The Neutrino Eye: A Megaton Low Energy Neutrino and Nucleon Decay Detector

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Abstract

Herein we describe a megaton scale neutrino detector with energy sensitivity reaching down to the solar neutrino scale. The technique suggested is for a detector of the AQUA-RICH style, employing ring imaging of the Cherenkov radiation from particle tracks in water. The device would be spherical of 125 meters diameter, having spherical mirrors on the inside surface of the outer shell. The mirrors focus ring images of track segments on an inner shell at roughly one half the radius.

We suggest that such an instrument, placed either underground or in the ocean, could follow up on the SuperK observations of oscillations in atmospheric neutrinos, advance about a factor of ten in nucleon decay search, monitor neutrino oscillations with a precision of about 4% each day, search for supernovae out to 2 Mpc, carry out various searches for exotica with unprecedented sensitivity, and conduct a watch for for neutrino correlates to sporadic phenomenon such as gamma ray bursts. The main thrust would be to detect actual muon neutrino appearance as well as disappearance, improving resolution on δm^2 and discriminating the oscillating partner.

0.1 Need for a Megaton Detector: Beyond SuperK

The sequence of large experiments (IMB, Kamioka, Super-Kamioka) employing the water Cherenkov technique have clearly demonstrated the efficacy of such multi-kiloton scale instruments in contrast to those which are extrapolations of instruments which have been employed at accelerator laboratories. The Cherenkov instruments have more nearly isotropic response and have costs that scale more with the surface area than volume. Of course one gives up the familiar ability to reconstruct track segments, as idealized in bubble chamber photographs. Still, a tremendous range of physics has been extracted from these, in some sense, crude but huge instruments. At the moment this is being written it seems that SuperK may be on the road to detecting neutrino oscillations in the atmospheric neutrinos and perhaps the solar neutrinos as well, landmark accomplishments despite the simplicity of the instrument.

One often hears the criticism that an instrument must be designed to do one thing well to the exclusion of trying to satisfy many constraints. Yet, despite the evident truth of that statement, the history of the water Cherenkov detectors demonstrates that sometimes an instrument can indeed be a "jack of many trades", serving well for many experiments. The best observations of atmospheric neutrinos and their oscillations, limits on nucleon decay lifetime, supernova observations (the only one being SN1987A), limits on high energy neutrino astronomy, searches for neutrinos from WIMPS and gamma ray bursts, and upon real time counting of solar neutrinos, are all from these devices. The reason is simply that the detection is very much the same for each phenomenon.

So, since SuperK is the leading edge in this line of exploration, and SuperK has been operating since April 1996 and we can now determine the limits of its potential, one is lead to ask: where next? There is clearly motivation to proceed, particularly for the search for nucleon decay and in cleaning up on the neutrino oscillations. The question is how? If we focus upon nucleon decay, part of the answer is clear: more effective mass is needed.

Twenty kilotons of matter (roughly the fiducial volume of SuperK) is about 1.2×10^{34} nucleons. One progresses in the lifetime limits linearly in time until encountering irremovable background, after which the scaling is with the square root of time. SuperK is close to that limit for the best detected modes (*eg.*, $e^+\pi^o$), and is already background limited for modes which are harder to discriminate from atmospheric neutrino interactions (*eg.*, νK). Thus, as the minimum price of entry one must first have more volume to push the nucleon decay lifetime limits.

A sensible goal seems to be another order of magnitude beyond that which SuperK is likely to achieve, thus aiming at proton decay sensitivity into the favored modes of up to 10^{35} years. Note that one wins either way with this approach: if SuperK finds hints at proton decay, then such a new instrument can explore decay modes; if nothing is found in SuperK, the new instrument either finds nucleon decay or pushes the limits out to values beginning to severely constrain grand unified theories.

However, at some point increased mass is not enough and it becomes important to achieve enhanced performance over the now standard water Cherenkov instrument (*eg.* SuperK), the type Tom Ypsilantis calls "proximity focusing", which simply collects photons as they strike the container walls, with no retention of arrival direction information. The wonderful phenomenon of ring imaging[1], see Figure 1, may provide that avenue. Given the geometry, an increase of a factor of 20 over the 50 kT gross tonnage of SuperK to a full megaton seems desirable. We shall use this number, though more careful study may move it up or down a bit.

One may ask if the ring imaging is the only means of increasing the resolving capability of a large Cherenkov detector. In the past I have proposed the use of imaging PMTs around a contained detector. The idea is to employ a lens system, such as with windows into the water tank and PMTs outside, so that parallel rays are focussed. If one thinks of utilizing mirrors instead of lenses, then one comes back to the RICH configuration herein. Still, I think one should explore alternative geometries, despite the evident beauty of the spherical symmetry and efficiency of the present plan.

0.2 How It Works

A parallel beam of light is focussed approximately by a spherical mirror, at a distance of a bit more than one half the radius of the mirror (actually 0.577 times the outer radius) onto a concentric spherical surface. Because of rotational symmetry around the axis of the track the image is a ring on the inner sphere. The optics details are not as simple as it first seems, but we shall not delve into the subtleties and particularly the treatment of aberrations here[2].

With such a concentric system one may measure the width of the Cherenkov ring, the diameter of the ring, the location of he center of the ring, the total light, and the time of arrival of the photons. If the optics are good enough then the width of the ring is controlled by the multiple scattering of the particle, which is inversely proportional to the particle's momentum. From the diameter of the ring one calculates the particle velocity. From the velocity and momentum one can obtain particle identification, in particular distinguishing protons, pions, kaons, electrons and muons up to ~ 5 GeV[2], which cannot be well done with proximity focussed detectors. From these and the other measured parameters one may reduce the observations to reconstructed track segments in space and time with measured rates of Cherenkov radiation.

However perhaps the most important improvement over proximity focussed detectors arises from the ability to untangle multiple tracks. As yet even SuperK has only been able to utilize single tracks and some cases of overlapping but well separated double rings in the reconstruction of π^o decays. In proximity focussed instruments, the light from several tracks overlap to a degree that ring counting is difficult and disentangling the contributions of the various tracks to time and amplitude becomes rapidly impossible with increasing numbers of rings. Note that the number of rings corresponds to the number of track segments, not the number of particles. Thus two rings may be two particles or one particle with a scatter. In a RICH detector one may more easily make the distinction, and as the

AQUA-RICH papers demonstrate, one may (in principle anyway) begin to make bubble chamber-like reconstructions of track segments strung together in real space reconstruction. For quantitative detail, see the AQUA-RICH papers[3, 4].

0.3 How to Build It

In the AQUA-RICH plan the detector would be placed in a mine tunnel or in a pit close to the earth's surface. The existing mine tunnels at the Gran Sasso lab (and anywhere else of which the author is aware) are not large enough for the size of detector proposed herein. The AQUA-RICH proposal strains to put an inherently spherical object into a rectangular container. Herein we take the position that one should follow the natural geometry of the AQUA-RICH technique and build a fully symmetric spherical detector.

In the same spirit as the AQUA-RICH, the concentric detection surface would have about 20% photocathode coverage, allowing most of the light to penetrate the shell and permitting imaging of tracks from within that shell. The photomultipliers (PMTs) would need to be of the newly developed hybrid photodetector (HPD) type[3] in order to achieve the spatial (about 100 pixels/HPD) and temporal (about 0.1 ns) resolution required.

Full ring images are formed only for a fraction of outgoing tracks in the outer volume and most tracks in the inner volume. Reconstruction can be carried out with partial rings. However, adding about 5% PMT coverage on the outer wall (roughly the fractional area coverage of IMB), between mirror segments, permits reconstruction of skewed tracks, those partially or not imaged. These latter PMTs do not need the pixilization nor fine timing of the focal shell, and can be similar to the twenty inch PMTs now employed in SuperK. At this level the number of 20 inch diameter PMTs would be 12,109 on the outer surface and 20,367 on the inner surface (as compared with about 13,000 PMTs total in SuperK). Since the cost of these PMTs, at about \$7K/HPD and \$3K/PMT, dominates the expected costs, study should be directed towards reducing the coverage fraction.

Reflections from the PMTs can be a serious problem in this hall of mirrors. It is worth study to determine if the employment of coatings such as MgF on the glass will mitigate that concern. Given the size of the detector, even with very clean water absorption lengths are at best only about 100 m, so photons will be absorbed before making many crossings.

The engineering of the structure depends upon the location, of which there seem to be two choices: deep mines or the ocean. This is one difference between this proposal and some versions of AQUA-RICH, wherein near surface deployment is considered, aiming the science at long baseline neutrinos in the GeV range, and perhaps upcoming atmospheric neutrinos as well. While one can probably achieve the rejections needed to accomplish those goals, the fact of being near the surface and exposed to tremendous rates of down-going cosmic rays (order of a million muons per second) means that low energies (solar neutrinos, supernovae neutrinos and such) are not going to be detectable, and also sensitive studies such as for nucleon decay will be out. As for the location studies for the previous instruments, it is desirable to have at least 2 Km water equivalent of overburden to get the cosmic ray shielding needed for having a manageable rate of muon induced nuclear excitations in order to distinguish solar neutrinos from background.

Deep mines are the simple choice, one with which we have much experience. However both cost and engineering limits may rule that option out. If we scale from the cost of about $30M for the 50,000 m^3 SuperK cavity, the cost is intimidating. Moreover, at the time of design of both IMB and SuperK these cavities were deemed the largest that were safe practice by the engineers. Nonetheless, progress has been made in intervening years on both fronts, so the whole issue is worth further investigation.

The more practical option appears to be to build a steel shell in the ocean, which would be buoyant when filled with fresh water. This is not the place to dwell upon preliminary plans, but suffice it to say that the size and structural requirements appear not to pose any special requirements. After all, there are million ton oil tankers, and there are oil platforms of much larger dimensions. Such a tank may be built, outfitted and filled in a harbor, and towed to the desired location and sunk to the desired depth, and recovered to near surface for service. Anchoring forces are not overwhelming. While such construction is not trivial, it is well within the state of the art.

This means that this detector can be located in the beam from an accelerator and have the distance varied, for example. Also for studying atmospheric neutrinos, the site can be made near the magnetic equator. And, if desired, the detector could be towed to locations permitting maximal occlusion of the solar neutrinos by the earth's core.

0.4 Science with a Sensitive Megaton Neutrino Detector

Basically, I think of this instrument as following directly in the heritage of the IMB, Kamioka and SuperK instruments, and thus to first order the science is the same, moved ahead by about an order of magnitude. This instrument will gain not only in size, but in resolution for some physics as well.

0.4.1 Cleaning up Atmospheric Neutrino Oscillations

At the time of writing the strongest physics motivation for setting out on this program comes from the definitive evidence for muon neutrino disappearance from the atmospheric neutrino interactions in SuperK. While SuperK makes a seemingly irrefutable claim for phenomena which involve neutrino mixing and mass, the exact details are not nailed down as yet. First, neutrino oscillations have not yet been demonstrated: that is the reappearance of muon neutrinos after initial disappearance. Secondly, the oscillation partner(s) of the muon neutrino have not been identified. While evidence seems to be leaning towards tau neutrinos, the case is far from closed. Moreover there are some oddities in the data that make this author wonder if there may be some complications in the physics, though that is a statement not justified by the statistics of the data.

Several long baseline neutrino detector efforts are being discussed (CERN-Gran Sasso) and underway (at KEK and Fermilab). As of now, none have great prospects for actually resolving oscillations, depending upon δm^2, nor are their prospects for unambiguously detecting taus very encouraging, to me anyway. If the solution to the puzzle involves sterile neutrinos, then the long baseline experiments are at best going to see muon neutrino disappearance, simply confirming SuperK (at a cost much greater than that for SuperK, I note).

This is where the present proposal may become the defining experiment. The atmospheric neutrinos provide a wonderful (free) source of neutrinos at a continuous range of distances from 10 to 10,000 km. The disadvantage over an accelerator source is that we have no *a priori* knowledge of the neutrino arrival direction and the beam is 1/3 electron neutrinos at the low end of the energy range. The lack of knowledge of initial neutrino direction will make it difficult to detect tau neutrinos in the cosmic rays with the proposed instrument, but tau detection is devilishly hard with any proposed detector, even those with a bubble chamber-like capability and an accelerator source. The problem is rate.

With an accelerator beam taus may be detectable via transverse momentum as many design studies have shown, and for that task this present proposal is well adopted by virtue of size and particle identification[4].

The unique capability of this proposed instrument, as the AQUA-RICH collaboration has shown, is for the resolution of few GeV atmospheric neutrino events, wherein the recoil proton can be observed and one see the entire final state. One thus measures the energy and direction of the incoming neutrino, permitting good resolution of L/E and thence evidencing oscillations in L/E over a wide range in δm^2, from near 10^{-2} down to a few times 10^{-4} eV^2. Note that the lack of resolution revealed in the studies for the 125kt AQUA-RICH in the δm^2 region above about 5×10^{-3} eV^2 is alleviated in the present proposal because of the spherical detector symmetry and the observations of neutrinos near the horizon at distances an order of magnitude less than in AQUA-RICH. Moreover the full 4π sr solid angle permits well controlled studies employing the natural symmetries in the situation, most particularly up/down above and below the horizon.

0.4.2 Proton Decay to 10^{35} Years

Detection of nucleon decay remains a holy grail for particle physics. Such observation probes physics near the Planck scale, and can be the key to grand unification. The physics is also intimately intertwined with baryogenesis at the time of the Big Bang. The line of detectors from IMB to SuperK has taken the lifetime from beyond the predictions of SU(5) now to $\simeq 2 \times 10^{33}$ years. The prospects are good for SuperK to push onwards to 10^{34} years in the well resolved modes such as $e^+\pi^o$, and to bring the more difficult SUSY favored modes such as νK^+ up to around 10^{33} years. The latter are already background limited, so progress can be made both in resolution and in mass (with square root dependence).

Unfortunately the theoretical predictions for nucleon decay are widely ranging, going from values that should already have been seen to lifetimes as high as 10^{36} years. Without definite direction from theory, we experimentalists can only push onwards scanning all modes as we are able. For the same reasons that this proposed instrument will be excellent for atmospheric neutrino oscillations, it represents a next logical step beyond SuperK in nucleon decay search.

0.4.3 Solar Neutrinos to 4% Every Day

The fractional area of photocathode coverage and number of pixels are dictated by the demands of the ring imaging resolution[2]. The total photocathode area coverage factor for SuperK is 40%, and it was 20% in Kamiokande. These detectors have achieved threshold for solar neutrino detection of 5.5 MeV and 6.5 MeV. IMB-III had 4% coverage, and achieved a threshold of around 10 MeV. Detailed simulations are needed, but I estimate that a sensitivity of 8 MeV may be achieved with the presently proposed level of photocathode coverage. Note that a proper calculation involves more than photocathode coverage, involving simulation of the full detector performance, expectations on background radon levels, external sources of radiation, and particularly detector depth. Water clarity will be very important for solar neutrinos: I estimate sensitivity at 5 PE/MeV, and thus 40 PE for an 8 MeV event, but with on average nearly one half absorbed in the water.

With some allowance for fiducial volume this detector may resolve 500 solar neutrino events per day, measuring the solar flux at a level of statistical accuracy of perhaps 4% each day, and 0.5% each month. Given present hints at solar neutrino oscillations in the vacuum oscillation regime this information would be excellent for resolving seasonal modulation (though it must be said that experiments such as Borexino and Kamland may have settled this issue by the time this proposal could be realized). Still, with an unrivaled rate of solar neutrino detection, this experiment can begin to probe for solar output drift and fluctuation with heretofore undreamed of sensitivity.

0.4.4 Supernovae Out to 2Mpc

The entire history of extra-solar neutrino astronomy consists of the the few second detection of SN1987A by Kamioka, IMB and Baksan. With detectors now on-line (SuperK, LVD, MACRO, and Baksan) and those soon on-line (SNO, KAMLAND, ICARUS and Borexino) we have rather good coverage of the Milky Way for supernovae. Recall that SN1987A was at 50kpc, outside our galaxy. The problem is that we do not well know the rate of (type II, gravitational stellar collapse) SN from our own galaxy, so blindly waiting is expensive and difficult to maintain.

Even being able to monitor our nearest neighbor spiral galaxy, Andromeda (M31) would only double the rate, and it is 600kpc away (and thus will give us less than 1SN187A). The number of detected SN neutrinos based upon SN1987A is about 1 event per 100 tons, times the $(distance/50kps)^2$, with a sensitivity comparable to Kamiokande. (Recall that the mean energy of the detected SN neutrinos is fortunately substantially larger than for solar neutrinos, being around 10 MeV.) Thus, for a 1 megaton detector the event number, N, versus range is roughly 5 $Mpc/\sqrt{N}$. This is a range getting close to the distance of the nearest "starburst" type galaxies ($\sim 3\ Mpc$), which may provide as many as one SN per year.

Of course, for a galactic supernova, with around 10^5 events detected, this instrument would provide a wonderful time profile of the supernova.

0.4.5 And More

As with IMB, Kamioka and SuperK, many other studies are possible with this instrument. Searches for exotica such as Rubakov monopoles, quark clusters, Q-balls, and such would be extended by roughly the area of the instrument, which in this case would be about a factor of 10 over what SuperK will achieve, and a factor of 100 over that which Kamiokande achieved.

The same factor applies to studies of muons emanating from the center of the earth or the sun, which might arise from WIMP annihilations.

This detector begins also to present a serious instrument for neutrino astronomy, though of course still small on the scale of the gigaton instrument long heralded as necessary for sure high energy neutrino astronomy. Still, with a megaton of sensitivity reaching down to a few MeV this instrument would wonderfully compliment the proposed and in-construction high energy neutrino telescopes (Baikal, AMANDA, NESTOR and ANTARES). These instruments are still in the same range of muon capture area ($\simeq 10^4\ m^2$) as the detector proposed herein, but their plans are all aimed towards $10^6\ m^2$ instruments, but with a threshold sensitivity above about 20 GeV to a few TeV.

Calculations have long indicated that galactic and extra-galactic objects are not likely to be seen in a megaton instrument, but it is energetically possible. For example, neutrinos from the sources which produce the enigmatic gamma ray bursts (GRBs) might be detectable under optimistic circumstances. If however, GRBs are due to inspiralling neutron stars at cosmological distances and having outputs similar to supernova neutrino production, detection would not be likely. Moreover, given the high energy gammas seen from these objects it is possible that higher energy neutrinos are present and in potentially detectable numbers (if the neutrino to gamma ray ratio is as high as 100).

Other neutrino astronomy attempts could prove fruitful, searching for point sources, diffuse neutrinos from the galactic plane and from the galactic center for example. Of course one cannot make such a list without including the unexpected. Any detector pushing the frontier out an order of magnitude or two such as this has the potential for discovery that we cannot yet envisage. This has been the history of such endeavors and there is no reason why it should not obtain here.

0.5 Prospects

In the foregoing note we have advocated an extension to the AQUA-RICH scheme for a neutrino oscillation experiment, evolving into a third generation water Cherenkov detector to succeed the Super-Kamiokande instrument now providing a cornucopia of physics. By making an instrument 20 times larger and with improved particle resolution one may advance in all the directions indicated above, and potentially making definitive contributions in the search for nucleon decay and cleaning up the neutrino oscillations picture. We estimate the cost of such a detector as being in the range of US$300M, a substantial sum but one consistent with large collider detectors, a cost to be expected for an extension to SuperK, and an expenditure not out of line compared to the funds being expended in long baseline searches. The bringing of this idea into realization will require much effort by many people and an international collaboration on a major scale. We hope that with this note such a discussion can begin.

Acknowledgments

This note and the technique described herein owes everything to Tom Ypsilantis. The author's only contribution is to take Tom's AQUA-RICH plan and expand upon it to a full spherical detector at the megaton scale, and amplify upon the multiplicity of physics topics which can be addressed. If there is any merit to this proposal credit certainly goes to Ypsilantis' collaborators and all those who developed the IMB and Kamioka detectors and the DUMAND group who inspired much of the water Cherenkov technology development.

Bibliography

[1] The ring imaging technique was first proposed by Arthur Roberts many years ago. I first learned of the ring imaging from Dick Davisson in about 1966. But it is Tom Ypsilantis and his colleagues who deserves the credit for bringing the technique to fruition and application as a major technique for particle identification in modern collider detectors (see references below).

[2] Letter of Intent for Long Baseline RICH, CERN-LAA/96-01, (1/1/1997); T. Ypsilantis, *et al.*, Nucl. Instr. and Meth. **A371**, 330 (1996); T. Ypsilantis, J. Seguinot and A. Zichichi, CERN-LAA/96-13, (6/1996).

[3] P. Antonioli, *et al.*, "AQUA-RICH: An Atmospheric and Long Baseline Neutrino Experiment", http://pclvd2.bo.infn.it/rich/aqr6.ps, 4/10/98.

[4] P. Antonioli, *et al.*, CERN/SPSC/98-37, SPSC/M624 (1998).

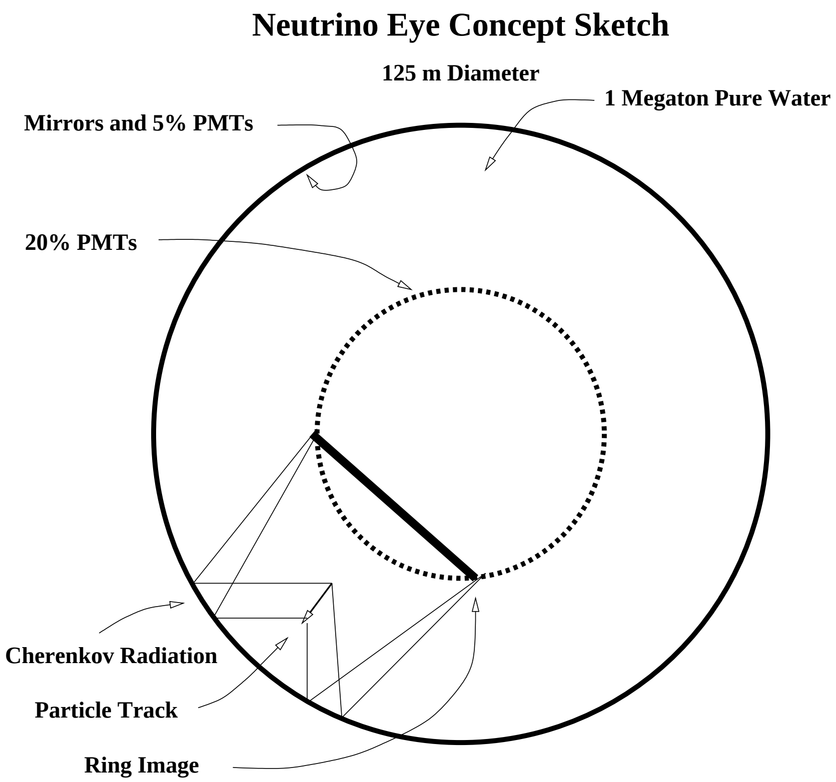

Figure 1: A sketch of the Neutrino Eye concept. One sees that the Cherenkov light from a radiating track is focussed onto a thin ring on a concentric sphere of about half the radius.