4 Neutrino Detectors

Because of the low neutrino interaction probability (discussed above), neutrino detectors are seldom all-purpose detectors, like for example, an e^+e^- collider detector. Rather, depending on the physics goals of the experiment, the neutrino detector is designed to provide an optimum match to these goals.

In retrospect, looking at the past neutrino experiments, a natural classification emerges. The detectors for “standard” accelerator or reactor neutrino experiments can be divided into three general categories, depending on which specific feature they emphasize. These three categories are: calorimeters, tracking detectors, and Cherenkov detectors. This classification is somewhat arbitrary since experiments frequently use experimental apparatus that combines more than one of these features. Nevertheless, usually one specific aspect is emphasized.

In addition, there is a fourth category of neutrino detectors, quite distinct from the three groups mentioned above, i.e., radiochemical detectors, so far used only in the solar neutrino experiments. We proceed now to discuss each one of these groups in turn, describing their strong and weak points and giving some specific examples.

4.1 Calorimetric Detectors

These detectors emphasize measurement of the total energy of the final state products. They naturally divide themselves into sampling calorimeters and total absorption calorimeters. The other relevant distinction useful for sampling calorimeters is between high Z, magnetized calorimeters and (generally) low Z, nonmagnetic ones.

Total absorption calorimeters rely almost entirely on active medium as both the target for the neutrino interaction and as the detecting medium. Thus, the energy loss of final state particles can be measured without introducing uncertainties due to sampling fluctuations.

In contrast, the sampling calorimeters generally have a passive medium (iron or aluminum) interspersed with an active detector, e.g., scintillator or gas chambers. The advantage of this scheme is that a larger target mass can be obtained for the same cost with some compromise on the accuracy of the energy measurement due to potential sampling fluctuations. In general, sampling calorimeters are more appropriate for high energy experiments; total absorption calorimeters for low energy experiments, e.g., they frequently utilize neutrinos from a reactor or are used in a low energy beam-dump experiment.

The main advantage of the iron sampling calorimeters with magnetized iron is the ability to measure muon energy by curvature. Such devices (used in the CDHS and CCFR experiments) became the standard tool in the study of nucleon structure functions via neutrino deep inelastic scattering. Magnetized iron allowed one to measure the muon momentum by using tracking chambers with an accuracy ordinarily limited by Coulomb scattering. The interspersed active detectors allowed one to measure the total hadronic energy and, by measuring the energy flow, the direction of the hadronic jet.

More specialized experiments frequently required a different detector. Thus, for example, studies of ν-e scattering required a good measurement of the direction and energy of the electromagnetic shower. Low Z sampling calorimeters were generally found to be most appropriate for this purpose. Some examples of such devices are the sampling calorimeter with aluminum absorber and proportional chambers which were used at Fermilab to measure $\bar{\nu}_\mu e^-$ scattering[45] and CHARM[46] and CHARM2[47] calorimeters at CERN studying the same problem.

The total absorption calorimeters generally use liquid scintillator, either segmented or in a large tank, as the energy measuring medium. Typical recent examples would be the CHOOZ[48] or Palo Verde[49] reactor experiment detectors, or the KARMEN detector[50] looking for neutrinos from π^+ and μ^+ decays at the ISIS accelerator at RAL.

4.2 Tracking Detectors

Besides the energy measurement, another important goal of neutrino detectors is to measure tracks of individual particles. There are two general ways to attack this problem depending on the goals of the experiment. They are quite different in relative difficulty. In one approach, one tries to measure only muons (relatively easy); in another one tries to measure all individual tracks (much harder and generally requiring a significant penalty in total tonnage of the detector). In this section we shall discuss three broad categories of tracking detectors: electronic, bubble chambers, and emulsions.

(a) The first accelerator neutrino experiment[4] used what was basically a tracking detector, i.e., a massive aluminum optical spark chamber, capable of distinguishing clearly muons from electrons. Its schematic arrangement is shown in Fig. 16 and is remarkable for its simplicity.

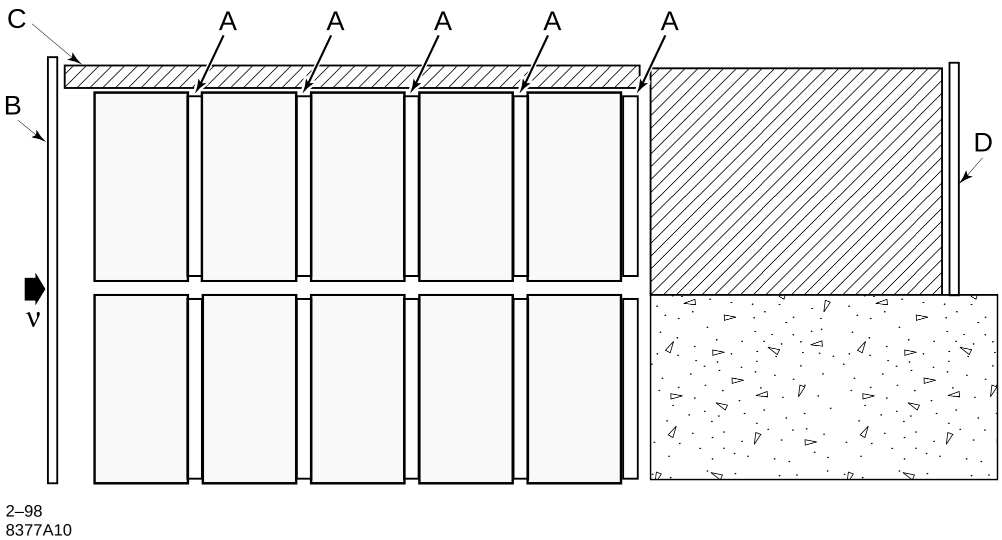

FIG. 16. Spark chamber and counter arrangement for the first neutrino accelerator experiment. A are the trigger counters. B, C, and D are the veto counters.

The subsequent evolution of neutrino detectors emphasized features typical of CCFR and CDHS detectors, i.e., a scintillator to measure hadronic components of the interaction and wire chambers to measure the muons. Thus, in some sense, these could be called hybrid detectors, combining calorimetry with tracking using two separate systems. A schematic of the CCFR detector is shown in Fig. 17.

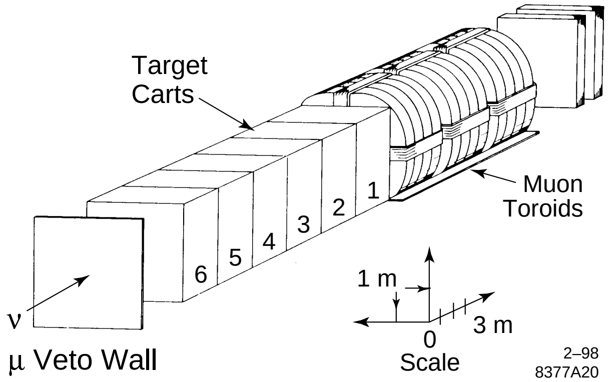

FIG. 17. The CCFR neutrino detector. Each of the six target modules contains layers of iron plates interspersed with scintillator and/or drift chamber planes. The muon spectrometer consists of three toroidal magnet units and a pair of drift chamber stations at the far downstream end.

More recently, more ambitious electronic tracking detectors have been built or are being planned. The NOMAD detector at CERN[51] uses a large number of thin low mass chambers in a magnetic field. These chambers serve both as a target and a detecting medium. Individual tracks in a hadronic shower can be seen and measured, as is shown in a "typical" NOMAD event shown in Fig. 18.

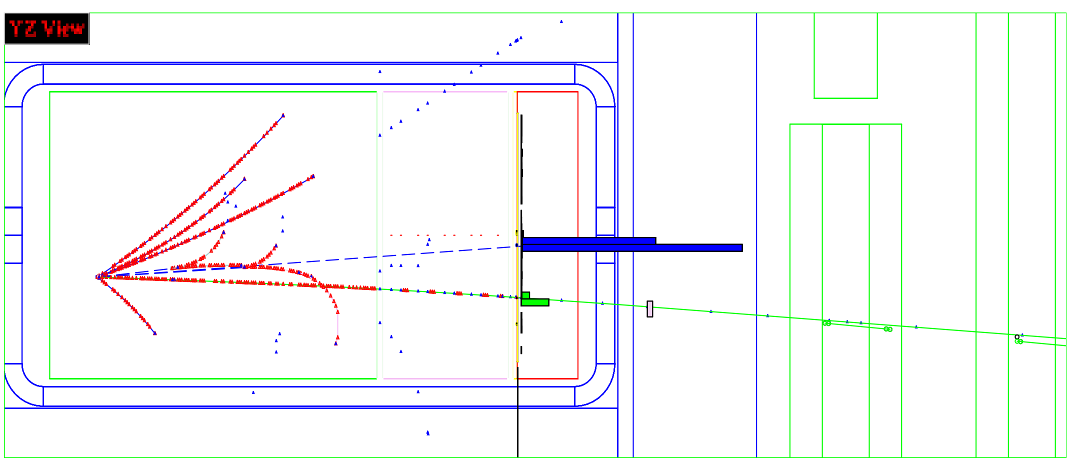

FIG. 18. A reconstructed CC candidate in the NOMAD detector. The longest track at the bottom is a muon matched to the segments in the muon chambers.

A very ambitious program centered in Italy has as its goal, construction of a massive liquid argon time-projection chamber (TPC), called ICARUS.[52] It uses the TPC principle to obtain the three coordinates and ionization associated with each space point. Prototypes up to three tons in size have been constructed and currently one full 600 ton module is being fabricated. The current plans call for several such modules to be constructed and installed in the Gran Sasso Laboratory. They could be used to search for proton decay, study solar neutrino interactions, and investigate potential long baseline oscillations if a beam from CERN to Gran Sasso is built.

(b) Bubble chambers played an important role in the development of neutrino physics. Their obvious strong point is the ability to see clearly and measure all the individual tracks. Hydrogen and deuterium exposures provided a clean simple target allowing one to study exclusive reactions as well as inclusive channels without the complexities of nuclear physics.[53] Their obvious shortcoming was the relatively low mass, difficulty of identifying muons and electrons, and very low efficiency for photon detection.

Some of the difficulties mentioned above could be alleviated by supplementing the chamber itself with high Z plates inside (to identify electrons and convert photons) and by surrounding the downstream end of the chamber with an external muon identifier (EMI).[54] A schematic of the Fermilab 15' bubble chamber with the EMI is shown in Fig. 19. Alternatively, these shortcomings could be overcome in cryogenic chambers by filling them with neon or neon-hydrogen mixture.[55] Large warm-temperature chambers filled with freon or other organic liquids were also built and played a very important role in neutrino physics.[56] The complexity of the target was compensated by higher mass, better particle identification, and high photon conversion efficiency.

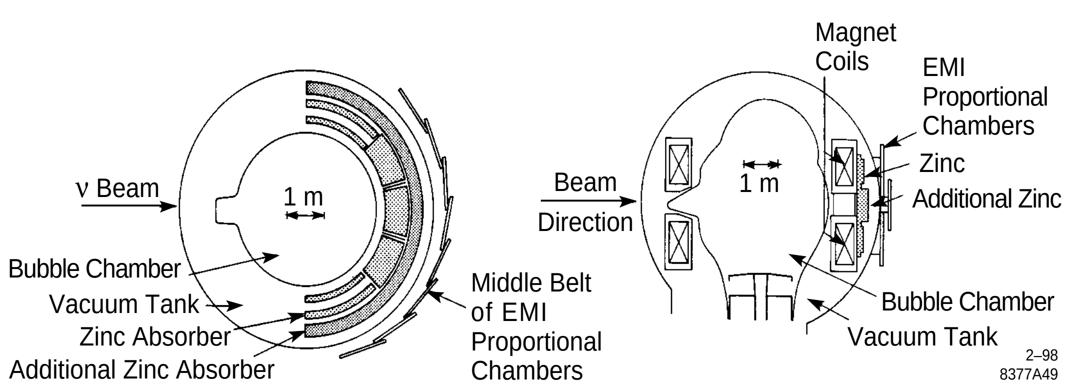

FIG. 19. Schematic of the 15' Fermilab bubble chamber with the external muon identifier.

In the waning days of the bubble chamber era there was a considerable effort made to improve the bubble chamber's spatial resolution so that one could identify charm and tau particles through their decay. Efforts of this kind led to an experiment at SLAC on charm photoproduction[57] and at Fermilab on charm production by neutrinos.[58] Even though the parallel effort, aimed at detections of ν_τ's in a beam-dump experiment,[59] never materialized, the R&D results were promising enough to lead one to believe that such a detection method of ν_τ's might be successful.

(c) In the last two decades or so we have seen a revival of the emulsion technique, again motivated by the discovery of short lived charm particles and tau leptons. This technique received a large boost by important developments in the scanning technology, which contributed to the ability to significantly increase the size of practical emulsion targets.

For τ leptons, $c\tau$ is about 89 μm. In the multi GeV energy range a typical γ will be about 5-10, resulting in the mean length of the τ track of the order of a mm or below. That number sets the scale both on the resolution and sampling frequency of the potential detection medium. So far, emulsion is the only known medium capable of such adequate resolution and thus, emulsions have been the cornerstone of detectors designed to see τ's via their decay kink.

Emulsion experiments for τ detection generally rely on electronic detectors downstream to localize the approximate volume in emulsion where the putative τ event might have occurred. This feature, combined with significant automation in the scanning technology, has resulted in a typical current processing capability of about 10^3 events/microscope/month. Further improvements are anticipated in the future.

Recently, there have also been new developments (and revival of older ideas) in how one could significantly increase the mass of the neutrino target in an emulsion-based detector, with only a very small loss in background rejection.[60] Traditionally, τ emulsion experiments used bulk emulsion so that the production and decay of the τ would occur in emulsion. Alternating thin heavy metal plates (Fe, Pb) with thin emulsion layers on a plastic sheet can increase the target mass by a factor of 100 or so for the same cost since it is the expense of emulsion that drives the total cost. The extreme form of this approach would be to look for finite impact parameter in a stack composed of a number of modules, each consisting of a metal plate followed by emulsion. Alternatively a cleaner but less efficient scheme would be to have a basic module composed of: metal plate, emulsion, air gap, emulsion. The detected τ's would ordinarily be produced in the metal plate and decay in the air gap. One emulsion on the upstream side of the air gap would measure the directions of the τ; the other one, the direction of the τ decay daughter. A significant difference between the two directions would be an indication of τ decay. Such a concept is the basis of the OPERA proposal discussed in Chapter 7.

4.3 Cherenkov Detectors

Neutrino detectors relying on detection of particles via Cherenkov light have filled an important niche in neutrino physics in recent years. In addition, they also promise to play an important role in the future. Their two most important positive characteristics are that some directional information can be obtained from the Cherenkov cone and the target/detector medium can be quite cheap e.g., water, and thus large masses are feasible. Again, in an effort to provide a systematic discussion, we choose to define four categories of Cherenkov detectors: nonfocusing, focusing, hybrid (Cherenkov/calorimeter), and large volume detectors (no man-made containers).

(a) Nonfocusing Water Cherenkov counters have played a prominent role in recent neutrino physics, in the study of solar neutrino physics,[61] atmospheric neutrinos,[62] and detection of supernova neutrinos.[63] They were developed originally to provide a medium which would be simultaneously a detector and a source for experiments looking for proton decay.

The design that these detectors have evolved into is basically a large container (e.g., an underground cavern) filled with ultrapure water and having all of its inside surfaces covered with photomultipliers facing inwards. The latest, and most ambitious of these detectors is Super-Kamiokande:[64] a cylindrical underground cavern of 45 m height and 50 m diameter filled with H_2O (Fig. 20). The walls and top and bottom surfaces are covered with 11,200 20" photomultiplier tubes, providing a 50% coverage of the total area.

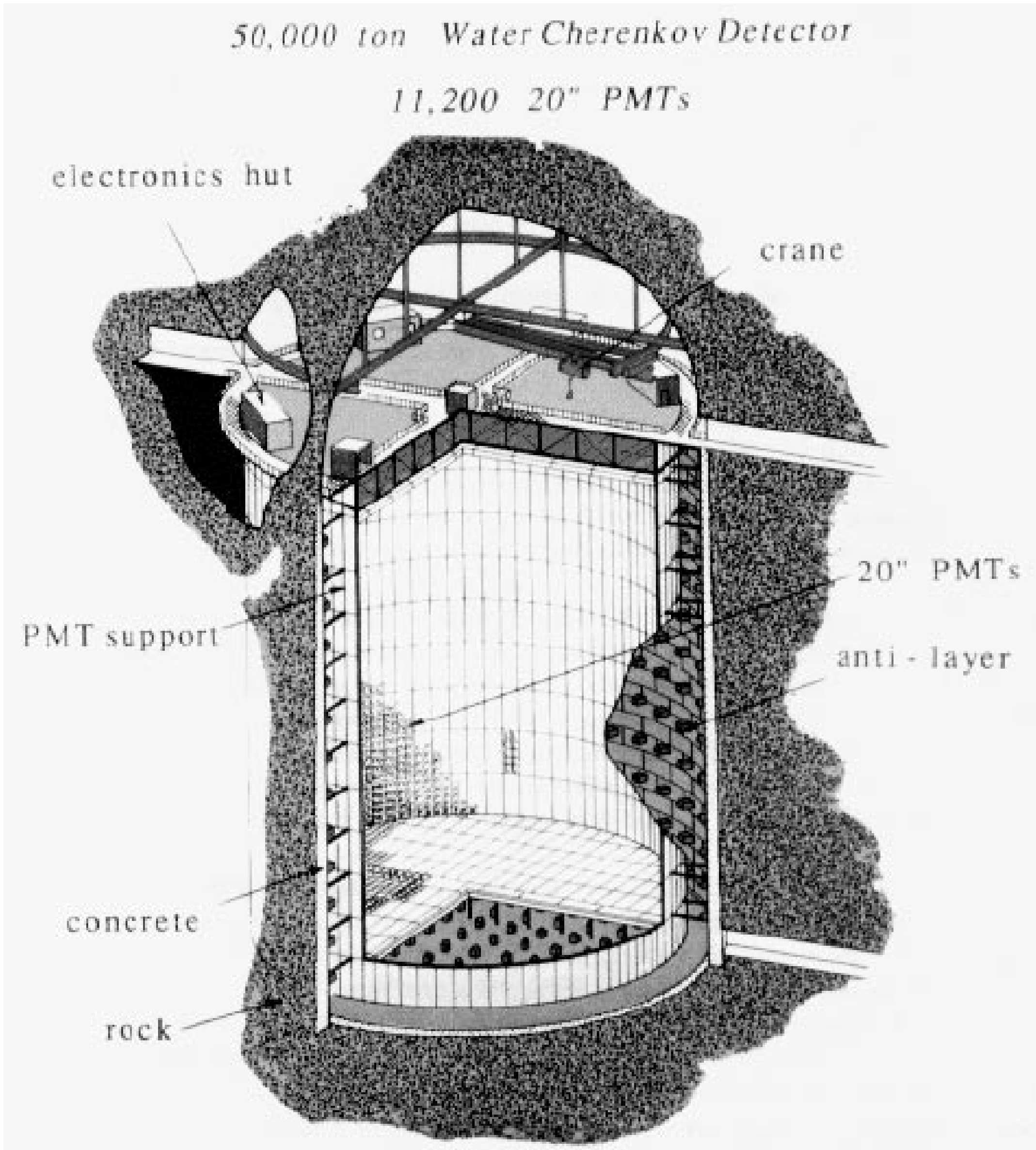

FIG. 20. Super-Kamiokande detector.

This system is nonfocusing, i.e., the Cherenkov light travels in a straight line from the point of origin to the photodetector on the wall. Because of the large detector size, the purity of the water is very important; an attenuation length of around 100 m has been achieved in the Super-Kamiokande. The purifying system must be running continuously so as to prevent growth of bio-organisms.

One can distinguish the electrons from muons by the sharpness of their Cherenkov light pattern in the photodetectors. Muons of low to medium energies will travel for a certain distance and then stop. Thus, the width of the illuminated part of the Cherenkov cone radius will be proportional to their range and its edges will be quite sharp. On the other hand, electrons will shower and thus generate a number of Cherenkov ring sources which will tend to have a variety of somewhat different directions. Thus, the resulting pattern in the photodetector will tend to be more filled in the center of the ring and more “fuzzy” on the outside. In the range of a few hundred MeV to 1 GeV separation between μ's and e's better than 100:1 is achievable as has been verified by exposing a water Cherenkov detector to muon and electron beams of well-defined energies at KEK.[65] This is illustrated in Fig. 21, which shows μ/e separation at different energies obtained by applying the Kamiokande algorithm to calculate the relative probability of an event having an electron or a muon. A typical Super-K event is shown in Fig. 22.

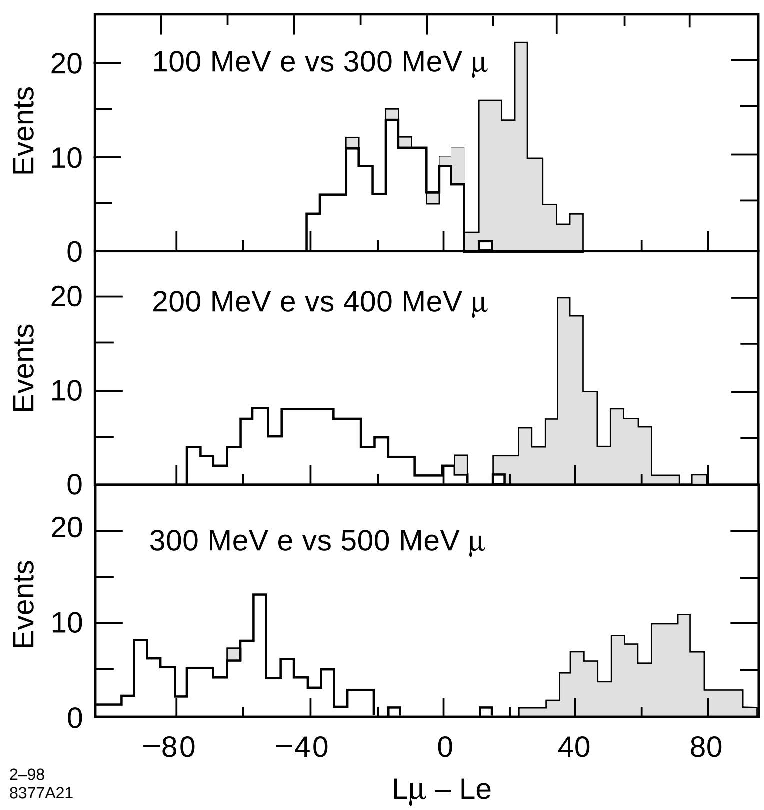

FIG. 21. The experimentally measured difference of the logs of likelihood. Shaded histogram represents muons; open histogram electrons.

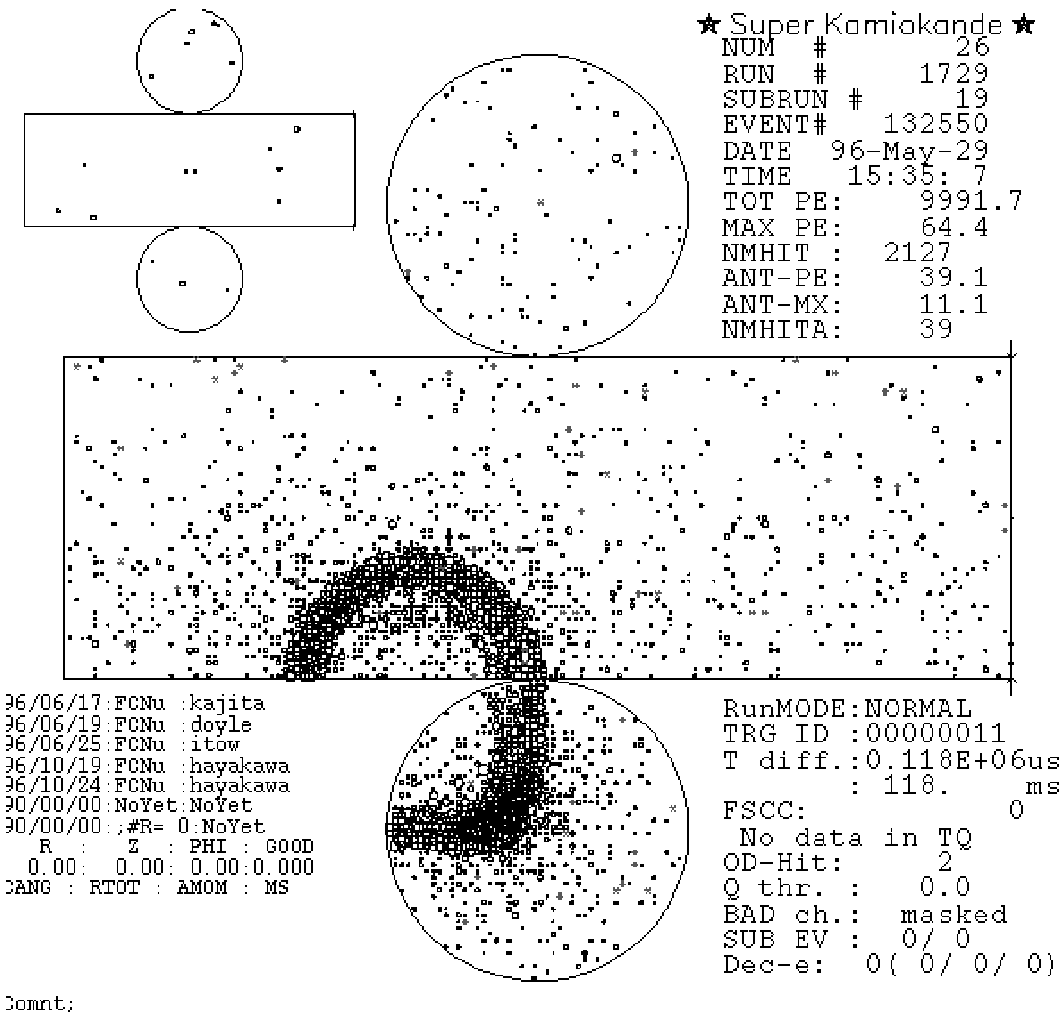

FIG. 22. Pattern of the hit photomultipliers in a typical Super-Kamiokande event.

(b) In principle, at least, the performance of a water Cherenkov detector could be enhanced by providing a focusing system, i.e., a focusing mirror which would provide sharp Cherenkov rings for a particle traveling continuously in the same direction. Such a system has never been executed before on a large scale, but is the basis of the RICH proposal for a Gran Sasso long baseline experiment utilizing a CERN neutrino beam.[66] A possible layout of such an experiment is shown in Fig. 23.

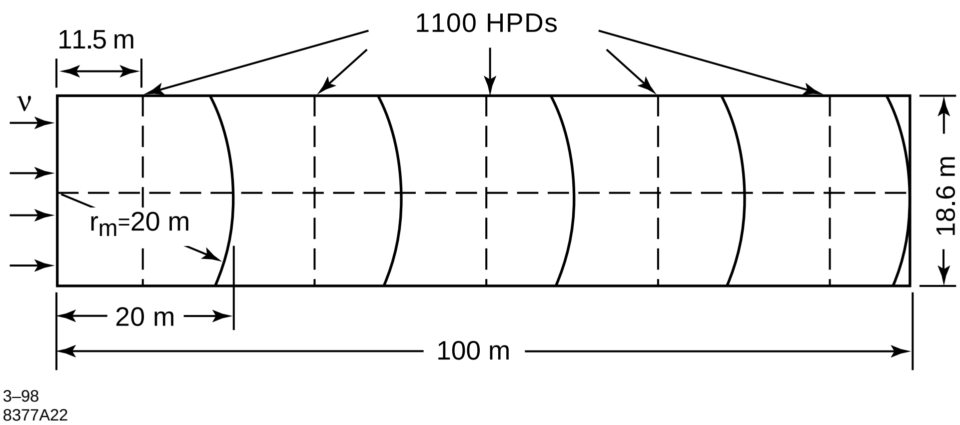

FIG. 23. Proposed layout of the 27 kt water target and radiator in the Gran Sasso tunnel. The system is composed of five equivalent sections of 20 m length, each with a reflecting mirror at the end and an array of hybrid photodetectors (HPD) 11.5 m downstream from the mirror center of curvature. 20% coverage of the area with HPD's is proposed.

(c) In certain applications, combining Cherenkov light with scintillator light might be productive. Cherenkov light is fast, and thus strongly correlated in time with the passage of a particle, and it retains the information at some level of the directionality of the particle which produced it. On the other hand, its intensity is about two orders of magnitude lower than the scintillation light from a good scintillating medium. By combining the two in a hybrid detector, the advantages of Cherenkov light could be retained and its deficiencies alleviated.

The LSND detector is a good example of such a hybrid detector.[13] The target and detector medium is mineral oil with a small amount of a scintillator additive. Thus, charged particles will give a sufficient amount of scintillator light so that their energy can be measured via calorimetry; simultaneously some time, direction, and position information is retained from the Cherenkov light.

Another kind of a proposed hybrid Cherenkov detector is the SNO neutrino detector.[67] Water (normal or heavy), is used as the medium to generate Cherenkov light from the produced positrons or electrons. But in addition, one wants to detect the neutron from the breakup of a deuteron. The SNO design aims to achieve this by providing supplementary neutron counters.

(d) Large Volume Cherenkov Counters. One can speculate how far the Cherenkov technique can be pushed. Since water (liquid or solid) is in a certain sense free, large detector arrays could be constructed in water or ice, where the main cost would be the cost of photodetectors. Such a scheme is attractive for detection of very high energy neutrinos from extragalactic sources. Because fluxes are low, large target mass is required. However, because energies to be investigated are very high, the sampling frequency, inversely proportional to the spacing between the detector elements, does not need to be very large to be able to reconstruct the muons from such high energy neutrino interactions.

The original idea for such a detector was the DUMAND underwater array in the Pacific Ocean near the Hawaiian Islands.[68] Some success in testing prototypes for this experiment has been obtained but the program has been plagued by a number of technical difficulties and a shortage of funds.

More recently, this general concept has been extended to a photomultiplier array in the ice, at the South Pole, called AMANDA.[42] The proposed AMANDA scheme is sketched in Fig. 24. The initial difficulties, associated with trapped air bubbles which caused dispersion, have been overcome by going to greater depths. The AMANDA project is proceeding and results from the deep arrays are expected to be available in the near future.

Water arrays have not been completely abandoned even though it is unlikely that DUMAND will materialize. Photomultipliers on strings have been installed and used in Lake Baikal,[69] and tower photomultiplier arrays are about to be installed in the Mediterranean off the Greek coast in the NESTOR project.[43]

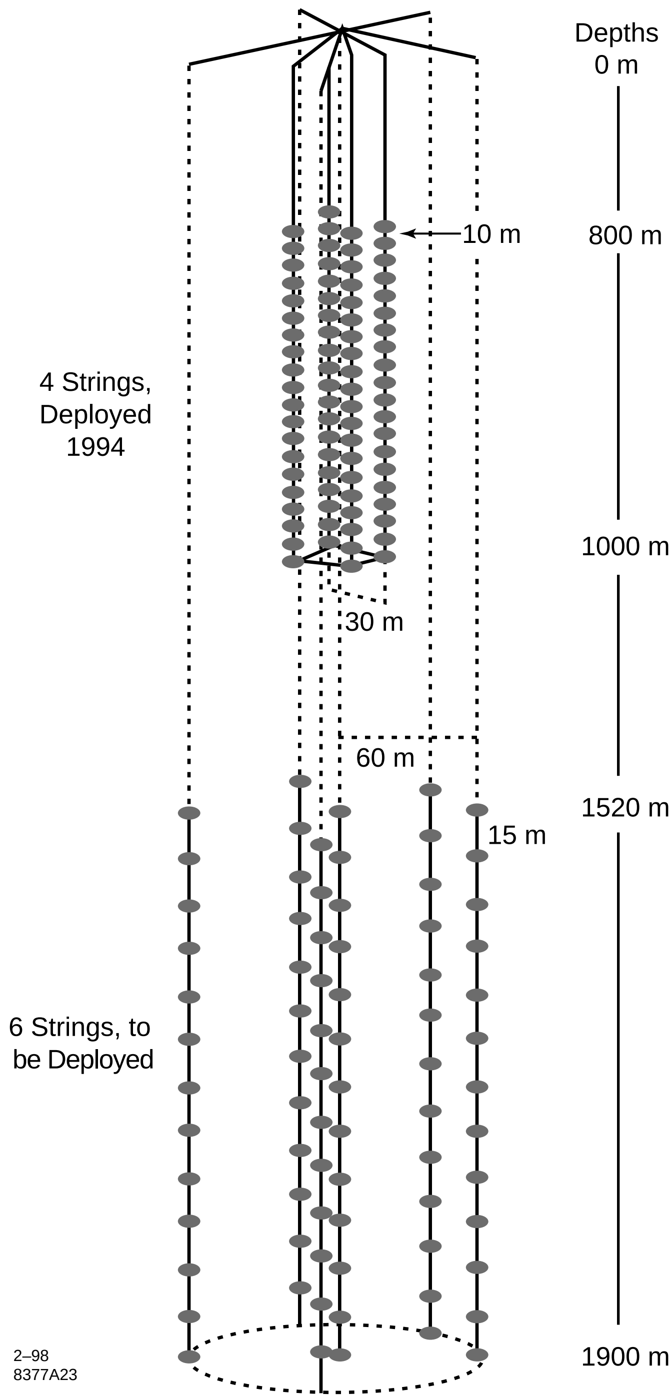

FIG. 24. Sketch of the AMANDA array located in the ice at the South Pole.

4.4 Radiochemical Detectors

These detectors incorporate the original ideas of Alvarez[70] and Pontecorvo[71] as to how one might be able to detect solar neutrinos. So far, they have been used solely for this purpose and possible applications elsewhere seem unlikely. The essence of the idea is to create (and subsequently identify) new atoms which would be produced via neutrino interactions. This is truly a heroic enterprise because typically, e.g., in the GALLEX experiment,[72] one makes 1 Ge atom per day in a tank of 30 tons of Gallium. Thus the challenge is to detect 1 atom of interest in the presence of 2.5 x 10^{29} other (uninteresting) atoms.

The neutrino channels that have been investigated so far are: in the Homestake[73] mine experiment:

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^- ,$$

and in the GALLEX[72] and SAGE[74] experiments:

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^- .$$

The former one has a neutrino energy threshold of 814 keV; the later of 233 keV.

The experimental technique relies on bubbling out the created atoms (in molecular or atomic gas form) by flushing the experimental tank with gas. An important feature of the technique is the fact that the produced nuclei are unstable but have relatively long (but not too long) lifetime (50.5 day half-life for ^{37}Ar, 11.4 days for ^{71}Ge). Thus after an extraction, whose frequency is determined by the lifetime of the produced unstable daughter atoms, one can count the decays of these atoms in low-background proportional counters.

Another channel that might be interesting and is actively being pursued[75] in the Homestake mine experiment is:

$$\nu_e + {}^{127}\mathrm{I} \rightarrow {}^{127}\mathrm{Xe} + e^- ,$$

with a threshold of 633 keV and ^{127}Xe half-life of 36 days.