The Antares neutrino telescope : performance studies and analysis of first data

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Introduction

Antares [1], BAIKAL [2], AMANDA [3] and ICECUBE [4] are experiments in the emerging field of *neutrino astronomy*. Neutrino astronomy, as part of a larger discipline called *astroparticle physics*, complements the astronomy based on the observation of electro-magnetic radiation emitted by astrophysical sources.

The first part of the *Antares neutrino telescope* became operational on the 2^{nd} of March 2006. At the time of this writing 80 % of the detector is operational. The work described in this thesis is based on the data taken in 2006. The prospects of the complete detector will be presented as well.

The complementarity of neutrinos for observational astronomy stems from their properties. Neutrinos are neutral, weakly interacting particles. The small interaction cross section of neutrinos with matter prevents their absorption on the way to Earth. High-energy photons (gamma-rays) can be absorbed by interactions with the infra-red, microwave and radio background photons, which limits the depth of view. As neutrinos are neutral, they are not deflected by galactic or extra-galactic magnetic fields. Hence, they point straight back to their source, which is essential for astronomy.

The first and only direct observation of neutrinos with a cosmic origin is the detection of neutrinos from Supernova 1987a by the Kamiokande [5] and IMB [6] detectors. Detection of neutrinos from the Sun, the atmosphere, nuclear reactors and particle accelerators have led to a determination of the neutrino oscillation parameters. Oscillations of neutrinos occur between three flavor eigenstates, namely : electron-, muon-, and tau-neutrinos.

One of the main questions in astroparticle physics is the origin and nature of high-energy cosmic rays. It has long been known that energetic charged particles bombard the Earth and produce particle showers in the atmosphere. While the energy spectrum of the cosmic rays can be measured up to very high energies ($\sim 10^{20}$ eV), their origin remains unclear. Recently, the Pierre Auger collaboration reported a correlation between high-energy cosmic rays and active galactic nuclei [7]. As the cosmic rays are charged, they are deflected by the (extra-) galactic magnetic fields. In addition, protons with energies exceeding $\sim 10^{19}$ eV interact with the cosmic microwave background. This effect, known as the Greisen-Zatsepin-Kuzmin cutoff [8], limits the range of high energy protons to the order of 100 Mpc. Assuming that a fraction of the high-energy protons interact with the ambient matter or photon fields, pions and hence neutrinos will be created. Potential sources of high-energy neutrinos include supernova remnants, active galactic nuclei, gamma-ray bursts and microquasars. Detection of neutrinos from such sources will shed light on the physical processes involved in their creation.

While the small interaction cross section of neutrinos allows them to come from far away, it is also a draw-back, as their detection requires a large target mass. The Antares collaboration is building a detector by instrumenting a large volume (0.05 km^3) of sea water. An array of 900 photo-multiplier tubes is being installed at the bottom of the Mediterranean Sea at a depth of about 2.5 kilometers. The photo-multiplier tubes are used to detect the light emitted by the products of an occasional neutrino interaction. The photo-multiplier tubes are mounted on 12 vertical strings, each having an instrumented length of about 350 m. On the 2^{nd} of March 2006, the first of these lines was connected via an electro-optical cable to the shore station, which is located in the town of La-Seyne-sur-Mer, France.

The detection of neutrinos is based on the detection of muons which are created in the charged-current interactions of muon-neutrinos. These muons, at sufficiently high-energies, retain information on the direction of the incident neutrino and can traverse several kilometers of sea water. Along their trajectory, the muons emit Cherenkov light. From the measured arrival time of the Cherenkov light, the direction of the muon can be determined. This process is referred to as muon track reconstruction. A new muon track reconstruction algorithm has been developed, which is described in this thesis. It is designed to have a minimal dependence on the models describing the processes leading to the detection of photons. This makes it especially suitable for the start of detector operations. It has been used to produce the first results of Antares. The algorithm has been extended by adding a final stage which is based on a detailed modelling of the arrival times of the photons from the muons. This allows the study of the final performance of the detector. This study is based on simulations.

The main background for the Antares detector comes from two sources. First, there is a flux of muons that originate from the interactions of cosmic rays in the Earths atmosphere. Despite the depth, some can reach the detector and cause a detectable signal. These muons must be distinguished from the neutrino induced muons. Second, the decay of radioactive ^{40}K and the biological activity in the sea water cause a significant rate in each photo-multiplier tube. Various ways to reduce these backgrounds have been developed. The performance of the complete detector in the presence of these backgrounds has been studied.

Outline

This thesis is organized in the following way.

In chapter 1 a brief overview of the field of neutrino astronomy is given. Several potential neutrino sources are presented.

In chapter 2 the detection principle of the Antares neutrino telescope is explained, followed by a description of the design of the detector, its data acquisition and calibration systems. In addition, an overview of the various backgrounds is given. Finally, the software tools which are used to simulate the processes that lead to a detectable signal and the response of the detector are presented.

In chapter 3, a new method to determine the direction of the muon track is described. The performance of this method is evaluated for different background conditions.

In chapter 4 the results of the analysis of the data of the first detector line of the Antares telescope are presented. A simulation is used to estimate the detector efficiency. The effects on the muon reconstruction due to the presence of electromagnetic showers along the tracks will be discussed. The precision with which the zenith angle of muon tracks can be determined is quantified using data. The dependence of the atmospheric muon flux on the depth has been determined.

In chapter 5, the performance of the complete detector is evaluated for various background conditions. The detection efficiency and the pointing accuracy of the Antares detector are determined.

Chapter 6 contains a summary and conclusion.