Long Baseline Neutrino Facility (for the comprehensive exam)

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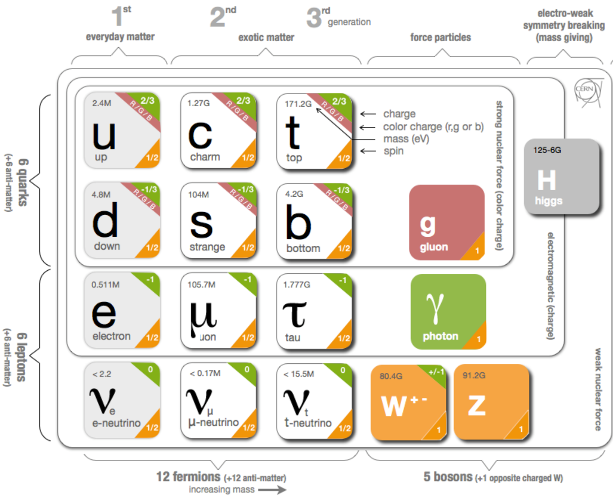
May 4th, 2015

Outline

- Introduction. Neutrinos in the Standard Model
- Neutrino Oscillations Overview
  - Discovery
  - Theory
  - Current Status
- Experimental Setup of the LBNF
  - Beam Production System
  - Near Detector
  - Far Detector
  - Comparison to the Other Facilities
- Conclusions

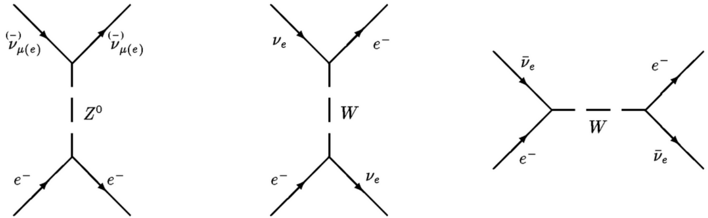
Introduction. Standard Model



All these and only these fundamental particles are discovered at the moment. Source of figure: [1]

Introduction. Neutrino Interactions

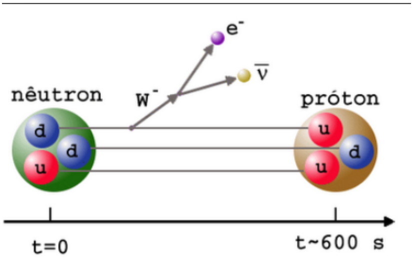
Feynmann diagrams of neutral current (NC, left), and charged current (CC, middle and right) neutrino scattering.



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".

Source of figure: [3]

Introduction. Neutron Beta Decay



Neutron beta decay $n \to p + e^- + \bar{\nu_e}$ -
example of very common and well known reaction with neutrino

d-quark of neutron transfers to u-quark through the W-boson with emission of

electron and antineutrino. Source of figure: [4]

Introduction. Lepton Flavor Number

3 flavors of neutrino, one for each generation: ν_e, ν_μ, ν_τ. 3 lepton flavor numbers: L_e, L_μ and L_τ

Table: 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

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.

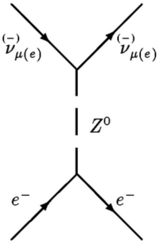
Neutrino Oscillations Discovery

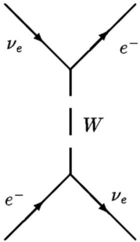
History of the neutrino oscillations discovery is described in the Griffiths textbook [2], chapter 11.

- Homestake experiment, 1968
  - Chlorino radiochemical detector ($\nu_e +^{37} Cl \rightarrow^{37} Ar + e$)
  - Sensitive to ν_e only
  - Recorded 1/3 of theoretically predicted neutrino flux
  - Solar neutrino problem postulated
- Bruno Pontecorvo proposed theory: neutrino can change flavor and, therefore, ν_e converted to ν_μ and/or ν_τ and weren't registered by Homestake experiment. But at first it was believed the experiment made mistake
- Over years, more neutrino experiments reported deficit of the Solar electron neutrinos

Neutrino Oscillations Discovery

- Super-Kamiokande experiment, 1998
  - Water Cherenkov detector ($\nu + e \rightarrow \nu + e$).
  - Sensitive to all ν but detection efficency of ν_e is 6.5 times bigger (ν_e has extra Feynmann diagrams with W-boson)
  - Recorded 45% of theoretically predicted neutrino flux (assumed all $\nu = \nu_e$)
- Solar neutrino observatory (SNO), 2002
  - Heavy water Cherenkov detector ($\nu_e + d \rightarrow p + p + e$, $\nu + d \rightarrow n + p + \nu$, $\nu + e \rightarrow \nu + e$)
  - Sensitive to all ν but can separate ν_e
  - Reported ν_e flux to be 35% of the predicted flux
- Combining Super-Kamiokande and SNO results
  - $45\% = 35\% + 10\%$, $10\% \cdot 6.5 = 65\%$, $35\% + 65\% = 100\%$
  - Neutrino oscillations theory confirmed
  - Solar neutrino problem resolved





Theory. Two Neutrinos Case

$$\nu_1 = \nu_\mu cos\theta - \nu_e sin\theta$$
$$\nu_2 = \nu_\mu sin\theta + \nu_e cos\theta$$

$$\nu_1(t) = \nu_1(0)e^{\frac{-iE_1 t}{\hbar}}, \nu_2(t) = \nu_2(0)e^{\frac{-iE_2 t}{\hbar}} \leftarrow \text{from quantum mechanics}$$

Suppose, at t=0 there were $\nu_e(0) = 1$, $\nu_\mu(0) = 0$
After calculations ([2], chapter 11):

$$P_{\nu_e \to \nu_\mu} = |\nu_\mu(t)|^2 = [sin2\theta sin\frac{(E_1 - E_2)t}{2\hbar}]^2 = [sin2\theta sin\frac{(m_1^2 - m_2^2)c^3}{4\hbar E}z]^2$$

$\longrightarrow$
For oscillations to happen, the following conditions must be satisfied:

- $\theta \neq 0$ (neutrino mixing presents)
- $m_1^2 - m_2^2 \neq 0$ (neutrinos are massive and masses are different)

Theory. Three Neutrinos Case

Mixing is determined by Pontecorvo-Maki-Nakagava-Sakata (PMNS) matrix:

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

U_{PMNS} depends on neutrino mixing angles θ_{12}, θ_{23}, θ_{13} and CP-violating phase δ_{CP}
Define $c_{ab} = cos\theta_(ab)$, $s_{ab} = sin\theta_(ab)$

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

Summary of Available Experimental Results according to Particle Data Group [6]

- $sin^2(2\theta_{12})$=0.846 ± 0.021
- $sin^2(2\theta_{23})$=$0.999^{+0.001}_{-0.018} \leftarrow$ if $m_3 > m_2 > m_1$
- $sin^2(2\theta_{23})$=$1.000^{+0.000}_{-0.017} \leftarrow$ if $m_1 > m_2 > m_3$
- $sin^2(\theta_{13})$=$(9.3 \pm 0.8) \cdot 10^{-2}$
- $|\Delta m^2_{21}|$=$(7.53 \pm 0.18) \cdot 10^{-5} eV^2$
- $|\Delta m^2_{32}|$=$(2.44 \pm 0.06) \cdot 10^{-3} eV^2 \leftarrow$ if $m_3 > m_2 > m_1$
- $|\Delta m^2_{32}|$=$(2.52 \pm 0.07) \cdot 10^{-3} eV^2 \leftarrow$ if $m_1 > m_2 > m_3$
- CP-violation phase δ_{CP} - not measured
- mass hierarchy - not determined
- absolute values of ν masses - not measured

$P(\nu_\mu \longrightarrow \nu_e)$ in presence of matter in uniform density approximation [5]

$$(1) = sin^2\theta_{23} sin^2 2\theta_{13} \frac{sin^2(\Delta_{13}-aL)}{(\Delta_{13}-aL)^2}\Delta_{31}^2$$

$$(2) = sin2\theta_{23} sin2\theta_{13} sin2\theta_{12} \frac{sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{sin(aL)}{aL}\Delta_{21} cos(\Delta_{31}+\delta_{CP})$$

$$(3) = cos^2\theta_{23} sin^2 2\theta_{12} \frac{sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

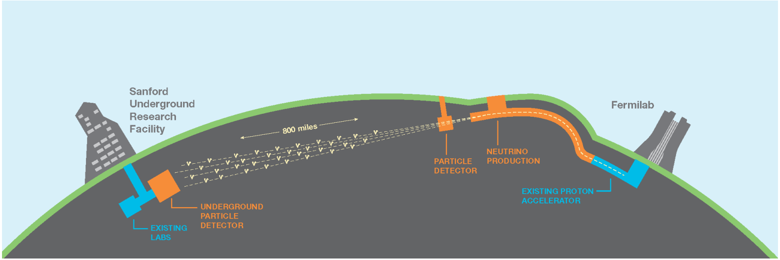
$$P(\nu_\mu \longrightarrow \nu_e) \simeq (1) + (2) + (3)$$

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

for $P(\bar{\nu_\mu} \longrightarrow \bar{\nu_e})$: $\delta_{CP} \longrightarrow -\delta_{CP}$ (because of $\nu - \bar{\nu}$ assymetry for δ_{CP}); $a \longrightarrow -a$ (because only e^- present in the Earth, not e^+)

effect $a \longrightarrow -a$ increases with L $\longrightarrow$ more sensitivity to mass hierarchy for experiments with larger baseline

Long Baseline Neutrino Facility (LBNF) Experimental Setup

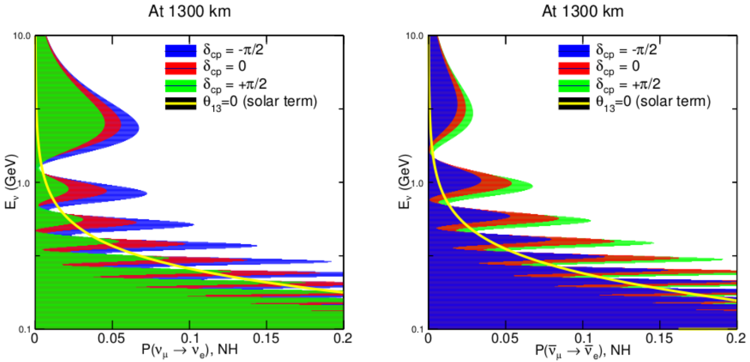


- neutrino beam production system at FNAL, Illinois
- near detector at FNAL, Illinois
- far detector at SURF, South Dakota

FNAL - Fermilab National Accelerator Laboratory, SURF - Sanford Underground Research Facility

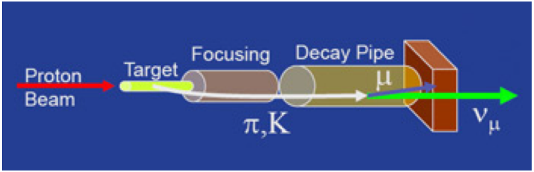
Source of figure: [7]

$P(\nu_\mu \to \nu_e)$ at a baseline of 1300 km



$P(\nu_\mu \to \nu_e)$ at a baseline of 1300 km (as LBNF will have), as a function of neutrino energy. Left - neutrinos, right - antineutrinos. Source of figure: LBNF CDR draft, volume physics [5]

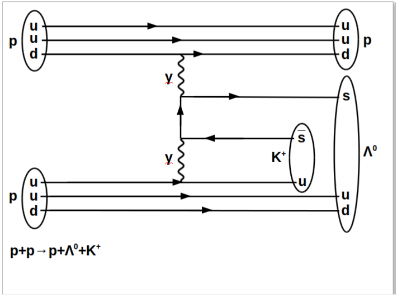
LBNF. Beam Production System

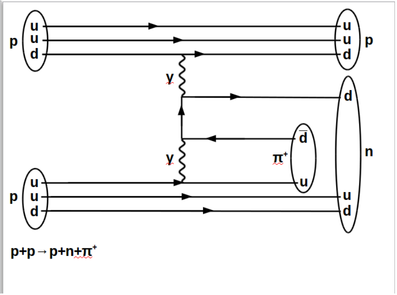


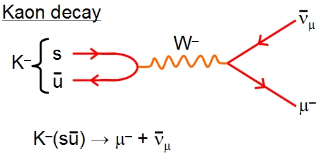
The neutrino beam production at the LBNF. Source of figure: [7]

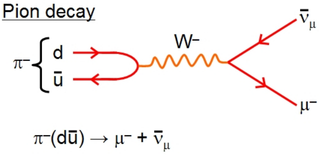
- Proton beam from Fermilab accelerator hits target
- Protons scatter on target atoms and produce pions and kaons (more details on the next slide)
- Charged pions and kaons are focused
- And decay in the decay pipe, producing muon neutrino beam
- Neutrinos are registered by near detector, $\sim$ 200 m away from the target
- And by far detector, $\sim$ 1300 km away from the target

LBNF. Feynmann diagrams of pions and kaons production and decay



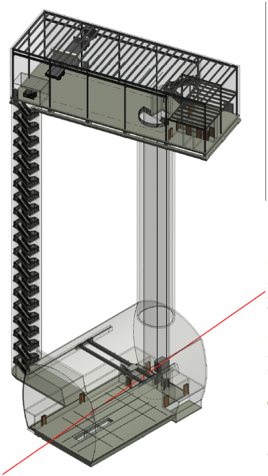






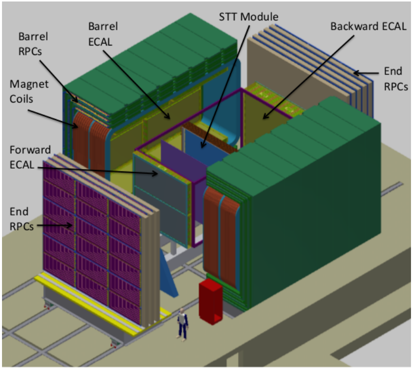
Source of bottom figure [8].

LBNF. Near Detector Cavern



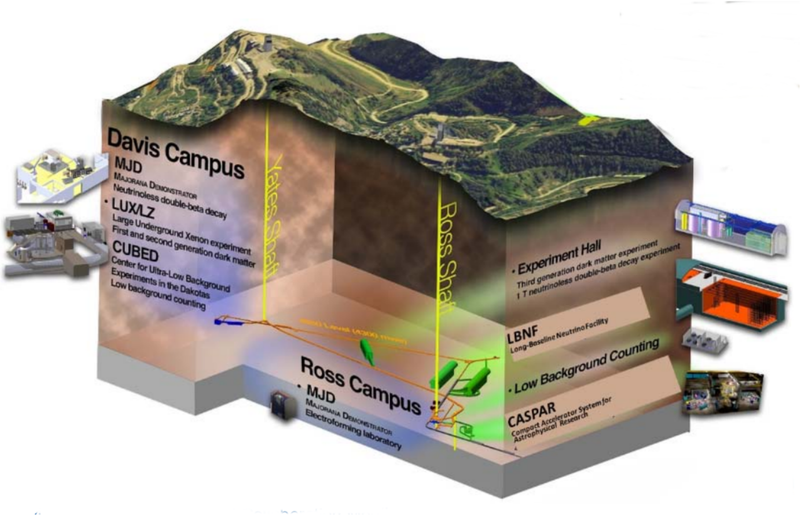
Deep Underground Neutrino Experiment (DUNE)
Quoting the LBNF website, "The DUNE near detector will require LBNF to excavate and provision a cavern 200 ft (60 m) below grade on the Fermilab site and to construct a surface building directly above it. An elevator will provide the primary access between 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."

LBNF. Near Detector

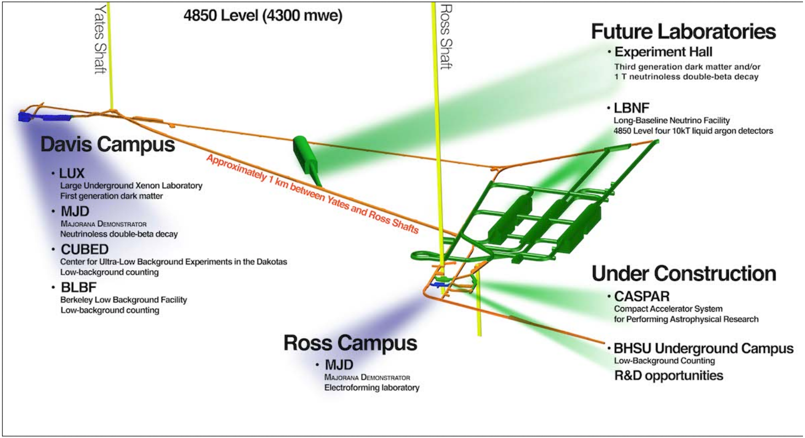


The detector will consist of central Straw-Tube Tracker (STT) modules, electromagnetic calorimeter (ECAL), magnet coils of 0.4T and muon identification system consisting of Resistive Plate Chamber (RPC) modules. The neutrinos would come from the bottom left corner of the picture, to the End RPCs.

LBNF. SURF (Far Detector Site)

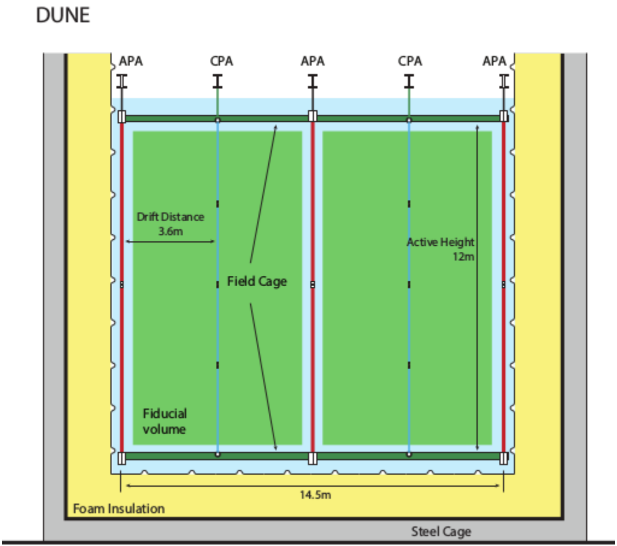


LBNF. SURF (Far Detector Site)



4 modules (15m x 12m x 58m, 10,000 tonnes of liquid argon each) placed into 4 caverns 1500 m underground. 5th cavern between two pairs - cryogenic equipment

LBNF. Far Detector. Liquid Argon Time Projection Chamber



LBNF Compared to the Other Experiments [9]

	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

Conclusions

- LBNF - long baseline neutrino oscillations experiment under development to be hosted by FNAL and SURF
- Conceptual Design Report (CDR) drafts are partially available
- First collaboration meeting took place on April 16th-18th, 2015
- Collaboration of > 750 people (~ 200 attended the 1st meeting on April 16th-18th of 2015)
- Expected parameters: baseline - 1300 km, beam power - 2 MW, far detector - 40kt of liquid argon
- Fermilab accelerator is available
- Cavern for the near detector to be excavated
- Caverns for the far detector exist (former Homestake mine)
- plan: far detector installation in 2021-2022
- plan on precise measuments of θ_{12}, θ_{23}, θ_{13}, $|\Delta m_{12}{}^2|$, $|\Delta m_{31}{}^2|$
- expected: to measure CP-violation phase δ_{CP} and ν mass hierarchy which never was measured before
- not expected: to measure absolute values of ν masses (different type of experiment would be needed)

* Paper and presentation for this comprehensive exam are available online: [10], [11]

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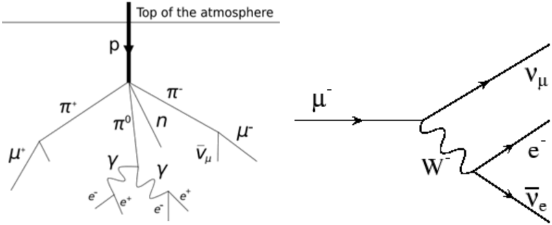
BACKUP

Cosmic Shower and Muon Decay

Figure: 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 $\pi^0 \rightarrow \gamma\gamma$, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\pi^- \rightarrow \mu^- + \bar{\nu_\mu}$. Muon decay [17](muon decays to electron, neutrino and antineutrino through W-boson



Theory. Two Neutrinos Case

$$\nu_1 = \nu_\mu cos\theta - \nu_e sin\theta$$
$$\nu_2 = \nu_\mu sin\theta + \nu_e cos\theta$$

$$\nu_1(t) = \nu_1(0)e^{\frac{-iE_1 t}{\hbar}},\ \nu_2(t) = \nu_2(0)e^{\frac{-iE_2 t}{\hbar}} \leftarrow \text{from quantum mechanics}$$

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

Then: $\nu_1(0) = -sin\theta$, $\nu_2(0) = cos\theta$, $\nu_1(t) = -sin\theta e^{\frac{-iE_1 t}{\hbar}}$, $\nu_2(t) = -cos\theta e^{\frac{-iE_2 t}{\hbar}}$
Therefore, 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 system for ν_e and ν_μ, one would get:

$$P_{\nu_e \to \nu_\mu} = |\nu_\mu(t)|^2 = [sin2\theta sin\frac{(E_1 - E_2)t}{2\hbar}]^2,$$
$$P_{\nu_e \to \nu_e} = |\nu_e(t)|^2 = 1 - [sin2\theta sin\frac{(E_1 - E_2)t}{2\hbar}]^2$$

Theory. Two Neutrinos Case

$$P_{\nu_e \to \nu_\mu} = |\nu_\mu(t)|^2 = [sin2\theta sin\frac{(E_1 - E_2)t}{2\hbar}]^2,$$
$$P_{\nu_e \to \nu_e} = |\nu_e(t)|^2 = 1 - [sin2\theta sin\frac{(E_1 - E_2)t}{2\hbar}]^2$$

Therefore, for freely travelling neutrinos, if ν_e was emmitted, 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 $E^2 = p^2 \cdot c^2 + m^2 \cdot c^4$ and assuming $m_{1,2}c^2 \ll E_{1,2}$:

$$P_{\nu_e \to \nu_\mu} = |\nu_\mu(t)|^2 = [sin2\theta sin\frac{(E_1 - E_2)t}{2\hbar}]^2 = [sin2\theta sin\frac{(m_1^2 - m_2^2)c^3}{4\hbar E}z]^2$$

Theory. Three Neutrinos Case (continued)

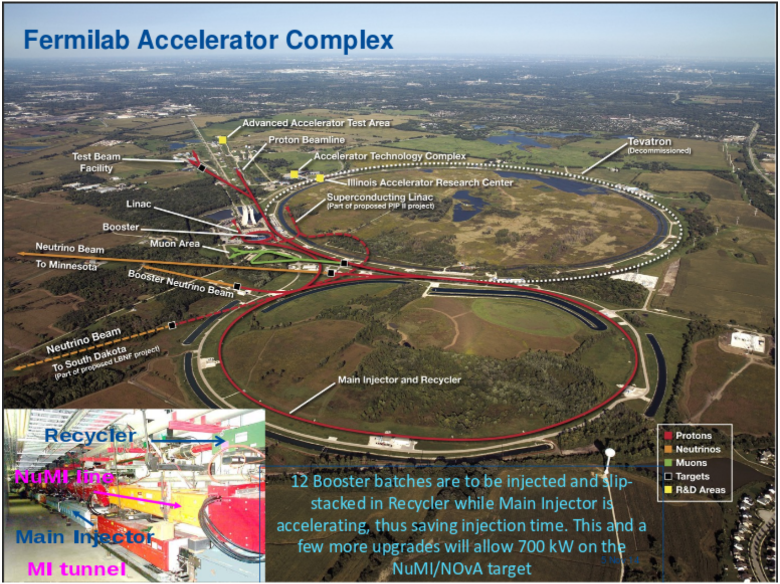
The probability amplitudes of neutrino mixing are defined by parameters of the U_{PMNS} but, analogous to simplified two-neutrino case described above, the differences of squares of neutrino masses also contribute to the probability. There are two independent expressionce for squares of masses differences: $\Delta m_{12}^2 = m_1^2 - m_2^2$ 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 $|\Delta m_{12}^2|$ and $|\Delta m_{32}^2|$ 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, Cabibbo-Kobayashi-Maskawa (CKM) matrix V_{CKM}, 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.


Fermilab Accelerator Complex
Advanced Accelerator Test Area
Proton Beamline
Test Beam Facility
Accelerator Technology Complex
Tevatron (Decommissioned)
Illinois Accelerator Research Center
Superconducting Linac (Part of proposed PIP II project)
Linac
Booster
Muon Area
Neutrino Beam To Minnesota
Booster Neutrino Beam
Neutrino Beam To South Dakota (Part of proposed LBNF project)
Main Injector and Recycler
Protons
Neutrinos
Muons
Targets
R&D Areas
Recycler
NuMI line
Main Injector
MI tunnel
12 Booster batches are to be injected and slip-stacked in Recycler while Main Injector is accelerating, thus saving injection time. This and a few more upgrades will allow 700 kW on the NuMI/NOvA target

LBNF. Near Detector Physics

- absolute flux measurement
- relative neutrino and antineutrino flux measurements
- 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 π^0, $\pi^\pm$, $K^\pm$, p, K_S^0 and Λ in the NC and CC
- nucleon structure, parton distribution functions and QCD studies
- 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 ν_μ, $\bar{\nu_\mu}$, ν_e and $\bar{\nu_e}$. To distinguish between flavors, the measurement should rely on charged current interaction (fig. **??**, middle and right) and measure the products of these interactions μ^-, μ^+, e^-, and e^+. (While the beam production system 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-$\bar{\nu_e}$ assymetries. For that, it's important not only distinguish between $\mu^\pm$ 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 backrounds 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 $\pi^\pm$ into the CC and the NC hadronic jets.