Journal of Scientific Research
Banaras Hindu University, Varanasi

Vol. 61, 2017 : 141-171
ISSN : 0447-9483

NEUTRINO PHYSICS WITH NUCLEAR POWER REACTOR

Venktesh Singh[*], Manoj Kumar Singh, Abhishek Kumar, Akash Pandey,
M. K. Singh[**], N. Marimuthu, Kapil Saraswat, Deepika Grover and Vivek Sharma
Department of Physics, Institute of Science, Banaras Hindu University, Varanasi, U.P., 221005, India
[*]Email : venkaz@yahoo.com
[**]D.S. Kothari Fellow at BHU, Varanasi; [*]Corresponding author

Abstract

Reactor neutrinos have played very important role in discovering and studying the properties of neutrino such as neutrino oscillation, mixing angle θ_{13} etc. In coming future, they will also shed light in answering about neutrino mass hierarchy and the existence of sterile neutrinos. In this review article, we reviewed the results of different reactor neutrino based experiments, which are currently operational. Their earlier results and recent findings have been discussed. Presently there are several reactor neutrino experiments, which are either under construction, or being planned to get the solution of unsolved problems in neutrino and other sectors. However, this journey started with the aim of answering the fundamental question of particle physics, but these developments in studying neutrino physics have also started serving the society.

PACS: 29.40.-n; 14.60.Pq

Keywords: Neutrino Magnetic Moment, Neutrino Oscillation, Mixing Angle θ_{13}, Sterile Neutrino, Mass Hierarchy, Scattering Cross Section, Reactor Monitoring.

1. Introduction

Though the birth of neutrino had taken place just after the big bang; almost 14 billion years ago, but this particle remained unknown to the scientific community until 1930. Today we know that it is the second most abundant particle after photon in the whole universe. Before 1930, in the study of radioactive β – decay, physicists observed a continuous energy spectrum. However, it is unlike the discrete energy spectra, which is observed in a two-body radioactive decay. If there is only two-particle decay then there must be a sharp peak for beta particle to conserve the energy and momentum. Nevertheless, experimentally it was not observed. In 1930, Wolfgang Pauli hypothesized for the existence of a third particle (chargeless and massless and hence undetectable as told by Pauli), which might carry away the observed difference of energy and momentum between initial and final particles of β- decay [1]. In 1934 Enrico Fermi coined the name Neutrino (small neutron) for this third particle because, it is neutral; and then developed a theory of weak interactions. In the same year, Hans Bethe and Rudolf Peierls used Fermi theory to calculate the interaction cross section of Neutrino with matter. They came to know that it is of the order of barns, which led them to conclude that neutrino is practically undetectable [2]. However, after a series of experiments in 1956, Frederick Reins and Clyde Cowan succeeded in detecting the Neutrino in the process of inverse beta decay [3]. In this process $\overline{\nu}_e$ (electron type anti neutrino) created in nuclear reactor is captured by proton and resulted in emission of a positron and a neutron (n)

$$\overline{\nu}_e + p \rightarrow e^+ + n. \tag{1}$$

Further, in 1962 after six year of discovery of ν_e, Leon Lederman established the existence of another type of neutrino, which is called muon neutrino (ν_μ) [4]. After the discovery of third lepton called tau (τ), physicists again started expecting the existence of another associated third type of neutrino (ν_τ: Tau neutrino). In the year, 2000 by the DONuT collaboration this third type of neutrino (ν_τ) came into existence experimentally [5].

Then an obvious but an important question arose in the scientific community– whether more flavours or different types of neutrino exists or not? It was a big question for the physicist of that time. However, in the neutrino physics, a fundamental result came to light, after a precise measurement of decay width of Z-boson confirmed the existence of only three types of active neutrino flavors (ν_e, ν_μ, ν_τ). Nevertheless, existence of sterile neutrino could not be thrown out [6 - 8].

In the Standard Model, the neutrinos and corresponding antineutrinos are massless and to conserve the lepton number they cannot change their flavors. But recent studies, show the existence of neutrino mass and flavor oscillation hence, the Standard Model of particles physics and neutrino physics needs to be modified. Therefore, study of neutrinos can lead to more generalization of the Standard Model [9 - 10].

Now, as we know that there are many sources of neutrino such as stars, nuclear reactors, supernova explosion, solar neutrino, atmospheric neutrino, geo neutrino, radioactive materials etc. However out of these sources, the reactor neutrinos are the best. With the help of reactors almost all types of issues related with neutrino physics such as measurement of the smallest mixing angle (θ_{13}), determination of mass hierarchy, solving the solar neutrino puzzle, issue related to the existence of sterile neutrinos, neutrino oscillation etc. may be solved [10]. Among all of these issues, for the study of neutrino oscillation, reactors play a very good role. In coming time, the above listed problems may be resolved with the help of reactor neutrinos based experiments.

Through this paper we review the current status and obtained results of the above mentioned neutrino issues, with the help of reactor neutrinos based experiments from Double Chooz, RENO, TEXONO and Daya Bay. Finally, we conclude this study by explaining the possible role that neutrino may play for our society.

2. Physics studies through reactor neutrino

2.1 Criterions for reactor neutrino experiments

The result of any experiment is completely dependent on the experimental setup. If we use different type of setup then we will also get different type of results. Similar thing also happens in case of reactor neutrino experiments. Some experiments are able to measure very precisely some property of neutrino while, other experiments measure some other property very precisely. This means, that every reactor experiment have their own criteria of working.

Today we have both short baseline (~1km) and long baseline (~100-1000 km) reactor neutrino experiments. Currently, three main reactor experiments (Double Chooz [11], RENO [12], and Daya Bay [13]) are going on and looking for the antineutrino disappearance. These are very sensitive for the measurement of third mixing angle θ_{13}. All of these experiments use Gadolinium (Gd) doped liquid scintillator target in their detector. Also this target is surrounded by a non-doped scintillator for the purpose of detecting all of those gamma rays which came out after the neutron capture process on Gd. For the detection of antineutrinos, the target in each of the experiments is made up of liquid scintillator loaded with 0.1% Gd. All the antineutrino events can be identified by using a coincidence between the fast coming positron signal and the delayed signal, which are coming from the neutron capture on Gd. In addition, all of the above three experiments, for reducing the uncertainty from reactor flux, make use of two detectors, one is placed near the neutrino source and the second one is far from the source.

The Double Chooz experiment is the successor of earlier CHOOZ experiment [14]. It has two reactors of 4.25 GWth separated at a distance of 140 meter. It uses two detectors, which are at 400 meter (near detector), and 1050 meter (far detector) distances from the reactor. Both detectors are identical and consist of gadolinium-doped liquid scintillators. Both are placed around the reactors to measure the disappearance of antineutrino. Of the two detectors, the far detector is situated inside a hill to obtain a 300-meter water equivalent of shielding from cosmic muons. The near detector is under a tunnel, which is able to provide a shielding of 120-meter water equivalent. The reason behind using identical detectors (identical in design and materials of the target) is to minimize the uncertainties in measurement of efficiency, for the reduction of cuts in the final analysis and to reduce the background at the negligible level. These detectors are also capable to minimize the problems, which may arise due to radioactivity, because in them there have been added buffer volume and during making their components caution has been taken in using minimum radioactive materials. Due to this, very less number of analysis cuts are enough and hence the contribution to the systematic uncertainty is very less.

Reactor **E**xperiment for **N**eutrino **O**scillations (RENO) is a short baseline reactor neutrino oscillation experiment. RENO also has two identical near and far detectors. The near detector is placed at 294 meter and far detector at 1383 meter from the Hanbit nuclear power plant, to observe the $\overline{\nu}_e$ produced by six reactor cores [15].

Daya Bay reactor neutrino experiment is established in Daya Bay, which is 52 km northeast from Hong Kong and from Shenzhen it is 45 km east. The experiment uses eight detectors for detecting antineutrinos and these are situated at three places within 1.9 km of total six reactor cores [17]. Every detector is filled up with liquid scintillators of ~20 ktons, which consist of linear alkylbenzene doped with gadolinium (Gd). These detectors are covered by photomultiplier tubes (PMTs) and proper shielding [151].

In a comparative way, the parameters related to the currently working reactor antineutrino experiments have been given in Table 1. This table consists of their thermal power, distances of near and far detectors, shielding (in m. w. e: meter water equivalent), mass of target in detector and expected sensitivities.

2.2 Reactor monitoring through flux of ν_e

The reactor neutrinos produce a very huge flux of $\overline{\nu}_e$ along with the production of very less amount of ν_e. The production of ν_e occurs through:

1. The electron capture by fissioning products
2. Inverse beta decay of fissioning products
3. The neutron activation on the used fuel rod materials, also by the construction materials (used in making the core of reactor) [18].

These ν_e can be detected properly by flavor dependent charged-current interactions (ν_eNCC). The calculation of flux of ν_e is completely dependent upon reactor neutron spectra (must be properly modeled) and on the amount of loaded materials; due to this dependency there exists only a few percent of statistical error.

The measurement of such monoenergetic ν_e flux and their detection methods have found possible application in the monitoring of reactor operation. This monitoring of reactor takes place by monitoring of unwarranted plutonium production during the operation of nuclear reactor [19]. This production of plutonium takes place due to the β-decays following ^{238}U (n, γ) ^{239}U. The cross section of it increases very largely at high energy (> 1 eV), but the ν_e produced through the (n, γ) are thermal [20].

The neutron spectra, coming from reactor core, can be modified through making use of cooling water and by control rod optimization, without any kind of hindrance to the fission rates. With the monitoring of thermal power output, the excessive plutonium production can be made undetectable. By the measurement of changes in neutron spectra, through the time variations of ν_eNCC event rates, one can monitor the ^{239}Pu accumulation rates.

2.3 Neutrino Magnetic moment

Since a long time, the physicists were in search of getting the answer experimentally for the existence of neutrino magnetic moment. Based on current experimental results, it has been confirmed that the neutrino do oscillations and hence due to their oscillation they posses mass too. This makes clear that neutrinos have magnetic moment. However, its value might be very small and it depends whether the neutrino mass is of Majorana or Dirac. Suppose if, neutrino is Dirac mass then, under the standard model interactions, the value of neutrino magnetic moment is ~ 3×10^{-19} (m_ν/eV) in Bohr magnetons (μ_B). This value may be more in the case of neutrino interactions beyond the standard model. The measurement of neutrino magnetic moment will play an important role [21]. In the proper understanding of the mass mechanism of neutrino.

In Table 2, we have shown the upper limits of neutrino magnetic moment obtained from earlier and present experiments. Of them the most current result was obtained by MUNU collaboration [26] using the reactor (Bugey) neutrinos and by the TEXONO collaboration [27] using Kuo-Sheng reactor neutrinos. Actually the result obtained by MUNU, is an improvement in the earlier obtained upper limits by Rovno [30] and Super Kamiokande experiment [25].

However, these values of neutrino magnetic moment are completely model dependent. These limits cannot be compared in a direct way. As neutrinos mix together, in which different flavors (ν_e, ν_μ, and ν_τ) have different contributions in different cases of reactor, solar and other experiments. However, it is the short baseline experiments (relative to E_ν (energy of neutrino)) using terrestrial neutrinos, which are originally produced as ν_e or $\overline{\nu_e}$ (anti-electron neutrino), have very less chance for flavor oscillation. Also depending on the energy of neutrinos, the long baseline experiments can be almost free of flavor oscillation of neutrinos and therefore they can be used for this purpose.

Now, as we know that neutrinos are found in three possible mass Eigen states and neutrino magnetic moment interaction occurs because of mass Eigen states. Therefore, after the ν_e interaction with photon it may reach into any possible three final states. For Dirac neutrinos, we have:

$$\mu_e^2 = \sum_i |U_{ie}|^2 \mu_i^2. \tag{2}$$

Where, μ_i is the Magnetic moment in the mass Eigen state basis and $|U_{ie}|^2$ = Entries in the Maki–Nakagawa–Sakata (MNS) matrix.

The magnetic moments are the diagonal elements of the MNS matrix. Nevertheless, if they are not so (which happens only for the existence of transition) then Eqn. (2) must be expanded for including the transition moments. In addition, one has to consider this transition moment for the case of Majorana neutrinos. Now, if we consider the case of scattering of any ν_e or $\overline{\nu_e}$ into any type of neutrino (ν_e, ν_μ, and ν_τ) through the magnetic moment, then without taking into consideration of neutrino mass Eigen states, we can compare the results of nuclear magnetic moment obtained from reactor neutrinos, tritium source and beta-beams.

The best possible way for making improvement in the limits of nuclear magnetic moment (or detecting it) requires three conditions, which must be fulfilled:

1. The spectrum of neutrino source must be understood in a very good manner.
2. One should be able to measure the electron recoil in the lowest possible energy region.
3. Neutrino flux of very high intensity.

Use of large Tritium source with a very low threshold Time Projection Chamber (TPC) detector is a very good idea for making improvement in the limits of neutrino magnetic moment. As the main advantage of using this configuration is that the flux of neutrino will be well known (neutrino spectrum will be well understood) and at low recoil energy large number of counts can be obtained. With this configuration, one can obtain the value of neutrino magnetic moment very sensitively to a few $\times 10^{-12}$ μ_B [21].

Beta-beam is a very good method to produce a very intense, well collimated and a pure beam of neutrino [31]. This method uses radioactive nuclei, which decay by β-decay. Very important benefit of using this method is that the spectrum of neutrino will be understood deeply. This method has been proposed by Volpe to produce the low energy neutrino from beta beams [32]. The beta beam method is very new and now plans are underway to get good results for neutrino magnetic moment using it [33]. However, this method has the limitation of production of neutrino flux, since to reach the current limit of few $\times 10^{-11}$ μ_B requires approximately 10^{15} ions/second. Using higher flux of neutrino one can get a much better result of neutrino magnetic moment.

In case of reactor neutrino, though we get a very intense neutrino flux, but still it has the limits of $\mu_\nu \leq 10^{-10}$ μ_B. As the recoil spectrum obtained from reactor is not well understood below ~ MeV region. Therefore, if one wants to improve the upper limit of neutrino magnetic moment then it is necessary to have a deep understanding of low energy part of the neutrino spectrum.

The GEMMA spectrometer at the Kalinin Nuclear Power Plant have provided most recently and worldwide best upper limit of 2.9×10^{-11} μ_B at 90% confidence level for the neutrino magnetic moment [28].

2.4 Neutrino Electron elastic scattering

The Savannah River Experiment was an initiative in doing the measurement of neutrino-electron elastic scattering experiment with reactor [34]. It is a very simple and purely leptonic weak process, which is capable in testing of standard model (SM) of electroweak interactions. This can also be used in measuring the electromagnetic properties of neutrinos, such as neutrino magnetic moment.

With the accelerator the neutrino-electron scattering has been studied, for many generations by making use of mostly ν_μ ($\overline{\nu_\mu}$) [35, 36]. In that, it was found that $Q^2 \sim 10^{-2}$ GeV^2 (Q: Four momentum transfer) and up to ± 3.6% accuracy the electroweak angle ($Sin^2\theta_w$) was probed. Instead of ν_μ, by making use of ν_e, the interaction has also been studied, at the accelerators of medium energy and at power reactors [31-34] [42].

$$\nu_e(\bar{\nu}_e) + e^- \rightarrow \nu_e(\bar{\nu}_e) + e^- \tag{3}$$

This plays an important role in making detection of solar neutrinos and from that, using standard model ν_e – e scattering cross section, it can be very easy to obtain the neutrino oscillation parameters [37]. This interaction can occur through the charge current (CC), neutral current (NC) and their interference (Int) [38], as shown in Figure 1. The source of matter oscillation, inside the sun (solar neutrinos) is the interference effect in ν_e – e scattering [39]. Findings of different experiments on ν_e – e and $\bar{\nu}_e$ –e scattering cross-section have been given in Table 3.

Now, for the ν_μ ($\bar{\nu}_\mu$) – electron, elastic scattering the differential cross section for the case of standard model, in the laboratory frame (means for NC only) can be given as [47] [48]:

$$[\frac{d\sigma}{dT}(\bar{\nu}_\mu e)]_{SM} = \frac{G_F^2 m_e}{2\pi}[(g_V \pm g_A)^2 + (g_V \mp g_A)^2.(1-\frac{T}{E_\nu})^2 - (g_V^2 - g_A^2).\frac{m_e T}{E_\nu^2}]. \tag{4}$$

Where, E_ν is the energy of incident neutrino energy; G_F is the Fermi's coupling constant; T is the kinetic energy of the recoil electron; g_V is the vector coupling constants; g_A is the axial-vector coupling constants and the upper (lower) sign refers to the interactions with ν_μ ($\bar{\nu}_\mu$).

For the case of ν_e ($\bar{\nu}_e$) - electron scattering [38] differential cross-section can be given as:

$$[\frac{d\sigma}{dT}(\bar{\nu}_\mu e)]_{SM} = \frac{G_F^2 m_e}{2\pi}[(g_V - g_A)^2 + (g_V - g_A + 2)^2.(1-\frac{T}{E_\nu})^2 - (g_V + g_A + 2).\frac{m_e T}{E_\nu^2}]. \tag{5}$$

The values of the coupling constants assigned by standard model are given as:

$$g_V = -\frac{1}{2} + 2\,Sin^2\theta_W \tag{6}$$

$$g_A = -\frac{1}{2} \tag{7}$$

Where, $Sin^2\theta_W$ is the weak mixing angle. Therefore, in terms of $Sin^2\theta_W$ the differential cross-section for the case of standard model can be expressed as:

$$[\frac{d\sigma}{dT}(\bar{\nu}_e e)]_{SM} = \frac{G_F^2 m_e}{2\pi}\{4(Sin^2\theta_W)^2[1 + (1-\frac{T}{E_\nu})^2 - \frac{m_e T}{E_\nu^2}]$$
$$+ 4\,Sin^2\theta_W[(1-\frac{T}{E_\nu})^2 - \frac{m_e T}{2E_\nu^2}] + (1-\frac{T}{E_\nu})^2\} \tag{8}$$

As we know that the event rates (R_{expt}) of any experiment represents the observable is in the unit of kg $^{-1}$ day^{-1}, and for the case of standard model, the predicted rate can be given as:

$$R_{SM}(\nu) = \rho_e \int_T \int_{E_\nu} [\frac{d\sigma}{dT}]_{SM} \frac{d\phi}{dE_\nu} dE_\nu dT . \quad (9)$$

Where: ρ_e = Electron number density per kg of target mass and $d\phi/dE_\nu$ = Neutrino spectrum.

Now, the cross section ratio

$$\xi = \frac{R_{expt}(\nu)}{R_{SM}(\nu)}, \quad (10)$$

can be used in probing the new physics in a model independent way. For the case of interference effects, measured rate are as follows:

$$R_{expt} = R_{CC} + R_{NC} + \eta . R_{Int} . \quad (11)$$

For the case of charge current – neutral current interference in ν_e ($\bar{\nu}_e$) – electron in standard model, it is destructive which means η(SM) = −1. With this, any deviation, either in sign or in magnitude of interference effect (η) can be measured.

From Eqns. (8) and (9), the expected accuracies on $Sin^2\theta_W$ (represented as, Δ [$Sin^2\theta_W$]), which are related with the experimental uncertainties in cross section ratio ξ (represented as Δ [ξ]) by:

$$\Delta[Sin^2\theta_W] \approx \begin{cases} 0.15.\Delta.[\xi(\bar{\nu}_e e)] \\ 0.35.\Delta[\xi(\nu_e e)] \end{cases} \quad (12)$$

respectively, for the reactor $\bar{\nu}_e$ –e [40] and accelerator ν_e - e experiments [31-32]. Similarly, the sensitivities of $Sin^2\theta_w$ and (g_V, g_A) from reactor $\bar{\nu}_e$ - e are expected to improve as for the case of ν_e - e measurements. The relative strength of the charge current, neutral current and their interference are in the ratios (normalized to R_{expt} = 1) as:

$$(R_{CC} : R_{NC} : R_{Int}) \sim \begin{Bmatrix} (0.77{:}0.92{:}0.69)\, for \bar{\nu}_e - e \\ (1.77{:}0.16{:}0.93)\, for \nu_e - e \end{Bmatrix}. \quad (13)$$

The standard model was tested and the value of $Sin^2\theta_w$ was also measured with accelerator experiments in both regions, high energy (Q^2 > GeV^2) as well as low energy (Q^2 < 10^{-6} GeV^2); and the value of $Sin^2\theta_w$ derived from high energy region was almost 3σ higher than the predicted value of standard model (SM) [47] [49]. The cross section ratio defined in Eqn. (10) can be obtained using a minimum χ^2 fit, which is defined as

$$\chi^2 = \sum_{i=1}^{N_{bin}} \frac{[R_{\exp t}(i) - \xi . R_{SM}(i)]^2}{\Delta_{stat}(i)^2}. \tag{14}$$

Where, R_{SM} (i) = Expected event rates at i^{th} bin by SM; R_{expt} (i) = Measured event rates at i^{th} bin by the experiment and Δ_{stat} (i) = Corresponding statistical error.

The TEXONO collaboration applied the same procedure for the case of reactor OFF, as they adopted for the ON case, only the earlier predicted background was reduced, and they worked on the resulting residual spectrum [40]. The best fit of the residual spectrum with Eqn. (14) have given:

$$\xi \text{ (OFF)} = 0.03 \pm 0.36\text{(stat)}, \tag{15}$$

at χ^2/dof = 10.3/9, which explains a good achievement in making control on the background subtraction. Taking into the consideration of systematic uncertainties and combining all reactor's ON and OFF data, which have been obtained from all period's data taking, the TEXONO collaboration derived the value of cross section ratio as

$$\xi = 1.08 \pm 0.21\text{(stat)} \pm 0.16\text{(sys)} \tag{16}$$

at χ^2/dof = 8.7/9. From here, it became clear that the result of measurement of $\bar{\nu}_e - e$ cross section was lying on the same plane as the prediction of standard model. The above obtained results demonstrate a probe to SM at $Q^2 \sim (3 \times 10^{-6})$ GeV^2 and at the same time TEXONO collaboration also represented the improvement attained by the earlier reactor neutrino experiments [37 - 38] [40] [42].

2.5 Neutrino oscillations

Neutrino oscillation is a quantum mechanical phenomenon. Under this phenomenon, a neutrino is created with a specific lepton flavour such as electron, muon, or tau and can be measured to have a different flavour. As neutrinos propagate through the space, probability of finding a particular neutrino at a particular place is changing periodically [50]. Bruno Pontecorvo [51-53] first time predicted this peculiar behaviour of neutrino in 1957 and later by Maki, Nakagawa and Sakata [54] therefore, the neutrino-mixing matrix is generally called as the PMNS matrix.

This property of neutrino has been observed by various experiments worldwide in several different contexts. It is found that this property of neutrino was the main cause of the solar neutrino problem. Observation of neutrino oscillation property confirmed that the neutrino has non-zero mass and originally zero neutrino mass was mentioned in the Standard Model of particle physics. This ignites interest of theoretical as well as experimental personals towards neutrino oscillation phenomenon [50]. Last year (2015) Nobel Prize for Physics has been awarded to Takkaki Kajita and Arthur McDonald for their significant contribution in neutrino physics and providing discovery of proof for neutrino oscillation [55].

Neutrinos can be found in a definite flavor such as ν_e, ν_μ, or ν_τ. However, if neutrinos have a finite mass state, the flavor composition of a neutrino could vary continuously as functions of the distance and neutrino's energy. This behavior of neutrino is called neutrino oscillation. In the framework of quantum mechanics, the assumption that a neutrino of a particular flavor need not be a state of a definite mass, but instead it could be a coherent superposition of several states of definite masses.

In the quantum mechanical framework, consider only two type of massive neutrinos ν_i; i = 1, 2 having different masses m_i. We know that the development of a function (ψ) with momentum p may be written as $\psi(t) = \psi(0)e^{ipL}$. Here we consider relativistic high-energy system of units where $\hbar = c = 1$. For relativistic neutrinos $p = \sqrt{(E^2 - m^2)} \sim E - m^2 / 2E$. Neutrinos acquires phase $\nu_i (L) = \nu_i (0).\ e^{-\frac{im_i^2 L}{2E}}$, as it, passes distance L in the vacuum and acquire additional phases when it passes in the matter, the so-called MSW effect [56] [57]. Further assume that the neutrinos flavour ν_e and $\nu_{e\alpha}$ are coherent superpositions of the states ν_i, i.e. $\nu_e = \text{Cos}\theta\nu_1 + \text{Sin}\theta\nu_2$, but orthogonal combination represents the other flavor neutrino $\nu_\alpha = -\ \text{Sin}\theta\nu_1 + \text{Cos}\theta\nu_2$, where parameter θ is the so-called mixing angle.

Consider a beam of neutrinos at initial distance (L = 0), it is pure ν_e having form

$$\nu_e (L) = \text{Cos}\theta . e^{-\frac{im_1^2 L}{2E}}\ \nu_1(0) + \text{Sin}\theta .\ e^{-\frac{im_2^2 L}{2E}}\ \nu_2\ (0). \tag{17}$$

Weak interactions will be used to check the purity of the beam at distance (L). Therefore, the projection of the ν_i back to the flavor basis ν_e and ν_α is necessary. Thus

$$\nu_e (L) = [\text{Cos}^2\theta .\ e^{-\frac{im_1^2 L}{2E}} + \text{Sin}^2\theta .\ e^{-\frac{im_2^2 L}{2E}}\ ]\ \nu_e(0) - \text{Sin}\theta\ \text{Cos}\theta\ [\ e^{-\frac{im_1^2 L}{2E}} - e^{-\frac{im_2^2 L}{2E}}\ ]\ \nu_\alpha(0). \tag{18}$$

The square of the amplitude of corresponding $\nu_e(0)$ will provide information about the probability of observing ν_e at a distance L. After simple algebraic steps, this becomes:

$$P\ (\nu_e \rightarrow \nu_e) = 1\text{- Sin}^2\ 2\theta\ \text{Sin}^2\ (\frac{\Delta m^2 L}{4E})\ \text{, and } P\ (\nu_e \rightarrow \nu_\alpha) = \text{Sin}^2\ 2\theta\ \text{Sin}^2\ (\frac{\Delta m^2 L}{4E}). \tag{19}$$

Where, Δm^2 (= $m^2_1 - m^2_2$) is the neutrino mass squares difference. If we place $\Delta m^2 \neq 0$ instead of $\Delta m^2 = 0$ as indicated in the standard model of particle physics, and θ

$\neq 0$ or $\pi/2$, the neutrino beam composition will oscillate as a function of L / E_ν with the amplitude $\sin^2 2\theta$ and the wavelength

$$L_{osc} = 4\pi.\frac{E}{\Delta m^2} \equiv L_{osc}\,(m) = \frac{2.48E(MeV)}{\Delta m^2(eV^2)}\ . \qquad (20)$$

Observation of neutrino oscillations sheds light in the generalization of the realistic case of three neutrino flavors and three states of definite mass is straight forward. The associated mixing is characterized by three mixing angles such as θ_{12}, θ_{13}, θ_{23}, with one possible CP violating phase δ_{CP}, and two mass square differences, Δm^2_{32} and Δm^2_{21}. The best measured values using current data are $\sin^2(2\theta_{12})=0.846 \pm 0.021$, $\sin^2(2\theta_{13})=0.093 \pm 0.008$, $\sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018}$, $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ eV^2$, and $\Delta m^2_{32} = (2.44 \pm 0.06) \times 10^{-3} eV^2$ (assuming $m_3 > m_2$) [58]. The neutrino mass hierarchy and the δ_{CP} value are still unknown.

At the beginning most of the reactor-based experiments were short-baseline ($L \leq 100$ m) experiments [59-66]. Although they were not able to observe neutrino-oscillation but they played an important role for the understanding of the reactor neutrino flux and spectrum. In the year 2000s, KamLAND experiment [67-69] – a reactor neutrino based experiment with enough precision showed that the long-standing problem of solar neutrino deficit is actually caused by neutrino oscillations. This experiment showed for the 1st time that the reactor anti-ν_e component is changing with L / E_ν and the most accurate mass-squared difference Δm^2_{21} value of that time.

The present reactor based experiments such as Daya Bay [70, 71], RENO [72] and Double Chooz [73, 74] measured the value of mixing angle $\theta_{13} \sim 8.9$ ($\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) $\pm$ 0.005 (syst.) [65] [149] [150]) with very high precision (5.2σ) and the measured value was unexpected from the earlier thoughts of many physicists [149]. In 2014 an updated result was reported by the Daya Bay collaboration [151] which used the energy spectrum for placing the bound on the mixing angle as $\sin^2(2\theta_{13}) = 0.090 + 0.008 – 0.009$. It is a matter of another achievement for Daya Bay, because by using its data for getting the signals of light sterile neutrinos they have exclusion of previous unexplored mass region too [152]. Recently Collaboration has presented a new best fit for mixing angle and mass difference values as [153] $\sin^2(2\theta_{13}) = 0.084 \pm 0.005$, $|\Delta m^2_{ee}| = 2.44^{+10}_{-11} \times 10^{-3}\ eV^2$. RENO collaboration announced in year 2012, a 4.9σ observation of $\theta_{13} \neq 0$, with $\sin^2(2\theta_{13}) = 0.113 \pm 0.013$ (stat.) $\pm$ 0.019 (syst.) [158-159]. In year 2013 RENO updated its earlier results and given [160] better result of $\sin^2(2\theta_{13}) = 0.100 \pm 0.010$ (stat.) $\pm$ 0.015 (syst.).

The first result of the Double Chooz collaboration was in the direction of a hint for a non-zero value of θ_{13} [155]. In year 2012, Double Chooz experiment measures θ_{13}, without excluding the concept of neutrino oscillation [156] and in year 2013 collaboration used delayed neutron capture on hydorgen measure the θ_{13} mixing angle [157] $\text{Sin}^2(2\theta_{13}) = 0.097 \pm 0.034$ (stat.) ± 0.034 (syst.). In 2014, from the data obtained in reactor off condition they measured the background and reported [155] the value of $\text{Sin}^2(2\theta_{13}) = 0.102 \pm 0.028$ (stat.) ± 0.033 (syst.). With this result they subtracted the background and systematic errors and then provide the result of $\text{Sin}^2(2\theta_{13}) = 0.090 + 0.032 - 0.029$ [154].

The planned reactor neutrinos based experiments, such as JUNO [75] and RENO-50 [15], have discovery potential and may shed light on the missing fundamental features of the oscillations, the neutrino mass hierarchy, and the phase δ_{CP} that characterizes the possible charge and parity (CP) violation. Although most of the neutrino oscillation results are explained by the three-neutrino assumption but few reactor antineutrino anomalies [86] cannot be explained with this assumption. If confirmed, they would indicate the presence of few more neutrino families such as fourth, or fifth, etc. called sterile neutrinos.

2.6 Search for the smallest oscillation angle

The atmospheric [76] and long baseline accelerator [77] based neutrino experiments measured the mixing angles of neutrino mixing. Unlike the Cabibbo–Kobayashi–Maskawa (CKM) matrix in quark sector [58], the mixing angle in the neutrino-sectors appears to be large, $\theta_{23} \sim 45°$. The solar neutrino and reactor neutrino based experiments such as KamLAND measured the mixing angle $\theta_{12} \sim 33°$. Therefore it was obvious to expect similar magnitude to the third mixing angle θ_{13}. To measure deficit of the electron antineutrino flux will give information about non-zero value of the third mixing angle and kilometer order reactor neutrino based oscillation experiments are the best suited for this purpose. The amount of the deficit is directly proportional to the value of $\text{Sin}^2 2\theta_{13}$. Through the reactor neutrino-based, experiment high precision results can be achieved.

Initially CHOOZ [78] and PALO VERDE [79], two reactor neutrino based experiments of the order of kilometers were constructed to measure θ_{13}. The distance of the CHOOZ detector from the twin core was around 1,050 m and it collected data until July 1998. The distances of the PALO VERDE detector were 750, 890 and 890 m from the 3 reactor cores and it took data until July 2000. However, unfortunately, none of them were able to observe the $\bar{\nu}_e$ deficit caused by θ_{13} oscillation and therefore only placed an upper limit of $\text{Sin}^2 2\theta_{13} < 0.10$ at 90% C.L. [78].

To know the precise value of θ_{13}, the scientific community developed the second-generation reactor neutrino based experiments such as Double Chooz [73], RENO [72] and Daya Bay [70]. The key parameters of such important experiments are summarized in Table 4.

We could say that the second-generation reactor neutrino based experiments were a great success. In a very short span of operation, Double Chooz, Daya Bay and

RENO, showed clear evidence of anti-ν_e disappearance at around kilometer baselines [70], [72 - 73]. Daya Bay experiment showed their best-fit value in 2015 as $\sin^2 2\theta_{13}=0.084 \pm 0.005$. Although, at present, the precisely measured θ_{13} value is now, the best among all three mixing angles. The KamLAND experiment shed light on the different oscillation component driven by θ_{13} and $|\Delta m^2_{32}|$, and pleased the best-fit frequency of the oscillation yields $|\Delta m^2_{32}| = 2.39^{+0.11}_{-0.10} \times 10^{-3}$ eV^2 considering normal mass hierarchy [80-81]. Up to the end of this year, Daya Bay experiment is expecting to measure both $\sin^2 2\theta_{13}$ and $|\Delta m^2_{31}|$ to precisions below 3% [82]. It seems that the longstanding issue of θ_{13} value is now successfully resolved. The unexpected large value of θ_{13} opens the new window for future experiments to observe the neutrino mass hierarchy and to measure the CP-violating phase in the leptonic sector [10].

2. 7 Determination of Neutrino Mass Hierarchy

At present, the values of $|\Delta m^2_{32}|$ and $|\Delta m^2_{31}|$ are almost known. Physics community does not know about their sign. The positive and negative sign will tell us about the neutrino mass ordering which is a problem of fundamental importance. Accurate determination of this parameter will shed some light on the measurement of the CP-violating phase, and on the neutrinoless double beta-decay experiments. It will certainly improve our understanding of the core-collapse supernovae. The information regarding neutrino mass hierarchy could be obtained by combining the medium baseline of around 60 km reactor $\bar{\nu}_e$ oscillation analysis with the long-baseline muon neutrino disappearance analysis [83].

JUNO [75] and RENO – 50 [15] are two proposed medium baseline reactor experiments with one of the goals to determine the neutrino mass hierarchy. JUNO experiment is under construction in the Kaiping city, China, and to be operational in 2020. The Yangjiang Nuclear Power Plant has six reactor cores of 2.9 GW$_{th}$ each and the Taishan Nuclear Power Plant has been planned four cores of 4.6 GW$_{th}$ each, both are under construction. It is expected that in operational mode all reactor cores together will provide the world's strongest flux of neutrino. JUNO will observe approximately 60 reactor $\bar{\nu}_e$ events per day. During the six year of continuous running, the expected $\bar{\nu}_e$ energy spectra with and without any background has been shown in Figure 2. For the determination of hierarchy and oscillation-parameters can be very effectively measured by the multiple oscillation structure as shown in the inset plot of Figure 2 [10]. The estimated sensitivity for the mass hierarchy determination will exceed 3σ value in first six years operation [84-86] and can be improved to 3.7 – 4.4σ [87].

The proposed RENO-50 experiment will be in the city of Naju, and will receive neutrino from six cores of the Hanbit Nuclear Power Plant having 2.8 GW$_{th}$ each and will be operational in 2021. It has similar sensitivity reaches as JUNO experiment. Both experiments, JUNO and RENO-50 have great potentials in the precisions better than 1% measurements of the neutrino oscillation parameters [88] and are important to guide the directions of next generation experiments as well as models.

3. Reactor antineutrino spectra

Antineutrinos are produced in the core of nuclear reactor through the decay of neutron rich fission fragments. A thermal neutron absorbed by the ^{235}U in the core of nuclear reactor and it fragments into ^{140}Cs and ^{92}Rb, along with these it produces few more neutrons and some energy around 200 MeV is taken away by the neutrinos, neutrons etc. It has been observed that ~ 200 MeV energy is released and six electron antineutrinos are produced. A nuclear reactor of 3GW thermal output will produce approximately 6×10^{20} electron antineutrinos per second.

Fission nuclei (^{235}U) have asymmetric fission fragments distribution into lighter and heavier nuclei usually peaked around atomic mass number 95 and 137, respectively; $^{235}U_{92} + n \rightarrow X_1 + X_2 + 2n$ where, X_1 and X_2 may most likely be $^{94}Zr_{40}$ and $^{140}Ce_{58}$. It can be seen from this reaction equation that left hand side uranium has 92 protons and 144 neutrons while in fragments on average 98 protons and 136 neutrons. It means that to reach stable matter nuclei have to convert on average 6 neutrons into 6 protons through beta decay and during each decays they will produce one electron antineutrino.

From nuclear reactor, almost pure (> 99.9%) electron antineutrinos are coming from fissions in ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu. In Figure 3, colored band is showing the uncertainty in the calculation. It has been observed [89 - 90] that the mean energy of the emitted electron anti-neutrino is around 3.6 MeV and therefore with this energy only electron antineutrino disappearance experiment can be performed.

From Figure 4 (a), it can be seen that production of almost all isotopes may be observed after four months of reactor operation except ^{239}Pu and ^{243}Am, which has fastest and slowest production rate, respectively. In production calculation of isotopes, we must consider some corrections because the percentage of the different primary isotopes changes with time and different fuel components yield different spectra. Neutrino experiments are receiving information related to the Figure 4 (b), from the nuclear power companies, who understand it very well. They are using information to calculate a time dependent rate of neutrino with energy including ~ 5% isotopes uncertainty in their yield.

4. Search for the existence of Sterile Neutrinos

Until today, based on experimental data, a question remains as before “clearly unanswered”. The question is that, are there other type of neutrinos except these three ν_e, ν_μ, and ν_τ. By the decay width measurement of Z-boson it came out that, there can be 2.92 ± 0.05 types of active neutrino flavors [91]. Hence, it is obvious that it refers for the existence of only three neutrino flavors. Not only this, but also explains the neutrino oscillation property using any of the solar, reactor, accelerator or atmospheric neutrino experiments. It was found that the concept of three neutrino flavors is very much obvious and true. Because, it was observed that for two mass squared difference Δm^2_{21} and Δm^2_{31} (whose values are ~ 7.6 × 10^{-5} eV^2 and ~ 2.4 × 10^{-3} eV^2, respectively) there exists only two oscillation frequencies. However, LSND – a Liquid Scintillator Neutrino Detector experiment firstly given indication for the breakthrough of the existence of only 3-neutrino flavors. The result obtained from the LSND collaboration, were very far from the above values of $\Delta m^2_{21}$and Δm^2_{31}. Though LSND collaboration has observed an excess of different type of event in $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ appearance channel [92] [93]. This event was represented as an oscillation with $\Delta m^2 \sim 1$ eV^2. This result of LSND experiment marked question on the existence of only three neutrino flavors and therefore it is known as LSND anomaly. From this LSND anomaly, it came out that, there could exist some other types of neutrinos in nature, with masses m ~ 1 eV. These additional neutrinos cannot go through weak interactions; because, they cannot couple to Z- bosons unlike the active three neutrino (ν_e, ν_μ, ν_τ). Therefore, they are called as sterile neutrinos and may play role in solving problems related to cosmology and astrophysics [94-97].

Other than some indications by other experiments, which support the LSND anomaly, so far it is not observed in any other experiment. Nevertheless, there are some strong motivations also towards the light sterile neutrinos from different experiments such as:

1. The MiniBooNE experiment (using accelerator neutrinos) provides similar findings as LSND, by observing event excess in the $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ appearance channels [98 - 99].
2. The GALLEX and SAGE experiments (using ^{51}Cr, ^{37}Ar neutrino sources) observed approximately 24% event deficit in the ν_e disappearance channel. This is also known as Gallium anomaly [100 - 101].
3. From the reactor experiments, currently it is observed that there is an increment in the antineutrino flux ($\overline{\nu}_e$) than the predicted one. It is observed that there is approximately 4-6% deficit between measured and predicted $\overline{\nu}_e$ flux obtained from reactors. This is called as reactor-antineutrino anomaly [102-105] [59-65].

The above-mentioned anomalies can be explained either by assuming the presence of light sterile neutrinos or by accepting that the theory of neutrino physics is still imperfect. In addition, this has been observed from some other appearance and disappearance events searches that the most preferred region ($\Delta m^2 \sim 1 eV^2$ and $Sin^2\theta \sim 0.1$) needs modification [65] [106-118].

These experimental observations lead the scientific community to think and hence propose of several neutrino oscillation experiments [119]. These include short baseline reactor $\overline{\nu}_e$ experiments (Osc SNS, LAr-TPC, LAr1-ND) [120-128] and VSBR (very short baseline reactor) $\overline{\nu}_e$ experiments (PROSPECT [129], NuLat [130],

NUCIFER [131], [132], STEREO [119], DANSS [133], NEUTRINO-4 [134], [135], POSEIDON [136],SOLID [137], HANARO [138]). To solve the LSND anomaly, it needs that the oscillation pattern in (L / E) must be observed. In this connection very short baseline reactor (VSBR) neutrino experiments can be very effective; though the VSBR experiments have many challenges such as:

1. For getting the minimum oscillation inside the core of reactor, the reactor must be very compact in size.
2. Since the detectors cannot be placed deep inside the earth (in VSBR experiments), therefore the cosmic ray background is very high. Not only this but presence of fast neutrons and Gamma rays are more difficult to determine because, they produce with $\overline{\nu}_e$. To resolve them proper shielding is required.
3. In VSBR experiments the detectors used are normally Gd or ^{6}Li (solid or liquid) loaded scintillators. In order to reduce the background and enhance the position resolution some of the detectors are segmented in small cells. However, it has also been observed that more cells are inactive. The calibration and controlling mutual variation of such detectors is very difficult. In addition, to measure the $\overline{\nu}_e$ spectrum, it requires sufficient light yield for all segmented detectors.

Apart from the above-mentioned challenges, the VSBR neutrino experiments (1-8 MeV energy range and 5-20 m baselines) are still able to give us the answer of existence of light sterile neutrinos and their oscillations.

5. Neutrino Coherent Scattering

Coherent neutral-current (NC) neutrino-nucleus scattering (CENNS) was first predicted theoretically in 1974 [1] but has never been observed experimentally. To know the physics beyond the standard model, coherent neutrino-atom and neutrino-nucleus scattering play a very crucial role [139-141]. Of these scattering processes, one of the most important out come observed is the cross section. Not only this, but neutrinos can scatter coherently with the nucleons as well as with the atom itself.

The condition of coherence requires sufficiently small momentum transfer Q to the nucleon so that the waves of scattered nucleons in the nucleus are all in phase and contribute coherently i.e. the Q must be smaller than the inverse of nucleus or atomic size ($QR \leq 1$). While interactions for neutrino energies in MeV to GeV range have coherent properties. Neutrinos with energies less than 50 MeV are most favorable, as they largely fulfill the coherence condition in most target materials with nucleus recoil energy of tens of keV. Generally, it is observed that the typical size of almost all nuclei is in the range of 25 MeV to 150 MeV. It is found that solar, supernovae, reactor and artificial sources of neutrino follow this condition very strictly [142].

However, after its prediction, the coherent neutrino nucleus scattering still requires its experimental confirmation. This is also one of the very challenging tasks, which physicists from all over the world must solve, in order to probe the physics beyond the standard model.

In neutrino-nucleus coherent scattering (NNCS) process, the associated wavelength of neutrino is of the order of nucleus dimension and therefore it interacts with the whole nucleus, and hence provides an interaction cross-section, which is directly proportional to the square of weak charge, which is given as

$$\frac{d\sigma}{d(Cos\theta)} = \frac{G^2}{8\pi}[Z(4Sin2\theta_W - 1) + N]^2 E_\nu^2 (1 + Cos\theta). \tag{21}$$

Where, θ = Scattering angle, Z = Number of protons in the target nucleus, N = Number of neutrons in the target nucleus, G = Fermi constant, θ_w = Weak mixing angle, and E_ν = Neutrino energy.

However, NNCS interaction cross section is balanced by very small recoil energies, which constitute the only observable signal of such interaction process. Generally, such recoil energy is inversely proportional to the atomic mass A, and [145] can obtain its average value

$$< E_r > = \frac{2}{3} \frac{[\frac{E_\nu}{MeV}]^2}{A} keV. \tag{22}$$

This shows that the value of recoil energy is of the order of few keV or less. Such small value of recoil energy is the one of the challenging reasons and culprit for not observing the NNCS still.

The detection of NNCS will not only shed light on specifying the fundamental elements of standard model but it has some other important applications too such as

1. The neutrino flavor independent property of NNCS; allowed us to measure or monitor the coming neutrino flux by oscillation experiments and supernova explosion.
2. For the search of sterile neutrinos [146].
3. In nuclear reactor monitoring [147].

We all know that reactors can provide a very high flux of neutrinos ($\Phi > 10^{12}$ cm^{-2} s^{-1}) with the energy of about 10 MeV. That is the reason reactor power plants are recognized as a good source for NNCS measurements. Also for many different reactor designs, it is possible to do the relative measurements and background characterization during reactor-OFF. The recoil energy of neutrinos produced by ^{235}U and ^{239}Pu is 243 eV and 207 eV, respectively but the recoil energy spectra extend up to ~ 6 keV. Currently near about 56 interactions / (kg-day) are being observed for neutrino-nucleus coherent scattering off Argon nuclei [148].

For the proper detection of NNCS recoil energy spectrum, the detection technology used is very important because in low recoil energy region dark matter and NNCS informations may interfere with each other. Various technologies are floating in the market but the dual phase detectors technique based on noble gases seem to be able to fulfill almost all the requirements of the experiment. However, using liquefied noble gas is more useful in place of gaseous or solidified, because of its higher density. Inside the detector, the recoil energy produces a weak ionization signal in the liquid. With the help of electric field signal will be send into the gas region. In the gas region, it starts accelerating and during this, it interacts with the gas molecules, hence produces excitation, and finally achieves a proportional scintillation, which is detected by the photomultiplier tubes (PMTs).

The most suitable noble gases for dual phase ionization detectors are Ar and Xe. Of them, though Xe has large cross section for coherent neutrino scattering but at the same time, it has lower average recoil energy than Ar. Due to which the average number of primary electrons produced in Xe will be lower than Ar. Therefore, it is Argon, which is used for target medium not Xe, and Ar is much cheaper than Xe.

Various groups around the globe are trying hard to observe neutrino – nucleus coherent scattering (NNCS) phenomenon including TEXONO group [143]. This collaboration has also indicated that with the result of detecting this NNCS, they will be able to make improvements in the limits of neutrino magnetic moment (NMM). In the search of supernova neutrino, the NOSTOS (A novel low-energy i.e. a few keV, neutrino-oscillation experiment) collaboration is also in the path for detection of NNCS [144].

In future, if it is possible to make use of larger (approximately 10 kg) liquid Ar detector at any nuclear power plant, then a few hundred events/day from NNCS interactions can be observed. If the signal of neutrino follows the OFF period of reactor then it would provide the first observation ever of the neutrino-nucleus coherent scattering interaction [145].

6. Role of neutrino for the society

The aim of worldwide study of neutrino is to learn the fundamental physics as well as to understand the fundamental laws of nature but on the way of this learning process, we developed some new facilities and technologies, which may be very useful to human beings. This will certainly improve our lifestyle in future. Especially, the reactor and accelerator - neutrino physics experiments have the potential to make our life better. At present, we have some important applications of the developed technologies during the study of neutrino physics, which are as follows:

1. Without using work force, a very small and simple neutrino detector could monitor the activity of the nuclear reactor core very easily and automatically. The main aim of such detector is to inform whether the reactor is working in a safe mode or going towards the danger mode; without direct access to the nuclear core itself. For this purpose, we just have to observe if there is any significant change in the relative yield of fissioning isotopes and in the spectrum of antineutrinos and accordingly action may be taken in its monitoring. Such detectors are also found very useful in measuring the thermal power and reactivity of reactor at a level of few percent. In California, there is such a detector, which is named as SANDS of size 1m^3. This detector is located at 25 meter away from the core of the San Onofre reactor site [161]. This detector is doing their work automatically and without using any work force.
2. At this time almost every country wants to establish nuclear reactors for production of electricity (mostly) and for research purposes. However, we also know how nuclear reactors can be misused in destroying peace on earth. To stop it and to make sure of using such technology in making a peaceful, safe and secure life, there is an international agency (IAEA – International Atomic Energy Agency) which works together with its member countries, in this direction. The main aim of IAEA is to verify the use of nuclear materials and activities by people / group who have absolutely no relation with military or terrorist whatsoever [162]. The neutrino detectors (such as Double Chooz) can help this agency (IAEA), in perfecting and polishing their job because, in near future Double Chooz will be able to get millions of neutrino events in the near detector and ~ 20000 events per day at the far detector. Such a huge statistics will help the IAEA in proper handling of its mission around the world [163].
3. As we know that, the heat flow rate of our earth is in between 30 to 40 TW. We also know that the earth contains several radioactive materials such as Uranium (U), Thorium (Th), Potassium (K) etc. There are several models, which suggest slightly changed composition of earth. These models also suggest that near about 20 TW of heat flow produces through the decay of U, Th and K [164]. We know that through the decay of U, Th and K, neutrinos are also coming out from the earth called as geoneutrinos. The end-point energies of Uranium and Thorium are greater than the threshold energy for the occurrence of inverse beta reaction with protons and therefore they can be detected as reactor antineutrinos. In addition, the geoneutrinos coming from Uranium and Thorium can be easily discriminated, because, their energy spectra are different. Thus, the antineutrinos (geoneutrinos) could be used in determining the exact contribution of earth heat flow from radioactive content of the earth and in determining the model, which is able to provide more exact content of the earth. At this time KamLAND experiment is working for detecting the geoneutrinos [165] and LENA (at the Center for Underground Physics in the Pyhasalmi mine, Finland) has been proposed [166]. In the near future, some more proposals may come for detection of geoneutrinos.

Thus, we see that there are many important applications of the study about neutrino physics, which are serving our society. In the coming future the above number of applications will surely increase. Therefore, one can understand the importance of neutrino physics has in our life is.

7. Summary

In understanding the fundamentals of physics and the laws of nature, study of neutrino has played a very important role. In this study, reactor-neutrinos are the experimental initiative. Using the reactor neutrinos, many serious questions have been answered. This starts with the discovery of neutrino. Recently using reactor neutrino the question of its oscillation has been answered which leads to the generation of mass of neutrino. Worldwide, there are several neutrino experiments which have been proposed (such as JUNO, RENO) and some are working (such as Daya Bay, Double Chooz, TEXONO), for answering other questions, such as, whether sterile neutrinos do exist or not. The answer to them might lead us to a new world of many more questions. Finally, all these studies will help the society, which will take some time. However, the earlier studies on neutrino physics is helping us presently in making use of nuclear energy for peaceful purposes.

Acknowledgements:

Authors are thankful to the Department of Science and Technology (DST), New Delhi for providing financial support and India-based Neutrino Observatory (INO) Collaboration for their continuous support and fruitful discussions. One author MKS is thankful to the UGC, New Delhi for providing generous financial support. There is not conflict of interest in this article. M. K. Singh is grateful to the UGC, New Delhi for providing D.S. Kothari fellowship.

References

[1] R. G. Arns, Phys. Perspect. **3**, 314 (2001).

[2] H. A. Bethe and R. E. Peierls, Nature **133**, 532 (1934).

[3] F. Reines and C. L. Cowan, Jr., Nature **178**, 446 (1956).

[4] G. Danby et al., Phys. Rev. Lett. **9**, 36 (1962).

[5] K. Kodama et al., Phys. Lett. **B 504**, 218 (2001).

[6] C. Athanassopoulos et al., Phys. Rev. Lett. **81**, 1774 (1998); Phys. Rev. **C58**, 2489 (1998).

[7] C. Athanassopoulos et al., Phys. Rev. Lett. **75**, 2650 (1995).

[8] A. Aguilar et al., Phys. Rev. **D 64**, 112007 (2001).

[9] B. Satyanarayana, Ph.D. Thesis, Tata Institute of Fundamental Research, Mumbai, pages **96 – 97** (2009).

[10] P. Vogel, L. J. Wen & C. Zhang, Nature Communications **6 (**6935), 1 (2015).

[11] F. Ardellier et al., arxiv:hep-ex/0606025v4, (2006).

[12] J. K. Ahn et al, (RENO Collaboration) arXiv: 1003.1391 [hep-ex] (2010).

[13] X. Guo et al., arxiv:hep-ex/0701029v1 (2007).

[14] M. Apollonio et al., Eur. Phys. J. **C 27**, 331 (2003).

[15] S. B. Kim, Nucl. Part. Phys. Proc. **265-266**, 93 (2015).

[16] Z. Djurcic, arXiv: 1201.1522v1 [hep-ex] (2012).

[17] F. P. An, Nucl. Instrum. Meth. **A 811**, 133 (2016**).**

[18] B. Xin et al. Phys. Rev. **D** 72 012006 (2005).

[19] J. Learned, Nucl. Phys. **B** (Proc. Suppl.) **143**, 152 (2005).

[20] T. R. England and B. F. Rider, ENDF-349, LA-UR-94-3106 (1993).

[21] G. C. McLaughlin, C. Volpe, Phys. Lett. **B 591**, 229 (2004).

[22] F. Reines, H. S. Gurr, H. W. Sobel, Phys. Rev. Lett. **37**, 315 (1976).

[23] P. Vogel, J. Engel, Phys. Rev. **D 39**, 3378 (1989).

[24] A. I. Derbin, A.V. Chernyi, L. A. Popeko, V. N. Muratova, G. A. Shishkina, S. I. Bakhlanov, JETP Lett. **57**, 768 (1993); Pisma Zh. Eksp. Teor. Fiz. **57**, 755 (1993).

[25] J. F. Beacom, P. Vogel, Phys. Rev. Lett. **83**, 5222 (1999).

[26] Z. Daraktchieva et al. (MUNU Collaboration), Phys. Lett. **B 564**, 190 (2003).

[27] H. T. Wong et al., Phys. Rev. **D 75**, 012001 (2007); H. B. Li et al. (TEXONO Collaboration), Phys. Rev. Lett. **90**, 131802 (2003); H. T. Wong, Nucl. Phys. **A 721C**, 495 (2003); H. T. Wong, Nucl. Phys. B (Procs. Suppl.) **138**, 333 (2005); H. T. Wong, Mod. Phys. Lett. **A 19**, 1207 (2004); H. T. Wong, Nucl. Phys. B (Procs. Suppl.) **143**, 205 (2005); V. Singh & H. T. Wong, Phys. Atom. Nucl. **69**, 1956 (2006); J.-W. Chen et al., Phys. Rev. **D 91**, 013005 (2015).

[28] A. G. Beda, V. B. Brudanin, et al., Adva. High Energy Physics, **2012**, 350150 (2012).

[29] G. G. Raffelt, Stars as Laboratories for Fundamental Physics: The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles, Chicago Univ. Press, Chicago, IL, 1996, and references therein.

[30] A. Derbin et al., JETP Lett. **57**, 768 (1993).

[31] P. Zucchelli, Phys. Lett. **B 532**, 166 (2002).

[32] C. Volpe, J. Phys. **G 30**, pp L1 (2004)., arxiv:hep-ph/0303222

[33] G. C. McLauaughlin, C. Volpe, Phy. Lett. **B 592**, 229 (2004).

[34] F. Reines, H. S. Gurr, H. W. Sobel, Phys. Rev. Lett. **37**, 315 (1976).

[35] J. Panman, in Precision tests of the standard electroweak model, ed. P. Langacker, 504-544, World Scientific (1995); W. J. Marciano and Z. Parsa, J. Phys. **G 29**, 2629 (2003).

[36] J. Dorenbosch et al., Z. Phys. **C 41**, 567 (1989); L. A. Ahrens et al., Phys. Rev. **D 41**, 3297 (1990); P. Vilian et al., Phys. Lett. **B 335**, 246 (1994).

[37] J. P. Cravens et al., Phys. Rev. **D 78**, 032002 (2008); B. Aharmim et al. Phys. Rev. **C 75**, 045502 (2007).

[38] B. Kayser et al., Phys. Rev. **D 20**, 87 (1979).

[39] B. Kayser, Phys. Lett. **B 667**, 163 (2008), and references therein.

[40] M. Deniz, et al. Phys. Rev. **D 81**, 072001 (2010) ; M. Deniz et al., Phys. Rev. **D 82**, 033004 (2010) ; S. Bilmis et al., Phys. Rev. **D 92**, 033009 (2015); S. Bilmis et al., Phys. Rev. **D 85**, 073011 (2012).

[41] R. C. Allen et. al., Phys. Rev. **D 47**, 11 (1993).

[42] L. B. Auerbach et. al., Phys. Rev. **D 63**, 112001 (2001).

[43] P. Vogel and J. Engel, Phys. Rev. **D 39**, 3378 (1989).

[44] G. S. Vidyakin et al., JETP Lett. **55**, 206 (1992).

[45] A. I. Derbin et al., JETP Lett. **57**, 796 (1993).

[46] C. Amsler et al., Nucl. Instr. and Meth. **A 396**, 115 (1997); Z. Daraktchieva et al., Phys. Lett. **B 615**, 081601 (2005).

[47] J. Erler and P. Langacker, Phys. Lett. **B 667**, 125 (2008), and references therein.

[48] J. Panman, Precision tests of the standard electroweak model, ed. P. Langacker, 504-544, World Scientific (1995); W. J. Marciano and Z. Parsa, J. Phys. **G 29**, 2629 (2003).

[49] G. P. Zeller et al., Phys. Rev. Lett. **88**, 091802 (2002).

[50] V. Barger et al., Princeton University Press, ISBN 0-691-12853-7 (2012).

[51] B. Pontecorvo, Zh. Eksp. Teor. Fiz. **33**,549 (1957); Sov. Phys. JETP **6**, 429 (1957); Zh. Eksp. Teor. Fiz. **53**, 1717 (1967); Sov. Phys. JETP **26**, 984 (1968).

[52] B. Pontecorvo, Sov. Phys. JETP **6**, 429 (1957).

[53] B. Pontecorvo, Sov. Phys. JETP **7**, 172 (1958).

[54] Z. Maki, M. Nakagawa, & S. Sakata, Prog. Theor. Phys. **28**, 870 (1962).

[55] Hamish Johnston, http://physicsworld.com/cws/article/news/2015/oct/06/2015-nobel-prize-for-physics Webb, (2015).

[56] L. Wolfenstein, Phys. Rev. **D 17**, 2369 (1978).

[57] S. P. Mikheev, & A. Y. Smirnov, Sov. J. Nucl. Phys. **42**, 913 (1985).

[58] K. A. Olive et al. (Particle Data Group), Chin. Phys. **C 38**, 090001 (2014).

[59] H. Kwon et al., Phys. Rev. **D 24**, 1097 (1981).

[60] G. Zacek et al., Phys. Rev. **D 34**, 2621 (1986).

[61] A. I. Afonin et al., J. Exp. Theor. Phys. **67**, 213 (1988).

[62] G. S. Vidyakin et al., JETP Lett. **59**, 390 (1994).

[63] Z. D. Greenwood et al., Phys. Rev. **D 53**, 6054 (1996).

[64] Y. Declais et al., Phys. Lett. **B 338**, 383 (1994).

[65] Y. Declais et al., Nucl. Phys **B 434**, 503 (1995).

[66] C. Bemporad, G. Gratta, & P. Vogel, Rev. Mod. Phys. **74**, 297 (2002).

[67] K. Eguchi et al., Phys. Rev. Lett. **90**, 021802 (2003).

[68] T. Araki et al., Phys. Rev. Lett. **94**, 081801 (2005).

[69] S. Abe et al., Phys. Rev. Lett. **100**, 221803 (2008).

[70] F. P. An et al., Phys. Rev. Lett. **108**, 171803 (2012).

[71] F. P. An et al., Phys. Rev. Lett. **112**, 061801 (2014).

[72] J. K. Ahn et al., Phys. Rev. Lett. **108**, 191802 (2012).

[73] Y. Abe et al., Phys. Rev. Lett. **108**, 131801 (2012).

[74] Y. Abe et al., Phys. Lett. **B 735**, 51 (2014).

[75] M. He, Nucl. Part. Phys. Proc. **265-266**, 111 (2015).

[76] T. Kajita, & Y. Totsuka, Rev. Mod. Phys. **73**, 85 (2001).

[77] G. Feldman, J. Hartnell, & T. Kobayashi, Adv. High Energy Phys. **2013**, 475749 (2013).

[78] M. Apollonio et al., Phys. Lett. **B 466**, 415 (1999).

[79] F. Boehm et al., Phys. Rev. Lett. **84**, 3764 (2000).

[80] P. Adamson et al., Phys. Rev. Lett. **112**, 191801 (2014).

[81] K. Abe et al., Phys. Rev. Lett. **112**, 181801 (2014).

[82] C. Zhang, AIP Conf. Proc. **1666**, 080003 (2015).

[83] H. Minakata, H. Nunokawa, S.J. Parke, & R.Z. Funchal, Phys. Rev. **D 74**, 053008 (2006).

[84] X. Qiane et al., Phys. Rev. **D 86**, 113011 (2012).

[85] M. Blennow, P. Coloma, P. Huber, & T. Schwetz, J. High Ener. Phys. **2014**, 028 (2014).

[86] S. Kettell et al., arxiv.org/abs/1307.7419 (2013).

[87] Y. Li, J. Cao, Y. Wang, & L. Zhan, Phys. Rev. **D 88**, 013008 (2013).

[88] X. Qian, C. Zhang, M. Diwan, & P. Vogel, arxiv.org/abs/1308.5700 (2013).

[89] Toshiyuki Iwamoto, PhD Thesis, pages 27 & 30, (2003).

[90] Jean-Louis Basdevant, James Rich, Michel Spiro, Fundamentals in Nuclear Physics from Nuclear Structure to Cosmology, Springer, ISBN 0-387-01672-4, page 320 (2005).

[91] S. Schael et al. (ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, SLD Collaboration, LEP Electroweak Working Group, SLD Electroweak Group, SLD Heavy Flavour Group), Phys. Rep. **427**, 257 (2006).

[92] C. Athanassopoulos et al., Phys. Rev. Lett. **75**, 2650 (1995).

[93] A. Aguilar et al., Phys. Rev. **D 64**, 112007 (2001).

[94] S. Dodelson & L. M. Widrow, Phys. Rev. Lett. **72**, 17 (1994).

[95] A. Kusenko, Phys. Rep. **481**, 1 (2009).

[96] M. Wyman, D.H. Rudd, R.A. Vanderveld & W. Hu, Phys. Rev. Lett. **112**, 051302 (2014).

[97] R. A. Battye & A. Moss, Phys. Rev. Lett. **112**, 051303 (2014).

[98] A. A. Aguilar-Arevalo et al., Phys. Rev. Lett. **98**, 231801 (2007).

[99] A. A. Aguilar-Arevalo et al., Phys. Rev. Lett. **110**, 161801 (2013).

[100] F. Kaether et al., Phys. Lett. **B 685**, 47 (2010).

[101] J. N. Abdurashitov et al., Phys. Rev. **C 80**, 015807 (2009).

[102] T. A. Mueller et al., Phys. Rev. **C 83**, 054615 (2011).

[103] P. Huber, Phys. Rev. **C 84**, 024617 (2011).

[104] G. Mention et al., Phys. Rev. **D 83**, 073006 (2011).

[105] C. Zhang, X. Qian & P. Vogel, Phys. Rev. **D 87**, 073018 (2013).

[106] C. Giunti & M. Laveder, Phys. Rev. **D 84**, 093006 (2011).

[107] B. Armbruster et al., Phys. Rev. **D 65**, 112001 (2002).

[108] P. Astier et al., Phys. Lett. **B 570**, 19 (2003).

[109] N. Agafonova et al., J. High Energy Phys. **07**, 085 (2013).

[110] M. Antonello et al., Eur. Phys. J. **C 73**, 2599 (2013).

[111] I. E. Stockdale et al., Phys. Rev. Lett. **52**, 1384 (1984).

[112] F. Dydak et al., Phys. Lett. **B 134**, 281 (1984).

[113] G. Cheng et al., Phys. Rev. **D 86**, 052009 (2012).

[114] K. B. M. Mahn et al., Phys. Rev. **D 85**, 032007 (2012).

[115] S. Fukuda et al., Phys. Rev. Lett. **85**, 3999 (2000).

[116] P. Adamson et al., Phys. Rev. Lett. **107**, 011802 (2011).

[117] J. M. Conrad & M. H. Shaevitz, Phys. Rev. **D 85**, 013017 (2012).

[118] F. P. An et al., Phys. Rev. Lett. **113**, 141802 (2014).

[119] K. N. Abazajian et al., arxiv.org/abs/1204.5379 (2012).

[120] A. Bungau et al., Phys. Rev. Lett. **109**, 141802 (2012).

[121] R. Allen et al., arxiv.org/abs/1307.7097 (2013).

[122] M. Antonello et al., arXiv.org/abs/1203.3432 (2012).

[123] C. Adams et al., arXiv/abs/1309.7987 (2013).

[124] D. Adey et al., Phys. Rev. **D 89**, 071301 (2014).

[125] M. Cribier et al., Phys. Rev. Lett. **107**, 201801 (2011).

[126] D.A. Dwyer, K.M. Heeger, B. R. Littlejohn & P. Vogel, Phys. Rev. **D 87**, 093002 (2013).

[127] G. Bellini et al., J. High Energy Phys. **08**, 038 (2013).

[128] A. Gando et al., arxiv.org/abs/1312.0896 (2013).

[129] J. Ashenfelter et al., arxiv.org/abs/1309.7647 (2013).

[130] C. Lane et al., arxiv.org/abs/1501.06935 (2015).

[131] A. Porta et al., IEEE Trans. Nucl. Sci. **57**, 2732 (2010).

[132] A. S. Cucoanes et al., J. Phys. Conf. Ser. **375**, 042063 (2012).

[133] I. Alekseev et al., Phys. Part. Nucl. Lett. **11**, 473 (2014).

[134] A. P. Serebrov, arxiv.org/abs/1205.2955 (2012).

[135] A. P. Serebrov et al., arxiv.org/abs/1310.5521 (2014).

[136] A.V. Derbin, A. S. Kayunov & V. N. Muratova, arxiv.org/abs/1204.2449 (2012).

[137] T. Lasserre, Phys. Dark Univ. **4**, 81 (2014).

[138] S. Yeo, J. Korean Phys. Soc. **64**, 377 (2014).

[139] D. Z. Freedman, Phys. Rev. **D 9**, 1389 (1974).

[140] Y. V. Gaponov and V. N. Tikhonov, Sov. J. Nucl. Phys. **26**, 31 (1977).

[141] L. M. Sehgal and M. Wanninger, Phys. Lett. **B 171**, 107 (1986).

[142] J. Barranco, et al., JHEP **0512**, 021 (2005).

[143] H. T. Wong et al., Nucl. Phys. B (Procs. Suppl.) **221**, 320 (2011) ; H. T. Wong, Nucl. Phys. **A 844**, 299c (2010) ; H. T. Wong, Mod. Phys. Lett. **A 23**, 1431 (2008).

[144] S. Aune et al., AIP Conf. Proc. **785**, 110 (2005).

[145] S. Sangiorgio, et al., Physics Procedia **37**, 1266 (2012).

[146] J. A. Formaggio, E. Figueroa-Feliciano, A. J. Anderson, Phys. Rev. **D 85**, 013009 (2012).

[147] C. Hagmann, A. Bernstein, IEEE Trans. Nucl. Sci. **51**, 2151 (2004).

[148] P. Vogel, J. Engel, Phys. Rev. **D 39**, 3378 (1989).

[149] F. P. An et al. (Daya Bay Collaboration), Physical Review Letters **108**, 171803 (2012).

[150] E. S. Reich, doi:10.1038/nature.2012.10202 (2012).

[151] F. P. An et al. (Daya Bay Collaboration), Physical Review Letters **112**, 061801(2014).

[152] F. P. An et al. (Daya Bay Collaboration), Phys. Rev. **D 90**, 071101 (2014).

[153] B. Z. Hu et al., arXiv:1505.03641 [hep-ex] (2015).

[154] Y. Abe et al. (Double Chooz Collaboration), JHEP **10**, 086 (2014).

[155] Y. Abe et al. Phys. Lett. **B 735**, 51 (2014).

[156] Y. Abe et al. Phys. Rev. **D 86**, 052008 (2012).

[157] Y. Abe et al. (Double Chooz Collaboration), Phys. Lett. **B 723**, 66 (2013).

[158] J. K. Ahn, et al. (RENO Collaboration), Phys. Rev. Lett. **108**, 191802 (2012).

[159] S. B. Kim, AAPPS Bulletin vol. 22, Issue No. **3**, 23 (2012).

[160] S. H. Seo (for the RENO Collaboration), aeXiv:1312.4111[physics.ins-det] (2013).

[161] A. Bernstein, N.S. Bowden, A. Misner, T. Palmer, J. Appl. Phys. **103**, 074905 (2008) ; V. Singh & H. T. Wong, Procs. ICPUAE **2**, 406 (2009), and references there in.

[162] Th. Lasserre, H. W. Sobel, Comptes Rendus Physique **6**, 749 (2005).

[163] F. Ardellier et al. (Double-Chooz Collaboration), hep-ex/0405032 (2004).

[164] G. Fiorentini et al., Nucl. Phys. **B** (Proc. Suppl.) **143**, 53 (2005); G. Fiorentini, Th. Lasserre, M. Lissia, B. Ricci and S. Schonert, Phys. Lett. **B 558**, 15 (2003).

[165] T. Araki et al., Nature **436**, 499 (2005).

[166] L. Oberauer, Mod. Phys. Lett. **A 19**, 337 (2004).

Table1. Parameters of currently working reactor antineutrino experiments [16] are listed.

Experiment	**Thermal Power (GW_{th})**	**Distance to Near/ Far (m. w. e)**	**Shielding Near/Far (m. w. e.)**	**Target mass (tons)**	**Sensitivity $Sin^2 2\theta_{13}$ (90% C.L.)**
Double Chooz (France)	8.4	390/1050	115/300	8/8	0.03
RENO (Korea)	17.3	290/1380	120/450	16/16	0.02
Daya Bay (China)	17.4	360/ 1985	260/910	2 × 2 × 20 (N) 4 × 20 (F)	0.01

Table 2: The bounds on neutrino magnetic moment are listed.

Experiment	**Type of neutrinos**	**Upper limit of μ_B**	**Confidence level**
Savannah River [22]	Reactor	$\mu_\nu < 2\text{-}4 \times 10^{-10}\ \mu_B$	90%
Kurtchatov [23]	Reactor	$\mu_\nu < 2.4 \times 10^{-10}\ \mu_B$	90%
Rovno experiment [24]	Reactor	$\mu_\nu < 1.9 \times 10^{-10}\ \mu_B$	--
Super Kamiokande [25]	Solar	$\mu_\nu < 1.5 \times 10^{-10}\ \mu_B$	90%
MUNU Collaboration [26]	Reactor	Recent $\mu_\nu < 9 \times 10^{-11}\ \mu_B$	90%
TEXONO [27]	Reactor	$\mu_\nu < 7.4 \times 10^{-11}\ \mu_B$	90%
GEMMA spectrometer [28]	Reactor	$\mu_\nu < 2.9 \times 10^{-11}\ \mu_B$	90%
Astrophysical/ Cosmological considerations [29]	Big Bang Nucleosynthesis, Star Lifetime and Cooling, Supernova explosions	In the range $10^{-11} - 10^{-12}\mu_B$	--

Table 3: List of neutrino-electron elastic scattering cross-section achieved from various experiment, using neutrinos of different energy (E_ν) [40].

Experiment			**E_ν in MeV**	**Cross-section**
Accelerator ν_e	LAMPF [41]		$7 < E_\nu < 50$	$[10.0 \pm 1.5 \pm 0.9] \cdot E_\nu \times 10^{-45}$ cm^2
	LSND [42]		$20 < E_\nu < 50$	$[10.1 \pm 1.1 \pm 1.0] E_\nu \times 10^{-45}$ cm^2
Reactor $\overline{\nu}_e$	Savannah River	Original [34]	$1.5 < E_\nu < 8.0$	$[0.87 \pm 0.25]\ \sigma_{V-A}$
			$3.0 < E_\nu < 8.0$	$[1.70 \pm 0.44]\ \sigma_{V-A}$
		Re-analyzed [43]	$1.5 < E_\nu < 8.0$	$[1.35 \pm 0.4]\ \sigma_{SM}$
			$3.0 < E_\nu < 8.0$	$[2.0 \pm 0.5]\ \sigma_{SM}$
	Krasnoyarsk [44]		$3.2 < E_\nu < 8.0$	$[4.5 \pm 2.4] \times 10^{-46}$ cm^2/fission
	Rovno [45]		$0.6 < E_\nu < 8.0$	$[1.26 \pm 0.62] \times 10^{-44}$ cm^2/fission
	MUNU [46]		$0.7 < E_\nu < 8.0$	$[1.07 \pm 0.34]$ events/day
	TEXONO [40]		$3.0 < E_\nu < 8.0$	$[1.08 \pm 0.21 \pm 0.16]\ \sigma_{SM}$

Table 4: Key parameters of the reactor neutrino based experiments [10].

	Power (GWth)	**Baseline (m)**	**Mass (ton)**	**Overburden (m. w. e.)**
CHOOZ [78]	8.5	1,050	5	300
PALO VERDE [79]	11.6	750–890	12	32
Double Chooz [73]	8.5	400	8	120
		1,050	8	300
RENO [72]	16.8	290	16	120
		1,380	16	450
Daya Bay [70]	17.4	360	2 × 20	250
		500	2 × 20	265
		1,580	4 × 20	860

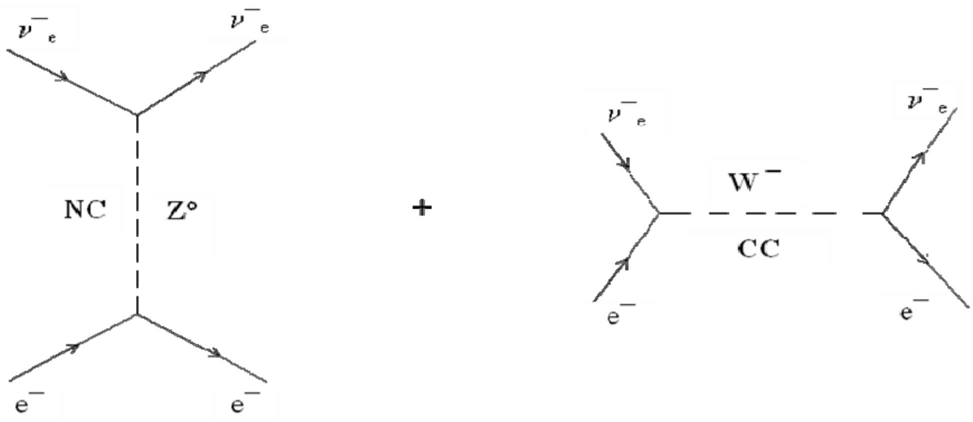

Figure 1: Interactions of $\bar{\nu}_e$ - e for the standard model charge current and neutral current channels [40].

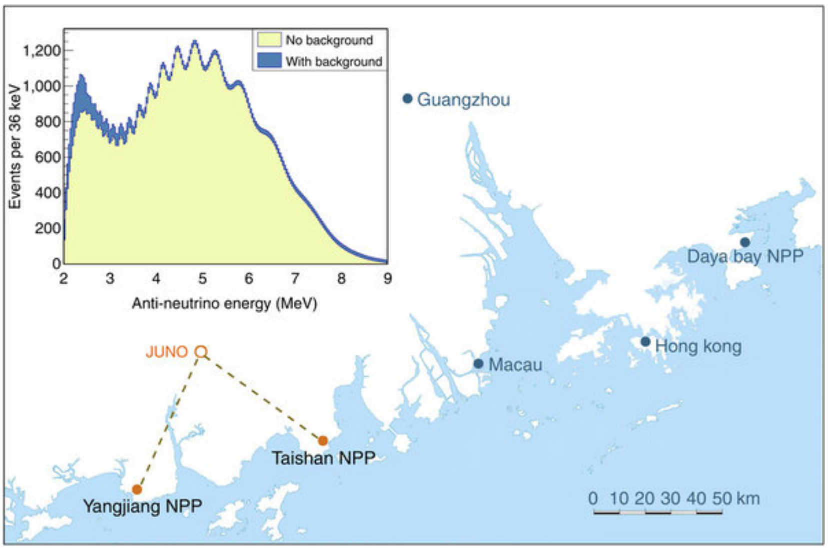

Figure 2: JUNO experiment's layout and inset is the expected signal spectrum.

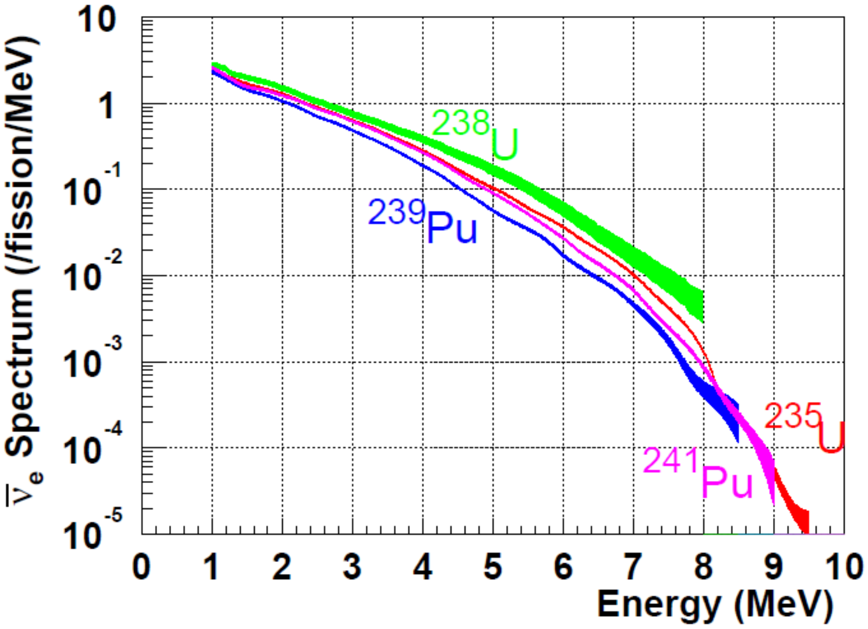

Figure 3: Production of neutrinos from ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu as a function of its energy (MeV) [89]

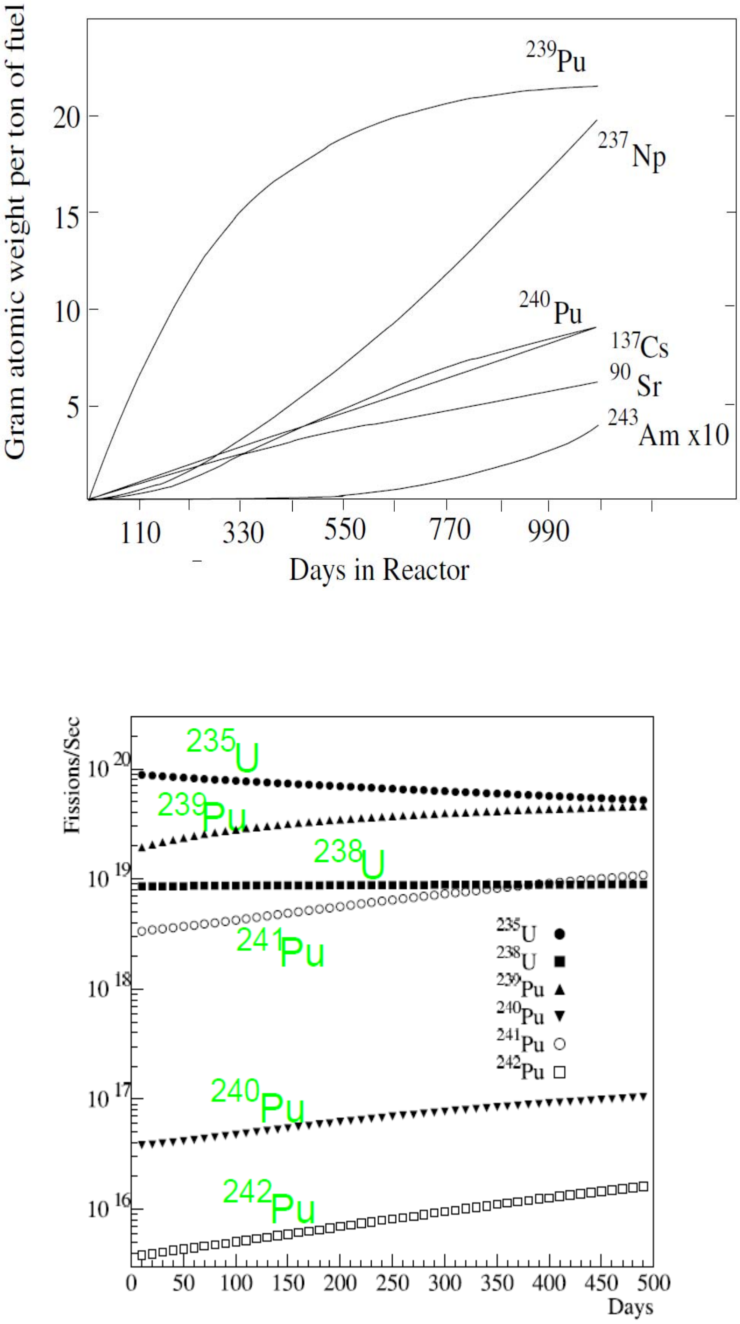

Figure 4: (a) Production of fission isotopes and **(b)** fission rate with respect to time is also shown [89].