Long Baseline Neutrino Facility (for the comprehensive exam)

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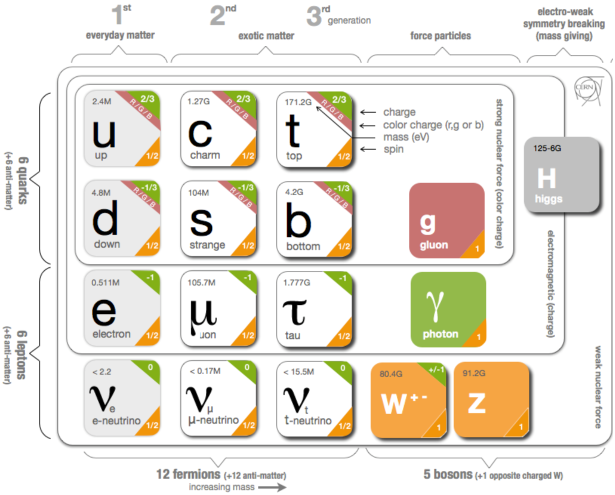
Outline

- 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

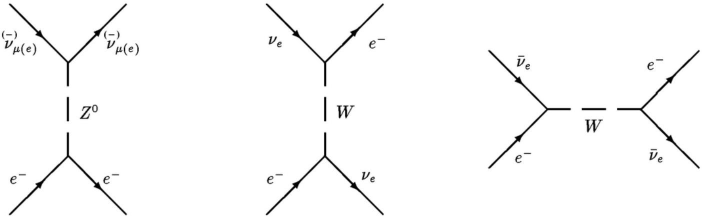
Introduction. Standard Model



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

Introduction. Neutrino Interactions

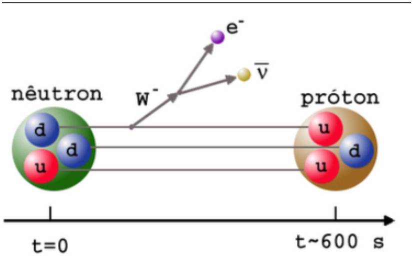
Feynmann diagrams of neutral current (NC, left), and charged current (CC, middle and right) neutrino scattering.



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 $n \rightarrow p + e^{-} + \bar{\nu_e}$ -
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.

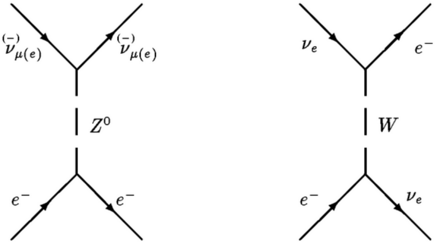
Neutrino Oscillations Discovery

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 ($\nu + e \to \nu + e$).
  - 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 ν=ν_e)
- Solar neutrino observatory (SNO), 2002
  - Heavy water Cherenkov detector ($\nu_e + d \to p + p + e$, $\nu + d \to n + p + \nu$, $\nu + e \to \nu + e$)
  - 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. Simplified Model for Illustration: Two Neutrinos in Vacuum

Assume:

- There are only two neutrinos exist, ν_e and ν_μ
- Stationary states of the free-particle Hamiltonian are ν_1, ν_2 (not ν_e, ν_μ)

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = U_{mixing} \cdot \begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix}$$

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

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 Mixing Matrix

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 $c_{ab} = cos\theta_(ab)$, $s_{ab} = sin\theta_(ab)$

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

$P(\nu_\mu \rightarrow \nu_e)$ in Presence of Matter in Uniform Density Approximation [5], Three Neutrinos Mixing

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

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

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

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

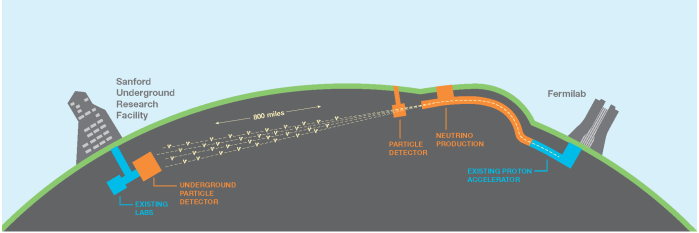
$$\text{where } \Delta_{ij} = \Delta m_{ij}^2 L/4E, \text{ and } a = G_F N_e/\sqrt{(}2)$$

Parameters which can be measured: θ_{12}, θ_{23}, θ_{13}, δ_{CP}, Δm_{21}^2, Δm_{32}^2
for $P(\bar{\nu_\mu} \rightarrow \bar{\nu_e})$: $\delta_{CP} \rightarrow -\delta_{CP}$ (because of $\nu - \bar{\nu}$ assymetry for δ_{CP}); $a \rightarrow -a$ (because only e^- present in the Earth, not e^+)
effect $a \rightarrow -a$ increases with L $\rightarrow$ more sensitivity to mass hierarchy for experiments with larger baseline
(Note: if $m_3 > m_2 > m_1$ - it's called normal mass hierarchy, if $m_1 > m_2 > m_3$ - it's called inverse mass hierarchy)

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

Long Baseline Neutrino Facility (LBNF). Future Experiment (start in 2022)



Plans to measure:

- θ_{12}, θ_{23}, θ_{13}, $|\Delta m_{12}{}^2|$, $|\Delta m_{31}{}^2|$
- CP-violation phase δ_{CP} and ν mass hierarchy (which never was measured before)

Experimental setup includes:

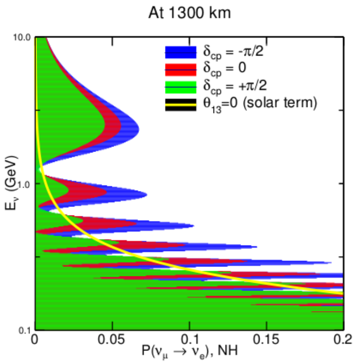
- neutrino beam production system at FNAL, Illinois
- near detector at FNAL, Illinois
- far detector at SURF, South Dakota

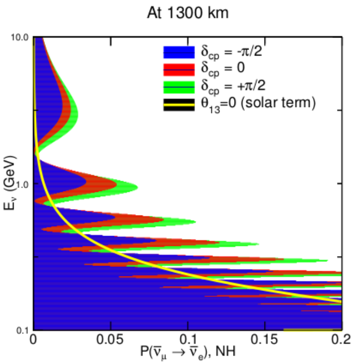
"long baseline" - means neutrinos are likely to oscillate while travel from beam production system to the Far Detector. Short baseline - means neutrinos are unlikely to oscillate at such distance and appear at the detector as they are produced. Near detector performs short baseline measurements

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

Source of figure: [7]

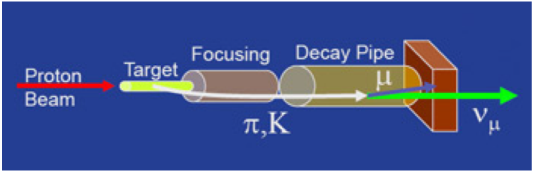
$P(\nu_\mu \to \nu_e)$ at a baseline of 1300 km





$P(\nu_\mu \to \nu_e)$ 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

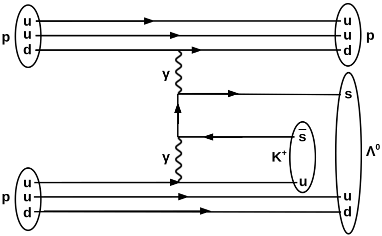


The neutrino beam production at the LBNF. Source of figure: [7]

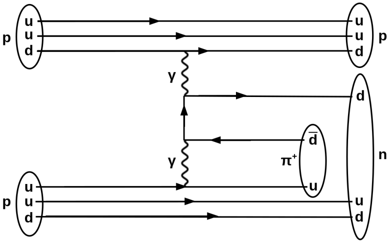
- Proton beam from Fermilab accelerator hits target ($6.5 \cdot 10^{20}$ protons on target per year [10])
- Protons scatter on target atoms and produce pions and kaons (more details on the next slide)
- Charged pions and kaons are focused
- And decay in the decay pipe, producing muon neutrino beam
- Neutrinos are registered by near detector, ~ 200 m away from the target
- And by far detector, ~ 1300 km away from the target

Source of figure: [7]

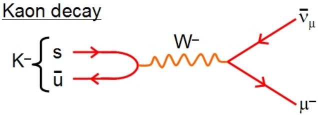
LBNF. Feynmann diagrams of pions and kaons production and decay



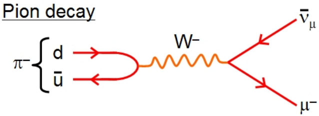
p+p→p+Λ^0+K$^+$



p+p→p+n+π^+



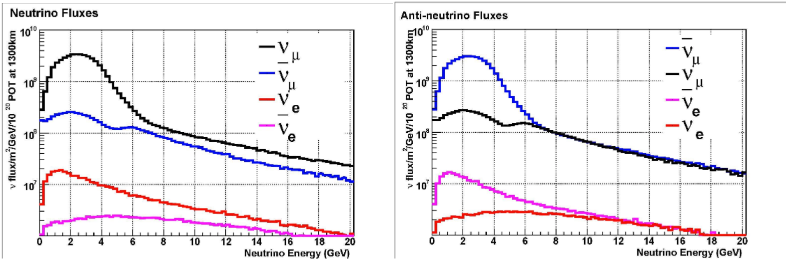
$K^-(s\bar{u}) \rightarrow \mu^- + \bar{\nu}_\mu$



$\pi^-(d\bar{u}) \rightarrow \mu^- + \bar{\nu}_\mu$

Source of bottom figure [8].

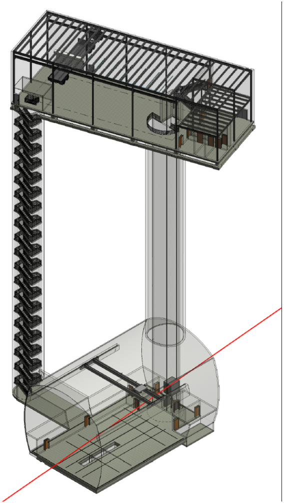
LBNF. Expected ν and $\bar{\nu}$ Fluxes in Absence of Oscillations



"POT" means # of protons on the target
for LBNF beam: $6.5 \cdot 10^{20}$ POT per year expected

Source of figure: [10]

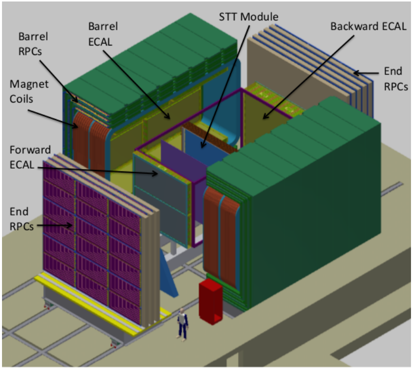
LBNF. Near Detector Cavern



Source of figure: [7]

Deep Underground Neutrino Experiment (DUNE) Quoting the LBNF website [7], "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."

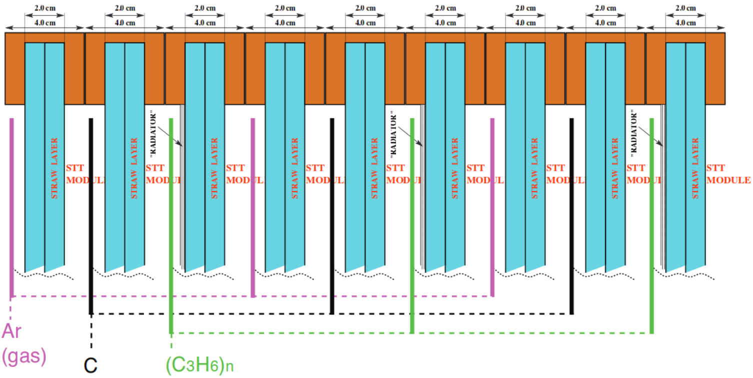
LBNF. Near Detector



The detector will consist of central Straw-Tube Tracker (STT) modules (neutrino targets will be built into the tracker), 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.

Source of figure: [20]

LBNF. Near Detector Targets

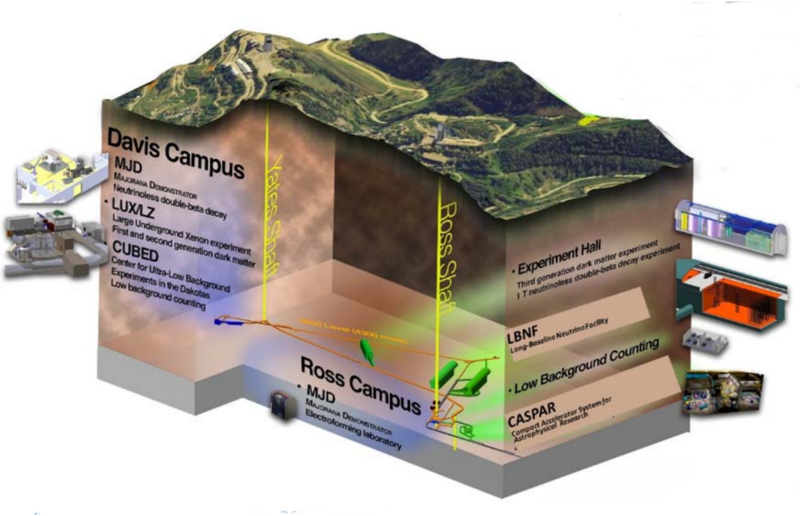


Targets mounted inside the Straw-Tube Tracker to perform Near Detector neutrino physics measurements

- pressured Ar(gas)
- $(C_3H_6)_n$ radiators
- C(graphite)

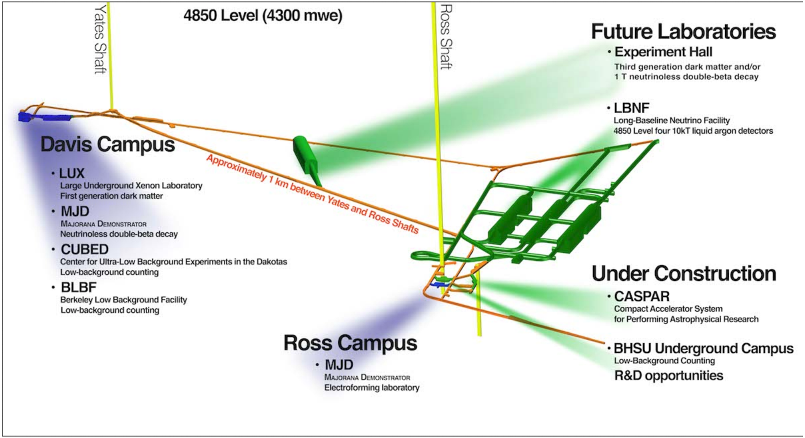
Source of figure: presentation "Nuclear Targets and Precision Measurements in DUNE ND" by R. Petti at [21]

LBNF. SURF (Far Detector Site)



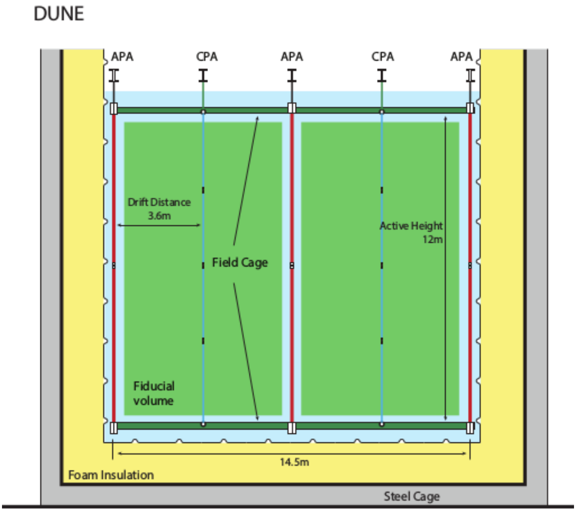
Source of figure: [21]

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 [7]

LBNF. Far Detector. Liquid Argon Time Projection Chamber



Source of figure: [20]

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)
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

LBNF Summary

- 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)

Conclusions

- Neutrino oscillations is newly discovered phenomenon and it's the only phenomenon which allows violation of lepton flavor number conservation.
- It can be described with 4 mixing-matrix parameters θ_{12}, θ_{23}, θ_{13}, δ_{CP} and 2 mass differences $\Delta m_{12}{}^2$, $\Delta m_{31}{}^2$ which can be measured experimentally.
- The parameters can be determined from measuring neutrino and antineutrino fluxes at 2 points: right after neutrino production, before any oscillations, and hundreds of kilometers away, after certain fraction of neutrinos would oscillate to the other flavors.
- Previous and currently existing experiments were able to measure mixing angles and absolute values of mass differences but not δ_{CP} and mass hierarchy.
- That's why the Long Baseline Neutrino Facility was proposed. It has more ambitious technical parameters and is expected to have enough sensitivity to determine δ_{CP} and mass hierarchy.

* Paper and presentation for this comprehensive exam are available online: [11], [12]

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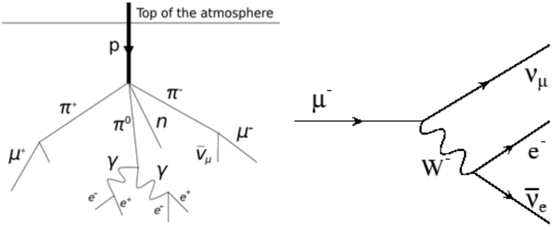
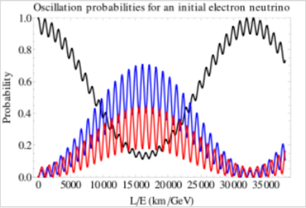
BACKUP

Cosmic Shower and Muon Decay

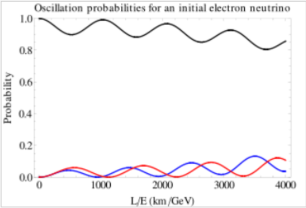
Figure: Cosmic shower induced by scattering of the incident cosmics proton of an air molecule. Charged and neutron pions are born in the reaction and then they further decay as $\pi^0 \rightarrow \gamma\gamma$, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\pi^- \rightarrow \mu^- + \bar{\nu_\mu}$. Muon decay (to electron, neutrino and antineutrino through W-boson



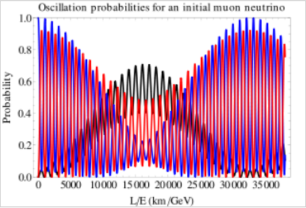
ν oscillations probability with L/E



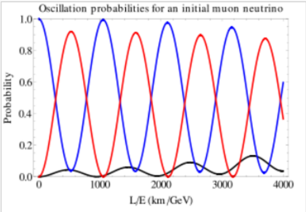
Electron neutrino oscillations, long range. Here and in the following diagrams black means electron neutrino, blue means muon neutrino and red means tau neutrino.



Electron neutrino oscillations, short range



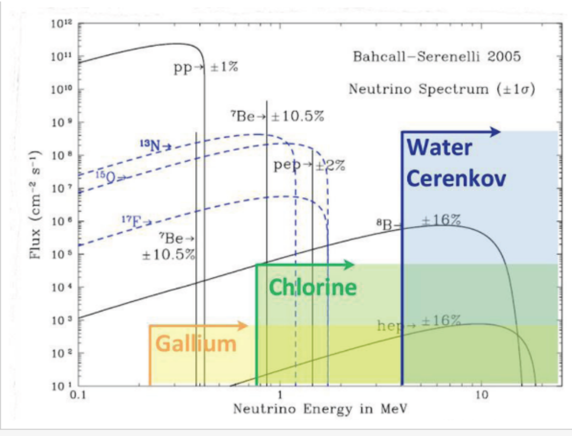
Muon neutrino oscillations, long range



Muon neutrino oscillations, short range

Source of figure: [28]

Solar ν spectrum and L/E



$E \sim 5\ MeV = 5 \cdot 10^{-3}\ GeV$, $L \sim 149.6 \cdot 10^6 km$, $\rightarrow L/E \sim 30 \cdot 10^9 km/GeV$
$\Delta E \sim 5\ MeV$, $\Delta L\ 2000km + 13000km = 15000km$,
$\Delta L/E \sim (L/E)^2 \cdot (\Delta E/E)^2 \sim 15 \cdot 10^9\ km/GeV$
while oscillation period is $\sim 30 \cdot 10^3\ km/GeV$

Source of figure: [29]

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 expressione 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.

About U_{PMNS} Parametrization

Parameterization [edit]

In general, there are nine degrees of freedom in any three by three unitary matrix, and in the PMNS matrix five extra parameters can be absorbed by redefinitions of the complex phase of the Dirac fields, with no change in the observable physics. The matrix can thus be fully described by four free parameters.[7] The PMNS matrix is most commonly parameterized by three mixing angles (θ_{12}, θ_{23} and θ_{13}) and a single phase called δ_{CP} related to charge-parity violations (i.e. differences in the rates of oscillation between two states with opposite starting points which makes the order in time in which events take place necessary to predict their oscillation rates), in which case the matrix can be written as:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}.$$

where s_{ij} and c_{ij} are used to denote $\sin\theta_{ij}$ and $\cos\theta_{ij}$ respectively. In the case of Majorana neutrinos, two extra complex phases are needed, as the phase of Majorana fields cannot be freely redefined due to the condition $\nu = \nu^c$. An infinite number of possible parameterizations exist; one other common example being the Wolfenstein parameterization.

The mixing angles have been measured by a variety of experiments (see neutrino mixing for a description). The CP-violating phase δ_{CP} has not been measured directly, but estimates can be obtained by fits using the other measurements.

Source: [31]

Fermilab Accelerator Complex

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

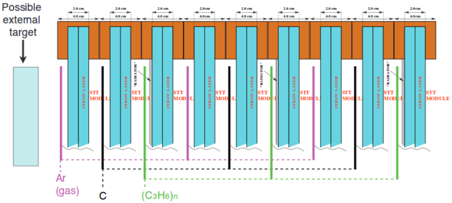
LBNF. Near Detector Physics, ν Oscillations

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.

LBNF. Near Detector Targets (all)

DIRECT MEASUREMENT OF NUCLEAR EFFECTS



MAIN target $(C_3H_6)_n$ radiators: fiducial mass $\sim$5t

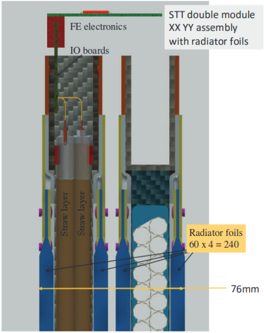
- *Multiple nuclear targets in STT: $(C_3H_6)_n$ radiators, C, Ar gas, Ca, Fe, H_2O, D_2O, etc.*
  $\Longrightarrow$ *Separation from excellent vertex ($\sim 100\mu m$) and angular (~ 1 mrad) resolutions*
- *Subtraction of* $\boxed{\text{C TARGET}}$ *(0.5 tons) from polypropylene* $\boxed{(C_3H_6)_n \text{ RADIATORS}}$ *provides* $5.0(1.5) \times 10^6 \pm 13(6.6) \times 10^3 (sub.)$ $\nu(\bar{\nu})$ *CC interactions on free proton*
  $\Longrightarrow$ *Absolute $\bar{\nu}_\mu$ flux from QE*
  $\Longrightarrow$ *Model-independent measurement of nuclear effects and FSI from RATIOS A/H*
- *Pressurized* $\boxed{\text{Ar GAS}}$ *target ($\sim$ 140 atm) inside Al/C tubes and solid* $\boxed{\text{Ca TARGET}}$ *provide detailed understanding of the FD $A = 40$ target*
  $\Longrightarrow$ *Collect $\times 10$ unoscillated FD statistics on Ar target*
  $\Longrightarrow$ *Study of flavor dependence & isospin physics*

Source of figure: presentation "Nuclear Targets and Precision Measurements in DUNE ND" by R. Petti at [21]

LBNF. Near Detector Targets (STT)

THE STRAW TUBE TRACKER

- *Main parameters of the STT design:*
  - *Straw inner diameter* 9.530 ± 0.005 *mm;*
  - *Operate with 70%/30% Xe/CO*$_2$ *gas mixture.*
  - *Straws are arranged in double layers glued together (epoxy glue) inserted within C-fiber composite frames;*
  - *Radiator/target integrated into front and back with 120 (C*$_3$*H*$_6$*)*$_n$ *embossed foils (25* μm*) for Transition Radiation;*
  - *Double module assembly (XX+YY) with FE electronics;*
  - *160 modules arranged into 80 double modules over* ~ 6.5 *m (total 107,520 straws);*
- *Proven design and technology:*
  - *Based upon the NOMAD experience*
  - *Combine tracking & particle ID like the ATLAS TRT*
  - *Basic design/geometry after COMPASS straw tracker*
- *Mass of the active target dominated by the radiators (82.6% of total mass) and can be tuned to achieve desired events & momentum resolution*



Source of figure: presentation "Nuclear Targets and Precision Measurements in DUNE ND" by R. Petti at [21]

LBNF. Near Detector Targets Descriptions

Radiator Targets

Radiators will be placed in the downstream STT modules and will serve as targets for both neutrino interactions and Transition Radiation (TR) production. Each STT module contains four radiators, where each radiator consists of 60 layers of 25-μm polypropylene $(C_3H_6)_n$ foils, which are embossed to keep 125-μm air gaps between consecutive foils. The mass of each radiator is $\sim$ 17 kg and the thickness is $\sim$ 9 mm. The use of thin plastic foils regularly spaced allows the emission of transition radiation for electron/positron identification, which is detected by the Xe gas in the straws. The plastic radiators account for about 83% of the mass of each STT module and also provide the main (anti)neutrino target. Overall, a radiator mass of about 5 tons is required to achieve the physics sensitivity discussed in Section **??** and in Ref. [**?**].

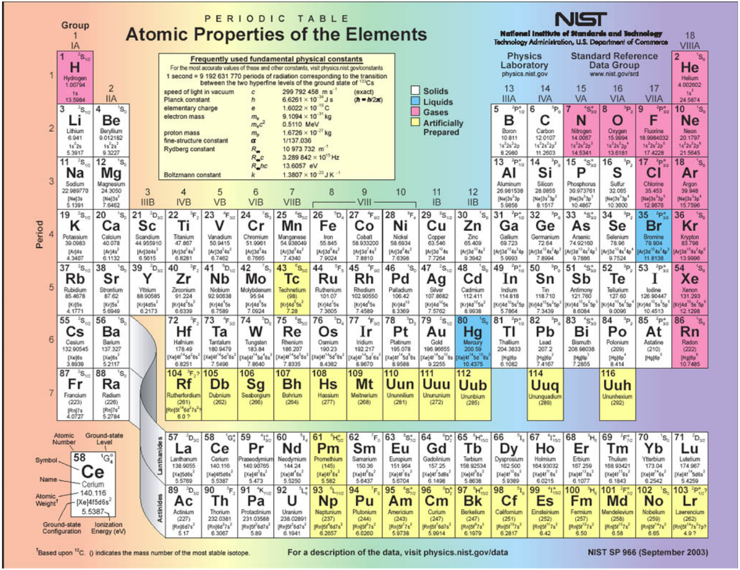
Nuclear Targets

The most important nuclear target is the argon target that comprises the DUNE far detector. This target will consist of planes of 0.5-inch diameter, 3.5-m-long aluminum tubes filled with argon gas pressurized to 140 atm ($\rho = 0.233$), with sufficient Ar mass to provide $\sim$10 times the unoscillated statistics expected in a 40t FD.

In this regard, a crucial target is calcium which has the same atomic weight ($A = 40$) as argon but is isoscalar. Since most nuclear effects depend on the atomic weight A, inclusive properties of (anti)neutrino interactions are expected to be the same for these two targets. This fact would allow the use of both targets to model signal and backgrounds in the LBNE far detector (argon target), as well as to compare LBNE results for nuclear effects on argon with the extensive data on calcium from charged lepton scattering.

Source of figure: [20]

Mendeleev Periodic Table of Elements



Source of figure: [30]