JOINT INSTITUTE FOR NUCLEAR RESEARC

Dzelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

A study for sensitivity of the NOνA experiment to neutrino oscillation parameters within an oscillation analysis program developing in JINR

Supervisor:
Oleg Samoilov

Student:
Anastasia Kalitkina

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Contents

Abstract

In the present report the following topics are considered: neutrino oscillation in vacuum and matter current, problems in neutrino physics, Global neutrino analysis (GNA) software and its examples of use for JUNO and NOνA experiments.

Introduction

Neutrino physics is an eventful area of modern high energy physics. Progress in investigating neutrino properties is really impressive. Among the most challenging problems are the neutrino's nature, neutrino masses (due to oscillation experiments we know that they are not zero), the existence of sterile neutrinos and CP violation in the lepton sector, the neutrino mass hierarchy problem and many others. We will discus it in the 1-st chapter.

Some of these questions can be clarified with the help of neutrino oscillation experiments. Now there are several experiments to solve the problems of neutrino physics, for examples, reactor experiments: Day Bay, Double Chooz, RENO, JUNO; accelerator experiments: OPERA, NOνA, T2K, DUNE.

Each experiment develops its own software to maximize sensitivity to oscillation results within specific neutrino modes and apparatus. JINR group created tools to analyses joint oscillation effect from different type of such an experiment, called GNA – Global neutrino analysis. Currently this software optimized only for reactor experiment Daya Bay and JUNO. We will discuss the possibilities of GNA in the 2-nd chapter.

To conduct global analysis for reactor and accelerator experiments with one software we want to add accelerator software based on NOνA experiment in GNA. Our first steps in this work we will discuss in the 3-rd chapter.

Chapter 1

Neutrino physics

1.1 Neutrino oscillations

Neutrino oscillations are the most sensitive method investigating neutrino mass and neutrino mixing parameters. The idea of neutrino oscillations was first introduced by Prof. B. Pontecorvo. The essence of this effect we can explain to consider, for example, a two-level quantum system.

In the case of neutrino oscillations, neutrinos are produced by the charged-current weak interactions and therefore are weak-eigenstate neutrinos ν_e, ν_μ, ν_τ. However, the neutrino mass matrix in this (flavor) basis is in general not diagonal. This means that the mass eigenstate neutrinos ν_1, ν_2, ν_3 (the states that diagonalize the neutrino mass matrix, i.e. the free propagation eigenstates) are in general different from the flavor eigenstates. Therefore the probability of finding a neutrino created in a given flavor state to be in the same state (or any other flavor state) oscillates with time.

Any flavor eigenstate neutrinos we can determine as linear combination of the mass eigenstate neutrinos

$$|\nu_a\rangle = \hat{U}^*_{ai}|\nu_i\rangle. \tag{1.1}$$

Assume that at a time t = 0 the flavor eigenstate ν_a was produced. The initial state at $t = 0$ is $|\nu_a(0)\rangle$ as (1.1). The neutrino state at a later time t is then

$$|\nu_a(t)\rangle = \hat{U}^*_{ai}e^{-iE_it}|\nu_i\rangle. \tag{1.2}$$

The probability amplitude of finding the neutrino at the time t in a flavor state ν_b is

$$A(\nu_a \to \nu_b; t) = \langle\nu_b|\nu_a(t)\rangle = \hat{U}_{bi}e^{-iE_it}\hat{U}^*_{ai}. \tag{1.3}$$

The probability of the transformation of a flavor eigenstate neutrino ν_a into another one ν_b, is then

$$P(\nu_a \to \nu_b; t) = |A(\nu_a \to \nu_b; t)|^2 = |\hat{U}_{bi}e^{-iE_it}\hat{U}^*_{ai}|^2. \tag{1.4}$$

Let us now consider neutrino oscillations in a simple case of just two neutrino species, ν_e and ν_μ. The lepton mixing matrix U can be written as

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \tag{1.5}$$

where θ being the mixing angle. Substituting (1.5) into (1.4) and taking into account that for relativistic neutrinos of the momentum p

$$E_i \simeq p + \frac{m_i^2}{2E}. \tag{1.6}$$

we find the transition probabilities

$$P(\nu_e \to \nu_\mu; t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} t\right). \tag{1.7}$$

In the case of three neutrino flavors. The neutrino flavor eigenstate and mass eigenstate fields are related through

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} \tag{1.8}$$

It is convenient to use the parametrization of the matrix U which coincides with the standard parametrization of the quark mixing matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{-i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{-i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{-i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{-i\delta} & c_{23}c_{13} \end{pmatrix}, \tag{1.9}$$

here $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$. The probabilities of oscillations between various flavor states are given by the general expression (1.4).

Neutrino oscillations in matter may differ from the oscillations in vacuum in a very significant way. The most striking manifestation of the matter effects on neutrino oscillations is the resonance enhancement of the oscillation probability – the Mikheyev - Smirnov - Wolfenstein (MSW) effect. Matter can enhance neutrino mixing, and the probabilities of neutrino oscillations in matter can be large (close to unity) even if the mixing angle in vacuum is very small.

Neutrinos of all three flavors – ν_e , ν_μ and ν_τ – interact with the electrons, protons and neutrons of matter through neutral current (NC) interaction mediated by Z^0-bosons. Electron neutrinos in addition have charged current (CC) interactions with the electrons of the medium, which are mediated by the $W^\pm$ exchange. So the evolution equation in the flavor basis is

$$i\frac{d}{dt}|\nu_a\rangle = \hat{H}|\nu_a\rangle = \left[U\hat{H}_0 U^\dagger + W(t)\right]|\nu_a\rangle, \tag{1.10}$$

where $\hat{H}_0 = diag(E_1, E_2, E_3)$, U is expression (1.9) and $W(t) = \pm\sqrt{2}G_F N_e$. We used G_F is the Fermi constant and N_e is the number density of electrons in the medium. [1], [2].

1.2 Neutrino mass hierarchy

Determination of mass eigenstates is one of the remaining undetermined fundamental features of the neutrino Standard Model. Experiments observing the oscillations of neutrinos produced in the sun have determined the squared difference of the masses m_1 and m_2, $\Delta m_{12}^2 = m_1^2 - m_2^2$, and the squared difference between the masses m_1 and m_3 as been measured using the oscillations of neutrinos produced in the Earth's atmosphere. At the present time, we cannot decide whether the ν_3 neutrino mass eigenstate is heavier or lighter than the ν_2 and ν_1 neutrino mass eigenstates in nature. These question is known as the neutrino mass hierarchy problem. The scenario, in which the ν_3 is heavier, is referred to as the normal mass hierarchy (NH). The other scenario, in which the ν_3 is lighter, is referred to as the inverted mass hierarchy (IH).

Accelerator and reactor experiments (NOνA,JUNO and other) want to decide the neutrino mass hierarchy problem. Let's discuss the NOνA experiment.

1.3 NOνA experiment

Neutrinos at the Main Injector Off-Axis ν_e Appearance (NOνA) experiment uses two detectors: a 330 metric-ton near detector at Fermilab and a much larger 14 metric-kiloton far detector in Minnesota just south of the U.S.-Canada border. The detectors are made up of 344000 cells of extruded, highly reflective plastic PVC filled with liquid scintillator. Each cell in the far detector measures 3.9 cm wide, 6.0 cm deep and 15.5 meters long. When a neutrino strikes an atom in the liquid scintillator, it releases a burst of charged particles. As these particles come to rest in the detector, their energy is collected using wavelength-shifting fibers connected to photo-detectors. Using the pattern of light seen by the photo-detectors, scientists can determine what kind of neutrino caused the interaction and what its energy was. The NOνA detector is located slightly off the centerline of the neutrino beam coming from Fermilab. At this off-axis location, scientists find a large flux of neutrinos at an energy of 2 GeV, the energy at which oscillation from muon neutrinos to electron neutrinos is expected to be at a maximum. More information about NOνA experiment you can read here [3].

In any accelerator experiment, neutrinos are generated by a high-energy proton beam striking a nuclear target to produce pions and kaons, which in turn decay into neutrinos and muons. First, energetic secondary pions and kaons are produced when high-energy proton beams interact with the nuclear target. Second, some of the charged pions and kaons within certain momentum range are focused by magnets, so that they are approximately traveling in parallel with the incident proton beam direction. The polarity of the magnet can be selected by changing the current in order to focus either the positive or negative charged particles. The charged pions and kaons then travel through a long decay pipe to provide enough time for them to decay. Finally, a thick absorber is placed at the end of decay pipe to absorb the muons (decay products of pions and kaons) and other remaining charged particles. [4]

In Long Baseline neutrino experiments NOνA also T2K and DUNE use Earth's crust as media for propagated neutrino flux. Due to the different sign in the matter term in the Hamiltonian the oscillation probability for neutrinos (i.e. number of oscillated neutrinos) is enhanced while the oscillation probability decreases for antineutrinos. Matter effects play a crucial role in measuring mass hierarchy in these experiments. [5], [6].

Beside the matter effect, MH can be determined by exploring the small difference (Δm^2_{21}) between Δm^2_{31} and Δm^2_{32} in the three-flavor neutrino framework with neutrino and antineutrino disappearance. This is what reactor neutrino experiment can do, for example, JUNO.

1.4 JUNO experiment

Jiangmen Underground Neutrino Observatory (JUNO) is a reactor neutrino experiment under construction in Jiangmen City, Guangdong Province, China. The JUNO detector will mostly receive ν_e from two reactor complexes at Taishan and Yangjiang. The average baseline of JUNO is 52.5 km with a RMS (root mean square) of 0.25 km. The experiment aims to achieve an energy resolution of better than 1.9 % at 2.5 MeV, which is essential for the MH determination.

Nuclear power reactors produce electricity by the sustained nuclear chain reaction, and are essentially pure electron antineutrino $\bar{\nu}_e$ sources. For each 1 gigawatt (GW) of the reactor thermal power, about 2×10^{20} $\bar{\nu}_e$ are emitted isotropically every second, making nuclear reactors one of the most powerful man-made neutrino sources. [7]

JUNO is designed to resolve the neutrino mass hierarchy using precision spectral measurements of reactor antineutrino oscillations.

Chapter 2

Global neutrino analysis

Global neutrino analysis (GNA) is a program, which can be used for neutrino oscillations analysis in different experiments. JINR group created this software and they are actively developing it. GNA principles is to introduce a number of simple independent computational blocks representing all the inputs or mathematical operations required to build a theoretical model of any experiment. The task of the user (analyzer) is to use those blocks as ingredient to construct a computational graph producing the theoretical predictions and finally the desirable statistic. Since the blocks are small, simple and independent, they may be easily implemented in a relatively low-level language (namely C++) making all the repeating computations fast, while all the relations between them may be expressed by means of a slower but dynamic language (namely Python), leading to great flexibility. [8]

Let's show following challenges, which can be solved with GNA.

A simple experiment

We can create some Gaussian peak and shift the position of any Gaussian to an arbitrary point. For very simple observable of event counts N: constant background b plus signal with strength μ, which is Gaussian-shaped peak at E_0 with width w the formula is

$$\frac{dN}{dE} = b + \mu \frac{1}{\sqrt{2\pi w}} \exp \frac{-(E - E_0)^2}{2w^2} \tag{2.1}$$

When we create tow Gaussian peak with $E_0^{(1)} = 1.9$, $E_0^{(2)} = 2.1$, we get the figure 2.1. GNA has analysis χ^2, which you can use. Also we can minimize this data and fit the shifted Gaussian with not shifted. The Gaussian peak can be n-peaks, so we can create more intricate experiment, for example, the figure 2.2. Here Theory has tow peaks with different E_0, and Data has tow peaks with different strength μ and E_0. For this case the χ^2-function is the right of the figure 2.2.

Minimizator

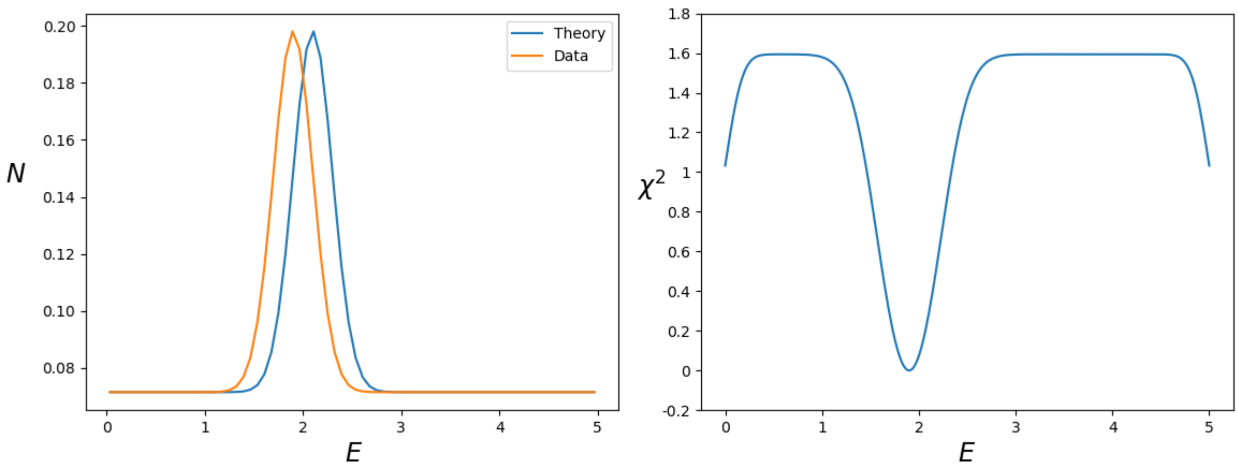

Figure 2.1: The simple experiment and statistical analysis by $chi^2(E)$.

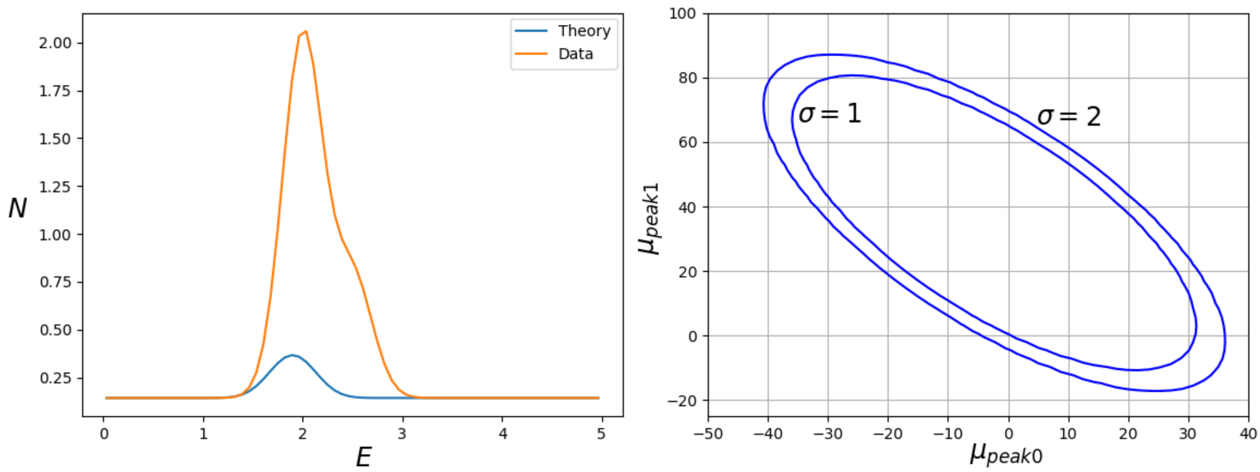

Figure 2.2: Gaussian with 2-peaks ans contour χ^2 by strength of peaks.

Certainly the Gaussian peak example we have used before is a very simple experiment model. To include some real life experiments into analysis more work have to be done to implement the whole computational graph leading to the experimentally observable values. So at the moment, the only implemented experimental model which have physical sense is the reactor experiment model. We'll check new GNA module about accelerator experiment in this paper in chapter 3.

The computation of observable spectrum is generally done with the following formula:

$$N_i = \int_{E_i}^{E_{i+1}} dE \int dE_\nu \frac{dE}{dE_\nu} \sigma(E_\nu) P(E_\nu) \sum_k n_k S_k(E_\nu) \tag{2.2}$$

N_i is the event number in the i-th bin containing events with energies $[E_i, E_{i+1}]$; E and E_ν is the positron and neutrino energy; $\sigma(E_\nu)$ is the inverse beta decay

(IBD) cross section; $P(E_\nu)$ is the oscillation probability; $S_k(E_\nu)$ is the neutrino spectrum of the k-th isotope with corresponding normalization n_k. The vacuum oscillation probability has the following structure:

$$P(E_\nu) = \sum_j w_j(\theta) P_j(\Delta m^2, E_\nu) \tag{2.3}$$

where the mixing angle only dependent weights w_j and mass difference dependent oscillatory terms P_j are factorized. Since only the oscillatory terms are energy dependent, when doing fits it's more computationally efficient to take the weights out of the integrals, making the re-computations a lot faster if only mixing angles are changed. The corresponding formula, which is implemented in code is:

$$N_i = \sum_j w_j \int_{E_i}^{E_{i+1}} dE \int dE_\nu \frac{dE}{dE_\nu} \sigma(E_\nu) P_j(E_\nu) \sum_k n_k S_k(E_\nu) \tag{2.4}$$

The given formula are only for the case of one reactor. If there are several of them, an additional summation inside the integral should be performed.

The formula (2.4) give us distribution at the left of the figure 2.3 and we can get the analogous χ^2-analysis at the right.

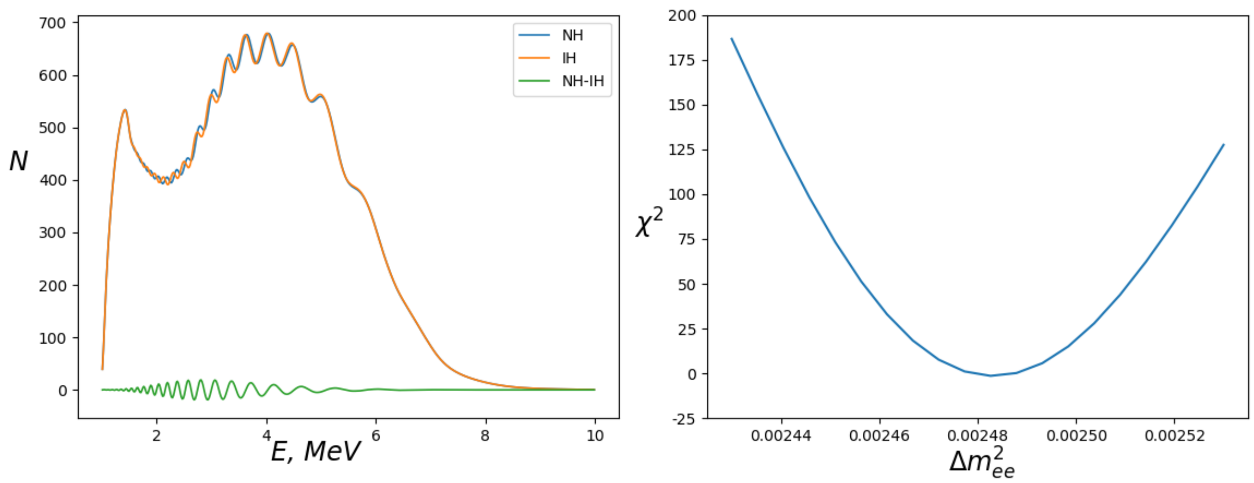

Figure 2.3: The expected spectra for normal (NH) and inverted (IH) hierarchies. χ^2 analysis by parameters Δm^2_{ee}.

Flux and cross − section

When we become the necessary modules in GNA, we can look at parameters such as cross-section or isotope spectra for all fissioned isotope in reactors. This is the figure 2.4.

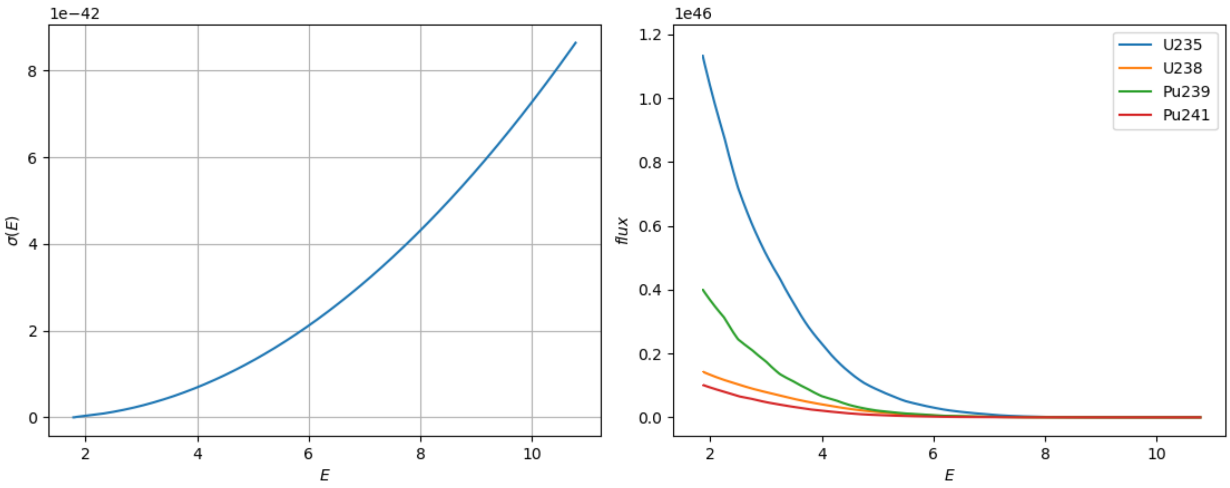

Figure 2.4: Cross-section against E_ν at the left and isotope spectra against neutrino energies at the right.

GNA modules

GNA has some modules. For example, the *script* is a module that allow you inject and execute arbitrary Python inside of GNA. One can access observables, parameters, create new datasets. So we reproduced a famous plot of P_{ee} vs L for reactor experiments (Daya Bay, JUNO, KamLAND). The result of this program is figure 2.5.

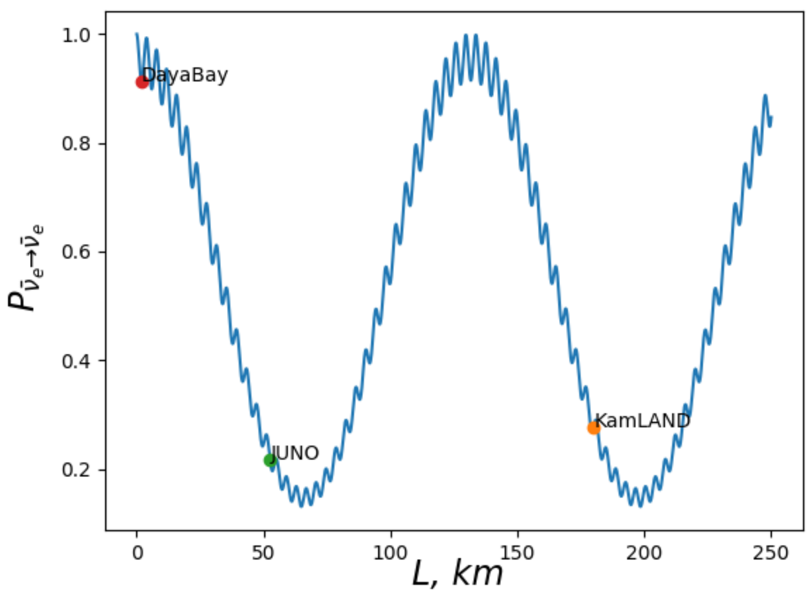

Figure 2.5: Survival probability of $\bar{\nu}_e$ for reactor experiments.

In the chapter we explained several examples of using GNA software within reactor neutrino experiments. And in was a 1-st part of SSP-17. Similar diagrams of relationship between oscillations probability and L or E we can create for NOνA experiment. So we've developed a new module, which do it. We'll discuss about it in following chapter.

Chapter 3

GNA and NOνA

During the Summer Student Programme we create new module in GNA. It is $OscProbMatterUniform$. It allows us to take into account the matter effect when we calculate the probability of oscillations for neutrino and antineutrino of three flavors. In the code we assumed that the Earth density is constantly and numerically equal $\rho = 2.7\ g/cm^3$. When $\rho = 0\ g/cm^3$ we get simple vacuum oscillations. We created the figure 3.1, which shows how the oscillations probability depends on hierarchy and type of particle. We see that the neutrino oscillations in matter become stronger in the normal hierarchy, but the antineutrino oscillations become stronger in the inverted hierarchy. So we can distinguish hierarchies in the NOνA experiment.

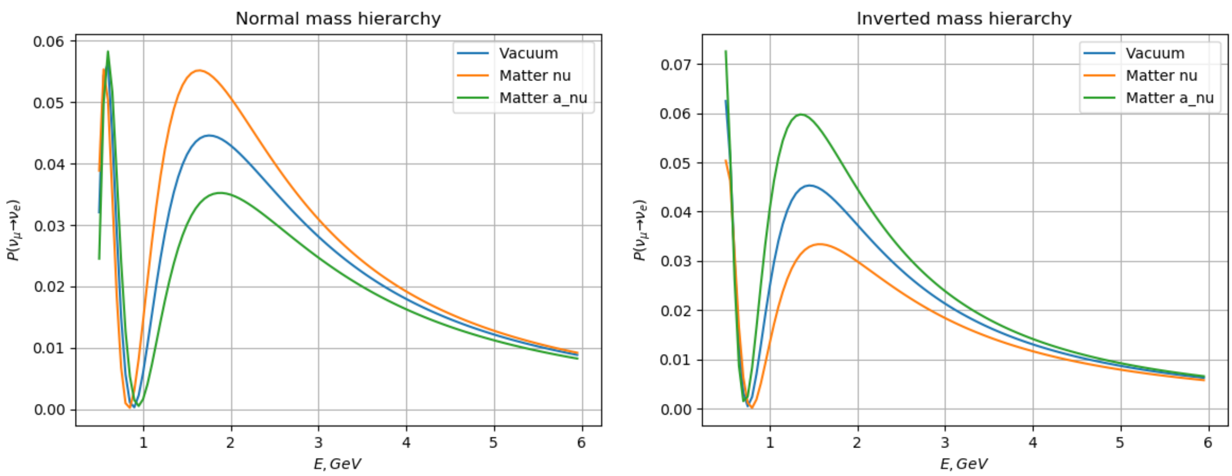

Figure 3.1: Oscillations probability of ν and $\bar{\nu}$ in vacuum and matter for the normal hierarchy at the left and inverse hierarchy at the right.

The simpler way to illustrate the experiment's ability to measure the mass hierarchy and δ_{CP} is a graph with two probabilities of oscillations for neutrino and antineutrino. This graph we can create with the new module (figure 3.2). Here we assumed that $E_\nu = 2\ GeV$, $\sin^2\theta_{23} = 0.5$.

Actually the latest analysis results for NOνA gave that for the mode of disappearance of muon neutrinos parameter $sin^2\theta_{23} = 0.403^{+0.030}_{-0.022}\ or\ 0.626^{+0.022}_{-0.030}$ for normal hierarchy and $sin^2\theta_{23} = 0.396^{+0.030}_{-0.022}\ or\ 0.618^{+0.022}_{-0.030}$ for inverted hierarchy

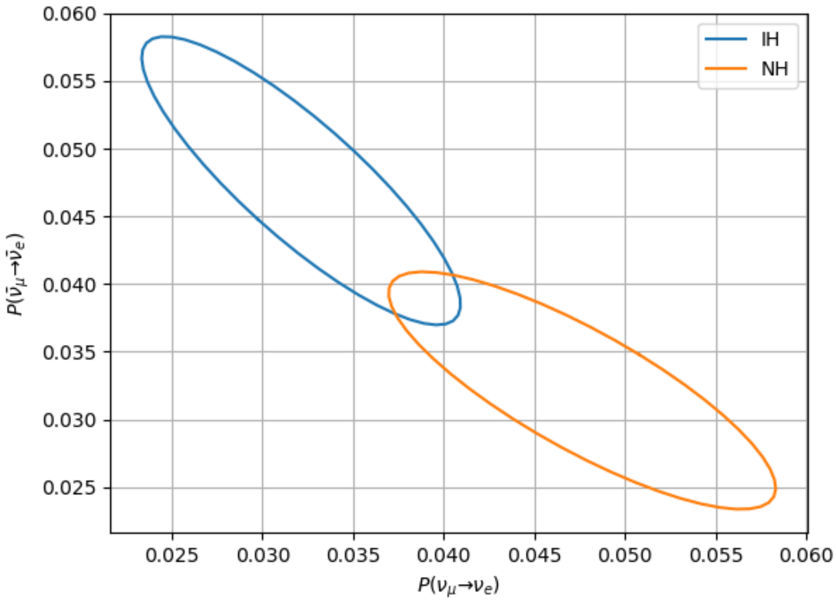

Figure 3.2: Oscillation probability $\nu_\mu \to \bar{\nu}_e$ for neutrino and antineutrino mode for NOνA for normal and inverted hierarchy. Every point on each ellipse implies different δ_{CP}.

(figure 3.3) [9]. So it is interesting to see how the oscillations probability varies with this parameter.

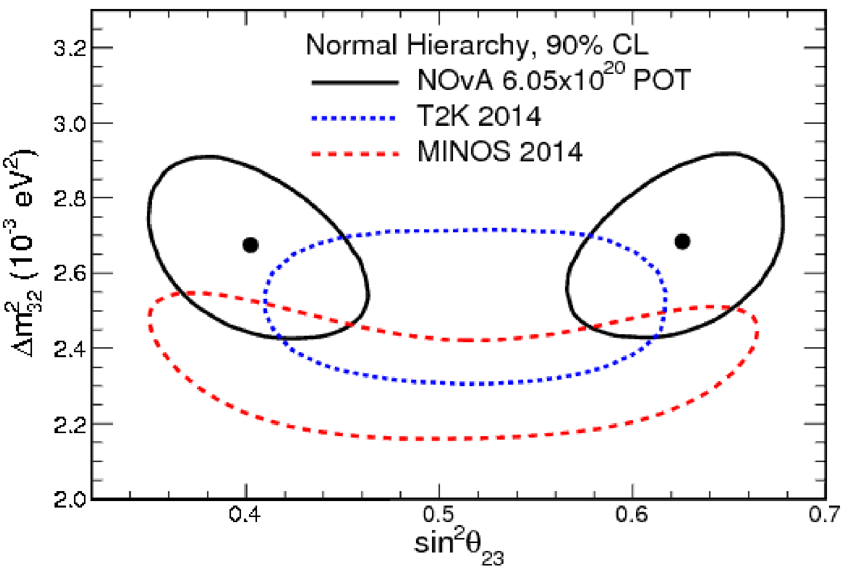

Figure 3.3: Best fit (black dots) and allowed 90% C.L. regions (solid black curves) of $\sin^2\theta_{23}$ and Δm^2_{32} for the NH [10].

GNA works well, so that we can freely change this parameters. For $sin^2\theta_{23} = 0.4,\ 0.5,\ 0.6$ we got figure 3.4. So when we get data from experiment for the mode of neutrino and antineutrino, we can determine the mass hierarchy and

δ_{CP}. We see splitting between those ellipses for lower θ_{23} octane in comparison with θ_{23} maximal mixing (central values).

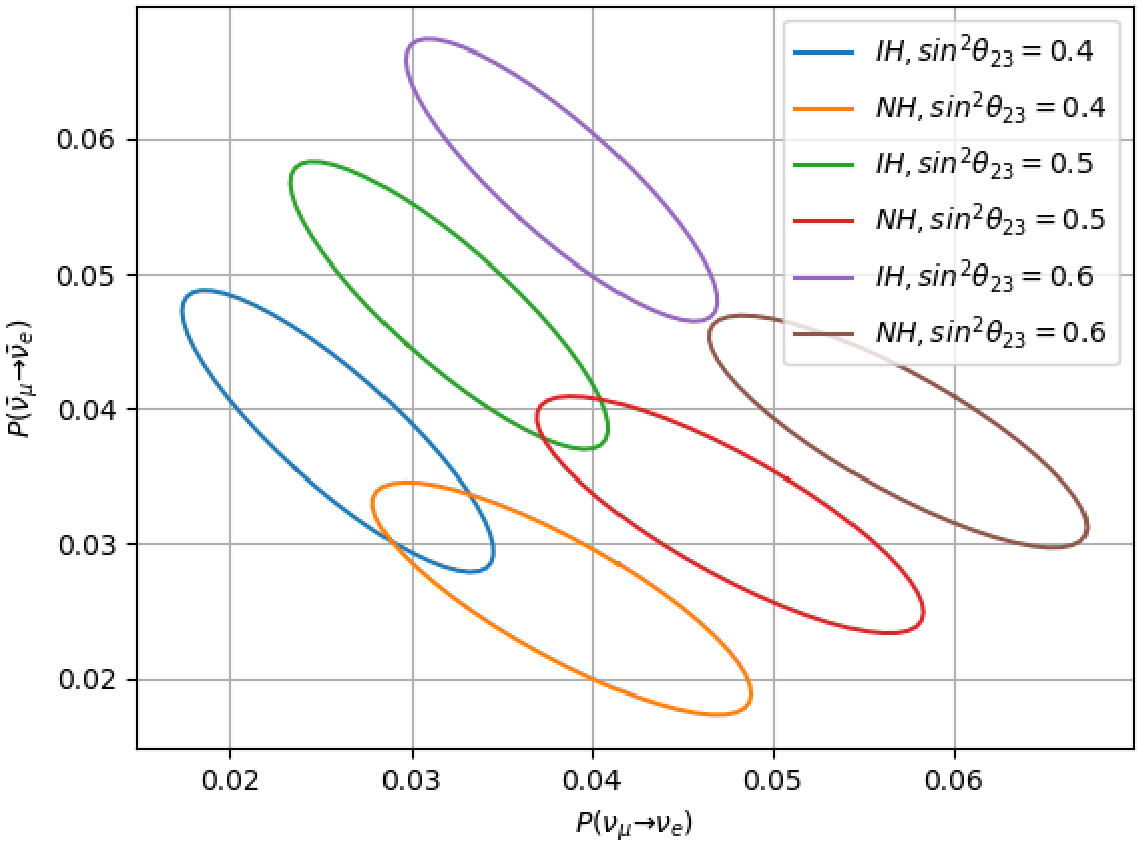

Figure 3.4: Oscillation probability $\nu_\mu \to \bar{\nu}_e$ for neutrino and antineutrino mode for NOνA for normal and inverted hierarchy. Every point on each ellipse implies different δ_{CP}.

At the end of the program, we implementing new module *nova.py* describing NOνA experiment setup in GNA. That module includes: lax, cross-section, resolution and effective. But this work is still ongoing and it is under debugging stage.

Conclusion

Now many international collaborations are working on the problems of neutrino physics. So in this report we give a short overview of neutrino physics. Neutrino oscillations are the most sensitive method investigating neutrino mass and neutrino mixing parameters.

Neutrino experiments give answers, which it is necessary to analyze. For this JINR group created GNA software and they are actively developing it. This work contributed to the development of GNA.

Test of $OscProbMatterUniform$ showed, that the new module for accelerator neutrino in GNA is operating correctly. In the near future, it is planned to add modules for calculating the cross section and neutrino flux for accelerator experiments with a long base. When we finish, we will be able to do global analysis for reactor and accelerator experiments with GNA. We implementing new module *nova.py* describing NOνA experiment setup in GNA. That module includes: lax, cross-section, resolution and effective. But this work is still ongoing and it is under debugging stage.

Bibliography

[1] Akhmedov E.Kh. Neutrino physics / E.Kh. Akhmedov // ICTP Series in Theoretical Physics. –1999. –Vol. 16. –P. 103 – 164.

[2] Taichenachev D. Determination of the neutrino mass hierarchy in reactor and accelerator experiments / D. Taichenachev // Diploma thesis ISU, JINR –2014.

[3] NOvA Technical Design Repor // https://www-nova.fnal.gov/nova_cd2_review/tdr_oct_23/tdr.htm

[4] Qian X. Neutrino Mass Hierarchy / X. Qian, P. Vogel // arXiv:1505.01891 [hep-ex]

[5] Kolupaeva L. Matter effect in neutrino oscillations for NOνA experiment / L. Kolupaeva, O. Samoylov, I. Shandrov // NOVA Document 14985-v2

[6] Kolupaeva L. Analysis of the matter effect on neutrino oscillations in accelerator experiments with a long baseline / L. Kolupaeva // Diploma thesis MSU, JINR –2017.

[7] Fengpeng An Neutrino Physics with JUNO / Fengpeng An, Guangpeng An, Qi An et al. // arXiv:1507.05613 [physics.ins-det]

[8] GNA repository // https://git.jinr.ru/gna/gna

[9] Adamson P. Constraints on oscillation parameters from ν_e appearance and ν_μ disappearance in NOνA / P. Adamson, L. Aliaga, D. Ambrose et al. // arXiv:1703.03328 [hep-ex]

[10] Adamson P. Measurement of the neutrino mixing angle θ_{23} in NOνA / P. Adamson, L. Aliaga, D. Ambrose et al. // arXiv:1701.05891 [hep-ex]