A Water Čerenkov Calorimeter as the Next Generation Neutrino Detector

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Abstract

We propose here a large homogeneous calorimeter as the next generation neutrino detector for $\nu$ factories and/or conventional $\nu$ beams. The active media is chosen to be water for obvious economical reasons. The Čerenkov light produced in water is sufficient to have good energy resolution, and the pattern recognition is realized by a modular water tank structure. Monte Carlo simulations demonstrate that the detector performance is excellent for identifying neutrino CC events while rejecting background events.

1 Introduction

Neutrino factories and conventional beams have been discussed extensively in the literature as the main facility of neutrino physics for the next decade. The main physics objectives include the measurements of $\sin^2 \theta_{13}$, $\Delta m^2_{23}$, the leptonic CP phase $\delta$ and the sign of $\Delta m^2_{23}$. All of these quantities can be obtained through the disappearance probability $P(\nu_\mu \rightarrow \nu_\mu)$ and the appearance probability $P(\bar{\nu}_\mu(\nu_e) \rightarrow \nu_e(\nu_\mu))$ and $P(\nu_\mu(\nu_e) \rightarrow \nu_e(\nu_\mu))$. To measure these quantities, a detector should: 1) be able to identify leptons: $e$, $\mu$ and if possible $\tau$; 2) have good pattern recognition capabilities for background rejection; 3) have good energy resolution for event selection and to determine $P_{\nu_\mu \rightarrow \nu_\mu}(E)$; 4) be able to measure the charge for $\mu^\pm$ in the case of $\nu$ factories; and 5) be able to have a large mass(100-1000 kt) at an affordable price.

Currently there are four types of detectors proposed, as listed in table 1. These detectors are either too expensive to be very large, or too large to have a magnet for charge identification. In this talk, I propose a new type of detector – a water Čerenkov calorimeter – which fulfills all the above requirements.
Table 1: Currently proposed detector for $\nu$ factories and conventional $\nu$ beams.

## Water Čerenkov Calorimeter

Water Čerenkov ring image detectors have been successfully employed in large scale, for obvious economic reasons, by the IMB and the Super-Kamiokande experiments. However, a substantial growth in size beyond these detectors appears problematic because of the cost of excavation and photon detection. To overcome these problems, we propose here a water Čerenkov calorimeter with a modular structure, as shown in Fig. 1.

![Diagram of water Čerenkov calorimeter](image)

Each tank has dimensions $1 \times 1 \times 10\text{m}^3$, holding a total of 10 t of water. The exact segmentation of water tanks is to be optimized based on the neutrino beam energy,
the experimental hall, the cost, etc. For simplicity, we discuss in the following 1 m thick tank, corresponding to 2.77 $X_0$ and 1.5 $\lambda_0$. The water tank is made of PVC with Aluminum lining. Čerenkov light is reflected by Aluminum and transported towards the two ends of the tank, which are covered by wavelength shifter (WLS) plates. Light from the WLS is guided to a 5" photon-multiplier tube (PMT), as shown in Fig. 2. The modular structure of such a detector allows it to be placed at a shallow depth in a cavern of any shape (or possibly even at surface), therefore reducing the excavation cost. The photon collection area is also reduced dramatically, making it possible to build a large detector at a moderate cost.

A through-going charged particle emits about 20,000 Čerenkov photons per meter. Assuming a light attenuation length in water of 20 m and a reflection coefficient of the Aluminum lining of 90%, we obtain a light collection efficiency of about 20%. Combined with the quantum efficiency of the PMT (20%), the WLS collection efficiency (25%) and an additional safety factor of 50%, the total light collection efficiency is about 0.5%. This corresponds to 100 photoelectrons per meter, which can be translated to a resolution of $4.5%/\sqrt{E}$. This is slightly worse than the Super-Kamiokande detector and liquid Argon TPC but much better than iron calorimeters[1].

If this detector is built for a $\nu$ factory, a tracking device, such as Resistive Plate Chambers (RPC)[3] will be needed between water tanks to identify the sign of charge. RPCs can also be helpful for pattern recognition, to determine precisely muon directions, and to identify cosmic-muons for either veto or calibration. The RPC strips will run in both X- and Y-directions with a width of 4 cm. A total of $\sim 10^5 m^2$ is needed for a 100 kt detector, which is more than an order of magnitude larger than the current scale[3]. R&D efforts would be needed to reduce costs.

The magnet system for such a detector can be segmented in order to minimize dead materials between water tanks. If the desired minimum muon momentum is 5 GeV/c, the magnet must be segmented every 20 m. Detailed magnet design still needs to be worked out; here we just present a preliminary idea to start the discussion. A toroid magnet similar to that of Minos, as shown in Fig. 3, can produce a magnetic field $B > 1.5 T$, for a current $I > 10^4$ A. The thickness of the magnet needed is determined.

![Figure 2: Schematic of a water tank.](image-url)
by the error from the multiple scattering: \( \Delta P/P = 0.0136 \sqrt{X/X_0}/0.3BL \), where \( L \) is the thickness of magnet. For \( L=50 \text{ cm} \), we obtain an error of 32\%. The measurement error is given by \( \Delta P/P \simeq \delta \alpha/\alpha = \sigma P/0.3BL \), where \( r \) is the track length before or after the magnet and \( \sigma \) is the pitch size of the RPC. For \( P=5 \text{ GeV}/c \), \( \sigma = 4 \text{ cm} \) and \( r=10 \text{ m} \), the measurement error is 9\%, much smaller than that from multiple scattering. It should be noted that \( P_\mu \) is also measured from the range. By requiring that both \( P_\mu \) measurements are consistent, we can eliminate most of the fake wrong sign muons. The iron needed for such a magnet is about 20\% of the total mass of the water.

![Figure 3: Schematic of a toroid magnet](image)

The cost of such a detector is moderate compared to other types of detectors, enabling us to build a detector as large as 100 - 1000 kt. The combination of size, excellent energy resolution and pattern recognition capabilities makes this detector very attractive. An incomplete but rich physics program can be listed as follows: 1) neutrino physics from \( \nu \) factories or \( \nu \) beams; 2) improved measurements of atmospheric neutrinos; 3) observation of supernovae at distances up to hundreds of kpc; 4) determination of primary cosmic-ray composition by measuring multiple muons; 5) searches for WIMP’s looking at muons from the core of the earth or the sun with a sensitivity covering DAMA’s allowed region; 6) searches for monopoles looking at slow moving particles with high dE/dx; 7) searches for muons from point sources; 8) searches for exotic particles such as fractionally charged particles. Depending on the location of the detector, other topics on cosmic-ray physics can be explored.
3 Performance of Water Čerenkov Calorimeter

To study the performance of such a detector, we consider in the following two possible applications in the near future: JHF neutrino beam to Beijing with a baseline of 2100 km and NuMi beam from Fermilab to Minos with a baseline of 735 km. The energy spectra of visible $\nu_\mu$ CC events are shown in Fig. 4.

We use a full GEANT Monte Carlo simulation program and the Minos neutrino event generator. A CC $\nu$ signal event is identified by its accompanying lepton, reconstructed as a jet. Fig. 5 shows the jet energy normalized by the energy of the lepton. It can be seen from the plot that leptons from CC events can indeed be identified and the jet reconstruction algorithm works properly. It is also shown in the figure that the energy resolution of the neutrino CC events is about 10% in both cases.

The neutrino CC events are identified by the following 5 variables: $E_{\text{max}}/E_{\text{jet}}$, $L_{\text{shower}}/E_{\text{jet}}$, $N_{\text{tank}}/E_{\text{jet}}$, $R_{xy}/E_{\text{tot}}$, and $R_{xy}^{\text{max}}/E_{\text{tot}}$, where $E_{\text{jet}}$ is the jet energy, $E_{\text{tot}}$ the total visible energy, $E_{\text{max}}$ the maximum energy in a cell, $L_{\text{shower}}$ the longitudinal length of the jet, $N_{\text{tank}}$ the number of cells with energy more than 10 MeV, $R_{xy}$ the transverse event size and $R_{xy}^{\text{max}}$ the transverse event size at the shower maxima. Fig. 6 shows $R_{xy}^{\text{max}}/E_{\text{tot}}$ for all different neutrino flavors. It can be seen that $\nu_e$ CC events can be selected with reasonable efficiency and moderate backgrounds. Table 2 shows the final results from this pilot Monte Carlo study. For $\nu_e$ and $\nu_\mu$ events, $\nu_\tau$ CC events are dominant backgrounds, while for $\nu_\tau$, the main background is $\nu_e$. It is interesting to see that this detector can identify $\nu_\tau$ in a statistical way. Similar results are obtained for a detector with 0.5m water tanks without RPCs. These results are similar to or better than those from water Čerenkov image detectors[4] and iron calorimeters[5].
Figure 5: The reconstructed jet energy and total visible energy. The fact that $E_{\text{jet}}/E_{\text{lepton}}$ peaks around one shows that the jet reconstruction algorithm finds the lepton from CC events. The fraction of total visible energy to the neutrino energy indicates that we have an energy resolution better than 10% for all neutrinos. The bias is due to invisible neutral hadrons and charged particles below Čerenkov thresholds.
Figure 6: The transverse event size at the shower maxima for various type of neutrino events. The distribution of $\nu_e$ is different from all the others.
|         | JHF-Beijing | NuMi-Minos |
|---------|-------------|------------|
| $\nu_e$ CC | 30%         | 15%        |
| $\nu_e$ NC | 53%         | 53%        |
| $\nu_\tau$ CC | 9.3%       | 15%        |
| $\nu_\mu$ CC | 3%          | 53%        |
| $\nu_\mu$ NC | >1300:1    | >1300:1    |
| $\nu_\tau$ NC | 60:1        | 600:1      |
| $\nu_\mu$ CC | 3:1         | 600:1      |
| $\nu_\mu$ NC | >6000:1     | >610:1     |
| $\nu_\tau$ CC | 20:1        | 320:1      |
| $\nu_\tau$ NC | 12:1        | 2000:1     |
| $\nu_\mu$ CC | 1:3         | 14000:1    |
| $\nu_\mu$ NC | 39:1        | 3200:1     |

Table 2. Results from Monte Carlo simulation: Efficiency vs background rejection power for different flavors.

4 Summary

In summary, the water Čerenkov calorimeter is a cheap and effective detector for $\nu$ factories and $\nu$ beams. The performance is excellent for $\nu_e$ and $\nu_\tau$ appearance and $\nu_\mu$ disappearance from a Monte Carlo simulation. Such a detector is also very desirable for cosmic-ray physics and astrophysics. There are no major technical difficulties although R&D and detector optimization are needed.

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References

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