RESULTS FROM AMANDA

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1. Introduction

Today, the Antarctic Muon and Neutrino detector Array array consists of 19 strings and 677 optical sensors. This expanded array, referred to as AMANDA-II, has been completed in February 2000 and calibrated in the austral summer 2000/01. Figure 1 shows a schematic view of the new AMANDA-II array. The newly added strings 11-19 are located on an outer ring of 200 m diameter. They use fiber-optic cables for high bandwidth analog signal transmission of the photomultiplier pulses.

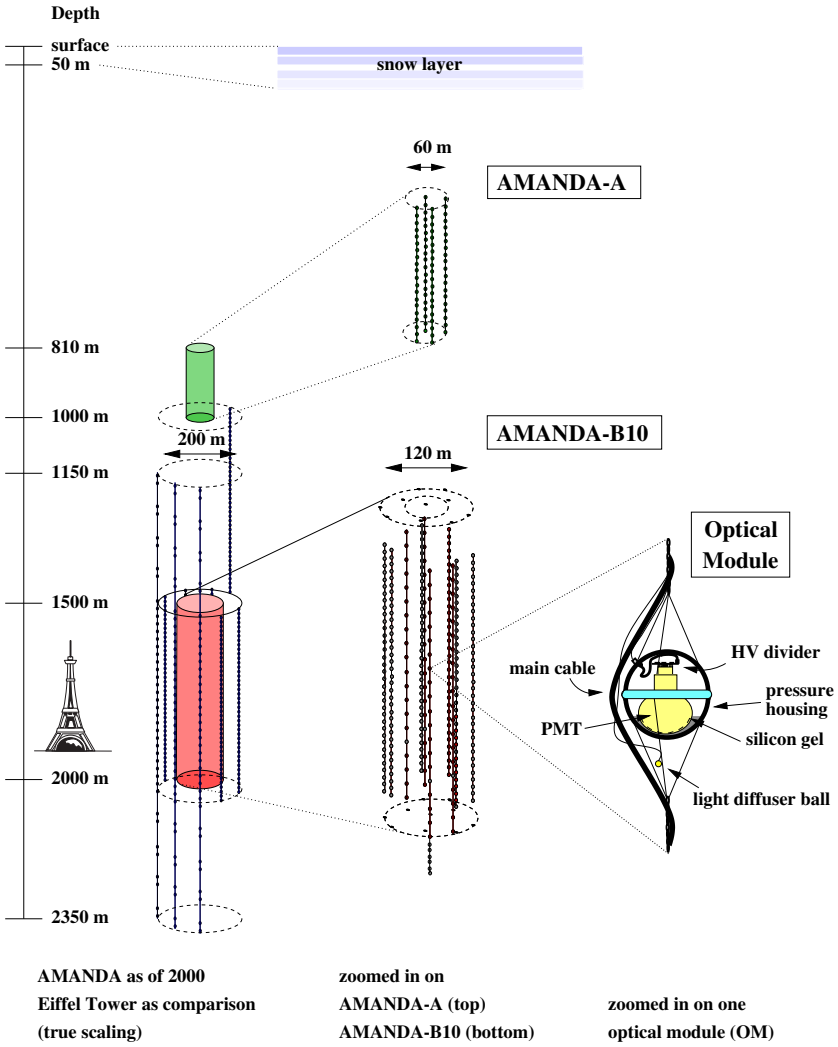

Figure 1: The AMANDA-II array at the South Pole

In this report we present results of the previously completed 10 string prototype array. The construction of this first generation Antarctic Muon and Neutrino Detector Array (AMANDA) was completed in January 1997. This detector, referred to as AMANDA-B10, consists of 302 optical sensors on 10 strings located at depths of 1500 to 2000 m in the deep Antarctic ice. We present some of the results obtained from data taken in the first year of operation in 1997.

The main goal of the AMANDA neutrino telescope is the search for astrophysical sources of high energy neutrinos. Before taking on this challenge we expect to detect the background, or better 'foreground' of neutrinos generated in the Earth's atmosphere. At present there are no well-known astronomical sources on which a high energy neutrino telescope can be calibrated. Thus observation of atmospheric neutrinos is an important basis to verify the sensitivity of the instrument located in

the natural ice shelf at the South Pole. The results obtained with the AMANDA-B10 array are presented in two steps. We focus first on the detection of neutrinos and compare them to the predicted flux of atmospheric neutrinos. Possible backgrounds will be discussed. We then apply the results to the search for high energy neutrinos of astrophysical origin, such as a diffuse flux of HE neutrinos, point like sources and gamma ray bursts.

2. Atmospheric Neutrinos

The results presented here are based on data taken during the austral winter of 1997. The effective livetime has been determined to be 130.1 days for the selected data. The method of calibration and the characteristics of the optical sensors are very similar to the 4 string prototype array described in ref. [1]. Simulations predict a rate of a few tens of events per day from atmospheric neutrinos above a threshold of 30-50 GeV, compared to $6 \cdot 10^6$ events from cosmic ray muons, as shown in Figure 2.

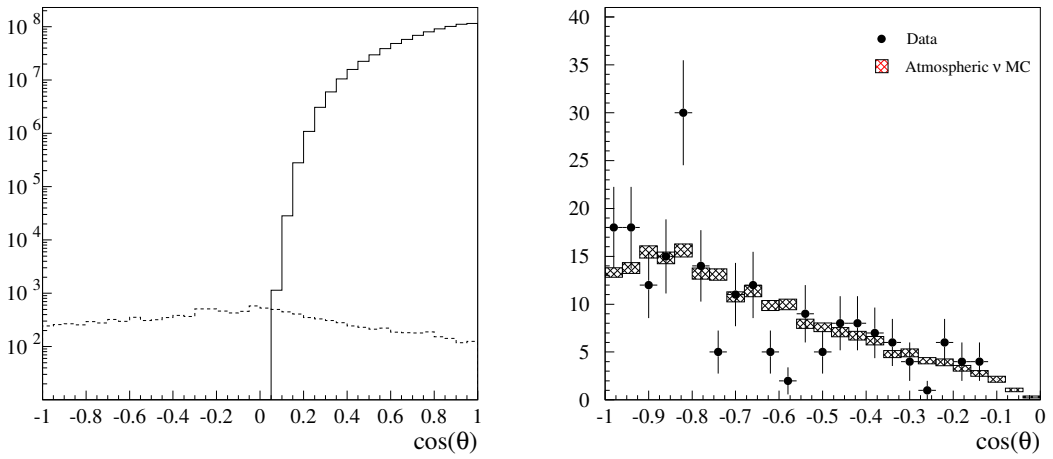

Figure 2: Left: The zenith angle distribution of AMANDA triggers. The solid line represents triggers from downgoing cosmic ray muons. The dashed line shows triggers produced by atmospheric neutrinos. Right: The zenith angle distribution of upward reconstructed events. The size of the hatched boxes indicates the statistical precision of the atmospheric neutrino simulation.

The analysis of the atmospheric neutrino sample with the AMANDA-B10 array has been performed independently by two working groups in the collaboration. Both groups come to very similar and statistically consistent results while the methods are quite different and partially independent. The figures and the method presented here are based on one analysis [4].

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

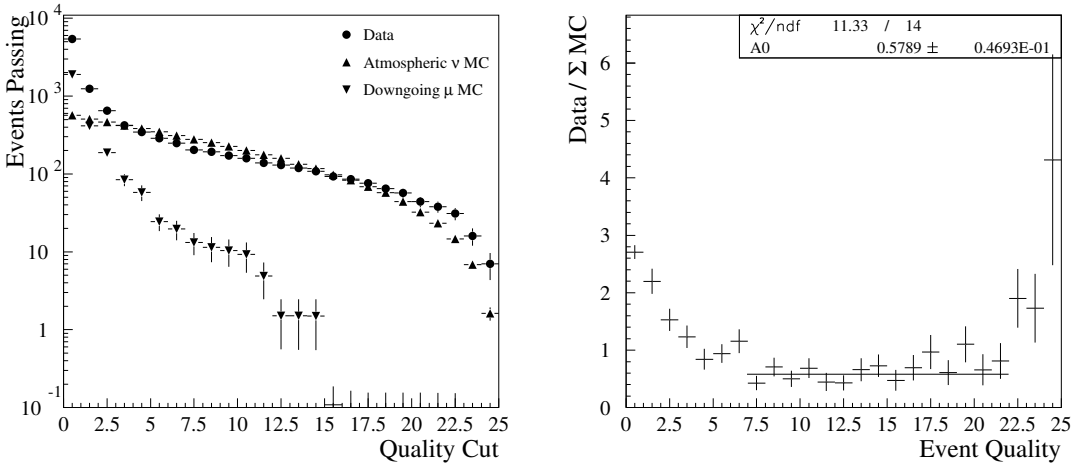

Figure 3: Event quality. Left: Passing rates of events above a certain quality level is shown for background MC, atmospheric neutrino MC and experimental data. Right: Differential presentation of the ratio data/MC.

arrival times. Events are reconstructed with a Bayesian method [5], in which the likelihood function is multiplied by a prior probability function. The prior function contains the zenith angle information in Fig. 2. By accounting in the reconstruction for the fact that the flux of downgoing muons from cosmic rays is more than 5 orders of magnitude larger than that of upgoing neutrino-induced muons, the number of downgoing muons that are misreconstructed as upgoing is greatly reduced. 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. By making increasingly stringent cuts on the event quality the background of a total of $1.2 \cdot 10^9$ events is reduced 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

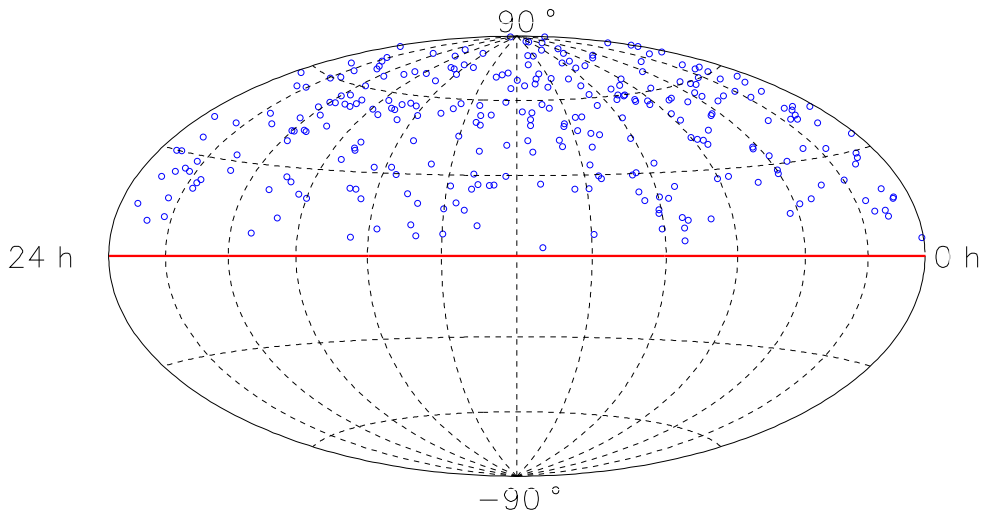

Figure 4: Neutrino sky of upgoing events as seen with AMANDA-B10. The background of non neutrino events is estimated to less than 10%.

of events passing various levels of cuts. This is done in Fig. 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 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 Fig. 3 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 2, and compared to that for the signal simulation. In the figure the MonteCarlo 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

	Experimental Data	MC: Atmospheric Neutrinos
Triggered	$1.2 \cdot 10^9$	4600
Reconstructed upward	$5 \cdot 10^3$	571
Upward going	204	279

Table 1: Event numbers are given at various cutlevels: Experimental data and atmnospheric neutrino Monte-Carlo.

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. A skyplot of these events is shown in figure 4. 223 events were found in an independent analysis. The overlap of 119 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. Pointing resolution

In order to establish AMANDA as a neutrino telescope, one more step is needed. That is the verification that AMANDA does indeed reconstruct the direction of events correctly in sky coordinates. This is done by analyzing events that are measured coincidently by AMANDA in the deep ice and by surface air shower detectors. In the 1997 data set we have three independent detectors at the surface in operation: the SPASE-1 air shower array, the SPASE-2 array, and the GASP air cherenkov detector. All three experiments agree in the average absolute pointing of the AMANDA array to within 1 to 2 degrees (sky coordinates) other[3)]. A full agreement with the true direction is achieved in azimuth, and a small offest of order 1 degree is observed in the in the zenith angle (data and Monte-Carlo). The offset is relatively small compared to the size of a search bin ($\approx$ 5 degrees half angle) for point sources. These instruments were also used to verify the angular resolution (median angular error) of about 3 degrees.

The observation of atmospheric neutrinos together with the verification of the angular resolution establishes AMANDA as a functioning neutrino telescope. From here we search the neutrino sky for various sources. Depending on the type of the investigated neutrino signal hypothesis (diffuse flux, point sources, GRB, WIMPs, etc.), we re-optimize the background rejection strategy.

4. Search for a diffuse high energy neutrino flux

The search for a diffuse neutrino flux of astronomical origin follows naturally from the observation of a diffuse flux of neutrinos generated in the atmosphere. Neutrinos from generic astrophysical sources are expected to extend to higher energies while the

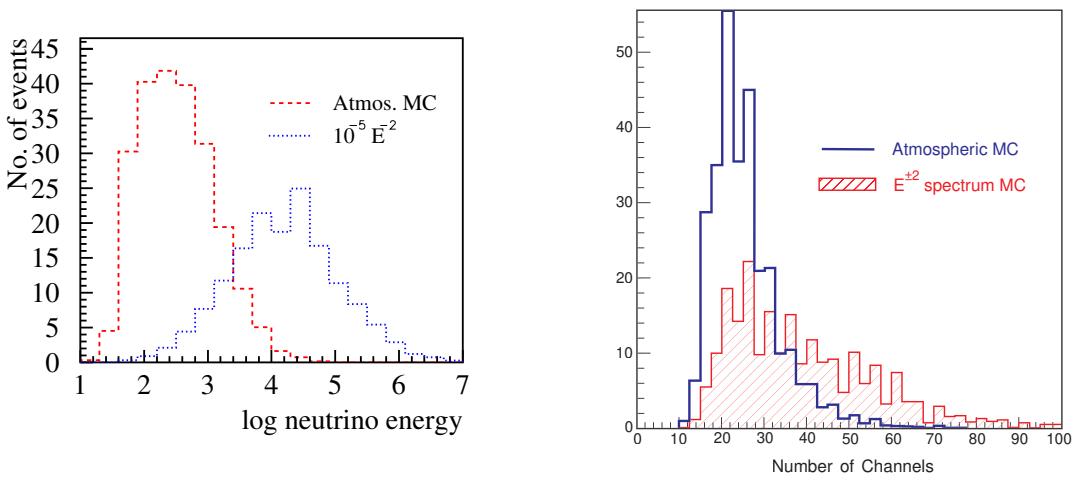

Figure 5: Left: Monte-Carlo simulation of the energy spectrum of atmospheric neutrinos shown in the skyplot in figure reffig:sky. Also shown is the energy spectrum of neutrinos generated by a neutrino flux of a E_ν^{-2}-type energy spectrum (see text).

energy spectrum of atmospheric neutrinos falls off steeply with increasing energy. A very simple and robust measure of the energy of the observed muons is the number of optical modules (OM) that observed at least one photoelectron in a given event. Figure 5 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 $dN/dE_\nu = 10^{-5} E_\nu^{-2}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1}$. When using the number of fired OMs as a measure of energy we obtain the distributions given in figure 5. The assumed astronomical neutrino flux would generate a significant excess at high multiplicities of fired photomultipliers. A preliminary analysis dos not show such an excess. This leads to a preliminary upper limit[12] (90%C.L.) of $dN/dE_\nu \approx 10^{-6} E_\nu^{-2}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1}$. However, the systematics of this analysis with respect to the high energy sensitivity is 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 [17], SPS-DUMAND [13], AMANDA-A [14], and FREJUS [15], and comparable to a limit presented by BAIKAL[18] at this conference.

It is comparable to the AGN prediction by Salamon and Stecker [10] and approaches the prediction of Protheroe [16].

5. Point sources

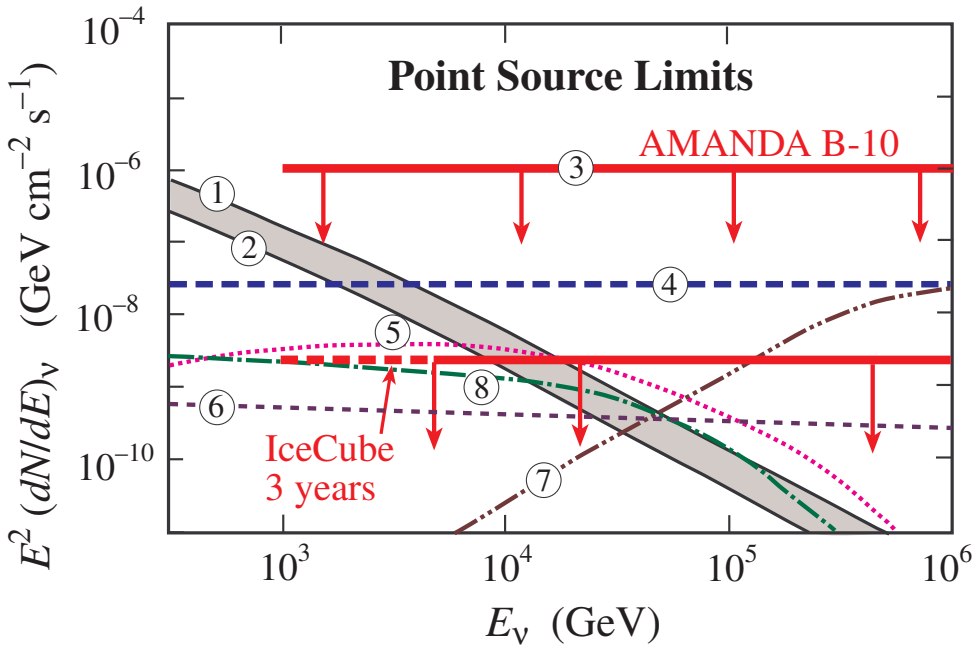

Figure 6: Predictions of high energy $\nu_\mu + \bar{\nu}_\mu$ fluxes from astrophysical sources are shown. Also shown are the preliminary average upper limit as obtained with AMANDA-B10 (3), as well as the sensitivity of the proposed IceCube array after three years of operation. The atmospheric neutrino flux[6] in 2 x 2 degree bin is given as reference: (1) horizontal, (2) vertical. Models: (4) 3C273 pp neutrinos [7], (5) Crab Nebula [8], (6) Coma Cluster [9], (7) 3C273 $p\gamma$ neutrinos [10], (8) Supernova IC443 [11].

The search for point sources allows us to measure the background off-source. Searches have been performed for specific point sources as well as all sky searches. The median angular resolution of the AMANDA-B10 array is 3 degrees. Thus, one hemisphere consists of 319 bins. Again the search strategy is optimized for the expected energy spectrum. The size of the search bins, the effective area and the livetime of the array enter the calculation of a neutrino flux limit. In absence of a signal we calculate upper limits to a neutrino flux from point sources. The preliminary average neutrino flux limits are at a level of $dN/dE_\nu \approx \cdot 10^{-6} E_\nu^{-2}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{GeV}^{-1}$.

The limit in case of Mrk 501 is of particular interest. Here our neutrino flux limit is only about a factor of 10 above the gamma emission of this blazar, during its high state in 1997. The sensitivity of the AMANDA array is thus beginning to approach observed fluxes of gamma rays.

Figure 6 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. Detailed simulations have been performed of IceCube, the proposed km-scale neutrino array. The achievable upper limit for an assumed E^{-2}-type spectrum for point sources is indicated in the figure.

6. Gamma-Ray Bursts

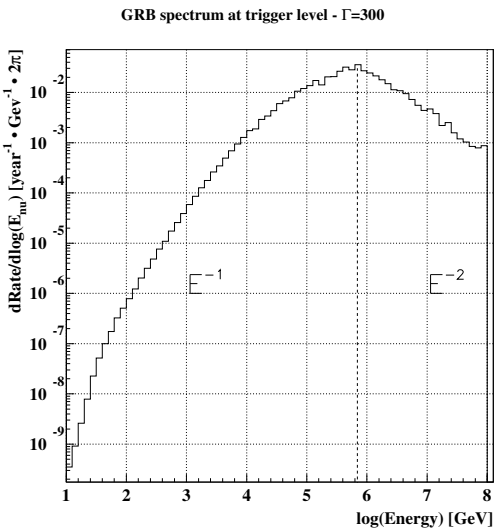

Figure 7: The energy spectrum of a neutrino flux as expected from gamma ray bursts triggered by AMANDA (Monte-Carlo simulation).

According to the relativistic fireball model, gamma-ray bursts (GRBs) are expected to be astrophysical sources of high energy neutrinos. The neutrino flux can be calculated as a function of the relative ratio of protons and electrons in the fireball. It can be fixed by the assumption that the GRBs are the source of the observed highest energy cosmic ray flux [21]. In this case energy should be approximately equally transferred to electrons and protons in the fireball [22]. The expected neutrino event rate in AMANDA has been determined from a full MC simulation of the GRB signal and the detector. GRB neutrinos are generated following a broken power law energy-spectrum [23]. Figure 7 shows the energy spectrum of Monte-Carlo events that triggered events in the AMANDA array. The search strategy has been optimized for this hypothetical signal. The number of expected events depends strongly on the assumed Lorentz factor. This scenario predicts event rates ranging from 10^{-4} events ($\Gamma = 1000$) to 1 event ($\Gamma = 100$) for the given data sample.

With $\approx 1/3$ 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 were examined for coincident neutrino emission. Because the time window of coincidence is rather short, typically of order 10 seconds per burst, there is very little background from cosmic rays and atmospheric

neutrinos. No excess of neutrinos has been found above a background of 17.2 events for all 78 bursts.

7. 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[24]. With only 130 days of exposure in 1997, AMANDA has reached a sensitivity in the region of high WIMP masses ($\geq 500\,\mathrm{GeV}$) that begins to constrain the theoretically allowed parameter space. It is comparable in sensitivity to other detectors with much longer live-times.

8. 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[25].

9. Magnetic Monopoles

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

– a factor of 20 below the Parker bound and a factor of four below best other limits.

10. Conclusions and Outlook

The detection of atmospheric neutrinos in agreement with expectation and the calibration of downgoing muons with surface detectors establish 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 $\approx 1\,km^2$ effective telescope area, above an energy of 1 TeV with an angular resolution of well below 1 degree.

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