1 Introduction

The AMANDA (Antarctic Muon And Neutrino Detector Array) detector, located at the South Pole station, Antarctica, was recently expanded with the addition of six new strings, completing the phase referred to as AMANDA-II. This detector has been calibrated and in operation since January 2000. Figure 1 shows a schematic view of the new AMANDA-II array. The first data analyses are currently underway. In this report we present an update on the results from the AMANDA-B10 detector, which operated during the austral winter 1997. This detector, consisted of 302 optical sensors on 10 strings located at depths of 1500 to 2000 m in the deep Antarctic ice.

The main science goal of the AMANDA project is to search for extra-terrestrial neutrinos, from sources such as active galaxies, or Gamma-ray bursts. As a precursor to such a search, we have focussed on the detection of atmospheric neutrinos, which essentially act as a calibration
source, allowing us to check the correct performance and understanding of the detector. In this paper, we first discuss the atmospheric neutrino search in some detail, then report on the status of the search for extra-terrestrial neutrinos.

2 Atmospheric Neutrinos

We have searched for atmospheric neutrinos in the 130.1 live days of data collected throughout 1997. Calibration and basic detector properties are similar to the prototype AMANDA-B4 detector. Figure 1 shows the expected trigger level fluxes of downgoing muons ($\sim 6 \cdot 10^6$ events per day) and atmospheric neutrinos (a few tens of events per day). The energy threshold for these atmospheric neutrinos is about 30-50 GeV.

The atmospheric neutrino analysis has been performed by two nearly-independent groups in the collaboration. This has contributed to the introduction of new ideas and has provided for some important cross checks of the analysis. While we here report the results of one analysis, the second comes to very similar and statistically consistent conclusions. Neutrinos are identified by looking for upward going muons. We use a maximum likelihood method, incorporating a detailed description of the scattering and absorption of photons in the ice, to reconstruct muon tracks from the measured photon arrival times. The events in the analysis presented here were...
We know a priori that downgoing muon hypotheses have a zenith dependence, and are overall more likely than upgoing hypotheses by about 5 orders of magnitude. We therefore search for the hypothesis $H$ that maximises the joint probability distribution $\mathcal{L}(E | H)P(H)$. This greatly reduces the number of downgoing muons that are misreconstructed as upgoing. A small fraction of the downgoing muons ($5 \cdot 10^{-6}$) are reconstructed as upward and form a background to the neutrino-induced events. This background is removed by applying quality criteria to the time profiles of the observed photons as well as to their spatial distribution in the array. A measure of the event quality has been defined by combining six quality variables into a single parameter. A high event quality is reached when the values of all six parameters agree with the characteristics of a correctly reconstructed muon track. The reconstruction and increasingly stringent cuts on the event quality reduces the background of a total of $1.2 \cdot 10^9$ events by a factor of approximately $10^8$, while retaining about 5% of the neutrino signal. The distribution of the single quality parameter for experimental data and for a Monte-Carlo simulation of atmospheric neutrinos is shown in Figure 3. It compares the number of events passing various levels of cuts; i.e., the integral number of events above a given quality. At low qualities, the data set is dominated by misreconstructed downgoing muons, most of which are reproduced in the Monte Carlo. At higher cut levels, the passing rates of data closely track the simulated neutrino events, and the predicted background contamination is very low.

We can investigate the agreement between data and Monte Carlo more systematically by comparing the differential number of events, rather than the total number of events passing various levels of cuts. This is done in figure 3 (right), where the ratios of the number of events observed to those predicted from the combined signal and background simulations are shown. One can see that at low quality levels there is an excess in the number of misreconstructed events observed. This is mainly due to instrumental effects such as cross talk which are not well described in the detector Monte Carlo. There is also an excess, though statistically less
Figure 3: Event quality. Left: Passing rates of events above a certain quality level is shown for background MC, atmospheric neutrino MC and experimental data. Right: Differential presentation of the ratio data/MC.

| Quality Cut | Data Passing Rate | MC: Atmospheric Neutrinos |
|-------------|-------------------|----------------------------|
| 0           | 1.2 · 10^9        | 4600                       |
| 2.5         | 5 · 10^3          | 571                        |
| 5           | 204               | 279                        |

Table 1: Event numbers are given at various cut levels: Experimental data and atmospheric neutrino Monte-Carlo.

significant, at very high quality levels, which is caused by slight inaccuracies in the description of the optical parameters of the ice. Nevertheless, over the bulk of the range there is close agreement between the data and the simulations, apart from an overall normalization factor. In the range where the line is shown the ratio of Data/MC is about 0.6. Counting all events above the quality cut (7.0) this ratio is 0.70. It should be emphasized that the quality parameter is a combination of all six quality parameters, and so the flat line in figure demonstrates agreement not only in individual cut parameters but also quantitative agreement in the correlations between cut parameters.

The zenith angle distribution for the 204 events is shown in Figure and compared to that for the signal simulation. In the figure the Monte Carlo events were normalized to the observed events. The achieved agreement in the absolute flux of atmospheric neutrinos is consistent with the systematic uncertainties of the absolute sensitivity and the flux of high energy atmospheric neutrinos. The shape of the zenith distribution of data is statistically consistent with the prediction from atmospheric neutrinos. The zenith distribution reflects the angular acceptance of the narrow but tall detector. Two hundred and twenty three events were found in an independent analysis. The overlap of 102 events with the sample presented here is within expectations. The observation of atmospheric neutrinos at a rate consistent with Monte-Carlo prediction establishes AMANDA-B10 as a neutrino telescope.

3 Neutrino science with AMANDA

The AMANDA-B10 data has been searched for evidence of several classes of neutrinos, and for magnetic monopoles. The following sections briefly describe the status of these searches.
3.1 Search for a diffuse high energy neutrino flux

Following on from the observation of atmospheric neutrinos, the first search we report is that for a diffuse flux of extra-terrestrial neutrinos. These neutrinos are expected to have a harder energy spectra ($\sim E^{-2}$) than that of the atmospheric neutrino background ($\sim E^{-3.7}$). Some method of energy determination must therefore be used. A simple measure of the energy of the muon, and thus indirectly the energy of the original neutrino, is the number of optical modules that fire during the passage of the muon. Higher multiplicities correspond to higher muon and neutrino energies. Figure 4 shows the energy distribution of events that pass the neutrino filter as predicted for a) atmospheric neutrinos and b) an assumed energy spectrum for astrophysical neutrinos following a power law of $dN/dE_{\nu} = 10^{-5}E_{\nu}^{-2}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}$. When using the number of fired optical modules as a measure of energy we obtain the distributions given in figure 4. The assumed astronomical neutrino flux would generate a significant excess at high numbers of fired optical modules. A preliminary analysis does not show such an excess. This leads to a preliminary upper limit (90\%C.L.) of $dN/dE_{\nu} \approx 10^{-6}E_{\nu}^{-2}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}$. However, the systematics of this analysis with respect to the high energy sensitivity are still subject to further investigation. A re-analysis with an updated version of the Monte-Carlo simulation is underway. This sensitivity on the diffuse neutrino flux is below previously stated upper limits by experiments such as Baikal, SPS-DUMAND, AMANDA-A, and FREJUS, and comparable to a recently presented Baikal limit. It is comparable to the AGN prediction by Salamon and Stecker and approaches the prediction of Protheroe.

![Figure 4: Left: Monte-Carlo simulation of the energy spectrum of atmospheric neutrinos shown in the skyplot in figure reffig:sky. Also shown is the energy spectrum of neutrinos generated by a neutrino flux of a $E_{\nu}^{-2}$-type energy spectrum (see text).](image)

3.2 Point sources

A search for a point source of neutrinos is, in some ways, easier than the diffuse neutrino flux search. Not only can we dramatically reduce the background by searching in a small angular bin about the postulated source direction, we can directly measure this background to the search by counting the events in the off-source bins at the same declination. This is in contrast to the diffuse search where the background has to be estimated from Monte Carlo. Of course, determining the sensitivity of the detector to calculate an expected signal (for determining a flux...
Point Source Limits

Figure 5: Limits on high energy neutrinos from point sources. The preliminary point source limit obtained with AMANDA-B10 (3), as well as the sensitivity of the proposed IceCube array, are shown. Curves 1 & 2 - horizontal and vertical atmospheric neutrino background in a $2^\circ \times 2^\circ$ search bin. See text for description of models 4–8.

One point source search of particular interest is that for Markarian 501. The AMANDA neutrino flux limit for this source is only about a factor of ten above the level of the gamma-ray emission during Markarian 501’s high gamma-ray emission state in 1997. This means that the AMANDA detector has reached the level of sensitivity where models that predict neutrino emissions of the order of the gamma emissions can be tested.

Figure 5 shows the expected neutrino fluxes from various sources, together with the current preliminary AMANDA upper limit (90% C.L.). The atmospheric neutrino background is given for a 2 by 2 degree bin. Also indicated in the figure is the expected limit that might be achieved by the proposed IceCube detector, a kilometre scale array planned for construction at the south pole. Several models of point source neutrino production are shown: curve 4 – 3C273 pp neutrinos, 5 – Crab Nebula, 6 – Coma Cluster, 7 – 3C273 pγ neutrinos, 8 – Supernova IC443.

3.3 Gamma-Ray Bursts

A search for neutrinos in coincidence with gamma-ray bursts has been conducted. According to the relativistic fireball model, gamma-ray bursts (GRBs) are expected to be astrophysical sources of high energy neutrinos. The GRB direction and burst time are known from satellite observations of these objects. In some models, neutrinos are expected within a short time (≈ 10 seconds) of the gamma-rays. This allows us to make nearly background free observations, by restricting the search bin to a specified direction and time. With ≈ 1/3 sky coverage, the BATSE satellite instrument detected 304 gamma-ray bursts in 1997. AMANDA data for 78 gamma-
ray northern hemisphere bursts detected on-board the BATSE satellite have been examined for coincident neutrino emission. No excess of neutrinos has been found above a background of 17.2 events for all 78 bursts. Due to the low background, the detection of even a few events from a single burst would be a significant observation.

3.4 WIMPs

AMANDA can be used to search for non-baryonic dark matter in the form of weakly interacting massive particles (WIMPs). A promising WIMP candidate, the neutralino, is provided by the Minimal Supersymmetric extension to the Standard Model of particle physics (MSSM). Assuming that the dark matter in the Galactic halo is (at least partially) composed of relic neutralinos, which were formed in the early universe, these massive particles do have a probability to get gravitationally trapped in the Earth and other massive objects in the Galaxy (sun, galactic center). In this theory, the WIMPs lose energy by elastic scattering on nuclei and concentrate close to the core of the Earth. There they can annihilate and neutrinos can be produced in the decay of the created particles. Thus, the search for nearly vertical up-going neutrinos can be used to constrain the parameter space of supersymmetry. No excess of vertical up-going neutrinos has been found.

The non observation of an excess of vertically up-going muons has been used to set a limit on the flux of neutrinos from WIMP annihilations in the center of the Earth. With only 130 days of exposure in 1997, AMANDA has reached a sensitivity in the region of high WIMP masses ($\geq 500$ GeV) that begins to constrain the theoretically allowed parameter space. It is comparable in sensitivity to other detectors with much longer live-times.

3.5 Supernova

By monitoring bursts of low energy neutrinos AMANDA can be used to detect the gravitational collapse of supernovae in the galaxy. This method takes advantage of the low noise characteristics (500 - 1500 Hz/PMT) of the optical sensors in the deep ice. A sensitivity for about 70% of the galaxy is reached at a 90% detection efficiency.

3.6 Magnetic Monopoles

A magnetic monopole with unit magnetic Dirac charge and a velocity of $\beta$ close to 1 would emit Cherenkov light along its path, exceeding that of a bare relativistic muon by a factor of 8300. From the non-observation of events with this clear signature, a limit of $0.62 \cdot 10^{-16}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for highly relativistic monopoles has been derived – a factor of 20 below the Parker bound and a factor of four below best other limits.

4 Conclusions and Outlook

The detection of atmospheric neutrinos in agreement with expectation establishes AMANDA as a neutrino telescope. Since February 2000, the significantly larger and improved AMANDA-II array has been collecting data. Its effective area for high energy neutrinos is about three times that of the B10 array. At the same time improved angular resolution and background rejection potential are available. The analysis of these data is under way and will improve the given results significantly. A proposal exists to construct the Icecube detector which would consist of 4800 photomultipliers to be deployed on 80 strings. It will allow us to reach $\sim 1$ km$^2$ effective telescope area, above an energy of 1 TeV with an angular resolution of well below 1 degree.
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