A non-QE signature of $\nu_e$ appearance in a water Cherenkov detector

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Abstract

We argue that analyzing the $\nu_e$-induced CC reaction $\nu_e n \rightarrow e^- \pi^0 p$ along with the quasielastic reaction $\nu_e n \rightarrow e^- p$ may significantly enhance the sensitivity of a water Cherenkov detector to the subleading oscillation $\nu_\mu \rightarrow \nu_e$ at neutrino energies $\sim 2$–$3$ GeV, as projected for the off-axis neutrino beam of NuMI. At the level of standard selections, the multi-ring signal of $\nu_\mu \rightarrow \nu_e$ yielded by this $\pi^0$-producing reaction is comparable to the 1-ring (quasielastic) signal in statistical significance. The neutral-current background to $\nu_e n \rightarrow e^- \pi^0 p$ can be further suppressed by analyzing spatial separation between the reconstructed primary vertex and the vertices of individual rings.

Detecting the "subleading" oscillation $\nu_\mu \rightarrow \nu_e$ in an off-axis beam with peak energy near 2–3 GeV has emerged as one of the major goals of the NuMI program [1], addressed at a Fermilab workshop in May 2002 [2] and in a recent Letter of Intent on the subject [3]. A 2.5–3 times bigger baseline than in the proposed JHF2K experiment [4], that will operate at a lower beam energy of $E_\nu \sim 0.7$–0.8 GeV, will allow to probe the matter effect by comparing the probabilities of the
\( \nu_\mu \to \nu_e \) and \( \bar{\nu}_\mu \to \bar{\nu}_e \) transitions. Detector options discussed include a fine-grained low-density calorimeter, a liquid-Argon TPC, and a water Cherenkov spectrometer. Of these, the latter option is based on proven techniques, has an excellent record in neutrino physics, and offers best opportunities in terms of maximum target mass at reasonable cost. It appears however that, in the quasielastic mode only discussed thus far, a water Cherenkov detector will perform worse in NuMI than in JHF2K because of more background to 1-ring electronlike events from single-\( \pi^0 \) production in NC collisions. It has been estimated that, due to considerable NC background to quasielastics, a water Cherenkov detector needs to be \( \sim 3 \) times as massive as a low-density calorimeter in order to reach similar sensitivity to \( \nu_\mu \to \nu_e \) in NuMI conditions. But can the performance of a water Cherenkov detector at \( E_\nu \sim 2-3 \) GeV be boosted by going beyond quasielastics?

We believe that at neutrino energies \( \sim 2 \) GeV or higher, the sensitivity to \( \nu_\mu \to \nu_e \) can be enhanced by also detecting the CC reactions producing a \( \pi^0 \), \( \nu_e n \to e^- \pi^0 p \) and \( \bar{\nu}_e p \to e^+ \pi^0 n \), that largely proceed through excitation of the \( \Delta(1232) \) and other baryon resonances. Compared to \( \nu_e n \to e^- p \) and \( \bar{\nu}_e p \to e^+ n \), the cross sections of these reactions are small for \( E_\nu < 1 \) GeV but significant at \( E_\nu \sim 2-3 \) GeV (see Fig. 1), so that these processes may be relevant to NuMI rather than JHF2K. Depending on whether or not the \( \pi^0 \) has been fully reconstructed, two different signatures are possible for a water Cherenkov detector:

- Three \( e \)-like rings, of which two fit to \( \pi^0 \to \gamma \gamma \);
- Two \( e \)-like rings that would not fit to a \( \pi^0 \).

Despite a smaller cross section, the \( \pi^0 \)-producing reaction may be competitive with

1. Without antineutrino running, this can be done by comparing the \( \nu_\mu \to \nu_e \) probabilities for a longer (NuMI) and shorter (JHF2K) baselines.
2. The first observation in a water Cherenkov detector of the corresponding \( \nu_\mu \)-induced reaction, \( \nu_\mu n \to \mu^- \pi^0 p \), has been reported in [7].
3. The cross sections of CC and NC reactions are quoted according to NEUGEN [8].
quasielastics because of less neutral-current background: two \( \pi^0 \) mesons, and not just one, have to be produced in order to mimic the aforementioned 2- and 3-ring signatures. At neutrino energies of a few GeV in particular, the cross section of the NC reaction \( \nu N \rightarrow \nu \pi^0 \pi^0 N \) should be kinematically suppressed compared to \( \nu N \rightarrow \nu \pi^0 N \). This simple conjecture is supported by NEUGEN predictions\(^4\) see Fig. 1.

The values of oscillation parameters assumed in the simulation are \( \Delta m^2 = 0.003 \text{ eV}^2 \), \( \sin^2 2\Theta_{23} = 1 \), and \( \sin^2 2\Theta_{13} = 0.1 \) (that is, at the CHOOZ limit \(^9\)). Matter effects are not accounted for, as here we only wish to compare the oscillation signals in the single-ring and multi-ring channels. Apart from enhancing the matter effect, increasing the baseline shifts the oscillation maximum to higher values of \( E_\nu \) where the cross sections of the reactions \( \nu_e n \rightarrow e^- \pi^0 p \) and \( \bar{\nu}_e p \rightarrow e^+ \pi^0 n \) are relatively big. Therefore, we select a baseline close to the maximum value for NuMI: \( L = 900 \) km. The displacement from the axis of the NuMI medium-energy beam \(^4\), \( R \), is varied in the simulation. The \( E_\nu \) distribution of all \( \nu_\mu \)-induced CC events in the absence of oscillations, illustrated in Fig. 2 for the neutrino mode and \( R = 10 \) km, peaks at \( E_\nu \simeq 2.6 \) GeV. In the peak region, the intrinsic \( \nu_e \) component of the beam is some 0.3\% of the \( \nu_\mu \) component (see Fig. 2). Running in the antineutrino mode will yield some 3 times less CC events for the same number of delivered protons.

Taking into account the experimental conditions of a water Cherenkov detector, actually simulated are the "quasi-inclusive" CC reactions \( \nu_e N \rightarrow e^- X \) and \( \nu_e N \rightarrow e^- \pi^0 X \)\(^4\) and flavor-blind NC reactions \( \nu N \rightarrow \nu \pi^0 X \) and \( \nu N \rightarrow \nu \pi^0 \pi^0 X \) in neutrino collisions with water. Here, \( X \) 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. These reactions are analyzed in terms of visible energy \( E_{\text{vis}} \), defined as a

\(^4\)The uncertainties of these predictions for the cross sections of \( \nu_e n \rightarrow e^- \pi^0 p \) and \( \nu N \rightarrow \nu \pi^0 \pi^0 N \) are hard to estimate, as the data are scarce for the former reaction and totally lacking—for the latter reaction.

\(^5\)Respective antineutrino reactions are implicitly included.
sum over the energies of all detectable particles: the $\pi^0$ mesons(s) and the charged lepton for CC reactions.

In a water Cherenkov detector, the two photons from $\pi^0 \to \gamma \gamma$ may show up as a single $e$-like ring because of a small opening angle (this largely occurs at high $\pi^0$ momenta), or because one of the photons from an "asymmetric" $\pi^0$ decay is too soft to be detected [3]. The efficiency of $\pi^0$ reconstruction as a function of its momentum will depend on the geometry and instrumentation of a Cherenkov detector; the estimates quoted below are based on the results for the 1-kiloton detector of K2K [10], as reported in [11]. The momenta of $\pi^0$ mesons emitted in $\nu_e N \to e^- \pi^0 X$ are plotted in Fig. 3, that also shows the distribution of reconstructed $\pi^0$ mesons (lower histogram). We assume that at least one photon from $\pi^0 \to \gamma \gamma$ is always detected, so that all 1-ring CC events arise from $\nu_e N \to e^- X$ and all 1-ring NC events—from $\nu N \to \nu \pi^0 X$ with unresolved photon showers. The probability for two photons to form a fake $\pi^0$ candidate is neglected (in SuperK, the r.m.s. width of the $\pi^0$ peak is only $\sim 40$ MeV [11]). Depending on whether or not the $\pi^0$ is reconstructible, a CC collision $\nu_e N \to e^- \pi^0 X$ will produce 3 or 2 rings in the detector. NC events showing 3 (2) rings arise from failing to reconstruct one $\pi^0$ (both $\pi^0$s) in the reaction $\nu N \to \nu \pi^0 \pi^0 X$.

The $E_{\text{vis}}$ distributions of events featuring 1, 2, and 3 $e$-like rings are shown in Figs. 4-6 for incident neutrinos and different values of $R$. The three components of the $E_{\text{vis}}$ distribution for either channel are: the $\nu_\mu \to \nu_e$ signal (yellow area), the NC background (green area), and the intrinsic-$\nu_e$ background (red area). The $E_{\text{vis}}$ interval for estimating the effect is selected so as to maximize the "Figure of Merit" $S/\sqrt{B}$, where $S$ is the number of signal events and $B$ is the total (NC plus intrinsic-CC) background. For either the $\nu$ and $\bar{\nu}$ settings of the beam, Table 1 compares the 1-ring and multi-ring samples in terms of total $\nu_\mu \to \nu_e$ signals, num-

\footnote{Failing to reconstruct a $\pi^0$ will but weakly affect the value of visible energy: in this case, either the two photons from $\pi^0 \to \gamma \gamma$ have merged into a single shower sampled as a whole, or one of them is very soft.}
bers of signal and background events in the selected $E_{\text{vis}}$ windows, and statistical significance. Predictably, the ratio between the multi-ring and 1-ring signals decreases with increasing $R$ (or off-axis angle). For incident neutrinos, the multi-ring signal is $\sim 2$ times less than the 1-ring signal in absolute value, but has comparable significance due to less NC background. For incident antineutrinos, the multi-ring signal is substantially less significant than the 1-ring signal.

| Beam, radius, signature | Total signal | $E_{\text{vis}}$ window | Signal in window | NC backgr. | Intr. CC backgr. | $S/\sqrt{B}$ (FoM) |
|-------------------------|-------------|-------------------------|-----------------|-----------|-----------------|------------------|
| $\nu$, $R = 9$ km:      |             |                         |                 |           |                 |                  |
| 1 ring                  | 101.        | 2.2–3.2 GeV             | 61.             | 11.6      | 4.8             | 15.0             |
| 2 or 3 rings            | 51.         | 2.0–3.4 GeV             | 39.             | 7.5       | 3.6             | 11.6             |
| $\nu$, $R = 10$ km:     |             |                         |                 |           |                 |                  |
| 1 ring                  | 92.         | 2.0–3.0 GeV             | 60.             | 11.0      | 4.7             | 15.1             |
| 2 or 3 rings            | 44.         | 2.0–3.0 GeV             | 30.             | 4.2       | 2.4             | 11.5             |
| $\nu$, $R = 11$ km:     |             |                         |                 |           |                 |                  |
| 1 ring                  | 81.         | 1.8–2.8 GeV             | 57.             | 10.5      | 4.4             | 14.6             |
| 2 or 3 rings            | 37.         | 1.6–2.8 GeV             | 31.             | 5.6       | 2.5             | 10.9             |
| $\bar{\nu}$, $R = 9$ km:|      |                         |                 |           |                 |                  |
| 1 ring                  | 80.         | 2.0–3.2 GeV             | 56.             | 5.0       | 4.9             | 17.9             |
| 2 or 3 rings            | 25.         | 2.0–3.2 GeV             | 17.             | 2.3       | 1.7             | 8.5              |
| $\bar{\nu}$, $R = 10$ km:|      |                         |                 |           |                 |                  |
| 1 ring                  | 69.         | 1.8–3.0 GeV             | 53.             | 5.1       | 4.5             | 17.0             |
| 2 or 3 rings            | 20.         | 1.8–2.8 GeV             | 14.             | 1.9       | 1.2             | 7.8              |
| $\bar{\nu}$, $R = 11$ km:|      |                         |                 |           |                 |                  |
| 1 ring                  | 59.         | 1.8–2.6 GeV             | 38.             | 3.2       | 2.8             | 15.3             |
| 2 or 3 rings            | 16.         | 1.6–2.8 GeV             | 12.             | 2.1       | 1.3             | 6.7              |

Table 1: The total $\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$) signal and the numbers of signal, NC background, and intrinsic-CC background events in the selected $E_{\text{vis}}$ window for 1-ring and multi-ring signatures and for the $\nu$ and $\bar{\nu}$ settings of the beam. Also quoted is the "Figure of Merit" $S/\sqrt{B}$, where $S$ is the number of signal events and $B$ is the total (NC plus intrinsic-CC) background. The assumed exposure is 100 kton–years.

In a realistic Cherenkov detector, recoil protons often escape detection even for momenta above the Cherenkov threshold [12]. On average, recoil protons have higher momenta in $\nu_e n \to e^- \pi^0 p$ than in $\nu_e n \to e^- p$ due to a broader $Q^2$ distribution, so that the multi-ring signal is expected to benefit most from keeping (some)
energetic protons. That lifting the upper cut on proton momentum effectively increases the ratio between the multi-ring and 1-ring signals is illustrated by Table 2, to be compared with Table 1.

| Beam, radius, signature | Total signal | $E_{\text{vis}}$ window | Signal in window | NC backgr. | Intr. CC backgr. | $S/\sqrt{B}$ (FoM) |
|-------------------------|--------------|--------------------------|------------------|------------|-----------------|-----------------|
| $\nu, R = 9$ km:        |              |                          |                  |            |                 |                 |
| 1 ring                  | 133.         | 2.0–3.4 GeV              | 87.              | 24.9       | 8.7             | 14.9            |
| 2 or 3 rings            | 80.          | 2.0–3.2 GeV              | 49.              | 9.9        | 5.4             | 12.4            |
| $\nu, R = 10$ km:       |              |                          |                  |            |                 |                 |
| 1 ring                  | 119.         | 1.8–3.0 GeV              | 80.              | 22.0       | 7.2             | 14.9            |
| 2 or 3 rings            | 68.          | 1.6–3.0 GeV              | 51.              | 12.3       | 5.6             | 12.1            |
| $\nu, R = 11$ km:       |              |                          |                  |            |                 |                 |
| 1 ring                  | 105.         | 1.8–2.6 GeV              | 58.              | 12.3       | 4.6             | 14.1            |
| 2 or 3 rings            | 56.          | 1.6–2.6 GeV              | 37.              | 7.2        | 3.6             | 11.3            |

Table 2: The 1-ring and multi-ring signals of $\nu_{\mu} \rightarrow \nu_e$ compared for incident neutrinos, no longer requiring that proton momenta be below the Cherenkov threshold in water.

As indicated in [3], fast PMT’s and good photocathode coverage may help discriminate between the electron- and $\pi^0$-induced showers by detecting the spatial separation between the conversion points of the two photons from $\pi^0 \rightarrow \gamma\gamma$. If shown to be realistic, this will equally apply to 1-ring and multi-ring signatures of $\nu_{\mu} \rightarrow \nu_e$. Yet another geometric handle may be possible for multi-ring topologies only, provided that spatial resolution of the detector is better than photon conversion length $\lambda_c$. An important advantage of having more than one ring is that constraining the axes of all rings to a common point in space will yield the position of the primary vertex. Within errors, this should coincide with the reconstructed vertex of a $e^-$-induced shower, whereas the vertex of an unresolved $\pi^0$ shower will be displaced by $\sim \lambda_c$ along the shower direction. The spatial resolution of SuperK has been estimated as 18 cm for the vertex of proton decay $p \rightarrow e^+\pi^0$ whose signature is very similar to that of $\nu_e n \rightarrow e^-\pi^0 p$, and as 34 cm for the vertex of a single $e$-like ring [3]. We have $\lambda_c \simeq 40$ cm for water, so that even a modest improvement in resolution over SuperK will allow to efficiently discriminate between CC and NC
multi-ring events and to measure the NC background (this of course needs to be checked by a detailed simulation of detector response).

To conclude, our preliminary results indicate that analyzing the reaction $\nu_e n \rightarrow e^- \pi^0 p$ along with the quasielastic reaction $\nu_e n \rightarrow e^- p$ may significantly enhance the sensitivity of a water Cherenkov detector to the ”subleading” oscillation $\nu_\mu \rightarrow \nu_e$ at neutrino energies $\sim 2$–$3$ GeV. At the level of standard selections, the statistical significance of the multi-ring signal of $\nu_\mu \rightarrow \nu_e$ is comparable to that of the 1-ring (quasielastic) signal. The antineutrino reaction $\bar{\nu}_e p \rightarrow e^+ \pi^0 n$ is a less efficient probe of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ because its cross section is small. The NC background to $\nu_e n \rightarrow e^- \pi^0 p$ can be suppressed by reconstructing the vertex of neutrino collision and analyzing spatial separation between the primary and secondary vertices.

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Figure 1: Cross sections per average nucleon in water of the reactions $\nu_e n \rightarrow e^- p$ and $\nu_e n \rightarrow e^- \pi^0 p$ (top left), $\bar{\nu}_e p \rightarrow e^+ n$ and $\bar{\nu}_e p \rightarrow e^+ \pi^0 n$ (bottom left), $\nu N \rightarrow \nu \pi^0 N$ and $\nu N \rightarrow \nu \pi^0 \pi^0 N$ (top right), and $\bar{\nu} N \rightarrow \bar{\nu} \pi^0 N$ and $\bar{\nu} N \rightarrow \bar{\nu} \pi^0 \pi^0 N$ (bottom right) as functions of neutrino energy. Also shown are the contributions of $\Delta(1232)$ excitation to the $\nu_e n \rightarrow e^- \pi^0 p$ and $\bar{\nu}_e p \rightarrow e^+ \pi^0 n$ cross sections.
Figure 2: The oscillation-free $E_\nu$ spectra of $\nu_e$- and $\nu_\mu$-induced CC events (top panel) and their ratios (bottom panel) for an off-axis location in the NuMI medium-energy beam ($L = 900$ km and $R = 10$ km). The exposure is 100 kton–years.
Figure 3: The momenta of $\pi^0$ mesons emitted in the CC reaction $\nu_e N \rightarrow e^- \pi^0 X$. The lower histogram shows the contribution of reconstructed $\pi^0$ mesons.
Figure 4: $E_{\text{vis}}$ distributions of events featuring one $e$-like ring (top left), 2 or 3 rings (top right), 2 rings (bottom left), and 3 rings (bottom right). Here and in subsequent Figures, shown for either event category are the $\nu_\mu \rightarrow \nu_e$ signal (yellow area), the NC background (green area), and the intrinsic CC background (red area). For incident neutrinos and $R = 9$ km.
Figure 5: $E_{\text{vis}}$ distributions of 1-ring and multi-ring events for incident neutrinos and $R = 10$ km.
Figure 6: $E_{\text{vis}}$ distributions of 1-ring and multi-ring events for incident neutrinos and $R = 11$ km.