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Latest results of AMANDA

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Abstract. In this contribution the latest analysis results of the Antarctic Muon And Neutrino Detector Array (AMANDA) are summarized. The status of recent hardware improvements is reported.

PACS. 96.40.Tv Neutrinos and muons – 95.55.Vj Neutrino and muon detectors, cosmic ray detectors – 95.85.Ry Neutrino, muon, pion; cosmic rays – 96.40.De Cosmic ray composition and energy spectra – 95.35.+d Dark matter

1 Introduction

The neutrino telescope AMANDA has been build up at the geographical South Pole between 1994 and 2000. It consists of 677 optical modules located at 19 strings mostly situated in a depth between 1500 m and 2000 m below the ice surface. There the clear ice is used as interaction medium for high energetic neutrinos and as detection medium for the Cherenkov light emitted by their charged interaction products. Though data taking started already in the construction phase of the experiment and first results were published with data taken with the 10 string sub-detector (called AMANDA B 10), only since the Austral summer 2000/2001 data is taken with the final in-ice configuration of the experiment. Main purpose of the experiment is the search for extraterrestrial neutrinos. This signal, however, is covered under an overwhelming background of downgoing atmospheric muons (at least 8 orders of magnitude in rate) and upgoing atmospheric neutrinos ($>$ 2 orders of magnitude). These background events can be used to investigate both the understanding of the detector and physics questions connected with particles produced by Cosmic Ray interactions with molecules of the atmosphere. Following the frequency of the various event signatures in AMANDA in this contribution the present (summer 2003) state of the data analysis is summarized. Further, the consequences of the hardware upgrade of the read-out electronics from a TDC/TOT based system to a system working with transient waveform recorders carried out in the Austral summer 2002/2003 is discussed.

2 Analysis results

2.1 Atmospheric muons: Systematic

The most frequent experimental signature recorded by the detector are Cherenkov light cones from atmospheric downgoing muons. Above the ice surface the differential muon flux follows roughly a power law with an exponent of -3.7 in the energy and an angular dependence of $1/cos(\Theta)$. Since the survival probability of muons in the ice depends on their energy and path length in the ice, the measurement of their energy spectrum is possible by measuring the muon rate from different depths respectively zenith angles. However, this measurement contains implicitly a non resolvable convolution of the muon flux with the primary hadron flux, the physics of the first interaction, the muon energy loss, the density and chemical composition of the ice, the light propagation through the ice and the sensitivity of the photomultiplier. Therefore in a complimentary second approach the energy dependence of the muon flux is unfolded from the light pattern recorded in each event. The combined result of both analyzes shows, that the flux normalization of the atmospheric muon spectrum is understood within 50%. The most important sources of this error are the uncertainty of the absolute primary flux and the uncertainty of the multiplicity of muons from the first interaction. The spectral index of the muon spectrum agrees within 10% with the expectation. Here the systematic uncertainty is related to uncertainties of muon energy loss and the light propagation in the ice. The collaboration is working on a reduction of these errors. For details of the analyzes see [1,2].

2.2 Atmospheric muons: All primary particle energy spectrum

Assuming the muon energy loss uncertainty to be small, the atmospheric muon signal can be used to determine the all particle energy spectrum of primaries above 2 TeV. Two independent methods were applied. With a regularized unfolding ansatz the differential primary spectrum was derived up to 1 PeV. One measures a spectral index of 2.7 ± 0.04 for QGSJET as hadronic interaction model in CORSIKA. Independently, the integral spectral index of the cosmic ray primaries was also derived by a specific analysis of the photon detection probability. Depending on the primary interaction model chosen in CORSIKA indices between 2.7 ± 0.02 (for QGSJET) and 2.58 ± 0.02 (for SIBYLL) were obtained. See [2,3].

2.3 Multiple muons: Chemical composition

For a higher primary energy and a larger primary mass, more muons are produced per primary interaction. Also the number of electrons reaching the Earth surface is increasing with the energy. The correlation between the electron number at the surface and the muon multiplicity under ground, respectively their experimental signatures, was used to determine the mean mass of the primaries in dependence on the energy. In agreement with other experiments and the expectation, an increase of the mean mass from $< \ln A >= 2.0 \pm 0.2$ below 1.2 PeV to $< \ln A >= 2.9 \pm 0.4$ at 6 PeV is found. For details see [4].

2.4 Atmospheric neutrinos: Energy spectrum

One signature of neutrino induced events are up-going muons. The fact that AMANDA is able to identify a neutrino signal agreeing in angular distribution and absolute flux (within 30%) with the expectation was demonstrated already for AMANDA B 10 [5,6]. From the AMANDA II data of the year 2000 an event sample optimized for neutrino point source search was extracted [7]. This sample contains 570 upgoing neutrino induced muon events, with a Monte Carlo expectation of a background contamination of less then four events. Using a combination of a neural network and energy sensitive directly measured variables as input of a regularized unfolding procedure, the angular averaged atmospheric neutrino energy spectrum was derived between 1 TeV and 100 TeV [2].

2.5 Limits on extraterrestrial neutrinos

Assuming a generic E^{-2}-spectrum for extraterrestrial neutrinos an integral limit of $E^2 \cdot \Phi(E) < 8 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} was derived from the number of neutrino induced muon events with a light output above a certain threshold for AMANDA B 10 (1997 data) [9]. Following the same concept with AMANDA II the limit improves to $E^2 \cdot \Phi(E) < 3 \cdot 10^{-7}\mathrm{GeVcm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ in the energy range below 1 PeV [8]. Searching for huge electromagnetic or hadronic cascades as signature of high energy neutrinos, the limit extends to $E^2 \cdot \Phi(E) < 9 \cdot 10^{-7}\mathrm{GeVcm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ between 80 TeV and 7 PeV for the sum of all three neutrino flavors [11,10]. Due to the rise of the cross section the Earth becomes opaque for neutrinos of energies between 1 PeV and 10 PeV depending on the zenith angle. The signature of such neutrinos are bright events from zenith angles close to the horizon from the upward (southern) hemisphere, where multi muon events provide the background. In a dedicated analysis the background can be largely suppressed by a neural net. Comparing the background expectation with the investigated signal leads to a integral limit of $E^2 \cdot \Phi(E) < 7.2 \cdot 10^{-7}\mathrm{GeVcm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ between 2.5 PeV and 5.6 EeV [12].

2.6 Search for extraterrestrial point sources

The search for extraterrestrial point sources was performed with data taken in 2000. This was the first year in which AMANDA was operated in its final experimental set up with 19 strings (AMANDA-II). Therefore the detector size and the corresponding effective area was substantially increased compared to previous analyzes of the 10 string sub-detector (AMANDA B 10). Due to the increased diameter of AMANDA-II especially the reconstruction probability for horizontal muons was improved, now being approximately direction independent. At the same time the trigger threshold was shifted towards a higher energy. To obtain a data set with a contamination of less than 3% of atmospheric muons declination band dependent cuts were applied leaving a sample of 697 neutrino induced muons for a declination $\delta < 85°$.

In this angular region a binned search for excesses was performed. The search grid contains 301 rectangular bins with a zenith-dependent width of bins ranging from 6° to 10°. This grid is shifted four times in declination and right ascension to fully cover boundaries between the bins of the first configuration. In this analysis no statistically significant excess was found. In an additional analysis limits were placed on a number of extragalactic candidate sources. Assuming an energy dependence of E^{-2}, an angular averaged neutrino sensitivity above 10 GeV of $2.3 \cdot 10^{-8}$ cm^{-2} s^{-1} is reached. This sensitivity reaches for a photon to neutrino ratio of one e.g. the measured photon intensity of the blazar Mkn 501. A further improvement of the sensitivity will therefore start to restrict models describing the physics of the astrophysical accelerators [7,13].

2.7 Search for muons from WIMP annihilation

If the cold dark matter in the Universe consists of supersymmetric particles in form of neutralinos, then these particles can gravitationally be trapped e.g. in the center of the Earth and annihilate. As decay products of particles produced in this annihilation process neutrinos are created. Thus the center of the Earth represents a potential source for a neutrino induced muon signal. Background for this event type are muons induced by atmospheric neutrinos from the northern hemisphere. The analysis of this source type has been extended from the data taken in 1997 to the 1999 data. From the non-observation of a signal over the expected background limits on the neutralino annihilation rate and the corresponding muon flux have been derived. Due to an improved analysis technique the limits from the 1999 data are significantly better than those previously obtained for the 1997 data. For details see [14,15].

2.8 Search for neutrinos from gamma ray bursts

The AMANDA data of the years 1997-2000 were examined for high energy neutrinos spatially and temporally coincident with one of the 317 Gamma Ray Bursts which were detected by the Burst and Transient Source Experiment (BATSE) on board of the CGRO satellite, and which were triggered by AMANDA. The preliminary result of this analysis is consistent with no GRB neutrino signal. However, an acceleration of cosmic rays in GRB fireball scenarios, which would have been confirmed by a coincidence detection, is not excluded by this non-observation either [16].

2.9 Search for neutrino bursts from supernovae

Because the noise of photomultipliers embedded in the deep, cold and sterile fresh-water ice of the South Polar glacier is only in the order of a few hundred Hz, AMANDA is capable of detecting a multi-MeV anti-electron neutrino signal from supernovae. The signature is the simultaneous increase in rate in all optical modules in the detector. In 2003 the already existing supernova DAQ system was supplemented by an elaborated data analysis software allowing now to detect 90% of the supernovae within a distance of 9.4 kpc and less than 15 expected fake candidates per year. This rate is low enough to contribute together with Super-Kamiokande, SNO, Kamland, LVD and BooNE to the world wide Supernova Early Warning System [17].

3 Hardware status

During the Austral summer 2002/2004, the AMANDA collaboration completed a major upgrade of the detector, especially aiming at the highest energy phenomena. The standard Data Acquisition (DAQ) is based on the use of multi-hit Time to Digital Converters (TDC) to measure the exact arrival time of the Cherenkov photons and peak sensing Analog to Digital Converters (ADC)to obtain the maximum pule height. The TDC, however, is only capable to store 16 edges, corresponding to a maximum number of 8 photons per event. This drawback has been overcome by the development of a parallel DAQ using Transient Waveform Recorders (TWR), which record the complete photomultiplier waveform in a time window of 10.24 μs with a time resolution of 10 ns and an accuracy of 12 bits. In total, 576 optical modules are connected to the TWR DAQ, working since installation nearly deadtime free. The dynamic range of up to 8 photoelectrons of the standard DAQ was improved by this upgrade to a range up to 5000 photoelectrons afterpulsing [19].

4 Conclusion

Concluding it may be remarked that the complete calibration and data analysis chain has been substantially ameliorated in the past year. This is reflected in a significant improvement of the analysis results. Depending on the subject, the investigated data set has been extended from 1997 to up to 2002. With AMANDA up to now only atmospheric muons and muons from atmospheric neutrinos were observed. While the atmospheric muons demonstrate the level of the systematic understanding of the experiment, the neutrino induced muon sample is used to derive limits to additional extraterrestrial neutrino flux contributions at high energies or at point sources. It is shown that the flux of atmospheric multi muon events is sufficiently well understood to derive conclusions about the primary cosmic ray composition. In most of the investigated topics (isotropic flux, point sources, GRB coincidences) AMANDA provides us with the presently best limits restricting the theoretical predictions in the investigated energy range. However, no indications for an high energetic flux excess, point sources, GRB coincidences, WIMPs, monopoles or supernova explosions were observed. The DAQ has been substantially improved in 2003. The future work of the AMANDA collaboration will focus to cover the complete recorded data set and to take advantage from the new TWR data.

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