*Moscow University*
*Physics Bulletin*
*Vol. 60, No. 5, pp. 15–21, 2005*

*Vestnik Moskovskogo*
*Universiteta. Fizika*
*UDC 621.039.8*

## ATOMIC AND NUCLEAR PHYSICS

# PROJECT OF AN EXPERIMENT TO STUDY NEUTRINO OSCILLATIONS WITH NEMO UNDERSEA NEUTRINO TELESCOPE

M. Anghinolfi*, M. V. Osipenko*, A. B. Plotnikov, and A. P. Chernyaev

**The undersea neutrino telescope NEMO project is currently under way in the National Institute of Nuclear Physics (INFN, Italia). It will serve for the study of cosmic and atmospheric sources of high energy neutrinos. This telescope can be used for the neutrino oscillation studies. In the present paper, computer simulation of the telescope and calculation of its effective volume are carried out. Our investigations demonstrated that the effective volume and statistics gathering are higher than for any neutrino detectors actually in operation.**

## INTRODUCTION

Neutrino plays a unique role in investigations in the physics of fundamental interactions. However, though a notable advance has been made in studying neutrino physics, some problems still remain insufficiently explored. In the first place, this is the theory of neutrino oscillations.

This theory describes the possibility of neutrino transitions between states with different flavors and enables one to solve the problem of the neutrino mass determination, which at present is one of the fundamental problems of the elementary particle physics [1].

Experimental studies of the neutrino oscillations are conducted at Homestake [2], SAGE [3], Gallex [4], Super KamiokaNDE [5], K2K [6], SNO [7], MINOS [8], and OPERA [9] laboratories.

At the Italian Institute of Nuclear Physics (Instituto Nazionale di Fisica Nucleare), an undersea neutrino telescope is projected in the framework of the NEMO experiment. In accordance with one of the preliminary projects, it is supposed to be installed in the Mediterranean Sea off the coast of Greece [10, 11].

In the present publication, we consider the problems related to the construction of the neutrino detector, i. e., calculation of its effective volume, and the possibility of using this detector to observe the neutrino oscillations in the beam from the SPS accelerator at CERN.

## THE UNDERSEA NEUTRINO TELESCOPE PROJECT

The undersea telescope operates by detecting the Cherenkov radiation of the muon produced in the reaction of interaction of the neutrino with the atomic nucleus,

$$\nu_\mu + N = \mu^- + X. \tag{1}$$

---

* Instituto Nazionale di Fisica Nucleare, Sezione di Genova, 16146 Genova, Italy.

The Cherenkov radiation photons are detected by means of the photomultipliers installed in a certain order in the detector [11]. The undersea telescope NEMO designed differs from its predecessors, i. e., the ANTARES telescope under installation [10], and already operating neutrino telescopes NT-200 [12] and AMANDA [13], by the order of spatial dispositions of photomultipliers in the detector volume.

The basic elements of the detector are the optical modules consisting of photomultipliers (Hamamatsu HR7081-20, diameter 10 inches, maximal sensitivity at $\lambda \sim 400$ nm) and the electronic devices for signal processing. They are enclosed in the pressure-resistant glass sphere. The electronics registers the amplitude and the arrival time of the signal.

Optical modules are organized into clusters. A cluster is a collection of optic modules placed in a horizontal plane. A cluster in a NEMO detector consists of 24 optical modules (Fig. 1) and a device that detects the cluster position with respect to the telescope base and the undersea current velocity. Each cluster consists of six rays 8 m in length, placed at an angle of 60° to each other. Two couples of optical modules are situated in each ray, with their axes in each couple directed vertically and opposite to each other.

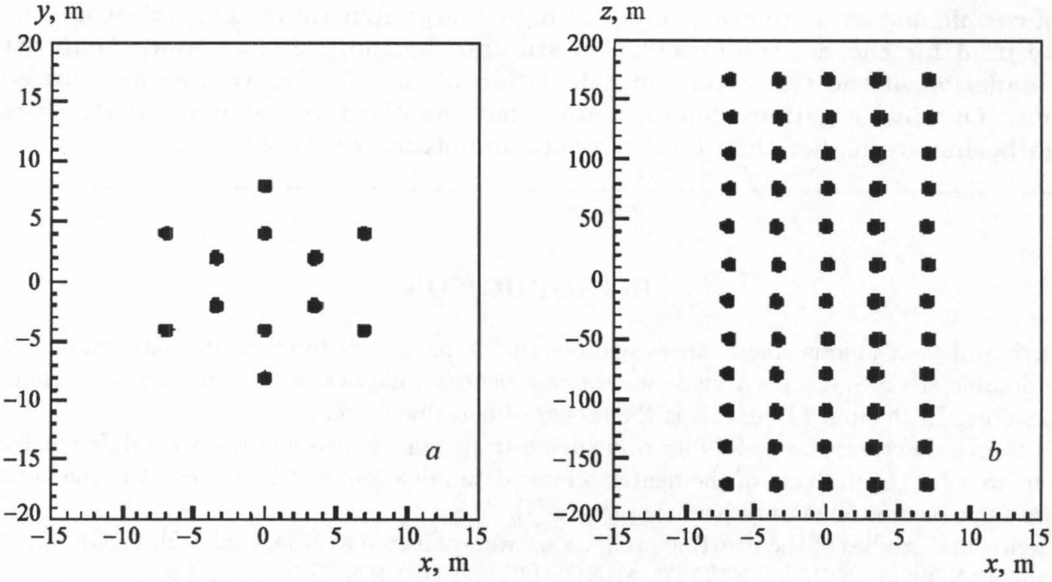

**Fig. 1**

Schematic view of the detector. Markers show optical modules positions in (*a*) horizontal and (*b*) vertical planes.

All the clusters are fixed at the vertical rope at various depths at a distance of 30 m between them (see Fig. 1), forming the detector tower. The electronics unit at the tower base is responsible for collecting information from the clusters and transmitting it to the surface station, connected with the telescope by an undersea cable [14]. The telescope volume with this geometry is $1.2 \times 10^6$ m$^3$.

In order to determine the parameters of the undersea telescope under design, computer simulation of the detector has been performed. The detector design calculation was performed using the program package developed specifically for modeling undersea neutrino telescopes and used in the design of the undersea neutrino telescope ANTARES. The detector configuration, the photomultiplier type, and the medium parameters are user-specified [15–17]. In the present work, a Hamamatsu HR7081-20 photomultiplier has been used, and the following parameters of the Mediterranean Sea: the photon absorption path in water 62.5 m, the scattering length 52.85 m, the refraction coefficient $n = 1.35$ (at $\lambda = 450$ nm).

The detector design calculation is performed in several stages. First, the detector configuration is specified [18]. Then, simulation is performed of the process of muon passage in the detector material [19] and of the detector photomultiplier response to the muon passage [20]. The process ends with reconstructing the muon track by the signals obtained [21, 22].

The main parameter that determines efficiency of the telescope and which is studied during simulation is the detector effective volume $V_{\text{eff}}$. It is calculated by the formula

$$V_{\text{eff}} = \frac{N_r}{N_g} V_d, \tag{2}$$

where $N_g$ is the total number of muons in the detector volume, $N_r$ is the number of muon tracks, reconstructed by the events reconstruction program from the data (the signal amplitudes in photomultipliers and the signal registration time) obtained from the optical modules of the telescope, $V_d$ is the detector volume equal to $1.2 \times 10^6$ m$^3$.

The following parameters were used to simulate the muon current: the current is horizontal along the $y$-axis with the uniform angular distribution in the solid angle of 10° (with respect to $y$-axis), the muon energy varied in the interval from 1 to 10 GeV. The energy spectrum of muons is uniform in the energy interval chosen.

In the present work, a track was considered reconstructed when the number of signals in different optical modules amounted to not less than five, as to construct the track by the photomultiplier coordinates and the registration time of the Cherenkov radiation, at least five points should be detected. The reconstructed events determine the number $N_r$ from formula (2).

Computer simulation of the NEMO detector designed demonstrated that the detector effective volume $V_{\text{eff}}$ depends on the muon energy (Fig. 2). With lowering energy, the effective volume tends to zero, as the track length becomes shorter than the distance between the optical modules. With growing energy, the detector effective volume increases up to the maximum possible value $2.1 \times 10^5$ m$^3$, as with the muon energy 100 GeV the length of its track is approximately 400 m, and this is greater than the detector linear dimensions.

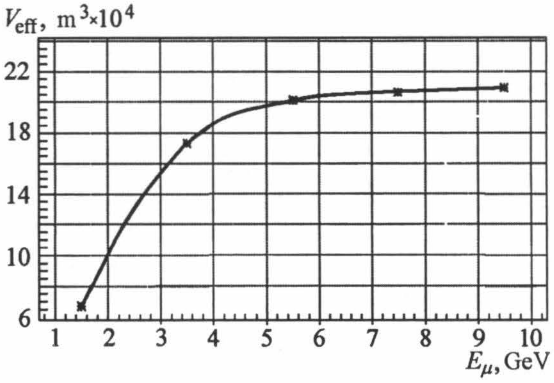

**Fig. 2**

The effective volume of the undersea neutrino detector designed as a function of the muon energy, obtained as a result of computer simulation of the detector.

## NEUTRINO OSCILLATIONS

One of the tasks for NEMO neutrino telescope is to study the neutrino oscillations by variations of the neutrino flux of definite flavor. Examples of similar experiments conducted in the world are Super KamiokaNDE [5], K2K [6], MINOS [8], and OPERA [9]. In NEMO, one can use both natural and artificial sources of neutrino with the energy higher than several gigaelectronvolts. In the experiment with the SPS accelerator as the neutrino source, the initial neutrino flux is determined by the parameters of the primary proton beam, properties of the target, and also by the length of the tunnel designed for the decay of secondary pions.

The neutrino oscillation phenomenon is based on the existence of the proper neutrino states, $\nu_1$, $\nu_2$, $\nu_3$, that are the mass eigenvalues, while the observed neutrino states with three flavors, $\nu_E$, $\nu_\mu$, $\nu_\tau$, are the linear superpositions of these three states with coefficients determined by the mixing angles $\theta_{12}$, $\theta_{23}$, $\theta_{13}$. Due to this, the neutrino flavor changes during neutrino propagation from the source. In the process of neutrino propagation through the space, the content of different neutrino components in the flux changes due to different propagation velocities of the proper neutrino components with different masses. For instance, the probability for muon neutrino conserving its flavor in oscillation into another flavor $x$ is

$$P_{\nu_\mu} = 1 - \sin^2\theta_{2x}\sin^2\left(\frac{\Delta m^2_{2x}L}{4E_\nu}\right). \tag{3}$$

Thus, the magnitude of neutrino oscillations is determined by two variables: the distance between the neutrino source and the detector $L$, the neutrino energy $E_\nu$, and also by the following parameters: the mixing angle $\theta_{2x}$ and the difference of the squared masses $\Delta m^2_{2x}$ of two neutrino flavors ($\nu_\mu$ and $\nu_x$) [23, 24].

According to equation (3), the neutrino oscillation probability is a periodic function of $L/E$. Hence, by fixing one of the quantities that enter the ratio, and varying the other one, we can choose the point on the oscillation probability curve that will give the largest effect of disappearance or appearance of the neutrino with definite flavor. The aim of calculating the probability of neutrino oscillation is to determine the values of the mixing angle $\theta_{2x}$ and the squared mass difference $\Delta m^2_{2x}$.

The experiment with disappearance of muon neutrino Super KamiokaNDE [5] demonstrated that lowering the muon neutrino flux does not lead to the increase of the number of the electron neutrinos. Then it was concluded that oscillations mainly into tau-neutrino take place. With the use of the results of the Super KamiokaNDE experiment [5] studying the weakening of the muon component of atmospheric neutrino as a result of oscillation $\nu_\mu$ into $\nu_\tau$, we can estimate the range of expected values of parameters

$$\sin^2\theta_{23} > 0.82, \quad 10^{-3} < \Delta m^2_{23} < 8\times10^{-3}\ \text{eV}.$$

The most probable values of parameters that followed from this experiment are $\sin^2\theta_{23} = 1$ (maximal mixing angle) and $\Delta m^2_{23} = 3.5\times10^{-3}\ \text{eV}^2$.

## NEMO EXPERIMENT USING THE CERN SOURCE

For neutrino oscillation measurements, it is planned to use the neutrino source at CERN (beryllium target hit by 450-MeV protons accelerated in the SPS). Geographical location of NEMO undersea telescope enables the beam directed from CERN to GRAN SASSO to be used. When protons interact with the target, reactions of multiple production of high-energy pions and $K$-mesons take place. While propagating, they in their turn decay for $10^{-8}$ s with emission of a muon neutrino,

$$\pi^\pm \to \mu^\pm + \nu_\mu/\bar{\nu}_\mu, \quad K^\pm \to \mu^\pm + \nu_\mu/\bar{\nu}_\mu. \tag{4}$$

After a 1 km decay pipe, the beam of charged muons is absorbed at the target, which at the same time plays the role of a Faraday cylinder, and this enables the neutrino flux to be measured. Since the Earth's surface is spherical, the undersea telescope is somewhat lower than the main direction of the neutrino flux. In order to direct the main neutrino flux to the telescope, one should deflect the pion beam. Moreover, for the oscillation experiment, one should cut out a part in the energy range 3–6 GeV (Fig. 3) from the spectrum of the initial neutrino flux. Distance $L$ from CERN to NEMO equals 1675 km. The optimal neutrino energy range for the neutrino oscillation search, calculated with consideration for the present values of $\theta_{23}$ and $\Delta m^2_{23}$, obtained at Super KamiokaNDE [5], is in the range 5–7 GeV (Fig. 4).

Basing on the results of the computer simulation of NEMO undersea telescope, one can draw preliminary conclusions about neutrino detection efficiency in this experiment, assuming known the initial flux $\nu_\mu$ and the energy spectrum of neutrino (see Fig. 3), the oscillation probability (see Fig. 4), and the telescope effective volume as a function of the muon energy (see Fig. 2). With this data being known, the number of detections of the neutrino expected in the NEMO telescope per year, as well as the accuracy of oscillation measurements were calculated. The calculation procedure was as follows.

(1) Basing on the values of the neutrino flux from the source $I$ and the neutrino scattering cross section on nucleon, $\sigma$, the number of interactions of the neutrino in 1 $\text{m}^3$ of the detector medium (sea water) per year $N_i = I\sigma\rho/N_a$, where $N_a$ is the Avogadro number, and $\rho$ is the detector matter density, was calculated.

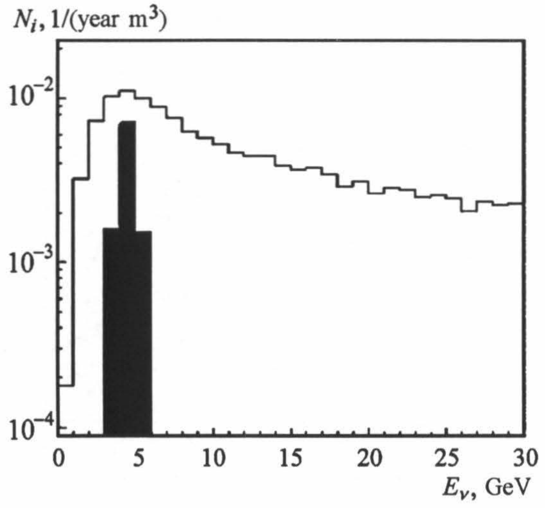

**Fig. 3**

Spectrum of the number of interactions of neutrino in the detector medium. Neutrinos are obtained at CERN in the proton beam from the SPS, $N_i = I\sigma_\mu\rho/N_a$ ($I$ is the flux [1/(year m$^2$)], $\sigma_\mu$ is the cross section of neutrino scattering on a nucleon [m$^2$], $\rho$ is the target matter density [g/m$^3$], $N_a$ is the Avogadro number). The flux, selected through the magnet deflecting secondary pions is marked by dark color.

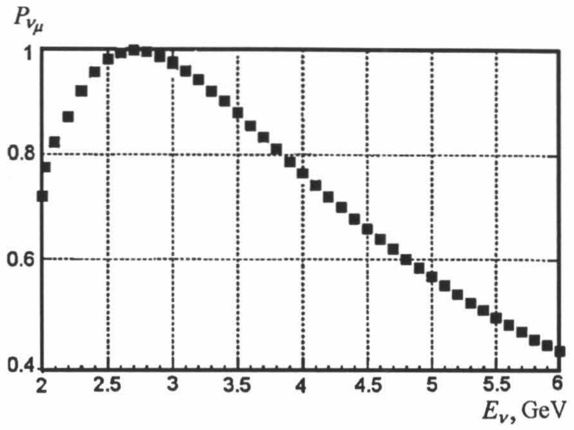

**Fig. 4**

Probability $P_{\nu_\mu}$ of muon neutrino survival as a function of the neutrino energy at a distance $L = 1375$ km, $\Delta m^2_{12} = 0.002$ eV$^2$, and $\cos\theta_{12} = 1$.

(2) From the family of curves for the probability $P_{\nu_\mu}$ of conserving the muon neutrino flavor, a curve was selected that corresponded to the value of parameters $\Delta m^2_{23} = 0.002$ eV$^2$ and $\sin\theta_{23} = 1$ (see Fig. 4). (Calculations were also conducted for $\Delta m^2_{23}$ from 0.001 to 0.004 eV$^2$ with the step-interval 0.0005 eV$^2$. These values cover the range of possible values of parameter $\Delta m^2_{23}$, estimated in the Super KamiokaNDE experiment.)

(3) Basing on the value of the probability of survival, the number of interactions of neutrino in 1 m$^3$ of the detector volume per year with consideration for oscillations, $N_{\text{det}} = N_i P_{\nu_\mu}$ was obtained, i. e., the decrease of the flux of neutrino of one flavor due to transition to another flavor.

(4) Muon neutrinos in the detector volume produce muons with approximately uniform spectrum from 0 to $E_{\max} = E_\nu$, where $E_\nu$ is the neutrino energy. Basing on these data, the uniform spectrum was obtained for muons produced by the neutrino beam.

(5) The number of events detected by the telescope per year was obtained through multiplying the number of muons produced in 1 m$^3$ of the detector by its effective volume calculated with consideration for the results of computer simulation (Fig. 5).

The results of computer simulation demonstrated that the detector designed enables only several hundreds of events per year in the energy range from 3 to 10 GeV to be detected in this experiment.

The accuracy of detection of oscillation parameters $\Delta m^2_{23}$ and $\theta_{23}$ was compared for Super KamiokaNDE and NEMO basing on the above calculation results (Fig. 6). The values of $\chi^2$ were determined by the formula

$$\chi^2 = \sum_{i_{E_\mu}=3}^{6} \frac{\left|N\left(\Delta m^2_{23}, \theta_{23}\right) - N\left(\Delta m^{2\,\text{exp}}_{23}, \theta^{\text{exp}}_{23}\right)\right|^2}{\left|\sqrt{N\left(\Delta m^2_{23}, \theta_{23}\right)}\right|^2}, \tag{5}$$

where $N(\Delta m^2_{23},\ \theta_{23})$ is the number of events detected in NEMO for the values of oscillation parameters $\Delta m^2_{23}$, $\theta_{23}$, $N(\Delta m^{2\,\text{exp}}_{23},\ \theta^{\text{exp}}_{23})$ is the number of events for fixed values of $\Delta m^2_{23}$, $\theta_{23}$, obtained in the similar experiment [5]. Comparison of the accuracy of results of the similar experiment in Super KamiokaNDE is

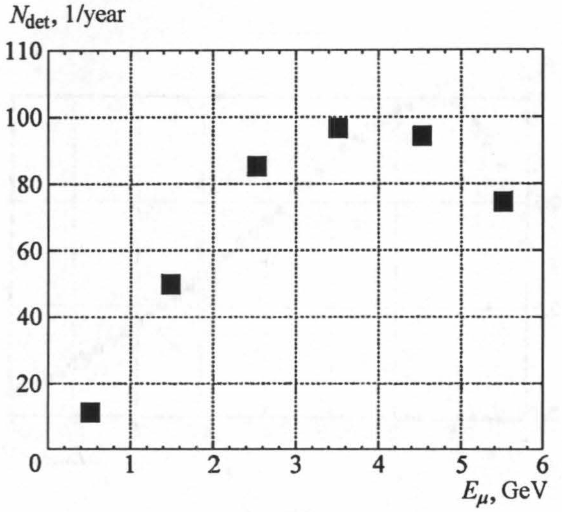

**Fig. 5**

The number of detected events per year as a function of the muon energy $E_\mu$. The results were obtained via calculations and computer simulation.

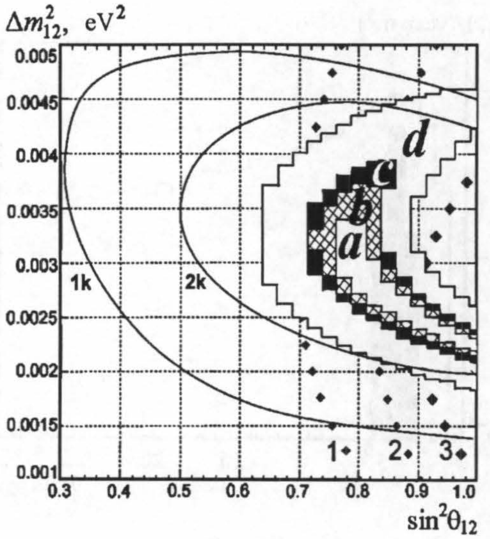

**Fig. 6**

Comparison of the accuracy of determination of $\Delta m_{12}^2$ and $\theta_{12}$ for Super KamiokaNDE and NEMO experiments. Colored regions are for oscillation parameters obtained in NEMO for various values of $\chi^2$: (*a*) $0 < \chi^2 < 1$; (*b*) $1 < \chi^2 < 2$; (*c*) $2 < \chi^2 < 3$; (*d*) $3 < \chi^2 < 8$. Dots separate the regions of confidence intervals of $\Delta m^2$ and $\theta$ obtained in the Super KamiokaNDE experiment: (*1*) SK 99%; (*2*) SK 90%; (*3*) SK 98%.

shown in Fig. 6. It should be taken into consideration that the intervals $0 < \chi^2 < 1$, $0 < \chi^2 < 2$, and $0 < \chi^2 < 3$ correspond to the confidence intervals 68, 90, and 99%, respectively. The number of detected events obtained by calculations (see Fig. 5) is approximately 400.

## CONCLUSIONS

Computer simulation and calculations made with regard to its results demonstrated that the accuracy in measuring neutrino oscillation in the undersea neutrino telescope NEMO is two or three times as much as that in the Super KamiokaNDE experiment [5] as well as that in the similar experiment with "distant" neutrinos K2K [6] (see Fig. 6). At present, the NEMO detector has the greatest effective volume among similar detectors used for the neutrino oscillation search. Measurements in "film" experiments can explain the results of this experiment by measuring appearance of $\nu_\tau$ in the muon neutrino beam [9]. The similar experiment MINOS [8] should obtain comparable statistics of disappearance of $\nu_\mu$. However, since parameter $L/E$ (3) is significantly different in NEMO and MINOS experiments, in the experiment in question another point at the curve of the probability of disappearance of $\nu_\mu$ will be studied (see Fig. 4). In fact, these two types of experiment complement each other.

## REFERENCES

1. R. Davis, Jr., *Usp. Fiz. Nauk*, vol. 174, no. 4, p. 407, 2004.
2. R. Davis, *International Symposium on Neutrino Astrophysics*, Takayama Kamioka, 1992.
3. J.N. Abdurashitov, V.N. Gavrin, S.V. Girin, et al., *Phys. Rev.*, vol. C60, p. 055801, 1999.
4. W. Hampel, J. Handt, G. Heusser, et al., *Phys. Lett.*, vol. B447, p. 127, 1999.
5. Y. Fukuda, T. Hayakawa, E. Ichihara, et al., *Phys. Rev. Lett.*, vol. 81, p. 1562, 1998.
6. M.H. Ahn, S. Aoki, H. Bhang, et al., *Phys. Rev. Lett.*, vol. 90, p. 041801, 2003.

7. Q.R. Ahmad, R.C. Allen, T.C. Andersen, et al., *Phys. Rev. Lett.*, vol. 89, p. 011301, 2002.
8. K. Lang, *Nucl. Instr. Meth.*, vol. A461, p. 290, 2001.
9. D. Duchesneau, *Nucl. Phys. Proc. Suppl.*, vol. 123, p. 279, 2003.
10. E. Aslanides, J. Aubert, S. Basa, and F. Bernard, *A Deep Sea Telescope for High Energy Neutrinos*, Genova, 1999.
11. M. Anghinolfi, *A Long Baseline Neutrino Oscillation Experiment*, INFN, Genova, 2003.
12. V.A. Balkanov, I.A. Belolapatnikov, L.B. Bezrukov, et al., *Phys. Atom. Nucl.*, vol. 63, p. 951, 2000.
13. J. Ahrens, E. Anders, X. Bai, et al., *Phys. Rev.*, vol. D66, p. 012005, 2002.
14. J. Brunner, *The ANTARES Project*, Toulon, 1999.
15. J. Brunner, *Antares Simulation Tools*, Toulon, 1999.
16. J. Brunner, *E-print: ANTARES-Soft/1998-005.*
17. F. Cassol and J. Brunner, *GENDET 1.2: Cards and Tags*, Toulon, 2000.
18. S. Navas and L. Thompson, *KM3. User's Guide and Reference Manual*, Toulon, 2000.
19. J. Brunner, *Updated Tag List for New ANTARES Event Format*, Toulon, ANTARES-Soft/1999-003.
20. J. Brunner, *General Purpose Data Format for ANTARES Simulation and Reconstruction*, Toulon, 1998.
21. A. Romeyer and Th. Stolarczyk, *Reconstruction Algorithms*, Toulon, 2001.
22. A. Heijboer, *An Algorithm for the Track Reconstruction in ANTARES*, Toulon, 2002.
23. E. Torrente-Lujan, *A Review on Neutrino Physics, Mass and Oscillations*, Toulon, 1999.
24. S.M. Bilen'kii, *Neutrino Oscillations* (in Russian), Dubna, 1983.

14 July 2004

Department of High-Enegry Accelerator Physics
Research Institute of Nuclear Physics