STATUS AND RESULTS FROM AMANDA/ICECUBE

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Abstract. IceCube is a cubic kilometer-scale neutrino telescope under construction at the South Pole since the austral summer 2004/2005. At the moment it is taking data with 22 deployed strings. The full detector is expected to be completed in 2011 with up to 80 strings each holding 60 digital optical modules. The progenitor detector AMANDA has been operating at the same site since 1997 and is still running as an integral part of IceCube. A summary of AMANDA science for its 10 years of standalone operations is presented, as well as the status and first physics results of the IceCube project.

1 Introduction

1.1 High-Energy Neutrino Astrophysics

Neglecting gravity, neutrinos interact only by way of the weak interaction. This precludes absorption by matter and radiation fields which affect photons and therefore potentially allows observation of objects and processes that are not accessible to conventional gamma-ray astronomy. Targets of interest include the neighborhood of black holes and active galaxies, photons from where are subject to absorption by ambient matter and extragalactic background light. The obvious disadvantage resulting from the restriction to weak interactions is the need for very large detector volumes to achieve at least a moderate event yield.

One of the longest-standing problems in astrophysics is the search for the origin of cosmic radiation [Halzen 2002]. Since the direction of charged cosmic rays, except at the very highest energies, effectively gets scrambled by magnetic fields, any information about their origin must come from electrically neutral particles, i.e. photons and neutrinos. Investigation of this issue is one of the main goals of Very High Energy (VHE) neutrino detectors, with instrumented volumes upwards of $10^6 \text{m}^3$. These take advantage of Cherenkov radiation of charged particles produced in interactions of neutrinos with ambient matter. The large fiducial

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volume required in the detection of the comparatively low neutrino fluxes at TeV-PeV energies makes it necessary to take advantage of large natural reservoirs of light-transparent media, such as the deep sea or polar ice sheets.

So far, no VHE neutrino signal from outside the solar system has been detected. This situation is expected to change after completion of a new generation of detectors with an instrumented volume of the order of $1 \text{km}^3$ [Halzen 2007].

1.2 The IceCube Neutrino Observatory

IceCube is expected to become the first operational cubic-kilometer scale neutrino detector. Built at the geographic South Pole around its predecessor AMANDA, the sub-surface detector (InIce) is scheduled to reach its full extent of 80 instrumented strings carrying 60 digital optical modules (DOMs) each by the year 2011 [Hill 2006]. Already, with 22 deployed strings, it is the largest neutrino telescope ever built and has started delivering data of unprecedented quality. An additional detector component, the surface air-shower array IceTop, will eventually comprise 80 pairs of frozen water tanks with two DOMs in each.

Physics topics in IceCube, other than astrophysics, include investigation of neutrino oscillations, indirect searches for dark matter and exotic particle physics, such as the search for magnetic monopoles. Due to its location, IceCube will be
Fig. 2. Significance map for 5-year AMANDA-II point-source search. The maximum value of 3.7σ excluding trial factors is fully consistent with random statistical fluctuations.

sensitive mostly to neutrino signals from the northern hemisphere, since above the horizon background from downgoing muons makes detection of neutrino events very challenging.

1.3 Phenomenology of γ-Ray Production

Processes leading to the production of VHE γ-radiation can be subdivided into two classes. In electronic mechanisms, gamma rays are produced by inverse Compton scattering of high energy electrons on ambient photons. Conversely, hadronic models assume gamma production through the decay of neutral pions, which in turn are produced in interactions involving high-energy protons. Observations by gamma-ray telescopes have so far not provided unambiguous evidence for either model, irrespective of the source type (Aharonian 2007).

Neutrino astrophysics provides a natural means to distinguish between the two mechanisms, since hadronic interactions will also produce charged mesons, all of which decay into final states containing at least one neutrino. Purely electronic emission processes produce neutrinos only in negligible quantities. Any detection of neutrinos from a specific source would therefore provide very strong evidence for the hadronic model (Halzen 2007) and consequently allow to identify the sources of cosmic radiation.

2 AMANDA Results

2.1 Astrophysical Point Sources

The search for point sources of extraterrestrial neutrinos has been a major analysis topic in AMANDA. For this purpose, muon neutrino candidate events originating from the northern hemisphere have been used. As of the time of writing, data from all years of AMANDA operation have been analyzed in separate searches. The best published limit so far covers the years 2000-2004. Using 4282 candidate events, the limit for the muon neutrino flux from point sources averaged over the
northern hemisphere is $E^2 d\Phi_{\nu_e}/dE = 5.5 \times 10^{-8} GeV cm^{-2}s^{-1}$ in the energy range between 1.6 TeV and 2.5 PeV \cite{Achterberg}. Here, as in all subsequent results, a spectral index of $\gamma = -2$ was assumed for the signal.

Recently, for the first time a combined point-source limit was calculated for the years 1997-99, during which AMANDA was operating effectively in a 10-string configuration. The result from this analysis, using 465 candidate events, is $E^2 d\Phi_{\nu_e}/dE < 5 \times 10^{-7} GeV cm^{-2}s^{-1}$. Also lately, data from the 2005 observation period were analyzed using a likelihood-based method \cite{Braun} yielding an improvement of 30% in both sensitivity and discovery potential over the old technique. None of the samples obtained so far shows any statistically significant excess over background expectation. A combined result using all available AMANDA-II data will be published soon.

### 2.2 Diffuse Neutrino Flux

The diffuse analysis represents an alternative approach in the search for a cosmic neutrino signal. Here, an all-sky search is conducted looking for an excess at high neutrino energies. To separate the signal from background, an energy-correlated parameter cut is applied after carefully cleaning the data of downgoing muon tracks. For AMANDA data from 2000 to 2003, this method yielded 6 events in the final sample, compared to an expected background of 6.1. This corresponds to a limit for diffuse muon neutrino flux from the northern hemisphere of $E^2 \Phi < 8.8 \times 10^{-8} GeV cm^{-2}s^{-1}sr^{-1}$ for an assumed $E^{-2}$ spectrum with $15.8 \text{TeV} < E_{\nu} < 2.5 \text{PeV}$, covering 90% of the simulated signal \cite{Achterberg}. The result also has implications for prompt (charm) production of atmospheric neutrinos, ruling out some of the highest-yielding models at 90% C.L..

### 2.3 Other AMANDA Results

Searches for neutralino WIMP signals from the Sun and Earth have been completed using data from 2001 and 2001-2003 respectively \cite{Achterberg}. The limits on the muon flux from neutralino annihilation are consistent with or slightly better than those from other indirect searches, in spite of AMANDA’s shorter integrated live time. Analyses for the remainder of AMANDA data are ongoing \cite{Hubert}.

Gamma Ray Bursts (GRB) are believed to be a likely source for ultra-high energy cosmic rays and high energy neutrinos, motivating a search for a neutrino signal in coincidence with transient gamma signals from satellite-borne detectors. For the years 2000-2003, 407 bursts were analyzed looking for corresponding up-going muon tracks, but yielding no neutrino candidate events inside the temporal and spatial search windows. Also, “rolling” searches were conducted looking for an excess of cascade events within a predefined time independent of known burst alerts. All results were consistent with background expectation. The best limit so far, obtained by the coincident muon analysis, lies slightly above the Waxman-Bahcall flux, one of the standard benchmarks in calculating neutrino yields from
Fig. 3. Zenith angle distribution of IceCube-9 atmospheric neutrino events after final cuts compared to Monte Carlo simulation.

Further studies have been undertaken looking for Ultra-High Energy (UHE) neutrinos (Gerhardt 2007), magnetic monopoles (Wissing 2007) and diffuse neutrino fluxes based on detection of electromagnetic and hadronic cascades from $\nu_e$, $\nu_\tau$ and neutral current interactions (Tarasova 2007). None of the results showed a statistically significant excess over background.

3 IceCube

3.1 IceCube Status

After the deployment period during austral summer 2006/07, a total of 22 strings have been completed containing 1424 DOMs, 97.6% of which are fully functional as of summer 2007. The trigger rate in this configuration is 550Hz, and expected to rise to 1650Hz in the full 80-string detector (Karle 2007). In addition to the InIce strings, 26 IceTop surface tanks are operational, each containing two DOMs. Construction of the detector is proceeding according to schedule and is expected to be completed by 2011.

3.2 First IceCube Results

Using data from the first nine strings during the 2006 observation period, several analyses have been conducted, largely with the goal of validating detector performance. An important result was obtained in the search for atmospheric neutrinos.
A total of 234 candidate events were identified, compared with an expectation of
$211 \pm 76.1^{(\text{syst.})} \pm 14.5^{(\text{stat.})}$. While there is some indication of residual con-
tamination by downgoing atmospheric muons near the horizon, at about 30 de-
grees below the distribution becomes fully consistent with a pure neutrino sample
(Achterberg et al. 2007b).

A point source search was conducted using the same data set. The sky-averaged
sensitivity for an $E^{-2}$ spectrum, $E^2 d\Phi_{\nu_m}/dE = 1.2 \times 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$, is compa-
rable to one year of AMANDA-II operation. Even with only nine strings, IceCube
already has a higher effective area at high neutrino energies than AMANDA-
II (Finley 2007). Results from searches for diffuse neutrino signals are expected to
be published soon (Ishihara 2007).

3.3 Outlook

As the IceCube detector increases in volume, new possibilities for physics analyses
will arise. One entirely new path of investigation is the search for tau neutrino
interactions. Due to flavor oscillations, one third of all astrophysical neutrinos
arriving at Earth is expected to be a $\nu_\tau$. For this type of interaction, several
characteristic signatures have been identified. The major advantage in detecting
tau neutrinos is the very low background from atmospheric interactions, making
detection of an extraterrestrial signal significantly less ambiguous than in other
channels (Cowen 2007).

Operation of the AMANDA detector as a subsystem of IceCube is expected to
continue for the foreseeable future. As a consequence, neighboring IceCube strings
can be used to veto tracks coming from above the horizon, extending the active
aperture for detection of muon neutrinos to the southern hemisphere. Since this is
where the bulk of the galactic plane, and hence the majority of potential galactic
neutrino sources, is located, it can be expected to have a significant impact on
science operations. Furthermore, with background vetoing, the effective energy
threshold should decrease to values below 50 GeV (Gross 2007).

Several analyses will make use of the entire combined IceCube system. The
combination of AMANDA and InIce will allow to set more stringent limits on solar
WIMPs. Preliminary investigations indicate an improvement by up to an order
of magnitude for low mass neutralinos, in part resulting from the recent introduc-
tion of a new Transient Waveform Recording (TWR) DAQ system in AMANDA
(Wikstrom 2007). The IceTop surface array together with the InIce component
should be able to study cosmic rays up to energies of 1 EeV. Combination of surface
and depth measurements of muon showers will allow investigation of cosmic ray
composition, especially around the “knee” at $E_{\text{primary}} = 3$ PeV (Song 2007).

Various techniques for multi-messenger campaigns have been proposed, among
them the use of “Maximum Likelihood Blocks”, preliminarily demonstrated on
blazar X-ray data (Resconi 2007). Also, a test run for Target of Opportunity
observations in coordination with the MAGIC VHE-gamma detector was recently
concluded (Ackermann 2007), and the beginning of a regular campaign is expected
for the near future.
4 Conclusion

AMANDA has during its time of operation become the world’s largest and most sensitive astrophysical neutrino detector at VHE energies and above. Results for a wide variety of physics investigations have been published, with several more in preparation.

The transition to IceCube has so far been remarkably successful. First physics results have been published, validating the excellent performance of the new detector. As IceCube continues to grow with every deployment season, increases in both volume and angular resolution should soon allow results to significantly surpass those from AMANDA. An important symbolic milestone for IceCube will be reached in 2008, as integrated exposure will exceed 1km$^3$yr. Data becoming available over the course of the next few years will allow important physics investigations, such as a probe of the diffuse Waxman-Bahcall flux and exclusion or confirmation of various emission models for individual cosmic objects.

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