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Observation of high energy atmospheric neutrinos with AMANDA

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Abstract.

We describe the analysis of atmospheric neutrinos measured with the AMANDA-B10 detector during the year 1997. Two independent analyses have been performed. Both find about 200 neutrino events. This yields a total number of 325 neutrino events above a threshold of about 65 GeV for 130 days of detector live-time.

The characteristic properties of these events agree with the expectation from atmospheric neutrinos within the assumed systematic uncertainties. Different methods to estimate the background lead to an estimation of about 10% in the final sample. The celestial distribution of events is consistent with a random distribution.

1 Introduction

The AMANDA neutrino telescope (Andres et al., 2000) aims for the observation of high energy neutrinos from astrophysical sources (see e.g. Gaisser et al. (1995) and Learned and Mannheim (2000)). The detection of high energy atmospheric neutrinos is a crucial test of the performance of the detector and can be considered a proof of method of the detection techniques as well as a calibration of its sensitivity to neutrinos in general.

The experiment is located at the geographical South Pole. Photomultiplier-tubes (PMTs), deployed deep in the antarctic glacier in depths between 1,500 and 2,000m, detect the Čerenkov light from charged relativistic particles, which travel through the ice. An unambiguous signature for a neutrino event is an up-ward going muon — the result of a charged current muon-neutrino nucleon interaction below the detector.

Main challenge is the proof of background rejection: the identification of up-going muons from the 10^6 times larger background of down-going muons, which are produced in the Earth's atmosphere. Another important aspect is the verification of a sufficiently high signal efficiency. The analysis of atmospheric neutrinos helps to understand the systematic uncertainties e.g. due to the optical properties of the deep Antarctic ice and their vertical structures.

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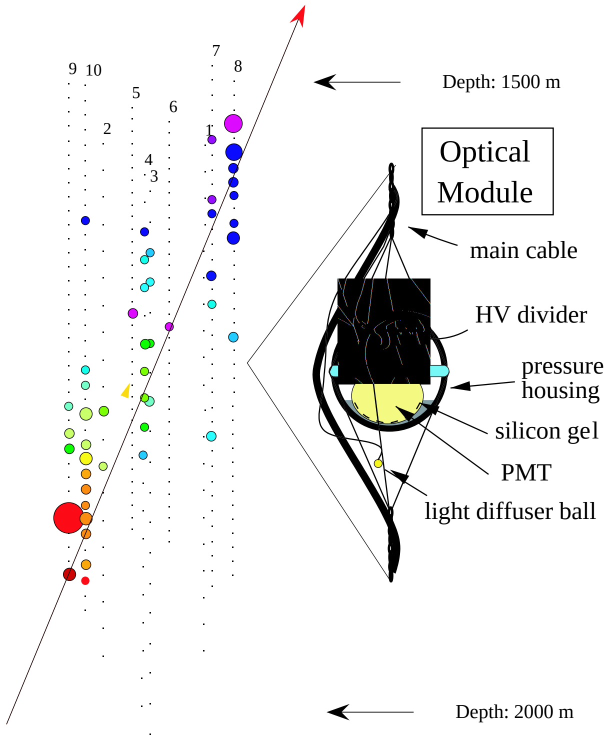

Fig. 1. The AMANDA-B10 detector as of 1997. Each dot represents an optical module. The modules are separated by 20m on the inner strings (1-4), and by 10m on the outer strings (5-10). Shown is an experimental neutrino event. The size of the circles indicates the amplitude of each detected signal the color indicates the time of the photon's arrival. Earlier times are in red, later in blue. The arrow indicates the reconstructed track of the up-going muon.

The installation of the AMANDA-B10 detector was finished in the austral summer 1996/97. The detector consists out of 302 8-inch PMTs, which are attached to 10 cable-strings, by which the PMT signals are transmitted to the surface (Fig.1). The instrumented volume is a cylinder of approximately 120m in diameter and 500m in height.

2 Data Analysis

2.1 Experimental data

The AMANDA-B10 detector operated in the year 1997 from early April to early November. The main trigger reads out events with more than 16 optical modules showing a signal within 2 μs. About 1.4 billion events were recorded in total — the dead-time corrected trigger rate was about 100Hz. These events are almost entirely due to atmospheric muons or muon bundles. They are produced in the air showers above the surface and propagate down to the depth of 1.5 km. Misreconstructed atmospheric muons are the main background for the detection of atmospheric neutrinos.

During the off-line analysis the experimental data was inspected for detector stability. Rejection of unstable PMTs and bad run periods lead to a data set of stable detector performance. In Bouchta et al. (1999) it was shown that variations in the "cleaned" trigger rate can be correlated with seasonal variations of the atmosphere down to the percent level.

After the selection of stable run periods and PMTs about 1.1 billion events are used for the physics analysis. Typically 260 out of the initially deployed 302 PMTs enter the analysis. The dead-time corrected live-time corresponds to 130.1 days.

2.2 Monte Carlo Data

Despite of the simplicity of the generic neutrino signature: an up-ward muon track, performing the experiment not under fully controlled laboratory conditions but in the deep antarctic ice, requires detailed Monte Carlo (MC) simulations.

An overview on the AMANDA offline software with further references. relevant for the following discussions is given in (Jacobsen and Wiebusch , 1999). Most notably is the detector simulation (Hundertmark , 1999), which calculates the detector response with a detailed modeling of the detector hardware. It includes the tabulated results from a single photon propagation simulation (Karle , 1999). The model includes defects of the re-frozen hole ice locally around the PMT and is done according to the measured depth dependence of optical ice-properties (Woschnagg et al., 1999).

One major effort in this analysis is a high statistics background simulation of atmospheric muons. Aim is a quantitative understanding of even rare backgrounds. A total of about 15 days equivalent live-time has been simulated. This corresponds to the simulation of more than $120 \cdot 10^6$ triggers, which again corresponds to more than 10^9 simulated air showers. Importance sampling techniques improve the statistical significance of the simulation. The achieved statistics is sufficient to verify, that our experimentally observed background contaminations are consistent with the predictions from the MC. However these simulations are not only limited by statistics but also by the systematically limited precision when simulating rare experimental processes down to the level of a rejection of 10^{-8}.

Air showers are simulated with the fast air shower program *basiev*. We verified the results with simulations, using the more precise *corsika* program. Generated muons are propagated to and through the detector depth including full stochastic energy losses using the *mudedx* code. Atmospheric neutrinos have been simulated in a similar way using the program *nusim*. In particular we have varied various input parameters, e.g. optical ice properties, within their range of assumed systematic uncertainties. More discussions on the systematics are given in section 3.

2.3 Reconstruction and filtering

The AMANDA collaboration has performed two independent analysis chains. Both aim for a clear separation of a relatively pure and large sample of atmospheric neutrino events but use different analysis techniques.

Common to both is a fast first level filter, with only small differences in the treatment of data. They typically reduce the data sample by about a factor 10. This algorithm is based on a simple track approximation (Stenger , 1990). Despite of neglecting the geometry of Čerenkov light and scattering of photons during their propagation through ice it gives a robust estimate from which hemisphere the track originates from.

This filter is followed by a maximum likelihood reconstruction, which models the probability densities of photon arrival times as function of the distance and orientation of the PMT relative to the muon track (Wiebusch , 1999). The track parameters are varied until the most probable track, which corresponds to a maximum likelihood — the product of all probabilities, is found. In order to avoid finding wrong maxima, the reconstructions are iterated by searching for the most probable track hypothesis after starting from different initial track parameters.

After this filter stage the data is reduced by more than a factor 100. Here the two analysis methods diverge.

Analysis-A uses a Bayesian inference motivated reconstruction (Hill , 2001) in which the likelihood is multiplied by a zenith dependent prior function. This function enhances the probabilities of down-ward track hypothesises up to a factor 10^6.This reflects the a priori knowledge of the zenith distribution of down-going muons. This results in large background rejection at the reconstruction level and thus a small, simplified final cut set.

Analysis-B uses an improved likelihood description for the photon response (Wiebusch , 1999). It involves the probabilities of PMTs being hit or not hit and a more accurate model for the photon arrival time, if the PMT measures more than one photon. In comparison to analysis A, this method is less efficient in the rejection of background but more efficient for signal. It is thus followed by further cuts. In particular cascade-like events, due to muon bremsstrahlung, are suppressed by rejecting events with a good cascade reconstruction (Taboada et al., 2001).

In addition to the MC simulated background we have observed rare backgrounds due to instrumental effects such as cross-talk between signal cables sometimes enhanced by unstable and high voltage supplies. Again both analysis have developed different but similarly efficient techniques to treat this background. Analysis-A inspects the signal pattern of each event for characteristic correlations in signal amplitudes and times. Suspicious signals are excluded from the reconstruction. In analysis-B the event topology is inspected. If the spatial pattern of hit PMTs is inconsistent with the reconstructed muon trajectory, the event is rejected.

After this level of cuts the data sets are reduced to well manageable sizes of a few 10^3 events. At this stage the data is still background dominated — the assumed number of neutrino induced events is less than 500.

2.4 Final neutrino cuts

For the final selection of a pure sample of neutrino-induced events, cuts on characteristic observables are tightened until the remaining background disappears — however this also involves a substantial loss in signal events. The two analyses proceed in slightly different ways.

In analysis-A, observables which are found being capable in the rejection of background, are parameterized according to the density of signal events, as predicted by MC. A quality scale can be achieved by requiring a certain fraction of signal events passing each criterion (DeYoung , 2001).

In analysis-B the final set of cuts are selected and optimized via a newly developed method: CUTEVAL (Gaug , 2000). This algorithm takes into account that cut parameters are not independent and have individual but correlated efficiencies. The principle of the CUTEVAL method is to numerically optimize the signal to background efficiency by a variation of the cut values within the allowed parameter boundaries. The explicit usage of parts of the experimental data as well as different MC simulations within the optimization procedure allows for a detection of systematic differences between MC and experiment for the used cut parameters. As first step a small set optimum parameters is derived. The final cut values are then calculated for different levels of background rejection and parameterized as function of the background parameter N_{BG}. This parameter is only a rough estimate of the expected background contamination — the true amount of background in the final experimental sample is measured with different methods. In this analysis a quality scale is defined by the amount of background in the data sample: $Q \equiv -\log(N_{BG}/N_{TL})$, with N_{TL} the number of events at trigger level.

In both analyses the final neutrino cuts are derived by tightening the quality requirements until the background is sufficiently rejected and a clear separation of neutrino-induced events is achieved.

Figure 2 shows the number of events, which survive the gradually tightened quality cuts. One can see that the experimental passing rate first follows the background prediction from trigger level (TL) over six orders of magnitude until the point, where neutrinos are expected to dominate the experimental sample. Here the experimental shape changes and turns over to follow the signal prediction up to the highest possible quality requirements. The total number of experimental events is smaller than the MC prediction, but agrees within the systematic uncertainties.

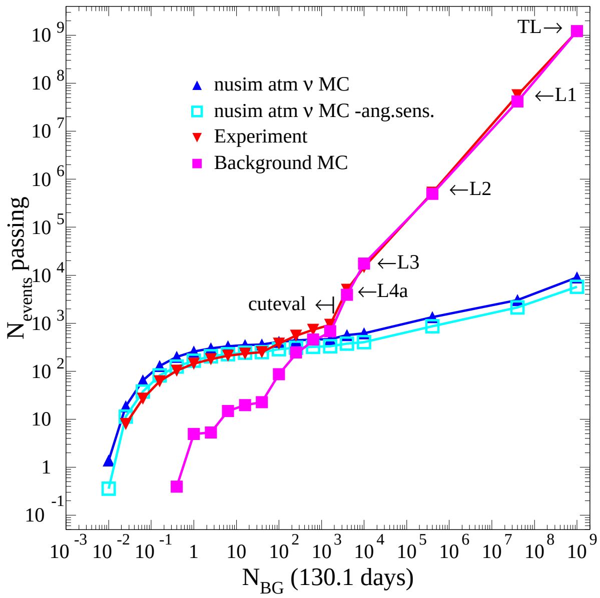

Fig. 2. Number of events versus the background parameter N_{BG} for analysis-B. Shown are results for the experiment, two simulations of atmospheric neutrinos and the background MC. The background parameter N_{BG} is equivalent to a certain strength of cuts. Smaller values correspond to tighter cuts. The final neutrino cuts are those for $N_{BG} = 10$. Note that N_{BG} is only a rough estimate of the background contamination. The actual amount of background is determined with dedicated methods. The plot covers the full range of the analysis showing results from the trigger level (TL) and intermediate cut levels (L1-L4a) up to cuts as tight as possible.

3 Results

Analysis-A leads to 204, analysis-B to 223 events — 102 events are common to both analysis. The total number of the combined sample is 325 events. The number of overlapping events is consistent with the expectation from the simulation. However the total number of found events is smaller than the expectation in each A: -23% B: -41% and the combined sample: -38%. When considering also the background from atmospheric muons, the deficits become slightly larger.

90% of the MC signal events have muon [neutrino] energies between 50 [65] GeV and 1.8 [3.4] TeV. We estimate the effective area [volume] of this analysis for muons of 1 TeV to be about 3×10^3 m^2 [8×10^6 m^3].

The backgrounds in the event samples are estimated by several methods: The most straight-forward is the MC estimate. Visual inspection of the final sample was done after testing the efficiencies with blind tests. An important experimental technique is the attempt to identify event prop-

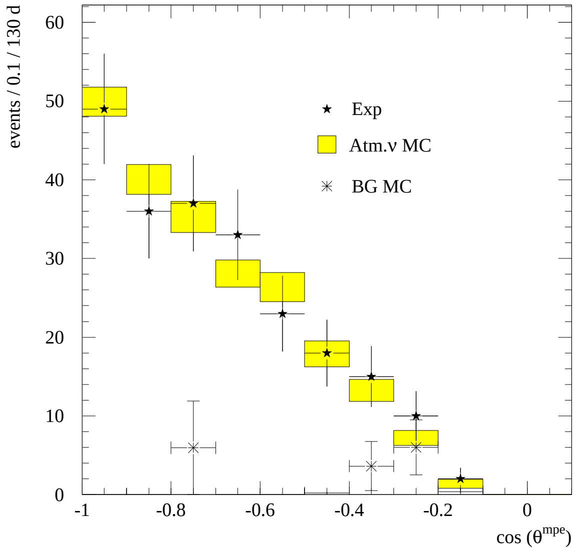

Fig. 3. Distribution of the cosine of the reconstructed zenith angle for analysis-B. Shown are the experimental data points with the MC expectations for the atm.μ-background and the atm. neutrino simulation. The MC includes effects from neutrino oscillations and local hole ice defects. Note that the BG simulation is limited by statistics.

erties, which are characteristic for background in the final event sample. Typical features here are a non-smooth depth dependence of the location of the events or pathological PMT signal features from malfunctions in the DAQ or cable cross-talk. Another powerful technique is to measure the experimental BG by removing each of the final cuts separately. The BG in the final sample is then determined by correcting the background MC for this experimentally measured background. We found all these methods to be quantitatively consistent. They agree to a contamination of about 5% to 10% background events in the final samples.

The absolute event deficit is most probably explained by our systematic uncertainties. Important uncertainties are the absolute flux prediction from atmospheric neutrinos: ∼30%, uncertainties in the muon range and thus effective volumes: ∼20% and due to uncertainties in the optical parameters of the ice: ∼15%. Another major uncertainty is the absolute sensitivity of PMTs. MC simulations show, that the total event number is almost proportional to the PMT efficiency. The generic value is known to about 10% precision, but is modified due to local bubbles around the PMT in the refrozen hole ice. This effect can lead, depending on the angle of incident light, to a 40% changed efficiency. Figures 2 and 3 show results of simulations (ang.sens.), which try to model these effects more precisely.

Due to a relatively high energy threshold of about 65GeV, effects from atmospheric neutrino oscillations are expected to be relatively small. For typical oscillation parameters, $\sin^2 2\theta = 1$ and $\Delta m^2 = 3 \cdot 10^{-3}$, we expect a 10% reduced event rate — an effect smaller than the other uncertainties.

The distribution of zenith angles (figure 3) is consistent

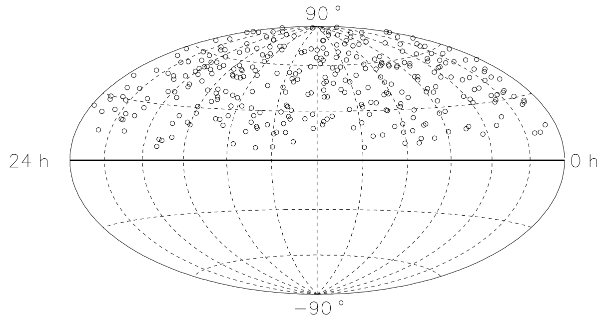

Fig. 4. Celestial distribution of neutrino directions in equatorial coordinates for all events from analysis-A and B. The median angular pointing resolution, estimated by MC, is about $3°$–$4°$.

with the expectation from the simulations of atmospheric neutrinos. The detector achieves the largest efficiency for vertical events. This is favored by the geometry of the AMANDA-B10 detector, which extends about four times more in vertical than in horizontal directions. The distributions of celestial coordinates are shown in figure 4. The distribution is consistent with the assumption of being random. No significant clustering of events is seen.

4 Conclusions

The here presented results from the first year of data taking with AMANDA-B10 demonstrate that a large neutrino detector can be built and operated in the antarctic ice. The achieved performance is as expected from simulations.

Since then, nine strings were added in a concentric circle around AMANDA-B10. This larger detector, AMANDA-II, consists of 677 PMTs. We observe a significantly improved efficiency (Wischnewski et al., 2001), especially for horizontal events. Plans are made for a much larger detector: ICE-CUBE, which is described in Goldschmidt et al. (2001).

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