Long Beam Neutrino Facility and Neutrino Mixing

Ekaterina Avdeeva

University of Nebraska-Lincoln, USA

April 14, 2015

Abstract

Paper for the Comprehensive Exam.

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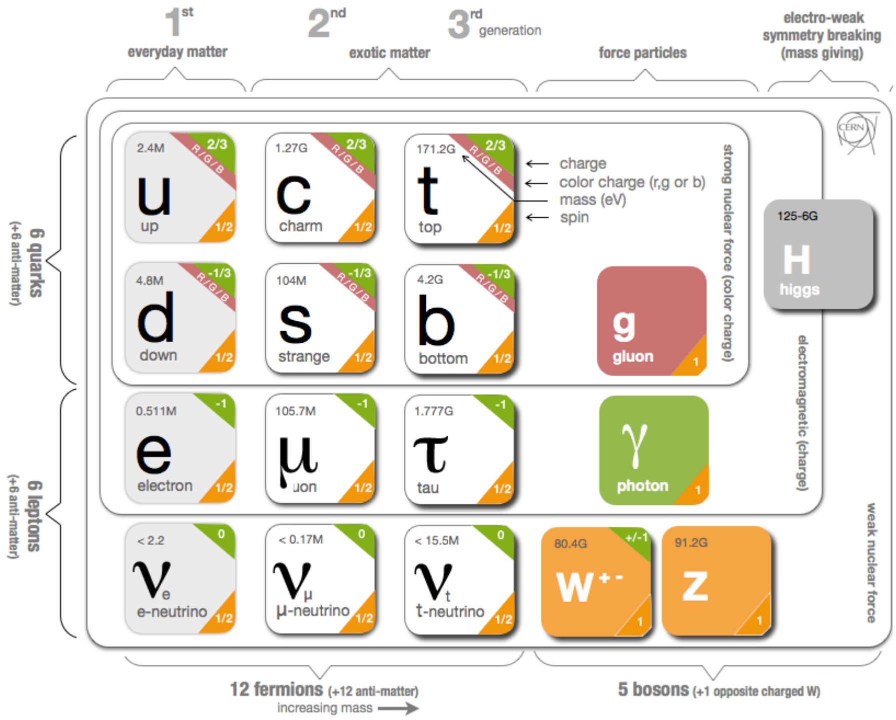
Figure 1: Fundamental particles and interactions



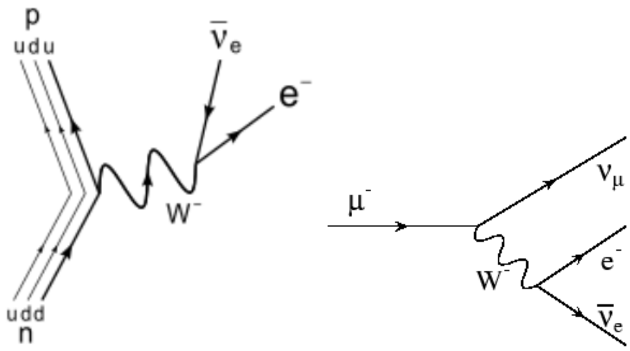
Three generations of fundamental particles and interaction mediators. Charged leptons and quarks are subjects to electromagnetic interactions (through photons). Quarks can also interact strongly (through gluons). All leptons and quarks can interact weakly (through $W^{\pm}$ and Z^0 bosons). All the particles shown are discovered at the moment and no other fundamental particle is discovered. [3]

1 Introduction

The Standard Model includes three charged leptons, three neutrinos and six quarks and their antiparticles which are splitted into three generations and can interact through gauge bosons (see 1). The neutrinos. neutrinos are fundamental particles of the Standard Model.**??**
Figure with Standard Model particles and interations.

How many neutrinos pass through the cm^2 per second (flux), check PDG.
Two very common and well known interactions which includes neutrinos 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 ${}^{49}{}_{19}K \rightarrow {}^{40}{}_{20}Ca$, ${}^{64}{}_{29}Cu \rightarrow {}^{64}{}_{30}Zn$, ${}^{3}{}_{1}H \rightarrow {}^{3}{}_{2}He$ [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, nuom 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: muon are produced in the upper layers of the Earth atmosphere from the interaction of the particles coming from cosmics with the atmosphere substances though the reaction [WHICH

Figure 2: Feynmann diagrams of neutron and muon decays



Feynmann diagrams of left: neutron beta decay [5](d-quark of transfers to u-quark through the W-boson with emission of electron and antineutrino), right: muon decay [4](muon decays to electron, neutrino and antineutrino through W-boson).

REACTION ?] and then some number of muons decay while traveling through the atmosphere to the ground.

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

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

The lepton flavor numbers are conserved in almost all particle physics processes and the only violation of this law observed so far is the neutrino oscillations - the ability of neutrino to change flavor. This paper reviews the main idea which stands beyond the neutrion oscillations from the theoretical point of view and the related experimental measurements. Section [REFERENCE] gives theoretical derivation of the neutrino oscillations phenomenon for the two neutrinos case, introduces the mixing matrix and lists the its parameters. Section [REFERENCE] reviews the parameters which already has been measured in variety of neutrino experiments and which questions are still open. Section [REFERENCE] discusses the physical program and the technical charasteristics of the future experiment - the Long Beamline Neutrino Facility which is under construction in Fermilab now and is going to be one of the most important concentrations for the Fermilab and for the whole USA and Worldwide experimantal particle physics program in the nearest future.

2 Theory of Neutrino Oscillations

2.1 Two Neutrinos Case

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,
$\nu_1(t) = \nu_1(0)e^{\frac{-iE_1t}{h}}$, $\nu_2(t) = \nu_2(0)e^{\frac{-iE_2t}{h}}$
Suppose, at t=0 there were $\nu_e(0) = 1$, $\nu_\mu(0) = 0$
Then $\nu_1(0) = -sin\theta$, $\nu_2(0) = cos\theta$, $\nu_1(t) = -sin\theta e^{\frac{-iE_1t}{h}}$, $\nu_2(t) = -cos\theta e^{\frac{-iE_2t}{h}}$
Thus, we are getting the system:
$-sin\theta e^{-\frac{iE_1t}{h}} = \nu_\mu(t)cos\theta - \nu_e(t)sin\theta$,
$-sin\theta e^{-\frac{iE_2t}{h}} = \nu_\mu(t)sin\theta - \nu_e(t)cos\theta$
By solving this sytem for ν_e and ν_μ, one would get
$P_{\nu_e\to\nu_\mu} = |\nu_\mu(t)|^2 = [sin2\theta sin\frac{(E_1-E_2)t}{2h}]^2$,
$P_{\nu_e\to\nu_e} = |\nu_e(t)|^2 = 1 - [sin2\theta sin\frac{(E_1-E_2)t}{2h}]^2$
Thus, 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 $E^2 = p^2 + m^2$ and assuming $m_{1,2} << E_{1,2}$, the probablities will take forms of
$P_{\nu_e\to\nu_\mu} = |\nu_\mu(t)|^2 = [sin2\theta sin\frac{(E_1-E_2)t}{2h}]^2$,

2.2 Mixing Matrix

Consider three neutrino case and put matrix and common notations here

3 Experimantal Measurements and Open Questions

3.1 Experiment

read through PDG carefully

3.2 Long Baseline Experiments

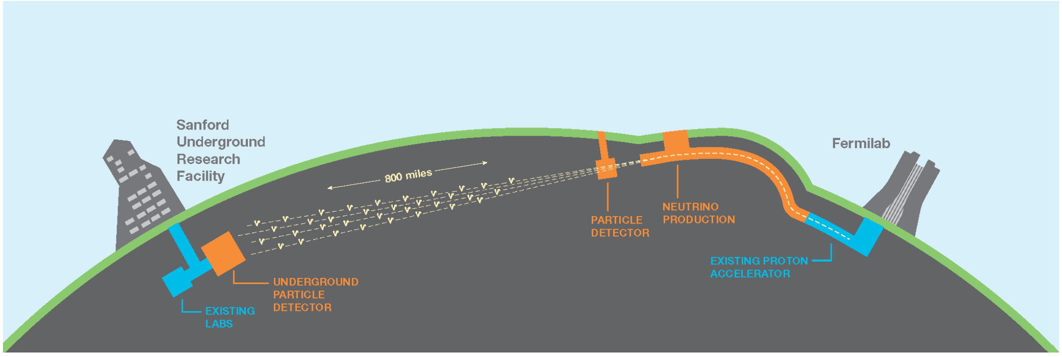
read through PDG carefully

3.3 Open Questions

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

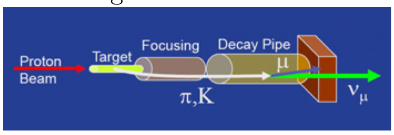
- whether the massive neutrinos are Dirac or Majorana (Dirac neutrinos are... Majorana neutrinos are...)
- what is the sign of $\Delta {m_A}^2$ ($\Delta m_3 1^2$) and what is the type of the neutrino mass spectrum [WHAT IS THAT]
- what the absolute values of neutrino masses are
- what is the value of the neutrino mixing angle θ_{13}
- how does the CP-symmetry behaves in the lepton sector
- what the values of $\Delta {m_{12}}^2$, θ_{12}, and $|\Delta {m_{31}}^2|$, θ_{23}.

Figure 3: Long Beamline Neutrino Facility



The neutrino flux will be produced using existing proton accelerator in Fermilab. Then neutrinos will be registered by close detector, travel 800 miles through the Earth mantle to the Sanford Underground Research Facility in South Dakota and be registed by far detector. [6]

Figure 4: Long Beamline Neutrino Facility



The neutrino beam production at Long Beamline Neutrino Facility. [6]

- 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 assymetry in the Universe

4 Long Baseline Neutrino Facility

The Long Beamline Neutrino Facility is the facility being internationally designed for the future Deep Underground Neutrino Experiment (DUNE) which is going to study neutrino physics. It's going to use 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 $p+p \to p+n+\pi^+$, $p+p \to p+\Delta^{++}+\pi^-$, $p+n \to p+p+\pi^-$, $p+n \to n+n+\pi^+$, $p+n \to p+\Delta^-+\pi^+$ 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 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, neutrinos are produced they go through the focusing camera in decay into the decay pipe as $\pi^+ \to \mu^+\nu_\mu$, $\pi^- \to \mu^-\bar{\nu_\mu}$, $K^+ \to \mu^+\nu_\mu$, $K^- \to \mu^-\bar{\nu_\mu}$. 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.

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.

4.1 What questions it's going to answer

4.2 How it's going to answer these questions and how it's better than other experiments

4.3 What questions it's not going t oanswer

References

[1] Particle Data Group

[2] Griffiths

[3] website: http://www.isgtw.org/spotlight/go-particle-quest-first-cern-hackfest

[4] website: http://www.hep.ucl.ac.uk/ jpc/all/ulthesis/node9.html

[5] website: http://en.wikipedia.org/wiki/Neutron

[6] LBNF website: http://lbnf.fnal.gov/