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Underwater laboratories for astroparticle physics and deep-sea science

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Abstract
The exploration of deep-sea environments is currently at the dawn of a new era: underwater laboratories, permanently installed on the seafloor and offering power and on-line data transmission links to the shore, will allow continuous monitoring of oceanographical properties. An important boost in this direction has been provided by the high energy physics scientific community, that aims at the realization of an underwater detector for cosmic high energy neutrinos. Neutrinos are considered a very promising probe for high energy astrophysics and many indications suggest that some of the most energetic sources known in the universe could also be high energy neutrino sources. The expected neutrino fluxes indicate that a km^3-scale detector must be realised to achieve this ambitious aim. The quest for the realization of such a detector in the Mediterranean Sea has already started.

Key words *high energy neutrino telescopes – deep-sea cabled laboratories*

1. Introduction

Ocean depths represent today a new frontier for the exploration of the Earth. The study of these vast regions is a scientific and technological challenge that has been undertaken by scientists of various disciplines.

The main problem in the exploration of deep-sea regions is represented by the very harsh environment (high pressure, corrosion, etc.). Up to now studies have been limited by the possibility to gather data only from surface vessels or by mooring instruments for limited time periods on the sea bottom. Recent developments in the field of communication technology, robotics and sensors may now allow a completely different strategy: realising permanent underwater infrastructures that can allow *in situ* continuous monitoring of deep-sea environments in real time. The possibilities that this new approach can open are of utmost importance in many fields of research: oceanography, geophysics, seismology and deep-sea biology.

Ocean depths have recently also attracted the interest of astrophysicists and high-energy physicists. Some years ago it was proposed to use deep waters as a detector of high energy cosmic particles. The proposed detector could be realized by setting up a lattice of optical sensors able to detect the faint light produced by the passage of these particles through the water. These apparatuses could detect the most elusive known particle, the neutrino, and open the new field of neutrino astronomy.

2. Astronomy with neutrinos

Almost everything we know about the Universe comes from its observation by means of

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electromagnetic waves. From the observational point of view, electromagnetic waves offer many advantages: they are copiously produced, they are stable, electrically neutral and therefore insensitive to magnetic fields, and they are easy to detect over a wide energy range that spans from low energy radio waves to infrared, visible, ultraviolet, *X*-rays up to high energy gamma rays. The disadvantage is that the internal regions of the astrophysical objects, where energy production takes place, are completely opaque to photons and therefore inaccessible to direct observation. For example the light that comes from the Sun comes from its «photosphere». Properties of its internal core, where nuclear reactions take place, can only be inferred indirectly.

Nevertheless, the observation of the sky by means of electromagnetic radiation has allowed the discovery of extremely powerful sources, which are probably powered by massive black holes, located in the most remote regions of the observable Universe. Unfortunately, the observation of these sources through their gamma ray emission is strongly unfavoured since high-energy gamma rays are absorbed by the cosmic Infrared and MicroWave background radiation. This limits the observable horizon for high energy gamma rays. In fact, this horizon is restricted to less than one million light years for gamma rays of more than 10^{15} eV (1 PeV).

Additional information comes from the observation of cosmic rays: protons or heavier nuclei. Unfortunately, due to their charge, these particles are deflected by the galactic and intergalactic magnetic fields, thus preventing the identification of their sources. Moreover, the extremely high-energy charged particles interact with photons of the infrared radiation background and with the cosmic microwave background. This is known as the Greisen-Zatsepin-Kuz'min (GZK) effect (Greisen, 1966; Zatsepin and Kuz'min, 1966).

In order to observe the inner workings of the astrophysical objects and to obtain a description of the Universe over a larger range of energies, we need a probe which is electrically neutral, such that its trajectory will not be affected by magnetic fields, stable, such that it will reach us from distant sources, and weakly interacting so that it will penetrate regions which are opaque to photons. The only candidate particle currently known to have these properties is the neutrino.

Several low energy neutrino detectors are currently active around the world (Boger *et al.*, 2000; Fukuda *et al.*, 2003). These detectors have allowed us to study the neutrino fluxes from the Sun, resulting from the nuclear reactions that take place in its inside, which is not accessible to direct observation. These «telescopes» are also sensitive to neutrinos produced in Supernova explosions. Two detectors, Kamiokande (Hirata *et al.*, 1987) and IMB (Bionta *et al.*, 1987), have in fact recorded a short burst of neutrinos in coincidence with the explosion of Supernova 1987A, which was the latest Supernova explosion taking place at a relatively close distance from the Earth.

Neutrinos interact so weakly with matter (Gandhi *et al.*, 1996) that only huge detectors can collect a sizeable sample of their interactions. Thousands of tons are needed to detect the low energy neutrinos coming from the Sun core, but these volumes are still not sufficient to detect low energy neutrino sources at cosmological distances. High energy neutrinos offer a better detection opportunity since their interaction cross section increases with energy and since the products of their interactions can be more easily detected as their energy increases. An instrument able to detect high-energy cosmic neutrinos and identify their direction of arrival, a «Neutrino Telescope», would enlarge the observation horizon allowing the study of objects at the limit of the Universe.

2.1. *High energy neutrino sources*

Astrophysical sources of high-energy neutrinos have not yet been observed directly, but their existence can be inferred from the properties of cosmic rays.

Primary cosmic rays are protons, with some admixture of heavier nuclei. The energy spectrum follows a power law that extends up to extremely high energies: values exceeding 10^{20} eV have been observed in recent years. Protons themselves have limited use as astrophysical messengers, because they are charged and therefore subject to deflection by cosmic magnetic fields: only the very highest-energy protons are likely to retain any memory of their source direction but, as already mentioned, they suffer from interaction with the background radiation.

The production mechanism of the highest-energy cosmic rays is currently unknown, although Supernova Remnants and Active Galactic Nuclei have been proposed as their sources. Whatever the source, it is clear that accelerating protons to such high energies implies also the production of a large flux of pions, originated in the interaction with the photon background. Pions subsequently decay to yield gamma rays and neutrinos. For these reasons it is generally assumed that the existence of very high-energy protons in the cosmic rays implies the existence of a flux of high-energy neutrinos.

Extra-galactic objects, such as the sources of Gamma-Ray Bursts (GRBs) and Active Galactic Nuclei (AGN), plausibly generate cosmic rays up to the maximum observed energies, and are therefore likely sources of neutrinos in the TeV (10^{12} eV) to PeV (10^{15} eV) energy range. GRBs are transient flashes of gamma-rays, lasting typically for $1 \div 100$ s, that are observed from sources at cosmological distances. Although we do not yet understand in detail the internal mechanisms that generate these powerful explosion, some evidences suggest that they are cataclysmic processes associated with the collapse of massive stars to a black hole. AGN consist of both persistent and flaring sources with apparent luminosities reaching about 10^{48} erg/s. They are tought to be powered by mass accretion onto supermassive ($10^6 \div 10^9$ solar-mass) black holes residing at the centre of galaxies. In both GRBs and AGN, the mechanism of mass accretion is believed to drive a relativistic plasma outflow that results in the acceleration of high-energy particles.

Both AGN and GRBs have been proposed as high energy neutrino sources, and neutrino observations will provide unique information on the physics of the underlying engine, which is not well understood despite many years of research. Other theorized neutrino sources are associated with compact astrophysical objects (SuperNova Remnants, *X*-ray binaries and microQuasars) or with the annihilation of the yet unobserved particles which may constitute the dark matter. A comprehensive review of candidate neutrino sources and flux model predictions can be found in Learned and Mannheim (2000) and in Halzen and Hooper (2002).

Neutrino observations are specifically interesting because the detection of high-energy (>TeV) neutrinos will provide unambiguous evidence for cosmic acceleration of protons and nuclei, and their arrival direction will point to the location of the accelerators.

Neutrino telescopes will permit us not only to look into the engines driving powerful sources such as distant AGN and GRBs that cannot be explored directly with photon observations, but also to look far into the universe. Cosmological sources cannot be observed at photon energies exceeding 100 GeV because of attenuation by γ-γ pair production on the diffuse intergalactic infrared background radiation. By contrast, high-energy neutrinos will propagate unhindered directly to us from their sources. Thus, neutrinos can provide a new window to explore the high-energy phenomena in the distant universe.

A question still remains on how large a high energy neutrino telescope must be to allow for an unambiguous detection of some sources. As we have seen the strongest case is based on the existence of extreme high energy cosmic rays. From this observed high energy charged particle flux we can derive a neutrino flux assuming that a cosmic accelerator produces equal energies in cosmic rays, gamma rays and neutrinos. These flux estimates set the needed scale for a high energy neutrino telescope: a 1 km^2 effective area telescope will be able to detect a few tens of events per year.

2.2. *High energy neutrino detection*

The most promising method to achieve the ambitious goal of realizing a km^2 scale Neutrino Telescope is the tracking of secondary muons produced in the interaction of neutrinos in the volume close to the telescope. High energy muons are extremely penetrating charged particles since they lose energy, interacting with matter, mainly through Coulomb scattering. Processes like the emission of high energy photons (bremsstrahlung), that is typical of high energy electrons, is strongly reduced since muons are heavier (≈200 times) than electrons.

When a high-energy muon, having a velocity v close to the speed of light in vacuum (c), propagates in a transparent medium with index of refraction $n > 1$, its velocity will be greater than the speed of light in the medium that is equal to c/n. In these conditions visible light is radiated along the track with an angle θ_C, with respect to the muon direction, defined by the relation $\cos(\theta_C)=1/(\beta n)$, where $\beta = v/c$. This process, called Cherenkov effect, is similar to the shock wave, the sonic boom, produced when an airplane exceeds the speed of sound in air. In the water, that has a refraction index $n \approx 1.35$ in the blue light region, θ_C is approximately 42°. The light radiated by Cherenkov effect forms a conical wavefront that propagates inside the detector, leading to a relation between the muon direction and the arrival time of photons in different points of the space (fig. 1).

The energy loss of a muon via Cherenkov radiation is only a negligible fraction of the total energy loss and the number of Cherenkov photons emitted in water is roughly 300 per centimeter of track. Nevertheless, numerical simulations show that equipping a large volume of a natural transparent medium (like the oceans or the Antarctic ice) with optical sensors capable to detect even single photon signals one can identify a muon track and reconstruct its direction. Water optical properties will determine the detector granularity (*i.e.* the optical sensor density). Water is transparent only in a narrow range of wavelengths ($350 \leq \mu \leq 550$ nm) in the blue light region of the spectrum. In this region the absorption length in clear ocean waters is about 70 m. This number roughly sets the spacing distance between the optical sensors of the detector.

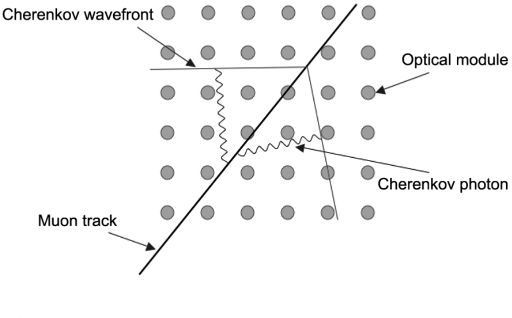

Fig. 1. Detection principle of an underwater neutrino telescope. Astrophysical neutrinos that interact close to the detector generate secondary muons that can be detected by means of their Cherenkov light emission. The measure of arrival times of the Cherenkov light on the optical modules allows to reconstruct the muon direction.

Muons carry, on average, a significant fraction of the neutrino energy and propagate with nearly the same direction of the incident neutrino. For neutrino energies larger than 10 TeV the angle between the originating neutrino and the emerging muon is on the average less than 0.2°. Therefore the reconstruction of the muon, if performed with an accuracy of the order of 0.2° or better, can infer the direction of the incoming neutrino. A significant excess of neutrino events coming from the same direction would yield the identification of an astrophysical source.

A high energy muon can travel up to several km in water. This implies that the Cherenkov Neutrino Telescope will be sensitive to neutrino interactions occurring even far outside the detector instrumented volume.

Muons originated by astrophysical neutrinos have to be selected out of the more intense flux of muons (the background for our signal) produced in atmospheric showers resulting from the interactions of primary cosmic rays (protons and heavier nuclei) in the atmosphere. The atmospheric muon flux at sea level is about times 10^{11} times more intense than the flux of muons produced by astrophysical neutrinos but is typically less energetic, therefore these atmospheric muons cannot penetrate large thicknesses of matter. This property can be used to reduce the background by installing the detectors in an underground laboratory (like the Gran Sasso Laboratory, near L'Aquila in Italy). Obviously a km^3 detector, like the one needed for high energy neutrino astronomy, cannot be hosted in a tunnel or in a natural cave, but one can obtain the same result by deploying it in the ocean depths where the overlaying water would reach the same effect. At 3000 m the flux of atmospheric muons would be reduced by a a factor 10^6 making it feasible the search for astrophysical neutrinos.

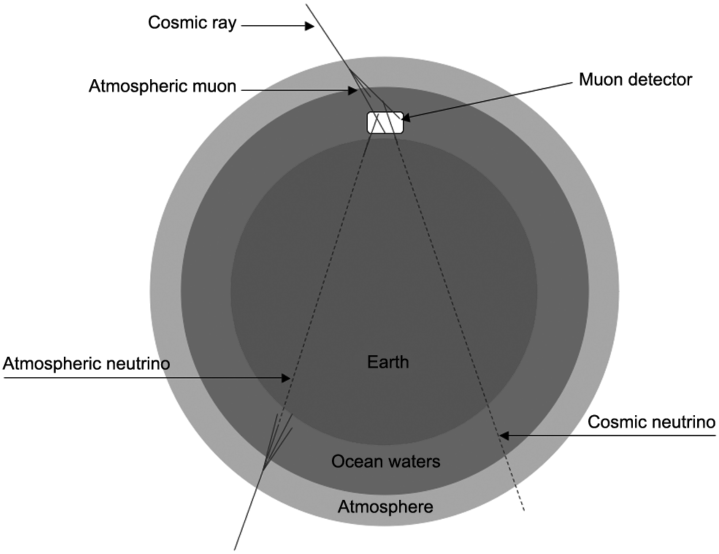

Fig. 2. Detection principle of an underwater neutrino telescope. This instrument will use the whole thickness of the Earth to shield the charged particles cosmic flux and therefore its field of view will be restricted to the hemisphere below the horizon. Nevertheless, a background of atmospheric neutrinos, originated by the interaction of charged particle in the atmosphere in the opposte hemisphere, will always be present.

The role played by seawater is therefore threefold: it constitutes the target where astrophysical neutrinos interact to produce the secondary muons; it acts as a transparent radiator where relativistic muons induce the Cherenkov light; it acts as a shield against the cosmic muon background.

Seawater above the detector can reduce the atmospheric muon background but not totally eliminate it. For each astrophysical neutrino about 10^5 down-going atmospheric muons will cross the detector. But none of these atmospheric muons can cross the Earth, unlike neutrinos that can traverse the whole thickness of the Earth and interact in the vicinity of the detector originating an up-going muon (fig. 2). This fact completely eliminates the atmospheric muon background: a track reconstructed as crossing the detector with up-going direction will be a clear signature of a neutrino-induced muon. The Neutrino Telescope will then be sensitive to neutrinos, originated in astrophysical sources or in atmospheric showers, coming from the Southern Hemisphere, from the «bottom» and not from the «sky» as all the other astronomical instruments we are used to.

However, a remaining background exists, due to neutrinos that are produced in the interactions of charged particles in the atmosphere and are therefore called «atmospheric neutrinos». This background is isotropic and becomes negligible at very high energy (above 10 TeV). Point like sources of cosmic neutrinos can be identified if they can emerge from this background.

3. High-energy neutrino telescopes

In recent years the water Cherenkov technique has been successfully used to detect solar and atmospheric neutrinos in 10^3-10^4 m^3 scale detectors, like SNO (Boger *et al.*, 2000) and SuperKamiokande (Fukuda *et al.*, 2003). As we have seen, the expected number of neutrino events from astrophysical sources in the $10^{12} \div 10^{15}$ eV range is of the order of $10 \div 100$ events per km^2 per year, much less than the number of events expected in the low energy range. Therefore, only 10^9 m^3 scale detectors could allow the source identification.

As we have seen, conceptually the idea at the base of a Cherenkov high energy Neutrino Telescope is simple. A high-energy muon neutrino interacts with a nucleus in the water and produces a muon travelling in nearly the same direction as the neutrino. The high-energy muon track can range from several hundreds metres up to few km, depending on its energy. The Cherenkov light emitted along the muon track, with a well defined angle with the track itself, can be detected by a sparse array of optical sensors, deployed in deep-sea (3000-4000 m depth) and arranged in a geometry that allows the reconstruction of the track direction. The average distance in between the sensors will be a function of the light propagation properties in the water: the lower the light absorption, the higher can be the distance between sensors. Also the detector cost is a function of the water transparency: the longer is the absorption length of deep-sea water the less is the number of light sensors needed to equip the same instrumented volume. Light sensors, also called Optical Modules (OM), constitute the active part of the detector. They are realised with large area (8 to 13 inches) PhotoMultiplier Tubes (PMT) hosted inside pressure resistant glass spheres. They have to provide the information of the intensity of the light that hits their surface and of the photons arrival time. These quantities are transformed locally into digital information that can be transmitted, by means of optical fibres, to a shore laboratory. On shore all the data received can be stored and analysed.

The idea to construct a high energy neutrino detector by instrumenting large volumes of natural media was proposed long time ago by Markov (1960) and Markov and Zheleznykh (1961), but only recently the technological developments in mechanics, electronics and data transmission system seems to be sufficient to transform the project in reality.

The payoff for this choice is that one has to face several technological problems for the construction, deployment and maintenance of the instrument. The construction of km^3 scale neutrino telescopes requires, in fact, detailed preliminary studies and intense R&D efforts.

The layout of the detector must be optimized to achieve an effective detection area close to 1 km^2 together with a pointing accuracy close to the intrinsic uncertainty due to the neutrino interaction and an energy resolution of the order of some tens percent.

The choice of the underwater installation site must be carefully investigated, since water properties strongly influence the detector performance.

The electronics design must limit power consumption and allow the transmission of high data flows from the detector to the shore. The mechanical design must allow easy deployment (and possibly maintenance and recovery) operations and the deployed structures must be reliable over a period of more than 10 years. The positioning system must be realised to determine the position of optical sensors with 10 cm accuracy.

The pioneering effort to develop a neutrino telescope was carried out by the DUMAND collaboration (Babson *et al.*, 1990), starting more than twentyfive years ago in the ocean waters offshore Hawaii Island. After several years the project was abandoned, mainly because of the problems encountered in the deployment of the equipment in the sea (Roberts, 1992).

At present two small scale neutrino telescopes are in operation, one at Lake Baikal and the other, AMANDA, under the ice of the South Pole.

Two other projects, ANTARES and NESTOR, are aiming at the realization of deep-sea prototypal detectors in the Mediterranean Sea. Studies and R&D activities towards the realization of a deep-sea km^3 scale neutrino detector in the Mediterranean have been up to now conducted by the Italian NEMO collaboration. These activities are expected to converge in the future in one large international collaboration to realize the Mediterranean km^3 detector.

3.1. *The running neutrino telescopes*

3.1.1. The Lake Baikal experiment

Baikal was the first collaboration to install an underwater neutrino telescope, which, after more than ten years of operation, is still the only one located in the Northern Hemisphere. The

Lake Baikal Neutrino Telescope (Belolaptikov *et al.*, 1997) exploits the deep fresh water of the great Siberian lake as a detection medium for high energy neutrinos. Its lifetime spans almost two decades from the small initial NT-36 detector, that has proven the capability of the experiment to search for neutrinos by the detection of first neutrino candidates (Balkanov *et al.*, 1999, 2000), to the present neutrino telescope NT-200, which was put into operation in 1998.

The experiment is located in the southern part of Lake Baikal, 3.6 km from the shore. The NT-200 detector is an array of 200 optical modules moored between a depth of 1000 and 1100 m. The deployment and recovery operations are carried out at the end of the winter season, when a thick ice cap (about 1 m) is still present over the lake. The limited depth and the qualities of lake water (light transmission length of $15 \div 20$ m, high sedimentation and bio-fouling rate, optical background due to bioluminescence) limit the detector performances as a neutrino telescope.

3.1.2. AMANDA

The AMANDA (Antarctic Muon and Neutrino Detector Array) detector (Andres *et al.*, 2000) is currently the largest neutrino telescope installed. It is located close to the Amundsen-Scott Research Station at the South Pole and uses the deep Antarctic ice as detection medium (more information on the AMANDA detector can be found on the experiment's web site at http://amanda.uci.edu). In the present stage, named AMANDA-II, the detector consists of 677 Optical Modules all downward oriented. Optical modules are arranged in 19 vertical strings deployed in holes drilled in the ice between 1.3 and 2.4 km depth, where the ice optical properties are suitable for Cherenkov detection.

Thanks to the high absorption length in ice (about 100 m), AMANDA is a good calorimeter for astrophysical events. On the contrary, due to the small light scattering length in ice (tens of cm), the detector angular resolution is worse than the one expected for underwater neutrino telescopes. The main advantage of the AMANDA location is the absence of optical noise sources, like ^{40}K and bioluminescent organisms in the bulk ice.

The AMANDA data have permitted to measure for the first time the upgoing atmospheric neutrino spectrum in the energy range from few TeV to 300 TeV, proving the capabilities of the Cherenkov detection technique and allowing to set what is up to now the most restrictive experimental bound on the diffuse high energy neutrino flux (Ahrens *et al.*, 2003; Ackermann *et al.*, 2005a). A search for cosmic point-like sources has also been attempted using a targeted search strategy focusing on known objects known to be candidate neutrino sources. However, among the collected sample of neutrino induced events, no significant excess due to astrophysical point sources has been observed (Ackermann *et al.*, 2005b).

3.2. *Small scale deep-sea demonstrator detectors*

3.2.1. NESTOR

NESTOR (Neutrino Extended Submarine Telescope with Oceanographic Research) was the first collaboration to propose the installation of a neutrino telescope in the Mediterranean Sea (Tzamarias, 2003). The goal was to deploy a modular detector at about 4000 m in the Ionian Sea (more information on the NESTOR experiment can be found on the experiment's web site at http://www.nestor.org.gr).

The NESTOR site is located 20 km SW offshore Methoni, in the Peloponnese (Greece).

The proposed array should comprise a series of semi rigid structures called «towers». Each tower would be 360 m high and 32 m in diameter and should be equipped with about 170 PMTs looking both in upward and downward directions. In march 2003, after a long R&D activity, NESTOR has successfully deployed 12 Optical Modules at a depth of 3800 m acquiring, onshore, underwater optical noise data and cosmic muon signals (745 events reconstructed) for about one month (Tzamarias, 2005).

3.2.2. ANTARES

The construction of the proposed ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) detector (AN-

TARES collaboration, 1999) is currently in a well advanced stage (more information on the ANTARES experiment can be found on the experiment's web site at http://antares.in2p3.fr). ANTARES will be a demonstrator with a detection area of 0.1 km^2 for high energy muons generated by astrophysical neutrinos, and will be a fundamental step towards the km^3 telescope in deep-sea.

The ANTARES site is located at 2400 m depth, 40 km SE off-shore the city of Toulon (France).

In the present design ANTARES will be a high granularity detector consisting of 12 strings, each one equipped with 75 Optical Modules, placed at an average distance of 60 m. This configuration is optimized to reduce the muon detection threshold down to about 10 GeV allowing the investigation of lower energy phenomena such as atmospheric neutrino oscillations and search for dark matter. With respect to AMANDA and BAIKAL, strongly affected by light scattering in the medium, the dense ANTARES detector is expected to reach a pointing accuracy which will be close to 0.1°.

In December 2002 the detector installation started with the deployment of the so called junction box, which will interconnect electro-optical cables from the strings to the shore. After a first operation of two prototypal lines in spring 2003 a new and improved version of a short line equipped with oceanographic instruments and optical modules has been put in operation in april 2005 and is taking data since then. Data recorded by the optical modules show an unexpectedly high optical background, strongly fluctuating, as a function of time, from a level of 50 kHz to a level of more than 250 kHz, with a strong contribution of bioluminescence bursts (Anton, 2005).

3.3. *Future km^3 neutrino telescopes*

The simultaneous observation of the full sky is an extremely important issue, since the distribution of some neutrino sources is expected not to be isotropic. To achieve this goal two km^3 scale neutrino telescopes, one in each Earth hemisphere, are needed.

In the Southern Hemisphere, and therefore looking at the northern sky, the ICECUBE telescope (Botner, 2005) will be the natural extension of AMANDA to km^3 size. Its construction started in January 2005 with the deployment of the first string. When completed in 2010 it will be an array of 4800 PMT arranged in 80 strings. All the Optical Modules will be downward looking as in AMANDA and simulations show that an average spacing of 125 m between the strings is an optimal compromise between the two requirements of angular resolution of better than 1° and a high energy muon detection area of approximately 1 km^2. It is worth mentioning that under-ice detectors are not affected by radioactive and biological optical noise. This makes them suitable for the search of low energy neutrino fluxes from galactic Supernova explosions (more information on the IceCube detector can be found on the experiment's web site at http://icecube.wisc.edu).

In the Northern Hemisphere the Mediterranean Sea offers the most favourable conditions for the construction and maintenance of an underwater km^3 Cherenkov neutrino detector: optimal water characteristics, deep-sea sites at close distance from shore, proximity to scientific and industrial infrastructures, good weather and sea conditions for a large fraction of the year.

An underwater detector offers, compared to ICECUBE, the possibility to be recovered, maintained and reconfigured. The long light scattering length of the Mediterranean abyssal seawater preserves the Cherenkov photon directionality and will permit excellent pointing accuracy (of the order of 0.1° for 10 TeV muons). Unlike deep polar ice, the sea is a biologically active environment where organisms produce background light. The selection of a marine site with optimal oceanographic and optical characteristics is therefore a major task for the collaborations involved in the km^3 project.

At present, the effort towards the construction of a large area underwater detector is focused on the development of submarine technologies. Deep-sea is an extremely hostile environment where pressure (100 bars per 1000 m depth), together with salinity, reduces the lifetime of most of metals and alloys used in surface and shallow water applications. The efforts presently conducted by the three Mediterranean collaborations (ANTARES, NEMO and NESTOR) will represent a valuable experience in the construction of the underwater km^3 detector, which should take place in the coming years.

4. Research and development for the km^3 detector

The construction of an underwater km^3 scale neutrino telescopes requires detailed preliminary studies: the choice of the underwater installation site must be carefully investigated to optimise detector performance; the readout electronics must have a very low power consumption; the data transmission system must allow data flow transmission, as high as 100 Gbps, to shore; the mechanical design must allow easy detector deployment and recovery operations, moreover the deployed structures must be reliable over more than 10 years; the position monitoring system has to determine the position of OM within ≈10 cm accuracy.

In order to propose feasible and reliable solutions for the km^3 installation the NEMO (NEutrino Mediterranean Observatory) collaboration has been conducting an intense R&D activity on all the above subjects since 1998 (Migneco *et al.*, 2004a), which will be briefly described in this section.

4.1. *Site selection and characterization*

The needs of the underwater neutrino telescope impose a series of requirements that the site must fulfill.

Depth – Thickness of the overlaying water has to be enough to filter out the down-going atmospheric muon background to allow the selection capability of the up-going tracks originated from neutrino interactions in the Earth and/or the water near the detector.

Distance from shore –The data transmission to the on-shore laboratory, as well as the transmission of power from the laboratory to the offshore detector, will be performed via an electro-optical multi-fibre cable. At distances closer than 100 km from the coast, commercial systems allow data and power transmission without special hardware requirements (*e.g.*, amplifiers) that would increase the cost and reduce the reliability of the project. Moreover, the proximity to the coast and to shore infrastructures simplifies the access to the site for deployment and maintenance operations.

Site geology – The seabed has to be flat and stable to allow the mooring of the telescope structures. For the detector safety, it should also be located at some tens of km far from the shelf break and submarine canyons.

Water transparency – The detector performance is not only directly determined by the extension of the instrumented volume but is also strongly affected by the light transmission properties of the water. Mainly two microscopic processes affect the propagation of light in the water: absorption and scattering. Light absorption directly reduces the effective area of the detector, the scattering spreads the photon arrival times and therefore worsens the detector angular resolution.

Optical background – Optical background in seawater comes from two natural causes: the decay of ^{40}K, which is present in seawater, and the so called bioluminescence that is the light produced by biological organisms. The first one shows up as a constant rate background noise on the optical modules (of the order of 30 kHz for a single 10″ PMT). The second one, when present, may induce large fluctuations (both in the baseline and as presence of high rate spikes) in the noise rate. The background directly affects the detector performances, in particular the quality of muon track reconstruction. In a high background environment severe cuts to the photon detector data must be applied, hence reducing the detector effective area.

Downward sediment flux – The presence of sediments in the water can seriously affect the performances of the detector. Sediments increase the light scattering, therefore worsening the track reconstruction angular resolution. Moreover, a deposit on the sensitive part of photon detectors, *i.e.* large surface photomultipliers, reduces the global detector efficiency. A direct consequence is that in a high sedimentation rate environment the operation of upward looking optical modules will not be possible.

Deep-sea currents – These must have low intensity and a stable direction. This is important for several reasons:

– it does not imply special requirements on the mechanical structures;

– the detector deployment and positioning is easier if the water current is limited;

– the optical noise due to bioluminescence, mainly excited by variation of the water currents, is reduced.

The Mediterranean Sea offers optimal conditions, on a worldwide scale, to locate an underwater neutrino telescope. The NEMO Collaboration has performed a long-term research program to characterize deep-sea sites that could be appropriate for the installation of a deep-sea high-energy neutrino detector. Studies of deep-sea water optical properties (absorption and diffusion) and the sites environmental properties (water temperature, salinity, biological activity, optical background, water currents and sedimentation) that will be briefly described in the following have been carried out. This activity has demonstrated that the abyssal plateau in the Ionian Sea (fig. 3) close to the southernmost cape of the coast of Sicily (Capo Passero) shows excellent characteristics to host the km^3 underwater neutrino detector.

The site was selected after a series of measurements in the region at varying distances from the coast. Its location at about 50 km from the shelf break about 80 km from the coast was chosen to ensure the best condition of stability in time of the water parameters and avoid any perturbation coming from the presence of the shelf break.

A geological survey of the area verified the flatness and the absence of any evidence of recent turbidity events. Deep-sea currents were measured to be, in the average, as low as 3 cm/s, never exceeding 15 cm/s.

The study of optical properties in the selected site is extremely important and must be carried out with a long-term program of characterisation carried out in all different seasons. Seawater, indeed, absorbs and scatters photons as a function of water temperature, salinity and concentration, dimension and refraction index of dissolved and suspended, organic/inorganic particulate. These parameters are different in different marine sites and change as a function of time. Seawater oceanographic parameters (temperature and salinity) and inherent optical properties (light absorption and attenuation) were measured as a function of depth, showing that, while at shallow depths water properties change as a function of season, at large depth (>1500) the water column has stable characteristics. The average value of blue ($\lambda = 440$ nm) light absorption length is of the order of 70 m, comparable with that of pure salt water.

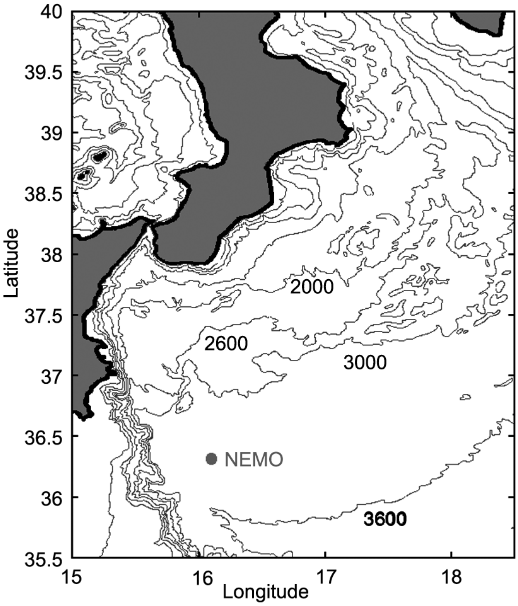

Fig. 3. The south Ionian Sea, showing the location of the site selected and characterized by the NEMO collaboration for the installation of the km^3 neutrino detector.

The optical background noise was measured at 3000 m depth in Capo Passero. Data collected in Spring 2002 and 2003, for several months, show that optical background induces on the optical modules a constant rate of 20-30 kHz (compatible with the one expected from ^{40}K decay), with negligible contribution of bioluminescence bursts. These results were confirmed by biological analysis that show, at depth larger than 2500, extremely small concentration of dissolved bioluminescent organisms.

4.2. *The underwater km^3 detector concept*

The underwater neutrino detector design must be optimised in order to reach the needed effective area of ≈ 1 km^2, a pointing accuracy better than 0.1° for 10 TeV muons, an energy resolution of the order of some tens percent in log(E) and an energy threshold close to 100 GeV.

4.2.1. Detector architecture

It is clear that the architecture of the km^3 detector should stem from a compromise between performances and technical feasibility of the detector.

As a first approach one can consider filling up a volume of about one km^3 with a lattice of equally spaced sensors, with a spacing of the same order of the absorption length of light in water. Taking the horizontal and vertical distance between down looking sensors equal to 60 m turns out in a total number of 5600 sensors arranged in 400 strings.

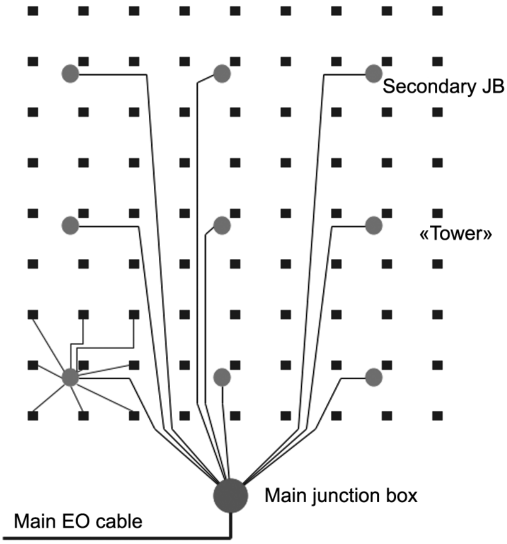

Fig. 4. The proposed layout of the km^3 detector. A hierarchical arrangement of Junction Boxes (JBs), a main one connected to the main electro-optical cable and a number of secondary JBs, will allow to concentrate the data flow coming from the detector structures and, at the same time, distribute the power.

Although the solution of arranging the sensors along a string presents some advantages in terms of simplicity, this architecture can be difficult to realise due to the close distance between strings (60 m) compared with their total height (780 m). Moreover, the large number of structures to be moored and connected raises the cost of the detector.

Therefore, alternative solutions should be studied for the architecture, in which the number of structures is reduced by gathering a relatively large number of sensors on each of them. In particular, constraints on the distance between structures (larger than about 120 m) and on their height (smaller than 1 km) were suggested by a preliminary feasibility study in terms of construction, deployment and maintenance operations of the detector within reasonable costs. Following these suggestions a structure composed by a square array of «NEMO towers», shown in fig. 4, was proposed. The proposed architecture is «modular», in the sense that it is expandable with the addition of extra towers, and configurable with different seafloor layouts.

The performances of this architecture in terms of effective area and angular resolution were evaluated by means of computer simulations, which have shown that a detector built with this architecture can meet the required goal of a detection area larger than 1 km^2 for muon energies larger than 10 TeV with the required angular resolution.

4.2.2. Mechanical structures

The NEMO collaboration has proposed an innovative structure, alternative to the string concept, to host optical modules: the NEMO tower. It is a three dimensional flexible structure composed by a sequence of stories (that host the instrumentation) interlinked by a system of cables and anchored on the seabed. The structure is kept vertical by appropriate buoyancy on the top.

The final features of the tower (number and length of stories, number of optical modules per storey, distance between the stories) can be optimized following the results of numerical simulations. However, the modular structure of the tower will permit us to adjust these parameters to the experimental needs.

In the preliminary design a 16-storey tower, where each storey is made with a 20 m long structure hosting two optical modules at each end (4 OM per storey), has been considered. The vertical separation between storeys is fixed at 40 m, giving a total active height of 680 m. An additional spacing of 150 m is added at the base of the tower, between the anchor and the lowermost storey to allow for a sufficient water volume below the detector. In its working position each storey will be rotated by 90°, with respect to the up and down adjacent ones, around the vertical axis of the tower.

The tower will also be equipped with an acoustic triangulation system for precise position reconstruction purposes and with environmental sensors.

One of the advantages of this structure is the fact that it can be compacted, by piling each storey upon the other, to simplify transport and deployment. The structure is unfurled, reaching its operating configuration, only after its deployment on the seabed.

4.3. *Technological challenges for the km^3 detector*

In recent years many innovations have been applied to underwater technology: DWDM (Dense Wavelength Division Multiplexing) is permitting a large increase in speed and bandwidth of the optical fibres data transmission; newly developed materials (synthetic fibres, alloys, plastics, ...) can improve long term underwater reliability of complex deployed structures; deep-sea ($\approx$3000 m depth) operations with Remotely Operated Vehicles (ROV) or Autonomous Underwater Vehicles (AUV) have been developed and standardised. The design of the Mediterranean km^3 will directly profit of these ultimate technologies.

Concerning the km^3 data transmission system, it is considered a wise approach to transmit all PMT signals, acquired at low threshold level, to shore. In such a way all filtering and event reconstruction procedures can be applied by on-shore data acquisition systems. This approach results in a very high data transmission rate (order of 100 Gbps) that has to be transmitted about 100 km offshore. The above considerations impose the use of a fibre optics transmission system based on DWDM telecommunication technique and composed of mainly passive optical components to reduce power consumption and increase reliability. The proposed NEMO architecture is designed to collect data hierarchically: each storey (hosting 4 OMs) transmits data to a tower main module using an assigned wavelength (or colour). Each tower module collects data from the stories and sends all data, multiplexed in one single fibre, to a collector. This collector can receive data from a number of towers, multiplexes them and sends them to the shore. A mirror system on shore de-multiplexes the signals, recovering data from each storey, then from each very single OM.

To cope with the problem of pressure and corrosion resistance of the underwater containers that have to host the electronics, a new concept has been proposed by the NEMO collaboration. This innovative vessel decouples the two problems by placing an inner pressure resistant steel vessel inside an outer glass epoxy vessel filled with non-corrosive oil.

Another crucial issue for deep-sea detector installation is the feasibility and reliability of underwater connections. However, the technologies of underwater connections have considerably advanced in recent years and reliable connection systems exist that can be operated underwater by means of ROVs. These connectors and their operability have been tested both by the ANTARES and NEMO collaborations.

4.4. *The NEMO Phase 1 project: a multidisciplinary underwater laboratory at 2000 m*

The technological solutions proposed for the km^3 detector require an adequate process of validation. For this reason the realization of a technological demonstrator is underway. It will consist of a subset of the proposed km^3 detector, including some critical elements like a junction box, a tower complete with data transmission, power and calibration systems. This project is called NEMO Phase 1 (fig. 5) and will be installed at the

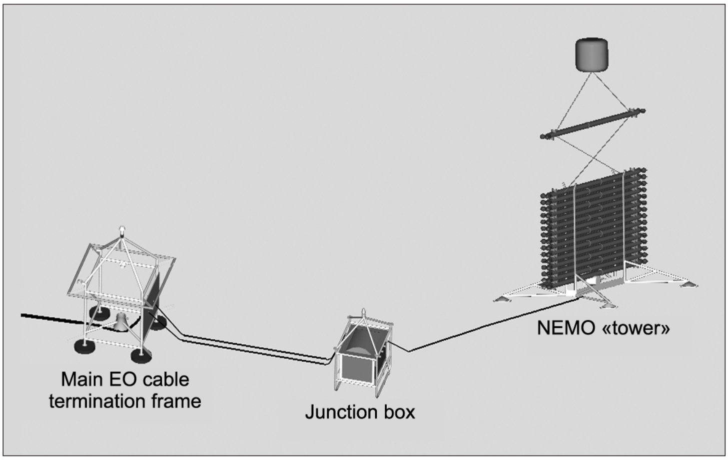

Fig. 5. Schematic layout of the NEMO Phase 1 project.

Underwater Test Site of the Laboratori Nazionali del Sud in Catania at a depth of 2000 m.

The test site of the Laboratori Nazionali del Sud consists of an electro-optical submarine cable, that connects the underwater installation to shore, and a shore station.

The cable system is composed of a 25 km main electro-optical cable, split in two branches, each one 5 km long. One branch dedicated to the NEMO Phase 1 experiment (Migneco *et al.*, 2004b; Piattelli, 2005), and the other one to the SN-1 underwater seismic monitoring station realized by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) (Favali *et al.*, 2003).

A shore station, located inside the port of Catania, will host the energy power system of the laboratory, the instrumentation control system, the landing station of the data transmission system and the data acquisition, as well as a mechanics and electronics laboratory for the assembly of the components.

In January 2005 the project achieved a major milestone with the installation of the two cable termination frames (that host the wet mateable underwater plugs) and the deployment and connection of a small acoustic detection station on the first branch and the SN-1 station on the second branch. Both these stations have been operational ever since, continuously transmitting data to shore.

The project will be completed in 2006 with the installation of the junction box and a prototype four storey tower. In its final configuration this project will not only represent a fundamental test of the technologies for the km^3 detector but it will also be a fully functioning multidisciplinary laboratory at 2000 m depth, offering the possibility of on line connection to a variety of experiments.

4.5. *The NEMO Phase 2 project: a deep-sea infrastructure at 3500 m*

Although the Phase 1 project will provide a fundamental test of the technologies proposed for the realization and installation of the detector, these must be finally validated at the depths needed for the km^3 detector. For these motivations the realization of an infrastructure on the site of Capo Passero has been started. This infrastructure will consist of a 100 km deep-sea cable, linking the 3500 m deep-sea site to the shore, a shore station, located inside the harbour area of Portopalo di Capo Passero, and the underwater infrastructures needed to connect prototypes of the km^3 detector.

The construction details of the cable have still to be defined, but it will have characteristics of power load (greater than 50 kW) and number of optical fibres (20 or more) sufficient to serve a detector such as the proposed NEMO neutrino telescope.

Construction work to restore an already existing building that will become the shore station is going to start soon. The station will host the power system, data acquisition and control facilities, together with a large assembling area.

The completion of this project is foreseen by the end of 2007. At this time it will be possible to connect one or more prototypes of detector structures, allowing a full test at 3500 m of the deployment and connection procedures. This project will also allow a continuous long term on-line monitoring of the site properties (light transparency, optical background, water currents, …) whose knowledge is essential for the installation of the full detector. The possibility of installing multidisciplinary observatories on the site is also foreseen.

5. Multidisciplinary researches in a km^3 scale underwater laboratory

The core discipline served by an underwater Neutrino Telescope is astroparticle physics, but it also has potential to attract significant interest from other scientific communities. In fact, the possibility to monitor continuously over long periods and in real time the sea bottom at depths of the order of 3000 m is of utmost interest to a large number of sea-related disciplines like geophysics, biology, chemistry and environmental sciences.

The underwater world has not yet been extensively explored. Current technology allows autonomous vehicles or Remotely Operated Vehicles (ROVs) to carry out scientific experiments at great depths only for relatively short periods and with accompanying support ships. A deep-sea neutrino observatory will provide the community of deep-sea scientists with a continuous supply of power and a high bandwidth data channel, enabling them to make local real-time studies. Moreover, the information gathered by the optical sensors and other oceanographic monitoring equipment needed for running the neutrino telescope can be of use to oceanographers and marine biologists.

More generally, other types of instrumentation can be added to the observatory array. For example, ocean bottom seismometers can transmit their recordings in real time, thus permitting the localization of the epicenters of seismic events with greater accuracy.

The effectiveness of this approach is shown by the realization of the Test Site Laboratory of the NEMO project, realized with the primary goal of testing technologies for the km^3 project at 2000 m, but also hosting the SN-1 deep-sea seismic and environmental observatory of the Istituto Nazionale di Geofisica e Vulcanologia (Favali *et al.*, 2003), which constitutes the first active node of the European seafloor Observatory Network – ESONET (more information about the ESONET network can be found on the web site at http://www.oceanlab.abdn.ac.uk/research/ESONET.shtml) (Priede *et al.*, 2004).

6. Conclusions

The realization of a km^3 telescope for high-energy astrophysical neutrinos is a challenging task at the frontiers of astroparticle science. Several collaborations in Europe are already working on the realization of first generation demonstrators. More efforts are needed to develop a project for the km^3 detector.

In its five years of activity the NEMO collaboration has contributed in this direction by performing an intense R&D activity.

An extensive study on a site close to the coast of Sicily has demonstrated that it has optimal characteristics for telescope installation, in particular as concerns the water optical properties and its proximity to already existing infrastructures like the LNS in Catania.

A complete study has been performed to analyse all the detector components both in term of their technical feasibility and their installation. This study, which has produced as a result a preliminary design of the detector, has shown that a detector with effective area over 1 km^2 is realizable at an affordable cost.

The realization of a demonstrator of some of the key technological solutions proposed for the km^3 detector has been started at the underwater Test Site in Catania. This project foresees the realization of an underwater laboratory including prototypes of the proposed structures. The completion of this project is foreseen by the end of 2006.

The design, construction and operation of a km^3 neutrino telescope is a great challenge that must be pursued by a large international collaboration. Recently, the scientific and technical experiences gathered by the ANTARES, NEMO and NESTOR collaborations have come together in the KM3NeT consortium (more information can be found on the KM3NeT web site at http://www.km3net.org), formed around the European institutes currently involved in the neutrino astronomy projects (Thompson, 2005), with the aim of carrying out a Design Study for the km^3 neutrino telescope. Based on the leading expertise of these research groups, the development of the km^3 telescope is envisaged to be achieved within a period of three years for preparatory R&D work plus five years for construction and deployment.

The underwater km^3 Neutrino Telescope will finally open a new observational window on the Universe, but will also represent a multidisciplinary facility by construction, since it will offer the availability of deep-sea infrastructures (like connection systems, power distribution, wide band data transmission system, etc.) to scientists of disciplines other than astrophysics, opening the possibility of the continuous on-line monitoring of the deep-sea environment.

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