ICRC 2001

Search for relativistic monopoles with the AMANDA detector

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Abstract. We present results obtained from a search for relativistic magnetic monopoles crossing the AMANDA detector at the South Pole. Monopoles with $\beta = 1$ would emit 8300 times more Cherenkov light than minimum ionizing muons. No events with a clear signature of a monopole have been found. We derive a preliminary upper flux limit well below the Parker limit and previous best limits from underground experiments.

1 Introduction

The existence of magnetic monopoles has been suggested seventy years ago (Dirac , 1931), with the magnetic charge of monopoles obeying the quantization rule $g = n \cdot e/(2\,\alpha)$, where $n = 1, 2, 3, ...$ and $\alpha = 1/137$. Monopoles are a vital ingredient to GUT theories ('tHooft , 1974; Polyakov , 1974). Various choices of symmetry group and symmetry breaking scheme lead to monopole masses between 10^8 GeV and 10^{17} GeV. According to current cosmological models, primordial monopoles have to be diluted in order to avoid overclosing of the universe. Usually this is achieved by inflation mechanisms, but other solutions to the cosmic monopole problem have been proposed (Langacker and Pi , 1980).

Observations of galactic magnetic fields, as well as observations matched with models for extragalactic fields suggest that monopoles of masses below 10^{15} GeV can be accelerated in these fields to relativistic velocities (see e.g. Weiler (2001)).

A magnetic monopole with unit magnetic Dirac charge $g = 137/2 \cdot e$ and a velocity β close to 1 would emit Cherenkov radiation along its path, exceeding that of a bare relativistic muon in water by a factor of 8300. The value 8300 is obtained from $(137/2)^2$ multiplied with n_r^2 (Tompkins , 1965), with $n_r = 1.33$ being the refractive index of water. This is a rather unique signature. Figure 1 shows the light emission from a monopole with unit charge as a function of β. Note that due to the production of δ-electrons, the monopole produces light even below its own Cherenkov threshold.

Neutrino telescopes in open water or ice provide huge detection areas for monopole searches since the large light output of monopole tracks makes them visible over very large distances. With a light output similar to that of a 14-PeV muon, monopoles crossing the array fire a very large number of photomultipliers.

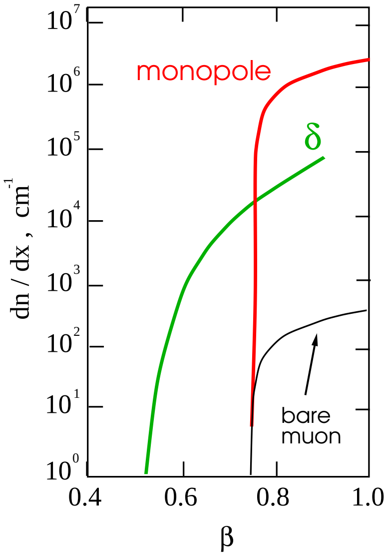

Fig. 1. Cherenkov light emission from magnetic monopoles (in photons per cm) as a function of velocity.

In this paper, we present results obtained with the AMANDA detector, a Cherenkov telescope located at the geographic South Pole at a depth of 1500–2000 m (Andres et al. , 1999; Andres et al., 2001; Wischnewski et al., 2001).

2 Data

For the analysis presented here, data from 1997 was used, which were taken with the AMANDA-B10 detector, consist-

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Correspondence to: christian.spiering@desy.de) ing of 302 optical modules at 10 strings. The data taking period extended over 180 days between calendar day 95 and 319. The deadtime of the DAQ at that time was 25%, resulting in an uptime of 135 days (This number is slightly different from the uptime of the neutrino analysis presented in Andres et al. (2001) due to of weaker run selection criteria).

3 Monte Carlo simulations

The response of the detector array to monopoles has been simulated with the detector Monte Carlo program *amasim*. We generated monopoles with speeds of $\beta = v/c =$ 1.0, 0.9 and 0.8, with the number of photons N per track segment dx and wavelength interval dλ given by

$$\frac{\mathrm{d}^2N}{\mathrm{d}x\mathrm{d}\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n_r^2}\right)$$

The trigger area for magnetic monopoles with β = 1.0 (0.9, 0.8) is 3.3 (2.9, 2.2) $\cdot 10^5$ m^2, respectively. The acceptance after all cuts (see below) is 3.3 (2.4, 0.8) $\cdot 10^5$ m^2 sr.

As background, muons produced in air showers above the array have been simulated. We used a primary energy spectrum according to Boziev (1989).

4 Analysis

The main signature of a magnetic monopole crossing the array is a high number of optical modules hit, n_{ch}. Multiple muons – or very energetic single muons – from atmospheric air showers can produce a total light output comparable to monopoles, with a similarly high number of hit modules. In order to reject this background, the search was confined to the lower hemisphere, i.e. to upward moving particles. This limits the search to comparatively heavy monopoles: monopoles capable to cross the Earth must have masses above $\sim 10^{11}$ GeV (Derkaoui et al. , 1998).

In order to separate upward moving tracks from downward moving muons, the direction of the track was estimated with a simple track approximation (Stenger , 1990). No full likelihood reconstruction (Wiebusch , 1999) was applied, since at present the neccessary likelihood parametrisations are available only for $\beta = 1$. Despite of neglecting the geometry of Cherenkov light and scattering of photons during their propagation through ice, this method gives a robust estimate from which hemisphere the track originates.

The ”upward sample” was cleaned by further quality cuts to ensure a sufficient suppression of tracks wrongly assigned to the lower hemisphere.The chosen observables are:

1. The number of hit modules, n_{ch},
2. the number of ”direct” hits, n_{dir} (A direct hit is one with a time residual smaller than 75 ns),
3. the track length in the detector, l_{dir}, which is defined as the distance of the projection of the first and the last module with a direct hit to the track,
4. the particle speed v resulting from the reconstruction.

Cutting on the observables has a comparable effect on background simulation and experimental data, as illustrated in figure 2 which compares the suppression power of the l_{dir}-cut for experiment and background Monte Carlo. However, at very high multiplicities and large signals, instrumental effects like cross-talk become important. Cross-talk hits which pass even the special cuts against cross talk will lead to enhanced observed multiplicities. Since these effects are not included in the simulation, Monte Carlo yields lower multiplicities than experiment. This leads to an underestimation of sensitivity and, consequently, to a too conservative result. By the same reason, MC background estimates will yield too low multiplicities.

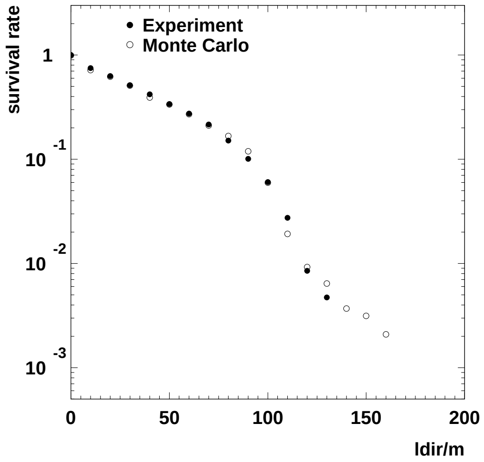

Fig. 2. Fraction of wrongly reconstructed tracks (i.e. tracks reconstructed as coming from below) as a function of a cut in l_{dir}.

To find the best cuts on the four observables and estimate the remaining background, we therefore have chosen a procedure based on experimental data only. With the help of neutral network, we try to find an expression which predicts the number of wrongly (i.e. upward) reconstructed events as a function of the cut values set on the observables. Based on a small data sample (the experimental data of 5 days), the network is fed with the number of wrongly reconstructed events as a function of the four observables given at the network input. The network's internal structure then represents the desired knowledge on the reconstruction behaviour. This can be controlled by applying the network to a bigger data sample and comparing results to the prediction. Figure 3 shows the distribution of fake events in the plane spanned by l_{dir} and N_{ch}, after having applied loose cuts in the other two parameters, $N_{dir} > 4$ and $v > 0.05$ m/ns. The contour lines mark the background predicted for 29 days by the neural network trained with the data from five days (starting from 100 and ending with 0.0001). This prediction was confronted with fake events from 29 days (colored areas) which indicate that the predictions from 5 days are reasonable. The thick line represents the finally chosen cut, which takes into account that the 5-day prediction turned out to be too optimistic at small n_{ch} and large l_{dir}. The cut results in an expected background of less than one event in 135 days.

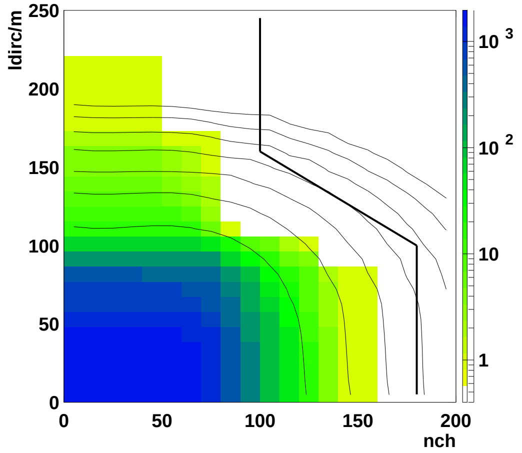

Fig. 3. Population of the the $n_{ch} - l_{dir}$ plane with fake events after cuts $v > 0.05$ m/ns and $n_{dir} > 4$. Colored areas are data from 29 days, contour line are predictions for 29 days based on a neural network trained with data from 5 days. Contour line correspond to 100, 10, 1, 0.1, 0.01, 0.001 and 0.0001 events. The bold line indicates the chosen cut.

Actually, three events from the full 135-day data sample passed the final cut. However, these events have been very clearly classified as technical artifacts in the surface electronics (e.g., none of three events had hits in the inner four strings, despite the very high occupancy of each of the other strings).

5 Result and discussion

Since no technically clean event passed all cuts, an upper limit on the flux can be derived:

$$\Phi_{\mathrm{CL}} \leq \frac{N_{\mathrm{CL}}}{A \times T \times \eta}$$

where N_{CL} is the 90% poisson upper limit in the case of zero observed event, 2.33. A is the acceptance of the detector which reflects the fraction of signal seen after the application of cuts integrated over the track directions ($= 3.28 \times 10^5 \mathrm{m}^2\mathrm{sr}$ for $\beta = 1.0$), T is the data taking time and η is the dead-time correction, the product being 135 days.

For $\beta = 1$, we obtain a preliminary upper limit of $0.62 \times 10^{-16} \mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$. Our result is compared to other published limits in figure 4.

This limit may be subject to slight changes due to several reasons. Firstly, the mentioned effects like cross-talk do not only enhance the multiplicity of background events, but would also enhance the observed multiplicity of monopoles. This results in a higher efficiency for monopoles. Secondly, recent improvements in the Amanda Monte Carlo tend to yield a lower efficiency for light produced far away from the optical module. This effect is of minor importance for tracks with low light emission, but may reduce the acceptance for monopoles which are visible over large distances. New analyses with cross-talk simulation and improved description of ice will show, to which degree these effects balance each other.

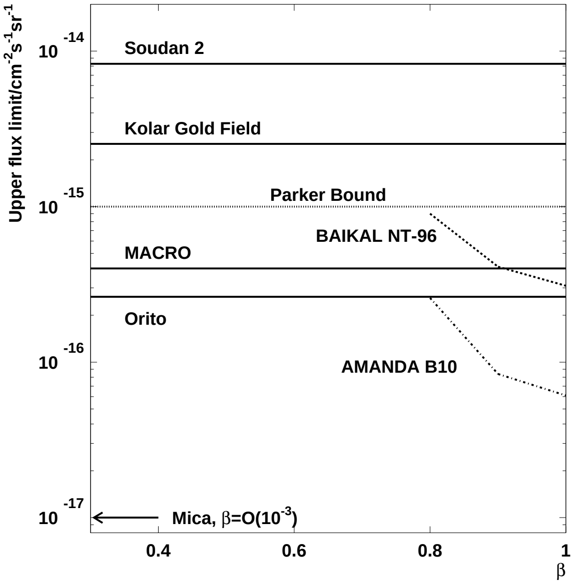

Fig. 4. Flux limits (90% C.L.) for relativistic monopoles gained from various experiments (Cei et al. , 1998). The BAIKAL result (Domogatsky et al., 2000) is based on $T \times \eta$=72 days live time.

In a new analysis, the present track approximation will be replaced by a full likelihood fit. The improved angular resolution will allow to search for monopoles at zenith angles above the horizon. This not only will enlarge the acceptance, but in particular enables the detection of monopoles with lower masses which would not have to cross the Earth. In a next step, monopoles with velocities between $\beta = 0.5$ and $\beta = 0.75$ will be searched for, via the light emitted by δ electrons. These tracks will emit less light, but have the signature of a velocity visibly smaller than c.

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