

Principle and Analysis of the Neutrino Detection

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Abstract. The neutrino research is one of the frontiers of physics at present. Though neutrinos were proposed decades ago, they have not yet been fully explored, whose properties are closely related to possible new physical models. This study focuses on neutrino detection including radiochemical, Cherenkov and scintillation. Based on existing results from JUNO, this paper mentions some problems that encountered in neutrino detection, and proposes some ideas for improvements. The long-term stability of the detector is significant for capturing neutrino signals. For the application of 20-inch PMTs, the experience gained on PMTs with smaller size is not fully useful, and further research on their properties is needed. Meanwhile, there is a lack of specific and detailed research models in this field for the anomalies PMTs may exhibit. A model that can explain and predict future detector anomalies will make very important contributions to extending detector lifespan and efficiency of neutrino identification. These results can provide possible directions for the development and improvement of neutrino detection methods in the future.

Keywords: Neutrino detection, scintillation, PMT, Photomultiplier Tube, JUNO.

1. Introduction

Neutrinos were firstly proposed by Pauli in his work on the beta-decay in 1930s [1]. He used the hypothesis of the existence of neutrinos to explain the continuity of energy spectrum in this process, which is $n \rightarrow p + e^- + \bar{\nu}$. His assumption now has become a clear proof. Neutrinos are believed to have three different types, which are electron (ν_e), muon (ν_μ) and tau (ν_τ), with their corresponding antiparticles. They can change from each other through decay. One of the most famous examples is the deficit of solar neutrinos [2]. Unlike other candidates which are still hypothetical, neutrinos now are a definite composition of the dark matter. The existence of neutrinos (~ 10 eV type) could explain the missing mass in cosmological metrics, and their contribution to the cosmology constant Ω is thought to be close to 1 [3]. Neutrinos are considered to be essential but not dominant part of the dark matter [4]. They may play irreplaceable role in the formation of the large-scale structure, the cosmic microwave background radiation, and take part in the nucleosynthesis in the early universe.

However, even though the study of neutrinos has been carried out for decades, scientists still lack sufficient understandings of this particle. Current researches have indicated that, the mass of neutrinos, which is the very basic property in physics, still remains uncertain. Discussions of positive and zero mass are both not persuasive enough [5]. Non-zero mass of neutrinos can lead to serious contradictions in theoretical models, but observations have proposed several results on positive massive neutrinos. Electron neutrinos are observed to have mass of either 2.5 - 2.8 eV, or 10 eV (Weinheimer [6], and two researches by Aseev et al. [7, 8]). Muon neutrinos have mass less than 0.17 MeV [9]. For tau neutrinos, the mass is measured to be less than 15.5 MeV, but if only statistics is used, it can reach 7-12 MeV with a confidence level of 95% [10]. In conclusion of these progress, the theoretical prediction of neutrino mass and derivative properties differs from data obtained from astronomical observations.

One important property of neutrinos related to mass is the oscillation. The neutrino oscillation is the process of spacetime evolution of a neutrino starts from an initial pure state, or “flavors”, such as the pure electron flavor produced by solar fusions [11]. The evolution of flavors can only occur when neutrinos have non-zero mass, however in the Standard Model it is prohibited. When massive neutrinos are not in eigenstates, they will transfer into three flavors (electron, muon and tau), and vice versa. The Maki-Nakagawa-Sakata-Pontecorvo matrix describes this transformation:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (1)$$

The matrix is not full rank, the equation itself can be rewritten with three mixing angles, θ_{12} , θ_{13} and θ_{23} . For example, the electron neutrinos obey the following formula: $\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$. If neutrinos are massless, the flavors will remain unchanged in both time and space. However if neutrinos have non-zero mass in their initial states, the transformation will be in the following way: $\nu_e(t) = U_{e1}e^{-iE_1t}\nu_1 + U_{e2}e^{-iE_2t}\nu_2 + U_{e3}e^{-iE_3t}\nu_3$, where $E_i^2 = p^2 + m_i^2$. The observable properties in this case will heavily depend on the space-time factors, making the neutrino oscillation more unpredictable. In addition to the debates on mass, neutrinos are known to have nearly no interactions with other types of substances. In the Standard Model, neutrinos do not carry any electric charge or magnetic moment. The only exception is the left-handed neutrinos, which transmit standard weak interactions through W^\pm - and Z^0 - Bosons [12]. For right-handed type, its magnetic moment is proportional to the mass and is very small, if they exist [13]. Proposing ideas and methods of detecting such non-interactive particle is relatively difficult, compared to simply proposing a theory.

The properties of neutrinos are now described by the Minimal Standard Model (MSM), combining existing theories with Quantum Chromodynamics (QCD). So far, experimental results match the MSM theory very well, and most of the model is consistent with other theories. However, observations have already given out anomalies in conflict with neutrino properties. The present theory will contradict itself if anomalies are all combined and considered. Further and harder works are required for a more comprehensive description, which means more detailed detection and analysis should be carried out. The researches on neutrinos are still on-going nowadays, covering subjects from particle physics and high energy physics, to astrophysics and cosmology. The analysis of neutrino properties can not only give a clearer picture of the universe, but also a configuration of the microscopic world. The motivation of this paper is to summarize works on detection of solar and manual neutrino sources, and discuss about improvements of techniques and details in detection.

2. Principle

Detection of neutrinos has been launched since Pauli proposed this “terrible postulate” [14]. The first direct proof was made in 1956 was based on a nuclear power plant [1]. It was carried out by a group led by Cowan, with the Savannah river reactor plant as the neutrino source in South Carolina [15]. They found signals of electron anti-neutrinos ($\bar{\nu}_e$), which come from the inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$, or $\nu_e + n \rightarrow e^- + p$. This success promoted following researches in the physics community among the world, neutrino observatories then sprang up like mushrooms after rain. For all present observation stations, their neutrino sources are divided into natural and artificial sources. Natural neutrinos usually come from radiations in the universe (astrophysical), the Sun (solar) and the Earth’s atmosphere (atmospheric). Artificial neutrinos are from nuclear power plants (reactor) and accelerators [16]. These detectors all are based on one of the following detection techniques: radiochemical methods, Cherenkov method, scintillation technique, tracking calorimeter, nuclear emulsions and liquid Argon method. One main difference of these two sources is the shielding. Observatories based on natural sources need to avoid interference from other radioactive sources. The ones using artificial sources need to be built at a certain distance from the power plants or accelerators, where the probability wave of neutrinos is at peak value. Therefore, the former needs to be buried very deep underground, while the latter always has to be near power stations and accelerators. Most detectors at present use artificial sources, mainly nuclear power plants and spallation neutron sources.

The principle of the radiochemical method of detection is the inverse beta decay: $\nu_e + n \rightarrow e^- + p$. An electron neutrino is captured by a nucleus, produces an electron and a proton. In the late 1960s, Davis and Bahcall used ^{37}Cl to collect neutrinos emitted from the Sun, and completed the famous Homestake experiment, or Brookhaven Solar Neutrino Experiment [17]. The reaction is as follows:

$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar}^+ + e^-$. The Chlorine atom accepts an electron neutrino, and turns into a radioactive isotope of Argon and an electron, which signal can be extracted and counted. The threshold of this reaction is 0.814MeV. Davis' experimental results were very close to one-third of the calculated theoretical value [18]. This contradiction led to the famous Solar neutrino problem. The experiment was repeated by was followed by similar experiments, such as Kamiokande, SAGE, GALLEX, Super Kamiokande, and SNO. Eventually, SNO discovered the neutrino oscillation which can explain the result. The idea is that, neutrinos can oscillate in one of the three flavors, and only one in three flavors can be detected by the Homestake experiment, which caused the problem of missing neutrinos [19].

The Cherenkov effect was found by Cherenkov in 1934. Generally, when a particle with charge traverses in a medium material with refractive index of n , its behaviour depends on the speed comparing to the local phase velocity of light, which is c/n . If the velocity of the particle v is larger than the local speed of light, it will polarize medium atoms along its trajectory and generates a sequence of time-dependent electric dipoles. These dipoles later turn into electromagnetic waves and then emit. This is the source of the Cherenkov light, which appears in bluish-white color [20]. However if $v < c/n$, this distribution of generated dipoles is symmetric w.r.t the particle position, and the total electromagnetic wave vanishes. This method is applied on a wide range of neutrino spectrum, from low to high energy [21]. The Cherenkov relation for the angle $\theta = 1/n\beta$, in which $\beta = v/c$ is related to the energy E :

$$E = mc^2 \left[\frac{1}{\sqrt{1 - \beta^2}} - 1 \right] \quad (2)$$

The threshold for radiation is at $\beta = 1/n$ and $\theta_c = 0$, which means particles with less than a specified kinetic energy value will not generate Cherenkov radiation. The maximum angle for emitting light is when travelling at ultra relativistic velocities, for which $\beta \rightarrow 1$ [20]. Therefore, the propagation path of Cherenkov light is actually a cone, with the axis following the direction in which particles advance. The electrons generated during the neutrino reaction can then be detected by an matrix of programmed detectors and analyzers, which can show the existence of neutrinos. This method has been used to find the tau neutrino [22].

Nowadays, the scintillation technology has two main types of development: the Solid Scintillation Counting (SSC) and Liquid Scintillation Counting (LSC). The scintillation materials vary by the purpose, but they all can detect the radioactive isotopes of common elements. The scintillation counting is popular in fields such as physics, biology, and environment, to better understand the process of reactions [23]. For neutrino detection, for energy from 3 MeV to 8 MeV, scintillation is the most ideal detection method. A scintillation counter is necessary for measurement of ionizing radiations inside the scintillation material. A complete set of scintillation counter includes a scintillator, a photo-multiplier tube (PMT), an amplifier, and a multichannel analyzer. The array of PMTs, as the eye of the detector, is the most core component. A photo-multiplier tube is an instrument that detects the faint light emitted by scintillators, with a structure similar to common light bulbs. However, PMT detects occasional occurrences of photons, while light bulbs would generate a large number of photons. A PMT has a photocathode which can converts photons into electrons. A sketch of PMT is shown in Fig. 1 [24].

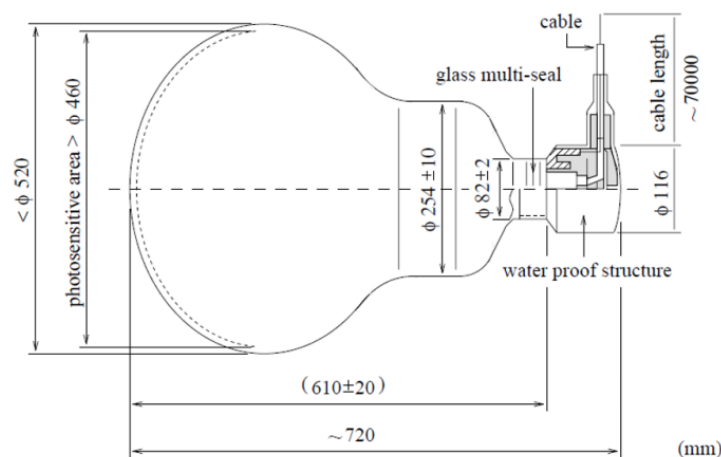


Fig. 1 A sketch of the HPK PMT used by Super-Kamiokande.

These photoelectrons then are guided by voltage potential to the dynodes or micro-channel plates (MCP), where impact of one electron can release several electrons. After the accumulation of chain reactions through multiple dynodes, the number of electrons is sufficient to cause an amplified voltage pulse. The final gain of electron signals can reach about 10^7 to 10^8 times the origin [25]. The magnitude of the pulse is proportional to the light intensity received by the photocathode [23]. This signal is then accepted by the following amplifier and analyzer, and eventually counted as one event. The final result is recorded as the dark count rate (DCR). The higher the value of DCR, the more signals PMT receives from neutrino reactions in unit time. There are several basic criteria for selecting a liquid scintillation. A scintillating material should have: high scintillation efficiency, linear dependency of emitted light on energy deposit, very weak self-absorption, short decay time of the emitted light, suitable isotropic properties and similar refractive index to the glass [21]. Two commonly used materials of scintillators are, aromatic polycyclic hydrocarbons (containing benzene rings, C_6H_6) and alkali halide crystals family.

3. Neutrino Detection Projects

Currently, several detectors (built and under construction ones) in the world are designed based on the aforementioned methods. Sudbury Neutrino Observatory (SNO) [24] was an underground laboratory in Canada, first proposed by Ewan et al., in order to verify Chen's solution to the Solar neutrino problem [26]. Chen proposed that, a heavy water detector can provide observable measurements if built large enough. At about 2100 meters underground, SNO used the Cherenkov method to detect the interactions between solar electron neutrinos and 1,000 tons of heavy water. The nuclear reactions on deuterium also provides possibility to observe all three neutrino types [27]. There are three main reactions involved in SNO: (1) Charged-Current (CC), $\nu_e + d \rightarrow p + n + e^- - 1.44\text{MeV}$ (2) Neutral-Current (NC), $\nu_x + d \rightarrow p + n + \nu_x - 2.2\text{MeV}$, $x = e, \mu, \tau$ (3) Electron-Scattering (EC), $\nu_x + e^- \rightarrow \nu_x + e^-, x = e, \mu, \tau$. Some experimental results prior to SNO, like SAGE and GALLEX, have proposed that, the neutrino oscillation seems more likely to be the cause of the Solar neutrino problem. In May 2002, the data from SNO verified this postulate, showing that neutrinos from beta decay in the solar core can change to muon flavor or tau flavor before detected by SNO. These results proved the existence of neutrino oscillation and led to the award of 2015 Nobel Prize in physics.

The Super-Kamiokande (Super-K) [28] is the world's largest water Cherenkov detector, upgraded from the previous Kamiokande detector. It has a stainless-steel water tank with nominal capacity of 50,000 tons of pure water. Within the tank, a stainless-steel framework supports separate arrays of 11,146 inward-facing 50 cm diameter hemispherical PMTs (called Inner Detector, ID), and 1,885 outward-facing 20 cm diameter hemispherical PMTs (called Outer Detector, OD). These PMTs are all made by HPK. The effective ID photocathode area covers about 40% of the inner surface. These

PMTs can detect the Cherenkov light produced by the reactions of neutrinos with pure water in a range from 4.5 MeV to more than 1 TeV. The Super-K aims at finding proton decays, researches on cosmic and on artificial neutrino sources. It confirms the truth of the the apparent deficit in the total Solar neutrino flux. Other results carried out by Super-K includes the first unambiguous evidence of atmospheric neutrino oscillation and the first measurement of the solar neutrino energy spectrum above 5 MeV. The Solar mixing angle measured by Super-K gives $\sin^2 \theta_{12} = 0.334^{+0.027}_{-0.023}$, with the determined mass splitting term be $\Delta m_{21}^2 = 4.8^{+1.5}_{-0.8} \times 10^{-5} eV^2$ [29].

Jiangmen Underground Neutrino Observatory (JUNO) [30] is a new large-volume and multi-purpose neutrino oscillation experiment, currently under construction. It is an upgradation of its predecessor, the Daya Bay Reactor Neutrino Experiment. The main purpose of JUNO is to carry out precise measurements of the energy spectrum of electron neutrinos. After completing the construction and collecting data for about six years, the neutrino mass ordering is expected to raise to a $3 - 4\sigma$ significance level, while the precision of neutrino oscillation parameters, $\sin^2 \theta_{12}$, Δm_{21}^2 and $|\Delta m_{32}^2|$ should be achieved at 0.6% or better, and the precision of $\sin^2 \theta_{13}$ will not exceed that of previous parameters [31]. It is based on the inverse beta decay, in which the electron antineutrinos are produced by two nuclear power plants nearby. JUNO will be the largest liquid scintillation detector using Cherenkov method, with about 20,000 tons of liquid scintillator and over 20,000 20-inch PMTs (seen from Fig. 2). There would be about nearly 5,000 PMTs from the Hamamatsu Photonics K. K. (HPK), and about 15,000 PMTs made by the Northern Night Vision Technology Co.

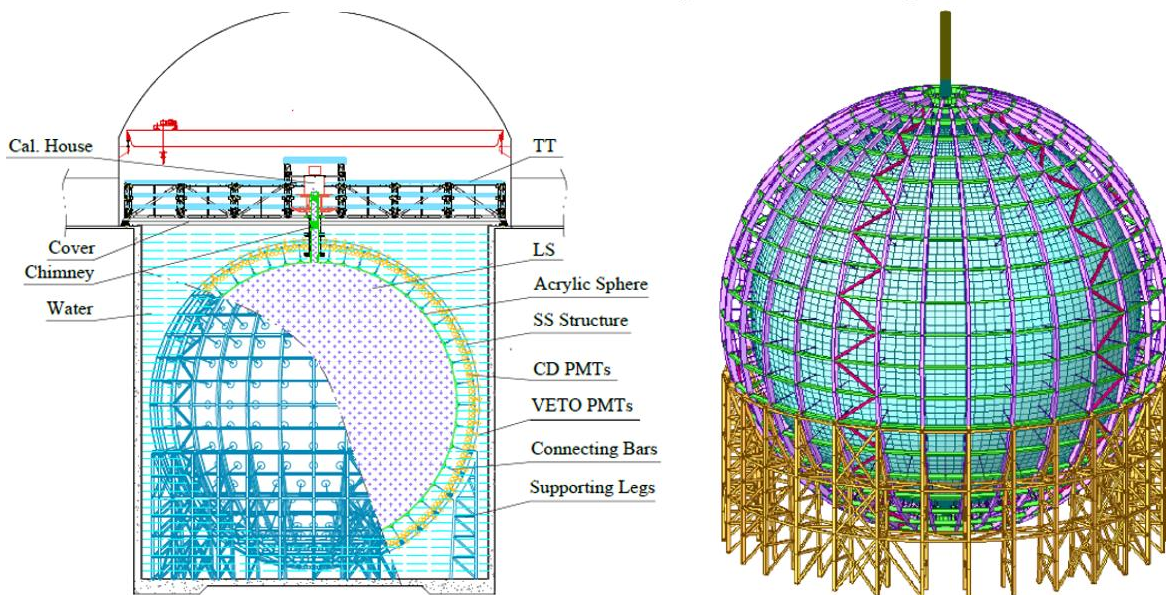


Fig. 2 Illustration of the JUNO Central Detector and Coverings.

The Online Scintillator Internal Radioactivity Investigation System (OSIRIS) is an independent detector from the main JUNO Central Detector (CD), in order to monitor the radio purity of the liquid scintillation (Fig. 3). It should guarantee that the special concentrations of ^{238}U and ^{232}Th in the liquid scintillation do not exceed the given limit of 10^{-15}g/g and 10^{-16}g/g , respectively. There will be an array of 64 20-inch HPK PMTs facing inside, and 12 same PMTs facing outside as the muon Veto detector. The central detector of JUNO has a similar design. The installation of the PMT array is expected to be completed in the second half of 2023, while the main project is estimated to be completed by the end of 2024, but OSIRIS and some other subsystems will start operation earlier.

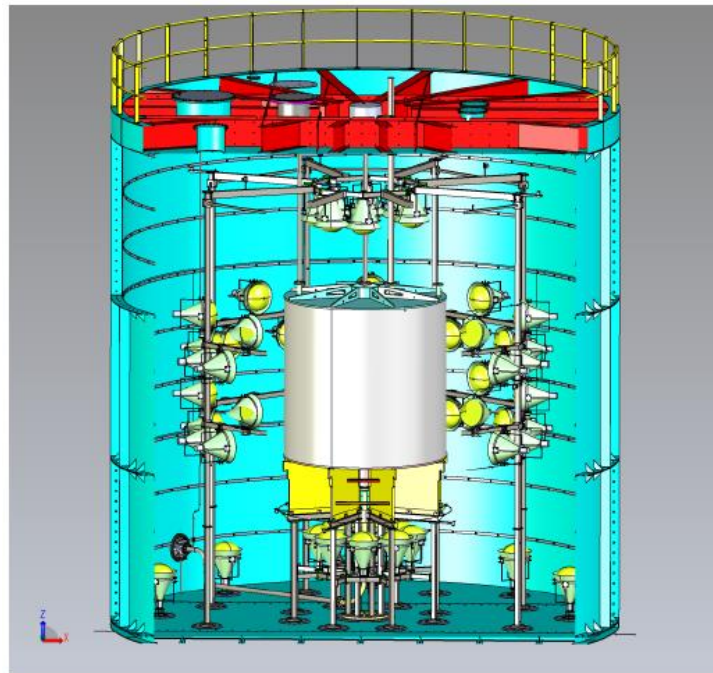


Fig. 3 Scheme of the OSIRIS detector.

4. Improvements and Suggestions

Slow aging property of the PMTs is one of the crucial features required by long-term operations. Long term stability ensures precise and reliable measurements. Although the production technology for 8-inch PMTs and other small PMTs has now developed quite well, the production process for larger PMTs is still in its early stages. However with larger photocathode area per unit area, larger PMTs are more effective in collecting neutrino interaction events, therefore the demand for them is also increasing. JUNO's PMT installation report has pointed out that, the performance of its 20-inch PMTs may vary with time, temperature, leak, gentleness, light, and several other unknown factors [31]. This property is reflected to varying degrees in both the PMTs from NNVT and HPK, with PMTs from the latter being relatively more sensitive and difficult to recover. At the same time, the technical details in installation and construction can also lead to a significant gap between the theoretical effect of PMT and the actual situation [32].

It should be considered that, with existing problems, the 20-inch PMT cannot be judged based on similar experience to other sizes and types of PMTs. They are still in a semi-black-box state, at least after sealing and their installation. In this situation, there is an urgent need to find new explanations to uniquely consider each problem. Specific comprehensive and detailed retesting and checking should be conducted in the circumstances. PMT focuses on extremely weak photon signals and is evidently very sensitive to external interference. Therefore the entire process for PMT, from production to installation, should avoid any unnecessary interference, including exposure, collision, squeezing, high humidity, high temperature, etc. In addition, for scintillation method, there is still room for improvement in the structure of PMT. In the future, the implementation of photomultiplier tube can also have more options besides dynode and MCP type.

Neutrinos are known to have very weak interactions with other materials, thus their signals are very rare and precious. However, paradoxically, the detectors need to be as sensitive as possible to detect very rare photons and electrons produced by the neutrino reactions, but they also need to be as insensitive as possible to particles not generated by neutrino reactions (e.g., thermoelectrons), to reduce the impact of very small fluctuations and disturbances. Therefore, the identification of signals collected by the detector array has become one of the core topics of the neutrino experiments. At present, the filtering algorithm of data collecting and integrating units is mainly aimed at the

background noise outside the target neutrino sources. For example, the role of OSIRIS in JUNO is to filter the influence of atmospheric and cosmic neutrino rays when detecting nuclear power plant neutrinos. For example, the Veto PMTs facing outside in JUNO are used to filter the influence of atmospheric and cosmic rays when detecting neutrinos from nuclear power plants, while the role of OSIRIS is to monitor possible interference from inner liquid scintillation [30]. But for detectors themselves however, other types of noises still exists and cannot be applied with current background noise analysis. For PMTs used in the scintillation method, their quality and stability should be carefully inspected before installed on the array. The on-going tests of PMTs show that, after long-term storage and transportation, previously qualified PMTs have become unstable once again, their variations are thought to be irregular. One manifestation of this anomaly is on the dark control rate, the core function of PMT. The DCR exhibits abnormalities in either short or long periods of time. In some cases, the value can rise above 1,000 kHz [33]. The self-generated signal without neutrino source is a type of interference, but it cannot be distinguished by the background noise detector.

This phenomenon may be related to the manufacturer's production process and design defects. Due to the impossibility of disassembling the PMTs in schedule for research, the changes in each single PMT are still in many black boxes. The lack of deep and further researches is particularly evident for the MCP-type PMT from NNVN, as it is newly developed [34]. However, no relatively complete model or theory is already published to explain the cause for this phenomenon. The most possible reasons are at the level of speculation, while others are still postulates. Establishing a physical process model based on PMT structures, or at least an empirical model based on current data bases, will greatly improve the acceptance rate of PMT testing, and the accuracy of future neutrino detection.

5. Limitations and Prospects

After Pauli proposed the existence of neutrino, experiments on the properties of neutrinos have been carrying out for decades. However, although the three non-zero mixing angles can achieve a measurement accuracy of 4% -10% [35], and other parameters have been limited or prompted, some key properties of neutrino are still unknown or controversial. Whether all neutrino flavors are all massless, or at least some are massive, may lead to the development of the Standard Model of particle physics, or even the discovery of new physics beyond the Standard Model [36]. However, if more progress and breakthroughs can be made in theory and detection, neutrinos can make great contributions not only to particle physics, astrophysics and cosmology, but also to nuclear physics, geology and material science. More importantly, and more practically, the corresponding statistics and data science have been developed for neutrino detection. The ideas of machine learning and optimization are increasingly being used to identify real neutrino signals and improve algorithms. Automated detection programs are considered to have great potential for future development. Data models based on detector properties may also be used to track the stability of long-term experiments. This can improve the working environment of the detector, reduce interference, improve accuracy and reliability, and extend the lifespan of detectors.

The cost of building a neutrino detector is also one of the difficulties in such researches. For example, the Super-Kamiokande Experiment consists of a cylinder tank with diameter 39m and height of 42m, with capacity of 50,000 tons of pure water [28], in order to compensate for the extremely small rate of neutrino interactions. Even though most of the current similar detectors make full use of the existing space, such as underground mines and the neighboring artificial neutrino sources, the costs for their construction and maintenance are still high compared with their use time. In 1974, Daniel Freedman proposed a method to measure a low-energy neutrino interaction with only one atomic nucleus. The probability of event is roughly scale with the square of the neutron count of the nucleus [37]. According to a report in 2017, seen from Fig. 4, the researchers of Oak Ridge National Laboratory have overcome the difficulties in this theory, and have already started the preliminary tests of miniaturized of neutrino detector [38]. The experimental results are currently

positive and supportive. If the miniaturization of neutrino detector can be realized, the detection of larger scale in neutrino research will become practical.

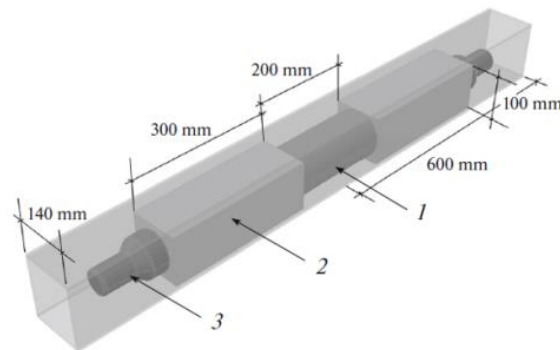


Fig. 4 Illustration of the small-volume detector.

6. Conclusion

Although the neutrino research still has many doubts and difficulties in both theory and detection technology, the current development has showed that, the future of neutrino research is bright and promising. This study briefly introduces the discovery of neutrinos, some important characteristics that have either been proved in experiments or not, and the doubtful conflicts which still exist between the theory and experimental results. Several detection methods (radiochemical, Cherenkov and scintillation) have been developed and used widely in neutrino detection experiments. Still, there are some difficulties in practice, the JUNO project which under construction is taken as a specific case to discuss. The photon-multiplier tubes are the most important instruments in detectors. Their use can be improved, especially for the newly developed and applied 20-inch types. Although many shortcomings of 20-inch PMTs are found in the testing program, there is still great potential for development after some improvements. Meanwhile, some clues that have been discovered during testing point to potential technical issues that may arise in future detection. These problems can be solved by developing more advanced algorithms and improving judgment criteria.

The future of neutrino detectors is predicted to be miniaturized. The bottleneck of related research has been solved, and the application is expected. Assuming that the cost of building a neutrino detector is greatly reduced, then the cost of relevant research will also decrease. The properties of neutrinos, which now are understood mainly through observations and experiments, are expected to be more complete. This paper does not expand in details on the neutrino theory or detection techniques, while only takes very few cases of projects for limited discussion and analysis. But however, some details mentioned in this paper about the implementation of neutrino detection, may provide ideas for future progress and improvements.

7. Disclosure

This paper have neither been submitted to any other journals nor delivered in any other conference.

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