A design outline for a Cherenkoff neutrino observatory

E.P. Bonvin * and S. T. Hatamian †

1California Institute of Technology Pasadena CA 91125 USA

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Abstract

An economical procedure to upgrade the existing Fairport water Cherenkoff detector is described. The detector will lower its energy threshold by increased photocoverage and light yield. Furthermore, by addition of a Gd salt it will become sensitive to neutrons produced by the inverse beta decay of anti-neutrinos on protons. The new detector can then take advantage of the existence of the Perry power nuclear reactor, located 12.9km away, as a large source of anti-neutrinos. The present gap in the exclusion plot of the neutrino oscillation parameters ($\Delta m^2$ from $2 \times 10^{-4}$ to $10^{-2} eV^2$) may be explored and closed within 12-18 months of run-time. The detector will be able to observe other types of neutrino sources (Boron-8 solar, atmospheric, and supernova) with unprecedented advantages. The low threshold also will allow searching for exotic modes of proton-decay.

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I. INTRODUCTION

The physics of neutrinos has been of increasing import among the high energy community. This has been especially true in the last ten years due in main part to the so called solar-neutrino puzzle: the measurement[1] in which the number of observed solar neutrinos is significantly lower than that expected from the ”standard solar model”. This has given rise to a surge of interest in the neutrino-oscillation hypothesis. The oscillation hypothesis suggests that the weak interaction neutrino eigenstates are a superposition of the mass eigenstates, which therefore, whence massive, may oscillate into one another. This oscillation may in turn be responsible for the apparent deficit in the expected electron neutrino flux, during its traversal of solar matter or in the vacuum.

Terrestrial oscillation experiments have been carried out with reactor neutrinos, accelerator generated (muon-)neutrino beams, cosmic ray neutrinos, and atmospheric neutrinos. The upper limits for the oscillation parameters are summarized in fig-1. Oscillation experiments are usually analyzed in terms of a two-parameter model (assuming only two neutrino flavors) characterized by the mass parameter \( \Delta m^2 = | m_2^2 - m_1^2 | \) line, and the mixing strength parameterized by an angle: \( \sin^2 2\theta \). The probability that a neutrino \( \nu_l \) of energy \( E_\nu \) will change into \( \nu_m \) after travelling a distance \( L \) (in vacuum) is given by:

\[
P_{\nu_{ml}} = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 [eV^2] L [m]}{E_\nu [MeV]}.
\]

While, the probability that \( \nu_l \) will remain unchanged is given by \( P_{\nu_{ll}} = 1 - P_{\nu_{ml}} \).

In order to explore smaller mixing angles\( (\sin^2 2\theta) \) one must increase the count rates of any given oscillation experiment. To reach smaller mass parameters\( (\Delta m^2) \), however, one must either search for longer neutrino oscillation wavelengths (implies longer separation from the source, hence less \( \nu \)-flux), or carry out the search for lower and lower energy neutrinos\( (E_\nu) \), or both. Particularly for the latter approach, the low energy reactor neutrinos are the most attractive choice, in addition to their relatively large flux, and an unrivaled understanding and control of their source. In order to cover the gap in mass parameter of the exclusion plot(fig-1), and given the energy spectrum of a typical power reactor, the separation of the detector from the reactor is then fixed to a value just over 10 Kilometers.

The Fairport facility (formerly used as a proton-decay detector) is located 12.9km away from the Perry (3.8 GWatt) power reactor. Though not designed as a neutrino detector,
this fortunate "accident" makes the Fairport facility a prime candidate for an inexpensive and powerful neutrino detector. In this article we delineate a method for upgrading of the Fairport detector to, not only take advantage of the large source of neutrinos at the perfect distance, but to in fact, serve as a neutrino observatory to explore a host of neutrino related questions. These include detection of not only reactor neutrinos, but also Solar, atmospheric, and supernovae neutrinos. Moreover, the design can make possible searching for proton decay via supersymmetric or other exotic modes. Since the main point of the upgrade is a lowering of the threshold of the detector, possible future experiments with (Fermilab) accelerator neutrino beams are not precluded.

Another proposal[2] has sought to take advantage of the proximity of the Perry nuclear power reactor, but using liquid scintillator as the light producing medium. Though the light produced by all forms of energetic particles is enhanced over 50-fold, many technical problems (relating to cost, handling, containment, ppt-purification, and Gd-loading of the liquid scintillator), make this alternative approach a challenge quite different from the design obstacles tackled in the water detector, described here.

In 1991, the IMB detector was decommissioned due to a leak which resulted in the loss of much of the water, and some structural damage. The discussion of this needed repair (albeit quite major), as well as other necessary civil engineering considerations are beyond the scope of our detector design synopsis, and will not be addressed here. Here we will only assume that the structure can be restored to a similar state as the original. In fact the necessary reconstruction is an opportunity to re-build a much better facility using the 12-years of operational experience, and indeed better suited to the new design. Alternatively, the design and the accumulated expertise may be transported to a whole new location at the proper distance from a nuclear reactor in a new underground, or submontane facility.

II. AN OUTLINE AND THE PHYSICS FOCUS

The Fairport detector is a large tank which contains a total mass of 8Ktons of water, purified through reverse osmosis. The present fiducial mass is 3.3Ktons at a depth 1570 meters of water equivalent(mwe). It is located at a Morton-Thiokol corp. salt mine in Fairport, Ohio(41.7°N, 81.3°W). The tank is 18m high, 17m on the N-S side and 22.5m along the E-W direction. Presently, it is designed to hold 2048 photomultipliers(PMT) of
8-inch diameter to give a photocoverage of approximately 6% of the walls, for an effective threshold of just under 20MeV of electron energy.

Our proposal will make the primary mode of detection, the inverse beta decay of antineutrinos on protons in the water. This reaction produces a positron and a neutron. After thermalization, the neutron via a large capture cross section on a nucleus such as Gd-157 (=240Kb) is converted into gamma rays, and hence becomes detectable. The threshold for a clean trigger must be reduced to a few MeV gamma rays from the present 20 MeV recoil electrons. This enables the detector to see reactor anti-neutrinos whose spectrum ranges from 0 to 8 MeV.

The low energy of the neutrinos observed will allow limits on smaller mass parameters on the mixing exclusion plot. The high flux of the reactor is another attractive feature: at $2 \times 10^7/cm^2s$ (at 12.9km) this is larger than any atmospheric, accelerator or solar source. The backgrounds in this mode of anti-neutrino detection are made very small by requiring a coincidence between the positron and the neutron signal, as the definitive signature of the anti-neutrino. Moreover, the ability to turn the source off and on, affords an unparalleled advantage in measuring backgrounds. In this manner, the proposed upgrade should inexpensively and speedily cover the exclusion plot gap between the mass parameter of $2 \times 10^{-2}eV^2$ to $10^{-4}eV^2$. If the parameters of the present proposal are successfully implemented, the expected rate of detected neutrinos will be around 10/day. This would allow to close the gap in a matter of a year’s running time. Background (reactor off) and systematic runs should take of order months. The detector may concurrently, as well as later on, observe neutrinos from other sources with much advantage over other techniques (presently in operation), as will be discussed later in this paper.

III. DISCUSSION OF THE UPGRADE TASK

The upgrade project may be summarized in a list of 3 items: 1. Create sensitivity to neutrons. 2. Lower the detector threshold to 5 Mev. 3. Reduce sources of potential backgrounds in this energy regime. Each of these tasks will be discussed in detail in this section.
A. Neutron Sensitivity

1. The choice of target nucleus

The best candidate for detection of neutrons is the gadolinium (Gd) nucleus. The first use of Gd additives as a detecting agent (particularly in liquid scintillators) dates back to early 1950’s (see for example Ref-7 for an early mention in the context of large detectors). Gd is a naturally occurring element comprised of (15.7%) Gd-157 and (14.7%) Gd-155 (among its other isotopes). The average thermal neutron capture cross section for natural Gd is 49Kb. The radiative capture reaction will release approximately 8MeV of energy in an average of 3.5 gamma rays with one quantum guaranteed to have at least 5.6Mev of energy. Cherenkoff light is then produced by electrons from the Compton scattering of these gamma rays. The feasibility of a similar process has been demonstrated by Kamiokande-II who used a Cf-252 source as a neutron emitter embedded in a block of Nickel as the capturer. Of the 9MeV of released gamma rays, they observed 7.8MeV deposited well above backgrounds, which also agreed well with their Monte-Carlo simulations. The actual case of Gd was simulated by researchers in Sudbury Neutrino Observatory (SNO). Their results show that nearly 60% of the Gd gamma rays would be detectable with a threshold of 4.5MeV at (40% of $4\pi$ steradian light-coverage). These studies suggest that as a rule, in this energy range, gamma rays convert some 85% of their energy into electron energy (Cherenkoff light). Based on SNO’s study, the efficiency of neutron detection is plotted as a function of detector threshold (or photocoverage), in fig-2. A threshold of approximately 5MeV at 44% photocoverage seems a reasonable goal. The above value for photocoverage is not unreasonable: Kamiokande-II already has a 20% photocoverage and a threshold of about 8MeV or less, but they are not fortunate enough to be near a nuclear power reactor (see also photocoverage below).

Further candidates (see table-1) for the neutron capture target may be natural Cd which yields slightly over 9MeV of gamma rays, but at 2.5Kb cross section, one would need 20 times more Cd nuclei to match the effect of Gd. Large concentration of additives might reduce the light transmission of the water. Another candidate is natural Sm which has an average cross section of 5.8Kb, and 8MeV of gamma rays, in return its fast neutron capture cross section might help with the timing of positron coincidence and thus increase signal to noise.
2. Containment of the Gd loaded water

Due to the need to continuously filter the water that is in contact with the electronics and cables, one may not allow the Gd loaded fiducial water to mix with the non-fiducial water. This necessitates the need for a transparent containment vessel or bag in which the water-Gd solution is contained, and is never routed to the reverse osmosis filters. These filters will very effectively extract the Gd-salt dissolved in the water. Fig-3 is a sketch of the proposed scheme: A cube of 13m (2.2Kton) on a side made of (1-2 cm thickness), transparent Teflon is suspended at the center of the detector. This bag (or vessel) will contain highly purified (of pollutants and radioactivity) water, loaded with a Gd-salt (and possibly wavelength shifters, discussed later). Note that the transparent bag needs only to contain the fiducial mass.

In case of a breakage, all is not lost. The water may be purified and the Gd is recovered, and the fiducial volume may be reconstructed. Alternatively, one can consider a solid, transparent vessel (e.g. of Acrylic) to contain the fiducial water. The vessel material can potentially cause, a large loss of light within it. For example, SNO’s 5cm thick Acrylic vessel is meant to securely contain the very expensive heavy water, but it is responsible for a 21% loss of light \[^4\]. Light loss can only be compensated by larger, costly photocathode area, or smaller detector volume (closer-in walls). Another consideration is the radiopurity of the bag or vessel material, This can become a major contributor in the case of acrylic\[^4\]. A thin Teflon layer however can be made at significantly lower levels of U and Th and contamination.
Teflon can also help to bring the fiducial mass (with the added weight of Gd-salt) to neutral buoyancy. It is, furthermore, a good choice due to its physical stability, and lack of chemical interaction with other material. However, careful studies of the growth of bacteria on the Teflon are of paramount import in the present design. The growth of such bacteria on glass and plastic media has been observed, and has proven quite a nuisance despite countermeasures in the water purification process. Light loss due to bacteria growth is a universal problem which all large water-based detectors such as SNO and Kamiokande must contend with. In our case, the presence of Gd salt(s), and possibly the complex molecules of wavelength shifters (if used) may significantly affect the growth rate of these parasites. The complete lack of fresh air flow in the sealed bag may prove a favorable factor.

3. Photocoverage

In order to lower the threshold of the detector, more light coverage is necessary. For a 5MeV threshold, this amounts to an effective 44% photocoverage. This may be achieved by simply increasing the area of the photocathode coverage. Alternatively, with a reasonable design for light-collecting reflectors, it seems feasible to lower the photocathode coverage requirement to below 35%. These figure are not unreasonable: we note that SNO and SuperKamioka proposals call for similar or even larger figures compared to 44%.

The PMT’s are mounted on a rigid outer shell, moved inward 2m from the walls to increase photocoverage, as well as to allow a buffer region to shield from low-energy radioactivity of the rock, salt, etc. of the walls. Another purpose of the 2m region is to install a small number of the PMT’s, facing out, to act as veto triggers. Another 1m is allowed in between the containment bag (fiducial volume) and the PMT structure, to shield against radioactivity from the glass in the PMT’s, other electronics, and objects on the mounting structure. The PMT’s will need to be magnetically shielded. However, a mu-metal grid for instance, can cut the light transmission by up to 10%\textsuperscript{3}. This spells out further need for added light collection by a reflector around the PMT’s.
4. **On Adding a Wavelength Shifter to Increase Light-yield**

Since the bulk of the cost of the proposed upgrade is expected to be that of the PMT price tag, further reduction in the required photocathode coverage is desirable. One method is suggested by noting that the Cherenkoff light spectrum has a significant component in the UV [5], a region that is not detected by ordinary photocathodes. Water soluble chemical additives, called wavelength shifters, exist whose molecules will absorb the higher energy photons and re-emit lower energy (visible) photons. While this process will increase the light collected from the Cherenkoff process, its shifted component will be isotropic and will not have the directionality of the Cherenkoff cone; this light may be used in a calorimetric mode only. Unfortunately, some (20%) of the visible (directional) light from the Cherenkoff process may also be absorbed and re-emitted thus resulting in dilution of the original directionality [6]. While this loss does not affect the energy-threshold, it will dilute the ability to reconstruct particle tracks. The latter becomes a concern, mainly in the search for proton-decay events.

A candidate for this task is beta-methylumbellapherone [5]. This liquid will shift light from the wavelength range of 250-350nm to 380-540nm, by absorbing light in the former range and re-emitting in the latter range. At a concentration of 50ppm, the average absorption length ($\alpha$) is 5cm for $\lambda \in [250,350]$nm ($\alpha > 20$ m for [400,700]nm). At this level, a factor of 1.74 in light-yield has been shown to be gained from the addition of the wavelength shifter [6]. Although the loss of directionality of light is an important concern, the use of a wavelength shifter could prove a major improvement in the effective photocoverage of the detector. Perhaps the development of a customized wavelength shifter may prove worthy of the investment to address the problem of loss of directional portion of the light for better track reconstruction. To summarize, a factor of 1.74 improvement in the light yield, will reduce the final photocathode coverage needed to 25% (and even lower with light collectors), while retaining an effective photocoverage of 44%.

5. **Detection of neutron-positron coincidence: Electronics**

The sequence of events following a neutrino interaction on a proton is as follows: first a positron (0-5.5MeV, median 1.5MeV) and a neutron are released. The positron will soon stop, giving a weak Cherenkoff signal below threshold. Given the 0.05% concentration of
Gd, by 100 microseconds later, the thermal neutron is radiatively captured. The gamma cascade will last about 100 nSec. The mean neutron capture time is 46 microseconds[7].

Although it is conceivable that the detection of the thermal neutron’s radiative capture will be sufficient to signify a neutrino event, a much cleaner signal would be the observation of the neutron-positron delayed coincidence. For the latter purpose, one would require an on-line (hardware) trigger on all neutron events, via the emission of nuclear gamma rays. Thereupon, the output of a system of high rate waveform digitizers, with a memory depth of approximately 100 microseconds, will be frozen for offline (software) acceptance, or veto of the subsequent neutron event. At the proposed levels of photocoverage, a neutrino event will be accepted if a 20-25 photoelectron event was preceded by a 6-7 photoelectron burst in its immediate past 100 microseconds. The accidental backgrounds for this event will be shown to be very small indeed in the following section.

A digitizing system (8 bit dynamic range) with quite similar characteristics as that needed here, has been demonstrated with a memory depth of 500 microseconds operating at 500 MHz in ref[8].

B. Background Considerations

1. Uncorrelated Background

Uncorrelated backgrounds are comprised of the accidental coincidences of relatively large singles rates. These are estimated and listed in table-2, assuming a 2.2Kton fiducial volume, and 5 MeV threshold. The sources labeled "internal" are due to radioactivity within the fiducial volume and hence mostly dependent on the purity of the water. The figures are scaled based on SNO’s careful computations at 0.02 ppt water (U and Th content), and at 40% photocoverage. In SNO’s actual case, this class of noise is some 10 times larger[4], simply due to the radioactivity in the acrylic containment vessel. A mass spectroscopic analysis of the Fairport water yielded the U+Th content of 20 ppt. Thus the fiducial water must be 1000 times purer than the Cleveland city water before it is sealed in the containment bag.
Table-2: Estimated rates of singles events in the proposed detector. Figures are based on 2.2Kton fiducial water and 5MeV threshold.

| Type       | Source                      | Reaction                                           | Rate     |
|------------|-----------------------------|----------------------------------------------------|----------|
| INTERNAL   | Water                       | Th+U at 0.02 ppt                                   | 10/day   |
| INTERNAL   | Water                       | Spontaneous fission                                | ≪ 1/day  |
| INTERNAL   | PMT’s                        | $(\alpha,p\gamma)$ at 30ppb U+Th                   | 10/day   |
| EXTERNAL   | Walls                       | Muon spallation on NaCl                            | 0.01/day |
| EXTERNAL   | Walls                       | $(\alpha,p\gamma)$ on Na at 30ppm U+Th             | 3/day    |
| EXTERNAL   | Walls                       | $(\alpha,p\gamma)$ on Al in concrete               | 5(x%Al)/day |
| EXTERNAL   | Walls                       | $(\alpha,n)$ and $(n,\gamma)$ on Na                | 0.03/day |
| COSMIC     | Muons                       | $\mu O^{16} \rightarrow \nu_{\mu} N^{16}$         | 30/day   |
| COSMIC     | Muons                       | muon decay                                         | 2000/day |
| COSMIC     | Muons                       | spallations                                        | 600/day  |

The ”external” class of backgrounds is referred to all sources of radioactivity which originate outside of the water. These sources are negligibly small, thanks to the large buffer regions allowed in between the fiducial volume and the walls.

Noise due to cosmic ray muons that interact directly with the fiducial volume are by far the largest source of uncorrelated background. These are primarily due to decay of muons inside the fiducial volume. Muons also cause break-up of nuclei present in the water. A small number of muons will convert O-16 into N-16 which will beta decay ($Q=10.4$ MeV) with a mean-life of 7-Seconds. Muons may decay inside the fiducial volume at a large rate. The released electron has an energy up to 100MeV. Muon induced spallations are rarer but more complex, as a variety of beta decay isotopes with $A < 16$ may be created; they have lifetimes ranging from 10-3 to 1 second, and $Q > 10$MeV.

Given the rates above and the coincidence window of a positron-neutron coincidence, the uncorrelated backgrounds pose little concern for the detector’s signal to noise. This is so, even without the constraint that the neutron and the positron events must appear within an approximately $8m^3$ volume due to finite travel time of the thermalized neutron.
2. Correlated Background

Of much greater concern, are correlated sources of noise: Non-neutrino events that mimic a positron-neutron coincidence signature. This is particularly problematic in the case of muon spallations: often a neutron is knocked free in addition to the creation of beta/neutron emitters (see table-3). As the result, the two ingredients of a genuine neutrino event are mimicked. The solution to this problem is the existence of the strong muon track that precedes the electron-neutron event. In addition, if not missed, the (one or more) freed spallation neutrons will precede the beta event, which will make the event even more distinguished as a spallation reaction.

| Isotope | Lifetime | $Q_\beta$ | Branching ratio |
|---------|----------|-----------|-----------------|
| Li$^9$  | 0.2 sec  | 13 MeV    | 35%             |
| Li$^{11}$ | 10 msec | 21 MeV    | 61%             |
| C$^{16}$ | 0.7 sec  | 4 MeV     | 100%            |

Table-3: Spallation isotopes that decay via prompt beta-neutron emission. The expected rate of these events are estimates around 35/day before rejection due to proximity to a strong muon track.

The detector’s larger photocoverage should further pay off here: the improved tracking of trajectories is needed to reject spallation events. The precise rate of these muon related events will also be measured during the reactor-off periods. In all, a high signal to noise ratio is in principle, achievable for detecting 10-15 reactor neutrinos per day.

IV. NON-REACTOR NEUTRINO PHYSICS

A host of new neutrino physics questions may be explored using the proposed low threshold water Cherenkov detector. Perhaps the most important is the case of the Boron-8 solar neutrinos. To date, the foremost electron-neutrino scattering experiment has been that of Kamiokande-II which has a threshold of around 8MeV. Fig-4 shows the energy spectrum of these neutrinos as transformed into recoil electrons. Clearly a threshold of 5MeV will vastly improve the observation of the Boron-8 neutrino flux. Based on extrapolations from
Kamiokande rates, the proposed detector will observe over 6 events per day of Boron-8 neutrinos, some 20 times larger than the present leader in this field, Kamiokande. For comparison, the proposed Super-Kamiokande detector will expect to see about 23 events per day.

Atmospheric neutrinos are another handle on possible oscillation phenomena. The observation of relative deficiency of muon neutrinos to electron neutrinos is fairly well established. Similarly to the case of the Boron-8 spectrum (fig-4), the upgraded Fairport detector with a low threshold, will improve observed rates over those achieved by Kamiokande-II. Moreover, there will be less difficulty with systematic errors in energy calibration, as it easily avoids very steep parts of the atmospheric neutrino energy spectra starting at just above 10MeV of electron recoil energy. With improved rates and less systematic effects, more precise comparisons of up-going vs. down-going neutrinos may be made, to search for terrestrial MSW effect.

If to occur during the life of the upgraded detector, supernovae neutrinos will yield unprecedented insight into mechanisms of stellar explosions. This is achieved because both of the expected neutrino and anti-neutrino bursts may be observed, and distinguished from one another. Neutrinos will be observed via electron scattering. The expected flux spectrum of each of these bursts are plotted in fig-5. Note that during the 1987A super-nova, Kamiokande (0.68Kton) had a threshold of about 8MeV and the Fairport (IMB-) detector (3.3Kton) had a threshold of about 20MeV. In addition, both could only observe the lower curve of neutrino-electron scattering. Whether or not there are two bursts of neutrinos, and how far apart they are in time, will confirm or refute entire classes of supernova theories.

Finally, search for supersymmetric proton decay could continue. In supersymmetric theories the proton may, for example, decay into a neutrino and a kaon, or a pion. Previously, The neutrino-kaon branch was searched for by looking for the muon decay of the kaon. Many new lower energy decays may be sought with a lower threshold detector. For example, one could consider the proposed recombination of nucleon-hole pairs as put forward in Ref. This mode may only be investigated with a detector threshold of order 5MeV or lower.

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efficiency, it does eliminate the loss of directionality. Combination of the plates with the liquid
wavelength shifter has been calculated to improve light yield by the factor 1.9 [op. cit.] com-
pared to 1.74 for the liquid alone. IMB also suggested placing the wavelength shifter liquid
and the PMT’s in individual enclosures at their respective sites. This way the shifting is done
just before the light hits the photocathode.

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FIGURE CAPTIONS

Fig-1. Exclusion limits for neutrino oscillation from experiments to date. The lower hollow region is the expected range of parameters for the MSW effect in Boron-8 solar neutrinos. The dashed curve outlines the goal of the upgraded Fairport detector.

Fig-2. Plot of neutron capture efficiency as a function of detector threshold, from ref. [4].

Fig-3. Schematic of the basic design proposed. The fiducial volume is defined by the transparent Teflon bag.

Fig-4. The recoil electron spectrum of solar Boron-8 spectrum. Kamiokande-II has a threshold around 8 MeV. Note the extent of improvement with a threshold at 5 MeV and with three times the fiducial volume.

Fig-5. The theoretical recoil electron spectrum of a supernova [10]. Both Kamiokande and Fairport/IMB were sensitive to the lower curve only, during the SN1987a. Fairport/IMB had a threshold of around 20 MeV.