Feasibility of a Next Generation Underground Water Cherenkov Detector: UNO

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Abstract. The feasibility of a next generation underground water Cherenkov detector is examined and a conceptual design (UNO) is presented. The design has a linear detector configuration with a total volume of 650 kton which is 13 times the total volume of the Super-Kamiokande detector. It corresponds to a 20 times increase in fiducial volume for physics analyses. The physics goals of UNO are to increase the sensitivity of the searches for nucleon decays about a factor of ten and to make precision measurements of the solar and atmospheric neutrino properties. In addition, the detection sensitivity for Supernova neutrinos will reach as far as the Andromeda galaxy.

INTRODUCTION

Large scale underground water Cherenkov detector experiments, Super-Kamiokande and its predecessors (IMB and Kamiokande), have been extremely successful in producing crucial physics results during the last two decades. Their accomplishments includes: the first real time measurement of the solar neutrinos, confirmation of the solar neutrino flux deficit, observation of the neutrino oscillations in the atmospheric neutrinos, observation of neutrinos from the Supernova 1987A, and setting the world best limits on the nucleon decays.

These detectors were originally conceived for searches for nucleon decays predicted by various Grand Unification Theories (GUTs). While no positive observation of nucleon decays have been made to date with these detectors, the evidence for neutrino oscillations now firmly established by the Super-Kamiokande atmospheric neutrino analysis provides us with a breakthrough in particle physics beyond the Standard Model.(1) This finding indicates that the neutrino masses are indeed very small if we assume no degeneracy in mass eigenstates, which in turn indicates that there may be a new very high energy physics scale that facilitates small neutrino masses via "See-saw" mechanism and allows protons to decay.

There are many theoretical models that predict proton decays and some of them were presented in this workshop (NNN99)(2). A specific example of such models can be found in Ref. (3) which presents a complete and detailed description of interplay between the neutrino masses, proton decays and other Standard Model observables in G(2,2,4) and SO(10) frameworks. The model predicts proton decay lifetimes within the reach of the Super-Kamiokande, especially in the SUSY favored decay modes. These predictions along with many other predictions from other models encourage us to turn our attention back to the proton decay searches with higher sensitivity.

If discovered, proton decay provides only and unambiguous direct evidence of existence of GUT scale physics at low energies. It certainly will be remembered as one of the most revolutionary discoveries in particle physics history. Some say the discovery is around the corner.

In order to further our effort to search for nucleon decays which I believe is in the category of "must-do" physics and to do high statistics studies of neutrino physics including solar neutrinos, atmospheric neutrinos and supernova neutrinos, I propose a next generation large underground water Cherenkov detector which is named UNO (Ultra underground Nucleon decay and neutrino Observatory).

In the following sections, the design considerations, baseline configuration, physics capabilities and cost estimation of the UNO detector is described in some detail.

ULTRA UNDERGROUND NUCLEON DECAY AND NEUTRINO OBSERVATORY DETECTOR

The design philosophy of UNO is to make a relatively simple extension of the well established water Cherenkov detector technology beyond Super-Kamiokande to achieve an order of magnitude better sensitivity in nucleon decay searches and to study various neutrino physics with higher precision. With water Cherenkov detector technology, we can utilize the tremendous amount of experience and expertise gained from the IMB, Kamioka and Super-Kamiokande detectors.

In order to establish reasonable detector parameters for physics capability studies and cost estimates, I set the benchmark fiducial volume of the UNO detector to be 20 times that of Super-Kamiokande. The design of the detector is kept to be simple and robust, and broad physics capabilities are required.

Several design options are considered keeping in mind the practical limitations in conventional water Cherenkov detector technique: namely, (1) the largest depth of water of a detector is limited by the current PMT pressure stress limit (8 atm for current $20''$ Hamamatsu PMTs) which can be overcome if one is willing use an optical high pressure water tight container for each PMT and compromising the PMT efficiency; 2) The maximum dimension of the detector without active detection element is limited by the finite light attenuation length in pure water ($\sim$80 m @400 nm in Super-Kamiokande).

Three different detector shapes are considered: Big, Torus and Linear. According to D. L. Petersen who is a rock engineer at the CNA Consulting Engineering at Chicago, Illinois, the excavation costs are more or less same independent of the shapes of the detector. (4) Then, if we want to keep the detector cost at minimum for a fixed fiducial volume (445 kton; $\sim$20 times the Super-Kamiokande), we need to keep the ratio *rv*=(fiducial volume/total volume) large and keep *rs*=(PMT surface area/total volume) small. These requirements obviously prefer fat detectors.

The Big detector design option considered has a cube shape with 86x86x86m outer dimensions. It has a potential problem with the PMT pressure limit for the PMTs at the bottom of the detector where the water pressure will be about 9 atmospheric pressure. It also has a diagonal length of 150 m which is much longer than the light attenuation length currently measured in the pure water.

The Torus detector design option considered turns out to be very inefficient in term of the *rv* value and is physically not possible if the cross-section is 60x60 m for a benchmark detector size. Even with a 50x50 m cross-section a torus would be too tight, *i.e.* the diameter of the central rock column will be too small to support the structure.

Thus, a Torus design will have to have a small cross-section which results in a small *rv* and large *rs* values. For example, a 40x40m cross-section torus has *rv*=0.6 compared to 0.7 for a Linear option considered below.

The Linear detector design option considered has a 60mx60mx180m outer dimensions and it appears to be the most optimal one. When compartmentalized as three 60mx60mx60m cubes in terms of active detection elements, it satisfies all of the requirements mentioned above and results in a reasonable *rv* and *rs* values. The compartmentalization option naturally makes the detector cost more expensive but provides several significant benefits compared to an open geometry option. First, it minimizes so-called flasher background events, which commonly occur in all water Cherenkov detectors that use PMTs, by confining them in an isolated compartment. Second, it minimizes inefficiency and variation in efficiency due to finite light attenuation length in water. Third, it keeps the detector operational live time to close to 100%. The current detector operational live time for Super-Kamiokande is about 90%. The 10% inefficiency is mainly due to detector calibrations. With compartmentalization we can ensure that at least one compartment will be alive during the detector calibration times. Keeping the detector live time very high (virtually at 100%) is of course very important for physics programs such as a supernova watch.

Another issue that needs to be dealt with concerning the compartmentalization is whether we should make the divisions among the compartments rigid so that the water can be filled and drained independently. Certainly making the divisions rigid walls will make any future repairing of the detector easier. (It should be noted that it takes two months to drain the current Super-Kamiokande tank.) However, it is not clear whether this is an important enough reason for us to consider such an option which will incur substantial additional cost.

One could also argue about whether the next generation detector should be built underground or underwater. Indeed there are a few ideas presented in recent meetings that consider very large underwater detectors. In my opinion, however, one of the most serious disadvantage of a underwater detector will be its inaccessibility for calibration and repair. The experience gained from the Super-Kamiokande tells us that a well selected and maintained underground detector environment is a wonderful environment for us to work and to operate the detector. It provides us an easy access to the detector for various calibrations and for trying out new ideas. On the other hand, I would assume that precision calibrations of a deep underwater detector will be extremely difficult if not impossible, especially if one is aiming to do a calibration for solar neutrino measurements using electron linac or DT generator etc. Thus, for a underwater detector design to become a viable option, a new sets of elaborate remote calibration systems has to be developed and tested. In addition, location and accessibility of other service facilities such as water purification system needs to be considered, and a practical and realistic solution must be found. Overall, I expect many more technical challenges for a underwater detector than for a underground detector.

Considering all of the above issues, I believe that, a large underground water Cherenkov detector with a linear configuration is the best option for a next generation

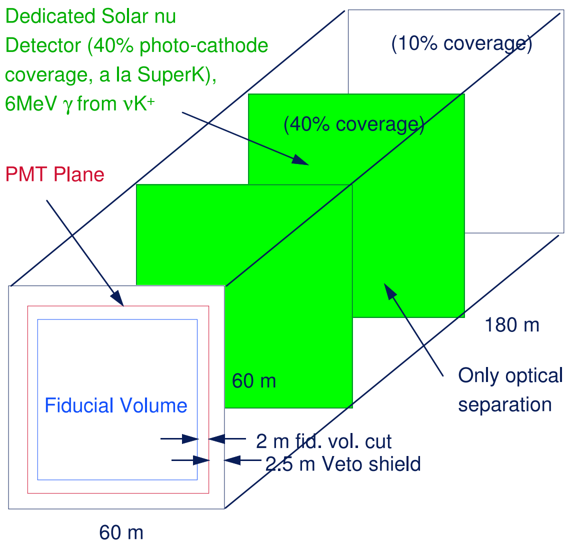

FIGURE 1. Baseline configuration of the UNO detector

nucleon decay and neutrino detector which can be built within next 10 years without requiring major R&D. A conceptual design of such a detector (UNO detector) is shown in Figure 1.

The detector has three compartmentalized sections with 60mx60mx60m dimensions resulting in a total length of 180 m and a total volume of 648 kton. The outer detector region of the detector has 2.5 m depth of veto shield and is instrumented with 14,901 8″ PMTs with a PMT density of 0.33 PMTs/m^2. The inner detector region has a total fiducial volume of 445 kton which is defined as the water volume 2 m inside of the inner PMT planes. The inner detector region is instrumented with 20″ PMTs with a PMT density of 1.96 PMTs/m^2 (40% photocathode coverage a la Super-Kamiokande) for the central section and 0.49 PMTs/m^2 (10% photocathode coverage) for the two sections at the wings. The total number of 20″ PMTs is 56,650 for this configuration.

UNO Physics Goals and Capabilities

The detector configuration proposed above presents excellent physics capabilities of UNO for broad ranges of nucleon decay and neutrino physics. The two wings of the detector with 10% photocathode coverage will have an energy threshold below 10 MeV which should be sufficient for nucleon decay searches, supernova neutrino detections, high statistics atmospheric neutrino studies and high statistics solar neutrino studies at the high energy end of the energy spectrum. The central compartment with a 40% photocathode coverage will serve as a dedicated low energy solar neutrino detector with a 5 MeV analysis threshold which will also provide UNO with a detection capability for 6 MeV γ's from $p \to \nu K^+$ decays in the oxygen nucleus. It also provides the capability to observe low energy supernova neutrino events ($\sim$ 5 MeV) which are important for core collapse modeling.

The primary physics goal of UNO is to obtain an order of magnitude better sensitivity in nucleon decay searches (especially in $p \to e^+\pi^0$ mode) than Super-Kamiokande. The exact amount of improvements in the sensitivity vary depending on the decay modes, particularly on their expected backgrounds. Obviously for the background free decay modes we expect more than a order of magnitude improvements but for the background limited decay modes we would expect a factor of 4 or 5 improvements.

The amount of improvement also strongly depends on the optimization of the analyses for high statistics sample. For example, if we continue current standard Super-Kamiokande analysis for $p \to e^+\pi^0$, one will encounter a background limited analysis situation in ten years (0.5 years for UNO). However, if we make a tighter cut on total momentum in an event, say 150 MeV (rather than 250 MeV for current Super-Kamiokande standard analysis), the signal efficiency will go down to about 25-30% from current 44%, but we will be virtually background free for many UNO years. Since we gain a factor of 20 in total fiducial volume, by keeping the efficiency better than 22% we can insure a factor of 10 or more gain in the search sensitivity as long as we can keep the background to be zero.

In order to estimate the potential improvements reliably, we need to do much more work. First of all, we need to have better understanding of the characteristics of the atmospheric neutrino background events. This can be accomplished by studying the K2K 1 kton neutrino events which are similar in many aspects to the atmospheric neutrino background events relevant to nucleon decay searches. Second, we need to reduce the systematic uncertainties associated with the atmospheric neutrino flux and the neutrino interaction cross-section for water target. Some of this information can come from the K2K fine-grained detector data. Finally, we need to improve the search analyses by developing more sophisticated algorithms and optimize the analyses for maximum sensitivity. I personally believe that there is much room for improvement in these areas, especially for the multi-ring event analysis. We also need to generate much larger MC events samples with detailed simulations for these purposes. While it is difficult to predict the exact sensitivity of the UNO detector for nucleon decay searches at this time, I am convinced that an order of magnitude

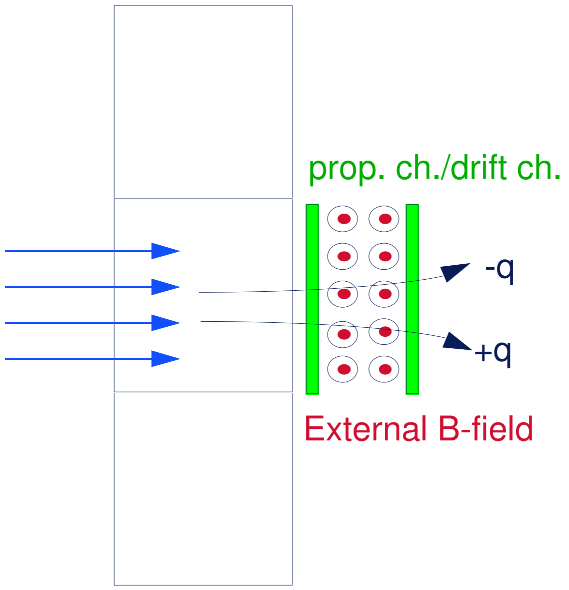

FIGURE 2. Conceptual layout of UNO as a far detector for a muon storage ring neutrino beam

improvements in the search sensitivity for various decay modes are attainable.

Another equally important physics goal of UNO is supernova neutrino detection. With the proposed configuration UNO will be able to record 100k neutrino interaction events from a supernova explosion at 10 kpc away. This will allow us to make a detailed mapping of the time structure of the neutrino flux providing valuable information for the theoretical modeling of the supernovae. The detection reach for neutrinos from supernova explosions will be about 1 Mpc from the earth which includes most of the local group of galaxies including Andromeda. We expect (optimistically) about one supernova explosion in every ten years within this range.

Although current Super-Kamiokande measurements of the solar neutrino properties provide crucial information on solar neutrino problems with unprecedented statistics, the measurements on energy spectrum, day-night flux ratio, and seasonal variations are limited by the lack of statistics in providing an unambiguous resolution to the solar neutrino problems. Thus, it is strongly desirable to build a large scale detector that has a capability of precision studies of the solar neutrinos. The proposed configuration of UNO will provide about 20 times more statistics for high energy end of the solar neutrino events and at least 7 times more statistics for the low energy end events. Even if we are able to establish a solution to the solar neutrino problem with the results from Super-Kamiokande, SNO, KAMLAND and Borexino within this decade, we will need more precision measurements to firmly establish the SSM (Standard Solar Model) and neutrino oscillation parameters. I believe that we will be entering a precision measurement era for SSM in this decade as the two last decades have been for the Standard Model.

If we assume the neutrino oscillations observed in the Super-Kamiokande atmospheric neutrino events are due to ν_μ to ν_τ oscillations, there should be about 20 tau appearance events produced per year from the ν_τ interactions in the Super-Kamiokande detector. For UNO the rate will be about 400 tau appearance events per year. While extracting a tau signal from background in water Cherenkov detector is not expected to be easy, it will be a worth while project to pursue, especially with a reasonably high statistics event sample. (Currently, we are pursuing such an analysis with the Super-Kamiokande data and the initial results appear to be promising. We are hoping to get about three sigma effect.) If the Δm^2 turns out to be relative low, say $\sim 3 \times 10^{-3}$ eV^2 or lower, the long baseline neutrino experiments will have difficult time in observing unambiguous signal of tau appearance. And thus, establishing a direct observation of tau appearance coming from neutrino oscillations may take much longer time than we currently hope for.

Finally, a possibility of using UNO as a far detector of a Muon Storage Ring produced neutrino beam experiment should be considered. A water Cherenkov detector is a good candidate for a far detector. It provides an relatively inexpensive large target volume, particle ID for electrons and muons, and reasonable calorimetry. It could also provide good charge separation if it is aided by an external spectrometer as shown in Figure 2.

Thus, if UNO is built, it will serve as a truly multi-purpose general underground detector for variety of great physics. Especially for nucleon decay searches, it will serve as a robust multi-decay mode search detector.

UNO Cost Estimates

In order to obtain a ball park figure cost estimate for UNO detector, I use the construction cost data for the Super-Kamiokande detector provided by K. Nakamura as a reference. I divide the major expense items into two categories according to their nature of scaling, i.e. volume-like scaling or surface-like scaling. And I apply my reasonable guesses to ultimately determine the scaling factor from Super-Kamiokande to UNO. Thus, these figures should not be taken too seriously. Table 1 shows my initial estimate of itemize costs for UNO along with the actual costs for Super-Kamiokande. The total cost for UNO with the baseline configuration proposed in this paper is then about \$520M and the cost for a detector with full 40% photocathode coverage for all inner surfaces (a la Super-Kamiokande) is about \$680M. And all of these figures do not include contingencies.

Table 1. UNO Cost Estimates (in thousands of US dollars): This is a quite complete list of expense items for all aspect of detector construction. The "v" and "s" symbols note the volume-like and surface-like nature of cost scalings used when the costs are extrapolated from the Super-Kamiokande (SuperK) to UNO. A conversion rate of 1\$ = 100 yen is used.

Item	SuperK		UNO
Cavity Excavation	27,640	v	168,000
Water piping and pumps	630	v	4,082
Water Purification Sys	1,850	v	11,988
Power Station	720	v	2,160
Crane	760	v	2,280
Water Tank	18,400	s	92,480
PMT support structure	4,580	s	23,019
Counting Room	330	s	990
Computer Building	1,860	s	2,232
Main Building	3,000	s	3,600
20″ PMT (including cables)	34,670	s	173,664
Electronics	6,330	s	9,495
DAQ	1,090	s	1,635
Air Conditioning	210	s	315
Veto instrumentation	3,000	s	9,000
8″ PMT (including cables)	2,262	s	17,881
Total	102,070		522,822

For the major cost items of the detector, I use more reliable quotes and estimates for unit costs from vendors and experts. As shown in Table 2, the unit cost for excavation is taken from the estimates by D. L. Petersen, and the unit costs for PMTs are taken from Hamamatsu corporation. I take liberty of reducing the per channel electronic cost by a factor of 5 and the water tank construction cost per unit surface by a factor of 2 from the Super-Kamiokande cost. The cost of these five items comprise the majority of the UNO detector cost.

Cost Reduction Possibilities

I believe that there is quite a bit of room to reduce the total cost for UNO. First of all we can reduce the excavation cost by finding an existing cavity or underground facility. Or we could simply get a better quote.

Table 2. Estimated Unit Costs: The excavation cost is assuming a horizontal access tunnel and rock quality (Q value) of 100. The PMT unit cost including cable cost is based on a 50k PMT order. It is \$2,850 if 100k PMTs are ordered. A conversion rate of 1\$ = 100 yen is used.

Item	Unit Cost	Source
Excavation	\$260/m^3	L. Petersen
20″ PMTs	\$3,100	Hamamatsu
8″ PMTs	\$1,200	Hamamatsu
Electronics	\$170/channel	
Water Tank	\$2,076/m^2	

It is said that the actual excavation cost charged to the mining company in Kamioka, Japan is only \$50/m^3. Second, we could use Mineguard type of liner rather than a stainless-steel container for the container tank structure. Third, we should optimize the PMT size and granuality for our physics goals and look into a way of developing new cheaper photo-detectors. For example, we could use two 8″ PMTs instead of a 20″ PMT, which may result in overall better performance and cheaper cost. We could also look for other vendors (from Russia?) than Hamamatsu.

Site Selection

Obviously, the issue of site selection is an important issue for the success of a project like UNO with this magnitude. In principle, a site near the Equator is desired if we are aiming for maximum information from UNO for the solar neutrino physics. However, the consensus among solar neutrino theorists indicate that it is not crucial unless the MSW small mixing angle solution looks very promising. Thus, I concentrate my attention to possible sites in the United States.

An extensive site search has been conducted by R.R. Sharp, Jr. and A. Mann during the early 1980s for a site for potential National Underground Science Facility (NUSF). They surveyed mostly in the western states for existing tunnels, inactive mines, active mines and new locations. They found a couple of sites in Nevada particularly attractive.(5) Although the size and depth requirements of the potential sites they searched for are quite different from the UNO requirements, the information gathered is found to be quite useful.

Another site search was conducted by W. Kropp *et. al.* concentrating on the site at San Jocinto, California. (6)

The results from this search also provides useful information for our current search.

The most attractive site so far presented to us is the WIPP (Waste Isolation Pilot Project) site at Carlsbad, New Mexico. The facility which is managed by DOE provides a hard salt rock geology, an already existing laboratory facility and tunneling machinery. With strong government interest to utilize this facility for scientific research, the site is indeed ideal for UNO or for any other large scale next generation underground detectors.

CONCLUSIONS

Feasibility of a next generation very large underground water Cherenkov detector, UNO, is considered. The detector configuration of UNO is a linear compartmentalized detector (60mx60mx60mx3) with a middle section with a 40% photocathode coverage and two wing sections with 10% photocathode coverage. The middle section is dedicated for low energy solar neutrino and supernova neutrino studies and for detecting 6 MeV prompt γ's from $p \rightarrow \nu K^+$ decays.

The detector which has a total volume of 650 kton and a corresponding fiducial volume of 445 kton (20 times larger than the fiducial volume of the Super-Kamiokande detector) can be built today at about $500M of construction cost. There are no known serious technical challenges in building such a detector. Although rigorous R&D is desired for cost reduction and improvement in detector performance, there are no critical path R&D items. If funding is available, we should be able to build this detector within next ten years.

Such a detector, if built, will provide us with a bonanza of exciting physics programs: Nucleon decay searches, precision solar and atmospheric neutrino studies, and supernova neutrino observations. The detector can also serve as a far detector for a possible future neutrino factory. It will also compliment any other major accelerator based initiatives such as NLC or neutrino factories in terms of providing diverse but crucial physics programs to the US HEP community.

In my opinion, physics program of searches for nucleon decays undoubtedly belongs to "MUST-DO" physics category and it should be vigorously pursued. I also believe if such a large scale detector is built it should be a multi-purpose general detector with a robust multi-decay mode search capability for nucleon decay searches. It should not be specialized single purpose detector with specific decay mode search capability.

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