HIGH ENERGY NEUTRINO TELESCOPES

L. K. RESVANIS
Physics Laboratory, University of Athens
104 Solonos St., Athens 10680, Greece

Abstract. A review of the potential of Neutrino Telescopes to contribute to Astrophysics and Elementary Particle Physics is presented. The status of the four neutrino telescopes presently under construction is reviewed. An inexpensive modular design of how to reach an 1 km^2 telescope with an energy threshold of a few GeV is proposed.

1. Introduction

The cosmic ray spectrum shows clearly that there exist cosmic rays with energies of at least up to $3 \times 10^{20} \text{ eV}$. These highest energy particles must be extragalactic because they are too energetic to be trapped in our galaxy by the galactic magnetic field. So neutrinos and gamma rays at high energies must exist because they are the ultimate decay products of interacting cosmic rays in the Cosmos.

Astronomy means "pointing back" to the source, i.e. the origin of production. From the charged cosmic rays only those of the highest energies (probably protons) travel rectilinearly i.e., they are not bent significantly by the galactic magnetic field. Therefore only very few of the cosmic ray protons are useful in "pointing back" to their origin. Neutrons are not very useful either, because only those with energies bigger than 10^{18} eV live long enough to cross our galaxy. Unfortunately there are very few of those too. So, they can not be helpful if their origin is outside our galaxy. In any case, the physics is understood and one can calculate that protons (or heavier nuclei) with energies above $4 \times 10^{19} \text{ eV}$ interact significantly with the primordial 2.7 K microwave background. Their energy is rapidly degraded and eventually these events of the highest energies (originally) get buried in the background of lower energies. So, charged hadrons cannot provide us with information for distances further away than 20-30 Mpc.

EGRET observations of gamma rays with energies up to the tens of GeVs and the recent observation of Mk421 by the WHIPPLE, Mount Hopkins Atmospheric Cherenkov Telescope, around 1 TeV have stimulated calculations on the interaction of very high energy gamma rays with the ambient intergalactic photons [Stecker 92]. The calculations can be interpreted to show that the mean free path of gamma rays with energies above some hundreds of GeV is around 100 Mpc due to scattering with the intergalactic ambient infrared and ultraviolet starlight. This conclusion combined with the well known calculations that show that gamma ray attenuation due to scattering with the 2.7 K background is very serious for gamma rays of hun-

SW 9520

dreds of TeV energies, leaves the neutrinos as the only promising particles for TeV or higher energies Astronomy. The neutrinos not only go through interstellar space without suffering any attenuation but they also escape their progenitor's acceleration and target sites without suffering any absorption. Therefore the only way to measure the emission/production spectrum at the source is to measure the spectrum of the neutrinos arriving on Earth.

The inescapable conclusion is that with neutrinos one can see "further" and "deeper" in the Cosmos than with any other known to date particle. The question is "what is the neutrino flux"? Or conversely, how big a detector do we need in order to start the field of "Neutrino Astronomy"? The only reasonable way to answer this question is to use the experience gained over the last 30 years or so by the construction and operation of the first and second generation neutrino telescopes and scale up by a few orders of magnitude in well defined steps. Each step should have the potential to contribute significantly to Astrophysics or Particle Physics: Relic neutrinos from the Big-Bang fill the Universe but no one has yet proposed a practical way to detect them. Low energy neutrinos of keV to ≈ 1 MeV are emitted continuously from the interior of stars like our Sun. At this moment there are at least half a dozen solar neutrino telescopes in operation, but there is no proposal to detect neutrinos produced in the interior of other stars. Slightly higher energy neutrinos (≈ 14 MeV) are produced during the explosions of supernovae and one can argue successfully that the birth of Neutrino Astronomy happened with the detection of supernova 1987A by KAMIOKANDE and IMB, although no one has yet proposed a practical way to detect supernovae neutrinos further away than the immediate neighbourhood of our galaxy. Neutrinos in the higher energies are produced from decays of particles produced from cosmic rays interacting and the subsequent cascades in the Earth's atmosphere. The shape of their spectrum is caused by the competing processes of meson production and decay in a target medium (the atmosphere) of continuously changing density. Neutrinos with energies in the range of one to a few hundred GeV for example may also come from the annihilation of WIMPs (Weakly Interacting Massive Particles) in the Sun or the central core of the Earth. Neutrinos from point sources are decay products of particles produced in hadronic interactions, in potential cosmic accelerators such as neutron stars, black holes and young supernova remnants. Our own galaxy is full of such candidates. Further the Cosmos is full with Active Galactic Nuclei (AGN) and they are very promising sources of Ultra High Energy neutrinos. Detection of neutrinos from point sources would unambiguously establish the existence of high energy hadronic interactions e.g.

$$\begin{array}{c}
 p + \text{target} \rightarrow \pi^0 \quad , \quad \pi^\pm \quad + \dots \\
 \downarrow \qquad \qquad \downarrow \\
 \gamma\gamma \qquad \mu^\pm \nu_\mu \\
 \qquad \qquad \downarrow \\
 \qquad \qquad e^\pm \nu_\mu \nu_e
 \end{array}$$

The observation on Earth of γ 's from π^0 decay can only be a rare event, because the target must be thick enough in order to produce π^0 's and at the same time thin enough ($\approx 5 - 100 \text{ g/cm}^2$) so as not to absorb the π^0 decay γ 's and then these γ 's should not interact with interstellar matter or the ambient starlight ultraviolet and infrared photons or the primordial 2.7 K microwave photons during their very long trip to the Earth. On the other hand high energy photons (up to a few TeV) can be produced not only in hadronic processes via π^0 decay but also by purely electromagnetic processes e.g. inverse Compton scattering or synchrotron radiation of energetic electrons and then they must escape the general environment of the target before they get absorbed.

2. Physics Scope

The physics aim of neutrino telescopes covers one or more of the following topics (in order of descending neutrino energy):

1. Neutrino Astronomy (galactic and extragalactic) and the search for cosmic accelerators [Berezinski 90, Stenger 92].
2. Particle Physics beyond the Standard Model (a few examples follow):
 - a) Search for dark matter particles. Their annihilation or decay will eventually give neutrinos e.g. neutralinos trapped in the Sun or the Earth [Bottino 92].
 - b) Ultra High Energy neutrinos have energies beyond 10^7 GeV in the Laboratory. No terrestrial accelerator can produce these energies. If the neutrino telescope is large enough the limitation of low flux can be, in part, overcome and this might be the only way for High Energy Physics to reach these Ultra High Energies. In any case we can start right away, the experimental problems of neutrino telescopes are well understood.
Multiple W/Z production [Ringwald 93].
Search for possible substructure of the elementary particles i.e. compositeness of quarks and leptons [Kovesi-Domokos, Domokos 92, 93].
3. Neutrino oscillations (and thereby contributing to the question of "dark matter" in the Universe) using neutrinos produced in the atmosphere. The large range of the available oscillation length (15 km to 13000 km) gives an extremely good sensitivity of $\Delta m^2 \geq$

10^{-4}eV^2 [Suzuki 88, 93], [Resvanis 92, 93], [Katsanevas 92], [Kourkoulis 93].

4. Long baseline neutrino oscillations using one of the high energy physics accelerators [Resvanis 92, 93], [Katsanevas 92].
5. Proton decay (in the sense that the ultimate background to proton decay experiment is atmospheric neutrino interactions and therefore a low threshold neutrino telescope can also be a proton decay detector).
6. Supernovae detection.
7. Magnetic monopoles.
8. The unexpected. A new observational window will open up with these neutrino telescopes. No one has ever viewed sites in the Universe shielded by more than a few hundred grams of matter. One should keep in mind that every time a new brand of astronomy opened up, a new class of phenomena was discovered.

The experimental requirements for the study of the above physics topics look incompatible at first glance e.g. low vs high energy threshold, good angular accuracy vs coarse, high fractional coverage with sensitive photocathode area vs maximising the detector's sensitive area, etc. After a couple of decades of operating small prototypes and R+D the High Energy Physics community seems to have the right tools to build a detector to study all the above. The approach must be stepwise and modular. The detector of today's measurements is the prototype for tomorrow's experiment. The background of today's measurement is the signal of tomorrow's experiment.

3. Production of Astrophysical High Energy Neutrinos

There exist some excellent review articles of the subject and the reader is referred to Berezhinski 1990, T. Gaisser 1986 and K.S.Thorne 1977, 1991. The point one should stress here, is that according to Stenger's calculations [Stenger 92] the optimal condition for high energy neutrino production in a cosmic beam dump (e.g., in a X-ray binary system) is a column density $z \geq 100 \text{ gcm}^{-2}$, target density $< 10^{-8} \text{ gcm}^{-3}$ and a primary proton spectral index $a \leq 2$. Then, a beam of 1 TeV neutrinos would be produced at a rate of 10% of the protons that strike the source. Under these conditions the neutrino flux emitted is at least 3 times bigger than the corresponding gamma ray flux produced by the same hadronic interactions. The photon interaction cross section is many orders of magnitude larger than the neutrino cross section, therefore high energy gamma rays can be destroyed much easier than neutrinos either near the source of their production by interacting with the matter or during their vast flight distance to Earth by interacting with the 2.7 K background or the intergalactic infrared and ultraviolet starlight

[Stecker 92]. The inescapable conclusion is that for very high energies we should expect more copious neutrino sources than gamma ray sources.

Another class of sources which has become rather popular in the last few years is neutrinos produced in the vicinity of Active Galactic Nuclei. In this mechanism, neutrinos originate from the decay of mesons which in turn are the decay products of photoproduced Δ resonances.

Recent calculations show that, although signals from individual AGNs will not be detectable with the neutrino detectors presently under construction, the sum of all AGNs [Hawaii 92] should be detectable. Finally, we should mention that high energy neutrinos may also originate from heavy (hundreds of GeV) dark matter particles e.g., WIMPs which are trapped in the Sun or the Earth and which eventually annihilate with their antiparticles producing neutrinos amongst other particles.

4. Choosing the Neutrino Energy

In order to detect neutrinos from the previously mentioned sources it is advantageous to focus on high energy neutrino detection. The reason is simple. The mere word astronomy implies that one ought to be able to point back to the source with high angular accuracy. In neutrino detection we cannot achieve the angular accuracy of traditional astronomy. Neutrinos are detected by observing mainly the muon which is produced from the charged current neutrino interactions with matter, in the vicinity of the detector. In high energy neutrino astronomy usually, one is NOT required to detect the vertex of the neutrino interaction, this way one maximizes the available detection volume. The physics of the interaction is such that, the angle between the detected muon and the parent neutrino direction [DUMAND 93] for 63% of the charged current events is $\approx 1.5^\circ / \sqrt{E(\text{TeV})}$. So, if a source is observed with a dozen events or so, one can greatly improve the directional determination by determining the centroid of the distribution and reach accuracies of a fraction of a degree. The pointing improves also with increasing energy not only because the muon goes further forward but also because the statistics improve due to the increase of the cross section ($\sim E_\nu$ until 10 TeV and then $\sim \log E_\nu$). Another parameter which improves with energy is the range of the muon ($\sim E_\mu$ until 1 TeV and then $\sim \log E_\mu$) and thus the effective detection volume of the detector is increased proportionately. Further, the signal to noise improves with energy

for the following reason. The inherent background comes from atmospheric neutrinos, which are the result of cosmic ray interactions in the atmosphere. The spectral index γ of the flux of atmospheric neutrinos (Stanev 92) follows that of the cosmic ray spectrum and is ≈ 2.7 up to 100 GeV or so, but then at higher energies it becomes ≈ 3.7 , while neutrinos produced extraterrestrially follow the hard core ($\gamma \approx 2.0 - 2.2$) cosmic ray spectrum. So, for neutrino energies larger than 100 GeV the signal to noise improves with energy.

For all the above reasons it is advantageous to optimise the telescope for detection of high energy neutrinos. One should keep in mind though, that the design of neutrino telescopes in the water with phototubes directed towards the Earth (in order to minimize background from downcoming cosmic rays that reach the detector) can be disadvantageous when one detects very high energy neutrinos (e.g., from AGNs) because then the Earth is no longer transparent to neutrinos (e.g., the mean free path for a 500 TeV neutrinos is about one Earth diameter). Therefore the upward coming neutrinos of energy larger than a few hundred TeV will be severely attenuated.

5. Backgrounds in Neutrino Telescopes

The first large neutrino telescopes, were designed for proton decay experiments e.g., IMB, KAMIOKANDE, but yesterday's background is today's signal. The neutrino interactions in or around the big proton-decay experiments were considered to be a source of background. In the quest for neutrino astronomy, part of it becomes the signal. But, on the Earth's surface the background due to the downcoming cosmic ray muon is overwhelming, the signal (for calculational purposes now we consider the atmospheric neutrinos as the signal) to noise (called up to down ratio) is of the order of 10^{-12} . Therefore, for shielding purposes, neutrino telescopes are located in deep mines inside mountains or in deep water. For instance, 4000 mwe of shield reduces the up to down ratio to about 10^{-4} . So, it is essentially impossible in the energy regime below 10 TeV to do neutrino astronomy by looking for downcoming muons, because neutrino induced muons are indistinguishable from downcoming cosmic ray muons. This is the reason that for those muons which originate outside the detector (and therefore no vertex determination is possible) only muons coming up from the lower hemisphere are useful. Then the only remaining background is due to the omnipresent atmospheric neutrinos because the earth is transparent to most of them. In general, well shielded detectors can "look" up at about 20° *above* the horizon, while shallow detectors (1000 mwe) can look up only 20° *below* the horizon. The kinematics of neutrino production and the multiple scattering is such that the best overall angular resolution is $\approx 1^\circ$. So in order to find point sources of neutrinos one would at best divide the sky into 1° square pixels and plot the detected muon direction in a Declination versus Right Ascension plot.

Fig. 1. A sky plot of the upward muon data for (a) the IMB experiment and (b) the KAMIOKANDE experiment.

A source would manifest itself as standing above the background caused by the atmospheric neutrino interactions, which constitute a flat background (with a slight zenith dependence visible over tens of degrees).

6. IMB - KAMIOKANDE - MACRO Results

There exists an excellent two year old review of High Energy Neutrino Astronomy [Learned 92]. So I will mainly focus on the progress in the field during the last two years.

Following the procedure outlined above, IMB and KAMIOKANDE have plotted their data [Giacomelli 92], figure 1, with granularity which is commensurate with their angular resolution. Clearly, there is no event clustering of statistical significance. KAMIOKANDE quotes limits from point sources which range from $2 \times 10^{-14} \text{ cm}^{-2}\text{s}^{-1}$ for Vel X-1 to 8.5×10^{-14} for Her X-1. In the '93 Calgary conference, the MACRO collaboration (Di Credico, 1993) reported on 230 days of data taking and calculated limits at the 95% c.l. of steady muon emission of $5.8 \times 10^{-13} \text{ cm}^{-2}\text{s}^{-1}$ for Cyg X-3 and Her X-1. For the Crab they find $6.0 \times 10^{-13} \text{ cm}^{-2}\text{s}^{-1}$. Although they improved these upper limits by a factor of 2 by taking advantage of the temporal characteristics of these sources which are known from photon astronomy, it is obvious that the field needs larger detectors.

TABLE I
Large underground detectors operating in the 80's and 90's

Detector	Location	Area(m ²)	Technique	Primary Purpose
IMB (o)	Ohio, USA	400	Water Cerenkov	Proton decay
Kamioka	Japan	120	Water Cerenkov	Proton decay
Soudan II	Minnesota, USA	100	drift tubes + Fe	Proton decay
MACRO	Gran Sasso, Italy	800	liquid scintillator + streamer tubes	monopoles
LVD	Gran Sasso, Italy	500	liquid scintillator + streamer tubes	supernovae ν

(o) It has been terminated

7. How Big a Detector?

Let us change line of approach now. Consider the recently reported gamma ray observations (WHIPPLE) and use the detected gamma ray flux to calculate the required detector sensitive area.

In the TeV range of energies the WHIPPLE Air Cherenkov γ -ray experiment has detected the following fluxes:

Crab Nebula: 2.5×10^{-11} gammas cm⁻² s⁻¹

Markarian 421: 7.5×10^{-12} gammas cm⁻² s⁻¹

Most likely the gamma ray flux from the Crab is electromagnetic in origin but no one doubts the hadronic origin (i.e. π^0 decay products) of the gamma rays from Markarian 421, which is a well known AGN. Therefore one can safely assume the pessimistic case of equal rate of production of gamma and neutrinos at the site of Markarian 421 and keep in mind that it is much easier to destroy gamma rays than neutrinos in their ≈ 100 Mpc journey from Markarian 421 to Earth. One should mention here that Markarian 421 is the closest blazar on the GRO catalogue of AGNs that emit GeV gamma rays.

Stenger [Stenger 92] has calculated that a deep underwater detector with a geometrical area of 20,000 m² (e.g. DUMAND II or the first phase of NESTOR) will be able to detect, in one year's observation, a source with a neutrino flux greater than $1.2 \approx 10^{-10}$ neutrinos cm⁻² s⁻¹ for neutrinos with energy greater than 1 TeV. (This does not mean that the detector has a threshold of 1 TeV, it is just a handy reference point).

Comparing this with the gamma ray flux from Mk421 we draw the conclusion that we need a detector that should quickly reach an active area of 200,000 m². Conventional particle detectors e.g., scintillators, drift tubes,

resistive plate chambers etc. cost about 10,000 to 20,000 Swiss francs per square meter. This means that a 10^5 m^2 detector will cost ≈ 2000 million Swiss francs which is twice the CERN budget for one year. The conclusion is that the cost must be reduced to 100 - 200 swiss francs per square meter. This is where the water Cherenkov technique comes in.

8. Large Volume Water Cherenkov Detectors

The index of refraction of sea water is 1.35, this gives a Cherenkov angle of 43° . In other words, relativistic particles will "illuminate" the sea water with a 43° degree cone, emitting about 250 Cherenkov photons/cm (between 3000 - 5000 Å) a range where most photomultipliers have a reasonable sensitivity. Then, depending on the water transmissivity (ranging from 20 m in clear lakes to 50 - 60 m in clean deep ocean waters), one can instrument large areas of water fairly cheaply, at a cost of about 100 Swiss francs per square meter. The long range of muons in water helps tremendously, a 1 TeV muon has a range of about 2.5 km in water. A variance to this technique is using the Antarctic ice as a Cherenkov radiator. The high energy physics community has accumulated considerable experience with the water Cherenkov technique mainly from the three big proton decay experiments IMB, HPW and KAMIOKANDE and the various test-deployments down to 4,000 m as done with the DUMAND I and the NESTOR tests, lake BAIKAL at 1,000 m and AMANDA in the ice. The deep water large Cherenkov neutrino experiments will also deploy hydrophones in the hope of determining very high energy neutrino interactions acoustically, the threshold of this technique is in the PeV range. The acoustic pulse is produced by the thermal expansion of the water when heat is deposited by the interaction. The energy transfer is very inefficient, about 10^{-4} [Learned 92], but the advantage is that the attenuation length, in the frequency range of 10 - 20 kHz, is of the order of a few kilometers. So, one could instrument literally, many cubic kilometers at low cost. DUMAND II is deploying hydrophones, while in the acoustic version of NESTOR, called SADC0, preliminary tests show that the usual 14°C ambient temperature of the bottom of the Mediterranean is more advantageous for acoustic detection (lower threshold) than the 4°C ocean bottom temperature. In any case it is far too early to make any comments on the acoustic detection technique. In order to demonstrate some of the advantages of the water Cherenkov technique we show in figure 2 the reconstruction efficiency as a function of the distance from the central axis of the NESTOR detector for vertical muons of energy 1 TeV, 10 TeV and 100 TeV. One should note that a reconstruction efficiency of 80% is achieved with vertical muons that cross 50 to 100 m outside the detector.

Fig. 2. Reconstruction efficiency versus distance from the axis of the tower (vertical incidence of muons) for one NESTOR tower (5° accuracy).

Even if a 10^5 m^2 detector finds neutrino sources, the physics of this field will not be harvested until square kilometer detectors come into operation. For this reason the quest for neutrino astronomy has three benchmarks.

- The reliable operation over a few years of a detector of 10,000 to 20,000 m^2 (i.e. a detector ten times to twenty bigger than the largest neutrino telescope in operation today).
- The quick growth of this detector to cover a sensitive area of 100,000 m^2 .
- The subsequent expansion of the detector in order to instrument an 1 km^2 in a timely and affordable fashion.

Fig. 3. Sky coverage of neutrino telescopes currently under construction. View limits for AMANDA, BAIKAL are 10° below the horizon and for DUMAND, NESTOR 10° above the horizon.

9. Description of Current Projects

The sky coverage by each of the four neutrino telescopes under construction, table II, is shown in figure 3. Note that DUMAND and NESTOR are 177° degrees apart in longitude, so their combination will monitor the Cosmos continuously.

10. AMANDA

The AMANDA project aims at building a neutrino telescope in the ice of the South Pole at a depth of 1000 m. Although the transparency of the ice had not been measured in situ, it was expected to be around 20 m. In this

TABLE II
High energy neutrino telescopes currently under construction

Detector	Location	Date- E.Y.O.(o)	Area (10^{-3} m^2)	Depth (mwe)	Technique	Threshold (GeV)
Baikal NT-200	Siberia	'96	3	1000	WC	10
DUMAND II	Hawaii	'96	20	4760	WC	20
NESTOR	Greece	'97	20	3700	WC	Few
AMANDA	Antarctic	??	8	???	WC in ice	Few

(o) Expected Year of Operation

experiment. 1.2 km long holes were to be drilled in the ice, the phototubes to be placed in and some hours later they would be frozen in. The cost and the limited supply of fuel in the South Pole is such that only 8 inch diameter holes were drilled. As a result of this, the AMANDA phototubes will only have about 1/4 the photocathode area of the 15 inch diameter phototubes used by BAIKAL, DUMAND and NESTOR. On the other hand AMANDA has the advantage that the Antarctic sea is fairly free of radioactive background.

The original plans of the full AMANDA array (figure 4) consist of 9 strings placed in a cylindrical configuration, on the surface of a 30 m radius cylinder, with a tenth string on the axis of the cylinder. The 10 strings are identical, they are 200 m long each, with one phototube every 12 meters, the total number of phototubes is 200. The array was to be located at a depth of 1000 m. The effective area and depth of the AMANDA array are similar to that of the Baikal telescope (i.e. a few thousand square meters for neutrinos of a few TeV).

During the winter (Australian summer) of 93-94 the collaboration deployed four strings to a depth of 1000 m, the deployment of a fifth string at the end of January 94 was not completed due to the breakdown of the drill and the approaching bad weather [Morse 94]. They have studied [Halzen 94] the ice transmissivity using their laser calibration system. Contrary to claims [Halzen 93] the ice does not seem to be bubble free, at least not at depths of 1000 m. Unfortunately the scattering length is extremely short (it varies from 11 cm at a depth of 800 m to 20 cm at a depth of 1000 m). This means that after traversing a few meters the direction of the Cherenkov light is totally randomised and therefore one cannot reconstruct the direction of the muon. However by doing an elaborate study of the calibration data they fit the absorption length to be 59 meters at 515 nm. In a shallow

Fig. 4. The AMANDA array as originally planned.

detector this is a mixed blessing because it shows that the effective area is much larger than what was originally anticipated. Given the shallow depth of 800 - 1000 m, the downcoming high flux of cosmic ray muons cannot be rejected because the very short scattering length does not permit any reconstruction of direction. Since the four deployed strings are frozen in (i.e. cannot be retrieved) the collaboration plans to use them together with their future array. Since one is concerned that the short scattering length might be caused not only by air bubbles alone but by dust, volcanic ashes or fluorescence, a program of measuring the optical properties of ice below 1000 m seems prudent.

The collaboration does not plan to do any drilling in the South-Pole during the 94-95 Australian summer [Halzen 94].

11. Lake BAIKAL

The lake Baikal experiment will be composed of 192 large (15 inch) phototubes (figure 5). The deployment is made in the spring when the lake is frozen, so a solid platform is available. In the spring of 93 part of the detector was deployed, consisting of 36 phototubes, the darkened phototubes in figure 5. The water transmission length is ≈ 20 m and it varies with the

seasons. Further, there seems to be an optical background in the water similar in magnitude of the K^{40} in the ocean. The data is transferred to shore via cable. The detector deployed in March 93 operated for almost one year, 30 of the 36 phototube channels were operating by August 93 and by the spring of 94 only 18 [Spiering 94]. Most of them had some intermittent problems, possibly connected with the substandard manufacture of a switch. All the photomultipliers themselves performed well and there were no problems with water leaks. The laser calibration system worked well. In the spring of 94 (April) again 36 photomultipliers were deployed in a different configuration than in 93. At the end of August 94, 30 channels were working satisfactorily [Wischnewski 94]. Clearly they must improve the reliability of the electronics. The group is studying and understanding the detector performance. They made tremendous progress with their reconstruction algorithms and their up to down rejection. They have demonstrated that their single muon and muon- bundle reconstruction agrees well with their Monte Carlo. They also understand well the zenith response of their detector to downcoming muons. They have not reported yet the reconstruction of any neutrino events. They have calculated preliminary limits on Monopole fluxes i.e. for a GUT monopole $< 3 \times 10^{-16}$ cm²/s.sr [Spiering 94], [Wischnewski 94].

The group deserves the whole hearted congratulations of the international scientific community because they managed to deploy and operate the world's first underwater neutrino telescope under the very difficult conditions that prevail in Russia at the present. They plan to deploy another 70 phototubes in the spring of 95 and to complete the detector in the spring of 96.

12. DUMAND II

The DUMAND experiment [DUMAND 93] is the progenitor of today's neutrino telescopes. They have been studying the problem for more than one dozen years now. They have offered a number of solutions and have developed and made available the technology required to operate and deploy neutrino telescopes in the water. The full DUMAND II array (figure 6) will be deployed at a depth of 4800 m, near Hawaii, and it will consist of an octagon of nine strings (eight on the perimeter and one in the center). A total of 216 large (15 inch) phototubes will be deployed facing downwards. There will be 24 phototubes per string in 10 meter intervals. The radius of the octagon will be 53 m, matching the 45 m long light transmission length that they have measured in the blue part of the spectrum. The total enclosed instrumented mass is about 2.7 Mtons. The sensitive area for a muon of one TeV energy will be 20,000 m² with an angular resolution of better than one degree (standard deviation).

Fig. 5. The Lake BAIKAL array.

The DUMAND II threshold for upcoming atmospheric neutrinos will be larger than 10 GeV so they should be able to study atmospheric neutrino oscillations because they will collect about 3000 atmospheric upcoming neutrino events per year in the full nine string array.

The DUMAND collaboration deployed successfully in December 93 its 36 km long electrooptical cable from the detector to the shore, together with the so called junction box (the plug in box for distribution of electrical power and receipt of data via optical fibers). One string of 22 photomultipliers was also attached to the junction box as well as the environmental and control instruments. Data were taken for a while and in fact one double muon event was reconstructed (cosmic ray). Due to a faulty connector water entered inside the housing which controlled the string electronics and the power supplies shorted out. The string was recovered in January 94 and was repaired. The other two strings are ready now. The collaboration is

Fig. 6. The full DUMAND II array.

ready now to deploy the triad of strings. In order to do this they must use a bathyscaph which will hook the three string to the junction box (and therefore to the cable) which is awaiting on the ocean floor. This operation is scheduled for 1996.

13. NESTOR

The NESTOR collaboration has located near the S.W. of Greece a 8 km by 9 km horizontal plateau at a depth of 3800 m [Resvanis 92]. The depth is constant to within ± 50 m over the entire plateau. The plateau is at a mere distance of 7.5 miles from the shore. Extensive studies of the water transmissivity were made employing I) spectrophotometric analysis of a very large number of samples, II) deployment of photometers in situ (i.e. down to 4000 m) and III) large acceptance photometric measurements in situ.

These measurements show that the water transmission length in the blue part of the spectrum is about 55 m. [Khanaev 92], [Anassontzis 94]. The underwater currents have been measured over five years and they have been found to be minimal [Demidova 92] i.e. a few centimeters per sec. Last, the sedimentology analysis is completed [Trimonis 92]. The NESTOR design differs from that of DUMAND and AMANDA in that it deploys half the phototubes looking upwards, like Baikal, thus having a 4π sensitivity and at the same time will be shielded by 3500 mwe. They employ a total of 168 large 15 inch phototubes like DUMAND but they are clustered closer so that they have a much lower energy threshold.

They have been making tests in situ, since 1991, of a half scale model of their basic detector element. This is a horizontal rigid hexagon made out of titanium, of 16 m radius. At each one of the corners and at its center there is a pair of two 15 inch phototubes (one looking up and the other one down). By stacking 12 of these hexagons in the vertical, with a distance between hexagons of 20 m, they create a tower (figure 7). Figure 8 shows that the effective area of a single NESTOR tower is equivalent to the full DUMAND II. The whole tower will be deployed in a single operation, currently planned for the spring of 97, its sensitive area for TeV muons will be $\approx 20000 \text{ m}^2$ (figure 8). The collaboration hopes to find quickly additional funds to build another six towers in order to deploy them in a hexagonal fashion around the first tower and at a distance of 100 - 150 meters from it (figure 9). This array would have a sensitive area larger than 10^5 m^2 , it would provide an overall angular resolution better than 1° , it would have an enclosed mass of > 20 Megatons and a total cost of about 20 million dollars. Within each one of the 7 towers the energy threshold is a few GeV, i.e. a low threshold active target of 1.5 Megaton mass.

With one NESTOR tower they claim to be able to do almost the same astrophysics of DUMAND II plus two experiments unique to NESTOR: One is atmospheric neutrino oscillations by doing a full zenith fit of the atmospheric neutrinos in an internally normalisable way, independent of cosmic ray flux calculations. They claim to have the sensitivity with only one tower to make a definitive statement to confirm or not the KAMIOKANDE neutrino oscillations claim [Resvanis 92, 93], [Katsanevas 92], [Kourkoumelis 93]. The other is a long baseline neutrino oscillations experiment from CERN in conjunction, perhaps, with another experiment at Gran Sasso which on a two dimensional projection falls on a straight line drawn between CERN and NESTOR [Resvanis 92, 93], [Katsanevas 92, 93].

14. An Affordable 1 km^2 Detector

Assuming operational success of the 7 tower hexagon of hexagonal NESTOR towers the next step is obvious. Employ another six towers in a hexagonal

Fig. 7. One NESTOR tower.

fashion 150 meters around the first hexagon and fill in the gaps between them in the perimeter with six strings. Each string has 24 phototubes (15 inch each) clustered in pairs and spaced with the same spacing between floors of the towers. This addition of 6 towers and six strings will cost less than 25 million dollars and the array will have a sensitive area of $430,000 \text{ m}^2$. For the following step it suffices to use strings only with 24 phototubes each. Employing 18 strings ≈ 150 meters outside the last perimeter will only cost 5 million dollars and the total sensitive area will be $850,000 \text{ m}^2$ for a total cost of 50 million dollars. The enclosed mass will be about 300 Megatons, of which 4 or 5 will be contained within each tower with local energy threshold of a few GeV. figure 10.

Fig. 8. Effective area of one NESTOR tower for three angular reconstruction accuracies.

15. Conclusions

In the next couple of years four large ($\approx 10^4 \text{ m}^2$) neutrino telescopes should be operational and we should learn a lot. In order to study the physics of copious sources of astrophysical neutrinos one would most likely need larger telescopes. It would make sense to pool resources and expertise in order to build jointly an 1 km^2 detector.

Acknowledgements

The author wishes to thank the organisers of this great workshop, especially Heinz Volk and Felix Aharonian. The author thanks A.Bottino, S.Kovesi-Domokos, G.Domokos, J.Learned and V.Stenger for many useful discussions.

Fig. 9. Full NESTOR array (view from above), sensitive area greater than $100,000 \text{ m}^2$, angular reconstruction $\approx 1^\circ$, enclosed volume greater than 20 megatons, total number of phototubes 1176.

Many thanks are also due to his colleagues of the NESTOR collaboration for myriads of useful discussions.

References

- E. Anassontzis, 1994, *Nuclear Instruments and Methods* **A349**, 242.
 Berezinski, 1990, *Astrophysics of Cosmic Rays*, North Holland.
 A. Bottino, 1992, *Fourth International Workshop on NEUTRINO TELESCOPES*, M. Baldo Ceolin, editor, Venice.
 Demidova, 1992, *2nd NESTOR International Workshop*, L.K. Resvanis, editor.
 Di Credico, 1993, *contributed paper to the Calgary 1993 cosmic ray conference by the MACRO collaboration*.
 DUMAND 89, 1993, *Proposal the DUMAND collaboration*.
 T. Gaisser, F. Stecker, A. Harding and J. Barnard, 1986, *Ap. J.* **309**, 674.

Fig. 10. Bird's eye view of the proposed 1 km² NESTOR. Distance between adjacent towers and/or strings is a 150 m, total number of phototubes 2760.

- Giacomelli, 1992, Cosmic Rays 92, Proceedings of the 13th European Cosmic Ray Symposium, July 1992, *Nuclear Physics B*, (Proc. Suppl.) **33A,B**.
- R.Gould and G.Schreder, 1967, "Opacity of the Universe to High-Energy Photons", *Physical Review* Volume **155**, p.1408.
- F.Halzen, 1994, Private communication.
- F.Halzen, 1993, "Particles and the Universe", *Proceedings of the 17th Johns Hopkins Workshop*, Budapest 1993, p.206, World Scientific.
- Hawaii, 1992, High Energy Neutrino Astrophysics, V.J.Stenger, J.G.Learned, S.Pakvasa and X.Tata editor.
- IMB, D.Casper et al, 1991, *Phys. Rev. Lett.* **66**, 2561.
- O.De Jager, F.Stecker, M.Salamon, 1994, "Estimate of the intergalactic infrared radiation field from γ -ray observations of the galaxy Mrk421", *Nature*, vol **369**, p294.
- KAMIOKA, K.S.Hirata et al, 1992, *Phys. Lett.*, **B280**, 146.
- KAMIOKA 94, 1994, "Atmospheric ν_μ/ν_e Ratio in the Multi GeV Energy Range", Fukuda et.al., ICRA Report 321-94-16 (June 94).
- Khanaev, 1992, *2nd NESTOR International Workshop*, L.K.Resvanis, editor.

- S.Katsanevas, 1992, *2nd NESTOR International Workshop*, L.K.Resvanis, editor.
- S.Katsanevas, 1993, *3rd NESTOR International Workshop*, L.K.Resvanis, editor.
- C.Kourkoumelis, 1993, *3rd NESTOR International Workshop*, L.K.Resvanis, editor.
- S.Kovesi-Domokos, G.Domokos, 1992, *2nd NESTOR International Workshop*, L.K.Resvanis, editor.
- S.Kovesi-Domokos, G.Domokos, 1993, *3rd NESTOR International Workshop*, L.K.Resvanis, editor.
- Learned, 1992, Cosmic Rays 92, *Proceedings of the 13th European Cosmic Ray Symposium*, July 1992, *Nuclear Physics B*, (Proc. Suppl.) 33A,B.
- R.Morse, 1994, Private communication.
- L.K.Resvanis et al. 1992, *High Energy Neutrino Astrophysics*, V.J.Stenger, J.G.Learned, S.Pakvasa and X.Tata editor.
- L.K.Resvanis, 1992, *2nd NESTOR International Workshop*, L.K.Resvanis editor.
- L.K.Resvanis, 1993, *3rd NESTOR International Workshop*, L.K.Resvanis editor.
- A.Ringwald, 1993, *3rd NESTOR International Workshop*, L.K.Resvanis editor.
- C.Spiering, 1994, Private communication.
- Stanev, 1992, *Neutrino Telescopes 1992*, M.Baldo-Ceolin, editor.
- F.Stecker et al. 1992, *Ap.J* 390, L49, 1992.
- Stenger, 1992, *2nd NESTOR International Workshop*, L.K.Resvanis, editor.
- A.Suzuki, 1988, *KEK preprint 88-38*, in: *Proceedings of the 13th International Conference on Neutrino Physics and Astrophysics, "Neutrino 88"*, Boston.
- A.Suzuki, 1993, *3rd NESTOR International Workshop*, L.K.Resvanis editor.
- K.S. Thorne and A.N.Zytkow, *Ap.J* 832,212 (1977) and G.T.Bienert, *Ap.J* 380,167 (1991).
- E.Trimonis, 1992, *2nd NESTOR International Workshop*, L.K.Resvanis, editor.
- WHIPPLe: G. Vacanti et al. *Astrophys. J.* 377,467 (1991) M. Punch et al. *Nature* 358,477 (1992).
- R.Wischniewski, 1994, Private communication.