Neutrino Oscillation Experiments at Fermilab*

ADAM PARA

Fermilab, Pine St., Batavia IL 60510, USA

Neutrino oscillations provide an unique opportunity to probe physics beyond the Standard Model. Fermilab is constructing two new neutrino beams to provide a decisive test of two of the recent positive indications for neutrino oscillations: MiniBOONE experiment will settle the LSND controversy, MINOS will provide detailed studies of the region indicated by the SuperK results.

1. Introduction

Neutrinos are special. They are the only elementary fermions which are neutral, thus they can be their own antiparticles. Their masses (if non-zero) are several orders of magnitude smaller than those of charged leptons or quarks. These two facts may be, in fact, related: with both Dirac and Majorana, masses present, the neutrino mass eigenstates will naturally split, with the light mass eigenstate being

\[ m_\nu \sim \frac{m_D^2}{m_R} \]  

If the Dirac mass \( m_D \) is of the order of a typical quark or charged lepton mass and the right-handed Majorana mass is of the order of the GUT scale, the left-handed neutrinos would then have a mass well below 1 eV.

Direct measurements of the neutrino masses are very difficult; experiments so far have been able to yield only upper limits. The best limit can be set for the \( \overline{\nu}_e \) from tritium \( \beta \) decay, which is of the order of 1 eV [1]. A very similar limit, although dependent on the assumed Majorana nature of the neutrino, is derived from the measured rates of the neutrino-less double beta decays. Mass limits for other neutrino species are considerably worse: \( m_{\nu_\mu} < 170 \) keV from the decay of charged pions and \( m_{\nu_\tau} < 24 \) MeV.

* Presented at the Cracow Epiphany Conference on Neutrinos in Physics and Astrophysics, Cracow, January 6-9, 2000
from the decay $\tau \to 5\pi^\pm + \nu_\tau$. Neutrino oscillations offer the only practical means to unravel details of the neutrino mass spectrum.

2. Neutrino Oscillations

If neutrinos have masses, we may expect in analogy with the quark sector, that the weak interaction eigenstates are mixtures of the mass eigenstates $\nu_1, \nu_2, \nu_3$, with the CKM-like mixing matrix $U$ [3]

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

(2)

usually parametrized as

$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

(3)

where $s_{ij} = \sin \theta_{ij}$ and $c_{ij} = \cos \theta_{ij}$ and $\theta_{ij}$ is the mixing angle of $\nu_i$ and $\nu_j$.

Differences of mass eigenvalues will lead, through differences in time evolution of the components of the wave function, to the phenomenon of neutrino oscillations[2] the beam of neutrinos of a given flavor, say $\nu_\mu$, will be observed as a mixture of all three neutrino flavors after a certain distance $L$. Frequency of these oscillation is governed by $\Delta m^2_{ij} = m^2_i - m^2_j$.

For example, starting with a pure $\nu_\mu$ beam and assuming $|\Delta m^2_{12}| \ll |\Delta m^2_{23}|$, we would expect probabilities of detecting of $\nu_\mu$, $\nu_e$ and $\nu_\tau$ to be

$$P(\nu_\mu \to \nu_\mu) = 1 - 4U_{\mu3}^2 (1 - U_{\mu3}^2) \sin^2 \left( \frac{\Delta m^2_{21}L}{4E} \right)$$
$$P(\nu_\mu \to \nu_e) = \sin^2 \theta_{23} \sin^2 \theta_{13} \sin^2 \left( \frac{\Delta m^2_{12}L}{4E} \right)$$
$$P(\nu_\mu \to \nu_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m^2_{23}L}{4E} \right)$$

(4)

where $E$ is the neutrino beam energy and $L$ is the distance of the detector from the neutrino source.

At present, there are three experimental indications, shown in Fig.1, that the neutrino oscillations might, in fact, occur in nature:

1. Solar neutrino deficit.

The flux of solar $\nu_e$ measured in several experiments is about 50% of the flux expected in the Standard Solar Model. This large discrepancy
is unlikely to be caused by our ignorance of the physics of the Sun; it can be interpreted as a result of $\nu_e \rightarrow \nu_x$ oscillations. The $\Delta m^2$ responsible for these oscillations would be of the order of $10^{-10}$ $eV^2$ if the oscillations occur in a vacuum, or $10^{-5} - 10^{-4}$ $eV^2$ if the oscillations occur in matter via the MSW effect.

2. Atmospheric neutrinos.

The SuperKamiokande detector[4] has been used to detect interactions of atmospheric neutrinos. The results show depletion of the $\nu_{\mu}$ interaction rate as a function of the zenith angle, while the $\nu_e$ interaction rate is consistent with the expectations[4], as shown in Fig.2. The observed depletion is consistent with the hypothesis of neutrino oscillations and strongly suggests $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations with a very large mixing angle and a $\Delta m^2$ in the range $0.003 - 0.01 eV^2$ [5]

3. LSND Experiment.

An 800 MeV proton beam at LAMPF was used to produce pions, which were subsequently stopped in the absorber. A liquid scintilla-
Fig. 2. Zenith angle distribution of atmospheric $\nu_e$ and $\nu_\mu$ events observed in SuperKamiokande experiment.

The detector recorded an excess of $82.8 \pm 23.7$ $\bar{\nu}_e$ interactions above the expected background of $17.3 \pm 4$ events. These interactions are consistent with the hypothesis of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations (Fig. 3), if the oscillation parameters are in the region shown in Fig. 1. Neutrino oscillations in the large mixing angle region are excluded by the reactor experiments. The large $\Delta m^2$ region is excluded by CCFR and NOMAD experiments, but the possibility of the neutrino oscillations in the region $0.3 < \Delta m^2 < 2$ eV$^2$ remains open.

Developing a consistent interpretation of the data shown in Fig. 1 is difficult. Three different massive neutrinos allow for only two independent $\Delta m_{ij}$. Most of the proposed scenarios invoke a new, hitherto unknown, sterile neutrino or postulate that some of the experimental results are not, in fact, manifestations of the neutrino oscillations.

Given the potential importance of the neutrino mass sector, the following questions pose an experimental challenge in the near future:
Are all three indications really examples of neutrino oscillations? Observation of oscillatory behavior as a function of distance and/or neutrino energy, would be particularly convincing proof. Seasonal or day-night variation of the solar neutrino flux could serve as a proof of the solar neutrino oscillation hypothesis. Observation of energy dependence of the disappearance of the $\nu_\mu$ flux is also possibility in the atmospheric or LSND regions.

What are the oscillation modes? The LSND result implies $\nu_\mu \rightarrow \nu_e$ oscillations. What are the oscillation modes responsible for the solar neutrino effect? The atmospheric neutrino deficit? Are there sterile neutrinos? Preliminary results from the SuperK experiment shown in Fig.2 disfavor such a possibility as the dominant oscillation mode, because matter induced effects would lead to a small reduction of the observed deficit.

What are the oscillation parameters? What are the patterns of the $\Delta m^2_{ij}$? The mixing angles? What are the elements of the lepton mixing matrix? Are there dominant and sub-dominant oscillation modes corresponding to each oscillation frequency ($\Delta m^2$)?

The presence of the phase factor $e^{-i\delta}$ in the mixing matrix $U$ implies a possibility of CP-violating effects in neutrino oscillations. How large
are they? What is the value of δ?

Studies of oscillations in the solar neutrino region require extra-terrestrial distances and/or very low energy neutrino sources, such as nuclear reactors. Oscillations in the atmospheric neutrinos region or the region indicated by the LSND experiment lend themselves to studies with neutrino beams produced in the laboratory. Such investigations of the neutrino oscillations are an important part of the scientific program at Fermilab.

3. Fermilab Accelerators and Neutrino Beams

The flagship of the Fermilab high energy physics program is the Tevatron Collider. Recent upgrades of the accelerator infrastructure were specifically designed to boost the luminosity of the Collider and at the same time to enable a fixed-target program, like neutrino experiments, to be carried simultaneously with the Collider experiments. Two of the existing Fermilab’s accelerators are being used to produce neutrino beams: the 8 GeV Booster and the newly constructed Main Injector.

3.1. 8 GeV Booster Neutrino Beam (MiniBOONE)

The Booster is the oldest part of the of the accelerator complex at Fermilab. Upgraded to 400 MeV injection in 1993, it is capable of delivering up to $5 \times 10^{12}$ protons per pulse. In the past, it was operated at 2.5 Hz, but after improvements of its pulsed magnets, its repetition rate can be as high as 7.5 Hz.

A Booster[7] neutrino beam is under construction. An 8 GeV proton beam is extracted onto a titanium or nickel target. Two magnetic horns focus secondary pions and kaons, their focusing power being optimized for 3 GeV secondaries. The secondary beam has a relatively short decay path which can be varied from 25 to 50 m. A variable decay path will provide additional information on the $\nu_e$ component of the beam.

Combining the high proton flux with a high efficiency horn focusing will provide a high flux neutrino beam, yielding over 2,000,000 $\nu_\mu$ interactions per kton-year at a distance 500 m from the source. The neutrino flux will have a maximum around $E_\nu = 1$ GeV and an exponential high energy tail falling to the 10% level at $E_\nu = 3$ GeV.

3.2. NuMI: Neutrino Beams from the Main Injector

The Main Injector accelerator is a 150 GeV proton synchrotron constructed to replace the original Fermilab Main Ring. It is expected to serve as a high intensity, fast-cycling accelerator for antiproton production, as
an injector into the Tevatron and simultaneously to support fixed target experiments using 120 GeV protons.

It is expected that after the completion of the NuMI construction project, the Main Injector will be able to deliver $3.6 \times 10^{20}$ protons per year onto the NuMI target, in parallel with the simultaneous support for the antiproton production for the Tevatron Collider experiments.

The high intensity and high repetition rate of the Main Injector offers an opportunity for neutrino beams of unprecedented intensity, thus creating an opportunity for long baseline neutrino oscillation experiments. The Main Injector will accelerate 6 batches of $8 \times 10^{12}$ protons each with a repetition rate of 1.9 secs. One of these batches will be used for antiproton production, while the remaining five batches will be extracted onto the neutrino target.

Secondary pions and kaons will be collected and focussed using a system of two parabolic magnetic horns, and subsequently they will produce a neutrino beam by decaying inside a 675 m long decay pipe. The beam optics is designed to allow tuning of the neutrino beam energy by moving the focusing elements (horns) in a manner similar to a zoom lens. The energy spectra of three possible beam configurations are shown in Fig. 4, together

![Image of Fig. 4](image-url)

Fig. 4. Neutrino beam spectra for different NuMI beam configurations

with a spectrum of a hypothetical beam, where all of the secondary particles were collected and allowed to decay. The NuMI beam design provides overall efficiency of the order of 50%, in all three beam configurations.
4. MiniBOONE Experiment: Checking the LSND Result

The primary goals of this experiment are:

- Unambiguously confirm or disprove the existence of the neutrino oscillation signal suggested by the LSND experiment
- Provide precise measurements of the oscillation parameters, should the existence of the effect be established, or improve the existing limits if the effect is not confirmed

The detector will consist of a 12 m diameter spherical tank filled with 769 tons of mineral oil, located at the distance of 500 m from the neutrino source. Cerenkov light emitted by particles produced in the neutrino interactions will be detected by 1220 eight-inch phototubes. The pattern of the detected Cerenkov rings will be used as a primary tool of the particle ID, as shown in Fig.5. The outer 50 cm volume, optically isolated from from the main detector volume and viewed 292 outward-pointing photomultipliers, will serve as a veto against cosmic rays.

**Cerenkov Light...**

![Cerenkov Light Diagram](image)

**Fig. 5. Particle identification in the MiniBOONE experiment**

The Booster neutrino beam is expected to yield 500,000 $\nu_\mu$ quasi-elastic CC interaction per year in the MiniBOONE fiducial volume. The expected
signal of the neutrino oscillations, predicted from the LSND results, will consist of a sample of 1000 identified $\nu_e$ CC interactions. The main background will be due to the intrinsic $\nu_e$ component of the beam: it is expected that there will be 1275 events of $\nu_e$ from muons decays and 425 events of $\nu_e$ from K decays. The background calculations can be experimentally verified by changing the length of the decay volume. An additional handle will be provided by the fact, that the sample of $\nu_e$ interactions due to $\nu_\mu \rightarrow \nu_e$ oscillations will have an energy distribution different from that expected $\nu_e$ component of the beam (see Fig.6).

![Fig. 6. Expected spectra of the excess $\nu_e$ interactions for two possible oscillation scenarios](image)

The large size of the expected LSND-inspired oscillation signal will enable a precise measurement of the underlying oscillation parameters whereas an absence of of the signal will lead to greatly improved limits on possible $\nu_\mu \rightarrow \nu_e$ oscillations, shown in Fig.7.

5. MINOS Experiment: Measuring Oscillation Parameters in the SuperK region

MINOS[8] experiment is designed to investigate neutrino oscillations in the region indicated by the atmospheric neutrino experiments. Two detec-
Fig. 7. Sensitivity of the MiniBOONE experiment

tors, functionally identical, will be placed in the NuMI neutrino beam: one at Fermilab and the second one in Soudan iron mine, 732 km away.

5.1. Two Detectors Neutrino Oscillation Experiment

Two identical detectors placed in the same neutrino beam make the oscillation experiment relatively easy. Observed interactions of $\nu_\mu$ can be divided into two classes: “CC”-like, with an identified $\mu$ track, and “NC”-like, muonless. The ratio of the observed numbers of the CC and NC-like events in the two detectors must be the same, provided that the same classification algorithm is used. This remains quite true, even if the beam spectra at the two detector locations differ slightly, as the ratio $\frac{\sigma^{NC}}{\sigma^{CC}}$ is energy independent.

If $\nu_\mu$ undergoes oscillations, then some fraction of the original $\nu_\mu$ beam will arrive at the far detector in an ‘oscillated’ form. The CC interaction of the oscillated neutrino (with the interaction cross section potentially reduced by a factor $\eta$ with respect to the $\sigma^{CC}_{\nu_\mu}$) will not, in general, produce
a $\mu$ in the final state and they will be classified as “NC”-like interactions. We will have, therefore:

$$N_{\text{near}} \left\{ \begin{array}{l} N_{\text{NC}} = \Phi_{\text{near}} (\sigma_{\text{NC}} + \varepsilon \sigma_{\text{CC}}) \\ C_{\text{near}} = \Phi_{\text{near}} (1 - \varepsilon) \sigma_{\text{CC}} \end{array} \right.$$ \hspace{1cm} (5)

and

$$F_{\text{ar}} \left\{ \begin{array}{l} N_{\text{far}} = \Phi_{\text{far}} (\sigma_{\text{NC}} + \varepsilon \sigma_{\text{CC}} + \eta \xi \sigma_{\text{CC}}) \\ C_{\text{far}} = \Phi_{\text{far}} (1 - \varepsilon) \xi \sigma_{\text{CC}} \end{array} \right.$$ \hspace{1cm} (6)

where: $\varepsilon$ is the fraction CC interactions misclassified as the “NC” events, $\xi$ is the fraction of the beam “oscillated” and $\Phi_{\text{near, far}}$ is the total neutrino flux at the near/far detectors.

The double ratio $R = \frac{N_{\text{NC}}(\text{near})}{N_{\text{CC}}(\text{near})} / \frac{N_{\text{NC}}(\text{far})}{N_{\text{CC}}(\text{far})}$ is a particularly sensitive measure of the oscillations:

$$R = \frac{1}{1 + \varepsilon \frac{\sigma_{\text{CC}}}{\sigma_{\text{NC}}}} + \frac{\varepsilon + \eta \sigma_{\text{CC}}}{\sigma_{\text{NC}}}$$ \hspace{1cm} (7)

R combines the sensitivities of the disappearance experiment, $\frac{1}{\xi}$ term, and the appearance experiment, $\eta \frac{\sigma_{\text{CC}}}{\sigma_{\text{NC}}}$ term. In addition R has very small systematic uncertainty, as most of the neutrino flux uncertainties cancel. The value of R will provide additional information about the oscillation mode through the value of $\eta$:

$$\eta = \begin{cases} 1 & \nu_\mu \to \nu_e \\ 0.2 - 0.3 & \nu_\mu \to \nu_\tau \\ 0 & \nu_\mu \to \nu_{\text{sterile}} \end{cases}$$ \hspace{1cm} (8)

5.2. MINOS detectors

The MINOS experiment will consist of two, nearly identical detectors: one located at the Fermilab site, some 500 meters behind the decay pipe, and the second one, in northern Minnesota, at the distance of 732 km from Fermilab. The far detector will be located in a new cavern, which is under construction in the Soudan mine, close to the existing Soudan II detector.

The far MINOS detector will consist of two supermodules, 2.7 kton each. They will be constructed as magnetized steel octagons, 8 m in diameter, with a toroidal magnetic field about 1.5 T. Steel plates, 2.5 cm thick, will be interspersed with planes of scintillator strips, to provide calorimetric measurement of the deposited energy, with energy resolution $\Delta E/E \sim 0.6/\sqrt{E}$. The active detector elements will consist of strips of extruded scintillator, 1
cm thick and 4 cm wide. Scintillation light will be collected by waveshifting fibers and read out by Hamamatsu M16 photomultipliers. The fine granularity of the scintillator strips will allow them to be used as a tracking detector to measure muon trajectories and determine the muon momentum from the curvature in the magnetic field.

The near detector, on the Fermilab site, will be as similar as possible to the far detector, except for its size.

The neutrino beam line and the MINOS detectors are under construction and the data taking is expected to commence in 2003. The choice of the initial beam energy is currently under discussion and it may depend on the forthcoming results of the K2K experiment.

5.3. MINOS Physics Measurements

Two massive detectors and an intense neutrino beam constitute a powerful tool to investigate neutrino oscillations, especially when the beam energy can be chosen to maximize the oscillation signal. MINOS will perform several independent measurements, which will provide a clear and complete picture of the neutrino oscillations in the SuperK region. These measurements fall into three different categories:

- Firm evidence for the oscillations.
  Near/far detector comparison will reduce the systematic uncertainties. The neutrino beam spectrum measurement with the near detector will constrain the predicted neutrino flux at the far detector. In the presence of the SuperK-indicated effect we expect at least two evidences for the oscillations:
    - A double ratio $R = \left( \frac{NC}{CC} \right)_{\text{near}} / \left( \frac{NC}{CC} \right)_{\text{far}}$ (see Eq.7) different from one. The sensitivity of this measurement for different possible $\Delta m^2$ depends on the selected beam energy, as shown in Fig.8
    - The $\nu_\mu$ charged current interaction rate and the observed energy distribution. Presence of neutrino oscillations will lead to a characteristic oscillatory modification of the spectrum observed at the far detector, as shown in Fig.9

- Measurement of the oscillation parameters: $\Delta m^2$ and $\sin^2 2\theta$.
  Fits of the observed depletion of the CC energy spectrum in Fig.9 will provide a precise estimate of the oscillation parameters. The expected precision of this determination depends somewhat on the oscillation scenario and on the choice of the beam. Two years exposure of the MINOS detectors will yield measurements with the precision illustrated in Fig.10.
- Determination of the oscillation mode(s)

  - $\nu_\mu \rightarrow \nu_{\text{sterile}}$?
    The large mixing angle indicated by the SuperK results leads to a significant contribution of the appearance term to $R$ in Eq.7. The measurement of $R$ will provide a decisive demonstration for or against sterile neutrinos as a dominant oscillation mode over the entire region of SuperK.

  - $\nu_\mu \rightarrow \nu_e$?
    The fine granularity of the MINOS detector will allow for identification of the $\nu_e$ interactions by topological criteria with efficiency of the order of $15 - 20\%$. The background of the mis-identified NC interactions as well as the intrinsic $\nu_e$ component of the beam (expected to be of the order of 0.6%) will be measured with high accuracy by the near detector. Fig.11 shows the sensitivity of the MINOS detector to this oscillation mode in comparison with the limits from CHOOZ experiment.
Fig. 9. Observed spectrum of the identified $\nu_\mu$ CC events in the presence (top) or absence (middle) of oscillations. Shaded histogram represents contribution of mis-identified NC events. Ratio of the observed and the expected distributions is shown at the bottom for 2 years exposure.

$-\nu_\mu \rightarrow \nu_\tau$?

Circumstantial evidence for this oscillation mode will be provided by the measurement of $R$ (Eq.7). For relatively high $\Delta m^2$, above $5 \times 10^{-3}$ eV$^2$ a significant sample of CC $\nu_\tau$ interactions can be identified by exclusive decay modes, like $\tau \rightarrow \pi$. The near detector will be again instrumental in reliable determination of the unavoidable background from the NC interactions.

6. Conclusions and Outlook

New experiments, under construction at Fermilab, will help to clarify the situation with neutrino oscillations in the $\Delta m^2 > 0.001$eV$^2$ region. The MiniBOONE experiment will settle, within coming 2-3 years, the issue of the LSND results by precise determination of the underlying oscillation parameters or by setting limits far outside the LSND-allowed region. MINOS experiment will decisively establish the phenomenon of neutrino oscillations
and measure precisely the corresponding mixing angles and $\Delta m^2$ values in the region indicated by the SuperK experiment within next 5-6 years. The question of the dominant oscillation mode: $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_{\text{sterile}}$ will be settled. The sub-dominant mode $\nu_\mu \rightarrow \nu_e$ will be established or the existing CHOOZ limit will be significantly improved. The next generation of the oscillation experiments will probably await a new generation of neutrino beams, derived from muon storage rings. The high intensity of such beams will make it possible to detect subtle effects like CP-vilation or matter induced effects. By providing $\nu_e$ beams along with the $\nu_\mu$ component, these beams will enable complete measurements of the neutrino mixing matrix elements.
Fig. 11. The 90% C.L. limits for $\numu \rightarrow \nue$ oscillation parameters for two years exposure with different beams: low (Ph2le), medium (Ph2me) and high (Ph2he) energy.

7. Acknowledgements

It is a pleasure to thank and to congratulate the organizers, especially Prof. M. Jezabek, for the flawless organization of such a pleasant and stimulating conference. Many of my colleagues in MINOS collaboration contributed to this presentation, I would like to thank in particular Dr. D. Petyt for his contribution to understanding of the physics potential of this experiment. Profs. J. Conrad and M. Shaevitz helped me to fully appreciate the beauty of the MiniBOONE experiment.

Apologies go to all those, whom I neglected to quote properly. The number of relevant papers is overwhelming.

REFERENCES

[1] J. Bonn, Neutrino Mass from Tritium Beta Decay: Present Limits and Perspectives, these Proceedings
[2] B. Pontecorvo, Zh. Eksp. Teor. Fiz. 33, 549 (1957)
[3] Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. 28, 870 (1962)
[4] Y. Fukuda et al, Phys. Rev. Lett. 81, 1562 (1998)
[5] D. Kielczewska, Recent Results from SuperKamiokande and K2K, these Proceedings
[6] C. Athanassopoulos et al, Phys. Rev. C 55, 2079 (1997)
   see also: http://www.neutrino.lanl.gov/LSND/pubs/
[7] http://www-boone.fnal.gov/
[8] http://www.hep.anl.gov/ndk/hypertext/minos.tdr.html