OECD MEGASCIENCE FORUM

Workshop on a Deep-Sea Neutrino Observatory
Taormina (Italy)
May 22/23, 1997

SUMMARY

1. BACKGROUND

One of the most exciting developments in modern science is the progress being made towards a unified description of the fundamental nature of matter, and the origin, structure, and fate of the Universe as a whole. A bold attempt is under way to understand Nature at the minutest level (the world of the elementary particles) and, within a common theoretical framework, to account for its largest structures (for example, superclusters of galaxies). This undertaking requires scientists to study the behavior of matter under the most extreme conditions, for example, during the Big Bang, or in the vicinity of black holes.

The investigation of these energetic phenomena stretches to the limit the nature of the scientific enterprise, since it becomes increasingly difficult to devise experiments to test theoretical predictions about these extreme phenomena. Fortunately, it is possible to take advantage of the small number of neutrinos, gamma rays and charged particles that arrive at the Earth's surface with energies that exceed, by a factor of one billion or more, those produced by the world's most powerful accelerators. Thus, the ability to detect these energetic particles is emerging as a powerful tool for gaining new insight into fundamental truths about matter and creation. At the same time, the origin of these particles is a mystery that challenges the ingenuity of astrophysicists, and promises to reveal new, exotic processes and objects in distant parts of the Universe.

The energy and the direction of travel of incoming high energy neutrinos can be reconstructed from an analysis of the flashes of light that are produced when muons (or other charged particles produced by the neutrinos) traverse a large volume of ice or water. The flashes of light can be detected by arrays of photomultiplier tubes. Obtaining a useful number of events in the highest energy range, from 1 Tev (1000 billion electron-volts) up to about 100 Eev (100 billion billion electron-volts), requires the deployment of many thousands of photomultipliers within a volume of approximately one cubic kilometer of ice or water. This presents formidable technical, operational and financial challenges.

Recognizing the growing importance of this field, and wishing to know whether the full potential of international scientific cooperation was being exploited in its development, the OECD Megascience Forum decided to sponsor a Workshop on a Deep-Sea Neutrino

Observatory. The decision was based on a proposal submitted by the governments of Greece and Italy.

The workshop was held in Taormina, Italy, on May 22/23, 1997. Organizational and financial support was provided by the Italian National Institute of Nuclear Physics, INFN. Workshop participants included scientists who are actively involved in neutrino physics, interested researchers from other fields (such as biology, oceanography, and earth sciences), and government science policy officials.

Among the goals of the workshop, as stated in the initial proposal, were:

... [to] conduct a critical review of technical issues, including results from the relevant projects (*Amanda, Dumand, Baikal, Nestor* and others), and to identify areas where future research and development are needed for enhanced performance, lower cost, greater reliability, and lower environmental impact. National centers of excellence will be identified with a view to defining potential international cooperative arrangements.

2. PRESENTATIONS AND DISCUSSIONS

The Scientific Case.
Session chaired by A. Bettini (Univ. of Padova, Italy)

Michel Spiro (Saclay, France) noted that strengthening international collaboration in astroparticle research had been one of the recommendations of the Megascience Forum Expert Meeting on Particle Physics in 1994. Since then, significant new experimental results have been obtained, independently, by several collaborations. The case for coordinated action is even stronger today than it was in 1994.

David Schramm (Univ. of Chicago) argued that the origin of the highest energy cosmic radiation is one of the greatest mysteries of modern astrophysics. Scientists speculate that observations of these particles can shed light on some of the exotic hypothetical constituents of matter, such as super-symmetric particles, WIMPS ("weakly- interacting massive particles" that may make up most of the mass of the Universe), or even monopoles, strings, walls, textures and other mysterious remnants of the Big Bang some twelve billion years ago. Observations of all three types of energetic astroparticles (gamma rays, charged particles, neutrinos) are needed to test the theories that are being developed to understand this unexplained radiation.

Thomas Gaisser (Bartol Research Institute) discussed predictions of event rates for high-energy neutrinos. Predicted rates depend on the hypothesized astrophysical production mechanisms, the ability to model the interactions of high-energy particles with the Earth, the oceans and the atmosphere, and the proposed configurations of detectors. There is an urgent need for experimental data to guide the computational models (and, incidentally, to confirm the very existence of ultra high-energy neutrinos).

Howard Seliger (Johns Hopkins University) discussed the potential applications of a large underwater detector for the study of marine organisms that emit flashes of light. These studies could make a valuable contribution to a scientific understanding of the oceanic food web, and marine ecology in general. With the addition of special-purpose mechanical stimulators, bioluminescence could be detected by the same photomultipliers used to search for neutrinos. The telecommunication cables connecting the neutrino detectors to the shore station could also transmit real-time data for these studies.

Lucien Laubier (COM, France) also considered the potential of a neutrino laboratory for research on bioluminescence, and he introduced additional study areas, such as deep-sea dynamics, fluxes of organic and inorganic matter, and the physical and chemical variability of deep waters on multiple time scales. In judging the potential of a neutrino observatory, the advantages of using the installed infrastructure (mechanical support, power, data communications, support vessels, etc.) have to be weighed against the inflexibility of a fixed site.

Technology: State of the Art.
Session chaired by Christos Fragakis (DGXII, European Commission)

The next series of presentations was devoted to the five experimental projects (of which four are active) that are exploring the feasibility of detecting high-energy neutrinos in ice and water.

Steven Barwick (Univ. of California, Irvine) presented results from *Amanda*. As analysis of the data continues, the group plans to deploy ten more "strings", each with fifty optical modules. The group reports module failure rates of less than three percent. The *Amanda* collaborators are confident that their technology could be used in a full-scale, cubic-kilometer detector, and they are encouraged by the continuing commitment of the United States to maintaining and upgrading the South Pole research station.

Jean-Jacques Aubert (CPPM, France) reported on results from the *Antares* program, which is pursuing a demonstration project off the southern coast of France. The current goal is demonstrate the feasibility of a deep-sea neutrino detector by building and deploying a demonstrator system consisting of several strings of approximately one hundred photomultipliers, connected to a shore station by an optical cable. Additional goals are to optimize deployment and operation practices, to study the underwater site, and to understand the costs and the technological challenges of scaling the system to the final size. An intermediate deployment, equivalent to one tenth of a cubic kilometer, could produce preliminary physics results.

Christian Spiering (DESY, Germany) described the work of the *Baikal* collaboration, which has been deploying strings of photomultiplier tubes (arranged in pairs to reduce the rate of extraneous signals) since the early 1980s in the deep waters of Lake Baikal in

Russia. In addition to the neutrino work, research is also being conducted to understand the changes that are taking place in this very important body of water. Alone among the experimental groups, *Baikal* reports the detection of three high-energy neutrino events (of which one is "gold-plated"). The collaborators believe that the lake site is competitive to ocean venues, while the deployment difficulties are considerably abated. They intend to continue their work despite the current economic problems in Russia.

Leonidas Resvanis (Univ. of Athens) described the work of the *Nestor* collaboration. Numerous measurements of the properties of the site have been followed by several deployments of photomultiplier arrays in deep water near the town of Pylos (Greece). Most recently, two full “floors” of the type foreseen for the final detector were deployed in the deep sea, and subsequently recovered. Like *Amanda, Antares* and *Baikal, Nestor* is pursuing technology development and operational tests, hoping to scale their equipment up to a size that will establish the approximate flux of astrophysical neutrinos.

David Nygren (Univ. of California, LBL) discussed the *Dumand* experiment, which was terminated in April, 1996, following a series of unsuccessful deployments that began in 1993 off the coast of Hawaii. A number of important lessons can be derived from this experience, most notably in the areas of systems engineering, and the design, construction and use of high-pressure electrical and optical connectors.

Neutrino researchers are not the only scientists who confront the challenges of operating complex equipment at great depths. A number of deep-sea observatory projects are now under way, among them:

USA:	O.S.N.
	HUGO
USA / Japan:	Geo-TOC
Japan:	VENUS
	OHNP
Greece:	LAERTIS
Eur. Union:	Geostar

The experiences gained during the course of this work are of direct relevance to neutrino studies.

Paolo Favali (ING, Italy) provided details of the *Geostar* project, whose goal is to design, construct, test and deploy a deep-sea observatory for geophysical and environmental monitoring. Onboard instruments will provide continuous and integrated data for long-term studies in seismology, gravimetry, geomagnetism, oceanography and geochemistry.

Eustratios Anassontzis (Univ. of Athens) gave a presentation about the *Laertis* program, which will share *Nestor's* deep-sea site. A recoverable array of instruments will be deployed along a buoyant "string" attached to the ocean floor. Measurements will be made of water temperature, circulation, radioactivity, transparency, etc., as well as seismic activity and bioluminescence.

Technology: Challenges for Large Detectors.
Session chaired by Jeffrey Mandula (Dept. of Energy, U.S.A.)

Following the descriptions of specific neutrino and non-neutrino projects, workshop participants heard a series of presentations on technical issues in general, and on experiences gained in the course of commercial and defense operations.

Peter Koske (Univ. of Kiel) presented the three main component systems of a deep sea neutrino observatory: the in-situ structure (detector); the shore station (laboratory); and the connecting cable with appropriate interface structures. After reviewing the main technical requirements for these components, he concluded that there are no fundamental obstacles to implementing reliable and effective detector systems.

David Nygren (Univ. of California, LBL) provided a broad overview of the main technical challenges that must be faced by every research team:

- Scaling (i.e., the ease with which prototype systems can be expanded to a much larger system).
- Interconnect strategy between high-pressure and low-pressure components.
- Deployment strategy.
- System architecture.
- Strong coupling between all of the technical requirements.

Fault-tolerance and maintainability will be key features of a successful final design. The speaker argued that they can best be achieved through the use of modern distributed microprocessor systems which can (when combined with other high-density analog and digital circuits) perform sophisticated signal processing and communications tasks at the level of individual system components. Among the many advantages of such a distributed architecture is its ability to adapt to the failure of some parts of the detector.

A series of short presentations were made by invited experts:

Terry Ewart (Univ. of Washington) discussed the use of acoustic transceivers to accurately locate the elements of a large underwater neutrino detector in three dimensions.

David Hyde (SAIC Corporation, USA) described his company's experience with deep-sea self-deploying sensor arrays, and ongoing projects in acoustic oceanography, geophysics, environmental monitoring and telecommunications.

Gian Mario Bozzo (Tecnomare) described design concepts and technologies for deep-sea stations, introducing existing technologies and experiences in other deep-sea programs. He stressed the necessity of taking into account, from the earliest design phases, the need for effective and affordable maintenance procedures for the system.

Peter Koske (Univ. of Kiel) presented the technology which was used for the recent deployment of two fully equipped *Nestor* "floors" to a depth of 2600m., using the cable-laying vessel *Thales,* and a crane-equipped barge.

Esso Flyckt (Philips Photonics, France) pointed out that approximately one-half of the cost of a cubic kilometer detector would be devoted to purchasing photomultiplier tubes. This means that it is worth considering ways to cut manufacturing costs, and to develop new, less expensive, more reliable components.

Leonid Bezrukov (INR, Russia) developed this theme with a presentation of research on a novel type of hybrid photodetector that combines a semiconductor avalanche detector with elements of a conventional photomultiplier tube.

Jean Rozmarin (DGA / CTME) described the fruitful collaboration of the *Antares* project with CTME and CTSN, who have extensive defense-related technical experience with the design and operation of large deep-water systems.

Ion Siotis (Demokritos Research Center, Greece) enumerated the criteria that should be used to evaluate deep-water sites for a very large detector. These criteria can be grouped in five categories: physics, logistics, financial, social and political.

Giuseppe Smriglio (ING, Italy) described the considerations that determined the choice of the site for the initial *Geostar* deployment, 25 kilometers north of the Mediterranean island of Ustica. He emphasized the importance of environmental factors for the execution of marine experiments.

Alan Ball (CERN) presented the work that is being carried out at CERN to direct a beam of neutrinos (with energies of several GeV) towards the Gran Sasso Laboratory in Italy, 731 kilometers away. With additional funding, such a beam could also be directed at the *Nestor* site.

Igor Zheleznykh (INR, Russia) discussed possible alternative techniques for neutrino detection, including measurements of radio emissions from the Antarctic ice or the Moon. He suggested that an existing sonar array located off the coast of Kamchatka could be used to detect acoustic signals from the very highest-energy neutrinos and cosmic rays. He also argued that a cubic kilometer detector could be constructed on the surface of the ocean, then deployed in deep water and held in place using cables, floats and anchors.

General Discussion, Conclusions, Recommendations.
Session chaired by Gérard Fontaine (CNRS, France)

Following these presentations, Workshop participants engaged in a general discussion on the state of the field, and on the role of international cooperation and coordination in advancing the scientific and political rationale for pursuing high-energy neutrino astrophysics. The consensus results of this discussion where presented by INFN President Prof. Luciano Maiani. They are embodied in the following Findings and Recommendations:

3. FINDINGS

1. The successful detection, and detailed study, of very energetic neutrinos of astrophysical origin promises to yield vital information about the fundamental properties of matter, the structure and history of the Universe, and the nature of exotic objects such as black holes. The field of Astro-Particle Physics has emerged as a valuable component of an integrated strategy for advancing the frontiers of physics and astronomy. This exciting new field deserves the special attention of science policy officials.

2. Observations of each of the three types of energetic astroparticles - gamma rays, charged particles, and neutrinos - can provide independent information about high-energy phenomena. Ultra high energy neutrinos, which are unaffected by magnetic fields or the presence of other particles, may provide information about black holes in galactic nuclei, or such hypothesized objects as topological defects in space, or WIMPS ("weakly- interacting massive particles", which are conjectured to constitute most of the mass of the Universe).

3. The energy and the direction of origin of an incoming high energy neutrino can be reconstructed from an analysis of the flashes of light that are produced when the neutrino transfers its energy to one or more charged particles which then traverse a large volume of ice or water. The light can be detected by an array of photomultiplier tubes. Obtaining a useful number of ultra high energy events requires the deployment of many thousands of photomultipliers throughout a volume of about one cubic kilometer of ice or water, which presents formidable technical, operational and financial challenges.

4. Four research projects are currently under way: three in water in the northern hemisphere (*Antares, Baikal, Nestor*) and one in the south polar ice (*Amanda*). Each project has been initiated by one nation, and includes collaborators from several foreign institutions. While nationally-lead efforts constitute a sensible strategy for R&D and feasibility studies, a final, high-volume neutrino observatory may need to be designed, built, and operated as an international effort on a regional or global basis.

5. The experience from ongoing programs, and from the canceled *Dumand* experiment, have not revealed any fundamental impediments to the implementation of a very large deep-sea neutrino observatory. However, there are significant technological and logistical obstacles that must be studied and overcome in the framework of ongoing activity and, perhaps, new undertakings as well. The principal challenges lie in the following areas:

   - Deployment and retrieval for maintenance or repair, of large, complex systems with electrical, optical and mechanical components and connections in the demanding environment of the open sea.

   - Remote diagnosis and maintenance of equipment at large depths.

   - Electrical, mechanical and optical connections between the low- pressure instrumentation (photomultiplier) volume and the very-high pressure ocean environment.

6. Deep-sea neutrino experiments constitute a resource that may be of value for scientists in other fields such as biology, oceanography and earth sciences. These scientists may be able to take advantage of the installed infrastructure (mechanical support, power, electronics, communications, shore facilities) to carry out independent investigations using the installed photomultipliers or special-purpose sensors.

4. RECOMMENDATIONS

1. Government officials who are responsible for long-term planning and priority setting for science on a national or regional basis are encouraged to monitor developments in high-energy neutrino astrophysics, and to consider progress in this field as an important component of an integrated strategy for advancing the frontiers of physics and astronomy. Officials should be aware that the full scientific exploitation of high energy neutrinos may require the construction of an underwater observatory of approximately one cubic kilometer in volume.

2. To develop and sustain the field of experimental high-energy neutrino astrophysics over the long term, a new committee should be established, possibly within the International Union of Pure and Applied Physics (IUPAP), on the model of that body's existing disciplinary committees (if this is not feasible, other international bodies should be considered). The committee would provide a neutral, open and supportive environment where researchers could share experiences, exchange information, and coordinate their efforts. It would meet periodically to review progress in the field, and it could sponsor technical workshops. The committee could invite a wide spectrum of individuals (including non-physicists) to participate in its activities, and to assist in formulating recommendations for advancing the field. It would also serve as a source of reliable information about the field in general and about specific technical issues. The committee could inform the OECD Megascience Forum about its progress on a regular basis, and recommend additional Forum activities (for instance, establishment of a Working Group), via a proposal from a Member country.

3. Scientists who are engaged in neutrino experiments should develop a sound technology strategy that emphasizes reliability, quality assurance, fault-tolerance, and a systems-based approach that takes into account the full life cycle of an experiment, including deployment, maintenance, and possible retrieval.

4. Given the current theoretical and experimental uncertainties, it is advisable to proceed towards a cubic kilometer detector in a gradual manner. The R&D and feasibility studies that are currently under way should be followed by small- and medium-scale deployments of instruments. Once sufficient operational experience is achieved, a sufficient volume should be instrumented to search for a detectable neutrino signal. Only then can a decision be made about the construction of a very large neutrino observatory. At each stage of the development, experimental work must be closely coordinated with advances in theoretical predictions and modeling.

5. Scientists should pursue the characterization and identification of candidate underwater sites for a future large observatory. In selecting a site, due consideration should be given to all scientific, technological and economic factors.

6. Neutrino scientists should strengthen their ties with other deep-sea researchers, and with companies that have experience in implementing underwater installations.

7. Further studies should be undertaken on the utility of underwater neutrino installations for other disciplines, such as biology, oceanography and earth sciences. It should be recognized, however, that each field has its own scientific requirements (location, number of sites, duration, mobility, etc.) and constraints (financial, manpower, etc.). If a cubic kilometer observatory is to be built, the cost and effort must be justified by the importance of the results to fundamental research in physics and astronomy.