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October 3, 1995

Dr. Martha A. Krebs
Director, Office of Energy Research
US Department of Energy
Forrestal Building
Washington, DC 20585

Dear Martha:

With this letter, I am transmitting the report of the HEPAP Subpanel on Accelerator-Based Neutrino Oscillation Experiments led by Professor Frank Sciulli. HEPAP unanimously endorses the subpanel's report and its recommendations.

The report was made available to HEPAP members well in advance of our September 18-19 meeting. During the meeting, Professor Sciulli made a presentation to the panel which was followed by extensive discussions with HEPAP members and a period of open discussion for comment by people attending the meeting. All members of HEPAP then had an opportunity to express their conclusions. Their support for the report and its recommendations was unanimous. Specifically, HEPAP noted and accepted the assumptions contained in the report regarding the national high energy physics program.

We believe that the program of neutrino oscillations, to be carried out at FNAL as recommended by the subpanel is an important component of the future national program. The beam at FNAL will be the most intense high energy neutrino beam in the world and will provide the greatest reach in the study of neutrino oscillations at accelerators. Discovery of neutrino oscillations accessible to accelerator experiments would revolutionize particle physics.

The time scale for the development of the program at FNAL will reflect the funding strictures associated with the commitments already made in the national program. There are major components of the national program still under development: the FNAL Main Injector and associated detector upgrades, and the PEP II B Factory and associated new detector. Most important, there is also the immediate need to define the US participation in the LHC, both in the accelerator and in the two detectors, ATLAS and CMS. Furthermore, the current budgets are very tight and are not sufficient to carry out current accelerator operations at the desired levels. Thus, without increased funding for high energy physics, we expect that the major funding needs of the neutrino oscillation program at FNAL can only be satisfied after the funding demands of some of the ongoing projects start to decrease in FY98 and beyond.

The members of HEPAP want to express their gratitude to the subpanel members, and especially to their chairman, Professor Frank Sciulli, for their devoted efforts to understand the many difficult issues and to make thoughtful recommendations to HEPAP and DOE.

Yours sincerely,

Piermaria J. Oddone
Acting Chair of HEPAP
For Consideration of Neutrino
Oscillation Experiments

Columbia University

DEPARTMENT OF PHYSICS

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August 31, 1995

Dr. Piermaria J. Oddone
Acting Chair, HEPAP Subpanel
Lawrence Berkeley Laboratory, Deputy Director
University of California
Berkeley, CA 94720

Dear Pier:

Enclosed is the Subpanel report. The charge contained in the letter from Dr. Krebs to the HEPAP chair is appended to the report, as are relevant data on our meetings and cost estimations. The members of the Subpanel deserve special thanks for their hard work and dedication in arriving at a timely resolution of the issues. The members of the Cost Review Subcommittee provided an highly competent professional element to the process. The DOE staff associated with the effort should also be congratulated for their important contributions.

In coming to a conclusion, the Subpanel members needed to apprise themselves on many questions related to neutrino mass and mixing, but especially the prevailing situation relating to the "atmospheric anomaly". Though one cannot now conclude that this anomaly demonstrates neutrino oscillations, it is an effect that needs to be pursued. The SuperKamiokande experiment is due to begin taking atmospheric neutrino data next year and is expected to take data with a neutrino beam produced at the KEK laboratory within the next three to five years. Though we sympathized with the desires by both U.S. proponents to do the first experiment demonstrating oscillations, there did not appear to the Subpanel any feasible way to compete with the time frame of the SuperKamiokande program.

On the other hand, there are important reasons to develop a program for the next decade that goes well beyond the plans in Japan. While both Brookhaven and Fermilab proposed programs to do this, it is not cost-effective to undertake both. The program recommended here is well designed to take advantage of physics developments over the next several years and, under any circumstances, will make unique contributions soon after it begins. The very high flux Fermilab Main Injector, built primarily to provide improved colliding beam rates, has the potential to provide a neutrino beam of unique capabilities for the field of neutrino oscillation science. It is incumbent upon our community to exploit existing capabilities in novel ways so as to provide the best physics for the money. We believe that the Subpanel recommendations do precisely this.

It is my hope that HEPAP will endorse the recommendations and the underlying logic.

Sincerely,

Frank

Frank Sciulli
Chairman, HEPAP Subpanel on Accelerator-Based
Neutrino Oscillation Experiments

DOE/ER-0662

High Energy Physics Advisory Panel

Subpanel on Accelerator-Based Neutrino Oscillation Experiments

September 1995

U.S. Department of Energy
Office of Energy Research
Division of High Energy Physics
Washington, D.C. 20585

DISCLAIMER

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EXECUTIVE SUMMARY

Neutrinos are among nature's fundamental constituents, and they are also the ones about which we know least. Their role in the universe is widespread, ranging from the radioactive decay of a single atom to the explosions of supernovae and the formation of ordinary matter. Neutrinos might exhibit a striking property that has not yet been observed. Like the back-and-forth swing of a pendulum, neutrinos can oscillate to-and-fro among their three types (or flavors) if nature provides certain conditions. These conditions include neutrinos having mass and a property called "mixing." The phenomenon is referred to as neutrino oscillations. The questions of the origin of neutrino mass and mixing among the neutrino flavors are unsolved problems for which the Standard Model of particle physics holds few clues. It is likely that the next critical step in answering these questions will result from the experimental observation of neutrino oscillations.

The High Energy Physics Advisory Panel (HEPAP) Subpanel on Accelerator-Based Neutrino Oscillation Experiments was charged to review the status and discovery potential of ongoing and proposed accelerator experiments on neutrino oscillations, to evaluate the opportunities for the U.S. in this area of physics, and to recommend a cost-effective plan for pursuing this physics, as appropriate. The complete charge is provided in Appendix A.

The Subpanel studied these issues over several months and reviewed all the relevant and available information on the subject. In particular, the Subpanel reviewed the two proposed neutrino oscillation programs at Fermi National Accelerator Laboratory (Fermilab) and at Brookhaven National Laboratory (BNL). The conclusions of this review are enumerated in detail in Chapter 7 of this report. The recommendations given in Chapter 7 are also reproduced in this summary.

At this time, there appear to be opportunities for fundamental discoveries in neutrino oscillations. The technology now exists to explore a broad range of oscillation parameters at the same time that a number of experimental, cosmological, and theoretical hints indicate possible parameter values. A discovery of neutrino oscillations and subsequent exploration of the phenomena would open a new window on nature with a significant and far-reaching impact on physics and related fields. The benefits from discovering or exploring the features of neutrino oscillations would be enormous; on the other hand, in spite of the existing hints, it is possible that neutrino oscillations may not exist in the experimentally accessible regions.

In deliberating, the Subpanel used available information on commitments and costs inherent in the ongoing U.S. program for the near and far term. The conclusions of this report assume that the ongoing program, as recommended in the report by the HEPAP Subpanel on the Vision for the Future of High-Energy Physics (Drell Subpanel), will be pursued. Our recommendations reflect the judgment that a new experimental effort on neutrino oscillations can be undertaken within the flexibility inherent in the funding projections of the ongoing program.

Searches for neutrino oscillations are also being actively pursued in experiments on solar and atmospheric neutrinos, at reactors, and at accelerators elsewhere in the world. The recommendations that follow are resilient to experimental developments over the next several years from those sources, including programs using the Super-Kamiokande detector. If oscillation phenomena are not demonstrated elsewhere, there will be a substantial range of parameters in which oscillations may be discovered through the recommended program. If, on the other hand, oscillations are found before a U.S. program can begin, this will imply at the least that one neutrino mass is non-zero. Since there are three light neutrinos, other mass values characterizing oscillations may be accessible to the recommended experimental program. If oscillations are found inside the mass region covered by this program, its substantial capabilities will place the program in a unique position to measure the specific flavor properties of the mixing, as well as to seek oscillations at other masses.

The Subpanel endorses the strong, broad-based, and flexible program of neutrino oscillation studies outlined in the following recommendations.

Recommendation 1

The search for neutrino oscillations with accelerator experiments, including a single long-baseline beam, should form an important segment of the U.S. high energy physics program.

The discovery of neutrino oscillations, and consequentially the discovery of neutrino mass, would constitute a major breakthrough in particle physics and the first evidence of physics beyond the minimal Standard Model. There are experimental hints of oscillations from the study of solar and atmospheric neutrinos. Measurements of the anisotropy of the cosmic microwave background have prompted theoretical speculation that neutrinos with mass could form part of the dark matter of the universe. Either Brookhaven or Fermilab is well suited to provide a beam for neutrino oscillation searches in unexplored regions.

Recommendation 2

The MINOS experiment at Fermilab should be supported; the E-889 experiment at BNL should not be supported.

Both Fermilab and Brookhaven have proposed long-baseline experiments to explore the neutrino mass range $10^{-3} < \Delta m^2 < 1$ eV^2. Anomalies have been reported from underground experiments observing neutrinos produced in the atmosphere. These anomalies could be attributed to neutrino oscillations with large mixing in this mass range. Both proposed programs aim to explore a substantially larger region in mixing angle than is encompassed by the atmospheric anomalies.

The Subpanel unanimously recommends the support of the MINOS experiment at Fermilab over the E-889 experiment at Brookhaven for the following reasons:

- The discovery potential of MINOS is superior to that of E-889 for both $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations for $\Delta m^2 < 2 \times 10^{-2}$ eV^2 and comparable for higher values of Δm^2.

- MINOS offers a better opportunity to explore possible discoveries since it has higher event rates, a larger variety of experimental signatures, and the option of a tunable narrow-band beam.

- The combination of COSMOS (see next recommendation) and MINOS in the same beamline is cost-effective.

Recommendation 3

The COSMOS experiment at Fermilab should be supported.

The Fermilab Main Injector can provide the world's most intense beam for the study of neutrino oscillations in the mass range $\Delta m^2 > 10$ eV^2 where neutrino mass would contribute to the dark matter of the universe. The COSMOS experiment will have significantly more sensitivity than the presently running NOMAD and CHORUS experiments at CERN, and thus will be a suitable next step.

Recommendation 4

The Fermilab program should remain flexible to react to new information.

Several experiments are expected to report new results on neutrino oscillations before the start of the proposed program. A failure to confirm atmospheric neutrino anomalies should not affect the decision to proceed with the MINOS experiment, since its purpose includes exploration of a much larger region of oscillation parameters. However, the COSMOS and MINOS experimenters and the Fermilab Directorate should be prepared to respond to any new information.

1.0 INTRODUCTION

The Subpanel on Accelerator-Based Neutrino Oscillation Experiments was formed in response to the charge (Appendix A) from Dr. Martha Krebs, Director of the Office of Energy Research (ER) of the Department of Energy (DOE), to Professor Stan Wojcicki, Chairman of the High Energy Physics Advisory Panel (HEPAP). Since the HEPAP chair is also a principal member of one of the proposed oscillation experiments, he recused himself from all deliberations of this issue. Dr. Piermaria Oddone was designated to be the Acting HEPAP chairman for the purposes of this Subpanel and participated in the final Subpanel meeting where the conclusions and recommendations were written.

The membership of the Subpanel is attached as Appendix B. The twelve members comprise both theoretical and experimental physicists, all of whom have experience with neutrino physics but are not presently members of any of the proposed U.S. experiments.

The Subpanel met first on March 22-24, 1995, in Bethesda, Maryland and next on May 4-5, 1995, in Reston, Virginia. In these meetings, the approach to address the issues contained in the charge was established and some of the relevant background information was collected and discussed. The detailed evidence for an atmospheric neutrino anomaly and from the Liquid Scintillator Neutrino Detector (LSND) at the Los Alamos Meson Physics Facility (LAMPF) was discussed. Other information on ongoing and proposed experiments world-wide was also presented and reviewed.

The Subpanel addressed in detail the competing proposals for long-baseline neutrino oscillation experiments for Brookhaven National Laboratory (BNL), E-889, and for Fermi National Accelerator Laboratory (Fermilab), MINOS. The wide region of the parameter space spanned by these proposals includes that indicated by the atmospheric neutrino anomaly. The costs associated with these proposed experiments are substantial, and major construction efforts will be required. Both proposals had been reviewed and recommended for approval by the respective laboratory Program Advisory Committee (PAC), and subsequently approved by the laboratory directors. Each experiment requires a new secondary neutrino beam and associated stations for proton extraction and targeting, as well as new detectors. The program proposed for Fermilab also contains a short-baseline experiment, COSMOS, which had been approved earlier by the Fermilab PAC and will also operate in the new neutrino beam. COSMOS is designed to explore a mass range that is of cosmological interest. The Subpanel, after studying the proposals and relevant information pertaining to the experiments, prepared a series of supplemental questions to be answered by the proponents.

Meetings were held at the two laboratories. The Fermilab meeting to review the MINOS and COSMOS programs took place on June 13-15, 1995; the BNL meeting to review E-889 on June 20-22, 1995. The agendas of all meetings are included in Appendix C. The Subpanel provided a list of additional questions for each of the proponents and laboratories, to be answered prior to the final Subpanel meeting in July.

At the BNL meeting, additional information was obtained on the long-baseline neutrino oscillation experiment proposed to the KEK Laboratory in Japan. The specific goal of this effort is to search for neutrino oscillations in the region suggested by the atmospheric anomaly using neutrinos created from an accelerator beam.

In order to verify costs estimated by the laboratories involved in the U.S. programs, a Cost Review Subcommittee (CRS) was appointed. The membership of the CRS consisted of two DOE staff and six outside experts on cost projections for the construction of the detectors and neutrino beams, including civil construction. The cost review process took place at the laboratories concurrently with the Subpanel reviews. The charge and membership of the CRS and the executive summaries from the reviews at both laboratories are provided in Appendices D and E, respectively. (The full reports of this subcommittee are available as separate documents.) The Subpanel also met in executive sessions, often with the CRS membership.

To complete the review, arrive at conclusions, and write its final report, the Subpanel met in executive session in Denver, Colorado, during the period July 24-28, 1995. All materials presented to the Subpanel (backup information, written responses, and answers to the questions) were available during this meeting. The chairman of the CRS presented his full report on the first day of the meeting. Present for the deliberations at Denver were all members of the Subpanel, the acting HEPAP chair, and members of the DOE high energy physics staff.

2.0 QUEST FOR NEUTRINO MASS (MIXING)

In 1934, Fermi showed that the mass of the neutrino must either be zero, or "very small with respect to the mass of the electron." Since then, much effort has been spent in trying to decide between these two alternatives. The theoretical and the phenomenological consequences of a non-zero neutrino mass, no matter how small, are so rich that a broad array of experiments has been mounted to search for it. Though no "smoking gun" has been found so far, there are intriguing hints about neutrino masses and mixing from several experiments searching for neutrino oscillations, the phenomenon most sensitive to small masses.

The rather complicated theoretical and experimental status of neutrino oscillations shown in Figure 2-1 is taken from the 1994 study by the Division of Particles and Fields of the American Physical Society.

2.1 Theoretical Motivation for Neutrino Mass Search

The masses of leptons and quarks remain the least understood feature of the Standard Model. In the exact electroweak symmetry limit, all quark and lepton masses, including the neutrino masses, vanish. Quark and charged lepton masses arise from electroweak symmetry breaking, but neutrinos could remain massless or attain only a very small mass. None of the precision tests of the Standard Model in any way precludes such small neutrino masses.

At present, there is no theoretical insight regarding the known masses of elementary fermions. For example, no formula relates quark and lepton masses to one another. Nevertheless, the discovery of neutrino masses, while requiring an extension of the Standard Model, could also provide new insight into the mass question.

One way of gaining new insight is through the apparent similarity between quarks and leptons: they have identical weak interactions; they exist in three families; and the charged leptons (e, μ, τ) have large mass ratios, as do their weak interaction analogues, the down quarks (d, s, b). This suggests the interesting possibility that there exists an exact quark-lepton symmetry which is broken at some high mass scale M. This notion is embodied in the SO(10) grand unified theory (GUT) in which the distinction between weak and strong interactions disappears at high mass scales.

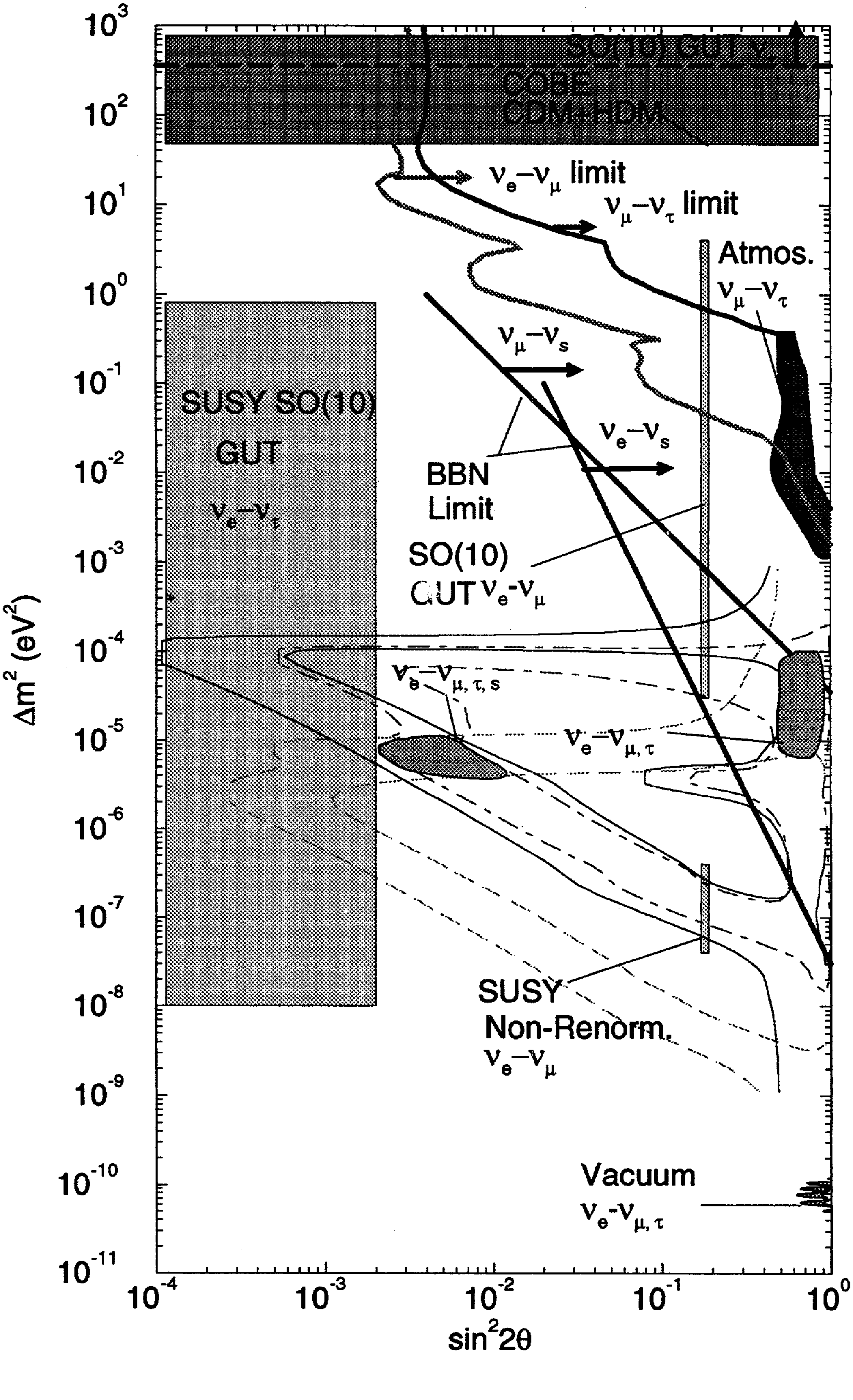

Figure 2-1. Summary plots of allowed regions in the oscillation parameter space of Δm^2 and $\sin^2 2\theta$ (from the Division of Particle and Fields study, 1994).

The question of neutrino mass within GUT models with quark-lepton symmetry was addressed by Gell-Mann, Ramond, and Slansky and by Yanagida. They proposed that when the GUT symmetry was broken at scale M, the right-handed neutrino obtains a large mass of order M. As a consequence of the so-called "see-saw mechanism," the familiar left-handed neutrino obtains a mass of about m^2/M, with m of the order of the mass of the corresponding charged lepton or up-type quark. Since M is likely to be very large (as large as 10^{16} GeV), this idea accounts for very small neutrino masses. Non-zero mass of the familiar neutrinos may be the best observable signal of physics near the GUT scale. Note that, if the see-saw mechanism is taken literally, one expects one flavor of neutrino (ν_τ) to have a mass much larger than the others (mass hierarchy).

If neutrinos have masses, their mass matrix generally should give rise to mixing among flavors, as occurs in the quark sector. Theory makes no definite predictions about masses or mixing angles. Hence, this is an experiment-driven field, where one needs to explore all accessible ranges of mass, using guidance from other fields such as cosmology and astrophysics when available.

2.2 Cosmological and Astrophysical Motivation for Neutrino Mass Search

The discovery of neutrino masses and mixing in the eV range would be of great importance for cosmology in particular for the problems of dark matter and galaxy formation. The "Big Bang" left behind a sea of relic neutrinos of all three flavors much like the photons in the Cosmic Microwave Background Radiation (CMBR). The relic neutrinos could overclose the Universe and have prevented galaxy formation if they are too heavy. Upper bounds on neutrino masses of order 50 eV have been set by requiring that the relic neutrinos not overclose the Universe. Some recent estimates suggest that light neutrinos constitute 30% of dark matter and that the sum of their masses is in the range of 5-10 eV. If this conjecture is combined with the mass hierarchy ansatz, at least one value of Δm^2 should be large ($\Delta m^2 >> 1$ eV^2).

Big Bang Nucleosynthesis (BBN) has been used to set bounds on the number of light neutrino flavors. The key point is that the expansion rate of the Universe is modified by the presence of light, but not massless, neutrino flavors; and this, then, influences the formation of light nuclei such as deuterium D, ^{4}He, and ^{7}Li. Similar BBN arguments have also been used to set limits on the mass and mixing parameters for the oscillation of active flavor neutrinos into sterile ones.

Neutrinos play a dominant role in supernova explosions. As a result of the large range of densities, matter-enhanced (or MSW) oscillations are possible for a large range of parameters. Such oscillations can affect energy loss mechanisms and explosive nucleosynthesis. Thus, the discovery of neutrino mass may have important implications for our understanding of supernovae and the origin of chemical elements.

Although there is strong interest in neutrino mass, no absolute theoretical necessity for it has yet emerged. Grand unified theories are speculative and even within the GUT framework it is possible to obtain vanishing neutrino mass. Cosmological and astrophysical arguments are intriguing, but not compelling. Thus, while we may hope to find definitive evidence for neutrino mass, we have no guarantees from theory of doing so.

2.2.1 Phenomenology of Neutrino Oscillations

If neutrinos have mass, they can undergo neutrino oscillations; this quantum mechanical phenomenon is the most sensitive way to measure small neutrino mass differences. Oscillations occur if the flavor eigenstates that take part in weak interactions are superpositions of mass eigenstates. As the flavor eigenstate evolves in time, the relative phases of its mass eigenstate components change and the resulting state becomes a superposition of different flavors.

In the two-flavor case, the mixing matrix relating flavor eigenstates (say ν_μ and ν_τ) to mass eigenstates (ν_1 and ν_2) is completely characterized by a single mixing angle, θ. The probability that a neutrino initially of muon flavor will have the tau flavor at a distance, L from the source takes the familiar form:

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2 \frac{\pi L}{L_o} \equiv \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2}{E} L\right)$$

where $\Delta m^2 \equiv m_2^2 - m_1^2$ is the difference of the squares of the mass eigenvalues m_1 and m_2, expressed in eV^2. The neutrino energy E is measured in GeV and L in km. The oscillation length L_o is defined to be

$$L_o = \frac{4\pi p}{\Delta m^2} \equiv 2.54 \frac{E(GeV)}{\Delta m^2 (eV^2)} \; km$$

Note that a larger value of the ratio L/E permits measurements to smaller values of Δm^2. When $(L/L_o) >> 1$, the oscillating term in the flavor probability is replaced by its average value of 1/2 and the probability becomes ½ $\sin^2\theta$.

In the real case of three flavors of neutrino, one expects three values of Δm^2 and oscillations with different amplitudes among all three flavors for each value of Δm^2. The possibility of CP violation arises in the same way as in the quark mixing matrix and may be investigated by comparing neutrino oscillations with anti-neutrino oscillations. Hence, if oscillations are discovered at a specific value of the mass parameter, there are many precise measurements to be performed which will be of great importance to physics, astrophysics, and cosmology.

2.3 Hints for Neutrino Oscillations

Hints for neutrino mass come from observations of neutrinos from the sun, from the interactions of high energy cosmic rays in the atmosphere, and from a beam stop at Los Alamos National Laboratory. Solar neutrinos are the lowest in energy ($E_\nu \leq 14 MeV$) and they travel the longest distance; hence, they probe to the smallest values of the mass difference parameter ($\Delta m^2 \geq 10^{-11} eV^2$). Atmospheric neutrino experiments measure neutrinos in the energy range from several hundred MeV to several GeV and they probe $\Delta m^2 \geq 10^{-4} eV^2$ for large mixing angles. The LSND experiment observes neutrinos from π and μ decay at rest, which travel several tens of meters, and probes relatively large values of Δm^2 for small mixing angles.

2.3.1 Solar Neutrinos

For more than 20 years, the radiochemical ^{37}Cl Homestake experiment has been observing a solar neutrino signal between one-quarter and one-half of that predicted by standard solar models. During the past decade, three other experiments have found similar deficits. The Kamiokande water Cerenkov detector has observed solar neutrinos via neutrino-electron scattering at about half the rate expected from solar model calculations, and the radiochemical ^{71}Ga experiments GALLEX and SAGE, which have a much lower threshold than the ^{37}Cl experiment, observe about 60% of the expected signal.

A great deal of analysis has been directed at trying to determine whether these solar neutrino deficits can be explained by reasonable modifications of the calculations of the solar neutrino flux. While it may be possible to explain one of the results in this way, it has been impossible to explain all simultaneously because they are sensitive to different parts of the solar neutrino energy spectrum. The Kamiokande result indicates that the ^{8}B neutrinos, the highest in energy but least copious, arrive as electron-neutrinos at about half the expected rate, while the combination of all four experiments seems to imply that the pp neutrinos, the lowest in energy and most copious in flux, arrive as electron-neutrinos close to 100% of the time. By contrast, the intermediate energy ^{7}Be neutrinos appear highly suppressed as electron-neutrinos. Such an energy-dependent suppression apparently cannot be explained by solar models. Neutrino properties provide alternative explanations of the solar neutrino anomaly and, if experimentally confirmed as oscillations, the non-zero magnitude of at least one neutrino mass and flavor-mixing have been discovered.

2.3.2 The Liquid Scintillator Neutrino Detector (LSND) Experiment

In February 1995, the LSND collaboration described preliminary evidence for $\nu_\mu \leftrightarrow \nu_e$ with a small mixing angle $\sin^2 2\theta \approx 3\text{-}6 \times 10^{-3}$ and a large mass difference squared, $\Delta m^2 \geq 1$ eV^2. This experiment is discussed in the following chapter (Chapter 3).

2.3.3 Atmospheric Neutrinos

Atmospheric neutrinos are created from the decays of pions and muons arising from collisions of cosmic ray protons with nuclei in the atmosphere. Approximately twice as many muon-type neutrinos as electron-type neutrinos are expected from naive counting arguments. In traveling from points of production to detectors below the surface of the Earth, atmospheric neutrinos cover distances ranging from 10 km to 10,000 km; and so neutrino oscillation lengths not previously accessible with accelerator or reactor neutrinos are explored.

The naive ratio of neutrino flavors seen at the surface of the Earth has to be modified to allow for the detailed mechanism of their production. The actual ratio at the surface of the Earth is calculated by elaborate Monte Carlo methods which take into account the spectrum of primary cosmic rays entering the atmosphere, geomagnetic effects, cosmic ray shower development, the production and decay kinematics of pions in the atmosphere, and the polarization of daughter muons. Calculations of the absolute neutrino fluxes differ by as much as 20-30%. However, these calculations are more consistent in predictions of the ratio of muon-neutrinos to electron-neutrinos, where they differ by no more than 5%.

2.3.3.1 Cerenkov Detectors

The first measurements of the neutrino flavor ratio [and of the "ratio of ratios", R(μ/e), comparing the observed ratio to the Monte Carlo prediction] were made with water Cerenkov detectors. Using events from charged-current neutrino scattering, lepton momenta were selected in the range $300\ c \leq p \leq 1500$ MeV/c. The events chosen were characterized by a single Cerenkov ring and the total containment of the event energy within the fiducial volume. Single ring events, classified according to the presence or absence of showering, provided a measure of electrons or muons in the final state, respectively. Thus, the observed ratio of nonshowering to showering single ring events, compared directly with Monte Carlo expectations, provides an experimental measure of whether the fraction of ν_μ and ν_e at the earth conforms to expectations.

In 4.92 kT-years of observation, the Kamiokande collaboration observed a total of 151 totally contained, single ring muon-events and 159 electron events. The momentum ranges were $200 \leq p_\mu \leq 1500$ MeV/c for the muons and $100 \leq p_e \leq 1330$ MeV/c for the electrons. The ratio of muon-to-electron-neutrino events is about 60% of the sub-GeV Monte Carlo prediction (see Table 2-1). Similar results for atmospheric neutrinos in the same energy range have been reported by the IMB collaboration. In a 7.7 kT-year exposure of the IMB detector, 610 single ring events were found. Of these events, 378 were showering with electron momenta in the range $100 \leq p_e \leq 1500$ MeV/c, and 232 were nonshowering with muon momenta $300 \leq p_\mu \leq 1500$ MeV/c. The corresponding muon-neutrino to electron neutrino ratio is about 54% of the Monte Carlo prediction (see Table 2-1).

The Kamiokande collaboration has also studied a sample of 233 additional events with much higher energies, called "multi-GeV" events. They are a mixture of fully contained single-ring and multi-ring events, plus partially contained events with a vertex within the fiducial volume of the detector. The lepton flavor of single-ring events is identified by the same showering versus nonshowering method used for "sub-GeV" events. With a mean energy of 6 GeV, the "multi-GeV" events provide an independent measurement of the μ/e ratio at a different neutrino energy. The ratio, about 57% of the Monte Carlo expectation (see Table 2-1), is consistent with the "sub-GeV" result but with slightly larger errors.

The zenith angle dependence of these "multi-GeV" neutrino events is of interest because the lepton direction is more closely correlated with the neutrino direction at the higher energies. Downward-going neutrinos travel a distance of order 10-20 km, whereas upward-going neutrinos travel distances of order 13,000 km, so that very different values of L/E are sampled at different zenith angles. The multi-GeV data show signs of an azimuthal dependence, albeit with large errors.

Table 2-1. The Atmospheric Neutrino Anomaly

The third column gives the confidence level (CL) associated with a x^2 comparing the data to expectations without oscillations (1). Note that the reference in footnote[1] has included correlations in the x^2 definition, as appropriate. The last column of the table gives the approximate number of standard deviations (σ) for the integrated tails of a gaussian distribution to provide a probability at the quoted confidence level.

Experiment	$R = (\mu/e)^{data}/(\mu/e)^{MC}$	CL (%) from x^2	σ
Kamiokande sub-GeV	$0.60 {}^{+0.07}_{-0.06} \pm 0.05$	0.2[1]	3σ
Kamiokande multi-GeV	$0.57 {}^{+0.08}_{-0.07} \pm 0.07$	1.2[1]	3σ
IMB	0.54 ± .05 (stat) ± 0.12 (sys)	4.7[1]	2σ
Frejus	1.00 ± 0.15 ± 0.08	85.2[1]	--
Nusex	0.99 ± 0.29	93.2[1]	--
Soudan 2 (prelim)	0.64 ± 0.17 ± 0.09	36.1[1]	1σ
Kamiokande zenith	(see graphs in reference[1])	5.2[1]	2σ

[1] G.L. Fogli and E. Lisi, BARI-TH/205-95. We have taken CL = 100% - CL(ref), where CL(ref) is that quoted in the reference.

[2] D. Saltzberg, HEP-PH-9504343 (presented at Moriond 1995).

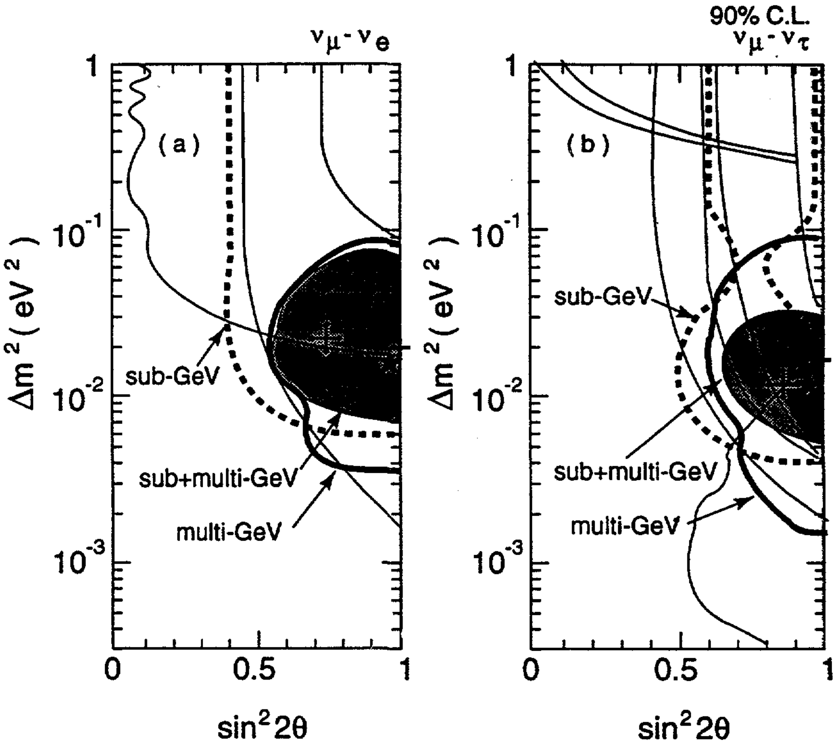

Figure 2-2. Neutrino oscillation parameters allowed by atmospheric neutrino data

The combined sub-GeV and multi-GeV allowed regions are shaded and the best-fit values are indicated by stars. (From Fukuda et al.)

The Kamiokande collaboration has done separate analyses of its "sub-GeV" and "multi-GeV" data sets and finds that they are mutually consistent with neutrino oscillations characterized by the same parameters. The best fits for the parameters both involve maximal mixing. The fitted values, for oscillations to electron or tau neutrino types, are:

$$\nu_\mu \leftrightarrow \nu_e: \quad (\Delta m^2, \sin^2 2\theta) = (1.8 \times 10^{-2}\ eV^2, 1),$$

$$\nu_\mu \leftrightarrow \nu_\tau: \quad (\Delta m^2, \sin^2 2\theta) = (1.6 \times 10^{-2}\ eV^2, 1).$$

2.3.3.2 Other Atmospheric Experiments

While mild support for the anomaly comes from the Soudan II detector, the similar Frejus detector with similar errors, sees no effect as seen in Table 2-1. Both measurements are of much poorer statistical significance than either Kamiokande or IMB.

The significance of all these data has been studied by Fogli and Lisi, who note that the significance of the deviation of R from unity can be misleading due to the non-Gaussian nature of the errors (e.g., R = 0.5 ± 0.1 differs from 1.0 by 5σ, but its inverse R^{-1} = 2.0 ± 0.4 differs from 1.0 by only 2.5σ). They have made a critical study of the statistical, systematic, and theoretical errors associated with each experiment, and have calculated the x^2 associated with each measurement compared to the null hypothesis of no oscillations. From this x^2, the confidence level for agreement with the absence of oscillations has been calculated and is shown in column 3. Table 2-1 also shows an independent calculation of the significance of the Kamiokande zenith angle distribution carried out by D. Saltzberg. From these, one concludes that several independent measurements at the levels of 2 - 3 standard deviations indicate deviation from expectations for atmospheric neutrinos.

The IMB collaboration has also analyzed the ratio of upward going muons to those that stop in the detector. These muons are produced by neutrino interactions in the earth surrounding the detector, and this ratio is sensitive to neutrino oscillations in the same approximate region of Δm^2. While they observe the ratio to be consistent with the absence of oscillations, others have argued that the predicted value is sensitive to assumptions in the calculations of flux and cross-sections. Other reported measurements on oscillations, recently reviewed in the Division of Particles and Fields (DPF) Long-Range Planning Study: Neutrino Mass and Mixing, do not add clarity to this subject.

In the view of the Subpanel, even though the available data satisfy many numerical criteria for "discovery," they do not constitute definitive evidence for the existence of neutrino oscillations, largely because of the complex and uncontrolled nature of the source. However, the evidence for an anomaly is sufficiently strong to make further experimental study essential.

2.4 The Roles of Accelerators and Reactors

Accelerators produce copious beams of high energy muon-type neutrinos, ν_μ, and so provide facilities for appearance experiments ($\nu_\mu \rightarrow \nu_{e,\tau}$) and disappearance searches ($\nu_\mu \rightarrow \nu_\mu$). The Brookhaven, CERN, and Fermilab accelerators have a long history of seeking evidence on various oscillation modes; some of their limits are yet to be superseded. For example, the E-531 emulsion experiment at Fermilab provided the best bound on mixing angle for $\nu_\mu \rightarrow \nu_\tau$ at large Δm^2. For $\nu_\mu \rightarrow \nu_e$, the BNL experiments E-734 and E-776, yield the best bounds on mixing at many values of Δm^2. In the case of $\nu_e \rightarrow \nu_\tau$, the best limits come from the bubble chamber BEBC at CERN and E-531 at Fermilab, but they are more than an order of magnitude weaker than the others.

Reactors are prolific sources of anti-electron neutrinos, $\bar{\nu}_e$; the spectrum peaks at about 1 MeV and extends out to 8 MeV. Because of this low energy, reactor neutrinos can only be used for disappearance experiments, providing the best limits on Δm^2 in the large mixing angle region, $\Delta m^2 < 2 \times 10^{-2}$ eV^2.

The present limits on oscillations from accelerators and reactors are summarized in Figure 2-3. Values of the parameters below and to the left of the limit curves are allowed by the respective experiments. Note that the most stringent limits on $\nu_\mu \rightarrow \nu_\tau$ arise from the Fermilab emulsion experiment, E-531, and that there are no accelerator-based limits on this mode in the region indicated by the atmospheric anomaly, $\Delta m^2 \approx .01$ eV^2, and large mixing.

2.5 Summary

The discovery of neutrino mass would be of great importance for particle physics, cosmology, and astrophysics. Ideas from cosmology and particle theory suggest that at least one neutrino mass may be larger than about 1 eV. Neutrino oscillation experiments provide the most sensitive limits at these and smaller mass parameters. Presently, solar and atmospheric neutrino experiments provide interesting hints of oscillations. Solar neutrino experiments suggest that electron neutrinos oscillate into other lepton flavors with a small mixing angle, $\sin^2 2\theta \approx 7 \times 10^{-3}$, and a small mass-squared difference, $\Delta m^2 \approx 5 \times 10^{-6}$ eV^2. Such very small masses can only be pursued at present using solar neutrino experiments. Atmospheric neutrino experiments, on the other hand, suggest that

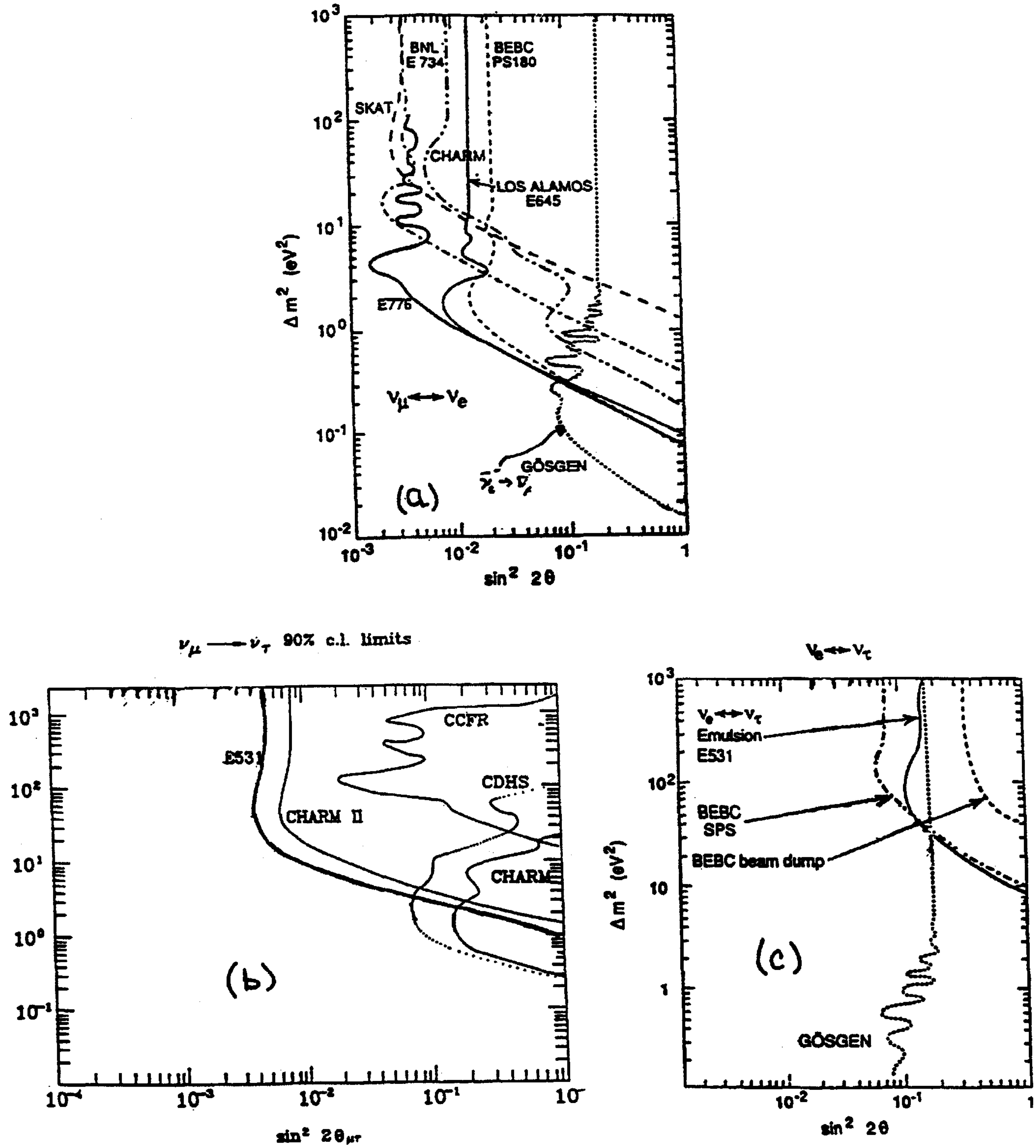

Figure 2-3. Present Accelerator and Reactor limits on neutrino oscillations: (a) $\nu_\mu \leftrightarrow \nu_e$; (b) $\nu_\mu \leftrightarrow \nu_c$; (c) $\nu_e \leftrightarrow \nu_c$

muon-neutrinos oscillate into other neutrinos with maximal mixing at $\Delta m^2 \approx 2 \times 10^{-2}$ eV^2, a region which long base-line experiments at accelerators and reactors can probe. Definitive tests of oscillations require more sensitive experiments than have been performed up to this time.

3.0 OTHER PROPOSED AND RELATED PROGRAMS

The Brookhaven National Laboratory (BNL) and Fermi National Accelerator Laboratory (Fermilab) proposals would come to fruition in an environment of intense world-wide activity directed toward further understanding of neutrino properties and the role of the neutrino in nature. Foremost in these activities are other experimental searches for neutrino oscillation effects, either recently begun or presently under construction or planned. Many are likely to have results prior to the initiation of data taking by a U.S. long-baseline experiment; prior or contemporary results may influence long-baseline strategy. However, we do not expect these results to alter the validity of the Subpanel's recommendations. Only one of these other experiments is a long-baseline accelerator experiment and, in general terms, they explore different regions of parameter space or are attempting to investigate other existing hints. Described below are the principal new or continuing projects expected to be complete or to be producing results when the BNL or Fermilab projects would be operational.

3.1 Searches Exploring the Parameter Space of the Atmospheric Neutrino Anomaly

The region of neutrino mass and mixing parameter space presently suggested by the atmospheric neutrino anomaly is centered around $\Delta m^2 \approx .01 \mathrm{eV}^2$ and $\sin^2(2\theta) \approx 1.0$. The BNL and Fermilab long-baseline proposals both encompass this region. There are four other projects that should obtain information in this region: the Super-Kamiokande underground atmospheric study; the KEK project to direct a neutrino beam at Super-Kamiokande (both in Japan); and two reactor experiments at CHOOZ (France) and at San Onofre (U.S.).

A long-baseline experiment involving a CERN SpS beam directed toward the Gran Sasso underground laboratory is under discussion in Europe. The Gran Sasso Laboratory has issued a call for letters of intent due December 31, 1995.

3.1.1 Atmospheric Neutrinos in Super-Kamiokande

Super-Kamiokande is a 50,000-ton water Cerenkov detector currently under construction in Japan by a Japan-U.S. collaboration. The large tonnage represents a major volume increase for the water Cerenkov technique (the IMB detector was 8,000 tons). Located at a depth of 3,000 meters-water-equivalent in the same mine as its predecessors, Kamiokande I - III, it is designed for new experiments on proton decay, solar neutrinos, and atmospheric neutrinos. The experiment also includes several improved features based upon the experience of the earlier Cerenkov detectors, which have suggested an atmospheric neutrino anomaly. The surface coverage by photocathodes is substantially larger than its predecessors.

The Super-Kamiokande fiducial volume is 22,000 tons, surrounded by a 4π active veto. This enormous fiducial volume implies that within approximately one year of operation, this experiment will have accumulated 22 kT-years of atmospheric neutrino data, which is substantially more than the total previously accumulated Cerenkov detector data (approximately 14 kT-years). The larger size, plus other improvements, suggest that the range of energies of contained events will be increased and that there will be greater control of edge effects. In addition, checks on particle identification using the water Cerenkov technique recently carried out in beam tests at KEK have improved the knowledge of systematic errors.

Super-Kamiokande is scheduled to begin data-taking in April 1996. It might be expected that, after the first year of running, a significant clarification of the atmospheric anomaly would result. The capability of the detector to measure angular distributions for contained and non-contained neutrino events might establish whether or not the anomalous e/μ ratio, along with the energy and angular dependences, suggested by the Kamiokande collaboration is indeed due to neutrino oscillations.

3.1.2 Neutrino Beam from KEK to Super-Kamiokande

A proposal has been submitted to KEK to mount a long-baseline oscillation experiment in which a neutrino beam from the KEK proton synchrotron is directed at the distant Super-Kamiokande detector. The plan to do so has received strong endorsement from an external panel reviewing the future five-year programs in particle and nuclear physics at KEK's 12 GeV proton synchrotron (PS). The goal is to explore the region of relatively large mixing for $\Delta m^2 > 3x10^{-3}eV^2$, and to test directly the oscillation hypothesis invoked to explain the atmospheric anomaly.

The experiment would utilize water Cerenkov detectors at three positions (500 meters, 24 km and 250 km from the source); the first two will be located on the Earth's surface and the third (Super-Kamiokande) is situated in the mine. Although Super-Kamiokande will be operational in April 1996, neither the two additional detectors nor the neutrino beam presently exist. It is estimated that three to three-and-a-half years and approximately $45M (3621M¥) are required to complete these components. To create a neutrino beam, several major changes are planned to the KEK facility: a fast extraction system for the 12 GeV protons; a proton beam transport including a 94° deflection; a target area and horn for secondary particle focusing; and a 200-meter-long decay tunnel directed downward into the Earth at 1.3°. A neutrino beam of 1.6 GeV mean energy would result.

The front detector at 500 meters would contain 2 kT (1.7-ton fiducial) and be preceded by a 200-ton, fine-grained tracking detector capable of measuring muon momenta below 3 GeV in a 30° cone for purposes of neutrino flux diagnostics. The beam which reaches the Super-Kamiokande detector and the intermediate detector will have passed through different regions of the front detector. The 3-kT (1-kT fiducial) intermediate detector at 24 km is to be located on the surface and thus about 1.3° off axis.

Expected event rates assume a total run in which 1×10^{20} protons on target are delivered over a two-year period. The current performance of the KEK PS utilizes a two second repetition period and yields 6×10^{12} protons per pulse.

Oscillation signals in the $\nu_\mu \rightarrow \nu_e$ channel would be tested by searching for the appearance of energetic single electrons above a small ν_e background (about 0.7% of ν_μ in the beam) in the far detector. The neutrino energies are below threshold for production of τ leptons. Therefore, the $\nu_\mu \rightarrow \nu_\tau$ channel is studied by comparison of the neutral to charged-current (CC) event ratios in the near and far detectors, as well as by ν_μ disappearance between them. The neutral-current (NC) candidates are selected by reconstructing π^o's from converted gamma pairs. The estimated neutrino event samples in the fiducial volumes for a two-year exposure are 400 CC (quasielastic) and 34 NC (π^o) in the far detector, 1,000 CC in the intermediate and 8,000 CC in the near. A 10% systematic error is expected for the disappearance normalization. As an example of the sensitivity for $\sin^2(2\theta) = 1$ and $\Delta m^2 = 0.01$ eV^2, it is estimated that for $\nu_\mu \rightarrow \nu_e$ appearance, there would be 77 events on a background of 3.5 events in the far detector. Under the same assumptions, $\nu_\mu \rightarrow \nu_\tau$ would yield 148 CC muon events instead of 400 while the 34 NC events remain.

For this experiment to meet its goal of operating in 1998, some funds must be committed in 1995. The proposers hope for machine improvements to increase the proton intensity by a factor of about two over the present 6×10^{12} per pulse. Some shutdown of the accelerator during 1997 may have to occur for the beam to be completed within the time frame proposed.

3.1.3 Reactor Experiments

Nuclear power reactors produce fission products which are neutron rich. The beta decays of these products produce an intense, very pure source of $\bar{\nu}_e$'s. As an example, the flux at 13.6 meters from the 2800 MW Bugey reactor in France is $2.3 \times 10^{13} \bar{\nu}_e$'s cm^{-2}s^{-1}. Most of the oscillation searches at reactors have used the inverse beta decay reaction ($\bar{\nu}_e + p \rightarrow n + e^+$). Since the $\bar{\nu}_e$ energy from reactors is less than 10 MeV, the neutron recoil energy in this reaction is small and the positron kinetic energy is $E_{e+} = E_{\bar{\nu}_e} - 1.8$ MeV. This means that a measurement of the e^+ spectrum yields the $\bar{\nu}_e$ spectrum. Since the energies of the $\bar{\nu}_e$ are below the μ production threshold, only neutrino disappearance experiments are possible.

Two classes of reactor experiments have been done. In the first, the positron spectrum was measured at two or more distances from the reactor and the results compared for an overall loss in predicted rates or for a distortion in the spectrum. This technique eliminates some systematic errors but limits the sensitivity at high Δm^2 since the neutrino can oscillate and reach equilibrium before reaching the first detector. In the second class, the positron energy spectrum was measured at one point and compared with a prediction. This technique requires well measured detector efficiencies and neutrino flux calculations but provides a sensitivity to arbitrarily large Δm^2.

Recent normalization experiments have been able to demonstrate a precision of about 3%. Since these experiments demonstrate the ability to measure the predicted change of the $\bar{\nu}_e$ flux due to isotopic evolution in the reactor fuel, there is confidence in the ability to predict the $\bar{\nu}_e$ flux.

Previous experiments did not see an effect requiring oscillations, but they cannot rule out the entire $\nu_e \rightarrow \nu_x$ region indicated by the Kamiokande results. A new generation of experiments is currently being built that should achieve a sensitivity down to $\Delta m^2 \sim 10^{-3} eV^2$ for large mixing. To get to this low value of Δm^2, the experiments have to be far from the source. The distances planned are approximately 10 times further away than previous experiments, implying that detector design has to deal with a factor of 100 reduction in the neutrino flux. Furthermore, the background for these experiments is largely due to high-energy neutrons produced by cosmic ray muons, and is therefore constant with distance. Thus, the experimenters must deal with the potentially large decrease in the signal-to-background ratio. The two experiments discussed below deal with this problem differently.

Two new experiments will be sensitive to the entire region of $\sin^2 (2\theta)$ and Δm^2 that is indicated by the atmospheric neutrino experiments in the $\nu_\mu \rightarrow \nu_e$ channel. The experiments will be ready in late 1995 or early 1996. We can expect the first results in early 1997.

3.1.3.1 CHOOZ Reactor Experiment

This experiment is being carried out by a collaboration of groups from France, Russia, the U.S. and Italy. The neutrino source is a pair of reactors at the CHOOZ nuclear power station in the Ardennes region of northeastern France. Each of the reactors will have a thermal power of 4.2 GW. The first is scheduled for startup by the end of 1995, and the second about six months later. An essential feature of the experimental site is the availability of a 1.025-km long tunnel with an overburden equivalent to 325 meters of water. Building the detector in this tunnel provides the cosmic-ray shielding necessary to maintain a reasonable signal-to-noise ratio. The neutrino target will be contained in a 5.5-meter diameter cylindrical steel tank shielded locally by about 75 cm of low radioactivity material. The tank will contain three concentric liquid scintillation detectors: an outer 90-ton veto counter; an intermediate 17-ton optically separated event containment detector; and a central acrylic vessel containing five tons of gadolinium-loaded liquid scintillator. Neutrinos above the threshold energy of 1.8 MeV will be detected with the inverse beta decay reaction using the trigger of a prompt positron event followed by a delayed event due to the neutron capture on gadolinium. The overall detection efficiency is 81%, giving an expected event rate of 31 events/day when both reactors are operating. The anticipated background is four events/day. Liquid filling will take place in September 1995 and data taking is expected to begin by the end of the year.

3.1.3.2 San Onofre Reactor Experiment

This experiment is being done by a collaboration of U.S. and Russian groups. The detector is a segmented 12-ton gadolinium-loaded liquid scintillator to be installed 25 meters-water-equivalent underground and 740 meters from the two operating reactors (total power 6.5 GW) at the San Onofre Nuclear Generating Station in Southern California. The detector will trigger on the inverse beta decay reaction by requiring a prompt triple coincidence of the positron and its two annihilation gammas, followed within 100 μs by 8 MeV in gamma radiation from the neutron capture on gadolinium. The prompt triple coincidence is necessary to reduce the correlated backgrounds induced by cosmic ray neutrons. The extra coincidence requirement lowers the overall efficiency to about 20%; to compensate, a fiducial volume larger than that of CHOOZ is used. The scintillator is surrounded by a one-meter thick water buffer and then by an anti-coincidence layer of acrylic scintillator panels. The collaboration anticipates an event rate of 25 events/day with a background of 18 events/day.

3.2 Searches in Different Mass and Mixing Regions

As we have discussed, any confirmed demonstration of the existence of non-zero neutrino mass would be a discovery of such importance that an entire new era of experimentation would result. Because we know there are three families of leptons, any neutrino oscillation effects resulting from non-degenerate neutrino masses would imply that several regions of mass and mixing should be measured. Consequently, experiments in regions different from the ones under review here could have some bearing on long-baseline experiments. There are six experiments which have such potential: two with undergound detectors for solar neutrinos (Sudbury Neutrino Observatory in Canada and Super-Kamiokande) and four short-baseline experiments at accelerators (CHORUS and NOMAD at CERN, LSND at Los Alamos and KARMEN at Rutherford). The CHORUS and NOMAD experiments explore a similar mass range to that of the COSMOS experiment at Fermilab.

3.2.1 The Solar Neutrino Experiments

Because of the extreme distance and low energies of neutrinos from the sun, the underground solar neutrino experiments test for values of Δm^2 down to 10^{-11} eV^2. There can be sensitivity to very small mixing angles for values of Δm^2 around 10^{-5} eV^2 due to the MSW effect.

3.2.1.1 Sudbury Neutrino Observatory (SNO)

SNO is a neutrino detection facility sited at the 6,800-foot level of the INCO nickel mine in Sudbury, Canada. Scientists from Canada, the U.S., and the United Kingdom are using a detector consisting of 1,000 tonnes of 99.92%-enriched ultra-pure heavy water (D_2O) in an acrylic sphere surrounded by 7,000 tonnes of light water as a shield. The Cerenkov light from CC and elastic-scattering events is detected in SNO by an array of 9,500 photomultipliers surrounding the acrylic sphere that holds the D_2O.

There are three principal modes by which solar neutrinos can interact with heavy water. The first of these reactions proceeds by the CC interaction of electron neutrinos. The second is the NC disintegration of deuterium and can be initiated with equal probability by any of the left-handed neutrinos (ν_e, ν_μ, ν_τ) and their antiparticles. The third is the elastic scattering of neutrinos (ES). The detected event rates (per day) expected for these reactions are 10, 6.8, and 1.4, respectively, if there are no oscillations.

If neutrino oscillations occur, the neutrinos may reach Earth as flavors other than electron and the ν_e spectrum may be distorted. The NC processes will occur independently of the neutrino flavor. An excess of the NC rate over the CC rate (suitably normalized for cross sections) or a distortion of the CC energy spectrum from the known ^8B spectrum would signal neutrino oscillations. SNO has the potential to reveal the presence of oscillations even if the solar properties are not precisely as expected. SNO will begin operation in late 1996.

3.2.1.2 Super-Kamiokande

This massive Cerenkov detector has been described above. Like its predecessor, Kamiokande, it will also have solar-neutrino detection capabilities via the elastic scattering from electrons (ES). However, the enormous fiducial mass (22,000 tons) means that, for a 5 MeV threshold, approximately 8,000 events per year will be recorded, 160 times more than with Kamiokande. A measurement of the recoil electron spectrum can determine if the primary spectrum has been distorted by the MSW effect. The experiment can measure time-dependent (day-night and seasonal) rates with precision, and an independent determination of the NC rate can be made by comparison with the pure CC data from the SNO experiment. Each of these measurements can potentially provide model-independent evidence of neutrino oscillations. Super-Kamiokande is scheduled to begin operation in April 1996.

3.2.2 Short-Baseline Accelerator Experiments

These experiments in general have sensitivities that are greatest at $\Delta m^2 > 1$ eV^2 and extend to $\sin^2(2\theta) << 1 \times 10^{-2}$ for Δm^2 large. They differ in important ways, particularly with respect to whether their appearance channel sensitivity is for ν_τ or ν_e and also with respect to backgrounds and systematic errors.

3.2.2.1 The CHORUS and NOMAD Experiments

The primary goal of the CHORUS and NOMAD experiments at CERN is to search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in a cosmologically interesting mass range (see Chapter 2.2). Both experiments aim at a sensitivity of $\sin^2(2\theta)$ down to 3×10^{-4} in the high mass limit, which is considerably more sensitive than the current limit. Additional planned CERN running has prompted CHORUS to predict even better sensitivity than the original goal.

Both experiments use the same double horn focused beam created by 450 GeV SpS protons. The average neutrino energy is 27 GeV (with an average interaction energy of 46 GeV). The experiments are located about 800 meters from the target and expect a nominal two-year run to yield 24×10^{18} protons on target. Running began in 1994 and is now scheduled through 1997.

CHORUS identifies τ's by searching for a kink from the τ decay in photographic emulsions. The emulsion target mass is 800 kg. Events are selected for scanning by kinematic criteria. Momenta of tracks are measured by fiber trackers before and after a pulsed magnet. Energies are measured by a fine-grained electromagnetic and hadronic calorimeter (lead-scintillating fibers). Muons are identified and measured in an iron toroidal spectrometer.

The NOMAD experiment identifies τ's purely by kinematics. Events are selected by cuts on the magnitude of the missing transverse momentum, the azimuthal angles between the τ decay products, the hadronic shower and on the missing transverse momentum. The 2.6-ton target consists of 132 planes of low-mass drift chambers. This is followed by a transition radiation detector (TRD), pre-shower, lead-glass electromagnetic calorimeter, iron-scintillator hadronic calorimeter, and a muon detection system. The experiment began major data taking during 1995.

While there are no definite plans for future running of these experiments beyond 1997, both experiments could have extended running, and possible improvements are under discussion.

3.2.2.2 The Liquid Scintillator Neutrino Detector (LSND) Experiment

The LSND performs a search for neutrino oscillations by appearance of $\bar{\nu}_e$ from $\bar{\nu}_\mu$. The LAMPF beam produces π^+ mesons which are brought to rest. The $\pi \rightarrow \mu \rightarrow e$ decay chain produces ν_μ, $\bar{\nu}_\mu$, ν_e (but no $\bar{\nu}_e$), the decay electron being absorbed in the target. A 200-ton liquid scintillator bath viewed by approximately 1,200 photomultipliers detects interacting $\bar{\nu}_e$ from the reaction $\bar{\nu}_e\, p \rightarrow e^+ n$. The signature is Cerenkov and scintillation light from a 36-60 MeV positron followed within 1 ms by light from conversion of the 2.2 MeV capture gamma ray from $np \rightarrow d\gamma$. (The mean capture time is 186 μs.)

The negatively charged pion decay chain can produce $\bar{\nu}_e$ directly, contributing a background. At the LAMPF energy, the production of π^- is lower than that of π^+ by a factor of seven; furthermore, stopped π^- are nearly all captured and absorbed before decaying. The main source of direct $\bar{\nu}_e$ background occurs because the pion production target is about 1.5 meters upstream of the beam dump (π^+ stopper), allowing about 2.5% of pions (including π^-) to decay in flight. The ensuing decay at rest of μ^- leptons gives $\bar{\nu}_e$'s with a spectrum only slightly softer than neutrinos from the oscillation $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

Other interactions from the $\pi \rightarrow \mu \rightarrow e$ decay chain yielding detected electrons are $\nu_e\ {}^{12}C \rightarrow e^-\ {}^{12}N$, $\nu_e\ {}^{13}C \rightarrow e^-\ {}^{13}N$, and $\bar{\nu}_e$ elastic scattering. The spectrum from the first lies below 36 MeV; the second is suppressed by the low abundance of ${}^{13}C$. Other backgrounds include the rare π_{e2} decays, and ν_μ interactions followed by $\mu \rightarrow e$ decay. Of these, the most important is $\bar{\nu}_\mu\ p \rightarrow \mu^+ n$, since it tends to satisfy the neutron coincidence requirement.

The detector records cosmic ray events, distinguishing those which come in time with the beam by a signal from the veto scintillator shell which surrounds the detector (except where the main tank rests on the floor). Michel electrons from decaying stopped muons provide calibration signals. The data have been used to study several Standard Model reactions, including ν_e and ν_μ scattering from electrons, carbon, and hydrogen in the target.

Electron positions and flight directions are reconstructed from the hit phototube pattern, including both the Cerenkov cone (for direction) and isotropic scintillation light patterns. Fits to these patterns and to the pulse shape, which has a slow scintillation tail, allow classification of particles into electron and neutron-capture gamma classes with approximately 10^{-3} cross contamination. Candidates for oscillation electrons are selected by the above reconstruction criteria and subjected to fiducial volume and veto requirements. The efficiency is about 25%. The resulting sample contains mostly electrons below 36 MeV from $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$. The analysis also required a delayed neutron capture. Data from 1993 and 1994 running of this experiment are now in hand.

The Subpanel heard two presentations of the analyses of these data. Each analysis came to a different conclusion. The first analysis, using a cut on likelihood ratios to identify gammas correlated with positrons, found a signal of nine events with an expected background of 2.1±0.3 events. The second analysis, with different cuts, found a null result. It is clear that more data are needed for the proper study of systematics in this measurement. Future running is expected, but the schedule is uncertain.

The KARMEN experiment is also sensitive to the $\nu_\mu \rightarrow \nu_e$ channel. KARMEN is a 56-ton liquid scintillator calorimeter which, like LSND, measures neutrinos from a beam dump of 800 MeV protons from the ISIS storage ring at Rutherford Laboratory. However, it differs from the LSND experiment in several ways. It employs gadolinium-loaded scintillator for neutron detection, has a much better duty factor, and is at a shorter distance (17.5 meters) from the source. While the regions of sensitivity for KARMEN and LSND are comparable, they are not identical. At the present time, the experiment does not report any significant number of events above the expected background and thus excludes much, but not all, of the LSND allowed region. The experiment has been taking data for four years and anticipates two more years of data taking.

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4.0 U.S. HIGH ENERGY PHYSICS PROGRAM

As a context for making a decision on the long-baseline neutrino oscillation program, it is useful to describe briefly the U.S. high energy physics (HEP) program foreseen for the next 5-10 years. This accelerator program is mostly focused in the three Department of Energy national laboratories—Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (Fermilab), and Stanford Linear Accelerator Center (SLAC)—and the National Science Foundation-supported Floyd R. Newman Laboratory of Nuclear Studies at Cornell University. There are also important efforts abroad and in the non-accelerator area.

At Brookhaven, the primary high energy physics activity for the next few years is the rare K-decay program. With the start-up of the Relativistic Heavy Ion Collider (RHIC) in 1999, the main activity at the Alternating Gradient Synchrotron (AGS) will be heavy ion physics. However, in the RHIC era it will be possible, if desired, to have some fraction of the AGS running time dedicated to HEP.

The physics program at Cornell is focused primarily on B physics. The luminosity at the Cornell Electron Storage Ring (CESR) is continuously being improved, with a goal of going above 10^{33}cm^{-2}sec^{-1} by 1998. In this same time frame, the CLEO detector is undergoing a major upgrade. With these upgrades in machine and detector, one can expect a competitive program in B physics at Cornell well past the year 2000.

In the near term, the Fermilab program will be running in collider mode through 1995, and then convert in spring 1996 to fixed target operation, which should last until the shutdown for Main Injector commissioning in 1998. A major component of the fixed target run is the study of charge conjugation and parity (CP) violation by the KTeV experiment, which aims to measure ϵ'/ϵ to the 10^{-4} level. In preparation for running in the Main Injector era, both collider experiments (Collider Detector at Fermilab and D-Zero) are undergoing substantial upgrades to allow them to take data at luminosities of 10^{32}cm^{-2}sec^{-1}. The Main Injector will make it possible to run collider and fixed target programs simultaneously. The Fermilab collider will remain the highest energy collider in the world, and the only place where one can readily study the top quark until turn-on of the Large Hadron Collider (LHC). Fermilab collider running will resume after the Main Injector is commissioned.

At SLAC, the near-term physics running is mostly focused on Z^o physics with the SLAC Linear Collider (SLC). Some efforts also are directed to testing linear collider concepts in the Final Focus Test Facility. Data from polarized Z^o decays taken with the SLAC Large Detector (SLD) will continue until the commissioning of the PEP-II asymmetric B-factory in 1998. In preparation for the turn-on of the PEP-II B-factory, the BaBAR detector is now under construction. This detector at SLAC will be actively pursuing CP violation in the B sector, and other allied physics topics, well beyond the year 2000.

It should be noted that construction of the Fermilab Main Injector and associated detector improvements, as well as construction of PEP-II and BaBAR, are not likely to be completed before 1998.

At present, a substantial number of U.S. high energy physicists are participating in accelerator experiments abroad. The principal centers of activity are the European Laboratory for Particle Physics (CERN) in Geneva and the Deutsches Elektronen Synchrotron (DESY) in Hamburg, with some groups also working at KEK, and in Beijing. At CERN, the Large Electron Positron (LEP) collider is presently running and LEP200 will begin taking data in 1996 and should run until the year 2000, engaging U.S. physicists presently involved in the four LEP detectors operating at the Z^o. There is also involvement of U.S. physicists in the NOMAD short-baseline neutrino experiment. At DESY, the main activity involves measurements of structure functions and related phenomena at the *ep* collider HERA, with major U.S. participation in the ZEUS detector collaboration. Some U.S. physicists are proposing to participate in the HERA-B experiment. Both the HERA accelerator and the HERA-B experiment should run through the year 2000. CERN has formally approved the LHC. There is a significant fraction of the U.S. HEP community participating in the two large detector collaborations (ATLAS and CMS). However, the U.S. participation in this project recommended by last year's HEPAP Subpanel, still needs to be formalized. When this happens, the LHC will involve an even bigger fraction of the U.S. high energy physics community beyond the year 2010.

Another element of the future U.S. high energy physics program concerns the non-accelerator based activities. This part of the program is less centralized and, on the whole, involves smaller experiments. However, the fraction of high energy physicists engaged in this area is on the rise. Some of the major efforts here are in the area of solar neutrinos (Sudbury Neutrino Observatory and Super Kamiokande), large arrays to detect cosmic rays (CASA-MIA and Fly's Eye/HiRES), gamma rays (Whipple/GRANITE and MILAGRO), monopoles (MACRO), reactor neutrinos (CHOOZ and San Onofre), very high energy neutrinos (AMANDA and DUMAND), and proton decay (Super-Kamiokande) with a number of new initiatives under consideration.

The status of the U.S. high energy physics program was reviewed recently by the High Energy Physics Advisory Program (HEPAP) Subpanel on Vision for the Future of High Energy Physics (Drell Subpanel) where new strategy and goals were recommended. The Drell report provided the context for the deliberation of this Subpanel.

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5.0 THE BROOKHAVEN NATIONAL LABORATORY (BNL) PROGRAM

The BNL oscillation experiment (E-889) proposes to search for ν_μ disappearance to an active left-handed species, ν_μ disappearance to a sterile neutrino, and $\nu_\mu \rightarrow \nu_e$ using the Alternating Gradient Synchrotron (AGS) neutrino beam and four identical water Cerenkov detectors. Since the neutrino energy is below τ threshold, the simultaneous investigation of the three oscillation modes permits one to infer whether $\nu_\mu \rightarrow \nu_\tau$ occurs.

E-889 has been designed to minimize systematic uncertainties through use of four identical detectors of a well understood type. Systematic errors in source characterization are greatly reduced by means of two near detectors. Some backgrounds can be well measured in the near detectors and extrapolated to the far detector, and the experimental limits are primarily determined by statistics and the value of L/E.

5.1 The Neutrino Beam

The neutrino beam is produced by interactions of 28 GeV protons in a copper target, producing pions that are focussed in a point-to-parallel dual horn system. The new AGS booster has raised the expected proton intensity threefold to 6×10^{13} protons per pulse. Rates in the E-889 proposal, as quoted in this Chapter, are based on 4×10^{13} protons per pulse. The microstructure of the proton pulses is 8 RF buckets 30 ns wide every 335 ns; the repetition period is 1.6 seconds. Secondary pions enter a 180 meter long, 3 meter diameter decay tunnel.

The neutrino beam is used in a novel off-axis geometry that sharpens the energy spectrum at the detectors and reduces its mean energy. The beam at 1.5° has the qualitative features of a "narrow-band" beam, peaking at 1 GeV and decreasing by more than a factor of 20 at 2 GeV. The beam has the further advantage of permitting all four detectors to be situated on the surface and receive the same neutrino spectrum, assuming azimuthal symmetry.

In its intended mode of operation, positive pions are sign selected by the horns to produce a majority population of ν_μ with approximately 95% purity (ν_e's are 1%, largely from kaons, and the rest are $\bar{\nu}_\mu$ from wrong-sign pions and kaons). Reversal of sign selection would produce a beam of principally $\bar{\nu}_\mu$ with about a factor of two lower total flux.

The calculated off-axis beam spectrum obtained by E-889 using GEANT + FLUKA agrees well with calculations made by the Subpanel using NUBEAM. Imposing a cut on pion energy at 1 GeV demonstrates that low-energy pions (the flux of which may be quite uncertain) contribute negligibly to the neutrino flux; the sharp low-energy neutrino spectrum results from the kinematics of the decay of pions in the 2-7 GeV band. Although this would be a new beam at the AGS, particularly with respect to the off-axis geometry, it has many similarities to, and is based on, the Laboratory's experience with the previous neutrino beam built for E-734 and E-776 in the 1980's.

5.2 Detectors

The proposed experiment consists of four linearly aligned, identical imaging water Cerenkov detectors, each of which is a cylinder 18 meters high and 18 meters in diameter, at distances of 1, 3, 24 and 68 km from the neutrino source. The two near detectors are located on the BNL site and the two far detectors are located at Northville (24 km) and at Plum Island (68 km). All four detectors will be at ground level with the horizontal line joining the detectors offset by an angle of 1.5° from the axis of the neutrino beam, as discussed above.

Each detector tank would be filled with 5 kT of water continuously circulated through a purification system to maintain a long mean free path for Cerenkov light. Each detector will be instrumented with 2,550 photomultipliers (PMT), each 25.4 cm in diameter. Of these, 2,200 inward facing PMT's will be mounted on a 0.7 meter x 0.7 meter grid, viewing a 15 meter high, 15 meter diameter fiducial volume, while the remainder outward facing PMT's will be mounted on a 3-meter x 3-meter grid, viewing the outer 1.5 meter thick annular volume. The Cerenkov light pulses from the inner PMT array provide the information for locating the trajectory of a single radiating particle in time and space, for measuring the total energy deposition and for identifying neutrino events having single muons, electrons, π^o's, or multiparticle final states. This technique is identical to that used in the earlier, and well tested, IMB and Kamiokande detectors. The PMT array covers about 10% of the surface area of the inner cylinder. The outer volume functions as a veto of cosmic rays and tags tracks leaving the fiducial volume. Much of the system design has been replicated from similar detectors (Sudbury Neutrino Observatory and Super-Kamiokande) presently under construction in Canada and Japan.

At each detector, a front-end electronics system developed by the Sudbury Neutrino Observatory (SNO) will be used to digitize the arrival time and charge of each PMT signal. The SNO electronics is designed to achieve a time resolution of less than 1.0 ns, a charge resolution of 0.1 photoelectrons, and a dynamic range of 14 bits. The timing resolution of 1 ns corresponds to a vertex spatial resolution of about 20 cm. The stored time and charge information is read out when a trigger based on PMT multiplicity occurs in coincidence with the 10 μs wide AGS beam-gate. Microwave links are employed to distribute the beam gate and to transfer digitized data to a central data acquisition system located on the BNL site. The event time will be measured to an accuracy of 10 ns by using Global Positioning System (GPS) receivers and atomic clocks. Time correlation between each event and the AGS radio frequency structure provides an important control for the rejection of cosmic-ray related background.

5.3 Observation of an Oscillation Signal

There are three accessible channels in which oscillations can be observed:

- Disappearance of the quasi-elastic charged-current (QE-CC) signal $\nu_\mu\, n \rightarrow \mu^- p$ as determined by the relative rates for this process in the four detectors,

- Change of the ratio of QE-CC to neutral-current (NC) events, the latter type being identified in the exclusive channel $\nu N \rightarrow \nu N' \pi^0$, and

- Appearance of electron neutrinos in the QE-CC process $\nu_e n \rightarrow e^- p$.

For certain specific oscillation scenarios, there is also a spectrum modulation that depends on distance and is independent of normalization; in view of the narrow beam spread, BNL does not treat this as a principal mode of analysis.

The signatures for μCC, eCC, and NC(π^0) events are, respectively, a single ring with a sharp edge at maximum radius, a single ring with diffuse edge, and either double diffuse rings or a single one with extra hits.

Table 5-1 summarizes the physical parameters and event rates of E-889.

Table 5-1. Parameters of the BNL Experiment
(Event numbers are normalized to 4.4×10^{20} POT [approximately 1 year[a]])

Item	Value			
Beam energy	28.3 GeV			
Beam per AGS pulse	4×10^{13} POT			
Protons/yr	4.4×10^{20} POT			
Decay tunnel	180 meter x 3 meter diameter			
Peak neutrino energy	1.0 GeV			
ν_e/ν_μ	0.0104			
$\bar{\nu}_e/\nu_\mu$	0.0011			
Total tonnes	4500 each			
Fiducial tonnes	1735 each			
PMTs	2195 each			
Coverage	10.4%			
Detector Locations	1 km	3 km	24 km	68 km
Azimuth, deg.	+3.0	+7.0	+5.1	-5.1
Mean ν_μ energy, GeV	0.922	0.956	0.956	0.956
Contained QE events	2.6×10^6	2.9×10^5	4550	566
μ Cosmic QE Bkg.	0.5	0.5	0.5	0.5
Neutron Cosmic QE Bkg.	34	34	34	34
NC 2-ring π^0	597,000	67,000	1,036	104
CC 2-ring Bkg.	120,000	13,000	204	25
ν_e appearance Bkg.	86,000	9,000	140	18

[a]One calendar year of eight months operation at 20 hours per day. AGS beam intensities 50% higher are now obtainable.

5.4 Discovery Capabilities and Detection Limits

If oscillations should exist with the parameters $\Delta m^2 = 0.01$ eV^2 and $\sin^2(2\theta) = 0.70$, E-889 would find a strong signal in the disappearance channel and in the CC/NC ratio. The distortion of the QE-CC energy spectrum further constrains the oscillation solution, although it improves the precision only modestly. If the oscillation is to ν_e, the additional signal of electrons in the far detectors further strengthens the conclusion.

Figures 5-1 and 5-2 show detection-limit contours at 90% confidence limits (CL) for $\nu_\mu \rightarrow \nu_x$ and $\nu_\mu \rightarrow \nu_e$, respectively. The sensitivity for larger mass, particularly above 1 eV^2, has not been explored in great detail by E-889 because the normalization detectors at 1 and 3 km become affected by oscillations, but the experiment retains some sensitivity at $\Delta m^2 \geq 1$ eV^2.

5.5 Backgrounds and Systematic Errors

E-889 has been designed to minimize systematic uncertainties through use of four identical detectors of a well understood type. Some backgrounds can be well measured in the near detectors and extrapolated to the far detectors. Hence the experimental limits are primarily determined by statistics and the value of *L/E*.

5.5.1 ν_μ Disappearance

The disappearance signal for oscillations is based on the number of contained quasi-elastic events observed in the 24-km and 68-km detectors, 4,550 and 566 events per year, respectively. This reaction cross-section is 60% of the total at these energies, and has been well measured by other experiments. With $\Delta m^2 = 0.01$ eV^2 and full mixing, these event samples would be reduced by 13% and 61%, respectively. Knowledge of the absolute flux is not required and beam systematics are controlled by measurements in the 1-km and 3-km detectors. The statistical errors for two years of running, approximately 1.0% at 24 km and approximately 3% at 68 km, dominate the sensitivity. The backgrounds to charged-current events come primarily from multipion, and single charged and neutral pions. The rates are estimated from existing bubble-chamber data and are believed to contribute less than 13% of the QE (μ) sample in any of the four detectors. These can be further reduced by observed muon decays and subtraction.

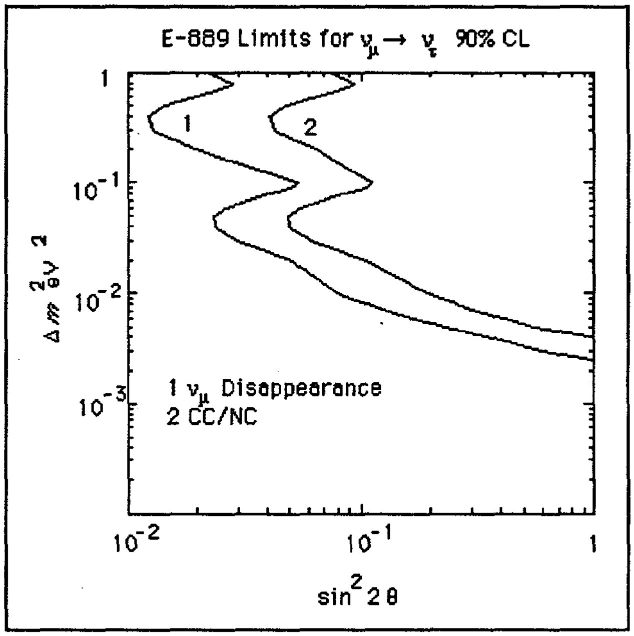

Figure 5-1. Exclusion limits for $\nu_\mu \rightarrow \nu_x$ in E-889.

The 90% CL contours are shown for ν_μ disappearance (in which case ν_x may be ν_e, ν_τ, or $\nu_{sterile}$), and for the CC/NC ratio (in which case ν_x may be ν_e or ν_τ).

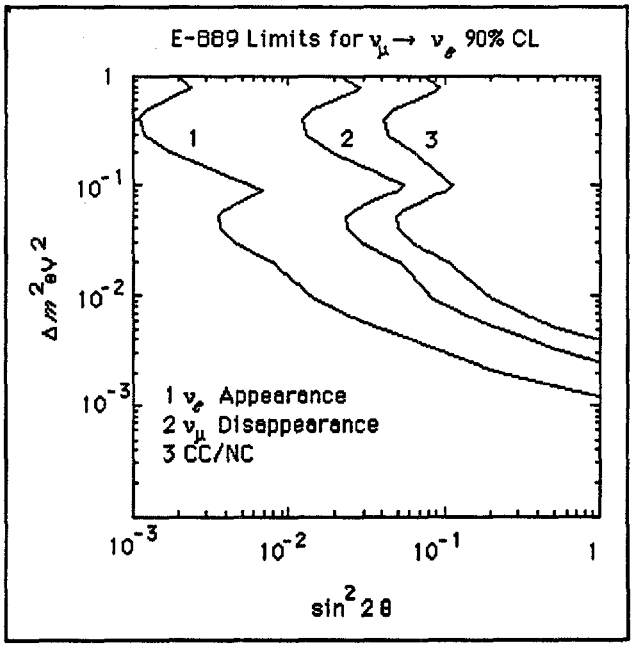

Figure 5-2. Exclusion limits for $\nu_\mu \rightarrow \nu_e$ in E-889.

Two of the curves are as in Figure 5-1, and the third is the 90% CL exclusion contour for ν_e appearance.

NC backgrounds are predicted to be less than 2.4% of the QE sample. Even a small cosmic-ray background could limit sensitivity since it contributes a constant number of events at each detector. However, the cosmic-ray background appears to be well controlled by a combination of active veto, beam time structure and event reconstruction. In each detector, after cuts, 34 neutron and 0.5 muon events per year are expected from cosmic background and could be subtracted. The beam-related systematic errors are expected to be about 1.3% at the far detectors and thus are smaller than the statistical errors for the disappearance experiment. The detector-related systematic errors arise from knowledge of detector location, fiducial volume, solid angle, dead time, spectrum, calibration, and background subtraction.

5.5.2 Neutral Current π^o Normalization

The neutral current signal is obtained from the mass spectrum of reconstructed γ - γ events. Events from reactions that do not contain a visible π^o, but reconstruct two particles with an effective mass near the π^o mass, are regarded as background. The dominant signal reactions are $\nu n \rightarrow \nu n \pi^o$ and $\nu p \rightarrow \nu p \pi^o$. The dominant reactions for the backgrounds are from single neutral and charged pion production by ν_μ CC events. It is estimated that at the level of raw events, the ratio of signal-to-background for π^o events is about 20%. The subsequent analysis chain, involving pattern recognition, reconstruction and particle identification, produces a sample of neutral-current π^o candidates having two good rings that cannot be uniquely distinguished as electromagnetic showers. Energy ($E_\gamma \geq 40$ MeV) and π^o mass ($80 < m_\pi{}^o < 270$ MeV) cuts are made on this sample. These cuts select 1,036 signal events per year on a background of 204 at 24 km, and 104 and 25 events per year at 68 km. The backgrounds are predominantly at low mass. Background subtractions are performed after studying a variety of event topologies outside the mass cut and extrapolating into the π^o mass region. It is estimated that a 5% systematic error results from this subtraction. This is designed to be less than the statistical error at the 24- and 68-km detectors.

5.5.3 ν_e Appearance

The principal backgrounds contributing to the ν_e appearance signal come from the contamination of ν_e's in the beam and from the misidentification as electrons of π^o's and muons from neutral and charged current reactions.

The ν_e spectrum in the AGS neutrino beam was measured by a previous neutrino experiment (E-734) and found to be in agreement with calculations from a beam simulation program. Using this program, the contamination of ν_e's in the 1.5° beam is calculated to be 1.04%, with a spectrum somewhat higher in energy than the ν_μ spectrum.

Neutral current reactions containing single π^o's can fake a ν_e quasi-elastic reaction if one of the two photons from the decay of the π^o escapes detection. The small cross section of this reaction, together with a fiducial cut and a cut on the angle of the showering particle, reduce this background to 3% of the quasi-elastic ν_μ rate.

The misidentification of muons from ν_μ quasi-elastic reactions as electrons results in a background for ν_e appearance measurements. The background resulting from CC reactions in which the muon is misidentified as an electron is estimated to be 1% or less, based on experience from previous water Cerenkov experiments and an energy deposition requirement of 500 photoelectrons. The contribution to ν_e background from beam contamination and from NC-π^o misidentification is measured in the near detectors and applied to the far detectors. The background in the 68-km detector is 18 events per year.

5.6 Timescale

If the program could be funded adequately in FY 1996, 1997, and 1998, the experiment could turn on at the completion of RHIC commissioning in 1999 with detectors at 3 km and 24 km. Continuation with the requested funding profile would provide the additional two detectors approximately one year later.

6.0 THE FERMI NATIONAL ACCELERATOR LABORATORY (FERMILAB) PROGRAM

The MINOS experiment is the central element of a long-baseline program proposed for Fermilab. MINOS consists of two similar fine-grained neutrino detectors, both viewing neutrinos produced in a new Main Injector neutrino beamline (NUMI). The far detector, located in the Soudan Mine, 730 km from Fermilab, would be the site at which interactions of oscillated neutrinos could be detected; the near detector would be located on the Fermilab site a few hundred meters downstream of the end of the NUMI decay pipe, and would provide a control sample of unoscillated neutrino events from the same beam.

The most important features of the experiment derive from the high event rate (20,000/year at the far detector), the clean separation of charged-current (CC) and neutral-current (NC) events, and the ability to measure both E_μ and E_{had} (and consequently E_ν) in CC events.

6.1 The Neutrino Beam

The neutrino beam is produced by 120 GeV protons extracted from the Main Injector, with a repetition period of 1.9 seconds. With an expected proton intensity of 3-5 $\times$ 10^{13} per cycle, this should provide about 4 $\times$ 10^{20} protons per year.

The NUMI beamline is to leave the Main Injector in the area behind the booster, pointing toward the northwest corner of the Fermilab site and 3° down in order to target the Soudan Mine. The proton target, as well as the beamline, decay pipe, and near detector halls, would all be positioned within the bedrock on the Fermilab site, with the detector hall at a depth of about 86 meters. The optimal decay pipe length for the MINOS and COSMOS detectors is in the range of 600-800 meters; 800 meters has been taken as the best choice for further studies. A 150-meter dolomite shield is planned to follow the decay pipe.

The beam will point toward the far detector at the Soudan Mine with an expected precision of 0.14 mrad, corresponding to 100 meters in transverse position at Soudan. Since the beam profile is relatively flat out to 400 meters, this should give a uniform and predictable flux at the far detector. Muon counters placed in the mine at 400 meter displacements on either side and above the detector would be sensitive to interactions in the rock, and hence provide a check and monitor of neutrino beam steering.

The experiment plans to begin running with a Wide Band Beam (WBB), which will use a two-horn focusing system. This will produce a high flux of ν_μ's over the range $3 < E_\nu < 40$ GeV, with about 14,000 CC events per year at the far detector. It is estimated that 92% of the interactions will be due to ν_μ from π-decay and 8% due to ν_μ from K-decay, with a ν_e background of about 0.7% from muon and kaon decays. The energy spectrum in the central 25 cm radius of the near detector is very similar to that at the far detector.

The beamline will also provide the option of a tunable Narrow Band Beam (NBB), which should provide better systematics and, for an optimized energy, a stronger signal if oscillations are observed. A hadron beam tuned for 45 GeV will produce a ν_μ flux peaked at 19 GeV with a 15% energy spread. The event rate for a 45 GeV narrow band beam, for example, is estimated to be 4,500 CC ν_μ and 1,200 NC events per year at the far detector. A lithium lens will provide the best focusing for the NBB; two different designs are being studied, one of which is quite similar to that planned for Main Injector extraction. Since the narrow band beam removes most of the low-energy flux, it gives a lower background and consequently has a significant advantage in searches for the appearance of ν_e or ν_τ interactions.

6.2 The MINOS Detector

6.2.1 The Soudan Mine Site

The Soudan Mine, now inactive for mining but maintained by the Minnesota Division of Natural Resources, has been used for physics experiments since 1980. The physics laboratory housing the Soudan II detector is located on the lowest developed level, at a depth of 713 meters. The MINOS detector would require a new hall located about 50 meters east of the existing Soudan II detector hall. While the site is somewhat remote, the experience in constructing and operating the Soudan II experiment gives confidence that the MINOS hall can be constructed as proposed. An engineering and cost study has already been carried out, and indicates that the new hall could be completed by the winter of 1997-98.

6.2.2 The MINOS Far Detector

The MINOS detector must be massive in order to provide the needed interaction rate, and also should be fine-grained enough to measure essential event properties such as penetration (to distinguish CC and NC events), total energy, and shower development (needed to help identify ν_e and ν_τ events). The design presented in the MINOS proposal represents a "proof-of-principle" concept rather than a detailed final design; other options are still being considered that might differ substantially from the baseline concept.

The MINOS far detector has a volume of 10 kT, containing magnetized steel plates interspersed with plastic limited streamer tubes with wire and cathode strip readout. The steel plates are octagonal in shape, each 4 cm thick and 8 meters in diameter (fabricated from smaller plates that can be transported down the mine shaft). Cathode strips will run along the open faces of the cells in the direction perpendicular to the wires. Since the tube cell configuration and readout are similar to those of the MACRO detector, this is a reasonably well-tested technology.

A magnetic field, varying from 2.0 T in the center of the detector to 1.1 T near the edge, is provided by normal-conducting water-cooled coils which run through a hole in the center of the detector. The measurement of the magnetic field in the detector is a problem that requires more study.

6.2.3 The MINOS Near Detector System

The near detector system consists of three sections: the Beam Monitor Detector, the Near Detector (a small version of the far detector), and a small version of the Soudan II detector.

The fine-grained sampling calorimeter which forms the Beam Monitor Detector will be used to measure and establish the beam characteristics. It consists of 2 cm thick aluminum plates interspersed with limited streamer chambers, providing a detector 3 meters by 3 meters by 4 meters long. The low Z absorber plates are necessary to allow for the identification and measurement of electrons. The most upstream two interaction lengths of this detector serve as the target mass and will give about 11 million neutrino interactions per year.

The MINOS near detector is a small scale version of the far detector. Event characteristics in the near detector will be used to compare directly with those of the far detector, thus providing normalization and background information. The steel absorber is made of 6 meter by 6 meter plates instead of 8 meter diameter octagons, and the detector magnet is made of two horizontal coils that are designed to produce the same average magnetic field in the central 3 meter by 3 meter area as in the far detector. The plate thicknesses, active elements, and readout will duplicate those of the far detector.

Twenty of the Soudan II modules will be placed in the near detector hall to provide the normalization for the full-scale Soudan II measurements. The modules will be installed in the hall at the same angle to the beam as Soudan II.

6.2.4 Simulation of Detector Response

Simulations of the MINOS detector have been carried out using a variety of Monte Carlo programs. The resolution of the muon momentum measurement, based on both range and curvature, has been studied. A resolution of $\delta p/p=0.070$ has been found for a 10 GeV muon, with range giving the better measurement for muons of 10 GeV or less. Momenta between 5 and 10 GeV can be measured by both techniques, providing a calibration check.

Hadron energy is measured from the number of crossings in each plane (roughly proportional to the number of particles traversing the plane), and is estimated to be $\delta E_h/E_h = 0.03 + 0.76/\sqrt{E_h}$ with E_h in GeV. A finer sampling segmentation does not appear to improve this resolution substantially.

NC and CC events are separated on the basis of the penetration length, ℓ, of charged particles. Defining short-length events to be those with $\ell<20$ planes and using the WBB spectrum, one finds 6.2% of CC events have $\ell<20$ and 7.4% of NC events have $\ell>20$, giving a fairly clean separation.

Quasi-elastic and resonance production of taus are important at the beam energies considered, accounting for up to about 20% of the total tau cross-section. Because these events have little or no hadronic activity at the event vertex, the kinematics are well defined with the lepton taking most of the energy. For ν_e appearance, the electromagnetic showers of the final electron give a distinctive signature.

Resolution of shower angles has also been studied, but more detailed simulations are needed.

6.3 Beam Monitoring and Associated Systematic Errors

Since the signature of neutrino oscillations is a difference in the neutrino rate, spectrum shape, or composition from one detector location to another more distant location, it is crucial to understand any inherent differences between data from these two detectors due to effects other than neutrino oscillations. Differences could be due to variations in the detector configuration or performance in the two locations, or it could be due to actual differences in the neutrino beam. In general, the far detector sees a point source of neutrinos, while the near detector sees an extended line source. This produces differences in the angular distribution of the neutrinos as well as differences in the energy spectrum and the total flux. It is the function of beam monitoring techniques to identify and understand these differences.

With the WBB, the flux spectrum illuminating the zone inside the 25 cm radius of the near detector rather closely matches that reaching the far detector; it is for this reason that the near detector employs a different coil arrangement than the far one, avoiding the central coil passage. The relatively small difference between these spectrum shapes will be determined by a combination of Monte Carlo program and measurements of events in the annuli at larger radii in the near detector. This information will be used to understand differences due to decay kinematics, beam divergence and secondary hadron production, detector acceptance and beam related backgrounds. During operation of the NBB, a segmented ionization chamber and a segmented Cerenkov detector will be used to measure the pion and kaon flux and angular distributions. The measurements will be used as input to calculate the neutrino flux at the near detector and to check the beam Monte Carlo. Using this calculated flux and the near detector measurements, the neutrino flux at the far detector will be predicted.

6.4 Observation of an Oscillation Signal

Some parameters of the MINOS detector and NUMI beam are shown in Table 6-1. Signal and background event rates normalized to one year of running are shown in Table 6-2. Discussion of the tests for neutrino oscillations are given below.

Table 6-1. Parameters of MINOS detector and NUMI-beam

Proton Energy	120 GeV
Pulse Period	1.9s
Protons/Pulse	4×10^{13}
Protons on tgt	3.7×10^{20} yr^{-1}
Decay tunnel radius	1 meter
Decay tunnel length	800 meter
Far detector total tonnes	10 kT
Far detector fiducial tonnes	7.5 kT
Far detector active planes	600
Far detector distance	732 km
Near detector distance	~600 m

Table 6-2. Signal and background events in MINOS with WBB and NBB

	WBB	NBB	
Proton energy/Hadron energy	120 GeV	20 GeV	45 GeV
Mean ν energy	18 GeV	8 GeV	19 GeV
Bkg. event ratio ($\nu_e + \bar{\nu}_e$)	0.007	NA	0.005
CC event rates (far det)/yr	14,600	1,800	4,500
L/E (km/GeV)	40.6	84	38

6.4.1 Wide Band Beam (WBB) Capabilities

Several major tests are sensitive to oscillation signals using the WBB. Other tests are sensitive to specific oscillation channels, and may be optimized using the NBB. The most important tests are:

The CC/total test. This is the measurement of the ratio of CC events to all events, integrated over all energies. Since oscillations of ν_μ into ν_e would move events out of the CC category and into the NC category, this test is quite sensitive to such oscillations. The effect is smaller for oscillation into ν_τ, since the ν_τ CC cross-section is significantly suppressed kinematically, and also because some ν_τ events give muonic final states.

If the oscillation probability for ν_μ to ν_τ is 10%, then a 7.5-σ effect would be found in a two-year run with the full MINOS detector (40,000 CC + NC events). Statistical and systematic errors are similar, with systematics perhaps somewhat larger. (The collaboration believes these can be reduced in future studies.)

The CC energy test. This test compares the CC total energy distributions of the near and far detectors; more precisely, it compares the Fourier transform of the distributions, with each event weighted by the oscillation factor $\cos(2.54 \times \Delta m^2 \times L/E)$. This gives a rather sensitive test that is independent of relative flux normalization. The dominant systematic effects are the uncertainties in relative detector resolutions and in relative neutrino flux distributions.

Near/far rate comparison. If oscillations exist, the rate of CC events in the far detector will be diminished relative to that expected from the near detector. The comparison is dominated by the systematic errors in the flux extrapolation (less than 2%); by comparison, the statistical error in a two-year WBB run will be about 0.5%. This test could provide an important confirmation if neutrino oscillation effects are observed in either of the first two tests. Moreover, it is equally sensitive to oscillations into a sterile neutrino (to which the CC/total test is insensitive).

The critical part of this measurement is the monitoring of the neutrino beam, as discussed in Section 6.4 of this chapter above. Recent studies by the MINOS group indicate that systematic errors as low as 1% might be achieved. However, at the Subpanel's request, a systematic error of 2% was used in evaluating the experiments' sensitivity for this review.

Electron appearance tests. ν_e CC events can be identified by the shape and distribution of energy deposition in the showers of short-length events. The MINOS collaboration estimates that they can identify such events with a 15% efficiency and backgrounds of less than 1% of all ν_μ interactions. This provides a sensitive test for $\nu_\mu \rightarrow \nu_e$ oscillations.

Tau appearance tests. Evidence for ν_τ (as well as ν_e) interactions could be seen in the E_{had} distributions of NC events and (for ν_τ) in the E_ν and E_{had} distributions of CC events. These searches are difficult in a WBB, but can provide a good test of the flavor composition of oscillations in a NBB.

6.4.2 Narrow Band Beam (NBB) Capabilities

The NBB gives a much smaller event rate at the far detector (factor of approximately 3 for E_{Beam} = 45 GeV and a factor of ~8 for E_{Beam} = 20 GeV), and consequently the WBB is more suitable for an initial search. However, once oscillations are observed, the NBB option gives several significant advantages:

- it allows important tests of calibration, resolution, and event reconstruction for each of the two detectors;
- it greatly reduces systematic effects in the near/far beam comparisons;
- with an optimized choice of beam energy, it could significantly enhance the magnitude of neutrino oscillation effects seen in the CC/total and near/far tests (while simultaneously reducing the systematic errors); and
- since the NBB has a greatly reduced low-energy flux, it can give a major reduction in backgrounds for the appearance searches of both ν_e and ν_τ.

Perhaps the greatest advantage of this option is that it gives the experimenters a way of making systematic and controlled changes in the energy spectrum. The effect of these changes on interactions in the far detector would provide an essential test for the existence of oscillations, provided that Δm^2 is in the appropriate range.

6.5 Discovery Capabilities and Detection Limits

If oscillations should exist with the parameters $\Delta m^2 = 0.01$ eV^2 and $\sin^2(2\theta) = 0.70$, then the MINOS experiment would see several definitive effects. From the shape of the measured CC energy distributions alone, a clear oscillation signal would be visible which would yield a high precision measurement of both Δm^2 and $\sin^2(2\theta)$ within the first year of running. Confirmation and improved precision would be given by the near/far event ratio, the ratio of CC/total events, and also by the measured distributions of E_{had} for NC events. These last measurements would also determine the relative amounts of $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations. Additional checks and improvements in the measurements of oscillation parameters could be provided by a subsequent NBB run; this would reduce systematic errors, and would enhance the capabilities of directly observing ν_e and ν_τ interactions.

If no oscillations are observed, the 90% confidence limits (CL) that the experiment could place on $\nu_\mu \rightarrow \nu_\tau$ oscillations are shown in Figure 6-1 from the three most sensitive tests; the 90% CL levels that would be placed on $\nu_\mu \rightarrow \nu_e$ oscillations are shown in Figure 6-2.

6.6 The COSMOS Detector

The COSMOS detector is designed to observe $\nu_\mu \rightarrow \nu_\tau$ oscillations through the appearance of ν_τ interactions. COSMOS complements MINOS by extending the $\sin^2(2\theta)$ sensitivity for Δm^2 values higher than those targeted by MINOS, in a range relevant to hot dark matter cosmology. It uses an emulsion stack in conjunction with a high-precision magnetic spectrometer and is sensitive to mixing with $\sin^2(2\theta) > 3\times10^{-5}$ at $\Delta m^2 > 20$ eV^2.

The COSMOS detector shares its experimental hall with the MINOS near detector. The emulsion provides a target of 865 kg in which about 2×10^6 ν_μ CC interactions per year would be detected. With dimensions of 1.8×1.4 meters, the target incorporates two modules, each with a 4.5 cm thickness of emulsion on 0.5 cm thick plastic stabilizer followed by a thin emulsion interface plate. The emulsion is followed by a 4-cm drift gap and 4 x-y fiber tracker

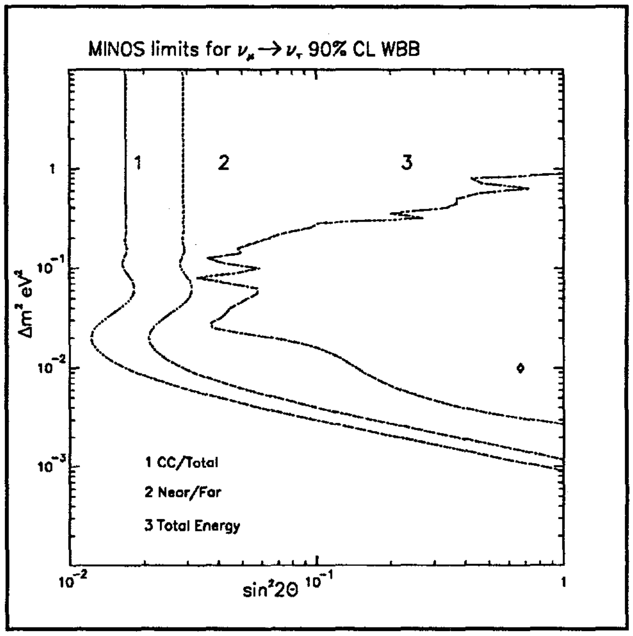

Figure 6-1. MINOS limits for $\nu_\mu \rightarrow \nu_\tau$ 90% CL WBB

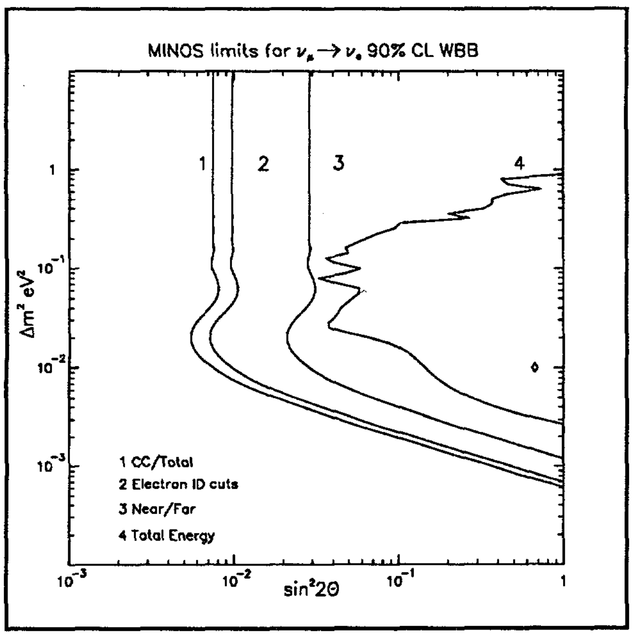

Figure 6-2. MINOS limits for $\nu_\mu \rightarrow \nu_e$ 90% CL WBB

planes sandwiched between interface plates. The fiber tracker gives a set of 500-micron point measurements linked to the downstream tracking planes for fine registration of the external track to the emulsion. The interface plates are exchanged frequently enough to keep their track density low. A powerful automatic scanning system has been developed within the collaboration by the Nagoya group to handle the data processing.

The downstream spectrometer is built around a large aperture (2.9 × 2.4 meter) magnet. Within, before, and after it are multisampling drift chambers followed by an electromagnetic calorimeter and muon identifier. Charged track momenta are measured with high precision in both the central and fringe fields of the magnet.

Since the target comprises three radiation lengths of material, the detection of photons requires tracking early produced electrons as well as interactions in the calorimeter.

The useful decay modes for detection of taus are $\tau \to \pi\nu_\tau$ and $\tau \to \rho\nu_\tau$ with the decay kink $\tau \to \pi\nu_\tau$ detected in the emulsion. These two-body modes are relatively free of backgrounds because of the kinematic constraint leading to a sharp Jacobian peak in decay angle. The precise momentum measurement and photon reconstruction allow a strong rejection of backgrounds.

Competition for COSMOS comes from NOMAD and especially CHORUS, running at CERN. CHORUS, like COSMOS, employs emulsion for tau detection. The COSMOS design has better momentum resolution and a more intense beam. In the COSMOS beam, L/E is about two times larger, the count rate for any oscillation signal is about a factor of five higher, and the background rate is lower. Within a wide range of running scenarios at the two laboratories, COSMOS should in its first year begin to expand the explored oscillation parameter space beyond that established in CHORUS and NOMAD, and eventually COSMOS should gain a substantial factor in each dimension.

6.7 Timescale

The NUMI program is planned to utilize the Main Injector, which is expected to complete commissioning in 1999. The proposed construction schedule would permit approximately one-third of the MINOS far detector to be operational when first beam is provided in mid-2001, with the remainder completed while running during the subsequent two years. The Laboratory also provided an aggressive schedule, with first data-taking possible in 2000. Both schedules required substantial funds throughout FY 1996-1998.

7.0 RECOMMENDATIONS AND COMMENTS

The Subpanel was charged (see Appendix A) to consider several issues relating to neutrino oscillation experiments. In carrying out this task, we reviewed the status and discovery potential of ongoing and proposed experiments in the U.S. and elsewhere. In the process, we have made in-depth reviews and comparisons of the E-889, MINOS and COSMOS proposals on the basis of scientific merit and discovery potential. Additionally, we were charged with recommending a cost-effective plan for carrying out an appropriate program if the physics is judged to be of sufficient importance. In this chapter, we present the recommendations based on our conclusions.

Recommendation 1

The search for neutrino oscillations with accelerator experiments, including a single long-baseline beam, should form an important segment of the U.S. high energy physics program.

The discovery of neutrino oscillations, and consequentially the discovery of neutrino mass, would constitute a major breakthrough in particle physics and the first evidence of physics beyond the minimal Standard Model. There are experimental hints of oscillations from the study of solar and atmospheric neutrinos. Measurements of the anisotropy of the cosmic microwave background have prompted theoretical speculation that neutrinos with mass could form part of the dark matter of the universe. Either Brookhaven National Laboratory (BNL) or Fermi National Accelerator Laboratory (Fermilab) is well suited to provide a beam for neutrino oscillation searches in unexplored regions.

Comments:

In making a decision to embark on a search for new phenomena, one must take into account the possibility that the sought-for phenomena either do not exist or lie outside the region of the search. In such cases, the results of the search add to our knowledge, but do not have the same impact as a discovery. Thus, the decision process must consider the scope of the proposed program in light of both the probability of a discovery and the importance of such a discovery.

On both counts, the Subpanel feels that a new program of neutrino oscillation searches is warranted at about the scope described in these recommendations. The probability of a discovery, always highly uncertain, has been enhanced in recent years by hints of oscillations from solar and atmospheric neutrinos, as well as from cosmological arguments. The impact of such a discovery would be enormous; an entirely new window on physics and cosmology would open.

In the deliberation process, the Subpanel obtained information on the commitments and costs inherent in the ongoing U.S. program outlined in Chapter 4 and on reasonable projections for funding over the next several years. The Subpanel's conclusions assume that this physics program, as recommended by the High Energy Physics Advisory Panel (HEPAP) Subpanel on Vision for the Future of High-Energy Physics (Drell Subpanel), will be pursued. Our recommendations reflect the judgment that a new program on oscillations may be undertaken within the flexibility inherent in these funding projections. On the other hand, it was also our judgment that construction of one long-baseline program on the time scale discussed below (in the comments to Recommendation 2) would be financially feasible, but that more than one would not be cost-effective. A well-planned neutrino oscillation facility will contribute unique discovery potential to a balanced U.S. program in the next decade.

Recommendation 2

The MINOS experiment at Fermilab should be supported; the E-899 experiment at Brookhaven should not be supported.

Both Fermilab and Brookhaven have proposed long-baseline experiments to explore the neutrino mass range $10^{-3} < \Delta m^2 < 1$ eV^2. Anomalies have been reported from underground experiments observing neutrinos produced in the atmosphere. These anomalies could be attributed to neutrino oscillations with large mixing in this mass range. Both proposed programs aim to explore a substantially larger region in mixing angle than is encompassed by the atmospheric anomalies.

The Subpanel unanimously recommends the support of the MINOS experiment at Fermilab over the E-889 experiment at Brookhaven for the following reasons:

- The discovery potential of MINOS is superior to that of E-889 for both $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations for $\Delta m^2 < 2 \times 10^{-2}$ eV^2 and comparable for higher values of Δm^2;

- MINOS offers a better opportunity to explore possible discoveries since it has higher event rates, a larger variety of experimental signatures, and the option of a tunable narrow band beam; and

- The combination of COSMOS (see next recommendation) and MINOS in the same beamline is cost-effective.

Comments:

Rationale for the Long-Baseline Program. In discussing the U.S. long-baseline proposals, the Subpanel took full cognizance of the intentions of the KEK-Super-Kamiokande collaboration to perform a long-baseline experiment on a fast time track, as described in Chapter 3, and to begin as early as 1998. This program uses the Super-Kamiokande detector, which will begin collecting data on atmospheric neutrinos in 1996. There is little question that, between studies of atmospheric neutrinos and of accelerator-generated neutrinos, such a program will discover oscillations if the parameters lie near the central value indicated by the atmospheric anomaly.

Though the KEK intentions of performing the necessary major accelerator modifications, building a targeting and decay region, and constructing several new small detectors on a time scale of 1998 seem optimistic, it is nevertheless likely that this effort will be pursued with high priority. The U.S. proponent laboratories have technical boundaries (including RHIC commissioning at Brookhaven and Main Injector commissioning at Fermilab), and there exist U.S. commitments to other high priority programs in the near future which limit funding flexibility over the next two to three years. The Subpanel concluded that, under any realistic scenario, first exploration of the central part of oscillation parameter space indicated by the atmospheric anomaly will likely be done by Super-Kamiokande.

If the atmospheric anomaly is confirmed as neutrino oscillations, it will be imperative to explore fully the parameter space with high precision. The much greater sensitivity of either MINOS or E-889 would uniquely allow such measurements. Even more important, the U.S. experiment will be ideally suited to explore the various flavor mixing amplitudes at the measured Δm^2, as well as to search for oscillations at other masses.

If the anomaly is not confirmed, the large increase in parameter space available to the U.S. program, as well as the larger number of redundant checks available to verify or pursue any promising effect, leads us to conclude that the U.S. program could provide an important and unique contribution in the early part of the next decade to the study of neutrino oscillations.

The Comparison between MINOS and E-889. In comparing the MINOS and E-889 proposals, the Subpanel was particularly interested in what it defined as "discovery potential," the ability of an experiment to discover oscillations in a way that would be convincing. We arbitrarily defined this to be the observation of the oscillation by one technique at the 99.9% confidence level with a supporting technique at the 95% confidence level. In defining the confidence levels, the Subpanel paid particular attention to the ability of each experiment to control systematic errors. In the case of one technique at MINOS, the comparison of ν_μ charged-current interactions in the near and far detectors, we required the proponents to use a larger systematic error than they had estimated. The resulting discovery potentials are shown in Figure 7-1. Our comparisons led us to conclude that the technical capabilities were comparable, with an advantage to MINOS for the mass range $\Delta m^2 < 2 \times 10^{-2}$.

The E-889 proposal uses the two near detectors to measure the effective source of the beam and thus to predict the absolute rate in the far detectors. This technique promises a low level of systematic error in this prediction. In our opinion, with only two detectors, the MINOS experiment does not have the same control of systematic errors for this test. However, the distribution of events as a function of radius in the MINOS near detector appears to provide sufficient information to control systematic errors adequately. Furthermore, the most sensitive test of the MINOS experiment, the comparison of the ratio of ν_μ charged current to total interactions, is not dominated by systematic errors.

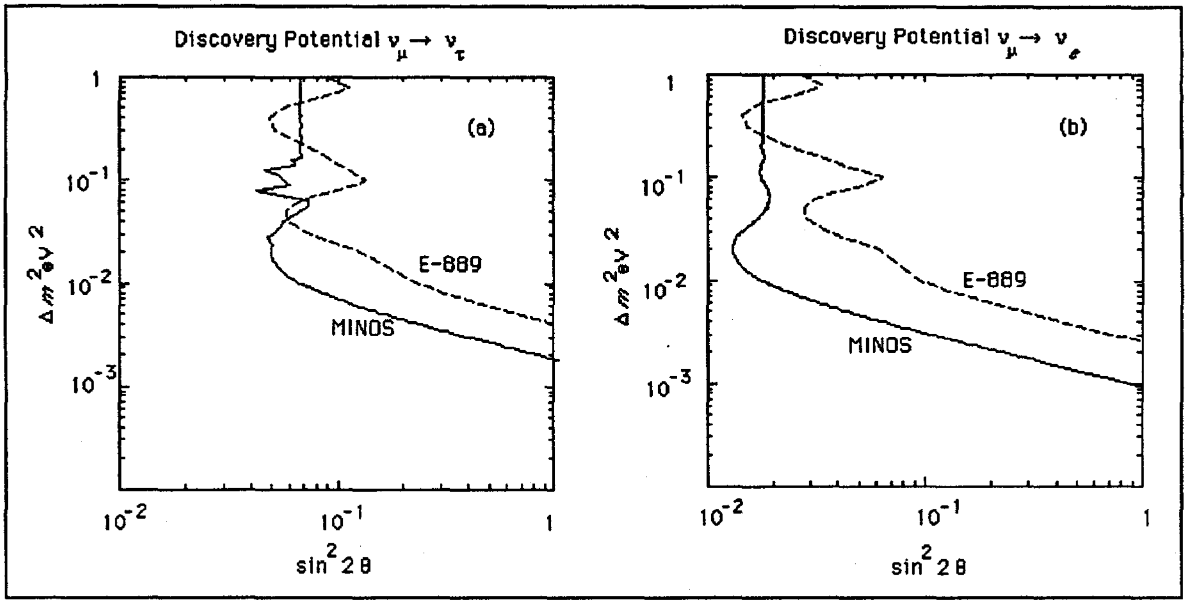

Figure 7-1. Comparison of "Discovery Potential" Between MINOS and E-889

Discovery potential is defined as one signal at the 99.9% confidence level and a supporting signal with another technique at the 95% confidence level. In every case the discovery potential is given by the sensitivity of the supporting signal. (a) $\nu_\mu \rightarrow \nu_\tau$ oscillations. The best test for MINOS is the ν_μ charged-current to total event comparison and the supporting test is generally the charged current rate comparison in the near and far detectors. In one region, a comparison of ν_μ charged-current energy spectra gives more sensitivity. The best test for E-889 is the charged-current rate comparison in the different detectors and the supporting test is the comparison of ν_μ quasi-elastic charged-current events to neutral current π^0 events. (b) $\nu_\mu \rightarrow \nu_e$ oscillations. The best test for MINOS is the same as for (a), the CC/total test, and the supporting test is a comparison of electron appearance by use of electron identification cuts. The latter occurs at the 99.1% confidence level. The best test for E-889 is a comparison of electron appearance in the different detectors and the supporting test is the ν_μ charged-current rate comparison.

MINOS will have more than an order of magnitude higher event rate in its far detector than E-889 would have in its farthest detector. (These two far detectors have comparable *L/E.)* High event rate provides for flexibility in understanding systematic effects and taking data under differing experimental conditions.

The higher energy of the Fermilab neutrino beam gives MINOS a wider variety of experimental tests that can be used to confirm and study oscillation signals. MINOS also has the ability to study oscillation signals in both wide and narrow band beams. Narrow band beams provide a lower event rate but better control of systematic uncertainties. These advantages are partially offset by the use of four detectors in E-889. There is one region, $\nu_\mu \rightarrow \nu_e$ oscillations with $2 \times 10^{-2} < \Delta m^2 < 1$ eV^2, in which one test of E-889 is clearly more sensitive than the corresponding test of MINOS. This better sensitivity arises from a comparison of electron appearance events in the two near detectors of E-889. However, by the Subpanel's definition, the discovery potential of E-889 is not better than that of MINOS in this region.

The judgment of the Subpanel was that, overall, MINOS has better physics potential than E-889 for operation in the envisaged time frame.

Future Research and Development at MINOS. The Subpanel believes that there are several questions remaining to be resolved in order to arrive at an optimal MINOS experiment. We understand that the Laboratory and the proponents agree. We believe that there is adequate time to address these issues and to react to changes in the physics situations over the next two years.

Recommendation 3

The COSMOS experiment at Fermilab should be supported.

The Fermilab Main Injector can provide the world's most intense beam for the study of neutrino oscillations in the mass range $\Delta m^2 > 10$ eV^2 where neutrino mass would contribute to the dark matter of the universe. The COSMOS experiment will have significantly more sensitivity than the presently running NOMAD and CHORUS experiments at CERN, and thus will be a suitable next step.

Comments:

The best existing limits for oscillations $\nu_\mu \rightarrow \nu_\tau$ are from the Fermilab E-531 experiment, which used photographic emulsions to detect the τ decay directly. The CHORUS (CERN) and COSMOS (Fermilab) experiments similarly exploit this technique. Both experiments contain a spectrometer to identify candidate events and to measure momenta of individual particles. The CHORUS experiment, presently taking data, will likely explore a substantial parameter space beyond that of E-531. COSMOS, to run later, claims a lower relative background rate than that claimed by CHORUS due to a better spectrometer, allowing a better measurement of the Jacobian peak in hadronic τ decays. (The NOMAD sensitivity is estimated to be similar to that of CHORUS.) The Main Injector beam will be considerably more intense than the CERN beam; COSMOS estimates, for an oscillation with large mass, about five times as many ν_τ charged-current interactions per year. In addition, the value of L/E will be larger at Fermilab. Taking these factors together, we estimated that COSMOS would obtain significantly higher sensitivity than the CERN experiments.

Recommendation 4

The Fermilab program should remain flexible to react to new information.

Several experiments are expected to report new results on neutrino oscillations before the start of the proposed program. A failure to confirm atmospheric neutrino anomalies should not affect the decision to proceed with the MINOS experiment, since its purpose includes exploration of a much larger region of oscillation parameters. However, the COSMOS and MINOS experimenters and the Fermilab Directorate should be prepared to respond to any new information.

Comments:

The MINOS and COSMOS programs will explore a significant new region of parameter space in neutrino oscillations. In addition, the Main Injector neutrino facility will provide the world's highest flux of neutrinos in the energy region above several GeV. Both wide band and narrow band beams permit broad surveys and incisive probes. The availability of space within 3 km of the source (on the Fermilab site) and of space at the Soudan site provides opportunities for future experiments to respond to experimental and theoretical indications of neutrino mass.

The viability of the proposed Fermilab neutrino program is resilient to new information expected in the next few years. Regardless of NOMAD and CHORUS results, COSMOS will remain interesting. If the CERN experiments report positive effects, they will need to be confirmed and refined. If only negative results are reported, COSMOS will explore regions in parameter space that lie beyond the CERN range. Similarly, new information is expected from the Super-Kamiokande atmospheric experiment and the KEK-Super-Kamiokande accelerator experiment, as well as from reactor experiments. As we have stressed above, positive results will find MINOS positioned to make critical measurements in what is likely to be the most important area of physics at the time. Negative results will leave a large region in mixing angle to be explored.

The Subpanel sees no need for it to set priorities between COSMOS and MINOS. We have confidence that any issues arising in the near term can be resolved best by Fermilab. In the future, we believe that the proper priorities will arise naturally from the need to respond to new experimental information.

APPENDIX A

Department of Energy
Washington, DC 20585

January 3, 1995

Professor Stanley Wojcicki
Department of Physics
Stanford University
Stanford, California 94305

Dear Professor Wojcicki:

I would like to request that the High Energy Physics Advisory Panel (HEPAP) form a Subpanel on Accelerator-Based Neutrino Oscillation Experiments. Brookhaven National Laboratory and Fermi National Accelerator Laboratory have been considering accelerator-based neutrino oscillation experiments and are now beginning to move ahead. Both laboratories would require additional funds and resources to carry out their proposed efforts. As was discussed at the November 18 19, 1994, HEPAP meeting, the Office of Energy Research requests advice from HEPAP on the optimal planning of accelerator-based neutrino oscillation experiments in the national program. Specifically, I request HEPAP to:

> Evaluate the existing evidence for neutrino oscillations, and consider the feasibility of testing this phenomenon in experiments at U.S. accelerator facilities. Review the status and discovery potential of ongoing and proposed experiments at accelerators in the U.S. and abroad. Conduct an indepth review of the neutrino oscillation experiments proposed at U.S. accelerators, and compare them on the basis of scientific merit, discovery potential, and likelihood of achieving a definitive result. Also, for each of these proposals, comment on the reliability of its cost and schedule estimates, and the impact on the host laboratory. Consider the priority of these experiments in the context of the U.S. accelerator-based High Energy Physics Program. If appropriate, recommend to the Department of Energy a cost-effective plan for pursuing this physics.

It would be most useful if the Subpanel report could be completed, reviewed by HEPAP, and transmitted to me no later than October 30, 1995.

Thank you for your assistance in this important matter.

Sincerely,

Martha Krebs

Martha A. Krebs
Director
Office of Energy Research

APPENDIX B

HEPAP SUBPANEL ON ACCELERATOR-BASED NEUTRINO OSCILLATION EXPERIMENTS

MEMBERSHIP

CHAIR

Frank J. Sciulli -- Columbia University

MEMBERS

Gary J. Feldman -- Harvard University

William T. Ford -- University of Colorado

Robert E. Lanou Jr. -- Brown University

T. Y. Ling -- Ohio State University

Frank S. Merritt -- University of Chicago

Roberto D. Peccei -- University of California at Los Angeles

R. G. Hamish Robertson -- University of Washington

S. Peter Rosen -- University of Texas at Arlington

Wesley H. Smith -- University of Wisconsin at Madison

Henry W. Sobel -- University of California -- Irvine

Lincoln Wolfenstein -- Carnegie-Melon University

EXECUTIVE SECRETARY

Thomas A. Romanowski -- Department of Energy

APPENDIX C

AGENDA

SUBPANEL OF THE HIGH ENERGY PHYSICS ADVISORY PANEL ON ACCELERATOR-BASED NEUTRINO OSCILLATION EXPERIMENTS

HYATT REGENCY BETHESDA
BETHESDA, MARYLAND

CARTIER/TIFFANY ROOM

Thursday, March 23, 1995

9:00 a.m.	Executive session: Organization of the Panel (charge, schedule, etc.)	
10:15 a.m.	Theoretical overview of ν oscillations	P. Rosen
10:45 a.m.	Coffee Break	
11:00 a.m.	Atmospheric ν oscillations in IMB	R. Svoboda
11:45 a.m.	Atmospheric ν oscillations in Kamiokande	E. Beier
12:30 p.m.	Lunch	
1:30 p.m.	Discussion	
2:15 p.m.	Long base line ν oscillations in Super-Kamiokande	W. Gajewski
3:00 p.m.	Coffee Break	
3:15 p.m.	Reactor ν oscillations	P. Vogel
4:00 p.m.	Executive Session and Discussions	
6:30 p.m.	Adjourn	

Friday, March 24, 1995:

9:00 a.m.	Solar ν oscillations	H. Robertson
9:45 a.m.	LSND Results A	W. Louis
10:30 a.m.	Coffee Break	
10:45 a.m.	LSND Results B	J. Hill
11:30 a.m.	Discussion	
12:15 p.m.	Lunch	
1:15 p.m.	CERN ν oscillation	G. Feldman
2:00 p.m.	Executive Session and Closeout	
5:00 p.m.	Adjourn	

AGENDA

SUBPANEL OF THE HIGH ENERGY PHYSICS ADVISORY PANEL ON ACCELERATOR-BASED NEUTRINO OSCILLATION EXPERIMENTS

SHERATON RESTON
RESTON, VIRGINIA

Thursday, May 4, 1995

Executive Session 9:00 a.m.- 12:00 Noon

9:00 a.m.	Discussion	
9:30 a.m.	Views on ν Oscillations Theory and Experiments	L. Wolfenstein
10:15 a.m.	Discussion of $\sigma(\nu_e Z)$ and $\sigma(\nu_\mu Z)$	H. Robertson
10:45 a.m.	Coffee Break	
11:00 a.m.	Parameters of H_2O Detector	H. Sobel
11:30 a.m.	Discussion	

Open Session 12:00 Noon - 6:00 p.m.

12:00 Noon	Lunch	
1:00 p.m.	SOUDAN and FREJUS Results	M. Goodman
1:45 p.m.	Analysis of Data from H_2O Detectors	E. Beier/ H. Sobel
2:45 p.m.	Comparison of LSND and BNL ν Oscillation Results	W. Lee
3:15 p.m.	Coffee Break	
3:30 p.m.	ν Oscillation Results from KARMEN	G. Drexlin
4:15 p.m.	Atmospheric Spectrum	T. Stanev
5:00 p.m.	Discussion	
6:00 p.m.	Adjourn	

Friday, May 5, 1995

9:00 a.m.	Discussion of the Process for the Review of the Costs, Schedule and Management of the Proposed Long Base Line ν Oscillation Experiments at BNL and Fermilab	D. Lehman
9:45 a.m.	Discussion of Visits to Labs and Formulation of Questions to the Proponents of ν Experiments and Labs	
10:30 a.m.	Coffee Break	
10:45 a.m.	Discussion of Motivations for Long Base Line Experiments and Related Questions: Technique Costs Schedule Strength of Collaborations and Commitments	
12:00 Noon	Lunch	
1:00 p.m.	Discussion Continued	
3:15 p.m.	Coffee Break	
3:30 p.m.	Discussion Continued and Wrapup	
5:00 p.m.	Adjourn	

AGENDA

SUBPANEL OF THE HIGH ENERGY PHYSICS ADVISORY PANEL ON ACCELERATOR-BASED NEUTRINO OSCILLATION EXPERIMENTS

FERMI NATIONAL ACCELERATOR LABORATORY
COMITIUM, WILSON HALL
BATAVIA, ILLINOIS

Tuesday, June 13, 1995:

HEPAP Subpanel and Cost and Schedule Committee (Comitium)

8:30 a.m.	Executive Session	
9:30 a.m.	Fermilab Neutrino Oscillation Program - Laboratory View	J. Peoples
10:00 a.m.	Oscillation Project Overview	R. Rameika
10:30 a.m.	Break	
10:45 a.m.	MINOS - Overview	S. Wojcicki
12:15 p.m.	Lunch	
1:15 p.m.	COSMOS - Overview	N. Reay
2:15 p.m.	Break	

(HEPAP Subpanel and Cost and Schedule Committee meet separately:)

HEPAP Subpanel Meeting (Comitium)

2:30 p.m.	NUMI Beam, Flux, Monitoring Overview & Civil Construction	J. Morfin
	Technical Components	A. Malensek
	Monitoring	W. Lee
4:30 p.m.	Near/far comparison, backgrounds, rates	J. Thomas

<u>Tuesday, June 13, 1995</u> Con't:

Cost and Schedule Committee (Snake Pit)

2:30 p.m.	Cost Estimate Overview, Schedule and Methodology	R. Rameika
3:30 p.m.	Subgroup Meetings	
	- Civil Construction - Beam Components, COSMOS	E. Crumpley A. Malensek R. Rameika J. Musser
	- MINOS	D. Ayres J. Thron K. Lau D. Wright
5:00 p.m.	Cost Committee Review	

HEPAP Subpanel and Cost and Schedule Committee (Comitium)

5:15 p.m.	Executive Session
6:15 p.m.	Adjourn
6:30 p.m.	Dinner

<u>Wednesday, June 14, 1995</u>:

Cost and Schedule Committee (Snake Pit)

8:30 a.m.	Management	R. Rameika

Detectors

9:15 a.m.	MINOS
10:00 a.m.	COSMOS

Conventional

9:30 a.m.	MINOS

Beam Lines

10:00 a.m.	COSMOS

Wednesday, June 14, 1995 Con't:

HEPAP Subpanel (Comitium)

8:30 a.m.	COSMOS Detector - Technology, Technique, Analysis	N. Stanton K. Niwa R. Thun
9:45 a.m.	MINOS Detector - Technology, Hardware	D. Michael
10:45 a.m.	Break	
11:15 a.m.	MINOS Detector - Oscillation Analysis	
	Overview, WBB Tests	P. Litchfield
	NBB Tests	Y. Ho
12:15 p.m.	Lunch	
1:15 p.m.	MINOS Detector (Alternative Technologies and R&D Plans)	K. Heller
1:45 p.m.	Role of Soudan II in Long Baseline Program	M. Goodman
2:15 p.m.	MINOS Summary	S. Wojcicki
2:30 p.m.	Break	
3:00 p.m.	Possibilities for Neutrino Oscillation Program at the Fermilab Booster	H. White

HEPAP Subpanel and Cost and Schedule Committee (Comitium)

3:30 p.m.	Executive Session including Discussion of Manpower
6:00 p.m.	Adjourn

Thursday, June 15, 1995:

HEPAP Subpanel and Cost and Schedule Committee (Comitium)

8:30 a.m.	Executive Session
11:30 a.m.	Closeout with Fermilab, MINOS, COSMOS
12:00 Noon	Lunch

HEPAP Subpanel (Comitium)

1:00 p.m.	Executive Session
5:00 p.m.	Adjourn

Cost and Schedule Committee (Snake Pit)

1:00 p.m.	Cost Subcommittee Report Writing
5:00 p.m.	Adjourn

AGENDA

SUBPANEL OF THE HIGH ENERGY PHYSICS ADVISORY PANEL ON ACCELERATOR-BASED NEUTRINO OSCILLATION EXPERIMENTS

BROOKHAVEN NATIONAL LABORATORY
BERKNER HALL
UPTON, NEW YORK

Tuesday, June 20, 1995:

HEPAP Subpanel and Cost and Schedule Committee, Berkner Hall, Room B

8:30 a.m.	Executive Session	
9:30 a.m.	Welcome	N. Samios
9:40 a.m.	Neutrino Oscillations at BNL	T. Kirk
10:00 a.m.	E889 - Overview	A. Mann
10:30 a.m.	Break	
10:50 a.m.	Experimental Features and Goals	J. Poutissou
11:30 a.m.	Discussion	
12:00 Noon	Lunch (Berkner Hall, Room A)	

HEPAP Subpanel Session on Technical Issues, Berkner Hall, Room B

1:00 p.m.	Proton Extraction, Transport and Targeting	A. Carroll
1:30 p.m.	Neutrino Beam	R. Helmer
2:00 p.m.	Detectors	M. Marx
2:30 p.m.	Electronics	K. Johnston
3:00 p.m.	Timing and DAQ	H. Takai
3:30 p.m.	Break	

Tuesday, June 20, 1995 Con't:

4:00 p.m.	Pattern Recognition and Particle ID	A. Mann
4:30 p.m.	Sensitivity and Systematic Errors	M. Diwan
5:15 p.m.	Discussion	
5:30 p.m.	End Presentations by BNL	

Cost and Schedule Committee, Berkner Hall, Room C

1:00 p.m.	Project Management Schedule Overview	M. Murtagh
1:30 p.m.	Cost Estimate Methodology	T. Kirk
2:00 p.m.	Focus Groups Meet as Detailed Below:	
	I. Conventional Construction (Plant Engr. Bldg. 134C, Conf. Room)	A. Raphael
	II. Beam Systems (AGS Bldg. 911B, Lg. Conf. Room)	A. Pendzick
	III. Detector Systems (Berkner Hall, Room C)	R. Van Berg
5:00 p.m.	Cost Subcommittee Reconvenes, Berkner Hall, Room C	

HEPAP Subpanel and Cost and Schedule Committee, Berkner Hall, Room B

5:30 p.m.	Executive Session	
6:30 p.m.	Reception, Physics Bldg. 510 Patio	
7:00 p.m.	Dinner	Berkner Hall

Wednesday, June 21, 1995:

HEPAP Subpanel and Cost and Schedule Committee, Berkner Hall, Room B

8:30 a.m.	Executive Session	

HEPAP Subpanel, Berkner Hall, Room B

9:00 a.m.	Special Presentations Requested by Subpanel	

Cost and Schedule Committee, Berkner Hall, Room C

9:00 a.m.	Project Management Issues	M. Murtagh
9:30 a.m.	Followup Presentations/Discussions with Cost Subcommittee	
12:00 Noon	Lunch, Berkner Hall, Room A	

HEPAP Subpanel, Berkner Hall, Room B

1:00 p.m.	(To be structured by the Subpanel)
5:00 p.m.	Adjourn

Cost and Schedule Committee, Berkner Hall, Room C

1:00 p.m.	
5:00 p.m.	Adjourn

Thursday, June 22, 1995:

HEPAP Subpanel and Cost and Schedule Committee, Berkner Hall, Room B

8:30 a.m.	Executive Session
11:30 a.m.	Closeout with E889 and BNL Management
12:00 Noon	Lunch, Berkner Hall, Room A

Thursday, June 22, 1995 Con't:

HEPAP Subpanel, Berkner Hall, Room B

1:00 p.m.	Executive Session
5:00 p.m.	Adjourn

Cost and Schedule Committee, Berkner Hall, Room C

1:00 p.m.	Cost Subcommittee Report Writing
5:00 p.m.	Adjourn

Friday, June 23, 1995:

Cost and Schedule Committee, Berkner Hall, Room C

8:30 a.m.	Cost Subcommittee Finalize BNL and Fermilab Reports
12:00 Noon	Adjourn

APPENDIX D

Cost Review of the Proposed Experiments to Search for Neutrino Oscillations at Fermilab and Brookhaven National Laboratory

CHARGE TO THE COST REVIEW SUBCOMMITTEE

The purpose of the HEPAP review is to carryout an integrated examination of the proposed technical scope, cost, schedule, and management for the experiments. Physics goals and overall designs of the experiments and detectors are to be reviewed by the HEPAP subpanel.

A major goal of this Cost Subcommittee is to establish cost and schedule baselines for the project. In addition to a general assessment of the current status and the identification of potential issues, the committee should address the following questions:

(1) Cost estimate: Does the cost estimate for the total detector, neutrino beams and the necessary infrastructure for the experiment appear reasonable to accomplish desired physics goals? Is the contingency on the funding to be provided by DOE adequate?

(2) Schedule: Does the proposed schedule to provide neutrino beams and complete the detector appear reasonable and appropriate in view of technical tasks and DOE funding profiles?

(3) Management: Is the management structure in place and formalized for this stage of design to adequately assure that the necessary planning, coordination, technical and cost control, and issue resolution process can be performed in order to keep the project within the estimated cost and schedule?

The Cost Subcommittee Review is to incorporate their report into the HEPAP Subcommittee Report. A separate cost report will be prepared for each proposed experiment site.

HEPAP SUBPANEL ON ACCELERATOR-BASED NEUTRINO OSCILLATION EXPERIMENTS

COST REVIEW SUBCOMMITTEE

MEMBERSHIP

CHAIR

Daniel R. Lehman -- U. S. Department of Energy

MEMBERS

Roger Carlini -- Continuous Electron Beam Accelerator Facility

Leigh Harwood -- Continuous Electron Beam Accelerator Facility

Lewis Keller -- Stanford Linear Accelerator Center

Otto Matherny -- Continuous Electron Beam Accelerator Facility

Gary Sanders -- LIGO Project/California Institute of Technology

Steve Tkaczyk -- U. S. Department of Energy

William Wisniewski -- Stanford Linear Accelerator Center

APPENDIX E

1.0 Executive Summary

The cost estimate and schedule for the Long Baseline Neutrino Oscillation (LBNO) Project at Brookhaven National Laboratory (BNL) was reviewed by the Cost Subcommittee. The BNL estimate and the Subcommittee's assessment of that estimate are presented in the table below at a summary level.

LBNO Cost Comparison Summary
(In Millions of FY 1995 Dollars)

	BNL	Committee	Variance
Total Project Estimate	67.7	79.3	11.6
Other Project Costs	3.7	3.7	0.0
Total Project Costs (TPC)	71.4	83.0	11.6

This summary excludes escalation and any credits for foreign contributions. A more detailed tabulation of the BNL LBNO estimate is included in Appendix 1.

Engineering, Design, Inspection and Administration (EDI&A) costs were estimated at 13% of the construction costs. An overall contingency of 15% was included. The Subcommittee identified areas where they felt additional EDI&A and contingency were warranted. Following their detailed estimate discussions with BNL personnel, the Subcommittee members compiled their assessments of the estimate at the detailed level (see Appendix 2), including an estimate and description of variances. A significant variance of approximately $7 million was identified for the phototube systems for a scope change to increase Photomultiplier Tubes (PMT) coverage to 10%. This scope change was identified and estimated by the collaboration. This change would be incorporated into the project if BNL's proposal is accepted.

Accounting for the above scope change, the remaining variance between BNL's and the Subcommittee's estimates is approximately $4.6 million or 6%.

Based on the detailed review of the project estimate, inclusive of the scope change, the subcommittee concluded that there was a sound basis for the LBNO estimate.

LBNO-BNL
(in Thousands of 1995 $)

WBS	SYSTEM	M&S K$	LABOR K$	S/C K$	SUBTOTAL K$	EDI&A K$	EDI&A %	CONTINGENCY K$	CONTINGENCY %	SUBTOTAL K$	O/H K$	TOTAL K$
1.1	CONVENTIONAL CONSTRUCTION	40	0	15,235	15,275	A	16%	2,291	15	17,566	2,745	20,311
1.1.1	LAND IMPROVEMENT	0	0	1,942	1,942			291	15	2,233	346	2,579
1.1.2	BUILDINGS & STRUCTURES	0	0	11,482	11,482			1,722	15	13,204	2,047	15,251
1.1.3	UTILITIES	0	0	1,811	1,811			272	15	2,083	323	2,406
1.1.4	STANDARD EQUIPMENT	40	0	0	40			6	15	46	29	75
1.2	PARTICLE BEAM SYSTEMS	577	3,090	5,181	8,848	B	22%	2,027	23	10,875	3,694	14,569
1.2.1	PROTON TRANSPORT	332	1,613	3,334	5,279			1,052	20	6,331	2,022	8,353
1.2.2	TARGET/HORN	160	1,260	1,591	3,011			822	27	3,833	1,392	5,225
1.2.3	BEAM DUMP	85	217	256	558			153	27	711	280	991
1.3	DETECTOR SYSTEMS	152	3,168	12,637	15,957	C	4%	1,344	8	17,301	4,287	21,588
1.3.1	PHOTOTUBE SYSTEMS	140	2,063	10,542	12,745			817	6	13,562	3,138	16,700
1.3.1	ELECTRONICS/DAQ	9	898	1,857	2,764			415	15	3,179	950	4,129
1.3.4	MAGNETIC SHIELDING	3	207	238	448			112	25	560	199	759
1.4	PROJECT SUPPORT	484	4,238	1,765	6,487			1,104	17	7,591	3,645	11,236
1.4.1	CONVENTIONAL CONSTRUCTION	35	700	1,765	2,500	A		375	15	2,875	818	3,693
1.4.2	PARTICLE BEAM SYSTEMS	259	1,657	0	1,916	B		419	22	2,335	1,404	3,739
1.4.3	DETECTOR SYSTEMS	66	616	0	682	C		102	15	784	468	1,252
1.4.4	PROGRAM MANAGEMENT	124	1,265	0	1,389			208	15	1,597	955	2,552
1.0	LBNO PROJECT ESTIMATE	1253	10,496	34,818	46,567		13%	6,766	15%	53,333	14,371	67,704
	STARTUP											3,500
	CDR											150
	NEPA											5
	TOTAL PROJECT COST (TPC)											71,359

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LBNO-BNL
(in Thousands of 1995 $)

WBS	System	LBNO Estimate: Base Estimate	LBNO Contingency K$	LBNO Contingency %	LBNO Total K$	Committee Estimate: Base Estimate	Committee Contingency K$	Committee Contingency %	Committee Total K$	Variance K$	Variance %	Comments
1.1	CONVENTIONAL CONSTRUCTION	15,275	2,291	15%	20,311	15,275	3,360	22%	21,547	1,236	6%	
1.1.1	LAND IMPROVEMENT	1,942	291	15%	2,233	1,942	427	22%	2,369	136	6%	1
1.1.2	BUILDINGS & STRUCTURES	11,482	1,722	15%	13,204	11,482	2,526	22%	14,008	804	6%	1
1.1.3	UTILITIES	1,811	272	15%	2,083	1,811	398	22%	2,209	126	6%	1
1.1.4	STANDARD EQUIPMENT	40	6	15%	46	40	9	23%	49	3	7%	1
	OVERHEAD 1.1				2,745				2,912	167	6%	
1.2	PARTICLE BEAM SYSTEMS	8,848	2,027	23%	14,569	8,760	1,987	23%	14,398	-171	-1%	
1.2.1	PROTON TRANSPORT	5,279	1,052	20%	6,331	5,158	1,054	20%	6,212	-119	-2%	2
1.2.2	TARGET/HORN	3,011	822	27%	3,833	2,984	830	28%	3,814	-19	0%	2
1.2.3	BEAM DUMP	558	153	27%	711	618	103	17%	721	10	1%	2
	OVERHEAD 1.2				3,694				3,651	-43	-1%	
1.3	DETECTOR SYSTEMS	15,957	1,344	8%	21,588	21,116	3,872	18%	31,180	9,592	44%	
1.3.1	PHOTOTUBE SYSTEMS	12,745	817	6%	13,562	17,256	3,248	19%	20,504	6,942	51%	3
1.3.2	ELECTRONICS/DAQ	2,764	415	15%	3,179	3,412	512	15%	3,924	745	23%	4
1.3.4	MAGNETIC SHIELDING	448	112	25%	560	448	112	25%	560	0	0%	5
	OVERHEAD 1.3				4,287				6,192	1,905	44%	
1.4	PROJECT SUPPORT	6,487	1,104	17%	11,236	6,922	1,350	20%	12,244	1,008	9%	
1.4.1	CONVENTIONAL CONSTRUCTION	2,500	375	15%	2,875	2,500	550	22%	3,050	175	6%	6
1.4.2	PARTICLE BEAM SYSTEMS	1,916	419	22%	2,335	2,033	442	22%	2,475	140	6%	7
1.4.3	DETECTOR SYSTEMS	682	102	15%	784	1,000	150	15%	1,150	366	47%	8
1.4.4	PROGRAM MANAGEMENT	1,389	208	15%	1,597	1,389	208	15%	1,597	0	0%	9
	OVERHEAD 1.4				3,645				3,972	327	9%	
1.0	LBNO PROJECT ESTIMATE	46,567	6,766	15%	67,704	52,073	10,569	20%	79,369	11,665	17%	
	OTHER ITEMS:				3655				3655	0	0%	
	START-UP				3500				3500	0	0%	
	CDR				150				150	0	0%	
	NEPA				5				5	0	0%	
	LBNO TOTAL PROJECT COST				71,359				83,024	11,665	16%	

Comments

1. The cost estimate is realistic. The 15% contingency is low therefore it was increased to 22%.

2. As the cost estimate is based on recent RHIC experience and previous horn beam line experience, the cost estimate appears reliable. Removed physicist labor from base estimate and susbsequent BNL changes in base estimate and contingency as follows:

WBS	Physicist Labor	BNL Changes	Total
1.2.1	-$56K	-$ 63K	-$119K
1.2.2	-$48K	+$ 29K	-$ 19K
1.2.3	0	+$ 10K	+$ 10K
1.4.2	0	+$140K	+$140K

3. Base estimate increased to cover scope change which increased PMT coverage to 10% (collaboration estimate used.) Contingency increased to cover tubes which fail to perform (500 PMT's) and to cover potential PMT cost increase.

4. Physicist cost removed from base estimate (-$400K). Collaboration adds precision clock system ($420K) to base estimate. Additional electronics for added PMT ($628K).

5. Estimated cost adequate for this element.

6. The EDI&A is ~16% of the construction cost with 15% contingency assigned. The contingency on the EDI&A was increased from 15% to 22%.

7. BNL adjustment to EDI&A - see comment 2.

8. EDI&A increased to cover increased channel count or change of PMT.

9. Estimated cost adequate to cover project management.

1.0 Executive Summary

The cost estimate and schedule for the FERMILAB Neutrino Oscillation Program (FNOP) Project at FERMILAB was reviewed by the Cost Subcommittee. The FERMILAB estimate and the Subcommittee's assessment of that estimate are presented in the table below at a summary level.

FNOP Cost Comparison Summary
(In Millions of FY 1995 Dollars)

	FERMILAB	Committee	Variance
Total Estimated Cost (TEC)	104.3	108.8	4.5
Other Project Costs	9.9	9.9	0.0
Total Project Costs (TPC)	114.1	118.6	4.5
Other Program Items	14.7	15.1	0.4
Total Program	128.8	133.7	4.9

This summary excludes escalation and any credits for foreign contributions. A more detailed tabulation of the FNOP estimate is included in Appendix 1.

For the Total Program Cost, the Engineering, Design, Inspection and Administration (EDI&A) costs were estimated at 13% of the construction costs. An overall contingency of 20% was included. Given the stage of development of the project, the Subcommittee felt that the EDI&A and contingency estimates were reasonable with a few exceptions. Following their detailed estimate discussions with FERMILAB personnel, the Subcommittee members compiled their assessments of the estimate at the detailed level (see Appendix 2), including an estimate and description of variances.

Based on a detailed review of the TEC, with an overall variance of 4%, the Subcommittee concluded that there was a sound basis for the FNOP estimate.

FNOP (FERMILAB)
(in Thousands of 1995$)

WBS	SYSTEM	M&S	LABOR	S/C	SUBTOTAL	EDI&A		CONTINGENCY		SUBTOTAL	O/H	TOTAL
		K$		K$	K$	K$	%	K$	%	K$	K$	K$
1.0	NUMI BEAM	34,589	INCL.	INCL.	34,589	6,607	19%	8,502	21%	49,698	5,282	54,980
1.1	TECHNICAL COMPONENTS	5,277	INCL.	INCL.	5,277	1,510	29%	991	15%	7,778	1,656	9,434
1.2	CIVIL CONSTRUCTION	29,312	INCL.	INCL.	29,312	4,241	14%	7,382	22%	40,935	3,283	44,218
1.3	PROJECT MANAGEMENT					856		129	15%	985	343	1,328
2.0	MINOS DETECTOR	33,160	INCL.	INCL.	33,160	2,848	9%	8,924	25%	44,932	4,357	49,289
2.1	ACTIVE DETECTOR	9,204	INCL.	INCL.	9,204	920	10%	3,037	30%	13,161	1,126	14,287
2.2	STEEL, MAGNETS, STRUCTURES	11,000	INCL.	INCL.	11,000	754	7%	2,611	22%	14,365	1,292	15,657
2.3	FAR DETECTOR SYSTEMS	6,132	INCL.	INCL.	6,132	770	13%	1,726	25%	8,628	1,037	9,665
2.4	ELECTRONICS	5,153	INCL.	INCL.	5,153	237	5%	1,090	20%	6,480	558	7,038
2.5	NEAR DETECTOR SYSTEMS	1,671	INCL.	INCL.	1,671	167	10%	460	25%	2,298	344	2,642
1.0+2.0	FNOP TEC	67,749	INCL.	INCL.	67,749	9,455	14%	17,426	23%	94,630	9,639	104,269
3.0	OTHER PROJECT COSTS	5608	INCL.	INCL.	5,608	1544		1567	22%	8,719	1152	9,871
3.1	NUMI CONCEPTUAL DESIGN	0	INCL.	INCL.	0	998		165	17%	1163	422	1,585
3.2	MINOS DETECTOR R&D	1710	INCL.	INCL.	1,710	0		513	30%	2,223	508	2,731
3.3	SOUDAN HALL EXPANSION	3898	INCL.	INCL.	3,898	546	14%	889	20%	5,333	222	5,555
1+2+3	FNOP TPC	73,357	INCL.	INCL.	73,357	10,999	15%	18,993	23%	103,349	10,791	114,140
4.0	OTHER ITEMS	13796	INCL.	INCL.	13796	196		598	4%	14590	94	14,684
4.1	COSMOS DETECTOR	11630	INCL.	INCL.	11630	INCL.		INCL.		11630	INCL.	11,630
4.2	NARROW BAND BEAM	1304	INCL.	INCL.	1304	196	15%	391	26%	1891	INCL.	1,891
4.3	SOUDAN NEAR DETECTOR	862	INCL.	INCL.	862	INCL.		207	24%	1069	94	1,163
1.0-4.0	TOTAL FNOP	87,153	INCL.	INCL.	87,153	11,195	13%	19,591	20%	117,939	10,885	128,824

FNOP (FERMILAB)
(in Thousands of 1995 $)

WBS	System	FNOP Estimate Base Estimate	FNOP Contingency K$	FNOP Contingency %	FNOP Total K$	Committee Estimate Base Estimate	Committee Contingency K$	Committee Contingency %	Committee Total K$	Variance K$	Variance %	Comments
1.0	NUMI BEAM	41,196	8,502	21%	54,980	43,102	9,364	22%	58,027	3,047	6%	
1.1	TECHNICAL COMPONENTS	6,787	991	15%	7,778	7,837	1,724	22%	9,561	1,783	23%	1
1.2	CIVIL CONSTRUCTION	33,553	7,382	22%	40,935	33,553	7,382	22%	40,935	0	0%	2
1.3	PROJECT MANAGEMENT	856	129	15%	985	1,712	258	15%	1,970	985	100%	3
	OVERHEAD 1.0				5,282				5,561	279	5%	
2.0	MINOS DETECTOR	36,008	8,924	25%	49,289	36,572	9,665	26%	50,722	1,433	3%	
2.1	ACTIVE DETECTOR ELEMENTS	10,124	3,037	30%	13,161	10,124	3,037	30%	13,161	0	0%	4
2.2	STEEL, MAGNETS, STRUCTURES	11,754	2,611	22%	14,365	11,754	3,311	28%	15,065	700	5%	5
2.3	FAR DETECTOR SYSTEMS	6,902	1,726	25%	8,628	7,133	1,726	24%	8,859	231	3%	6
2.4	ELECTRONICS	5,390	1,090	20%	6,480	5,390	1,131	21%	6,521	41	1%	7
2.5	NEAR DETECTOR SYSTEMS	1,838	460	25%	2,298	2,171	460	21%	2,631	333	14%	8
	OVERHEAD 2.0				4,357				4,485	128	3%	
3.0	OTHER PROJECT COSTS	7,152	1,567	22%	9,871	7,317	1402	19%	9,871	0	0%	
3.1	NUMI CONCEPTUAL DESIGN	998	165	17%	1,163	1163			1,163	0	0%	9
3.2	MINOS DETECTOR R&D	1,710	513	30%	2,223	1,710	513	30%	2,223	0	0%	10
3.3	SOUDAN HALL EXPANSION	4,444	889	20%	5,333	4,444	889	20%	5,333	0	0%	11
	OVERHEAD 3.0				1,152				1,152	0	0%	
4.0	OTHER PROGRAM ELEMENTS	13992	598	4%	14,684	14,292	675	5%	15,061	377	3%	
4.1	COSMOS DETECTOR	11630			11,630	11630			11,630	0	0%	12
4.2	NARROW BAND BEAM	1,500	391	26%	1,891	1,800	468	26%	2,268	377	20%	13
4.3	SOUDAN NEAR DETECTOR	862	207	24%	1,069	862	207	24%	1,069	0	0%	14
	OVERHEAD 4.0				94				94	0	0%	
TEC	TOTAL WBS 1.0+2.0	77,204	17,426	23%	104,269	79,674	19,029	24%	108,749	4,480	4%	
TPC	TOTAL WBS 1.0+2.0+3.0	84,356	18,993	23%	114,140	86,991	20,431	23%	118,620	4,480	4%	
	TOTAL WBS 1.0+2.0+3.0+4.0	98,348	19,591	20%	128,824	101,283	21,106	21%	133,681	4,857	4%	

Comments

1. Added alignment, $50K. Added 1 year mechanical design, 1 year electrical design, 2 years, mechanical engineering, 1.5 years electrical engineering, $400K. Costed large steel baffles needed to prevent ground water activation, $600K. Increased contingency from 15% to 22%, $733K.

2. The cost estimate was reviewed in detail and found to be conservative and appropriate for this early stage of the program. There are some construction items that readily lend themselves for value engineering and may result in cost savings.

3. Staff increased from 3 FTE's at the peak to 6 FTE's for adequate control of project cost, schedule, scope, configuration, contract management, and collaboration management.

4. Estimate appears adequate for this stage of development.

5. Absorber steel contingency increased to reflect price above $0.24/lb quotation as market price is potentially higher.

6. EDI&A increased by $231K to support necessary engineering, design and installation supervision.

7. Costs added to cover possible electronics design of preamplifier if active detector is run in proportional mode.

8. EDI&A increased by $333K to support necessary engineering and design of aluminum and steel detector modules and installation supervision.

9. Estimate is adequate.

10. Estimate is adequate to perform specified scope .

11. The Soudan Hall Expansion excavation cost estimate is similar to the other civil construction estimate and is deemed to be appropriate.

12. Estimate adequate for this stage of design development.

13. Added 1.5 man years EDI&A, 126K.
    Added 2 man years tech labor not included, 126K.
    Added materials not included, 126K.

14. Estimate is adequate.