ^{40}K decay (a) and γ-rays at E_γ = 2.6 MeV (d). Middle: the distribution of deviation between real and constructed vertex in coordinate space for ^{40}K decay (b) and γ-rays at E_γ = 2.6 MeV (e). Right: the distribution of the multiplicity of fired PMTs for ^{40}K decay (c) and γ-rays at E_γ = 2.6 MeV (f).

Unfortunately, whether the detected particle is an e^{-} or a γ-ray, it is always observed as an e^{-}, identical to the e-e^{-} scattering event. The only distinction between the signal and background lies in the e^{-} energy. To differentiate the neutrino signal from the background, a cut is imposed on M_{pmt} to suppress events caused by the intense radioactive sources in the seawater. Fig. 12(a) shows the multiplicity distribution as a function of the incident neutrino kinetic energy E_ . The goal is to reject the ^{40}K background due to its extremely high event rate. Based on Fig. 11(c), a threshold condition of M_{pmt} $\geq$ 20 is set, as indicated by the dashed line in Fig. 12(a). As the neutrino energy increases, more events are accepted. For E_ = 6 MeV and 10 MeV, the ratios of events with M_{pmt} above the threshold are 55% and 80%, respectively, as shown in Fig. 12(b). After filtering, the reconstruction efficiency becomes 25.6% and 52.2%, respectively, which remains acceptable for detection. The events induced by the ^{40}K background are suppressed by a factor greater than 10^{7}.

Fig. 12 [Figure 12: see original paper]. (Color online) (a) Distribution of multiplicity of fired PMT number as a function of neutrino energy E_ . (b) Ratio of the events above the M_{pmt} threshold as a function of E_ . The final reconstruction efficiency after HT transformation for 6 and 10 MeV neutrinos is indicated by the red cross symbol.

IV. NEUTRINO SOURCE RECONSTRUCTION

With the background suppression scheme, one can consider a simple application to identify an existing neutrino emission source, using the Sun as an example. Genuine neutrino-induced events are overwhelmed by intense background radiation. While the suppression factor for ^{40}K radiation is 10^7, the dominant background is not necessarily ^{40}K. Instead, the remaining background could include 2.6 MeV γ-rays from ^{208}Tl, ^{40}K decays that pass the cuts, neutrino events from other potential sources, and other unaccounted backgrounds.

The event rates for these backgrounds remain unknown until tested in a realistic scenario. Fortunately, background events are isotropic. Therefore, if a background event passes the cuts, it can be manually added to the final data spectrum with an arbitrary incident direction. Simultaneously, neutrinos from the source position trigger e-e$^-$ scattering events, producing recoil electrons that emit Čerenkov photons along specific directions, as described in Fig. 8. To infer the location of the e source, one must accumulate a sufficient number of e-e$^-$ scattering events and perform the Hough transform once more.

Once the electron's direction is reconstructed from the fired PMTs, the Hough transform can be applied using the probability distribution defined in Eq. (5). Fig. 13 illustrates the transformation process in - space. Each data point represents the reconstructed direction of one event. A total of 1000 events are used for the search. In Fig. 13(a) and 13(b), all events are neutrino signals, while in Fig. 13(c) and 13(d), the background-to-signal ratio is set to 5:1, with background events (83%) randomly sampled from all directions. The input source direction is set at an angle of 45° relative to the axis to test the detector's homogeneity, with initial directions = 135° and = 90°. In Fig. 13(a), the dense population of events near the set value is distinguishable even by eye.

Fig. 13(b) shows the corresponding Hough transform result, with the most probable reconstructed position at = 137.3° and = 89.1° (red star). The principle of HT here is the same as the one used to construct event direction in Section III.B, with the probability distribution for HT procedure changed to Eq. (5) instead. In Fig. 13(c), it is much harder to identify the source from the data distribution plot alone. However, the Hough transform result in Fig. 13(d) reconstructs the direction as = 140.8° and = 80.1°, deviating by only 8.8° from the initial direction.

Fig. 13 [Figure 13: see original paper]. (Color online) Plot of source searching Hough transform procedure. (a) Data points of 1000 e-e$^-$ events. (b) The corresponding Hough transformed probability distribution in and space. (c)

Data points of 1000 events with background-to-signal ratio being 5:1, where the background (83%) are from all directions randomly. (d) The corresponding Hough transformed probability distribution in and space.

A. Sun Location Attempt

The detector's search capability can be evaluated using the Sun as a neutrino source. In this analysis, the Sun's apparent motion was neglected by adopting a space-fixed coordinate system anchored to distant stars rather than an Earth-fixed frame. The solar neutrino flux for E_ $\geq$ 6 MeV is approximately $\Phi = 2.5 \times 10^6$ cm^{-2}s^{-1} [56]. The energy-dependent cross-section for e-e$^-$ elastic scattering is given by Eq. (9) [50]: $\sigma = 93$(E_ /MeV) $\times 10^{-46}$ cm^2

The event rate is calculated as: n = $\sigma\Phi = 0.005$ m^{-3}day^{-1} = 2 module^{-1}day^{-1} where $= 0.56 \times 10^6$ N_A is the electron density in water.

Considering a construction efficiency of 33% (as described in Section III.D), we expect approximately 20 detected neutrino events per module per month. With 15 detector modules, this yields 300 solar neutrino events per month from the same direction. For the background, since most ^{40}K events are excluded by the cuts, a background-to-signal ratio of 50 is reasonable, corresponding to 15,000 background events above the threshold. These background events are randomly sampled across all directions. When these signals and backgrounds are input into the Hough transform, the source direction can be inferred as explained in Fig. 13.

To obtain a comprehensive result, a statistical ensemble containing 10,000 simulations is performed. The angle Θ_s between the real source direction and the reconstructed direction is shown in Fig. 14. The search accuracy must meet the requirements of real-world application scenarios. Now defining successful reconstruction by cos Θ_s $\geq$ 0.8 (dashed line), the success rate is approximately 90% for a 30-day search with 300 solar neutrino events and a background-to-signal ratio of 50.

Fig. 14 [Figure 14: see original paper]. Distribution of cosine of the angle (cos Θ_s) between real and constructed neutrino source direction with 10,000 simulated searches.

B. Discussion of Search Capability

Given that the detector is capable of searching for multiple neutrino sources, it is critical to optimize the experimental setup, specifically the number of modules, the total volume of the sensitive medium, and the search duration, as these factors collectively determine the number of collected neutrino signals, even under high background-to-signal ratios. Qualitatively, more neutrino signals improve the search success rate even at higher background-to-signal ratios.

To achieve the same success condition (90% success rate), the minimum number of accumulated events as a function of the background-to-signal ratio is investigated, as shown in Fig. 15. The minimum number of neutrino events N_{min}(90%) required to ensure a 90% success rate is approximately linear with the background-to-signal ratio. For example, if the background-to-signal ratio reaches 270, one must accumulate 1000 neutrino events.

Fig. 15 [Figure 15: see original paper]. (Color online) The minimum accumulation of events N_{min}(90%) required to ensure 90% success rate as a function of background-to-signal ratio. The band represents a 99% confidence interval.

This linear relationship provides confidence that, regardless of how large the background-to-signal ratio becomes, one can achieve the same search capability by scaling the number of detector modules. This is reasonable because the condition for identifying the true source is that the signal peak on the Hough transform probability plane exceeds the background fluctuation. Assuming that the signal peak height scales proportionally with the total number of signal events (N_s) and N_b, one obtains that the background fluctuations scale as √N_b. With appropriate rescaling, this relationship can be expressed as Equation (10): N_s = k√N_b where k is a factor positively correlated with the success condition. This implies that by increasing the number of detector modules, the increased signal can overcome higher background fluctuations, thereby maintaining a 90% success rate.

V. CONCLUSION

The feasibility of locating neutrino sources using a deep-sea water Čerenkov detector through GEANT4 simulations has been demonstrated. A spherical water volume, instrumented with PMTs, is employed as the sensitive detector submerged in seawater. The production and transport of Čerenkov photons generated by the e-e^- reaction are simulated. The vertex and direction of the high-speed electron producing the Čerenkov photons are reconstructed using the Hough transform. The γ-radiation background in seawater is carefully accounted for, and it is found that setting a threshold on the number of fired PMTs can effectively suppress the background. The reconstruction efficiency of the neutrino increases with neutrino energy and averages approximately 33% for neutrinos in the 6–10 MeV range. To locate an existing neutrino source, a finite number of neutrino events are required, depending on the background intensity above the PMT threshold. With 300 accumulated neutrino events, the source direction can be inferred with angular accuracy cos Θ_s > 0.8 under a background-to-signal ratio of 50.

The deep-sea environment offers an effective scenario in which the detector volume is treated as unlimited, thereby providing a scalable framework for detector design. While an idealized detector configuration, with a virtually unlimited volume and sufficient detector modules, ensures that the direction of an unknown neutrino source can be inferred irrespective of background levels, practical constraints (such as the high cost required to deploy additional modules and achieve a sufficient counting rate) may significantly limit real-world implementations.

Furthermore, the accuracy of source reconstruction is inherently linked to the energy of the target neutrino, with lower energy events posing greater challenges for accurate detection and localization. Future research should focus on optimizing key design parameters, such as the detector volume, PMT placement, and coverage rate, to better match the expected energy spectrum and event rate of specific neutrino sources. Such optimization would enhance detection sensitivity and operational feasibility. In conditions where the background-to-signal ratio is excessively high, additional attention is required for accurately identifying neutrino events from known sources (e.g., inverse beta decay signals from reactor neutrinos). Future work should explore alternative background suppression techniques that are specifically tailored to mitigate distinct background components, thereby improving overall signal discrimination and detection sensitivity.

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