Megaton Modular Multi-Purpose Neutrino Detector

Alfred K. Mann
Department of Physics & Astronomy
University of Pennsylvania
Philadelphia, PA 19104

July 24, 2001

Abstract

This brief note outlines a detector for the Homestake Laboratory and the physics experiments that might be done with it. The note might go on record as a letter of intent to be converted to a formal proposal at a later time.
A major challenge to be faced in the construction of a multipurpose underground laboratory lies in the design of the rooms required by the most massive detectors, their sizes, implementation, configuration, and depth. Smaller rooms present other, usually less serious problems. Accordingly, it is useful to address the physics that demands massive detectors at an early time so that the issues and expense involved in constructing them are appropriately delineated in the overall description of the laboratory. That is the purpose of this note.

The characteristics of the Homestake Underground Laboratory, very deep laboratory chambers and very strong rock, open the possibility of a new generation of extremely large detectors that can explore hitherto unexamined domains of the Universe and of fundamental physics interactions. Among the recognized scientific goals of such a detector system are:

a. Search for proton decays one or more orders of magnitude in lifetime beyond the present experimental limits

b. Search for localized or diffuse astrophysical sources of ultra high energy (UHE) neutrinos.

c. Extend the investigation of neutrino flavor transitions of atmospheric neutrinos beyond the range explored by Superkamiokande by significantly more statistics.

d. Detect neutrino bursts from supernova and, especially, detect the neutrinos from the electron capture reaction at the formation of the protoneutron star.

e. Provide a potential target for future very intense terrestrial sources of neutrinos with emphasis on a search for CP invariance violation in the neutrino sector.

f. Permit additional high statistics investigations of solar neutrino emission, if that is still required.

The large water Cerenkov detectors at Lake Erie, Sudbury and Kamioka, (Kamiokande II and Superkamiokande) have beautifully demonstrated the capability of such detectors to study neutrino emission by the Sun, to investigate the time of flight dependence of neutrino flavor transitions, to search for baryon number violation via the decay of the proton and to observe neutrinos from supernova. The largest of these detectors, Superkamiokande (SK), has a total water volume of 50,000m$^3$ and is at a depth of approximately 2700 mwe.
We visualize an array of at least ten detectors for the Homestake Laboratory, each of 100 kilotons (50m × 50m × 50m in volume), with a total detector mass of the order of a megaton that can ultimately extend the range of proton decay lifetime searches by two orders of magnitude from the present value and simultaneously serve as a hodoscope for ultrahigh energy (UHE) neutrino detection. The array would provide a high statistics observation of the main neutrino emission from a supernova but one of the array filled with a low threshold material for neutrino interactions, e.g., \(^{37}\)Cl, would make possible observation of the \(\nu_e\) from \(e^- + p \rightarrow n + \nu_e\) at the formation of the protoneutron star. In addition, the array would serve as a target to provide high statistics observations of reactions produced by intense sources of neutrinos (e.g., neutrino factories) for searches for CP violation in the neutrino sector.

Locating the array at a depth of, say, 6000 mwe would result in a cosmic ray muon flux background per module that is more than two orders of magnitude less than that at the SK detector and a total muon background for the entire megaton array that is an order of magnitude lower than the background in the 50 kton SK detector. Considering the successes of SK and SNO (at 2700 and 6200 mwe, respectively) in coping with the cosmic ray background at their respective sites, the possibility exists that the water cerenkov detectors in the Homestake laboratory might be operated without any, or at least a minimal, loss of useful volume occupied by all-enclosing veto-counters as has been conventional since K-II. This idea might be tested by a “shotcrete” cover on the surface of the first large room, over which would be an adequate waterproof coat that would allow the room to be completely filled with water. The usual array of photomultiplier tubes (PMT) would be suspended as in the SK detector, saving money and labor, and permitting a megaton detector system to be achieved.

After half a century, the deeper questions addressed by elementary particle physicists—although broader and subtler—are no less difficult to answer, no less directed at fundamental issues than the questions they asked when the science began. One of the most basic, because its ramifications are so extensive, concerns the stability of the proton against spontaneous decay. Another fundamental question concerns the intrinsic nature of the neutrino, made even more interesting by the recent observation that neutrinos of different type possess small but different mass and are capable of making a transition from one type to another.

Apart from the profound physics that these questions have in common, they are also
related by the practical need to extend experimental methods beyond their present boundaries in order to address them. This means, on the one hand, extending the present lower limit on the proton lifetime beyond its approximate value of $10^{33}$ years and, on the other hand, searching for neutrino behavior in phenomena where new neutrino properties might be exhibited, for example, at neutrino energies far higher than any so far observed. Modern techniques indicate that a common detector method can be employed in both studies provided that the detector can be adequately shielded against extraneous phenomena, i.e., cosmic rays and their products. This has been achieved in the past two decades during which the lower limit above on the proton lifetime was acquired and the science of neutrino astrophysics successfully launched.

To go further means appreciably larger, more sophisticated detectors and—particularly important—significantly improved protection of them against cosmic rays. This latter can be attained by embedding the detectors deeper in the Earth than heretofore or deep under ice, say at the South Pole, or deep in the sea. A new underground laboratory with the features likely to be found in the Homestake Laboratory opens that possibility. And the array of detectors described above and shown schematically in Fig. 1 allows for all of the detectors to be used in an additive mode, i.e., as a megaton detector for most experiments, e.g., proton decay, and UHE neutrino searches, supernova observations, and CP violation search, while an individual member of the array is devoted to a different but related purpose, i.e., detection of the $\nu_e$ as well as the $\bar{\nu}_e$ from a supernova.

**Proton Decay**

As indicated above, the size of the cavity or room module for the detector that we suggest is about 100 kilotons of H$_2$O. We envision building and completing one module as soon as possible after formation of the underground laboratory with a cylindrical water-filled Cerenkov detector, equipped with photocathode coverage and fast sensitive electronics adequate to measure the energies of the charged products of possible products of proton decay. Roughly 20 percent of the total cylindrical area would be sufficient to allow a number of the decay modes to be seen; observation and study of neutrino interactions in the module would make clear necessary improvements in photocathode coverage and indicate the decay modes for which the module detection efficiency is especially low.

After the design of the first module and detector are fine-tuned, more completed mod-
ule/detector units will be added to the proton-decay complex at a rate limited by money and cavity excavation progress. A conservative estimate suggests that a complex of a dozen or so modules can be excavated and prepared to accept Cerenkov counters within a period of two to three years for approximately $150 million. They will be equipped for particle detection for approximately an equal amount, a number of them at the same time as excavation of the latter ones is proceeding. A possible configuration in which they might be arranged is shown in Fig. 1.

Building on the previous work on proton-decay of the earlier water Cerenkov detectors at Kamioka- Kamiokande, Kamiokande-II, Superkamiokande, and at the Fairport Salt Mine under Lake Erie, few new problems in analyzing the data from the Homestake complex should arise, and summing the output of the Homestake detectors should yield an ultimate lower limit on restricted decay modes of proton-decay about two orders of magnitude lower than the present SK limit ($10^{33}$ yr).

**UHE Neutrinos**

There are several serious predictions of the possible flux of UHE neutrinos from various astrophysical and cosmological remnant sources. The predictions cover a wide range of neutrino energies and fluxes from a few TeV for the known atmospheric neutrinos to roughly $10^9$ TeV for neutrinos suggested by speculations on topological defects; they are shown in Fig. 2 [1]. A clear positive result in the search for UHE neutrinos would open new unexplored areas in physics, astronomy and cosmology. The modular detector described above is well-suited for such a search. Roughly, we expect a large UHE muon-background-free region in the angular interval $70^0 < \theta < 120^0$, where $\theta$ is the zenith angle defined by the normal to the plane of the detectors in Fig.1. A UHE neutrino-induced muon signal, for example, will traverse between one and three modules depending on their spatial configuration, which will act as a sampling detector to determine muon direction and muon energy within an order of magnitude or better. We expect the detector in Fig. 1, depending on final dimensions, to subtend a solid angle relative to the solid angle subtended by the canonical km$^3$ detector often referred to in possible UHE neutrino searches of $0.01 < \Delta \Omega < 0.10$. That relative solid angle interval would be satisfactory for an initial survey in which the goal would be to observe a small number of events to show that UHE neutrinos exist. A positive signal from the proposed detector or any other would be impetus to expand the array in Fig. 1 further.
It is realistic to consider the prospect of observing low intensity fluxes such as shown in Fig. 2 because the reaction cross section for neutrino plus nucleon rises steeply with increasing neutrino energy for both neutrinos and antineutrinos. For example, the cross section rises by five decades as the neutrino energy increases by seven decades despite the production of real intermediate vector bosons. This is given in more detail in Fig. 3 [2].

An important consequence of the rapid increase of neutrino interaction cross sections is that the Earth becomes a significant absorber of neutrinos above roughly $10^4$ GeV and is essentially opaque to neutrinos with energy above $10^7$ GeV. The neutrino survival probability as a function of $\cos \theta_Z$ for those neutrino energies is plotted in Fig. 4; $\theta_Z$ is the zenith angle at the detector [3]. In obtaining the curves in Fig. 4, the Earth is modeled as a high density (15 gm/cm$^3$) core and a low density mantle, which accounts for the sharp break near large negative values of $\cos \theta_Z$ at the lower energies. This effect requires serious consideration in formulating plans for UHE neutrino searches, especially if the actual fluxes are much lower than suggested by Fig. 1.

A less dramatic, but nevertheless highly interesting, measurement that also becomes possible with the array and the increase of neutrino cross sections is the mapping of the density of the Earth’s interior as described briefly in Fig. 5 [4].

**Supernovae Neutrinos**

Since the first observations of neutrinos from the type II supernova, SN 1987A, the intent of neutrino astrophysicists is to be prepared to study the neutrino emission from a type II supernova in our own or a nearby galaxy if and when the occasion arises. One of the detectors in the array in Fig. 1 would provide a good statistical sample of such neutrinos for analysis; however, utilization of another member of the array for a different but correlated measurement might be particularly rewarding if the second module is properly equipped.

The current model of a type II supernova core collapse involves a step in which the protoneutron star is formed through complete dissociation of the components of the nuclei in the collapsed iron core followed by a newly freed proton capturing an electron; the reaction giving rise to a neutron and $\nu_e$. The resulting burst of $\nu_e$ was not observed during SN 1987A because it is expected to be short-lived ($\lesssim 1$ sec), and to carry only about ten percent of the total neutrino energy emitted by the supernova in the subsequent $\nu_e$, $\bar{\nu}_e$, etc. pairs. Measurement of the short $\nu_e$ pulse would mark the instant from which to measure all later
times of interest in the event.

However, in a water Cerenkov detector, the low energy of $\bar{\nu}_e$ from a supernova are much easier to detect than the $\nu_e$ because the two protons in the water molecule are essentially free to participate in the reaction $\bar{\nu}_e + p \rightarrow e^- + n$, while the neutrons which are required to satisfy separate lepton number and charge conservation in the particle reaction $\nu_e + n \rightarrow e^- + p$ are tightly bound in the oxygen nucleus and accordingly demand higher energy neutrinos to make the latter particle reaction go. The $\bar{\nu}_e$ from SN 1987A were in fact the ones detected.

If a second module contained chlorine in the form, say of NaCl, however, the reaction $\nu_e + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar}$ would occur in it with a neutrino energy threshold of 0.814 MeV; and electrons with kinetic energy above roughly 7 MeV from that reaction would be detected as would their emission times and energies. This is shown schematically in Figure 6. A comparison of the energy and time spectra of the $\nu_e^-$ and $\bar{\nu}_e^-$ induced electron spectra from the two reactions would describe the direct neutrino emission from the supernova completely with at least adequate statistical samples. Diversion of one of the 50 kiloton detectors for this purpose would not render it unuseful for the other experiments described here.

**Search for CP Violation in the Neutrino Sector**

Still another interesting use of the massive, multipurpose neutrino detectors is to search for CP violation in the neutrino sector with an intense, accelerator-produced neutrino beam. The principle involved in the search is a precision comparison of neutrino reactions in which the rates are required by CP invariance to be equal.

The neutrino detector array in the Homestake Laboratory is particularly well-suited to conduct a search for CP-invariance violation in the neutrino sector because of:

(a) its large mass to provide high reaction rates when combined with high neutrino fluxes

(b) its high sensitivity to charged leptons over a wide momentum range and its capability to measure accurately momentum and direction of the lepton

(c) with different fillings (as in the supernova measurement above), the array can distinguish between $\nu_x$ and $\bar{\nu}_x$ at low $\nu$ energy

(d) the distance at which the CP violating effect is likely to appear is large, i.e.
$\geq 3000$ km., so that an intense accelerator neutrino beam or neutrino factory beam can be aimed at the Homestake Laboratory and be effective.

**Summary and Conclusions**

This brief note outlines a portion of the physics experiments that might be carried out with the megaton modular multi-purpose neutrino detector array described herein. The physical properties of the Homestake Mine are especially favorable for the construction and operation of a laboratory to accommodate such a detector array which would be difficult or impossible to house in most other deep mines. These experiments are among the most penetrating to be done in the neutrino sector and their results will contribute to the resurgence of that sector in astro-particle physics.

**Acknowledgement**

This note is the product of many discussions with Ken Lande and information about Homestake obtained from him.

**References**

1. L. Nellen, K. Mannheim, P.L. Biermann, Phys. Rev. D 47 (1993) 5270; A.P. Szabo, R.J. Protheroe, Astropart. Phys. 2 (1994) 375; K. Mannheim, Astropart. Phys. 3 (1995) 295; D. Kazanas, in: Proc. Third NESTOR International Workshop, October 1993, L.K. Resvanis, ed. (Athens Univ. Press, 1994); F.W. Stecker, M.H. Salamon, Space Sci. Rev. 75 (1996) 341; E. Waxman, J. Bahcall, Phys. Rev. Lett. 78 (1997) 2292; Phys. Rev. D 59 (1999) 023002.

2. R. Gandhi, C. Quigg, M.H. Reno, I. Sarcevic, Astropart. Phys. 5 (1996) 81; G.C. Hill, Astropart. Phys. 6 (1997) 215.

3. Astropart Physics 10, 321 (1999).

4. Alfred K. Mann, Proc. Seventh Int’l Workshop on Neutrino Telescopes, Venice, 1996, ed. Milla Baldo Ceolin, p. 415.
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