Title: Accelerator-Based Neutron Oscillation Searches

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David. A. Whitehouse, R. Rameika, and N. Stanton

1. INTRODUCTION
This paper attempts to summarize the neutrino oscillation section of the Workshop on Future directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities. There were very lively discussions about the merits of the different oscillation channels, experiments, and facilities, but we believe a substantial consensus emerged.

First, the next decade is one of great potential for discovery in neutrino physics, but it is also one of great peril. The possibility that neutrino oscillations explain the solar neutrino and atmospheric neutrino experiments, and the indirect evidence that Hot Dark Matter (HDM) in the form of light neutrinos might make up 30% of the mass of the universe, point to areas where accelerator-based experiments could play a crucial role in piecing together the puzzle. At the same time, the field faces a very uncertain future. The LSND experiment at LAMPF is the only funded neutrino oscillation experiment in the United States and it is threatened by the abrupt shutdown of LAMPF proposed for fiscal 1994. The future of neutrino physics at the Brookhaven National Laboratory AGS depends the continuation of High Energy Physics (HEP) funding after the RHIC startup. Most proposed neutrino oscillation searches at Fermilab depend on the completion of the Main Injector project and on the construction of a new neutrino beamline, which is uncertain at this point. The proposed KAON facility at TRIUMF would provide a neutrino beam similar that that at the AGS but with a much increase intensity. The future of KAON is is also uncertain.

Despite the difficult obstacles present, there is a real possibility that we are on the verge of understanding the masses and mixings of the neutrinos. The physics importance of such a discovery can not be overstated. The current experimental status and future possibilities are discussed below.

2. EXPERIMENTAL STATUS

2.1 Solar Neutrinos
The deficit of solar neutrinos reported by Homestake, Kamiokande, Sage and GALLEX\textsuperscript{1} is very difficult to reconcile with the Standard Solar Model unless the $\nu_e$ undergo flavor oscillations. A combined analysis of all experimental data\textsuperscript{2}, assuming MSW oscillations, is shown in Figure 1. The two allowed regions in the $\sin^2(2\theta)$ vs $\Delta M^2$ parameter space are:

\[
\Delta m^2 = (0.3 - 1.2) \times 10^{-5} \text{ eV}^2 \quad \sin^2(2\theta) = (0.4 - 1.5) \times 10^{-2} \\
\Delta m^2 = (0.3 - 3) \times 10^{-5} \text{ eV}^2 \quad \sin^2(2\theta) = (0.6 - 0.9)
\]

In the near future the Sudbury Neutrino Observatory (SNO), Super Kamiokande and possibly Borexino will test the MSW solution by measuring the neutrino energy spectrum to lower energies and/or measuring the rate of neutral current interactions.
2.2 Atmospheric Neutrinos
IMB, Kamiokande, and Soudan II all report a deficit in the number of atmospheric $\nu_\mu$ interactions relative to $\nu_e$ interactions. Because of large uncertainties in the absolute rates, the double ratio

$$R = \frac{(N_\mu/N_e)_{\text{measured}}}{(N_\mu/N_e)_{\text{predicted}}}$$

is reported. The results of the three experiments are

$$R = 0.60 \pm 0.07 \pm 0.05 \text{ (Kamiokande$^3$)}$$
$$0.54 \pm 0.05 \pm 0.12 \text{ (IMB$^4$)}$$
$$0.55 \pm 0.27 \pm 0.10 \text{ (Soudan II$^5$, Preliminary)}$$

It is possible that this discrepancy between theory and experiment is due to the oscillation of $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_e$. The $\nu_\mu \rightarrow \nu_\tau$ solution is disfavored by the nucleosynthesis bound of $N_\nu < 3.4 \times 10^{56}$. The allowed region for oscillations is shown in Figure 1.

2.3 Astrophysics and Cosmology
There is renewed interest in massive neutrinos as a component of dark matter. Models with 70% cold dark matter and 30% hot dark matter, consisting of a 7eV neutrino, can fit the observed anisotropy of the cosmic microwave background reported by COBE, and the absolute density of the universe from small to very large scales. An analysis of the dark matter problem in conjunction with the solar and atmospheric neutrino results is given in reference 8.

2.3 Accelerator Oscillation Searches
Accelerator based oscillation searches have placed stringent limits on $\sin^2(2\theta)$ for values of $\Delta m^2$ greater than about $0.1 \text{ eV}^2$ for the oscillation channels $\nu_\mu \rightarrow \nu_\tau$, $\nu_\mu \rightarrow \nu_\tau$, $\nu_\mu \rightarrow \nu_\tau$, and $\nu_e \rightarrow \nu_\tau$. The best limits on $\nu_e \rightarrow \nu_\tau$ are from the GOSGEN reactor experiment. The current oscillation limits from accelerator and reactor experiments are shown in figure 2.

There are currently three accelerator-based neutrino oscillation experiments under construction and one running experiment. The KARMEN experiment at the Rutherford Laboratory ISIS spallation neutron source is searching for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations using neutrinos from stopped $\pi^+$ decay. After several years of data taking KARMEN will obtain oscillation limits near the current bounds. The Liquid Scintillator Neutrino Detector (LSND) will improve the limits on $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ by an order of magnitude for all values of $\Delta m^2 > 0.1 \text{ eV}^2$. Data taking will begin in July 1993. Unfortunately LAMPF is facing the possibility of an abrupt shutdown at the end of fiscal 1993 and the future of LSND is uncertain. The CHORUS and NOMAD experiments at CERN will improve the limits on $\nu_\mu \rightarrow \nu_e$ by about an order of magnitude for $\Delta m^2 > 0.3 \text{ eV}^2$. Both experiments are under construction with data taking scheduled to begin in 1994.

Figure 3 summarizes the the sensitivities and timescales of the proposed and ongoing accelerator based neutrino oscillation experiments which could begin taking data by the end of the decade. The indications of neutrino oscillations from the solar and atmospheric neutrino experiments have led a focus on searching for $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu$ disappearance in both short and long baseline experiments.
A proposal to search for $\nu_\mu$ disappearance at the Brookhaven National Laboratory AGS was approved by the AGS PAC in March 1992. E889 would use three massive water Cherenkov detectors, with the far detector at 20 km, to search for $\nu_\mu$ disappearance. The technical review process is underway and it is hoped that funding will be obtained by fiscal 1995. P822 at Fermilab is another long baseline $\nu_\mu$ disappearance experiment which would also cover the parameter space favored by the atmospheric neutrino results. P822 would utilize a new beam and the Main Injector upgrade to send a neutrino beam 730 km to an augmented Soudan II detector. P803 is a short baseline experiment which would also use the Main Injector neutrino beam to search for $\nu_\mu \rightarrow \nu_\tau$ in a fine grained emulsion detector, capable of identifying $\tau$ production. P803 would be an order of magnitude more sensitive than the the ongoing CHORUS and NOMAD experiments. Long baseline experiments are also being pursued at KEK in conjunction with the SuperKamiokande detector and at CERN.

Fermilab proposal P860 is unique in that it would utilize a $\nu_e$ beam from the Fermilab debuncher and search for $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\tau$ oscillations. If approved data taking could begin in 1997.

SUMMARY
The 1990s can be a decade of opportunity for neutrino oscillation searches. Given the positive indications of neutrino mass and the capabilities of existing and planned accelerator facilities, the possibility of discovery is high. As the limits on the neutrino mass and mixings have improved, the cost of neutrino oscillation experiments have increased, however, given the fundamental nature of the physics involved, the costs remain quite reasonable.

REFERENCES
7. D.O. Caldwell and R.M. Mohapatra (???)
Figure 1. Summary of all available data for the neutrino oscillation channels $\nu_\mu \rightarrow \nu_\tau$ and $\nu_e \rightarrow \nu_\tau$ in the $\Delta m^2 \cdot \sin^2(2\theta)$ region shown. (Figure taken from the AGS E889 Proposal).
Figure 2. Current published (and some proposed) neutrino oscillation limits for a) $\nu_\mu \rightarrow \nu_e$, b) $\nu_e \rightarrow \nu_\tau$, and c) $\nu_\mu \rightarrow \nu_\tau$ (Figure taken from FNAL P860). Other proposed experiments are summarized in Figure 3.
Figure 3. Summary of proposed neutrino oscillation experiments. The peak sensitivity in $\sin^2(2\theta)$ and the value of $\Delta m^2$ at $\sin^2(2\theta) = 1.0$ are given. The timeline assumes an optimal funding profile. The possible long baseline experiment using the KEK and the SuperKamiokande detector since it has not yet been formally proposed, but is would cover the same region as AGS E889 and FNAL P802 and could be running by the end of the decade.

<table>
<thead>
<tr>
<th>Year</th>
<th>LAMPE-LSND</th>
<th>CERN-NOMAD/CHORUS</th>
<th>FNAL-P860 (pre-MI)</th>
<th>FNAL-P803-P822</th>
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<tr>
<td>94</td>
<td>$\sin^2 2\theta = 3 \times 10^{-4}$</td>
<td>$\nu_\mu \rightarrow \nu_\tau$</td>
<td>$\nu_\tau \rightarrow \nu_\mu$</td>
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<td>$\Delta m^2 = 2 \times 10^{-2}$</td>
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<tr>
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<td>$\sin^2 2\theta = 1 \times 10^{-2}$</td>
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<td></td>
<td>$\nu_\mu \rightarrow \nu_\tau$</td>
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<td>$\Delta m^2 = 3 \times 10^{-1}$</td>
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<td>$\Delta m^2 = 2 \times 10^{-3}$</td>
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<td>$\nu_\mu \rightarrow \nu_\tau$</td>
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