Status of Searches for Magnetic Monopoles, Q-Balls and Nuclearites with the AMANDA-II Detector

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Abstract

Neutrino telescopes are sensitive to a variety of hypothetical super-heavy exotic particles. We review the status of current searches for magnetic monopoles, nuclearites, and Q-balls using data taken with the AMANDA-II detector.

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1. Introduction

The existence of magnetic monopoles is mandatory in a large class of Grand Unified Theories (GUTs). Monopoles are supposed to be copiously produced as topological defects in symmetry breaking phase transitions in the early universe, but their density will have been strongly diluted by inflation. GUTs predict monopole masses to range from 10^8 - 10^{17} GeV, depending on the symmetry group and unification scale of the underlying theory [1]. The monopole magnetic charge will be an integer multiple of the *Dirac charge* $g_D = e/(2\alpha)$, where e is the electric elementary charge and $\alpha = 1/137$ is the fine structure constant. Since magnetic monopoles are topologically stable, they should still be present in today's universe and can be searched for in cosmic radiation. Once created, monopoles can efficiently be accelerated in large scale magnetic fields or by gravitation. Monopoles with masses below $\sim 10^{14}$ GeV can have been accelerated to relativistic velocities [2] and could be detected in neutrino telescopes through their direct Cherenkov emissions. In some GUTs, monopoles can act as "catalysts" in interactions that violate baryon number conservation [3]. In a neutrino telescope, the signature of these "catalyzing" monopoles would be a series of closely spaced light bursts from nucleon decay products produced along the monopole trajectory. Other massive particles have also been hypothesized to exist in cosmic radiation: Nuclearites (nuggets of strange dark matter) and Q-balls (supersymmetric coherent states of squarks, sleptons and Higgs fields, predicted by supersymmetric generalizations of the standard model). Electrically neutral Q-balls will have the same experimental signature in a neutrino telescope as catalyzing monopoles, although the underlying process [4] is different from nucleon decay catalysis. Nuclearites and charged Q-balls might also be detectable, as, traveling through matter, they would generate a thermal shock wave which emits blackbody radiation at visible wavelengths [6,7].

2. The AMANDA-II Neutrino Telescope

AMANDA-II is a neutrino telescope located at a depth between 1500 and 2000 m under the ice at the geographic South Pole. A cylindrical volume of roughly 200 m diameter of the Polar ice was instrumented with a total of 677 optical modules (OMs), consisting of a photomultiplier tube (PMT) and supporting electronics enclosed in a transparent pressure sphere. The OMs were deployed on 19 vertical strings, which are arranged in three concentric circles (see figure 1).

The detector was built in three stages, each incorporating step-wise improvements to the PMT signal transmission techniques. The inner ten strings of the detector are read out electrically via coaxial or twisted-pair cables, while the outermost strings use optical fiber transmission. The detector is operated with a variety of different triggers, two of which are relevant to the analyses presented here: First, the 24-fold multiplicity trigger requiring a minimum of 24 OMs hit within a fixed coincidence window of 2.5 μs, and second, a so-called correlation trigger, requiring n OMs to be hit in any group of m adjacent OMs on the same string. For each triggered event, PMT pulse data is recorded over a time window of $\sim 33\,\mu$s. For each OM, up to eight subsequent pulses (or *hits*) can be recorded. The vast majority of triggers are due to down-going atmospheric muons, yielding an average event rate of roughly 90 Hz.

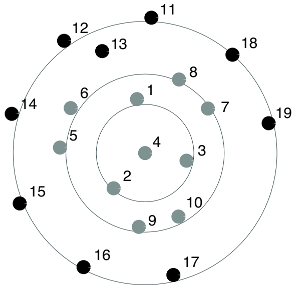

Fig. 1. Arrangement of the 19 strings of the AMANDA-II detector in the horizontal plane.

3. Search for Relativistic Magnetic Monopoles

The number of Cherenkov photons N_γ emitted per path length dx and photon wavelength $d\lambda$ radiated from a relativistic magnetic monopole carrying one Dirac charge passing through matter with index of refraction n is [8]

$$\frac{dN_\gamma}{dx d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(\frac{g_D n}{e}\right)^2\left(1 - \frac{1}{\beta^2 n^2}\right), \tag{1}$$

where β is the velocity of the monopole as a fraction of the velocity of light. The Cherenkov light intensity in ice radiated from the monopole is enhanced by a factor $(g_D \cdot n/e)^2 = 8300$ compared to the intensity radiated from a particle with electric charge e and the same velocity. Thus, in a neutrino telescope, a relativistic magnetic monopole will stand out as an extremely bright event relative to the background of atmospheric muons.

We are presently searching for the signal of relativistic magnetic monopoles in data taken with AMANDA-II during the year 2000. This data set corresponds to 194 days of effective livetime. Only events that fulfill the 24-fold multiplicity trigger are included. The analysis is "blind", meaning that the entire data selection chain is optimized exclusively on Monte Carlo simulations, and only a small subset of the experimental data is used to verify the detector simulation.

We have simulated the detector response to relativistic magnetic monopoles carrying one unit Dirac charge passing the detector's sensitive volume with four different velocities $\beta = 0.76, 0.8, 0.9$, and $\beta = 1$. The background of down-going atmospheric muon bundles was simulated with the air-shower simulation package `CORSIKA` [9]. In several data filtering steps we reject the bulk of low-energy atmospheric muons. We select events in which a large number of photons are detected. Observables like the number of hit OMs, the total number of PMT pulses recorded, and the pulse amplitudes are measures for the light deposition in the detector. We

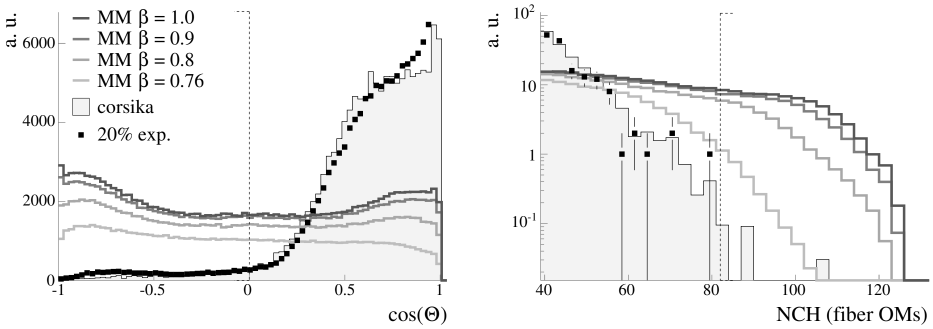

Fig. 2. Left: Zenith angle distribution from a likelihood track reconstruction. The region $\cos(\Theta) < 0$ corresponds to events in which the particle direction is reconstructed as up-going. Right: Number of hit fiber OMs for the "up-going" event sample ($\cos(\Theta) < 0$). This observable serves as final cut parameter. In both figures, the full histograms represent the simulated atmospheric muon background. Black markers represent 20% of experimental data taken during the year 2000, and the four open histograms represent the simulated signal of relativistic magnetic monopoles with four different velocities.

use these observables either as one dimensional cut parameters or as input variables to a discriminant analysis [10]. By selecting events with large light deposition alone, we can identify relativistic magnetic monopoles among the background of down-going atmospheric muons, even if they were arriving from above the horizon. In this document, however, we present the search of up-going monopoles only. The mass range over which this search is sensitive is limited, since only monopoles with masses larger than 10^{11} GeV can penetrate the entire Earth and still be relativistic upon reaching the detector [11].

We reconstruct the particle track using a likelihood method [12] and consider only events for which the zenith angle of the track is bigger than 90°, corresponding to a particle entering from below the horizon. Some of the down-going atmospheric muon bundles are mis-reconstructed as up-going particles, posing a background to the search for up-going monopoles (see figure 2). We reject this remaining background with a final cut on the number of hit OMs with fiber readout. We use only fiber OMs for this last cut. Located at the outermost strings, these OMs define the detector's surface area and are consequently most crucial to the acceptance of extremely bright signals. Also, their response to large amounts of light is simulated most accurately by the detector simulation (which is essential in a "blind" analysis). We optimize the final cut such that we achieve the optimum "sensitivity". In this context, "sensitivity" means the 90% C.L. flux upper limit that we expect to obtain for a given background prediction, if no true signal were present (see [13], and references therein). The final cut parameter is shown in figure 2. The signal acceptance, and hence the sensitivity of this analysis, depends on the monopole velocity. We expect the analysis of 194 days of experimental data to yield sensitivities between $\sim 5 \times 10^{-17}$ ($\beta = 1$) and $\sim 1 \times 10^{-15}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ ($\beta = 0.76$). This sensitivity range does not yet include the effect of systematic uncertainties. As of this writing, our sensitivity is comparable to the best upper limit on the flux of relativistic magnetic monopoles published by the BAIKAL Collaboration [14].

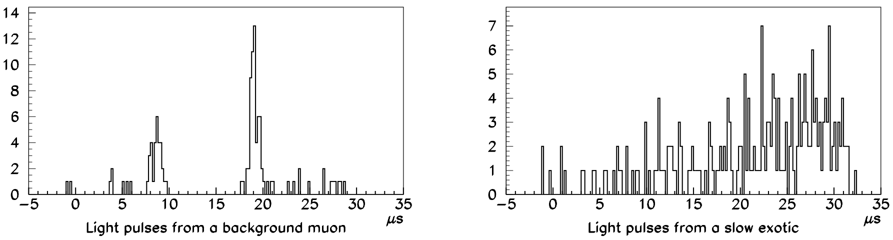

Fig. 3. Left: a background event with a triggering and a non-triggering muon. Right: a simulated signal event from a particle traveling at speed $\beta = 0.01$.

4. Search for Subrelativistic Particles

In the search for sub-relativistic particles, two hypothesized mechanisms for light production are exploited. Magnetic monopoles have been suggested to catalyze nucleon decay with a cross section which is large enough to make them detectable but uncertain with several orders of magnitude [3]. Here only protons are considered, which have several possible catalyzed decay channels. The channel $p \rightarrow e^+\pi^0$ creates an electromagnetic shower with energy close to the proton mass. Other channels lose some of their shower energy to neutrinos.

Neutral Q-balls dissociate baryons in a fundamentally different way, but the experimental signature is quite similar [4]. The cross section is their geometric size. By limitations given in [5], it ranges from $\sim 10^{-26}\mathrm{cm}^2$ and many orders of magnitude upwards.

The luminosity of thermal shock waves from nuclearites and charged Q-balls, as given by [6,7], is also determined by their geometric size. Their luminosity would exceed that of neutral Q-balls by several orders of magnitude.

All particles are simulated with isotropic directions and with speed $\beta = 10^{-2}$. In the simulations, the luminosity is expressed as the mean distance λ between two electromagnetic showers, whose energy is the proton mass. The only value for λ used so far is $2\,\mathrm{cm}$, and only hydrogen decays in the decay channel $e^+\pi^0$ with a branching ratio of 0.9 are considered [15]. The corresponding cross section of monopole catalyzed decay is $9 \cdot 10^{-24}\mathrm{cm}^2$, which is at the upper edge of what appears to be allowed by the theoretical uncertainties. For neutral Q-balls, oxygen nucleon decay is considered, making λ correspond to a cross section of $9 \cdot 10^{-25}\mathrm{cm}^2$. For nuclearites and charged Q-balls, the chosen λ corresponds to a much lower luminosity than that given by [6,7].

Simulations show that the correlation trigger is substantially more sensitive to this type of signal than the multiplicity trigger. In each triggered event, hits are collected during a time window of 33μs. Background relativistic muons emit light during $\sim 3\mu$s, whereas slow particles emit during a large fraction of the time window. A comparison is shown in fig. 3. The left picture shows a background event with a triggering muon at time 19μs, and an accidental early non-triggering muon at 9μs. The right picture shows a simulated signal event. The signal separation from background is based on hits at times when no light from triggering muons is expected, the *early and late hits* outside the interval $16 - 24\mu$s.

A period of 113 days in 2001 when a constant correlation trigger definition was used, is considered here. The background properties and a preliminary expected sensitivity is determined using 20% of the data. A first filter reduces the data by 99%, requiring a total of at least 14 early and late hits. The second filtering uses additional trigger cleaning and three additional cuts based on early and late hits.

The events passing the filter have an exponential distribution in the number of early hits. It is shown in fig. 4, along with a fit. Since about 80% of any signal events would be expected above 20 (as seen from simulations), but none were found, fig. 4 must be almost signal free. Thus, the fit parameters are suitable for background estimation. Using the same sensitivity optimization scheme as in the relativistic case, the optimal final cut for the 80% sample requires > 24 early hits. The corresponding expected sensitivity is $\sim 5 \cdot 10^{-17}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$. This updates the oral presentation, where the correlation trigger had not been included in the simulations and data filtering.

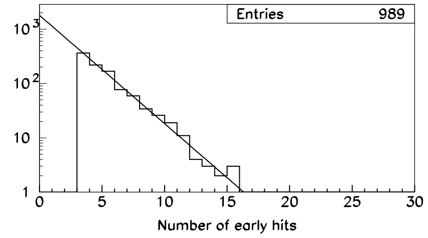

Fig. 4. An exponential fit parametrizes the background distribution in the number of early hits.

5. Discussion and Outlook

The AMANDA neutrino telescope is an excellent instrument to search for several postulated super heavy exotic particles. In this document, we present first studies of the sensitivity of AMANDA to magnetic monopoles, Q-balls and nuclearites. The given sensitivities are still preliminary. Specifically, systematic uncertainties are not yet included. So far, we have used relatively small sub-sets of the available AMANDA data in order to outline our analysis strategies. The sensitivity of the two analyses will improve substantially with more data.

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