DUMAND

A New Window on the Universe

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For the DUMAND Collaboration*

The Deep Underwater Muon and Neutrino Detector (DUMAND) is a completely new concept, based on the detection of Čherenkov radiation produced by relativistic muons particles as they move through a dielectric medium (the ocean water) faster than the phase velocity of light in the medium. In enabling the construction of a detector system of a size capable of identifying sources of high-energy neutrinos with a reasonable hope of success, DUMAND opens the era of high-energy neutrino astronomy. It employs the ocean's water mass as a multi-purpose medium: as a shield against the unwanted cosmic-ray background, as a well-behaved absorber for particles and radiation, as a target for muon and neutrino interactions, as a Čherenkov radiator for charged particles, and as a dark room to prevent light from interfering with faint Čherenkov radiation.

Comparatively small optical sensor modules constitute the detectors. They are distributed in the form of a three-dimensional matrix array throughout a well-defined volume at great depth in the ocean and separated by a distance of the same order as the attenuation length of light in ocean water (Fig. 1). The system is capable of detecting high-energy muon-neutrinos and their antiparticles of terrestrial and extraterrestrial origin that interact within the detector matrix or its immediate vicinity, producing detectable and reconstructable muon trajectories in the array. Very high-energy cosmic ray muons originating from even more energetic interactions of the primary cosmic radiation in the atmosphere are also monitored.

Distinction between cosmic-ray muons and neutrino induced muons is achieved by excluding from the neutrino analysis dowward-going muons within a zenith angle range between 0° and 70°. Discrimination against atmospheric neutrinos is achieved by statistical analysis and angular correlation of arrival direction in conjunction with energy cuts. DUMAND also has the capability to detect electron-neutrinos and antineutrinos, but this option will not be discussed.

The DUMAND detector system is, in principle, freely expandable and allows the construction of a truly giant experiment. Unlike typical underground experiments, it is not confined to the size of an underground cavity and the interpretation of data will not be troubled by uncertainties in the density of the surrounding rock or in the complexity of the surface topography. The very large background rate found in detectors placed in shallow lakes will also not be a problem.

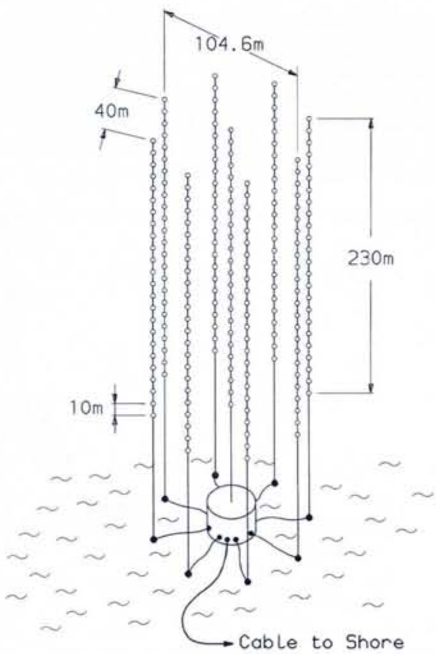

Fig. 1— DUMAND II array layout, showing the 216 optical modules arranged in strings moored on the ocean floor some 4500 m deep. Systems for control, data handing, auxiliaries, and support are not shown.

Prototype Experiment

The main concern with this novel concept is that completely new technologies have had to be developed; they must then be deployed in an unusual environment. A large amount of exploratory and pioneering work therefore had to be carried out during the early phases of the DUMAND project.

One of the foremost technical problems, of course, was the development of a suitable detector module which met the many stringent requirements, keeping in mind the ever-present high pressure of the surrounding water masses. Major problems demanding great effort, ingenuity and much time were tackled during optimisation of the overall response of the detector matrix, of its sensitivity, efficiency and track reconstruction capability. Questions related to the optical background, high-speed long-distance data transmission, system deployment and installation in the ocean, and continuous high-precision sonar tracking of the location of each module had to be solved.

This work, together with extensive theoretical studies and the construction and successful operation of a prototype system, DUMAND I, lead to the present scope of scientific activities and to today's system configuration for the DUMAND II detector.

Site and Environmental Aspects

The site where the detector matrix will be installed as well as the 25 km cable route to the site have been carefully surveyed. Composition and topography of the sea floor are well-known along with significant ocean parameters around a depth of 4500 m such as ocean currents (≤ 50 mm/s), water temperature (≈ + 4.0°C), the optical attenuation length in the visible (≈ 40 m), salinity, *etc.*

The optical background in the ocean has been investigated [1]. It is chiefly due to background light from seawater radioactivity (specifically, Čherenkov radiation from the beta decay of ^{40}K) and to bioluminescence. The former can be eliminated by noting local coincidences between neighbouring modules. High levels of light were observed during ship-tethered measurements owing to wave motion inducing local turbulence causing bacteria to release light flashes. This stimulated bioluminescence whenever excessive turbulence is present is not expected to be a major problem for DUMAND modules that are moored from the ocean floor, because ocean currents at the site are weak. Sedimentation and biofouling have been studied and were found to be of no concern. Lost equipment that we have recovered some one and a half years after immersion at a depth of nearly 5000 m showed no signs of growth on its surface.

Prototype System and Experiment

To deliver the ultimate proof of the feasibility and practicability of the DUMAND concept, and to test the reliability of our technology, a one-dimensional prototype, called the Short Prototype String (SPS), was constructed and deployed for an experiment carried out in the Pacific Ocean about 30 km west of the island of Hawaii in November 1987 [2]. The roughly 70 m long SPS string consisted of seven optical modules, two calibration modules, an extensive environmental data recording system, wide-band hydrophones, and a sonar system.

The primary purpose of this experiment was to demonstrate that muons could be detected in the deep ocean and their trajectories reconstructed. Because of the limited

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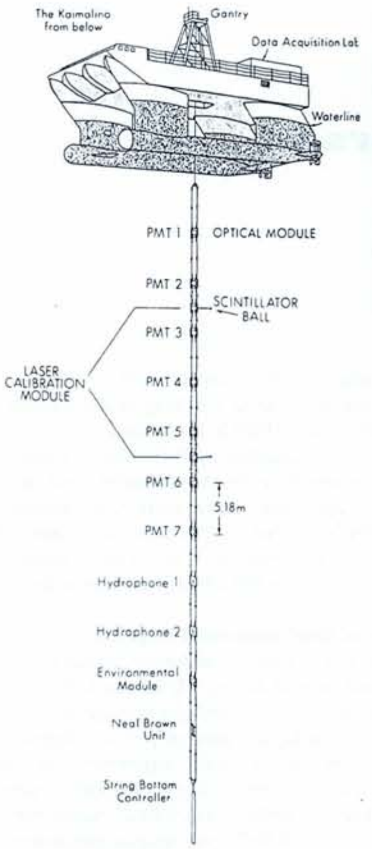


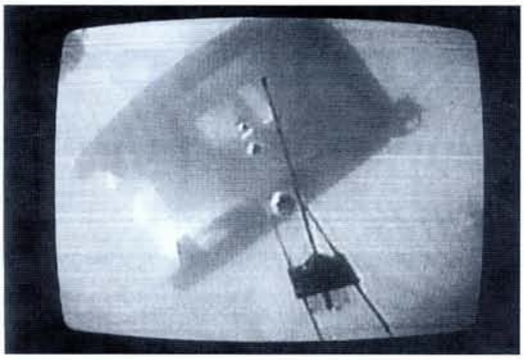


Fig. 2 — a, left) schematic view of the Short Prototype String used for the first phase of DUMAND: b, upper) diver's view from a depth of 30 m of the top portion of the string during deployment to a depth of over 4000 m from the US Navy's SSP Kaimalino, a highly stable ship. The dark unit in the foreground with the protruding rod is an optical calibration module.

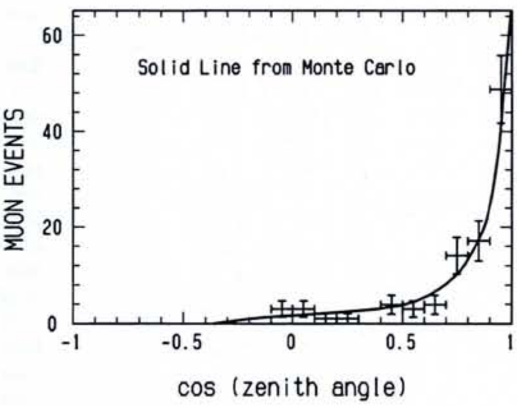


Fig. 3 — Zenith angular distribution of muons at a depth on 4000 m in the ocean, measured with the DUMAND Short Prototype String.

size of the SPS (Fig. 2) and the very short time that was available for the experiment (11 days), the test was performed using high-energy muons produced by interactions of cosmic rays with the earth's atmosphere that penetrate deep into the ocean. The final DUMAND II array will in fact be used to detect the much rarer muons induced by the interactions of high-energy neutrinos with the surrounding ocean water.

The prototype system was deployed from a highly stable ship (it had a twin-hull design with a small wetted area) and was kept suspended for the duration of the experiment using a cable with an adjustable tension to further reduce turbulence. A combined electro-optical cable supported the full load, delivered power to the SPS, and carried the data stream to the control room aboard the ship. The intensity of cosmic-ray muons was measured at different depths using coincidence requirements within a well-defined time window. This involved fitting an individual trajectory to each downward-going muon event, employing both the arrival time of the conical wavefront of Čherenkov light at each detector module and the light intensity for the reconstruction. Controllable light emitting calibration modules were used to calibrate timing and sensitivity of the detector modules and to measure the attenuation length of light in the ocean.

The observed angular distribution of the muons (Fig. 3) agreed with the results of a Monte Carlo simulation. The simulation also gave the effective detection area for muons as a function of the zenith angles. Multiplying the events rates by the area gave the total muon intensity as a function of depth. Vertical intensities obtained by multiplying by a correction factor agreed with previous estimates from underground experiments.

DUMAND II

After the successful completion of the prototype experiment, which delivered unconditional proof of the practicability of the DUMAND principle and of the capability and dependability of the technology we have developed through the years, the DUMAND collaboration has designed an intermediate-size detector, DUMAND II [3] which is now under construction, as a next step towards a truly giant, deep ocean detector. The project is funded by the US Department of Energy, the Swiss National Science Foundation and Japanese agencies.

The array (Fig. 1) will be moored from the ocean floor. The site is about 25 km west of Keahole Point on the Island of Hawaii at a depth of 4500 m — the same location as the SPS trial. The array will consist of a total of 216 optical modules (Fig. 4) similar to those used in the SPS trial, mounted on vertical strings each with 24 modules, located at the corners of an equilateral octagon, with the ninth string at the centre. The strings will be equipped with auxiliary and support systems similar in principle to those employed for the SPS, and a very high precision sonar.

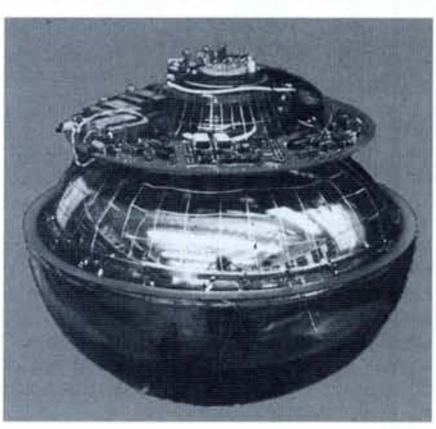
Capabilities

The size and configuration of the array were chosen to yield a reasonably even rate and adequate sensitivity to detect *neutrinos* from extraterrestrial high-energy neutrino sources at their expected flux levels. Moreover, the array has been optimised for the detection of high-energy *muons* from neutrino interactions because calculations indicate that this is the best compromise for detecting the same sources. Finally, the system can has also detect contained neutrino-induced *cascades*. In order to carry out useful astronomy, a high angular resolution (typically < 1°) is required. Čherenkov light from through-going particles will illuminate on average a photomultipler in each of 13 modules so the detector spacings ensure that muons with energies ≥ 50 GeV which pass through from outside will be detected with high efficiency and reconstructed in direction with a median accuracy of about 1°. The array will be able to resolve the direction of a neutrino to this accuracy if the neutrino energy is ≥ 1 TeV, when the scattering angle between a neutrino striking a nucleon and the resulting muon which passes into the detector will be ≤ 1°.

Muons from atmospheric neutrinos will dominate the downward going muons above a zenith angle of about 80° (Fig. 5) leaving a solid angle of 2.357π steradians for neutrino observations. There will be about 3500 atmospheric neutrino events detected each year. This gives a background rate of about one atmospheric neutrino per $(2.8°)^2$ per year. Thus, with the calculated resolution of 1° for muon direction reconstruction, we will be largely signal limited, rather than background limited, in the search for extraterrestrial point sources.

As in the case of the SPS, the array will also contain wide-band hydrophones to

Fig. 4 — Optical detector module for DUMAND II with the upper hemisphere of the glass pressure housing removed. The coarse wire mesh is the magnetic shield. Each unit is fully monitored and computer controlled from shore. For each string, data and command transmissions are handled locally by a string centre controller, each of which has two-way communication with the shore via colour multiplexed optical fibre links operating at nearly 1 Gbd.



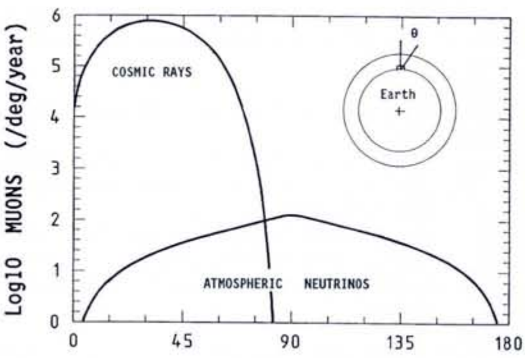


Fig. 5 — Calculated counting rates per degree and year for through-going cosmic-ray muons and atmospheric neutrino induced muons as a function of zenith angle.

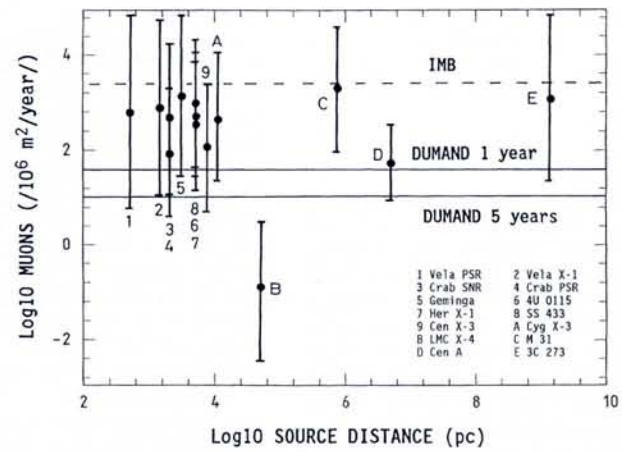


Fig. 6 — Extraterrestrial neutrino source detection capability of DUMAND II and comparison with the Irvine-Michigan-Brookhaven (IMB) detector, until recently the US's largest operational muon and neutrino underground observatory. Shown is the number of muon detections from a particular source versus source distance. Estimates are based on gamma-ray data.

explore the possibility of detecting acoustic shocks generated by ultra high-energy cosmic rays upon impact on the water. It has long been known that high-energy particles excite acoustic waves in water. As the attenuation length for high frequency (20-50 kHz) acoustic radiation is in the kilometre range (compared to 40 m for light) a truly gigantic array could be used for very high-energy air showers.

Scientific Goals

High-energy neutrino astronomy and astrophysics

Astrophysical sources of high-energy neutrinos are the prime target for DUMAND II. The aim here is to search the universe for point sources of energetic neutrinos and determine the gross features of the neutrino spectrum, in an attempt to locate and study possible sources of very high-energy cosmic rays and other astrophysical aspects.

We expect detectable signals from a number of point sources both inside and outside the Galaxy and probably a more or less homogeneous flux of ultrahigh-energy neutrinos from the recently proposed neutrino sources in active galactic nuclei (AGN) for which no generally accepted model exists. Fig. 6 shows a number of likely extraterrestrial neutrino sources and their expected intensities in muon detections, based on gamma-ray intensities (see below). The point source sensitivity of the array is approximately $4\text{-}7 \times 10^{-10}$ $cm^{-2}s^{-1}$ for neutrinos of energy ≥ 1 TeV. Possible point sources such as the X-ray binary pulsar Cygnus-X3 in the Galaxy may produce 100 counts/year in DUMAND II: one-tenth this level would be significant relative to the expected noise from atmospheric neutrinos.

An important future aspect will be the study of neutrino-gamma correlations, provided that sources emitting simultaneously high-energy neutrinos and gamma rays exist and can be discovered. The production of energetic neutrinos is always accompanied by the simultaneous gamma-ray production so both probe regions where particles are accelerated to high energies. We can expect neutrino fluxes of anywhere from equal to the gamma-ray flux to greater by a very large factor, depending on the thickness and density of material surrounding a source, the distance to the source, and the nature of intervening matter that attenuates

DUMAND
Planning for Remote Operation

The DUMAND neutrino telescope consists of 216 photomultiplier tubes in spherical glass housings, 45 hydrophones for acoustically surveying the 350 m tall, nine-string array, and 15 laser calibration units to monitor the sensitivity of the optical detectors and to calibrate their timings. The various modules in a string all communicate *via* fibre optic links to an electronics package at the bottom of each string. This unit contains an application-specific digitising chip to record the arrival of Čherenkov light pulses with 1 ns precision. The data and other control signals from an entire string are then multiplexed onto a single-mode fibre link to the shore station some 30 km distant. Ten data-carrying fibres working at 1300 nm (one for each string plus one for environmental data) transmit data at 625 Mb/s; filtering will reduce the final data rate to 80 kb/s.

The array will be lowered one string at a time and connected to a cable to shore by a manned research submarine. The junction box at the end of the cable will have instrumentation to monitor this activity. Power will be sent down the 15 mm diameter armoured cable at high DC voltage, delivering 5.5 kW to the array. The fibres also carry commands at 1550 nm out to the array which will contain about 250 networked-linked computers to adjust switches and many variables such as voltages. The DUMAND array can thus be remotely tuned and even reprogrammed to cope with the unexpected, or to deal with any failures.

Remote Operation

Traditionally in astronomy and high-energy physics, physicists operate equipment directly and manually, with around-the-clock watches in classical experiments. Direct operation of DUMAND is not sensible. The experiment, once debugged and operating, has no moving components and no part can be adjusted mechanically. The data rate after filtering and compression at the shore station is low enough (6×10^9 bytes/week) for optical or magnetic storage, or for transmission through networks to remote computers. However, there will still be a need for constant monitoring and control. The operating parameters of such a complicated system in the deep ocean have to be watched by a human observer who has to be able to adjust the mode of operation. This duty need not be performed at the shore station and no component or system at the station, excluding storage devices, will normally require manual intervention.

All operations will be controlled and monitored through a main computer, with all functions centralised at a single control workstation. If possible, we want to be able to run the experiment sequentially from remote stations using teams of physicists on shift in Hawaii, Japan, Europe, and mainland USA. To such an end, we have standardised on portable computer code as well as vendor-independent platforms (*e.g.*, C and OSF/MOTIF) in order to present the same interface to remote operators.

Networked Videoconferencing

We are currently investigating various networking alternatives to link the shore station to universities around the world. Given the geographic spread, DUMAND could benefit from videoconferencing. However, the minimum "near acceptable" bandwidth for this is 1 Mb/s for the foreseeable future. Equipping DUMAND to use this bandwidth for voice and data when video is not transmitted is expensive. Decreasing the size of images and their number to 2-3 per second and using commercial videoconferencing communications products (*e.g.*, DECSpin) reduces the rate to 128 kb/s. But the local telephone operator only offers 56 kb/s lines so apart from dedicated lines for video, it is still early days for videoconferencing *via* wide-area networks. A solution being explored is to team up with the 64-mirror, CLUE gamma-ray detector planned for deployment next year on Maui Island (CLUE is a joint project between the University of Hawaii, three Italian universities and the Italian INFN).

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gamma rays (attenuation of gammas by photons in the neighbourhood of some sources may also occur). Knowing gamma-ray fluxes would allow the computation of neutrino fluxes.

Cosmic ray physics

DUMAND will also study the properties of high-energy cosmic ray (atmospheric) muons, in order to deduce spectral features, and other aspects of the parent primary radiation at energies ≥ 10 TeV. Although optimised for up-coming muons from neutrinos (*i.e.*, for muons produced by neutrinos transversing the Earth), DUMAND will still have an effective area of 12 000 m^2 for downward-going muons, or a yield of 3.3 x 10^6 events per year, and has the capability of resolving the 2% of events which involve multiple muons. By determining the muon energy spectrum from the angular distribution of down-going muons and measuring the spectrum of the electromagnetic bursts caused by the muons we shall be able to study the primary cosmic ray spectrum up through the ultrahigh-energy range. Multiple muons will be resolved for spacings > 10 m and energy flows in tight muon bundles of a few metres in diameter so the composition of primary cosmic rays can be determined in the disputed energy region between 100 and 10 000 TeV.

Muon and neutrino physics

DUMAND will complement accelerator-based high-energy physics research since there are no existing or planned facilities that offer a neutrino beam above about 600 GeV. There will be investigations of muon and neutrino interactions and other topics of particle physics at energies far beyond the range of present and planned accelerators (*e.g.*, CERN's LHC and the SSC now under construction in Texas, USA), including testing the neutrino oscillation hypothesis in hitherto untouched domains such as those provided by long-baseline experiments. These experiments involve using high-energy particles (especially protons) produced by accelerators as a source. Owing to still unknown interactions, neutrinos may change their nature from say a muon-neutrino to an electron-neutrino by a process involving periodic changes in flavour (the MSW-effect). Theory predicts that the rate of change depends on the difference in neutrino masses Δm and the overlap of the two states of which $\sin^2(2\theta)$ is a measure, where θ is the mixing angle. Increasing the baseline simply extends the time available for mixing. DUMAND will make contributions in the range $0.01 \leq \Delta m^2 \leq 100$ eV^2 for $\sin^2(2\theta) \geq 0.1$.

The rising neutrino cross-section and the large effective volume of DUMAND, which is 10^8 m^3 for 2 TeV neutrinos, offer the best available opportunity to study neutrino interactions at energies above 1 TeV, employing the dominant atmospheric muon-neutrinos. DUMAND will also be capable of setting limits several orders of magnitude better than any previous detector in searching for exotic particles, rare phenomena such as WIMPS, dark matter, baryon decay by magnetic monopoles, *etc.*

Miscellaneous topics

Other topics of interest include: searches for ultrahigh-energy gamma-ray point sources *via* TeV muon astronomy, assuming that appropriate processes which enhance muon production do exist; searches for particular forms of dark matter; the monitoring of supernova explosions, *etc.*

Moreover, DUMAND and its support system make it possible to carry out simultaneously research projects in other fields such as oceanography, ocean biology, geophysics, environmental sciences, and climatology. A small number of carefully selected experiments will be incorporated.

The time schedule for DUMAND II foresees the beginning of data taking with the central plus two other strings in 1993, and regular observation of the universe in "neutrino light" with the complete array in 1994. The shore building and the 20 m tunnel to carry cables underwater are presently being built.

[1] Aoki T. *et al., Nuovo Cimento C* **9** (1986) 642.
[2] Babson J. *et al., Phys. Rev. D* **42** (1990) 3613; Matsuno S. *et al., Nucl. Instr. Meth. A* **276** (1989) 359.
[3] *DUMAND Joint Proposal,* The International DUMAND Collaboration, University of Hawaii, Manoa, Honolulu: **HI.HDC-2-88** (1988).

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High Energy Neutrino Telescopes

The most elusive of the established fundamental particles because of their extremely weak interaction with matter, neutrinos are unique tracers of phenomena occurring in otherwise inaccessible regions of the Universe. There are three well-recognised families of neutrino (electron-, muon- and tau-neutrino) of so far undetected but thought to be increasing mass. Being uncharged, neutrinos maintain their directionality so point sources are identifiable. The lifetime of the neutron is too short to survive great distances, even at the highest energies, so of the other known uncharged particles, only gammas are used for direct astrophysical observations.

High-energy neutrinos and gammas coming from a point source interact at the top of the atmosphere to produce a cascade containing muons that points back approximately to the source since the transverse momentum of the muons produced is small. So high-energy particle astrophysics essentially relies on gamma-ray astronomy (using large extensive air-shower arrays of detectors), and neutrino and muon astronomy (using well-shielded detectors): Fig. 1 illustrates schematically the various alternatives.

Neutrino Observatories

The wide range of detectable neutrino energies may be divided into experimental ranges according to principal aims:

< 40 MeV — *e.g.*, solar neutrinos, and neutrinos emitted within seconds of stellar collapse;

>10^8 eV — solar flare neutrinos;

>1 GeV — "high energy neutrinos" which may be:

- Cosmic-ray generated neutrinos produced by the decay of mesons produced in the nuclear interactions of cosmic-ray particles with the Earth's atmosphere ("atmospheric neutrinos");
- Astrophysical sources of three basic types (point, diffuse emission from the interstellar medium, and cosmological).

Neutrino detectors are classified according to the type of neutrinos involved, energy, target size, detection technique, location, and angular resolution. Arrays designed to observe cosmic neutrinos expected from celestial sources are called neutrino telescopes.

Neutrinos, being weakly interacting, are difficult to detect. Nearly all neutrino telescopes are placed in neutrino observatories located deep underground or deep underwater in order to be shielded from atmospherically generated, charged-particle secondaries of cosmic rays. There are some 20 neutrino observatories around the world, and new ones are being proposed all the time.

Cosmic-Ray Physics

Cosmic rays are mostly relativistic protons with a significant fraction of elections and heavier nuclei. There is a need to explore the

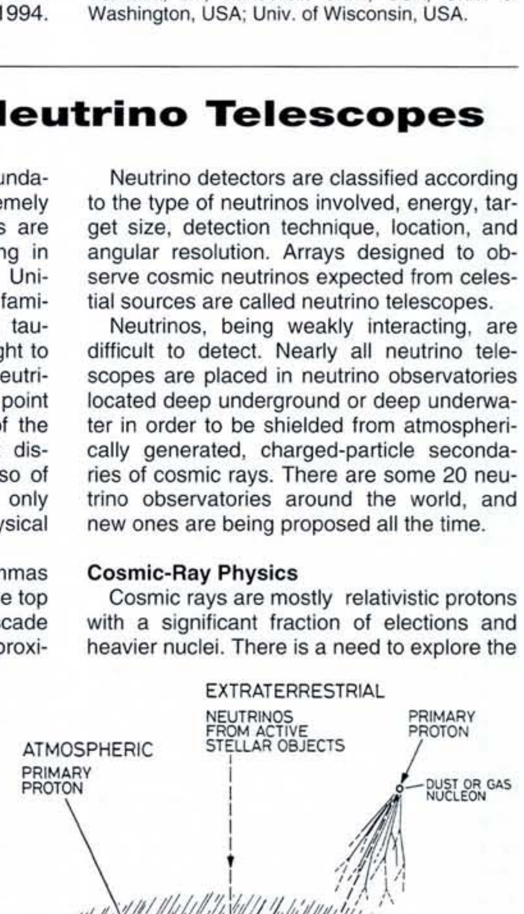
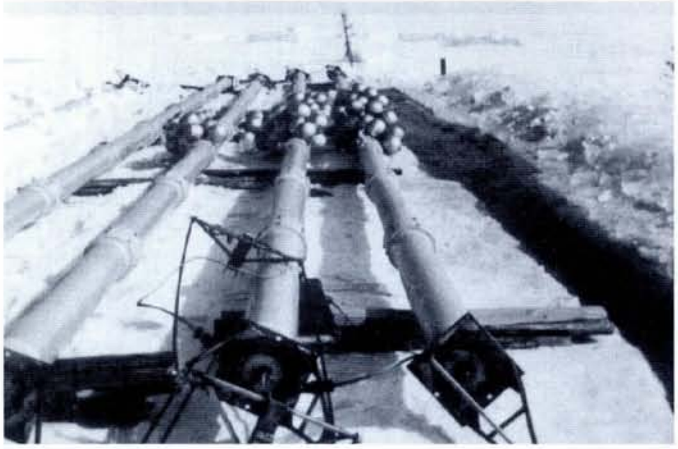
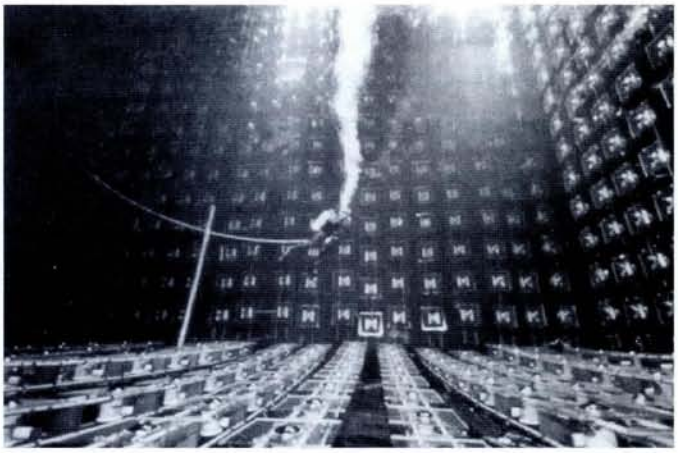


Fig. 1 — Muon and neutrino phenomenology. Shown are sources of atmospheric and extraterrestrial high-energy neutrinos and of muons [from Grieder, P.K.F., Proc 6th Int. Symp. on Very High Energy Cosmic Ray Interactions (Editions Frontières) 1990].



Setting up the NT pilot experiment on the frozen surface of Lake Baikal. Shown are the spherical detector modules and components of the support structure.



Inside the 8.10³ m³ water-filled tank of the US's Irvine-Michigan-Brookhaven (IMB) underground detector. The walls, are covered with Čherenkov counters.

energy spectrum and elemental (chemical) composition of the primary radiation (before it interacts with the atmosphere) at very high energies. This is because indirect measurements indicate a change of slope in the primary spectrum around a few 100 TeV, and possibly a flattening beyond 10^6 TeV. Several explanations have been proposed for these phenomena

Muon and muon-neutrino physics are closely related and muon-neutrino experiments are, in principle, suitable for detecting muons arising from interactions of primary cosmic rays in the atmosphere. Existing experiments to measure the cosmic-ray muon spectrum are too small to acquire reliable statistics and estimates of the energies are poor. Observations of multi-muon events gives data of the primary chemical composition because the multiplicity distribution depends on the elemental mass composition of primaries. But such events may possibly be confused with sequences of events unless the angular resolution is good. Hence the importance in cosmic-ray physics of large muon-neutrino detectors with good angular resolution.

Underwater Telescopes

The main deep underwater, large-area detectors primarily intended for searching for astrophysical point sources are NT-200 (pilot in operation; 2.10^3 m^2 planned; Lake Baikal, CIS); DUMAND (2.10^4 m^2; under construction off Hawaii, see p. 167); and NESTOR (3.10^3 m^2 pilot under construction; 10^5 m^2 proposed; in the Mediterranean off Pylos, see page 172). All are based on the concept suggested in 1969 of detecting charged current interactions of neutrinos by observing the Čherenkov radiation of the produced muons as they move through highly transparent water.

The NT (Neutrino Telescope) collaboration involving three Russian institutes and DESY's Zeuthen lab in Germany saw the deployment during the 1991/2 winter from the frozen surface of Lake Baikal of the basic heptagonal "umbrella" mechanical structure to 1360 m in deep, clear water. A two-string mini-array of 14 detector modules was suspended for long-term tests and to make a space reconstruction of atmospheric muons. However, only four of the 14 Russian-designed upward and downward-looking modules with "intelligent" phototubes survived at 1070 m owing to leaky feedthroughs. This illustrates the difficulty of deep underwater experiments. Preliminary data analysis gave 60% of the Monte Carlo predicted rate. The plan is to deploy NT-48 comprising four half strings of 12 detectors modules in 1993, and the full 192 module NT-200 array of eight strings of 24 detectors in 1994.

Shallow Underwater Observatories

A number of large-area, Čherenkov-type shallow water (< 1000 m) neutrino and muon observatories have been, or are being, operated including LENA, Lake Issuk-Kul, and AMANDA: proposed are GRANDE, PAN, NET, and a shallow water NESTOR. The backgrounds associated with such arrays are about 10^5-10^6 times higher than for the deep underwater experiments so it is difficult to convince people that they can be used effectively for detecting astrophysical neutrino point sources.

The Japanese 4.10^4 m^2 LENA project was abandoned in 1991 after a pilot phase. Preliminary data taking has been reported this summer for a 2.10^6 m^3, 256-module Cherenkov array operating at 600 m in Lake Issuk-Kul, CIS. AMANDA, sited on Antarctic ice, offers some intriguing advantages but faces horrendous logistics. Funded by the US National Science Foundation, the first phase calls for two strings of five detectors spaced 5 m apart to look for muons produced by rare neutrino interactions in the ice; gradual extensions to 10^5 m^2 are foreseen. Relatively small upward looking detectors have already been sunk to detect energetic muons associated with extensive air showers. Measurements of the transmission length are needed to see if trapped air bubbles are a problem as the length sets the detector scale (and cost).

The 3.10^4 m^2, 50 m deep GRANDE artificial lake project proposed for a quarry in Arkansas, USA, was discontinued in favour of DUMAND. The Swedish PAN collaboration for a 10^4-10^5 m^2 array in a northern Swedish lake has recently made some hydrological measurements and is presently exploring the possibility of joining another collaboration. The Gran Sasso lab in Italy has proposed NET, a 10^5 m^2 detector placed in a purified water filled, artificial lake built above the existing underground facilities. Finally, there is the possibility of shallow water (50 m) detector for the NESTOR collaboration in the Bay of Pylos, Greece.

Underground Experiments

Some large underground detectors also have the capability to carry out neutrino astronomy of a limited sort. The 400 m^2 Irvine-Michigan-Brookhaven (IMB) experiment was original designed to study nucleon decay processes. It comprised 8.10^3 m of highly purified water in tank located 1600 mwe (metres, water-equivalent) underground with 2048 photo-multipliers to detect Čherenkov light mounted on six sides of the tank. IMB, which operated from 1982 to 1991, detected along with the Japanese Kamiokande experiment, the neutrino burst from supernova SN1987A that heralded the era of neutrino astronomy. Upgrading of the Kamiokande water Čherenkov detector some 2400 mwe underground from 2.10^3 to 5.10^4 m^3 by 1996 will extend possibilities. Meanwhile, the 3.10^3 m^2 MACRO and the 3.10^3 m^3 LVD liquid scintillator detectors in the Gran Sasso lab some 3200 wme underground will continue searches for neutrino point sources begun in 1989 involving the observation of energetic muons produced by interactions with the Earth's atmosphere. Although having good background rejection and good pointing ability, MACRO and LVD may be either too small or too marginal to effectively observe astrophysical point sources of neutrinos.

A model of the MACRO detector in the Gran Sasso underground laboratory. Each of the six 12 x 12 x 5 m³ supermodules comprises streamer tubes interleaved with passive detector material.