

Long Baseline Neutrino Facility

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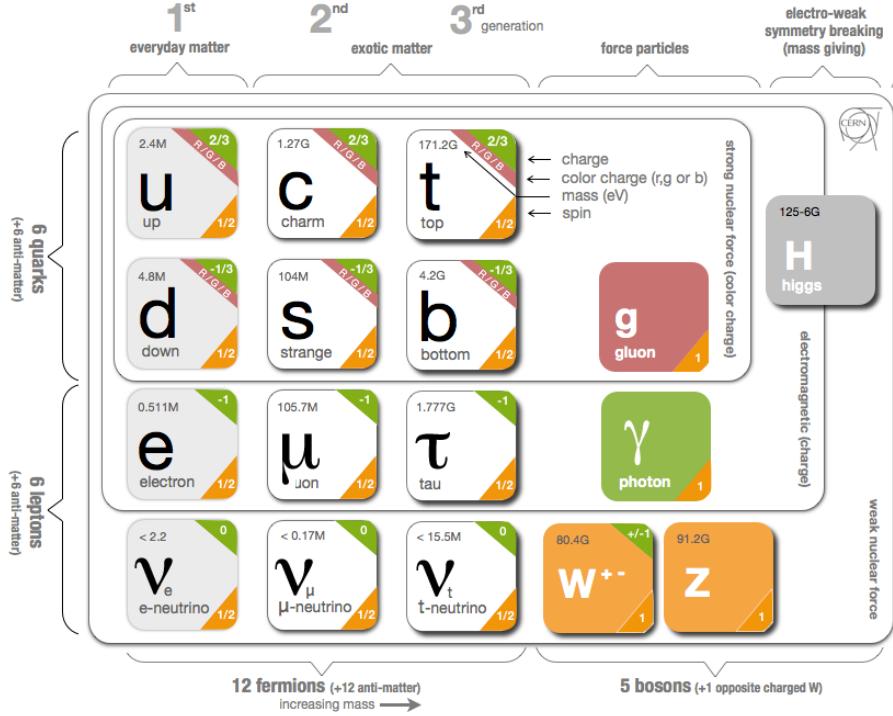
Abstract

The paper reviews the techniques of the Long Baseline Neutrino Facility, which is currently under construction, as the most ambitious experiment to study neutrino oscillations in the World. General properties of neutrinos, theoretical and historical backgrounds of the oscillations, techniques and achievements of several other experiments are also discussed. The paper is prepared as a part of the author's Comprehensive Exam at the Physics&Astronomy Department of the University of Nebraska-Lincoln.

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Figure 1: Fundamental particles and interactions. Three generations of fundamental particles and interaction mediators. Charged leptons and quarks are subjects to electromagnetic interactions (through photons). Quarks can also interact strongly (through gluons). All leptons and quarks can interact weakly (through W^\pm and Z^0 bosons). All these and only these fundamental particles are discovered at the moment. Source of picture: [9]



1 Introduction. Neutrinos as Fundamental Standard Model Particles

The Standard Model can be summarized in a table like one at fig. 1. It includes three charged leptons, three neutrinos and six quarks and their antiparticles which are splitted into three generations. In addition, it includes gauge bosons, Higgs boson and three fundamental interactions: electromagnetic, strong and weak. Charged particles, which include three leptons (electrons, muons and τ -leptons), all quarks, W -bosons and their antiparticles can interact electromagnetically, through exchange of virtual photon. Quarks also posses additional quantum number which is called "color" and can also participate in strong couplings, through exchange of gluons. All those particles and also neutrinos can interact through weak interactions through charged current (CC), by exchanging W -boson, and through neutral current (NC), by exchanging Z -boson. The corresponding Feynmann diagrams for the NC and CC are shown at fig. 2

All known substance in the Universe consists of millions of different molecules which are composed by hundreds different atoms. Each atom consists of certain number of protons, neutrons and electrons. All protons and neutrons are composed of three quarks (uud for proton and udd for neutron) which are glued together by strong interactions. Therefore, all known substance consists on only three fundamental particles from the fig. 1: u- and d-quarks and electrons. Despite neutrinos are not part of substances, large number of them exist in the nature, without any human-built machines. Quoting [2], 11.1: "John Bahcall, who was responsible for most of the calculations of solar neutrino abundances, liked to say that 100 billion neutrinos pass through your thumbnail every second; and yet they are so ethereal that you can look forward to only one or two neutrino-induced reaction in your body during your entire lifetime".

Figure 2: Feynmann diagrams of neutral current (NC, left), and neutral current (CC, middle and right) neutrino scattering.

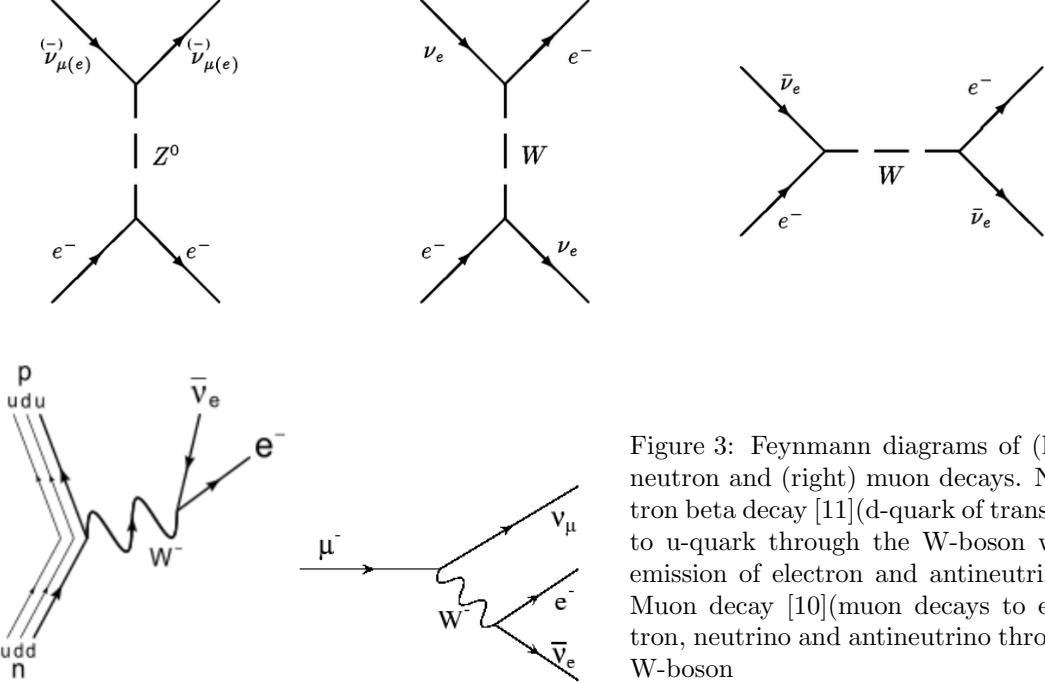


Figure 3: Feynmann diagrams of (left) neutron and (right) muon decays. Neutron beta decay [11](d-quark of transfers to u-quark through the W-boson with emission of electron and antineutrino). Muon decay [10](muon decays to electron, neutrino and antineutrino through W-boson)

Two very common and well known interactions with neutrino participation are neutron beta decay and muon decay. The Feynmann diagrams of these processes are shown at ???. Mean lifetime of free neutron is 15 minutes and > 99.9% of those which decay will do it though the beta decay: $n \rightarrow p + e^- + \bar{\nu}_e$ [1]. At the level of fundamental particles, neutron consists of two d-quarks and one u-quark and in the beta decay one of the d-quarks transfers to u-quark though the weak interaction mediated by W^- boson. Thus, the proton, which consists of two u-quark and one d-quark, is being produced. When this happens, the electron and electron antineutrino are emitted to preserve the charge and the lepton Flavor number conserved. The examples of the neutron beta decay in nature include $^{49}_{19}K \rightarrow ^{40}_{20}Ca$, $^{64}_{29}Cu \rightarrow ^{64}_{30}Zn$, $^3_1H \rightarrow ^3_2He$ [2] (the positive beta decay, $p \rightarrow n + e^+ + \nu_e$, is not possible for free proton but it can happen when the proton is the part of the nuclei). As for the muon, it's mean lifetime is $2\mu s$ and 99% of muons which decay would do that to electron, muon neutrino and electron antineutrino as $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$ though the the W boson. This process is also common in nature, in cosmic rays: muons are produced in the upper layers of the Earth atmosphere from the interaction of the particles coming from cosmics with the atmosphere molecules though the reaction, for instance, $p + p \rightarrow n + p + \pi^+$ with further pion decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and then some number of muons decay $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ while traveling through the atmosphere to the ground. The scheme of the shower in the Earth atmosphere induced by the primary incident proton is shown on fig. 4.

There are three flavors of neutrino, one for each generation: electron neutrino, muon neutrino, τ -neutrino. And in the processes described above (neutron beta decay and muon decay) the lepton flavor numbers L_e , L_μ and L_τ are conserved. The table 1 shows the value of this number for all leptons and antileptons.

The lepton flavor numbers are conserved in almost all particle physics processes and the only violation of this law observed by this time is the neutrino oscillations - the ability of neutrino to change flavor.

This paper reviews the theoretical background and the most important experimental measurements related to the neutrino oscillations, related open physics questions which raised over the last several decades, and techniques of the future experiment Long Baseline Neutrino Facility and the anvantages it will have over the other experiments of this kind.

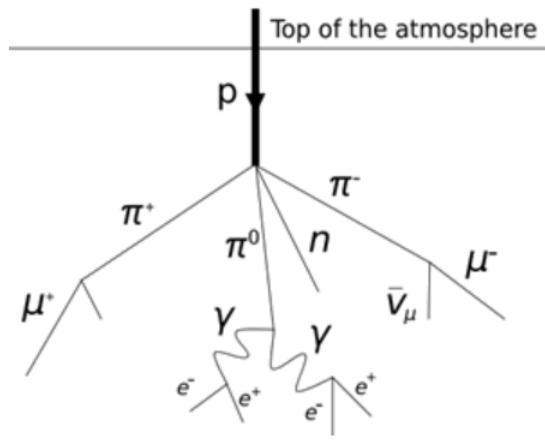


Figure 4: Cosmic shower induced by scattering of the incident cosmics proton of an air molecule. Charged and neutron pions are born in the reaction and then they further decay as $\pi^0 \rightarrow \gamma\gamma$, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$.

Table 1: Lepton Flavor Number

particles	L_e	L_μ	L_τ
e^-, ν_e	+1	0	0
$e^+, \bar{\nu}_e$	-1	0	0
μ^-, ν_μ	0	+1	0
$\mu^+, \bar{\nu}_\mu$	0	-1	0
τ^-, ν_τ	0	0	+1
$\tau^+, \bar{\nu}_\tau$	0	0	-1

2 Neutrino Oscillations. History and Status

2.1 First Discovery and Confirmation

History of the discovery of these phenomena is described in [2], chapter 11. The first evidence of the neutrino oscillations had place in the Ray Davis's experiment in 1968 with solar neutrinos which registered number of neutrinos three times smaller than theoretically predicted. The phenomenon was called "solar neutrino problem". This experiment used Chlorine radiochemical detector neutrino interacted with chlorine-37 atom and converted it to argon-37 through the reaction $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e$ or, at more fundamental level, $\nu_e + n \rightarrow p + e$. Then argon atoms were separated and counted. The detector was sensitive to electron neutrinos only. Soon after Bruno Pontecorvo proposed the explanation to the solar neutrino problem that neutrino can change its flavor on its way from the Sun to the detector. The theory was confirmed in 2001 by Super-Kamiokande collaboration. This experiment used water detector and could register any sort of neutrino through the $e + \nu \rightarrow e + \nu$ scattering. But the NC scattering can not distinguish between different neutrino flavors and also electron neutrinos could interact through CC which made detection efficiency of electron neutrinos 6.5 times higher than other flavors. They assumed all neutrinos to be electron neutrinos and recorded 45% of the predicted amount. Thus, the Super-Kamiokande were able to register any neutrino but couldn't distinguish between neutrino flavor and had lower detection efficiency for non-electron neutrinos. Then the Sudbury Neutrino Observatory (SNO) which used heavy water and were able to measure separately electron and total neutrino flux, confirmed that some of neutrinos coming from the Sun are registered as ν_μ and ν_τ . The reactions in the detector's working volume can be summarized as the following:

- Homestake experiment (1968): $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e$
- Super-Kamiokande experiment (1998): $\nu + e \rightarrow \nu + e$
- Solar neutrino observatory (2002): $\nu_e + d \rightarrow p + p + e$, $\nu + d \rightarrow n + p + \nu$, $\nu + e \rightarrow \nu + e$

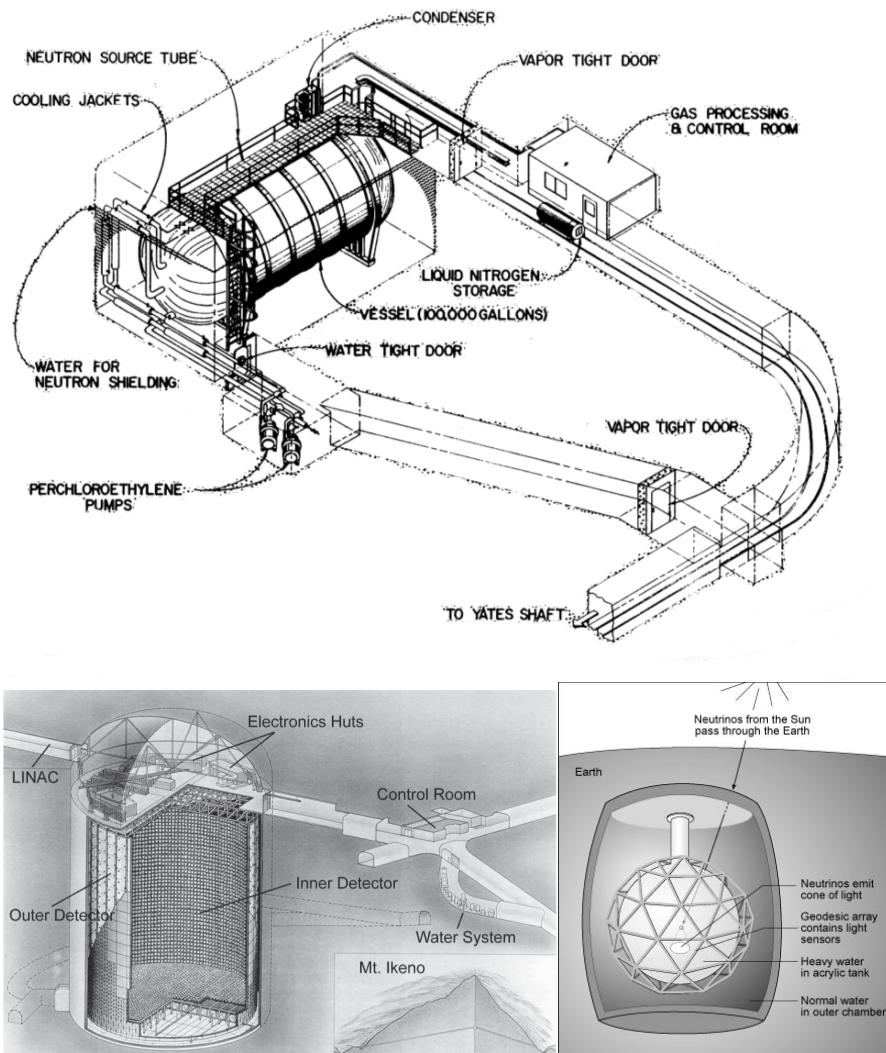
The result of the SNO was 35% of the ν_e predicted flux. Comparing it to the Super-Kamiokande results and knowing the detector was 6.5 times less sensitive to ν_μ and ν_τ , one could get $45\% = 35\% + 10\%$, $10\% \cdot 6.5 = 65\%$, $35\% + 60\% = 100\%$. After that, the neutrino oscillations theory is considered to be confirmed and the solar neutrino problem - resolved.

2.2 Neutrino Detection Techniques

Neutrinos can scatter on detector electrons through weak neutral current (Z-boson). In this interaction, electron would leave the nuclei and would be detected. By measuring electron momentum and energy, it would be possible to receive information about original neutrino energy and momentum but there would be no information about neutrino flavor. Also, neutrinos can interact through weak charged current (W^\pm -bosons) and produce charged lepton (e^\pm , μ^\pm or τ^\pm if tau-neutrino is energetic enough). The properties of charged lepton can be measured in the detector and then from momentum and energy conservation laws, the original neutrino properties will be reconstructed. Lepton flavor numbers are always conserved in these reactions and therefore it would be possible to determine the flavor of neutrino too (electron neutrino can only produce electron, muon neutrino can only produce muon and tau-neutrino can only produce tau-lepton). The wikipedia page of Neutrino Detectors list the main detection techniques which make possible to register neutrinos [8]:

- Scintillators. Was used in the first experiment which registered antineutrinos - Savannah River nuclear reactor experiment. Water with cadmium chloride solution was used as a target. Antineutrinos from the reactor interacted with protons of the target as $\bar{\nu}_e + p \rightarrow n + e^+$. Then positron annihilated with electron $e^+ + e^- \rightarrow \gamma + \gamma$ and the resulting photons are detected by scintillators. The neutron is captured by the cadmium nuclei with radiation of photon. This photon is also detected by the scintillator with delay of several microseconds.

Figure 5: Schemes of the Solar neutrino experiments: Homestake Experiment, Super Kamiokande and Sudbury Neutrino Oscillations



- Radiochemical methods. Chlorine radiochemical detector was used in south dakota experiment: neutrino interacted with chlorine-37 atom and converted it to argon-37. Then argon atoms were separated and counted. The experiment was the first to indicate the Solar Neutrino Problem. Same idea is used in certain experiments with gallium → germanium trasformation. The radiochemical methods are only useful for counting neutrinos but can't measure their kinematic characteristics.
- Cherenkov detectros. A charged particle travelling through the medium with speed $v > c/n$ where c/n - is speed of light in this medium radiate photons which are called Cherenkov radiation. In general, this is threshold type of detection - particle is either detected or not. However, by having several layers with different n (refractive index), it's possible to differentiate charged particles by velocities better. Common working substance for Cherenkov detectors in neutrino physics are ice, water and heavy water.
- Tracking calorimeters. For high energy neutrinos, neutral current weak interactions cause hadronic shower and charged current weak interactions cause electromagnetic shower. The showers produced by charged particle (product of original neutrino interaction) identify track parameters, momentum and energy of charged particle.

2.3 Theory of the Neutrino Oscillations

Lets consider two neutrinos case as it's described in Griffiths[2].

Suppose there are only two neutrinos ν_e and ν_μ . Then true stationary states of the system would be the orthogonal combinations:

$$\nu_1 = \nu_\mu \cos\theta - \nu_e \sin\theta$$

$$\nu_2 = \nu_\mu \sin\theta + \nu_e \cos\theta$$

Then, according to the quantum mechanics,

$$\nu_1(t) = \nu_1(0)e^{-\frac{iE_1 t}{\hbar}}, \nu_2(t) = \nu_2(0)e^{-\frac{iE_2 t}{\hbar}}$$

Suppose, at $t=0$ there were $\nu_e(0) = 1$, $\nu_\mu(0) = 0$

$$\text{Then } \nu_1(0) = -\sin\theta, \nu_2(0) = \cos\theta, \nu_1(t) = -\sin\theta e^{-\frac{iE_1 t}{\hbar}}, \nu_2(t) = -\cos\theta e^{-\frac{iE_2 t}{\hbar}}$$

Thus, we are getting the system:

$$-\sin\theta e^{-\frac{iE_1 t}{\hbar}} = \nu_\mu(t) \cos\theta - \nu_e(t) \sin\theta,$$

$$-\sin\theta e^{-\frac{iE_2 t}{\hbar}} = \nu_\mu(t) \sin\theta - \nu_e(t) \cos\theta$$

By solving this sytem for ν_e and ν_μ , one would get

$$P_{\nu_e \rightarrow \nu_\mu} = |\nu_\mu(t)|^2 = [\sin 2\theta \sin \frac{(E_1 - E_2)t}{2\hbar}]^2,$$

$$P_{\nu_\mu \rightarrow \nu_e} = |\nu_e(t)|^2 = 1 - [\sin 2\theta \sin \frac{(E_1 - E_2)t}{2\hbar}]^2$$

Thus, for freely travelling neutrinos, if ν_e was emmited, at any point there is a certain probability to register ν_e or ν_μ and those probablities change with time periodically, by $[\sin(At)]^2$ law. That's why the phenomenon is called the neutrino oscillations. Suppose momenta $p_1 = p_2$. Then using $E^2 = p^2 + m^2$ and assuming $m_{1,2} \ll E_{1,2}$, the probablities will take forms of

$$P_{\nu_e \rightarrow \nu_\mu} = |\nu_\mu(t)|^2 = [\sin 2\theta \sin \frac{(E_1 - E_2)t}{2\hbar}]^2 = [\sin 2\theta \sin \frac{(m_1^2 - m_2^2)c^3}{4\hbar E} z]^2$$

Three neutrino case is described in the "Long-baseline Neutrino Oscillation Physics" section of the draft Conceptual Design Report of the LBNF. For three neutrino case, the oscillations are determined by complex unitary matrix which is called Pontecorvo-Maki-Nakagava-Sakata (PMNS) matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The U_{PMNS} matrix depends on three neutrino mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and CP-violating phase δ_{CP} . If define $c_{ab} = \cos\theta(ab)$, $s_{ab} = \sin\theta(ab)$, the U_{PMNS} matrix can be splitted into three multipliers, each would be responsible for mixing of one pair of neutrino flavors:

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & e^{i\delta_{CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The probability amplitudes of neutrino mixing are defined by parameters of the U_{PMNS} but, analogous to simplified two-neutrino case described above, the differences of squares of neutrino masses also contribute to the probability. There are two independent expression for squares of masses differences: $\Delta m_{12}^2 = m_1^2 - m_2^2$ and $\Delta m_{32}^2 = m_3^2 - m_2^2$. Mass differences were measured in other neutrino oscillation experiments but the Δm_{12}^2 and Δm_{32}^2 present in the equations evenly and therefore the signs of these expressions were not measured. If the masses order as $m_3 > m_2 > m_1$, it's called normal neutrino mass hierarchy because other fundamental particles orders in a way that later generation particles have higher masses than lower generation particles. If the masses order as $m_1 > m_2 > m_3$ it's called inverted neutrino mass hierarchy. The mixing angles θ_{12} , θ_{23} , θ_{13} and differences of squared masses Δm_{12}^2 and Δm_{32}^2 are measured and give U_{PMNS} matrix form of

$$|U_{PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.5 & 0.6 & 0.6 \\ 0.2 & 0.6 & 0.8 \end{pmatrix}$$

The CP-violating phase δ_{CP} is unknown.

The analogous matrix for quark mixing, CabibboKobayashiMaskawa (CKM) matrix, is much more diagonal:

$$|V_{CKM}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

One of the important questions in modern particle physics is why the quark mixing angles are so much smaller than neutrino mixing angles and the other important question is whether there is any relationship between quark and neutrino mixing matrices.

The [14] gives the following expression for $\nu_\mu \rightarrow \nu_e$ probability in presence of the Earth matter assuming it has constant density:

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) \simeq & \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{13} - aL)}{(\Delta_{13} - aL)^2} \Delta_{31}^2 + \\ & + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \cos(\Delta_{31} + \delta_{CP}) + \\ & + \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2 \end{aligned}$$

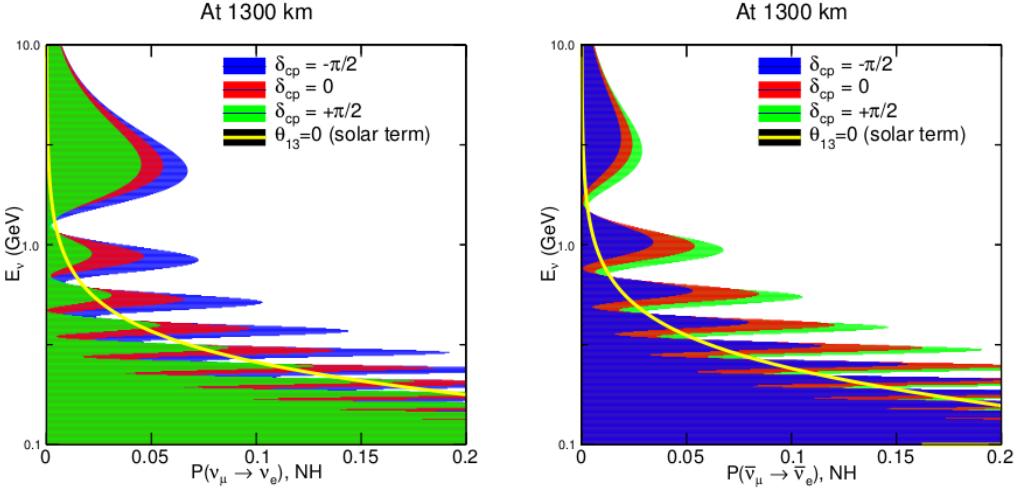
where $\Delta_{ij} = \Delta m_{ij}^2 L / 4E$, and $a = G_F N_e / \sqrt{2}$

For $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ one would need to change $\delta_{CP} \rightarrow -\delta_{CP}$ (because of neutrino-antineutrino assymetry for CP-violationg phase) and $a \rightarrow -a$ (because only electrons present in the Earth, not positrons). The effect of $a \rightarrow -a$ increases with L which means more sensitivity to mass hierarchy for experiments with larger baseline. The DUNE's baseline is 1300 km and it's expected to be enough to determine the neutrino mass hierarchy and also the CP-violation phase.

The figure6 shows that magnitude and frequency of oscillations both depend on δ_{CP} and the differences become more significant for higher oscillation nodes which correspond to lower energies of neutrino/antineutrino. Since changes due to different δ_{CP} s are opposite for neutrinos and antineutrinos, it's important for the experiment to operate both.

2.4 Recent Experimental Results

The neutrino oscillation parameters measured in other experiments are summarized in the table 2 as quoted in the PDG [1] (section Particle Listings → Leptons → Neutrino Mixing):

Figure 6: $P(\nu_\mu \rightarrow \nu_e)$ at a baseline of 1300 km

$P(\nu_\mu \rightarrow \nu_e)$ at a baseline of 1300 km, as a function of neutrino energy. Left - neutrinos, right - antineutrinos. Figure is taken from the LBNF CDR draft, volume physics[14]

Table 2: Neutrino oscillation parameters measured in other experiments

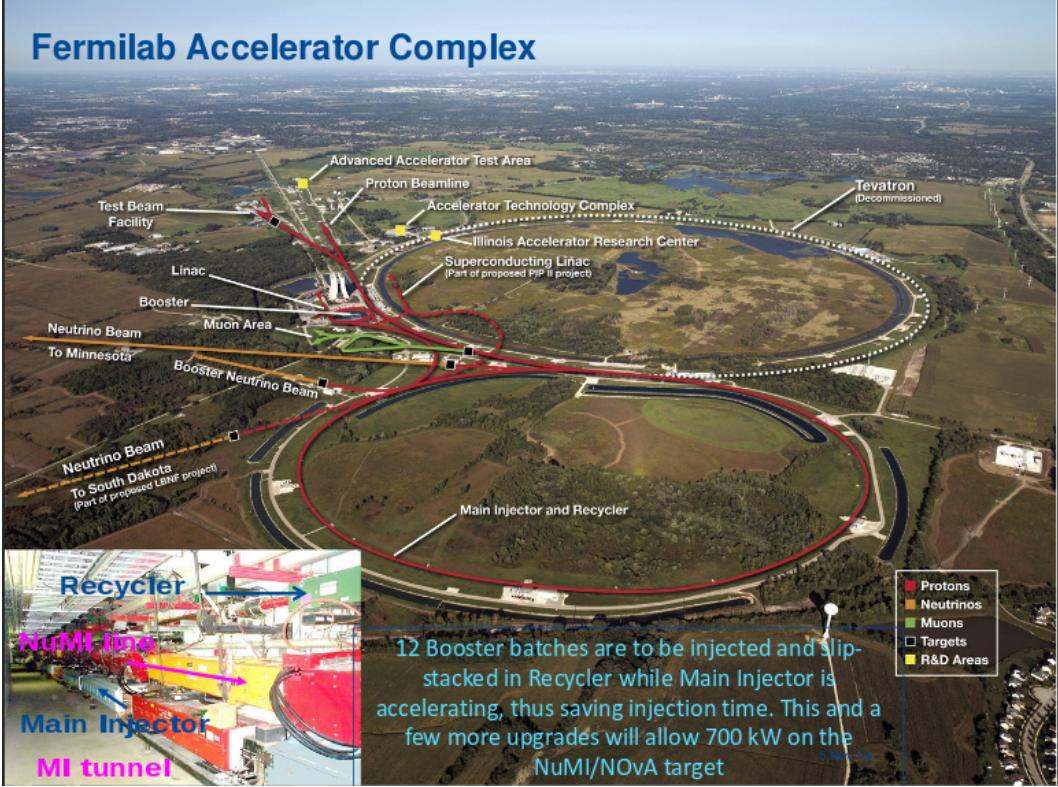
Parameter	Value and uncertainty	Experiment(s)
$\sin^2(2\theta_{12})$	0.846 ± 0.021	KamLAND + global solar + SBL +accelerator: 3ν
$\sin^2(2\theta_{23})$	$0.999^{+0.001}_{-0.018}$	T2K (if normal mass hierarchy)
$\sin^2(2\theta_{23})$	$1.000^{+0.000}_{-0.017}$	T2K (if inverted mass hierarchy)
$\sin^2(\theta_{13}), 10^{-2}$	9.3 ± 0.8	DayaBay, Chooz, Yonggwang
$\Delta m_{21}^2, 10^{-5} eV^2$	7.53 ± 0.18	KamLAND + global solar + SBL +accelerator: 3ν
$\Delta m_{32}^2, 10^{-3} eV^2$	2.44 ± 0.06	T2K, MINOS, DAYA(if normal mass hierarchy)
$\Delta m_{32}^2, 10^{-3} eV^2$	2.52 ± 0.07	T2K, MINOS, DAYA (if inverted mass hierarchy)

According Particle Data Group Review [1] the following questions will be the main priority to answer by current and future neutrino experiments:

- whether the massive neutrinos are Dirac or Majorana (Dirac means neutrinos and antineutrinos are different particles; Majorana means neutrinos are their own's antineutrinos)
- what is the mass hierarchy
- what the absolute values of neutrino masses are
- how does the CP-symmetry behaves in the lepton sector
- are the neutrino oscillations indication of new fundamental symmetry in particle physics
- what is the relation between neutrino and quark mixing if any
- what is the nature of the CP-violation terms in the neutrino mixing matrix
- can better understanding of neutrino mixing give a hint to baryon asymmetry in the Universe

In addition, more precise measurements of already measured mixing matrix parameters θ_{12} , θ_{23} , θ_{13} , Δm_{12}^2 , $|\Delta m_{31}^2|$ are part of new neutrino experiments physics programs.

Figure 7: The Fermilab Accelerator Complex as it is described in the presentation "The LBNF Beamlne and PIP-II" by Vaia Papadimitriou at the fisrt LBNF Collaboration meeting [16]



3 LBNF Experimental Setup

The Long Beamlne Neutrino Facility is the facility being internationally designed for the future Deep Underground Neutrino Experiment (DUNE) which has wide physics program for variety of precision measurements and searches beyond the Standard Model. The general scheme of the facility is shown on figure 8. This section gives more details on neutrino beam production and the detector descriptions. The information if taken mostly from the LBNF website [12] and the Conceptual Design Report which is currently under development but drafts are partially available [13], [14]. The first collaboration meeting took place on April 16th-18th of 2015 in Fermilab [16]. There were about 200 participants out of total of 750 members. The statuses and prospectives of the Near Detector, Far Detector, Neutrino beam, software infrastructure and other related technical topics were discussed. Most information written in this section is taken from the presentations of this collaboration meeting, the CDR drafts and the main pages of the LFNF website.

Scheme of the Fermilab accelerator complex is shown at the (fig. 7) and the overall scheme of the Long Baseline Neutrino Facility (LBNF) is shown at the (fig. 8). The protons from the accelerator will induce the neutrino beam which will be travel trough the Earth in direction of the Deep Underground Neutrino Experiment (DUNE) detector in South Dakota. It is common for the long baseline neutrino oscillations experiments to have a near detector (several hundred meters from the neutrino production) and far detector (hundreds of kilometers away). Comparing measurements of neutrino flux characteristics at two points allows to extract parameters of neutrino oscillations physics.

General requirements for the experiment are listed in [13].

- neutrino beam of high intensity which would be able to produce large amount of neutrinos to be registered at the far site
- the detector to register neutrinos and measure the beamline characteristics at the near site

Figure 8: Long Baseline Neutrino Facility (LBNF). The neutrino flux will be produced using existing proton accelerator in Fermilab. Then neutrinos will be registered by near detector, travel 800 miles through the Earth mantle to the Sanford Underground Research Facility in South Dakota and be registered by far detector. Source of figure: [12]

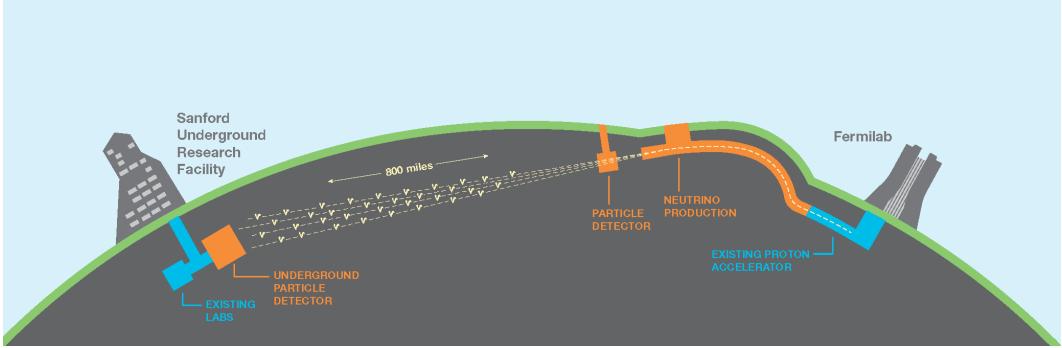
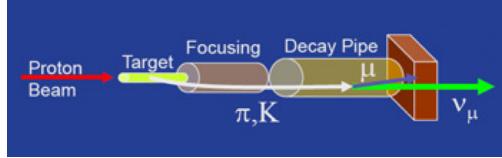


Figure 9: The neutrino beam production at the LBNF. Source of figure: [12]



- the liquid argon time-projection chamber for the far site detector (LArTPC)

3.1 Neutrino Beam

The LBNF neutrino beam will be the highest intensity neutrino beam ever created. The proton accelerator in Fermilab which was already used in other experiments in Fermilab before will produce the beam of protons. Then protons will hit a target and create kaons and pions through the same reactions as take place in atmosphere when the cosmic protons hit molecules of air. Pions can be created in the reactions $p+p \rightarrow p+n+\pi^+$, $p+p \rightarrow p+\Delta^{++}+\pi^-$, $p+n \rightarrow p+p+\pi^-$, $p+n \rightarrow n+n+\pi^+$, $p+n \rightarrow p+\Delta^-+\pi^+$ etc which go electromagnetically though photon. In more general words, one quark from the accelerator beam proton scatters on the other quark from the proton or neutron of the target substance. They exchange photon which produces quark-antiquark pair. At this moment, the system has seven quarks and one antiquark. The antiquark pairs up with one of the quarks participating in the reaction and the remaining six

Figure 10: Examples of the Feynmann diagrams of charged pion and kaon productions in proton-proton scattering.

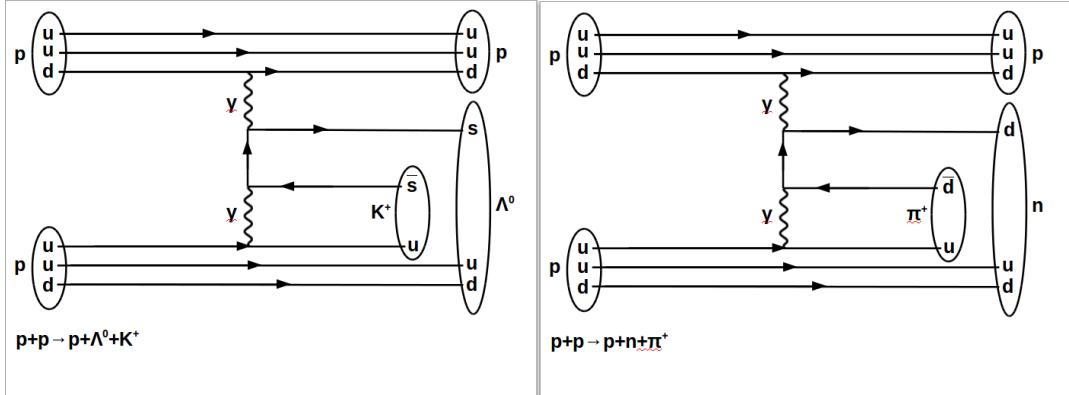
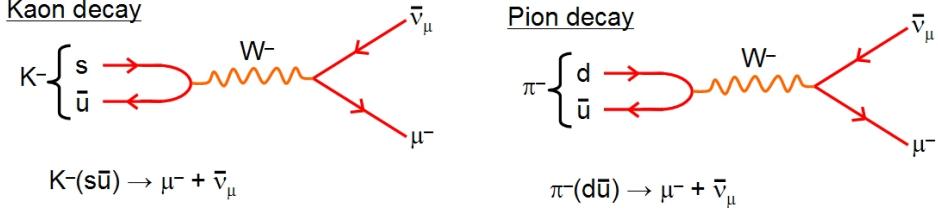


Figure 11: Feynmann diagrams of charged pion and kaon decays to muon and muon antineutrino weakly through W-boson. Figures taken from [15].



quarks make two baryons. The charged pions have formulas $\pi^+ = u\bar{d}$ and $\pi^- = \bar{u}d$ and can be produced with the reactions which only include first generation quarks. The formulas of charged kaons are $K^+ = u\bar{s}$, $K^- = \bar{u}s$. Thus, to produce kaons, the photon has to produce $s\bar{s}$ pair.

After the mesons are created, they go through the focusing camera and decay into the decay pipe (the length of the decay pipe is about 200 meters) as $\pi^+ \rightarrow \mu^+\nu_\mu$, $\pi^- \rightarrow \mu^-\bar{\nu}_\mu$, $K^+ \rightarrow \mu^+\nu_\mu$, $K^- \rightarrow \mu^-\bar{\nu}_\mu$. The branching ratios of charged pions and kaons to decay into $\mu^+\nu_\mu$ ($\mu^-\bar{\nu}_\mu$) are ($> 99.9\%$) and ($63.55 \pm 0.011\%$) respectively therefore most neutrinos produced into the decay pipe will be muon neutrinos. (While the neutral kaons can also be produced in the target and later decay in pions which could further decay and produce muon neutrinos, but the focusing is being done with the certain configuration of the magnetic field and thus only charged particles can be focused. Neutral pions, π^0 s, are very likely to be produced as well but they decay as $\pi^0 \rightarrow \gamma\gamma$ and thus can't contribute to the neutrino production.)

After being produced in the rections described above, the neutrinos will be detected in the close detector in the Fermilab. Then the neutrinos will travel 800 miles underground and will be detected by Sanford Underground Research Facility in South Dakota.

Beam requirements listed in the "Beam Requirements and Beam Optimization talk" during the first LBNF collaboaration meeting include:

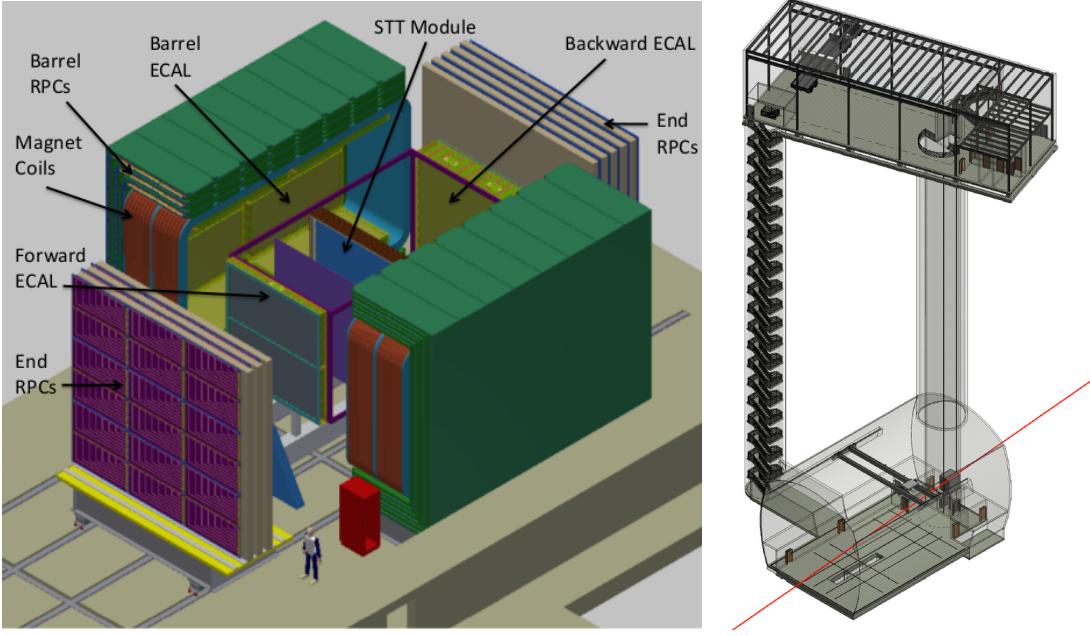
- the beam must have high intensity, be wide-band
- must be able to produce muon neutrinos or antineutrinos by experimenter's choice
- fraction of the opposite sign neutrinos must be small
- the energy range of the first oscillation node (1-5 GeV) must be fully covered
- the second oscillation node, ~ 0.8 GeV must be achievable too
- must work at $>\sim 2$ MW at 60-120 GeV/c
- the option to tuned the lower primary proton momenta down to 60 GeV/c must present
- the systematic error to the parameters of the neutrino flux must be reduced
- the parameters of the neutrino flux must be stable

3.2 Near Detector

A near detector is an important part of any long baseline neutrino oscillation experiment. It measures the primary neutrino beam flux as it is produced by the beam production system. Chapter 6 of the draft LBNF Conceptual Design Report (CDR) [13] lists the following precision measurements to be performed by the Near Detector:

- absolute flux measurement
- relative neutrino and antineutrino flux measurements

Figure 12: Scheme of the DUNE Near Detector (left) and related complex (right).



- flavor content of the neutrino source
- determination of the E_ν -scale of neutrinos versus antineutrinos
- event-by-event measurements of NC interactions
- measurement of $\pi^0, \pi^\pm, K^\pm, p, K_S^0$ and Λ in the NC and CC
- nucleon structure, parton distribution functions and QCD studies
- neutrino-argon interactions and nuclear effects
- precision measurements of electroweak physics

More specifically, the list of the physics measurements related to the neutrino oscillations to be performed by the Near Detector includes:

- fluxes of $\nu_\mu, \bar{\nu}_\mu, \nu_e$ and $\bar{\nu}_e$. To distinguish between flavors, the measurement should rely on charged current interaction (fig. 3, middle and right) and measure the products of these interactions μ^-, μ^+, e^- , and e^+ . (While the production has the highest probability to produce muon neutrinos, the production of certain number electron neutrinos is also possible, for example, from charged kaon decays)
- ν_e - $\bar{\nu}_e$ assymmetries for which will help with CP-violating phase measurement. For that, it's important not only distinguish between μ^\pm and e^\pm but also between e^- and e^+ .
- the absolute ν_μ and $\bar{\nu}_\mu$ fluxes need to be measured with $\simeq 3\%$ precision in the neutrino energy range 0.5-8 GeV
- cross section of NC versus CC processes as a function of hadronic energy. NC is one of major backgrounds which contribute to neutrino oscillation measurement
- yields of π_0 and photons. These particles are the most significant background to ν_e and $\bar{\nu}_e$ contamination
- fractions of the π^\pm into the CC and the NC hadronic jets.

The scheme of the near detector is shown at the fig. 12. The detector will consist of central Straw-Tube Tracker (STT) modules, electromagnetic calorimeter (ECAL), magnet coils of 0.4T and muon identification system consisting of Resistive Plate Chamber (RPC) modules. The neutrinos would come from the bottom left corner of the picture, to the End RPCs.

Quoting the LBNF website [12], "The DUNE near detector will require LBNF to excavate and provision a cavern 200 ft (60 m) below grade on the Fermilab site and to construct a surface building directly above it. An elevator will provide the primary access between the two spaces; the stairway shown is planned for emergency egress. This complex will be constructed a minimum of 690 feet (210 m) downstream of the beamline target."

3.3 Far Detector

That's how the LBNF website describes the far detector [12]: "The DUNE far detector will consist of four modules, each of which will be housed in a cryostat containing 17,000 metric tons of liquid argon target material. LBNF will excavate and provision a set of four caverns 5,000 ft (1500 m) underground arranged as a pair of double caverns, in which to place them. The double caverns, aligned parallel to the beam, will each have 50 ft (15 m) of rock separating two end-to-end modules. A fifth cavern, between the pair, will house the cryogenics equipment." General view pictures of the Sanford Underground Research Facility (SURF) in South Dakota are shown at fig. 13 and fig. 14. That's how Tia Miceli, postdoctoral researcher at New Mexico State University, in her post for the Fermilab today [23] explains why liquid argon is excellent working substance for the neutrino detectors: "For particle physics, perhaps liquid argon's most important feature is that it acts as both a target and detector for neutrinos [...] with 40 protons and neutrons, liquid argon is denser than water or oil, so liquid-argon detectors see more neutrino collisions per unit volume than their oil- or water-based predecessors. That means faster measurements and consequently faster discoveries. Another advantage of liquid argon is that, when a neutrino interacts with it and subsequently generates charged particles, it produces two separate kinds of signals; oil- or water-based detectors produce only one. One type of signal, unique to liquid argon, results from its ability to record the charged particles' trajectories. Charged particles are created in the liquid argon after a neutrino flies in and collides with an argon nucleus. The charged debris travels through the argon and easily knocks off electrons from the neighboring atoms along its path. The electronic traces in the liquid argon are pushed by an applied electric field toward an array of wires (similar to a guitar's) on the side of the detector. The wires collect data on the particle trajectories, producing a signal. The second signal type is one shared with oil- and water-based detection: a flash of light. When a charged particle bumps into an argon atom's electron, the electron transitions to a higher energy. As the electron transitions back to its original state, the excess energy is emitted as light. It turns out that argon is also relatively cheap. Companies liquefy air and heat it slowly. Since each of air's components has a unique boiling temperature, they can be separated. The boiled-off argon is moved to a separate chamber where it is again condensed. The commercially available liquid argon that we buy is still not pure enough for our experiments, so once the liquid argon arrives at the lab, we filter out the remaining impurities by a factor of 10,000." [she means for the proposed LBNE experiment which now transitioned to the discussed here LBNF]

The LBNF will provide the cryostats as well as the cryogenics equipment that is used to maintain the argon in the liquid state and to keep it pure and circulating smoothly during operations.

The Far Detector consists of

- Liquid Argon Time Projection Chamber (LArTPC)
- Data Acquisition System (DAQ)
- Cold Electronics
- Photon Detector (PD)

The liquid argon TPC is the main working volume of the detector. The chamber is merged into the liquid argon at temperature of 89 K. On the figure ?? the cathod plane assemblies

Figure 13: Sanford Underground Research Facility (SURF)

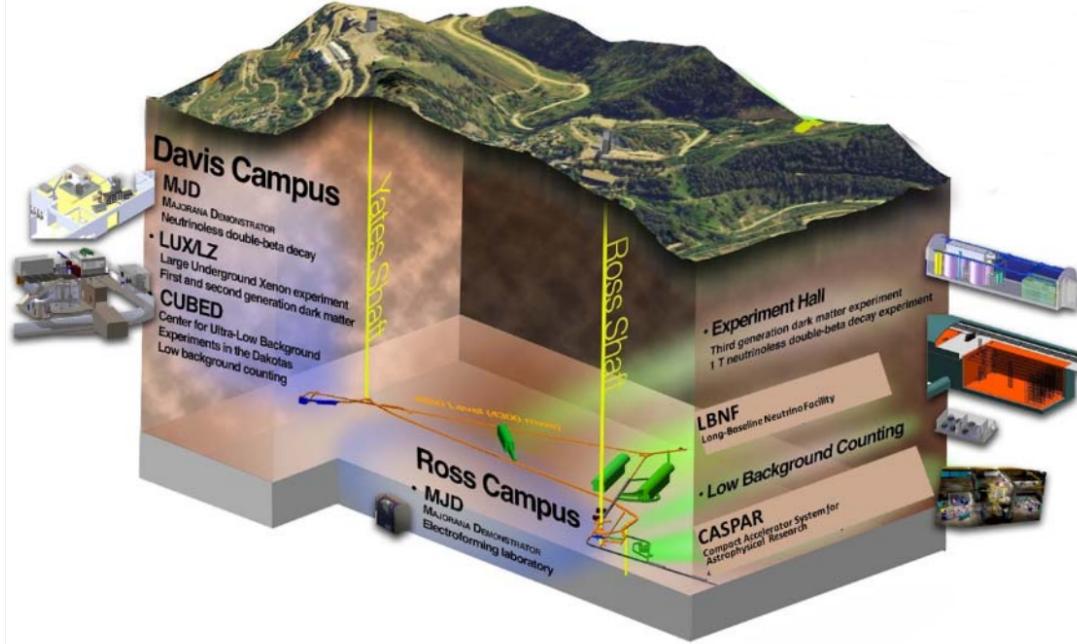
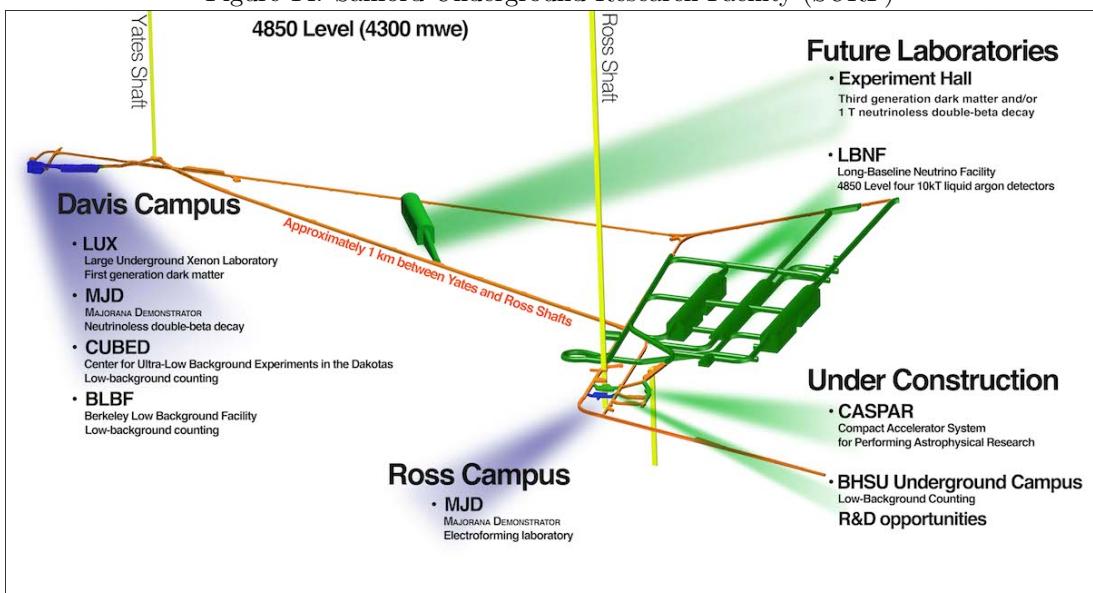


Figure 14: Sanford Underground Research Facility (SURF)



DUNE

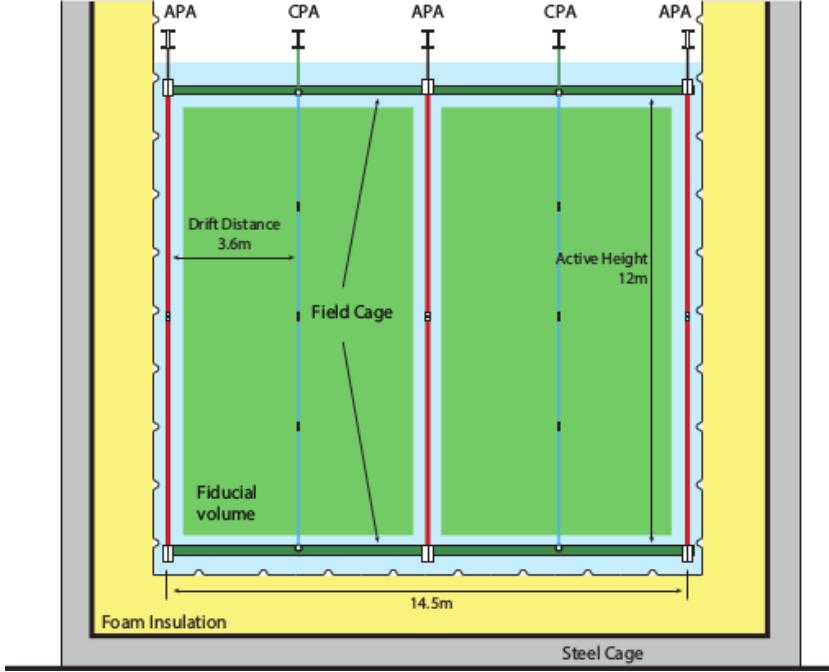


Figure 15: The scheme of the cross section of the LArTPC for far detector of the DUNE. Source of figure: [13]

(CPAs) and the anode plane assemblies (APAs) are shown. The voltages on the APAs and the CPAs are applied in such a way to create uniform electric field between anode and cathode planes. Charged particle traveling through the electron field ionizes argon atoms. Electrons induced in the ionization process drift to the APAs and produce signal on the readout electronic elements. The important requirements to the TPC include:

- be able to perform electron/photon discrimination
- wire sag shouldn't affect the position and energy resolutions
- discriminate electrons coming from photon conversion from primary electrons
- has good performance in measurements of high-energy and low-energy tracks
- make sure that materials used wouldn't contaminate high purity argon

3.4 LBNF compared to the other long baseline neutrino oscillation experiments

The review article [7] describes beams and detectors of the long baseline neutrino experiments KEK [19], NuMI [20], CNGS [21] and J-PARC [22]. The main parameters, compared to those of the LBNF, are summarized in the table 3. Common in facility setups for all these experiments is that they all include neutrino beam production system incremented to large accelerator facility, tracking near detector allowing precise measurements of the initial beam parameters and large volume far detector. Japanese old experiment K2K which operated in 1999-2004 and its update T2K use different starting points (KEK and J-PARC) but the same far detector - Super-Kamiokande, which is 50 kilotonnes water Cherenkov detector. T2K, which already delivered many important results, including the first measurement of θ_{13} is currently operating and looking forward to perform part of the LBNF physics program too. T2K's baseline is 295 km. The experiment hosted in USA, the NuMI, as well as proposed LBNF, uses neutrino beams produced in Fermilab but its far detector, MINOS, is located in Minnesota and the experiment's baseline

is 735 km. The working volume of the MINOS is magnetized tracker and polystyrene scintillator, totalling to 5.4 kilotonnes. The European experiment, the CERN Neutrinos to Gran-Sasso (CNGS), as one can tell from its name, has its neutrino beam produced in CERN and the neutrinos measured in Gran-Sasso, Italy. This experiment has two far detectors: fine-grained tracker OPERA and, as well as the DUNE far detector, the liquid argon time-projection chamber ICARUS. But the DUNE has much larger working volume: 4 caverns, 10 kilotonnes each, compared to 760 tones ICARUS. As for the beam power, the LBNF is planned to have 2MW while other operating experiments has only beam powers of few hundred Watts. Therefore, among the experiments discussed, the LBNF is going to have the longest baseline (1300 km), the highest beam power and the most sensitive detector (while Super-Kamiokande has larger volume, it's filled with water which is not as favorable for the neutrino detection as liquid argon, as discussed in the subsection "Far Detector"). These characteristics will allow the LBNF to perform more precise measurements than previous and currently existing experiments can do and become sensitive to effects which weren't observed before.

Table 3: Comparison of different long baseline neutrino oscillations experiments. Abbreviations and notations used in the table: CNGS - CERN Neutrinos to Gran-Sasso, PS - Proton Synchrotron, J-PARC - Japan Accelerator Research Complex, FNAL - Fermilab National Accelerator Laboratory, E_p - proton energy, DUNE - Deep Underground Neutrino Experiment, FGD - Fine-Grained Detector, ChD - Cherenkov Detector, SuperK - Super-Kamiokande, MINOS - Main Injector Neutrino Oscillation Search, OPERA - Oscillation Project with Emulsion-tRacking Apparatus, ICARUS - Imaging Cosmic And Rare Underground Signals, LAr - liquid argon

	KEK (K2K)	NuMI	CNGS	T2K	LBNF (DUNE)
location	Japan	Illinois - Minnesota	Switzerland - Italy	Japan	Illinois - South Dakota
accelerator	KEK PS	FNAL	CERN's SPS	J-PARC	FNAL
time of oper.	1999-2004	2005-2012	2006-2012	2010-	future
beam power	5 kW	300-350 kW	300 kW	750 kW	2000 kW
E_p	12 GeV	120 GeV	400 GeV	30 GeV	60-120 GeV
baseline	250 km	735 km	730 km	295 km	1300 km
near detector(s)	(water ChD) (FGD)	MINOS (track. and scint.)	(muon detector)	ND280 INGRID	DUNE (FGD)
ND mass	1 kt (ChD)	0.98 kt			
far detector(s)	SuperK (water ChD)	MINOS track. and scint.	ICARUS (LAr) OPERA (FGD)	SuperK (water ChD)	DUNE (LAr)
FD mass	50 kt	5.4 kt	0.76 kt (ICARUS) 1.25 kt (OPERA)	50 kt	40 kt

4 Conclusions

The DUNE's baseline is 1300 km and it's expected to be enough to determine the neutrino mass hierarchy and also CP-violation phase. These two important neutrino mixing parameters were never measured before.

However, the LBNF will not be able to measure the neutrino masses themselves - neutrino oscillations are only sensitive to differences. Neutrino mass measurement require different kind of experiments - for example, studying high energy cut-off on the electron energy spectrum in beta-decay of tritium but so far all the experiments trying to measure it were able only to set limits on neutrino masses ([2], 11.4).

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