Up- and down-going muons in the AMANDA-B4 prototype detector

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Abstract

The first stage of the AMANDA-B neutrino detector has been operating in 1996 with 86 photomultipliers along 4 strings at depths between 1520 and 2000 m. The analysis of the recorded data allowed to develop and test the methods needed to operate a large neutrino detector in the deep antarctic glacier. This paper sketches the reconstruction of muons, gives the intensity vs. depth relation for atmospheric muons and describes the identification of first up-going muon events.

The detector

AMANDA (**A**ntarctic **M**uon **A**nd **N**eutrino **D**etector **A**rray) is a high-energy neutrino telescope presently under construction at the geographical South Pole. The detector consists of strings of optical modules (OMs) frozen in the 3 km thick ice sheet at the South Pole. An OM consists of an 8" photomultiplier in a glas vessel. The strings are deployed into holes of $\sim$ 60 cm diameter, drilled with pressurized hot water. In the Austral summer 1995/96, an array of 86 optical modules (OMs) arranged on 4 strings was deployed at a depth between 1.5 and 2 km. Each string carries 20 OMs with a vertical spacing of 20 m along 380 m, electricaly connected to the surface with a coax cable. Six additional OMs with twisted pair cable are mounted at the bottom of string four. Time calibration is performed with a laser mounted at the surface, which light is guided through optical fibers to light isotropisers close to each module. Fig.1 shows a schematic view of AMANDA-B4.

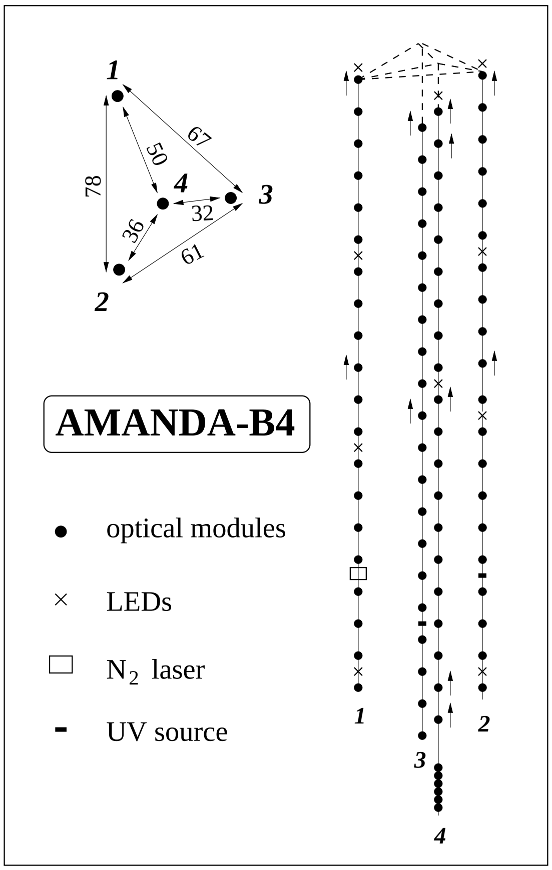

Figure 1: AMANDA-B4: Top view, with distances between strings given in meters, and side view showing optical modules and calibration light sources. Upward looking PMTs are marked by arrows.

Reconstruction of muon tracks

Before being analysed, the data (experimental and Monte Carlo) is reconstructed. This procedure consists of different steps, being listed below:

1. Rejection of isolated noise hits.
2. A line approximation following [13] yielding a velocity $\vec{v}$ (with $\vec{v_z}$ being the z-component).
3. A likelihood fit based on the measured times taking the result of the line approximation as start value. This "time fit" results in angles and coordinates of the track as well as a likelihood $\mathcal{L}_{time}$ [14].
4. A second likelihood fit varying the energy by using the hit and not-hit information of the OMs. This "hit fit" does not vary the direction of the track but gives an additional likelihood $\mathcal{L}_{hit}$.
5. A quality analysis in order to reject bad reconstructed events.

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The reconstruction is giving a set of quality criteria, being exploited with different emphasize in the two searches for upward moving muons. The most efficent are the following:

- Speed $|\vec{v}|$ of the line approximation. Values close to the speed of light indicate a reasonable hit pattern.
- "Time" likelihood per hit OM, $\log(\mathcal{L}_{time})/N_{hit}$.
- "Hit" likelihood per all working channels, $\log(\mathcal{L}_{hit})/N_{all}$.
- Number of direct hits, N_{dir}[1].
- The maximum projected length of direct hits onto the reconstructed track, L_{dir}.
- The vertical coordinate of the center of gravity given by hit OMs, z_{COG}.

Intensity vs. depth relation

The muon intensity $I(\theta_\mu)$ as a function of the zenith angle θ is obtained from:

$$I(\theta_\mu) = \frac{S_{dead}}{T \cdot \Delta\Omega} \frac{N_\mu(\theta_\mu) \ \cdot m(\theta_\mu)}{\epsilon_{rec}(\theta_\mu) \cdot A_{eff}(\text{mult}, \theta_\mu)} \tag{1}$$

The right-hand side include the following values: $N_\mu(\theta_\mu)$,the number of events with a reconstructed zenith angle $\cos(\theta_\mu)$. $T = 22.03$ hours is the run time, corresponding to $9.86 \cdot 10^5$ events being sucessfully reconstructed and having more than 7 hit OMs on three strings. The deadtime of the data acquisition system results in S_{dead}=1.14. $\Delta\Omega$ is the solid angle covered by the corresponding $\cos(\theta_\mu)$ interval. $A_{eff}(\text{mult}, \theta_\mu)$ is the effective area at zenith angle θ_μ. The effective area is a strong function of the requested OM multiplicity. The reconstruction efficiency at a certain zenith angle is represented by $\epsilon_{rec}(\theta_\mu)$. The value is $\sim$0.8. The mean muon multiplicity $m(\theta_\mu)$ is about 1.2 for vertical tracks and decreases towards the horizon.

Without having applied quality criteria after the reconstruction the zenith angle distribution of the reconstructed muons is strongly smeared. The relation between the reconstructed angle and the true angle is known from the Monte Carlo. To calculate the elements of the parent angular distribution $N_\mu(\theta_\mu)$ from the reconstructed distribution $N_\mu(\theta_{rec})$ a standard regularized deconvolution procedure was used [5]. Fig.2 shows the unfolded angular distribution of the flux of downgoing muons, $I(\theta_\mu)$, as obtained from eq.(1). The method is rather robust against the multiplicity chosen. Deviations between fluxes derived from samples with $N_{hit} \geq 8, 10, \ldots, 18$ are within 25%, while the total number of events is reduced by a factor of 20 between the extrem cases [10]. For further studies we use the sample with $N_{hit} \geq 16$. The measured flux $I(\theta)$ can be transformed into a vertical flux $I(\theta = 0, h)$, where h is the ice thickness in mwe[2] seen under angle θ:

$$I(\theta = 0, h) = I(\theta) \cdot \cos(\theta) \cdot c_{corr} \tag{2}$$

The $\cos(\theta)$-conversion corrects the sec(θ) behaviour of the muon flux, valid for angles up to 60° [9]. The term c_{corr} is taken from [11] and corrects for larger angles. It's value varies between 0.8 and 1.0 for the angular and energy ranges considered here. The vertical intensities obtained in this way are plotted in fig.3. The results are in agreement with the depth-intensity published by DUMAND [3], Baikal [4], and the prediction given by Bugaev et al. [7].

We also fitted the data to a parametrization taken from [1, 12]:

$$I(h) = I_0 \cdot E_{crit}^{-\gamma} = I_0 \cdot \left(\frac{a}{b_{eff}} \cdot \left[e^{(b_{eff} \cdot h)} - 1 \right] \right)^{-\gamma}, \tag{3}$$

E_{crit} is the minimum energy necessary to reach the depth h. We approximate $b(E_\mu)$ by an energy independent parameter b_{eff}. Fitted to eq.(3), our data points yield:

$$I_0 = (5.04 \pm 0.13)\,\text{cm}^{-2}\text{s}^{-1}\text{ster}^{-1} \qquad b_{eff} = (2.94 \pm 0.09) \cdot 10^{-6}\,\text{g}^{-1}\,\text{cm}^2.$$

The fitted value of b_{eff} is in agreement with the value given in [2].

[1] A direct hit is defined as having a time residual t_i(measured) $- t_i$(fit) smaller than a certain cut value. We use cut values of 15 nsec (N_{dir}(15)), 25 nsec (N_{dir}(25)) and 75 nsec (N_{dir}(75)). Increasing the time window leads to higher cut values in N_{dir} but allows a finer graduation of the cut. The reconstruction quality increases with the number of direct hits [14].

[2] meter water equivalent

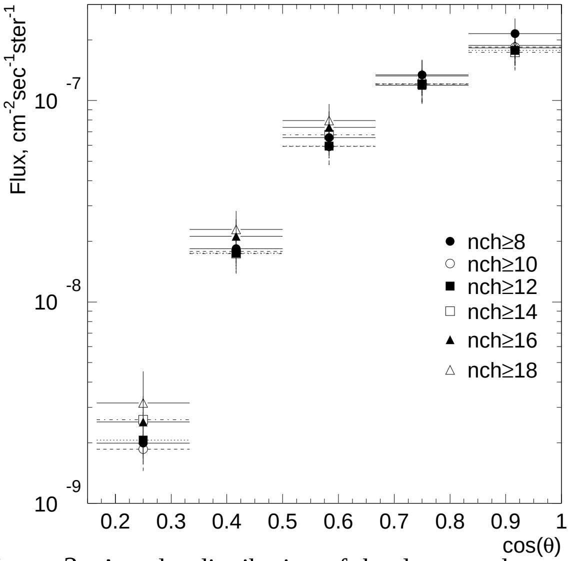

Figure 2: Angular distribution of the downward going muon flux, $I(\theta_\mu)$, as obtained from eq.(1).

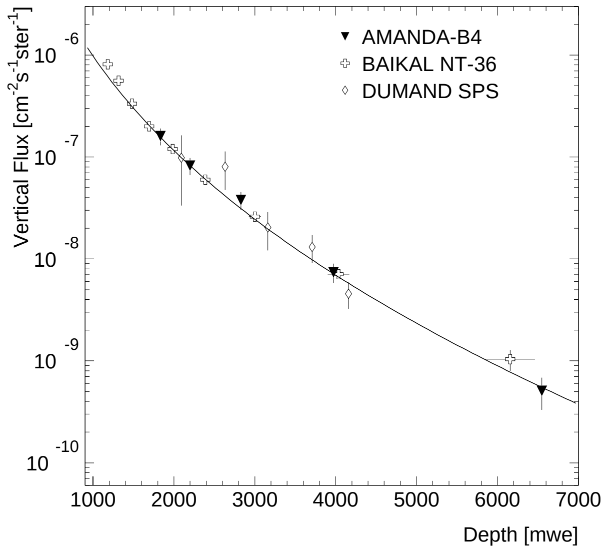

Figure 3: Vertical intensity versus depth for Amanda, Baikal and Dumand. The full line gives the prediction of [7].

Search for Upward Going Muons

AMANDA-B4 was intended to demonstrate the principal possibility of muon track reconstruction in Antarctic ice. The small number of optical modules complicates the rejection of misreconstructed events. Despite of this the separation of a few upward muon candidates was possible.

Two full, but independent analyses were performed with the experimental data set of 1996. Because of the time consuming reconstruction, the first approach reduced the number of events by a fast pre-filter from $3.5{\cdot}10^8$ down to 5.2%. This pre-filter divided the detector in four z-slices, requiring a pattern of hits prefering long, upward moving muons. Applying this pre-filter to the background Monte Carlo sample, a passing rate of 4.8% was achieved. 49.8% of simulated upgoing events survived this pre-filter [6]. Full reconstruction and application of the following criteria:

1. Hits on $\geq$ 2 strings.
2. reconstructed zenith angle $\theta > 90°$.
3. $\log(\mathcal{L}_{time})/N_{hit} > -6$.
4. $\vec{v_z} \geq 0.15$ m/nsec.

led to 2 events with $N_{dir}(15)$ $\geq$6, being in agreement with the Monte Carlo expectation for atmospheric neutrinos. The combination of the pre–filter and the criteria on the reconstruction selected events close to the opposite of the zenith, a region where also the second analysis concentrated on. Here the data set was reconstructed completely (with a different algorithm) and than reduced by the subsequent application of the following criteria:

1. zenith angle of the line approximation and of the reconstruction $\theta > 120°$
2. $0.15 < |\vec{v}| < 1$ m/nsec
3. $\log(\mathcal{L}_{time})/(N_{hit} - 5) > -10$ (i.e. normalizing to the degrees of freedom)
4. $\mathcal{L}_{hit}/(N_{hit} - 5) > -8$
5. $N_{dir}(25) \geq 5$
6. $N_{dir}(75) \geq 9$
7. $L_{dir}(25) > 200$ m
8. $|z_{COG}| <$ 90m

These cuts reduced the experimental data sample to 3 events. The passing rate for Monte Carlo upward moving muons from atmospheric neutrinos is 1.3%, thus leaving an expectation of 4 events. The corresponding enrichment factor is $\approx 1.5 \cdot 10^6$. One of the three experimental events was also identified in the previous described search. The parameter distributions of the events agree with what one expects for muons from atmospheric neutrinos, and they are separated well from the rest of the experimental data. Fig.4 shows the distribution in L_{dir}(25) and N_{dir}(75). The three events passing *all* cuts are separated from the bulk of the data. On the right side of fig.4, the data are plotted versus a combined parameter, $X = ((N_{dir}$(75)-2) $\cdot L_{dir}$(25)/20). In this parameter, the data exhibit a exponential decrease. Assuming the decrease of the background dominated events to continue at higher X values, one can calculate the probability that the seperated events are fake events. The probability to observe one fake event at $X \geq 70$ is 15 %, the probability to observe three fake events is $6 \cdot 10^{-4}$. We conclude that tracks reconstructed as up-going are found at a rate consistent with what we expect for atmospheric neutrinos.

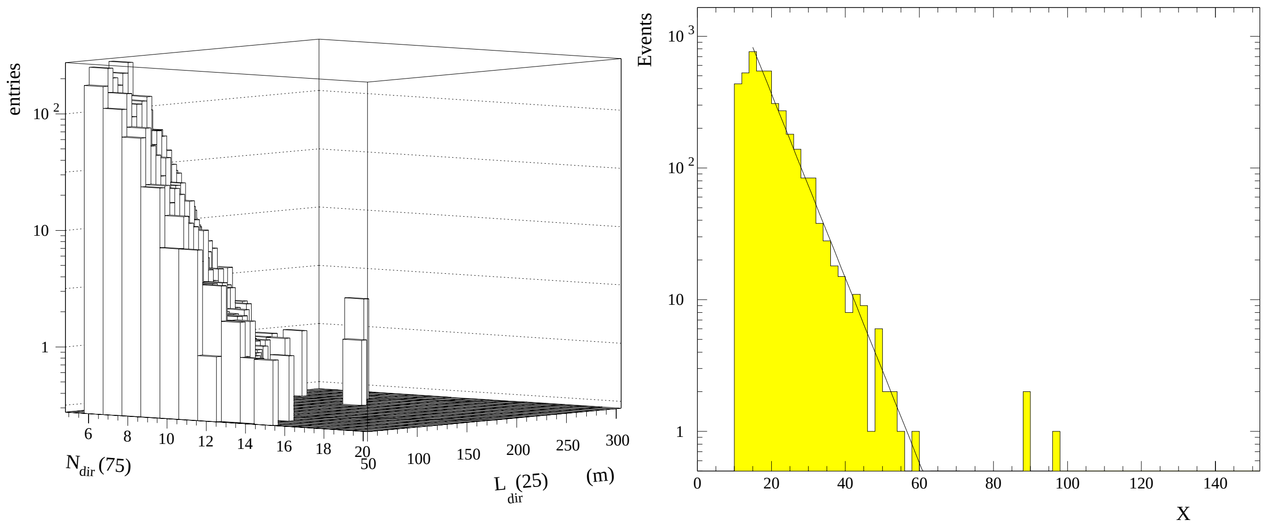

Figure 4: After application of cuts with the exception of cuts 6 and 7: *left* – distribution in parameters L_{dir}(25) vs. N_{dir}(75), *right:* distribution in the "combined" parameter ((N_{dir}(75)-2) $\cdot$ L_{dir}(25)/20 m.)

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