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# UNDERGROUND NEUTRINO DETECTORS

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(Invited talk given at the $20^{th}$ Johns Hopkins Workshop
on Current Problems in Particle Physics
Heidelberg 26–28 June 1996)

Underground detectors are designed to study neutrinos that originate from the sun, from supernovae explosions, from cosmic ray interactions in the atmosphere and from pointlike sources, galactic or extragalactic. In this report recent results on solar and atmospheric neutrinos are presented and the status of the art in neutrino telescopes is reviewed.

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## 1 Introduction

In underground neutrino physics everything varies over many orders of magnitude:

- the energy, from $\sim 10^5$ eV for pp reactions in the sun to $\sim 10^{19}$ eV for neutrinos produced in the blazars jets;
- the cross section, from $\sim 10^{-46}\text{cm}^2$ for the nuclear reactions relevant to solar neutrinos, to $\sim 10^{-32}\text{cm}^2$ at the highest energies;
- the flux, from $\sim 6\times10^{10}\text{cm}^{-2}\text{s}^{-1}$ to $\sim 10^{-20}\text{cm}^{-2}\text{s}^{-1}$

The decrease in the flux is only partially compensated by the increase in the cross section, therefore the mass of the detectors varies as a function of the processes they are designed to study: from $\sim$ 30 ton for the solar neutrino detectors to $\sim 10^9$ ton for the planned $\text{km}^3$ neutrino telescope.

Underground neutrino detectors differ hugely, but they have two things in common: they are *underground*, since they need to be shielded, as much as possible, from the penetrating cosmic ray component and they are *extremely challenging*; but the physicists who are involved in this field of research feel that the excitement resulting from the exploration of stars and quasars through the most evanescent particles in the world is well worth the effort.

This report is intended more as an introduction to the subject than as an extensive review of the field, and the references are indicative, rather than exhaustive; therefore I apologize to all authors and experiments whose work is not treated adequately or even not quoted at all.

In Sec. 2 I'll cover recent results obtained on solar neutrinos and describe the so called "solar neutrino problem". In Sec. 3 I'll discuss atmospheric neutrinos and the "atmospheric neutrino anomaly". Possible interpretations of the "problem" and the "anomaly" in terms of neutrino oscillations are treated in Sec. 4. Sec. 5 contains a status report on the neutrino telescope projects which are or have been actively pursued. In the last section I'll suggest arguments in favour of the possible relevance of the planned km$^3$ telescope to the detection of electroweak non perturbative phenomena, the main topic of this workshop.

## 2 Solar neutrinos and the solar neutrino problem

The content of this section is largely based on the very comprehensive book *Neutrino Astrophysics* by J.N. Bahcall[1].

Solar neutrinos were detected for the first time almost thirty years ago[2], slightly more than ten years after the detection of the first terrestrial antineutrinos[3]. The method of detection had been suggested twenty years earlier by Pontecorvo[4]. It is based on the neutrino capture reaction

$$^{37}Cl(\nu_e, e^-)^{37}Ar \tag{1}$$

which has a threshold at 814 keV.

The solar neutrino problem started with the discrepancy between the rates for this reaction, calculated in the framework of the Standard Solar Model and the rates measured by the experiment. The discrepancy has been confirmed by three later experiments.

### *2.1 The Standard Solar Model*

The Standard Solar Model (SSM) has been developed by J.N. Bahcall and his collaborators over many years[5–6]. It calculates the flux and the energy spectrum of solar neutrinos and is the generally accepted reference for the experiments.

The main assumption in the model is that the basic energy generating process in the Sun is the fusion of four protons into a Helium nucleus, with emission of two positrons and two electron neutrinos,

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e \tag{2}$$

and a Q value of approximately 26 MeV.

The thermal energy supplied by nuclear fusion is transported by radiation and emerges about one million years later from the surface of the sun as sunlight. The neutrinos, which interact very weakly, pass through the sun at the

speed of light and arrive on earth 8 minutes later. Since both the luminosity and the neutrino fluxes are produced by nuclear reactions in the solar core, the solar constant ($\sim$ 1370 $Wm^{-2}$) places strong constraints on the neutrino flux.

The main nuclear reactions for energy and neutrino production belong to the so called pp chain, which supplies 98.5% of the Sun luminosity. The reactions are listed in Table 1.

Table 1: pp Chain Reactions in the Sun.

| Reaction | Label | $\nu$ Energy (MeV) | Flux ($10^{10}cm^{-2}s^{-1}$) |
|---|---|---|---|
| $p + p \rightarrow {}^2H + e^+ + \nu_e$ | pp | $\leq 0.42$ | 6.0 |
| $p + p + e^- \rightarrow {}^2H + \nu_e$ | pep | 1.44 | 0.014 |
| ${}^2H + p \rightarrow {}^3He + \gamma$ | | | |
| ${}^3He + {}^3He \rightarrow {}^4He + 2p$ | | | |
| ${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$ | hep | $\leq 18.8$ | $7.6 \times 10^{-7}$ |
| ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$ | | | |
| ${}^7Be + e^- \rightarrow {}^7Li + \nu_e$ | ${}^7Be$ | 0.86(90%) | 0.47 |
| | | 0.38(10%) | |
| ${}^7Li + p \rightarrow {}^4He + {}^4He$ | | | |
| ${}^7Be + p \rightarrow {}^8B + \gamma$ | | | |
| ${}^8B \rightarrow {}^8Be + e^+ + \nu_e$ | ${}^8B$ | $< 15$ | $5.8 \times 10^{-4}$ |
| ${}^8Be \rightarrow {}^4He + {}^4He$ | | | |

Important for neutrino production are also the reactions of the CNO cycle, listed in Table 2, in which the fusion of four protons into a Helium nucleus is achieved through catalization from carbon, nitrogen and oxygen[a].

### *2.2 Solar Neutrino Experiments*

Solar neutrino experiments are very difficult since the rates are low and the backgrounds from natural radioactivity and from cosmic rays are high.

To date four experiments have produced results. They belong to two different cathegories: radiochemical experiments, which detect the atoms formed in nuclear transmutations due to neutrino interactions, and electronic or real time experiments, which detect the scattered electron in the reaction

$$\nu + e^- \rightarrow \nu + e^- . \tag{3}$$

[a]The labels indicated in the Tables will be used in the following text to identify the various neutrino producing reactions.

Table 2: CNO Cycle Reactions in the Sun.

| Reaction | Label | $\nu$ Energy (MeV) | Flux ($10^{10}cm^{-2}s^{-1}$) |
|---|---|---|---|
| $^{12}C + p \rightarrow ^{13}N + \gamma$<br>$^{13}N \rightarrow ^{13}C + e^{+} + \nu_e$<br>$^{13}C + p \rightarrow ^{14}N + \gamma$ | $^{13}N$ | $\leq 1.20$ | $6.1 \times 10^{-2}$ |
| $^{14}N + p \rightarrow ^{15}O + \gamma$<br>$^{15}O \rightarrow ^{15}N + e^{+} + \nu_e$<br>$^{15}N + p \rightarrow ^{12}C + ^{4}He$ | $^{15}O$ | $\leq 1.73$ | $5.2 \times 10^{-2}$ |
| $^{15}N + p \rightarrow ^{16}O + \gamma$<br>$^{16}O + p \rightarrow ^{17}F + \gamma$<br>$^{17}F \rightarrow ^{17}O + e^{+} + \nu_e$<br>$^{17}O + p \rightarrow ^{14}N + ^{4}He$ | $^{17}F$ | $\leq 1.74$ | $5.2 \times 10^{-4}$ |

The first, and for almost twenty years the only, experiment designed to study solar neutrinos is the $^{37}Cl$ or Homestake experiment of R. Davis and collaborators[7]. It is a radiochemical experiment, located at a depth of 1480 m (4100 hg/cm$^2$) in the Homestake Gold Mine in Lead, South Dakota. The experiment has been taking data since 1967.

The target is a 380 m$^3$ tank containing 615 ton of perchloroethilene($C_2Cl_4$); $^{37}Cl$ represents 24% of the natural clorine, so that there are approximately 125 ton of $^{37}Cl$ in the tank.

Every few months the $^{37}Ar$ produced in reaction 1 is removed from the tank by flushing it with helium. $^{37}Ar$ is unstable and transforms again into $^{37}Cl$ via electron capture, with a half life of 35 days.

The argon is trapped, first in a large and successively in a small charcoal trap, purified and transferred to small proportional counters, where are detected the 2.82 keV Auger electrons produced in the electron capture process. The counting continues for about one year, about 15 atoms of $^{37}Ar$ are extracted from the $\sim 10^{30}$ atoms in the tank.

Due to the 814 keV threshold of reaction 1, the experiment is not sensitive to pp neutrinos. Given the increase of the neutrino cross section with energy, 70–80% of the rate is expected to come from $^{8}B$ neutrinos.

Two more radiochemical experiments have been taking data in the last few years: the GALLEX experiment[8], in the Gran Sasso Laboratory in Italy and the SAGE experiment[9], located in the Baksan underground laboratory in the Caucasus Mountains.

Both experiments are based on the detection of the Germanium atoms produced in the reaction

$$^{71}Ga(\nu_e, e^-)^{71}Ge \tag{4}$$

with a 233 KeV threshold, which allows the detection of neutrinos from the basic pp reaction. $^{71}$Ge transforms back into $^{71}$Ga via electron capture, with a half life of 11.4 days.

The GALLEX experiment uses 30 ton of Gallium, 40% of which is $^{71}$Ga, in a solution of $GaCl_3$ in hydrochloric acid. The SAGE experiment uses 55 ton of metallic Gallium, which is liquid below 30° C. For both experiments the exposure time is of the order of three to four weeks.

The results from radiochemical experiments are presented in terms of rates, that is in terms of the average of the product of the nuclear neutrino capture cross section times the incoming neutrino flux: R=$< \sigma \cdot \phi >$. To measure the rates and compare with theoretical calculations the Solar Neutrino Unit is used (1 SNU=$10^{-36}$ captures/target atom/s).

Recent results from the three experiments have been presented at the Helsinki neutrino conference of June 1996:

**Homestake**[10] R = 2.56±0.16 SNU

**GALLEX**[11] R = 70±8 SNU

**SAGE**[12] R = $72^{+12}_{-10}$ SNU

The second experiment to detect solar neutrinos was the Kamiokande experiment, a real time detector, originally designed to search for proton decay, which started recording data on solar neutrinos ( Kamiokande II[13]) in 1987.

Kamiokande is a water Cerenkov detector, located 1000 m underground (2700 hg/cm$^2$) in the Kamioka zinc mine in Gifu, central Japan. The detector contains 3000 ton of water viewed by 948 photomultipliers. The fiducial volume used for solar neutrino detection is 680 m$^3$.

Neutrinos are detected through the elastic scattering reaction 3 and therefore the experiment is sensitive to all neutrino flavours, but the $\nu_\mu$ and $\nu_\tau$ neutral current cross sections are lower than the $\nu_e$ cross section by a factor of approximately seven.

The detector can measure the energy and the angle of the recoil electrons and therefore Kamiokande is the only experiment which has been able to establish that indeed the detected neutrinos originate from the direction of the sun. The energy threshold was initially 9 MeV, and has been lowered to 7 MeV in 1990 (Kamiokande III); it could not be lowered further to avoid radioactive low energy background mainly from radon, which is abundantly produced in underground caverns.

With a 7 MeV detection threshold the experiment is sensitive to $^8$B and hep neutrinos.

The final measurement on the solar neutrino flux from 1043 days of running of Kamiokande II and 1036 days of running of Kamiokande III has been presented in Helsinki:

**Kamiokande**[14] $\phi = (2.80 \pm 0.19) \times 10^6$ cm$^{-2}s^{-1}$

A new, very much enlarged version of the Kamiokande experiment, Superkamiokande[15], with a tank of 40 m diameter and 42 m height which contains 50000 ton of water has started taking data on 1 April 1996.

The central 32000 ton of water are surrounded by 11200 twenty-inch photomultiplers. The 18000 ton outer part of the detector, used for shielding and anticoincidence is viewed by 1800 eight-inch photomultipliers. Only the central fiducial volume of 22000 ton is used for solar neutrino detection.

An increase of the number of events of a factor of 100 in comparison with Kamiokande is expected. Due to the much larger shielding the electron detection threshold can be lowered to 5 MeV. The first atmospheric neutrino events have already been detected and analyzed; results on solar neutrinos are eagerly awaited.

### *2.3 The Solar Neutrino Problem*

The comparison between the rates measured in the radiochemical solar neutrino experiments and the rates predicted by the SSM is presented in Table 3. The first column contains the experimental data, expressed in SNU. For the Gallium experiments the results from GALLEX and SAGE, which are very close, have been averaged. The second column contains the average of the predictions from two versions of the SSM[6,16], which differ slightly in the high energy part of the spectrum. The third column contains the ratio between data and predictions.

Table 3: Comparison of the Results from Radiochemical Experiments with the SSM Predictions

| Target | Data (SNU) | SSM (SNU) | Ratio |
|---|---|---|---|
| $^{37}$Cl | 2.6 | 7.1 | 0.35 |
| $^{71}$Ga | 71 | 127 | 0.56 |

In Table 4 the comparison between the flux measured in Kamiokande and the SSM calculation is presented.

Table 4: Comparison of Kamiokande Results with SSM Predictions

| Target | Data ($10^6 cm^{-2}s^{-1}$) | SSM ($10^6 cm^{-2}s^{-1}$) | Ratio |
|---|---|---|---|
| $H_2O$ | 2.8 | 5.1 | 0.55 |

From the comparisons presented in Table 3 and Table 4 it is clear that a definite deficit, in comparison to the calculations, is present in the data from all experiments. There is general consensus that it is very hard to explain this deficit in terms of standard or non standard solar models[17–18].

To the non expert a problem which consists in a discrepancy of a factor of two between the measured rates and the results of calculations which depend (at least in part) on very high powers of the Sun's central temperature might seem more an astounding success than a problem. But the experts take it seriously and tend to interpret it in terms of non standard neutrino properties, and notably in terms of neutrino oscillations, to be discussed in Sec. 4.

The most important question is whether the deficit is energy independent or if it is a particular energy domain to be depleted. Since the clorine experiment, which covers a broader energy region, seems to show a higher deficit than Kamiokande the current interpretation is that neutrino oscillation parameters are such that pp neutrinos are untouched, boron neutrinos are suppressed in the low energy part of the spectrum and beryllium neutrinos are totally suppressed.

### *2.4 Future Directions*

Many projects are currently being developed in order to improve the solar neutrino measurements and give an answer to the open questions. They are essentially of two types: low threshold experiments designed to address directly the beryllium neutrinos question (Borexino, HELLAZ) and high threshold experiments, sensitive to neutral current events, which can address directly the question of neutrino oscillations: SNO, Icarus, and the already mentioned Superkamiokande.

- Borexino[19] is a proposed 300 ton liquid scintillator detector, to be located in the Gran Sasso Laboratory. The liquid scintillator will be contained in a transparent vessel, surrounded by 3600 ton of ultra pure water. It will

be mainly sensitive to beryllium neutrinos, detected through the elastic scattering reaction 3.

- HELLAZ[20] is the project for a high pressure, low temperature Time Projection Chamber (TPC), containing 12 ton of helium. The very long radiation length of helium allows the measurement of direction and energy of the recoil electrons from the pp neutrino elastic scattering reaction 3. The expected energy threshold is 100 keV and the expected rate is 33 events/day. The proposed location for the detector is the Gran Sasso Laboratory.

- SNO [21]is a 1000 ton heavy water imaging Cerenkov detector, located 2070 m below ground in a nickel mine near Sudbury in Canada. The heavy water will allow the detection of charged current events, through the reaction

$$\nu_e + {}^2H \rightarrow p + p + e^- \tag{5}$$

and of neutral current events through the reaction

$$\nu + {}^2H \rightarrow p + n + \nu \tag{6}$$

The charged current reaction, for which the electron detection threshold is 5 MeV, will allow the measurement of the shape of the high energy part of the $^8$B $\nu$ spectrum. The expected event rate is 15 per day.

The neutral current reaction is sensitive to all neutrino flavours. The signature is given by the detection of the neutron: four events per day are expected. The neutral current to charged current ratio is sensitive to neutrino oscillations. The detector will also be sensitive to the elastic scattering reaction 3.

- ICARUS [22] is a proposed 600 ton (to be successively increased to 5000 ton) liquid argon TPC to be installed in Hall C of the Gran Sasso Laboratory. It will detect electrons from reaction 3 with a 5 MeV threshold and compare the results with the $\nu_e$ absorption on the argon nucleus.

## 3 Atmospheric Neutrinos and the Atmospheric Neutrino Anomaly

Atmospheric neutrinos are the decay end products of pions, kaons and charm particles produced in the upper layers of the atmosphere by the interactions of primary cosmic rays.

The first atmospheric neutrinos were detected by the Kolar Gold Fields project [23] in India and by the Case Witwatersrand Irvine collaboration [24] in

South Africa. Only muons produced by neutrino interactions in the rock surrounding the scintillator detectors were recorded. The signal was a very clear plateau in the plot containing the muon flux as a function of depth, for depths greater than 14000 hg/cm$^2$ (see Fig. 9 in Ref [25]). The measured flux was approximately $2\times10^{-13}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$. The number of events was quite small, given the small areas of the detectors.

Much larger statistics have been collected by the large underground detectors developed for proton decay searches.

### *3.1 Atmospheric Neutrino Experiments*

Seven experiments have taken atmospheric neutrino data in recent years, two of them are water Cerenkov detectors, Imb-3 [26] and Kamiokande [27], Baksan [28] is a liquid scintillator and concrete calorimeter, while NUSEX [29], Frejus [30], Soudan-2 [31] and MACRO [32] are tracking calorimeters. Their detection threshold is of the order of few MeV. Two types of measurements are performed:

- determination of the upward going muon flux produced by neutrino interactions in the rock below the detector (upward muons)
- identification of the interactions which occur within the detector (contained events).

The results of the measurements are compared to simulated predictions, which are treated through the same analysis chain as the detected events, to take into account detector acceptance and efficiency.

Predictions of the flux of atmospheric neutrinos depend on the primary cosmic ray flux at the top of the atmosphere and on high energy hadron–hadron cross sections. A discrepancy of the order of 30% among the different calculations [33–36] is therefore not surprising. But the discrepancy is reduced to less than 5% in the calculation of the ratio $(\nu_\mu+\bar{\nu_\mu})/(\nu_e+\bar{\nu_e})$ In table 5 are presented the results, expressed in terms of the ratio of measured to simulated ratios $((\nu_\mu+\bar{\nu_\mu})/(\nu_e+\bar{\nu_e}))_{data}/\ ((\nu_\mu+\bar{\nu_\mu})/(\nu_e+\bar{\nu_e}))_{MC}$, from the experiments which can measure contained events.

It is evident from the table that the measured ratio is definitely lower than the predicted. This fact constitutes the atmospheric neutrino anomaly. A natural explanation of the anomaly is in terms of neutrino oscillations, that will be discussed in the next Section.

In the analysis of upward muons the situation is much less clear than for contained events, since the flux is measured and in this case there is no cancellation of uncertainties for the predictions.

Table 5: Atmospheric Neutrino Results

| Experiment | Ratio |
|---|---|
| IMB-1 | 0.68±0.08 |
| IMB-3 | 0.54±0.05 |
| Kamiokande | 0.60±0.06 |
| NUSEX | 0.99±0.29 |
| Frejus | 0.87±0.13 |
| Soudan-2 | 0.64±0.19 |

The average incoming neutrino energy for upward muon events is of the order of 100 GeV, compared to about 1 GeV for contained events. Also in this high energy regime the discrepancy among different flux predictions [37-40] is over 20%.

There are experimental indications [32] of a possible deficit of the measured upward rate as compared to calculations and of a distortion of the angular distribution, of still low statistical significance. The measurement of the angular distribution is very important for an interpretation of the deficit in terms of neutrino oscillations, given the very large difference in neutrino paths between horizontal (~300 km) and upward (~13000 km) incidence.

## 4 Neutrino Oscillations

If neutrinos are massive and neutrino flavour is not conserved the weak eigenstates $\nu_e$, $\nu_\mu$ and $\nu_\tau$ could be a mixing of the mass eigenstates $\nu_1$, $\nu_2$ and $\nu_3$ and there could be oscillations among the different flavours [41-42].

In a two component oscillation model, which is a good approximation if the masses are widely separated, two parameters are sufficient to describe the process:

- $\Delta m^2$, the difference between the squares of the mass eigenstates
- $\sin^2 2\theta$, where $\theta$ is the mixing angle.

For oscillations in vacuum the probability that a neutrino remains a neutrino of the same type after travelling a distance L is given by the expression

$$P(\nu \rightarrow \nu) = 1 - sin^2 2\theta \cdot sin^2(\pi L/L_o) \tag{7}$$

where the oscillation length $L_o$ is given by

$$L_o = 4\pi E_\nu/\Delta m^2 \approx 2.5(km)E_\nu(GeV)/\Delta m^2(eV^2) \tag{8}$$

The oscillation length determines the observability of oscillations in an experiment:

- if $L \ll L_o$ no effect is visible,
- if $L \approx L_o$ the oscillation pattern is displayed,
- if $L \gg L_o$, an average reduction of the signal is detectable.

The presence of matter in the neutrino path modifies the picture [43-44]: due to charged current interaction with atomic electrons, electron neutrinos have a different index of refraction in matter than other flavours, which can lead to a resonant amplification of the oscillations.

The main question in discussing the solar neutrino deficit in terms of neutrino oscillations is the energy dependence of the effect. If there is an energy dependence, the most favoured solution is matter enhanced oscillations [18,44].

In this case beryllium neutrinos are strongly suppressed, $\nu_e$ transform into $\nu_\mu$ in the Sun, where the mixing angle is enhanced by the electron density, with an oscillation length of a few thousand km.

The parameters of the solution are

$$\Delta m^2 \approx 5 \cdot 10^{-6}, sin^2 2\theta \approx 0.008 \tag{9}$$

In this case the atmospheric neutrino anomaly solution must be found with a full three generation [45-46]formalism, using also information from reactor and accelerator experiments. The analysis is compatible with the hypothesis that there are two scales of neutrino mass squared difference which can accommodate the solar neutrino problem (at a scale of about $10^{-5}$ eV$^2$) and the atmospheric neutrino anomaly (at a scale of about $10^{-2}$ eV$^2$).

In the hypothesis that the solar neutrino depletion is energy independent, a complete three flavour analysis of the solar and atmospheric neutrino data, together with the data from reactors and accelerators, has been performed recently [47], which claims to find a unique solution for the values of the masses and mixing angles for the mass eigenstates.

Assuming that the mass eigenstates follow the hierarchy $m_1 \ll m_2 \ll m_3$ the values for the masses are $m_1 \ll 10^{-2}$ eV, $m_2$=(0.18±0.06) eV and $m_3$=(19.4±0.7) eV, with mixing angles $\theta_{12} = 0.55 \pm 0.08$, $\theta_{13} = 0.38 \pm 0.06$ and $\theta_{23} < 0.03$.

Second generation solar and atmospheric neutrino experiments, together with new reactor and accelerator experiments, short and long base line, will undoubtedly completely clarify the situation in the next few years.

## 5 Neutrino Telescopes

Neutrino telescopes are in reality muon detectors: they detect the Cerenkov light produced by muons traversing a transparent medium, water or ice. They consist of a lattice of photomultiplers, protected by pressure resistent glass housings. Their purpose is to identify muons produced by neutrino interactions in the surrounding medium. At high energy the muon follows closely the neutrino direction ($< \theta > \sim 1.5^\circ/\sqrt{E_\nu(TeV)}$), therefore the direction of the muon will point to the neutrino source.

It is now generally accepted that the most likely pointlike neutrino sources are extragalactic: Active Galactic Nuclei, which are the most powerful emitters of radiation in the Universe, seem at present to be the best candidates for detection by neutrino telescopes.

While the individual AGN neutrino fluxes might be too low to be detected by the experiments now under construction, there is a general consensus[48 – 53] that the integrated flux will be detectable.

Since the incoming neutrino flux is very low, a very large detection area is required and in order to keep the costs within a reasonable bound there must be large spacing between the lattice elements, therefore a high transparency of the medium is an important prerequisite.

Many neutrino telescope projects have been proposed (see Ref. [54] for a review), of which four have been actively pursued. In order of seniority they are: DUMAND, Baikal, AMANDA and NESTOR (see Ref. [55] for a recent review), their principal characteristics are listed in Table 6.

The backgrounds for the detectors are of two types:

- optical backgrounds.
- downcoming muons from atmospheric showers.

. The fundamental optical background in the sea is due to $^{40}$K decays. The $^{40}$K isotope, with a half- life of $1.27 \times 10^9$ years, represents 0.0118% of the natural potassium. The main decay mode, with a branching ratio of 89.5%, is $\beta$ decay to $^{40}$Ca. The maximum electron energy is 1.31 MeV.

A second source of optical background is bioluminescence, present in the sea and also in the lakes.

The downcoming muon flux decreases from approximately $10^2$ $m^{-2}s^{-1}sr^{-1}$ on the surface to $\sim 10^{-2}$ $m^{-2}s^{-1}sr^{-1}$ at a depth of 1000 m and to $\sim 10^{-4}$ $m^{-2}s^{-1}sr^{-1}$ at a depth of 4000 m.

The main difference among the projects consists essentially in a different evaluation of the importance of the downcoming muon background. DUMAND and NESTOR have chosen to go very deep and therefore they prefer to work

in the sea and face the difficulty of deployment inherent in a sea operation and the background noise from $^{40}K$ (50–100 kHz in each photomultiplier).

Baikal and AMANDA have chosen a relatively easier deployment and a site which is less deep.

Table 6: The four Projects

| Detector | Loc. | Depth (km) | Medium | Number PMT | PMT size (inches) | Array Height (m) |
|---|---|---|---|---|---|---|
| DUMAND | Hawaii | 4.8 | sea | 216 | 15 | 230 |
| Baikal | Siberia | 1.1 | lake | 192 | 15 | 70 |
| AMANDA | S. Pole | 2.0 | ice | 478 | 8 | 190 |
| NESTOR | Greece | 3.7 | sea | 1176 | 15 | 220 |

### *5.1 DUMAND*

DUMAND is the precursor of all neutrino telescopes, it has been developed for many years and has created the technology for working in the sea.

The detector consists of eight strings, spaced horizontally by 40 m in an octagonal pattern with a ninth string in the center. On each string there are 14 optical modules, spaced vertically by 10 m, 14 lasers for calibrations and detectors for environmental monitoring. An optical module (OM) consists of a glass sphere containing a fifteen-inch photomultiplier and the necessary electronics. A junction box to connect the cables from the nine strings to the electrooptical cable which transmits the data to shore is at the bottom of the central string.

The cable was laid from the site to the shore station in December 1993. One string was installed and took data for a few hours, but then failed because of a leak in the central electronics housing. The string was later recovered, by actioning a remote control release which allowed the string to float to the surface. In June 1995 a Remotely Operated Vehicle was used to inspect the junction box, which appeared to be in excellent condition, after two years at the bottom of the ocean.

The effective area of DUMAND for muon detection is about 20000 $m^2$, and the volume inside the open cylinder is about $2\times10^6$ ton. The threshold energy is about 20 GeV for muons, the downgoing cosmic ray muon rate is about 3/min.

The calculated[56] number of muon events per year expected in DUMAND from AGNs according to various models[49–52] presented at the workshop in Hawaii in March '92, and for atmospheric neutrinos[37] are listed in Table 7.

Table 7: Number of Muon Events per Year Expected in DUMAND

| Source | $E_\mu$ $> 100\ GeV$ | $E_\mu$ $> 10\ TeV$ | Model |
|---|---|---|---|
| Sum of AGNs | 154 | 66 | SDSS |
| | 109 | 23 | Protheroe |
| | 366 | 75 | Biermann |
| | 897 | 148 | Sikora |
| Atmosphere | 2950 | 23 | Volkova |

Unfortunately in Summer 1996 financial support for DUMAND has been withdrawn.

### *5.2 Lake Baikal*

The Baikal Neutrino Telescope has started operation in 1993 at a depth of 1100 m in Lake Baikal[57] in Siberia. The site studies began in 1980 and the deployment technique which uses, at the end of the winter, the frozen surface of the lake as a solid platform was developed in the meantime.

An optical background, increasing in the spring, due to bioluminescence has been found in the lake water, at a rate similar to that produced by the $^{40}$K in the sea.

From 1993 to 1995 the detector NT-36 consisted of three strings anchored to the bottom of the lake and held in the vertical position by buoys. Each string had twelve QUASAR photomultipliers which have a time resolution of 2 ns. The photomultipliers are in clusters of four, two facing upwards and two facing downwards, in local coincidence.

In April 1995 NT-36 was upgraded to NT-72 and in April 1996 to NT-96 with four strings and 96 photomultipliers.

Over 30 million events have been recorded and two upward going muons have been found. Given the relatively small depth of the site, the probability of misidentification of two downgoing muons is not negligible, but rather small, estimated at less than 3%.

The installation of the NT-200 array, with 192 photomultipliers and an effective area of about 2000 m$^2$ is forseen for the winter 1997–1998.

### *5.3 AMANDA*

The AMANDA project [58] aims to exploit the deep ice at the South Pole to build a neutrino detector consisting of strings equipped with photomultipliers.

The polar ice is free from bioluminescence and radioactivity due to $^{40}K$, but at shallow depths contains many air bubbles which should disappear at a depth of more than a thousand meters. The advantage of a polar experiment is that the ice forms a rigid support structure for the detector elements. At the South Pole there is a well equipped american base which provides the infrastructure.

During the antarctic summer 1993–1994, a prototype detector consisting of four strings, each with 20 photomultipliers was deployed to a depth of 800 to 1000 m. The spacing between photomultipliers is 10 m, the photomultiplers are downfacing, like in DUMAND, to optimize the detection of upward going muons. Each string was put in a hole of 60 cm diameter and 1 km depth, drilled by hot water. It took four days and 12000 liter of fuel to drill one hole and one day to deploy the string [59].

It was found that at those depths the bubbles have not yet disappeared, giving to the ice a milky appearance which precludes track reconstruction, but at the same time analysis of the data indicates that the absorption length for blue light in deep ice is extremely long. If this remains true at the greater depths were scattering is not dominant, the detector spacing could be very large.

A new drill was performed in the 1995–1996 season and a new array has been deployed down to 2 km.

### *5.4 NESTOR*

The NESTOR project is described in detail in the proceedings of two workshops [60–61] held in Pylos in 1992 and 1993. Recent status reports have been presented [62]. The selected site is an underwater plateau, at a depth of 3.8 km and at a distance of eleven nautical miles from the town of Methoni, near Pylos in South-West Greece. The location has coordinates 36° 37.5'N, 21° 34.6'E.

The detector will consist of 7 titanium towers, with a height of 220 meters and a diameter of 32 meters. Each tower will have twelve hexagonal floors and each floor will contain seven pairs of OM, one pair at the center and the others at the vertices of the hexagons. In each pair one OM will be looking up and the other one will be looking down. One OM is formed by one hemispherical, bialkali Hamamatsu R 2018–03 15″ photomultiplier, protected by a pressure resistent 17″ glass Benthos sphere. The distance between OM in one floor will be 16 m and the vertical spacing will be 20 m.

A titanium sphere containing the electronics will be placed at the center of the hexagon.

The detector is designed to study not only the astrophysics but also the physics of neutrinos and therefore it is rather compact and isotropic, its sensitive area for TeV muons will be $\sim$ 100000 $m^2$. The readout electronics aims at registering the shape of the photomultiplier pulses, in addition to the time and total charge.

The data acquisition system is designed to provide the transmission to the shore laboratory of the pulse shape from each fired photomultipler. The signals from the 14 photomultipliers of each floor are sampled and transmitted through a monomode optical fiber imbedded in a submarine optical cable. The trigger will be on shore. Each floor will be electrically and electronically independent of the other floors.

The whole tower will be deployed in a single operation, the possibility of retrieving it for "servicing" by activating anchoring releases and allowing the tower to float is under study.

During the period 1989–1994 four major cruises were devoted to environmental measurements. All the measurements of light transmissivity gave consistent results indicating very clear water suitable for the detector. The attenuation length at depths of more than 2000 m, in the wavelength interval between 470 and 490 nm, is in the range 45–65 m.

The underwater current velocities were measured to be consistently smaller than 10 cm/sec. Water temperature measurements were carried out together with the current velocity measurements. The water temperature, below a depth of 2.5 km, is 14.0 degrees Celsius, constant in time, with a variation of less than 0.5 degrees in a year.

In May 1996 optical background measurements were carried out. The rate due to $^{40}K$ is $\sim$55 kHz. Also intermittent bursts of duration 3–5 seconds, with a frequency of 1% of the experiment live time, consistent with being bioluminescent activity, were found.

In July 1991, a detector prototype consisting of a titanium alloy hexagonal structure (7 m radius) equipped with ten 15″ Hamamatsu photomultipliers was deployed to a depth of 4.1 km. Six of the phototubes were located at the vertices of the hexagon and four 3.5 meters below the center. The sensitive area of this experiment was 373$\pm$75 $m^2$. The vertical muon intensity and the angular distribution of downcoming muons were measured at depths of 3.3, 3.7 and 4.1 km.

In November 1992 the measurement was repeated using a linear string with five 15″ photomultipliers. Both sets of measurements are in very good agreement with the results from previous experiments. At depths between 3.7

and 3.9 km the vertical muon flux is $(9.8 \pm 4.0) \times 10^{-9}$ $cm^{-2}s^{-1}sr^{-1}$.

All the environmental measurements carried out so far have demonstrated that the site chosen for NESTOR is ideal for the deployment and proper functioning of a neutrino telescope.

At present funding is available only for the first tower, deployment and electronics tests have started in September 1996, a fully equipped prototype array of two floors will be deployed in 1997 and the deployment of the full tower is forseen for the following year.

### *5.5 The km$^3$ Project*

There is general agreement that in order to detect pointlike neutrino sources a neutrino detector with a volume of about one cubic kilometer will be needed.

Many interested physicists in the United States and in Europe have met several times in the last two years, in Venice, Berkeley, Saclay, Pasadena and Aspen, and have formed working groups to define the specifications for a next generation neutrino telescope.

In the United States a group from the JPL in Pasadena and a group from LBL in Berkeley have obtained funds for simulation studies and electronics prototypes.

Saclay is orginizing a meeting in Paris for 1997. Greece has proposed the formation of a km$^3$ Working Group of the Megascience Forum of the OECD, which will meet in Taormina in May 1997.

## 6 Non Perturbative Electroweak Behaviour at High Energy?

A few years ago a paper was published[63], with the title *How Strong are Weak Interactions in the Multi-TeV Range?*; the title was interesting and even more so the abstract, that I quote: " Weak interactions at high energies ($\sqrt{s} \geq m_w/\alpha_w$) may lead to strong multiparticle production of weakly interacting particles. This effect is connected to infrared divergences of the underlying gauge theory. Cross sections for the production of many weakly interacting particles of the order 1 nb to 10 $\mu$b above a threshold (parton) energy of 2 to 20 TeV could be observable at future colliders."

The paper was very timely: it appeared at the same time of the publication of a very optimistic estimate of the integrated isotropic neutrino flux from the sum of all AGN [48] and at the time when the different Neutrino Telescope projects were making the transition from the R&D stage to the beginning of the construction stage. Rather soon a few papers appeared on the search for

a possible non perturbative multiple production of intermediate vector bosons in very high energy cosmic neutrino interactions [64–66].

The signature for the process is a narrow muon bundle with muon energies of the order of hundreds of TeV. The estimates on the expected number of events are affected by an error of several orders of magnitude, due to the lack of knowledge of the basic cross sections and to the lack of knowledge of the incoming neutrino flux.

For an incoming neutrino flux of $10^{-13}$ cm$^{-2}$s$^{-1}$ [48] above a neutrino energy of 10 PeV it is not unreasonable to expect, in the full NESTOR array, from a few to a few dozens of events a year in the zenith angle interval between 80° and 90° [65]. The lower limit on the angular range is dictated by the requirement that the signal be clearly separated from the atmospheric muon bundles, while the upper limit is due to the absorption of the incoming neutrinos by the earth, for incidences lower than the horizontal, given the comparatively large cross sections ($\sim 10^{-32} - 10^{-29}$ cm$^2$) of the relevant processes.

It is interesting to observe that the total expected number of events depends on the neutrino flux, while the angular distribution depends on the size of the partonic cross sections. Therefore in case of a positive experimental signal, both these quantities can be determined.

An order of magnitude more events are expected in the km$^3$ array, which will probably be needed in order to identify the phenomenon, since the detection efficiencies will be much less than 100%. For a positive identification of the effect the capability of recording and analyzing multiple muon events and giving at least an order of magnitude estimate of the muon energy is essential. NESTOR with its data acquisition system meets these requirements, which should be kept in mind for the km$^3$ project.

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