Neutrino Superbeams and the Magic Baseline

A. Asratyan, G.V. Davidenko, A.G. Dolgolenko, V.S. Kaftanov, M.A. Kubantsev, and V. Verebryusov

Institute of Theoretical and Experimental Physics,
B. Cheremushkinskaya St. 25, Moscow 117259, Russia

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Abstract

We examine the sensitivity to $\nu_\mu \rightarrow \nu_e$ of a conceptual experiment with a neutrino superbeam incident on a Megaton-scale water Cherenkov detector over a "magic" baseline $\sim 7300$ km. With realistic beam intensity and exposure, the experiment may unambiguously probe $\sin^2 2\theta_{13}$ and the sign of $\Delta m^2_{31}$ down to $\sin^2 2\theta_{13} \sim 10^{-3}$.

Detecting the subdominant oscillation $\nu_\mu \rightarrow \nu_e$ on the "atmospheric" scale of $L/E$ has emerged as a priority for long-baseline accelerator experiments. This is because the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ probabilities are sensitive to yet-unknown parameters of neutrino mixing: the mixing angle $\theta_{13}$, the sign of the "atmospheric" mass-squared difference $\Delta m^2_{31}$, and the $CP$-violating phase $\delta_{CP}$ [1]. However, extracting the values of these parameters from measured probabilities will encounter the problem of degenerate solutions [2]. In particular, the asymmetry between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ may arise from either the intrinsic $CP$ violation and the matter effect...
that is correlated with the sign of $\Delta m^2_{31}$ [3]. The degeneracies can be resolved by comparing the data taken with a shorter and longer baselines [4]. Selecting the latter as the "magic" baseline $L_{\text{magic}} \simeq 7300$ km will render this strategy particularly effective: for $L = L_{\text{magic}}$, all $\Delta m^2_{21}$-induced effects like $CP$ violation are predicted to vanish up to second order of the small parameter $\Delta m^2_{21}/\Delta m^2_{31}$ [2, 5]. Therefore, selecting $L = L_{\text{magic}}$ may allow to uniquely determine $\sin^2 2\theta_{13}$ and the sign of $\Delta m^2_{31}$, but not $\delta_{\text{CP}}$ which should be probed with a shorter baseline.

In this paper, we discuss a conceptual experiment that involves a neutrino "superbeam" incident on a water Cherenkov detector over a magic baseline of $L = 7340$ km\footnote{This is chosen to match the distance from Fermilab to Gran Sasso or from CERN to Homestake.}. A water Cherenkov target is selected on the merit of good separation and spectrometry of electromagnetic showers [6], and is assumed to be a megaton-scale detector like UNO or Hyper-Kamiokande [7]. In tuning the energy of the neutrino beam, one must take into account that the $E_\nu$-dependence of oscillation probability for $L = 7340$ km is strongly affected by Earth matter: for $\Delta m^2_{31} > 0$, the matter effect [3] shifts the first maximum of $P(\nu_\mu \rightarrow \nu_e)$ down to $E_\nu/\Delta m^2_{31} \approx 2.5 \times 10^3$ GeV/eV$^2$ from the vacuum value of $5.9 \times 10^3$ GeV/eV$^2$. Assuming $\Delta m^2_{31} = 0.003$ eV$^2$, the oscillation maximum is at $E_\nu \approx 7.5$ GeV which conveniently matches the peak of $\nu_\mu$ flux in the "Medium-Energy" (or PH2me) beam of Fermilab’s Main Injector, as designed for the NuMI–MINOS program [8]. Therefore, this is selected as the model beam in our simulation. We assume $1.6 \times 10^{21}$ protons on neutrino target per year, as expected upon the planned upgrade of Main Injector’s intensity [9]. In the absence of oscillations, the beam will produce some 58 $\nu_\mu$CC (21 $\bar{\nu}_\mu$CC) events per 1 kton$\times$yr in the far detector with the $\nu$ ($\bar{\nu}$) setting of the focusing system.

At neutrino energies below 1 GeV, as in the proposed JHF–Kamioka experiment [10], $\nu_e$ appearance can be efficiently detected in a water Cherenkov apparatus by selecting 1-ring $e$-like events of the reaction $\nu_e N \rightarrow e^- X$ that is dominated by quasielastics. (Here and in what follows, $X$ denotes a system of hadrons other than the $\pi^0$, in which the momenta of all charged particles are below the Cherenkov threshold in water.) At substantially higher energies considered in this paper, using the 1e signature of $\nu_\mu \rightarrow \nu_e$ is complicated by more background from the flavor-blind NC reaction $\nu N \rightarrow \nu \pi^0 X$: its cross section increases with $E_\nu$, and so does
the fraction of $\pi^0$ mesons whose $\gamma\gamma$ decays produce a single $e$-like ring in the water Cherenkov detector\(^2\). In \[12\], we have demonstrated that $\nu_e$ appearance can be analyzed with less NC background by detecting the reactions $\nu_e N \rightarrow e^-\pi^+X$ and $\nu_e N \rightarrow e^-\pi^0X$ that involve emission of a charged or neutral pion\(^3\). We proceed to briefly describe the selections of these CC reactions, as formulated in \[12\].

The reaction $\nu_e N \rightarrow e^-\pi^+X$ is selected by requiring two rings in the detector, of which one is $e$-like and the other is non-showering and has a large emission angle of $\theta_\pi > 50^0$. This is referred to as the ”$e\pi$ signature”. The selection $\theta_\pi > 50^0$ is aimed at suppressing the NC reaction $\nu p \rightarrow \nu\pi^0p$ in which the momentum of the final proton is above the Cherenkov threshold\(^4\). The residual NC background is largely due to the reaction $\nu N \rightarrow \nu\pi^0\pi^\pm X$ with two pions in the final state. The $\nu_\mu$CC background arises from the reaction $\nu_\mu N \rightarrow \mu^-\pi^0X$ in which the muon is emitted at a broad angle. The $\nu_\tau$CC background arises from the dominant oscillation $\nu_\mu \rightarrow \nu_\tau$ followed by $\nu_\tau N \rightarrow \tau^-\pi^+X$ and $\tau^- \rightarrow e^-\nu\bar{\nu}$.

The reaction $\nu_e N \rightarrow e^-\pi^0X$ is selected by requiring either three $e$-like rings of which two fit to $\pi^0 \rightarrow \gamma\gamma$, or two $e$-like rings that would not fit to a $\pi^0$. This is referred to as the ”multi-$e$ signature”. The NC background arises from the reaction $\nu N \rightarrow \nu\pi^0\pi^0N$ in which at least one of the two $\pi^0$ mesons has not been reconstructed. Note that in the latter reaction the two $\pi^0$ mesons are emitted with comparable energies, whereas in $\nu_e N \rightarrow e^-\pi^0X$ the $e^-$ tends to be the leading particle. This suggests a selection based on the absolute value of asymmetry $A = (E_1 - E_2)/(E_1 + E_2)$, where $E_1$ and $E_2$ are the energies of the two showers for the two-ring signature, and of the reconstructed $\pi^0$ and the ”odd” shower—for the three-ring signature. In this paper, we use the selection $|A| > 0.6$. The $\nu_\tau$CC background is largely due to electronic decays of $\tau$ leptons produced in association with a $\pi^0$. The $\nu_\mu$CC background originates from CC events with a muon below the Cherenkov threshold and two $\pi^0$ mesons in the final state, and is negligibly small.

In the simulation, the matter effect is accounted for in the approximation of uniform matter density along the neutrino path ($\langle \rho \rangle = 4.3 \, \text{g/cm}^3$ for $L = 7340 \, \text{km}$),

\(^2\)This happens when the opening angle is too small for the two showers to be resolved \[11\].
\(^3\)Here and below, corresponding antineutrino reactions are implicitly included.
\(^4\)This reaction may also be rejected by identifying relativistic protons by ring shape, as proposed in \[13\].
which adequately reproduces the results of exact calculations for the actual density profile of the Earth \[3\]. Relevant neutrino-mixing parameters are assigned the values consistent with the atmospheric and reactor data \[14, 15\]: \(\Delta m_{31}^2 = \pm 0.003 \text{ eV}^2\), \(\sin^2 2\theta_{23} = 1\), and \(\sin^2 2\theta_{13} = 0.01\) (the latter value is ten times below the upper limit imposed in \[15\]). The simulation relies on the neutrino-event generator NEUGEN based on the Soudan-2 Monte Carlo \[16\], that takes full account of exclusive channels like quasielastics and excitation of baryon resonances.

The \(E_{\text{vis}}\) distributions of 1\(e\)-like, \(e\pi\)-like, and multi-\(e\)-like events are illustrated in Fig. 1 assuming \(\Delta m_{31}^2 > 0\) and incident neutrinos. Here, \(E_{\text{vis}}\) stands for the net energy of all \(e\)-like rings. Total background to the \(\nu_\mu \to \nu_e\) signal is seen to be the greatest for 1\(e\)-like events, and therefore we drop these from further analysis. Combined \(E_{\text{vis}}\) distributions of \(e\pi\)-like and multi-\(e\)-like events are shown in Fig. 2 for either beam setting and either sign of \(\Delta m_{31}^2\). With equal \(\nu\) and \(\bar{\nu}\) exposures of 1 Mton\(\times\)yr, the oscillation signal reaches some 250 events for \(\Delta m_{31}^2 > 0\) and incident neutrinos, and some 140 events for \(\Delta m_{31}^2 < 0\) and incident antineutrinos.

The experimental strategy we adopt is to share the overall exposure between the \(\nu\) and \(\bar{\nu}\) running so as to equalize the expected backgrounds under the \(\nu_\mu \to \nu_e\) and \(\bar{\nu}_\mu \to \bar{\nu}_e\) signals, and then analyze the difference between the \(E_{\text{vis}}\) distributions for the \(\nu\) and \(\bar{\nu}\) beams. The motivation is that many systematic uncertainties on the background should cancel out in the difference\(^5\). The \(\nu\) and \(\bar{\nu}\) backgrounds are approximately equalized by running 1.7–1.8 times longer in the \(\bar{\nu}\) mode than in the \(\nu\) mode (see Fig. 2). The difference between the \(E_{\text{vis}}\) distributions for the \(\nu\) and \(\bar{\nu}\) beams, assuming \(\nu\) and \(\bar{\nu}\) exposures of 1.0 and 1.8 Mton\(\times\)yr, is illustrated in Fig. 3. Depending on the sign of \(\Delta m_{31}^2\), this distribution shows either a bump or a dip at oscillation maximum with respect to the background that corresponds to \(\sin^2 2\theta_{13} = 0\).

In order to estimate the significance of the oscillation signal in Fig. 3 we vary the \(E_{\text{vis}}\) interval so as to maximize the "figure of merit" \(F = (S_\nu - S_{\bar{\nu}})/\sqrt{B_\nu + B_{\bar{\nu}}}\). Here, \(S_\nu\) and \(S_{\bar{\nu}}\) are the numbers of \(\nu_\mu \to \nu_e\) and \(\bar{\nu}_\mu \to \bar{\nu}_e\) events falling within the \(E_{\text{vis}}\) interval, and \(B_\nu\) and \(B_{\bar{\nu}}\) are corresponding numbers of background events. We

\(^5\)This is particularly important here, as the large dip angle of the neutrino beam (\(\sim 35^0\)) will rule out the construction of a "near" water Cherenkov detector.
obtain $F = +19.6$ for $\Delta m^2_{31} > 0$, and $F = -20.8$ for $\Delta m^2_{31} < 0$. Recalling that these figures refer to $\sin^2 2\theta_{13} = 0.01$, we estimate that at $90\%$ CL the sensitivity to either $\sin^2 2\theta_{13}$ and the sign of $\Delta m^2_{31}$ will be maintained down to $\sin^2 2\theta_{13} \simeq 8 \times 10^{-4}$. Still lower values of $\sin^2 2\theta_{13}$ may perhaps be probed with a neutrino factory in combination with a magnetized iron–scintillator detector \footnote{\cite{1,6}}. Note however that the experimental scheme proposed in this paper is based on proven technology and involves a multi-purpose facility \footnote{\cite{7}} rather than a dedicated detector.

To summarize, we have examined the physics potential of an experiment with a neutrino superbeam that irradiates a Megaton-scale water Cherenkov detector over the ”magic” baseline $\sim 7300$ km. With realistic beam intensity and exposure, the experiment may probe $\sin^2 2\theta_{13}$ and the sign of $\Delta m^2_{31}$ down to $\sin^2 2\theta_{13}$ values below $10^{-3}$. Thus obtained values of these parameters, that are not affected by degeneracies, can then be used as input for extracting $\delta_{CP}$ from the data collected with a shorter baseline as in the JHF–Kamioka experiment \cite{10}.

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Figure 1: $E_{\text{vis}}$ distributions of 1e-like events (left-hand panel), $e\pi$-like events (middle panel), and multi-$e$-like events (right-hand panel) for $\Delta m^2_{31} > 0$ and incident neutrinos. From bottom, the depicted components are the $\nu_\mu \rightarrow \nu_e$ signal (shaded area), intrinsic $\nu_e$CC background (white area), $\nu_\tau$CC background (black area), $\nu_\mu$CC background (white area), and the NC background (light-shaded area). Event statistics are for an exposure of 1 Mton×yr.
Figure 2: Combined $E_{\text{vis}}$ distributions of $e\pi$-like and multi-$e$-like events for incident neutrinos and antineutrinos (left- and right-hand panels) and for positive and negative values of $\Delta m_{31}^2$ (top and bottom panels). From bottom, the depicted components are the $\nu_\mu \rightarrow \nu_e$ signal (shaded area), intrinsic $\nu_e$ CC background (white area), $\nu_\tau$ CC background (black area), $\nu_\mu$ CC background (white area), and the NC background (light-shaded area). Event statistics are for equal $\nu$ and $\bar{\nu}$ exposures of 1 Mton$\times$yr.
Figure 3: The difference between the $E_{\text{vis}}$ distributions for the $\nu$ and $\bar{\nu}$ settings of the beam, assuming unequal $\nu$ and $\bar{\nu}$ exposures of 1.0 and 1.8 Mton$\times$yr, respectively. The upper and lower histograms are for $\Delta m^2_{31} > 0$ and $\Delta m^2_{31} < 0$, respectively. The expectation for $\sin^2 2\theta_{13} = 0$ is illustrated by points with error bars that depict the statistical uncertainty.