Research of neutrino oscillations in the experiment 2LAr@CERN PS

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Abstract

This report investigates the sensitivity of the 2LAr@CERN PS experiment to the mixing angle θ_{14} in the presence of the oscillation of muon neutrinos into sterile neutrinos and sterile neutrinos to electron neutrinos beyond the Standard Model with the CERN-PS. The core of the experiment will be the now operational ICARUS T600 (ultra-pure cryogenic liquid Argon detector), the largest LAr-TPC ever built, with a size of about 600 t of imaging mass. Presented brief overview of the theory of neutrino oscillation. Also set out a description of the experiment. The discussion then focuses on the research of setups of experiment and their contribution to the sensitivity of the detector using GLoBES framework. The results of the study of sensitivity are compared with results presented in the proposal of the experiment. It is found what parameters make the greatest contribution to increasing of sensitivity of the detector and found values of these parameters.

Contents

1 Introduction

The neutrino was first postulated in 1930 by Wolfgang Pauli to preserve the conservation of energy, conservation of momentum, and conservation of angular momentum in beta decay - the decay of an atomic nucleus (not known to contain or involve the neutron at the time) into a proton, an electron and an antineutrino.

$$n^0 \longrightarrow p^+ + e^- + \bar{\nu}_e$$

He theorized, that an undetected particle was carrying away the observed difference between the energy, momentum, and angular momentum of the initial and final particles.
In 1942 Kan-Chang Wang first proposed the use of beta-capture to experimentally detect neutrinos. In the July 20, 1956 issue of Science, Clyde Cowan, Frederick Reines, F. B. Harrison, H. W. Kruse, and A. D. McGuire published confirmation that they had detected the neutrino, a result that was rewarded almost forty years later with the 1995 Nobel Prize.
In this experiment, now known as the Cowan and Reines neutrino experiment, neutrinos created in a nuclear reactor by beta decay were captured into protons producing neutrons and positrons.

$$\bar{\nu}_e + p^+ \longrightarrow n^0 + e^+$$

The positron quickly finds an electron and they annihilate each other. The two resulting γ rays are detectable. The neutron can be detected by its capture on an appropriate nucleus, releasing a gamma ray. The coincidence of both events, positron annihilation and neutron capture, gives a unique signature of an antineutrino interaction.
In 1962 Leon M. Lederman, Melvin Schwartz and Jack Steinberger showed, that more than one type of neutrino exists by first detecting interactions of the muon neutrino. When the third type of lepton, the tau, was discovered in 1975 at the Stanford Linear Accelerator Center, it too was expected to have an associated neutrino (the tau neutrino). First evidence for this third neutrino type came from the observation of missing energy and momentum in tau decays analogous to the beta decay leading to the discovery of the neutrino. The first detection of tau neutrino interactions was announced in summer of 2000 by the DONUT collaboration at Fermilab, making it the latest particle of the Standard Model to have been directly observed.
Starting in the late 1960s, several experiments found that the number of electron neutrinos arriving from the Sun was between one third and one half the number predicted by the Standard Solar Model. This discrepancy, which became known as the solar neutrino problem, remained unresolved for some thirty years. The Standard Model of particle physics assumes that neutrinos are massless and cannot change flavor. However, if neutrinos had mass, they could change flavor (or oscillate between flavors).
A practical method for investigating neutrino oscillations was first suggested by Bruno Pontecorvo in 1957 using an analogy with kaon oscillations; over the subsequent 10 years he developed the mathematical formalism and the modern formulation of vacuum oscillations. In 1985 Stanislav Mikheyev and Alexei Smirnov (expanding on 1978 work

by Lincoln Wolfenstein) noted that flavor oscillations can be modified when neutrinos propagate through matter.
Starting in 1998, experiments began to show that solar and atmospheric neutrinos change flavors. This resolved the solar neutrino problem: the electron neutrinos produced in the Sun had partly changed into other flavors which the experiments could not detect.
Currently running MiniBooNE experiment suggested, until recently, that sterile neutrinos are not required to explain the experimental data[1], although the latest research into this area is on-going and anomalies in the MiniBooNE data may allow for exotic neutrino types, including sterile neutrinos[2]. By the MiniBooNE experiment at Fermilab was tested the controversial LSND (Liquid Scintillator Neutrino Detector) result. The Liquid Scintillator Neutrino Detector was a scintillation counter at Los Alamos National Laboratory that measured the number of neutrinos being produced by an accelerator neutrino source. The LSND project was created to look for evidence of neutrino oscillation, and its results conflict with the standard model expectation of only three neutrino flavors, when considered in the context of other solar and atmospheric neutrino oscillation experiments. Cosmological data bound the mass of the sterile neutrino to $m_s < 0.26\text{eV}$ (0.44eV) at 95%(99.9%) confidence limit, excluding at high significance the sterile neutrino hypothesis as an explanation of the LSND anomaly.
A recent re-analysis of reference electron spectra data from the ILL[3] has also hinted at a fourth, sterile neutrino[4]. Recently analyzed data from the Wilkinson Microwave Anisotropy Probe of the cosmic background radiation is compatible with either three or four types of neutrinos. It is hoped that the addition of two more years of data from the probe will resolve this uncertainty[5].
We see that neutrino physics is a young progressive science where there are many questions that should be answered. Until now we haven't exact values of absolute masses of different types of neutrino and haven't exact values of mixing angles. Also we practically know nothing about sterile neutrino. There are new experiments which will be done in the future and which should answer the key questions. Among these experiments is 2LAr@CERN PS.

2 Theory

There are three known types (flavors) of neutrinos: electron neutrino ν_e, muon neutrino ν_μ and tau neutrino ν_τ, named after their partner leptons in the Standard Model. The current best measurement of the number of neutrino types comes from observing the decay of the Z boson. This particle can decay into any light neutrino and its antineutrino, and the more types of light neutrinos available, the shorter the lifetime of the Z boson. Measurements of the Z lifetime have shown that the number of light neutrino types is 3 [6]. The correspondence between the six quarks in the Standard Model and the six leptons, among them the three neutrinos, suggests to physicists' intuition that there should be exactly three types of neutrino. However, actual proof that there are only three kinds of neutrinos remains an elusive goal of particle physics.

A sterile neutrino is a hypothetical neutrino that does not interact via any of the fundamental interactions of the Standard Model except gravity. However it mixes with the other types of neutrinos. It is a right-handed neutrino or a left-handed anti-neutrino. Such a particle belongs to a singlet representation with respect to the strong interaction and the weak interaction and has zero weak hypercharge, zero weak isospin and zero electric charge. The left-handed anti-neutrino has a B-L (difference between the baryon number B and the lepton number L) of 1 and an X charge (conserved quantum number associated with the SO(10) grand unification theory, $(X = 5(B-L) - 2Y_W)$ of 5 . Sterile neutrinos may mix with ordinary neutrinos via a Dirac mass. Sterile neutrinos and ordinary neutrinos may also have Majorana masses.
Very important that neutrino flavour eigenstates not equal to the neutrino mass eigenstates. That is, the three neutrino states that interact with the charged leptons in weak interactions are each a different superposition of the three neutrino states of definite mass. Neutrinos are created in weak decays and reactions in their flavor eigenstates. As a neutrino propagates through space, the quantum mechanical phases of the three mass states advance at slightly different rates due to the slight differences in the neutrino masses. This results in a changing mixture of mass states as the neutrino travels, but a different mixture of mass states corresponds to a different mixture of flavor states. So a neutrino born as, say, an electron neutrino will be some mixture of electron, mu, and tau neutrino after traveling some distance. Since the quantum mechanical phase advances in a periodic fashion, after some distance the state will return to the original mixture, and the neutrino will be again electron neutrino. The electron flavor content of the neutrino will then continue to oscillate as long as the quantum mechanical state maintains coherence. It is because the mass differences between the neutrinos are small that the coherence length for neutrino oscillation is so long, making this microscopic quantum effect observable over macroscopic distances.
The unitary transformation relating the flavor and mass eigenbases can be written:

$$|\nu_\alpha >= \sum_i U_{\alpha i} \, |\nu_i >$$

$$|\nu_1 >= \sum_\alpha U^*_{\alpha i} \, |\nu_\alpha >$$

where$|\nu_\alpha >$ is a neutrino with definite flavor. $\alpha = e$, μ or τ

$|\nu_1 >$ is a neutrino with definite mass $m_{i,j} = 1, 2, 3$.

The asterisk (*) represents a complex conjugate. For antineutrinos, the complex conjugate should be dropped from the second equation, and added to the first.
$U\alpha i$ represents the Pontecorvo–Maki–Nakagawa-Sakata matrix (also called the PMNS matrix, lepton mixing matrix, or sometimes simply the MNS matrix). It is the analogue of the CKM matrix describing the analogous mixing of quarks. If this matrix were the identity matrix, then the flavor eigenstates would be the same as the mass eigenstates. However, experiment shows that it is not.
When the standard three neutrino theory is considered, the matrix is 3×3. If only two neutrinos are considered, a 2×2 matrix is used. If one or more sterile neutrinos are added it is 4×4 or larger. In the 3×3 form, it is given by:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 1} & U_{\tau 1} \end{pmatrix} =$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & \mathrm{s}_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ \text{-}\mathrm{s}_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \mathrm{e}^{i\alpha_1/2} & 0 & 0 \\ 0 & \mathrm{e}^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} =$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & \mathrm{s}_{13}e^{-i\delta} \\ \text{-}\mathrm{s}_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ \mathrm{s}_{12}s_{23} - c_{12}c23s_{13}e^{1\delta} & \text{-}\mathrm{c}_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \begin{pmatrix} \mathrm{e}^{i\alpha_1/2} & 0 & 0 \\ 0 & \mathrm{e}^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Where $c_{ij} = cos\theta_{ij}$ and $s_{ij} = sin\theta_{ij}$. The phase factors α_1 and α_2 are physically meaningful only if neutrinos are Majorana particles i.e. if the neutrino is identical to its antineutrino (whether or not they are is unknown) and do not enter into oscillation phenomena regardless. The phase factor δ is non-zero only if neutrino oscillation violates CP symmetry. This is expected, but not yet observed experimentally. If experiment shows this 3×3 matrix to be not unitary, a sterile neutrino or some other new physics is required.
The physical region for the mixing angles and δ phases are defined as follows:

$$0 \leq \theta_{12},\ \theta_{23},\ \theta_{13} \leq \pi/2,\ 0 \leq \delta \leq 2\pi$$

Also observed condition

$$\Delta m_{12}^2 + \Delta m_{23}^2 = \Delta m_{13}^2$$

Observed values of oscillation parameters:

$$\sin^2\theta_{13} < 0.032 \ at \ 95\% \text{ confidence level } (\theta_{13} < 10.3^\circ)$$ [14]

$$\tan^2\theta_{12} = 0.45^{+0.09}_{-0.07} \text{ this corresponds to } \theta_{12} = 33.9^{+2.4\circ}_{-2.2}$$ [15]

$$\sin^2(2\theta_{23}) = 1^{+0}_{-0.1} \text{ corresponding to } \theta_{23} = 45 \pm 7^\circ$$ [16]

$$\Delta m_{21}^2 = 8.0^{+0.6}_{-0.4} \times 10^{-5}\ eV^2$$ [14] $$|\Delta m_{31}^2| = 2.43^{+0.13}_{-0.13} \times 10^{-3}\ eV^2$$ [14]

In Figure 1 a graphical representation of the neutrino mixing angles.

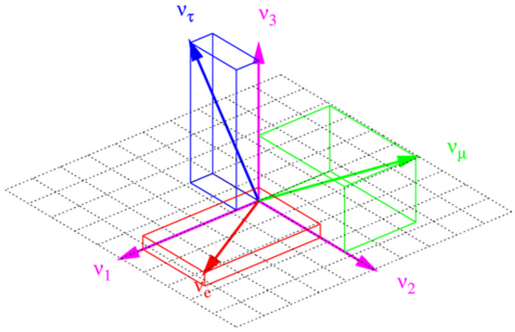

Figure 1. Graphical representation of the neutrino mixing angles. Here $\theta_{12} = 33.9°$, $\theta_{23} = 45°$, $\theta_{13} = 10°$.

Studying the sterile neutrino have been analyzed two distinct classes of phenomena, namely a) the apparent reduction in the $\bar{\nu}_e$ detected by low energy neutrinos from nuclear reactors[7] and from the signal from Mega-Curie sources in the Gallium experiments[8][9] originally designed to detect solar neutrino deficit[7], and b) strong hints for a $\bar{\nu}_e$ excess signal of in interactions coming from neutrinos from particle accelerators[8][9][10].
These experiments may all point out to the possible existence of the fourth non standard neutrino state driving neutrino oscillations at a small distances, with typically $|\Delta m^2_{new}| > 1eV$ and relatively large mixing angle $|sin^2_{new}| \approx 0.1$ [11]
The class a) of phenomena hint at a significant fast disappearance rate in the initial $\bar{\nu}_e$ production and the class b) predicts an anomalous $\nu_\mu \longrightarrow \nu_e$ oscillation, and with similar, large $|\Delta m^2_{new}|$ values, much greater than the ones of the Standard Model.
The general expression for the probability of oscillations in vacuum between two types of neutrinos (α and β) is as follows:

$$P(\nu_\alpha \rightarrow \nu_\beta) =$$
$$\delta_{\alpha\beta} - 4\sum_{k>j} Re[U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}] \sin^2 \frac{\Delta m^2_{jk} L}{4E_\nu} + 2\sum_{k>j} Im[U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}] \sin^2 \frac{\Delta m^2_{jk} L}{2E_\nu}$$

where $\alpha, \beta = e,\ \mu,\ \tau,\ \ E_\nu$ - neutrino energy, L - baseline. The corresponding expression for antineutrinos is obtained by replacing $U \leftrightarrow U^*$.

3 Simulation

3.1 What is GLoBES?

GLoBES (General Long Baseline Experiment Simulator) is a flexible software package to simulate neutrino oscillation long baseline and reactor experiments. On the one hand, it contains a comprehensive abstract experiment definition language (AEDL), which allows to describe most classes of long baseline experiments at an abstract level. On the other hand, it provides a C-library to process the experiment information in order to obtain oscillation probabilities, rate vectors, and $\Delta\chi^2$ - values.
GLoBES allows to simulate experiments with stationary neutrino point sources, where each experiment is assumed to have only one neutrino source. Such experiments are

neutrino beam experiments and reactor experiments. Geometrical effects of a source distribution, such as in the sun or the atmosphere, can not be described. It is, however, possible to simulate beams with bunch structure, since the time dependence of the neutrino source is physically only important to suppress backgrounds.
With the C-library, one can extract the $\Delta\chi^2$ for all defined oscillation channels for an experiment or any combination of experiments. Of course, also low-level information, such as oscillation probabilities or event rates, can be obtained. All oscillation parameters can be fixed or can be kept free to precisely localize degenerate solutions.

3.2 The experimental setup at the 2LAr@CERN PS

The experimental setup is as follows. The 19.2 GeV/c proton beam is extracted from the PS and impinges on a 80 cm long, 6 mm diameter beryllium target. After interaction with target proton produce positive and negative pions (π^+,π^-) and kaons (K^+,K^-). Then beam is directed to a pulsed magnetic horn which separate the beam into two parts: the first with positive pions and kaons, second with negative pions and kaons. A magnetic field deflects necessary beam of into a decay tunnel of about 50 m length, and unnecessary assigned to another tunnel where beam is extinguished. The decay tunnel cross section is $3.5 \times 2.8\ m^2$ for the first 25 m of length and $5.0 \times 2.8\ m^2$ for the rest of the length, allowing the decay of mesons with large angular divergence with respect to beam axis in the horizontal plane. The tunnel is followed by a 4 m thick iron shield and 65 m of earth to absorb the remaining hadrons and most of the muons (Figure2).

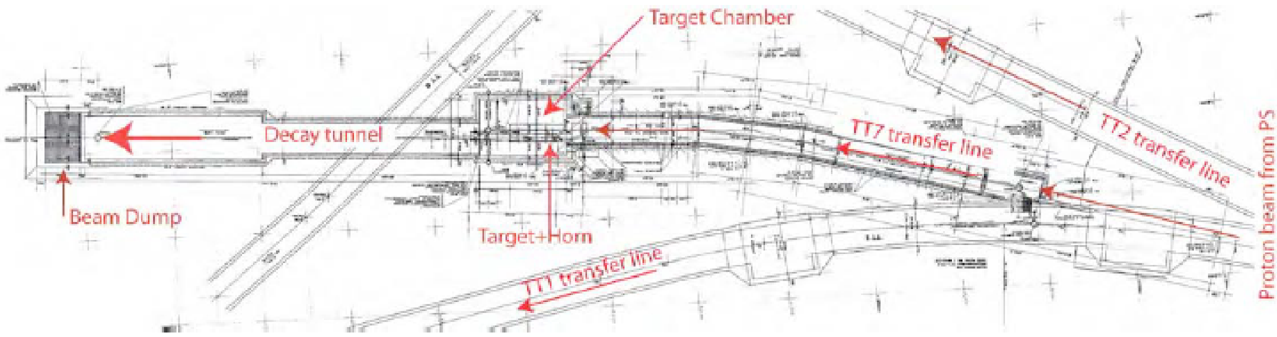

Figure 2. CERN-PS neutrino beam layout.

In the decay tunnel pions will decay into μ^+ and ν_μ (in case of beam of positive pions and kaons) or μ^- and $\bar{\nu}_\mu$ (in case of beam of negative pions and kaons) with probability 99.988%. But with a small probability ($1.2 \cdot 10^{-4}$%) positive pions can decay into e^+ and ν_e, and the negative pions can dacay into e^- and $\bar{\nu}_e$. After the formation of the muon neutrino (or muon antineutrino) it begins to oscillate (by the channel):

$$\nu_\mu \to \nu_{sterile} \to \nu_e$$
$$\bar{\nu}_\mu \to \nu_{sterile} \to \bar{\nu}_e$$

The two closely similar LAr-TPCs will be located respectively at 850 m and 127 from the PS target (Figure 3) in the existing locations B191 and B181 respectively.

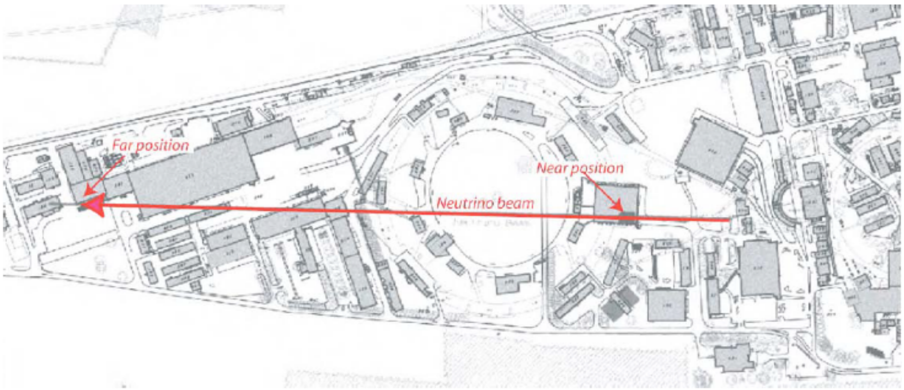

Figure 3. Neutrino beam from the CERN-PS. Two locations, respectively at 850 and 127 m from the target are simultaneously recorded in order to evidence possible oscillation effects.

“Near” argon detector (mass 150 tons) is at a distance of 127 m from the neutrino source. “Far” argon detector “Icarus T600” (mass 600 tons)(Figure 4) is at a distance of 850 m from the neutrino source.

Figure 4. The ICARUS T600 detector installed in Hall B at LNGS.

Table 1: Standard setup of experiment

Time of experiment	2 years per mode
Beam power	$1.25 \cdot 10^{20}$ pot
Fiducial target mass	475 t
Baseline	0.85 km
Energy window	[0.5 ; 7.0] GeV
Efficiency[1]or ν_e appearance	95%
Efficiency for ν_e disappearance	90%

3.3 The results of the sensitivity of the "Far" detector.

Using the settings given in Table 1 was obtained a detector's sensitivity to the mixing angle θ_{14}:

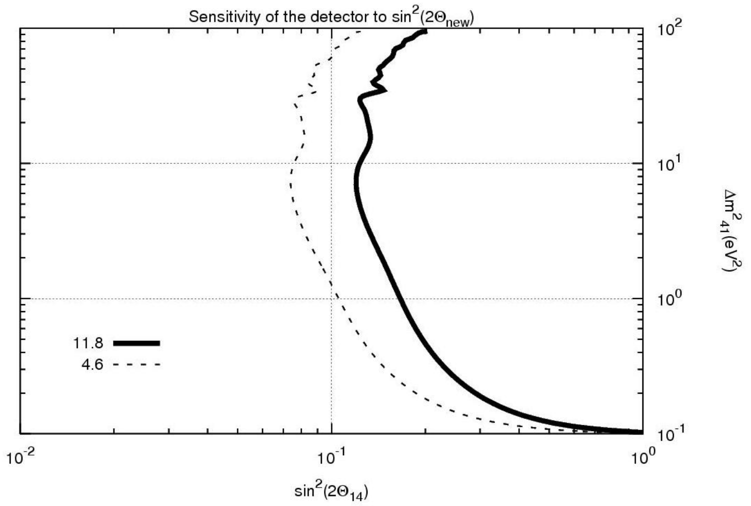

Figure 5. Sensitivity of the detector to the mixing angle θ_{14} (with standard setups). Dotted line is 3σ. Full line is 90% certainty level.

We can see that at these experimental settings the sensitivity of the detector to the mixing angle θ_{14} is small. Let's see how E window affect the sensitivity of the detector and in what ranges should use E window in order to increase the sensitivity. When choosing a borders E window will consider that the maximum probability of oscillation at $E = 700$ MeV. At this point we have a large peak of oscillation probability but before this peak we have many small peaks in the probability of oscillation.

[1]Efficiency defines effective part of events used for analysis after cuts etc.

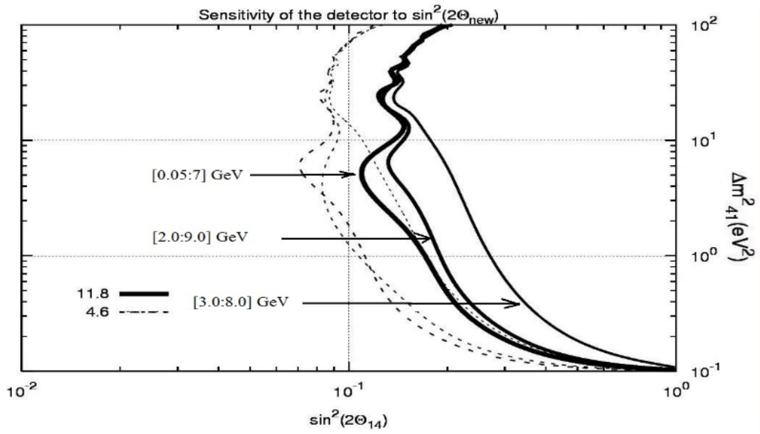

Figure 5. Sensitivity of the detector to the mixing angle θ_{14} with different E window. Dotted line is 3σ. Full line is 90% certainty level.

We can see that in the ranges of E window [0.05 ; 7.0] GeV sensitivity of the detector more than if we use ranges [0.5 ; 7.0]. This is explained by the fact that in the ranges [0.05 ; 7.0] bigger number of small peaks of probability of oscillation that make contribution to the general probability of oscillation. Similarly explained reducing probability for E windows [2.0 ; 9.0] GeV and [3.0 ; 8.0] GeV. Let's see how the change of beam power will change sensitivity of the detector. To do this, set the values of beam power same as at the proposal for experiment.

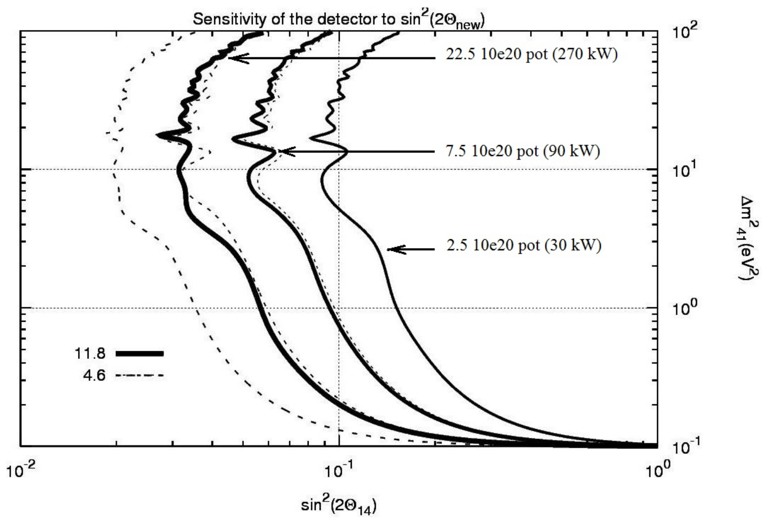

Figure 5. Sensitivity of the detector to the mixing angle θ_{14} with different beam power. Dotted line is 3σ. Full line is 90% certainty level.

We see that the beam power is making a big contribution to changing the sensitivity. Sensitivity increases proportionally with increasing beam power. It was also investigated what contribution to the sensitivity of the detector makes efficiency for ν_e appearance and for ν_e disappearance. (Figure 6)

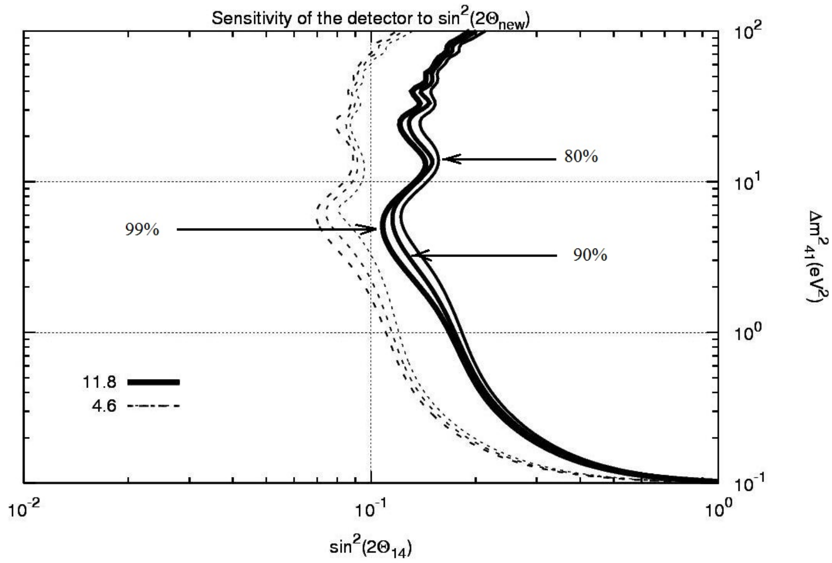

Figure 6. Sensitivity of the detector to the mixing angle θ_{14} with different efficiency for ν_e appearance and for ν_e disappearance (where 99%, 90%, 80% values for both efficienies). Dotted line is 3σ. Full line is 90% certainty level.

Also considered influence of the target mass (Figure 7) and time of the experiment (Figure 8) to the sensitivity of the detector.

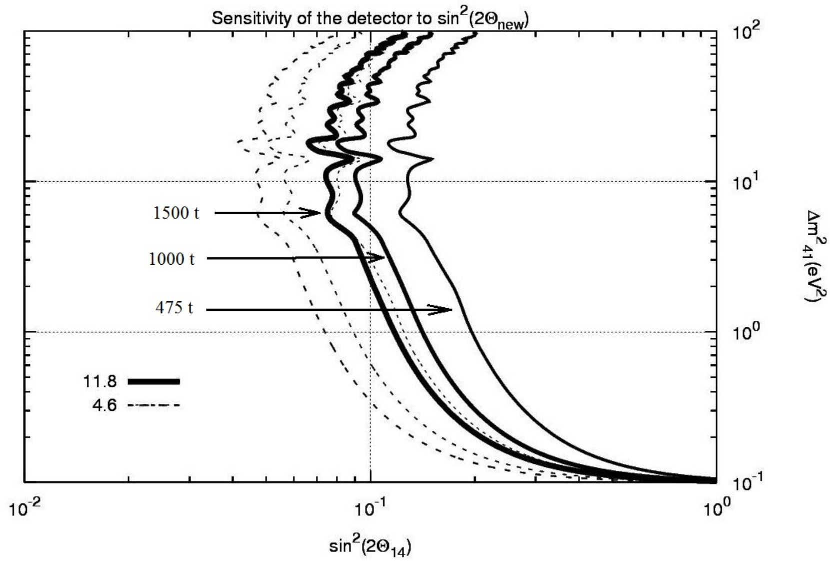

Figure 7. Sensitivity of the detector to the mixing angle θ_{14} with different fiducial target mass. Dotted line is 3σ. Full line is 90% certainty level.

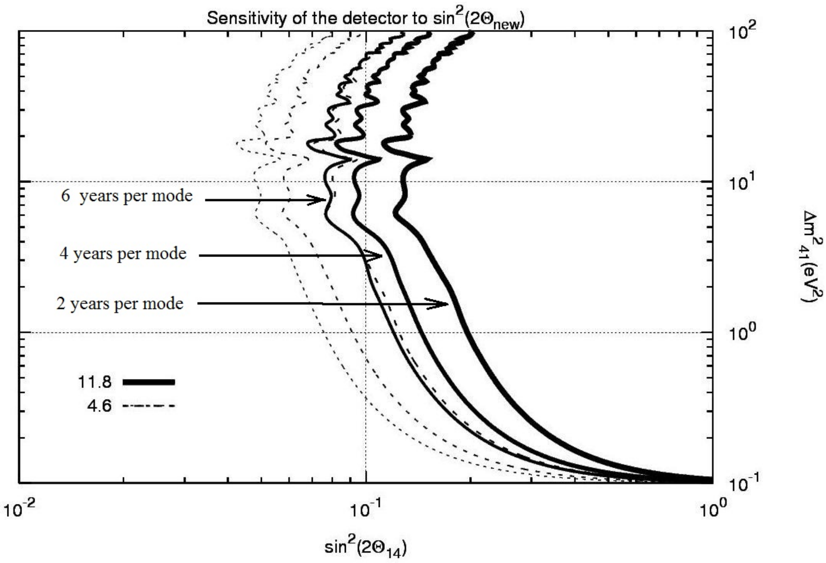

Figure 8. Sensitivity of the detector to the mixing angle θ_{14} with different run times of experiment per mode. Dotted line is 3σ. Full line is 90% certainty level.

There is a direct correlation between the mass of the target (time of the experiment) and the sensitivity of the detector. Thus we have two more ways to increase the sensitivity of the detector. The results of sensitivity with different beam power which are presented in the proposal are shown in Figure 9.

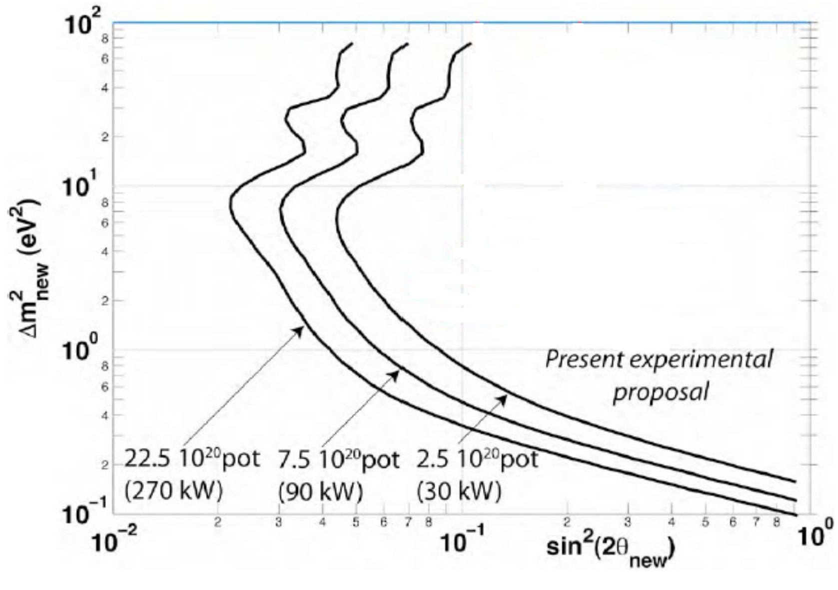

Figure 8. Sensitivity of the detector to the mixing angle θ_{14} with different beam power. Each line is 90% certainty level.

It is seen that the sensitivity of the detector with the different beam power used in the proposal and results presented in Figure 5 are in good agreement (provided that other experiment setups for Figure 8 are not fully known).

Investigated the influence of such parameters as energy window, beam power, efficiency, target mass, time of experiment on sensitivity of the detector can be concluded that we have direct relationship between this parameters and the sensitivity of the detector. The largest contribution to the increase of sensitivity of the detector makes beam power (at beam power $= 22.5 \cdot 10^{20}$ pot is the biggest sensitivity). The smallest contribution to the increase of sensitivity of the detector makes efficiency.

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