Track Reconstruction and Point Source Searches with Antares

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Introduction

As we know, there are known knowns. There are things we know we know.
We also know there are known unknowns.
That is to say, we know there are some things we do not know.
But there are also unknown unknowns: the ones we don't know we don't know.
— D.H. Rumsfeld

In 2002, the Nobel prize for physics was awarded to Raymond Davis, Masatoshi Koshiba, and Riccardo Giacconi. Giacconi is one of the founders of the field of X-ray astronomy. Davis and Koshiba were awarded the prize *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"*.

Davis and his colleagues were the first to take on the challenge to measure neutrinos from the Sun by detecting the reaction $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$ in a tank of chlorine [1]. The detection of these neutrinos proved that nuclear fusion is the energy source of the Sun. However, the number of detected neutrinos was smaller than what was predicted by models of the nuclear processes in the Sun. These observations were confirmed, amongst others, by the group headed by Koshiba using the Kamiokande-II detector [2]. In 1998, the successor of this experiment, called Super-Kamiokande, observed evidence for oscillations of atmospheric muon-neutrinos, which implies a non-zero neutrino mass. Since then, it has become widely accepted that neutrino oscillations also offer an explanation for the observed deficit of solar neutrinos. The final piece of this puzzle was provided in 2002 by the SNO experiment. By measuring (flavour blind) neutral current interactions, this experiment showed that the total number of neutrinos is in agreement with the model predictions [3]. The missing electron-neutrinos must therefore have oscillated into muon- or τ-neutrinos.

In 1987, the Kamiokande-II [4] and IMB [5] detectors observed a total of 20 neutrinos from a supernova explosion in the Large Magellanic cloud, thereby confirming the theoretical models for core collapse supernovae. The observation of cosmic neutrinos has thus not only lead to an increase in our understanding of the Sun and of supernova explosions, but it has also provided new knowledge in the field of particle physics. In fact, the existence of massive neutrinos is one of the few experimental results available today that hint directly at physics beyond the standard model of particle physics. Interestingly, other clues also seem to come predominantly from the field of astronomy (e.g. dark matter) or cosmology (dark energy).

Another longstanding problem that involves both particle physics and astronomy is the origin of high energy cosmic rays. Since their discovery in 1912, it has become clear that primary cosmic rays consist of protons and nuclei that have been accelerated up to (very) high energies. The acceleration is thought to take place in astrophysical objects that release large amounts of energy, such as Active Galactic Nuclei, Gamma Ray Bursts and (Galactic) Supernova remnants. However, this hypothesis cannot easily be tested because the detected cosmic rays do not point to their source, because they are deflected by the magnetic fields in the universe. Fortunately, many models of cosmic ray acceleration predict that a fraction of the accelerated particles interacts with matter or photons in the source. These interactions inevitably produce neutrinos, which will escape from the acceleration region. Since the neutrinos are not perturbed by magnetic fields, their detection could make it possible to identify the source, thus providing evidence for the acceleration of cosmic rays in that source.

More generally, at very high energies astronomy with photons becomes infeasible, because they are absorbed on the low energy photons from the cosmic background radiation. This limits the path length of a 10 TeV photon, for example, to roughly the distance of the nearest active galaxy [6]. In contrast, neutrinos offer a means to study the universe at very high energies or large distances. Moreover, they can be used to study dense regions of the universe from which photons can not escape.

Whereas the neutrinos produced in the Sun and in supernova explosions have energies of the order of several MeVs, the neutrinos produced by cosmic ray accelerators are thought to have much higher energies. The ANTARES detector, which is described in this thesis, is being built to detect these neutrinos. Focusing on high energy neutrinos has several advantages: 1) The cross-section for neutrino interactions increases with energy, which enhances the detection probability. 2) The energetic reaction products are detectable with a sparsely instrumented detector. This makes it possible to use very large (natural) detection volumes cost effectively. 3) The direction of the particles produced in a neutrino interaction is closely correlated to the direction of the neutrino. The direction of the neutrino can thus be determined, provided that the direction of the reaction products can be determined.

In this thesis, the emphasis is on the detection of muon-neutrinos. The direction of the muon that is produced in a charged current interaction, must be reconstructed from the measurement of the Cherenkov light it emits while traversing the detector. A method that was developed for this purpose is one of the subjects of this thesis. If multiple neutrinos will be observed from the same direction in the sky, this may indicate the presence of a point-like source of neutrinos. A method to search for point sources and the expected discovery potential of the ANTARES detector are also presented.

This thesis is organised as follows. In chapter 1 a brief overview of the knowledge of cosmic rays and the mechanism for neutrinos production is given. Chapter 2 starts with an introduction to the ANTARES experiment. This is followed by a summary of the first measurements that were obtained with a small prototype detector. In chapter 3 the tools used for the simulation of the neutrino interaction, the propagation of the muon and the response of the detector are described. Chapter 4 describes the method that was developed for the reconstruction of the direction of the muons that traverse the detector, which is of crucial importance for the pointing accuracy of the telescope. The method used to reconstruct the muon energy is also briefly discussed. In chapter 5 it is discussed how the background from atmospheric muons can be rejected. This is followed by a discussion of the detector performance in terms of pointing accuracy and effective area.

In chapter 6 a method is presented that can be used to search for astrophysical point sources of neutrinos. This leads to an estimate of the discovery potential of the final ANTARES detector.