# Search for relativistic monopoles with the AMANDA detector

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## Abstract

We simulated the response of the AMANDA-B10 detector to the passing through of relativistic magnetic monopoles ($0.8 < \beta < 1$). The Cherenkov light output is 8300 times as high as for muons yielding a correspondingly large detection area. The background was simulated as well, and methods were developed to extract the predicted signal. A search was performed using the AMANDA-B10 data of 1997 and an upper limit of $1.55 \times 10^{-16}/\mathrm{cm}^2$s sr for $\beta = 1$ on the monopole flux was calculated.


**Introduction and Motivation**

In 1931, P.A.M Dirac showed that adding magnetic charge and current terms to the Maxwell equations and requiring gauge invariance and single-valuedness of the wave function lead to a minimum magnetic charge of $q_m = 1/2\alpha \approx 137/2 \cdot e$ (Dirac, 1931). 43 years later, 't Hooft established monopoles within the framework of GUTs (t'Hooft, 1974) which required the creation of monopoles in the early universe at the time of the GUT phase transition. They were then accelerated by the galactic fields ($10^{-6}$G). Because of their high mass, it seems unlikely that monopoles can reach relativistic speeds. However, it has been suggested that the highest energy cosmic rays (HECR, $E > 10^{20}$eV) do not consist of protons, photons or neutrinos, but are in fact magnetic monopoles (Kephart & Weiler, 1996). In this scenario monopoles are assigned a mass of $\sim 10^{10}$GeV. On the other hand, recent studies indicate that the observed HECR energy spectrum does not agree with simulated energy spectra of cosmic monopoles (Escobar & Vázquez, 1999). This controversy makes it interesting to study monopoles in the relativistic regime.

This search used the AMANDA-B10 telescope (Halzen, 1998). 302 photomultiplier tubes (PMTs) are arranged in 10 strings 1497m to 1977m below the surface of the central Antarctic glacier. A monopole passing through the array would cause very high light output (8300 times that of a $\mu$ (Jackson, 1962)) which again would lead to many PMTs hit. This is the basic principle of monopole detection.

**Description of Monte Carlo and reconstruction**

In order to calculate the acceptance for monopoles of AMANDA-B10, simulated monopoles with different velocities were tracked through the detector using the AMASIM (Hundertmark, 1999) program. A continuous light emission along the track was assumed and the track directions were chosen isotropically around the detector center. The direction information of the track was extracted from the light arrival times at the PMTs in several stages: As a first step, PMTs whose behaviour was known to be not stable were rejected. Next, a procedure called "hit cleaning" was performed: hits caused by extremely delayed photons and hits outside the bulk of the photon field were removed. These hits were defined as hits in PMTs which did not have neighbouring PMTs firing in a reasonable time window or had a high time separation from the bulk of hits. After that, all events which had fewer than 75 hits were rejected. Finally, a line approximation (Stenger, 1990) to the times of the hits was used, yielding (among other parameters) the zenith angle and the speed of the monopole. Fig. 1 shows the result of the reconstruction on signal Monte Carlo for the velocities $\beta =$ 0.8, 0.9 and 1.0.

The acceptance $\mathcal{A}_{\mathrm{eff}}$ of the detector was then defined as $\mathcal{A}_{\mathrm{eff}} = n_{\mathrm{rec}}/n_{\mathrm{gen}} \times A_{\mathrm{gen}} \times 4\pi$ where $n_{\mathrm{rec}}$ is the number of events after triggering and reconstruction, $n_{\mathrm{gen}}$ the number of generated events, $A_{\mathrm{gen}}$ the area of the monopole generation plane and $4\pi$ takes into account the isotropic generation.

**Description of experimental data**

Monopoles were searched for in a total of 80 (calendar) days of data recorded in 1997. The experimental data were extracted from two subsets. One consists of the "normal" data written by the DAQ, the other was

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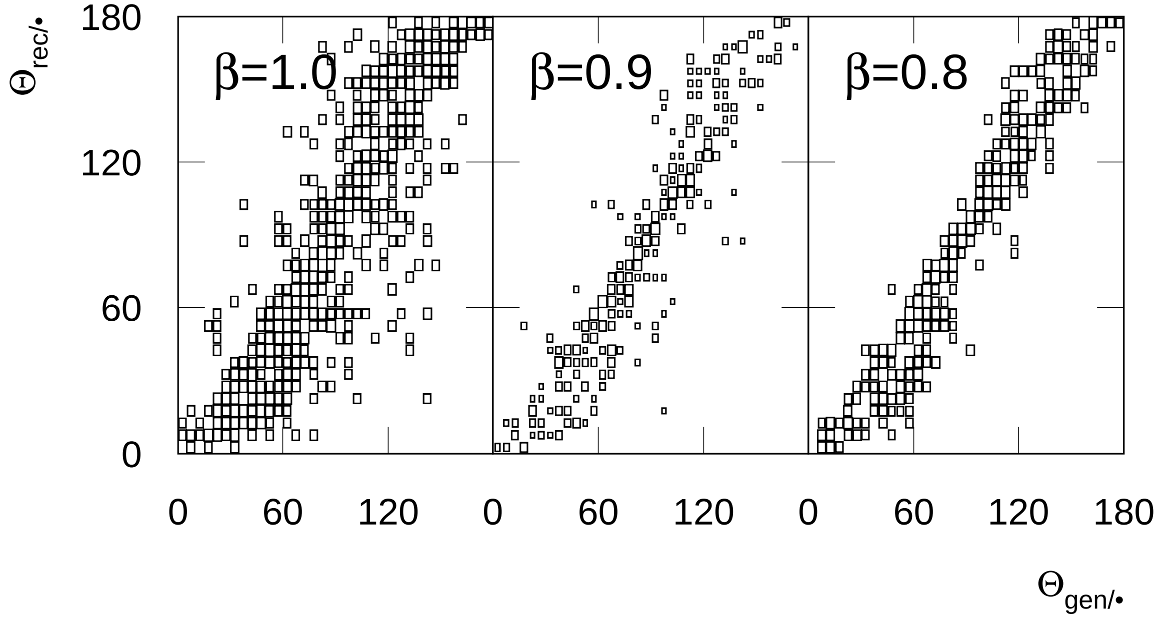


Figure 1: Reconstructed vs. simulated zenith angle for $\beta$=1.0, 0.9, 0.8 in signal MC

prefiltered for events with hit multiplicity greater than 100. Both samples were subjected to hit cleaning and reconstruction like the Monte Carlo data. Quality criteria were applied to exclude bad runs. This reduces the observation time from $6.9 \times 10^6$s (80 days) to $3.9 \times 10^6$s (45 days), representing approximately 1.8 million events.

**Analysis**

The distribution of hit multiplicity for experiment and Monte Carlo with $\beta$ =0.8, 0.9 and 1.0 is shown in fig. 2. Experimental events reach PMT multiplicities of up to 200, monopole Monte Carlo reaches up to 250. Obviously, a simple cut on multiplicity reduces the passing rate for signal events. Most of the experimental high multiplicity events are caused by atmospheric showers, which produce bright muon bundles in the detector. To exclude this background, only upward muons were accepted and a cut in the reconstructed zenith angle had to be applied. For this reason, monopoles were searched for in the The minimal mass required for a relativistic monopole to be able to reach AMANDA from below is in the order of $10^{10-11}$ GeV (Kephart & Weiler, 1996, Derkaoui *et al.*, 1998).

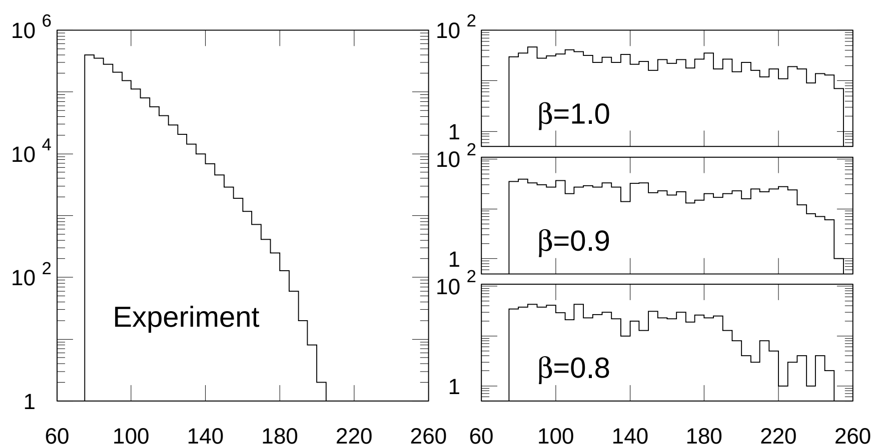


Figure 2: Multiplicity distributions for Experiment and Monte Carlo

When looking into the earth, i.e. regarding tracks with zenith angles above $90°$, it was found that rare transient cross talk by the DAQ hardware can fake almost vertically upgoing tracks. These can efficiently be removed by rejecting events which show a high number of simultaneous hits in the recording electronics. The multiplicity and time window were set so that cross talk in experiment is effectively removed but signal Monte Carlo is minimally affected. After this, one is left with the events shown in fig. 3 where the speed of the particle is plotted vs. the reconstructed zenith angle $\Theta$. One sees that atmospheric muons which are clearly reconstructed as down going ($0° < \Theta < 60°$) mostly have a speed of $0.2 < v_{\rm LF} < 0.35$m/ns. Events which are reconstructed as up going however, yield speeds of $v_{\rm LF} < 0.2$m/ns. Thus a low speed was taken as a indication for misreconstructed tracks. Speeds above 0.3 m/ns are artefacts of the reconstruction.

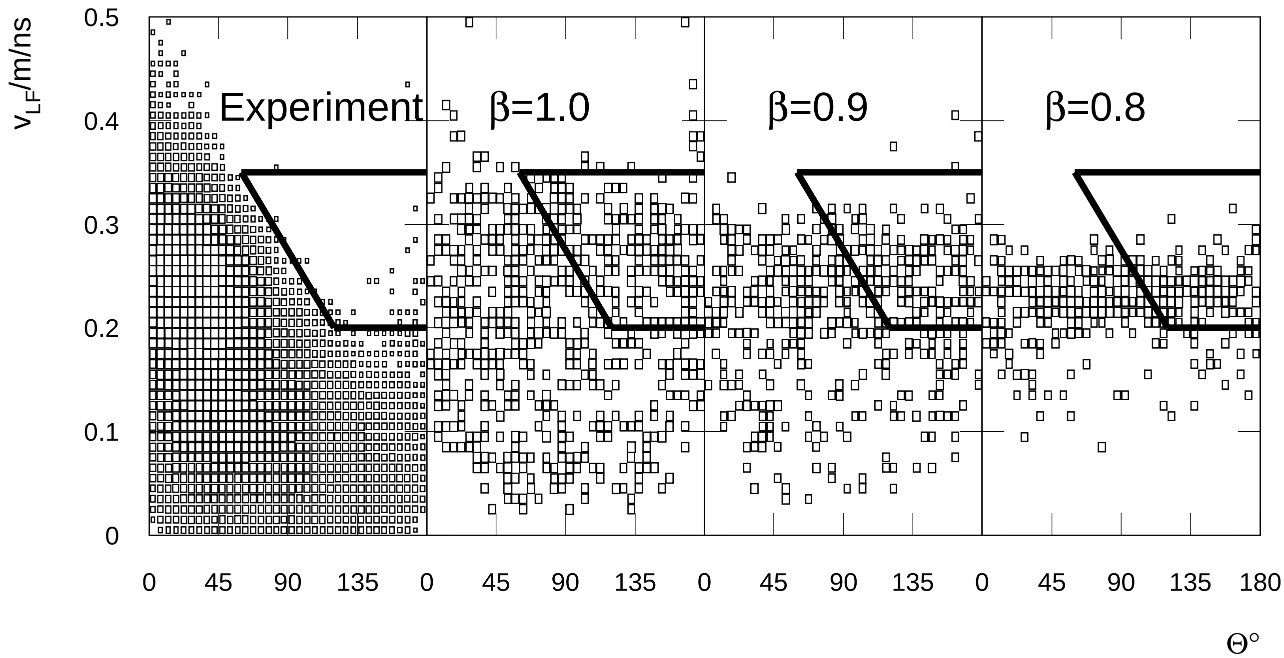


Figure 3: Speed of particle ($v_{\rm LF}$) vs. zenith angle ($\Theta$). Events outside the wedge shaped area are rejected. Logarithmic scale perpendicular to paper plane.

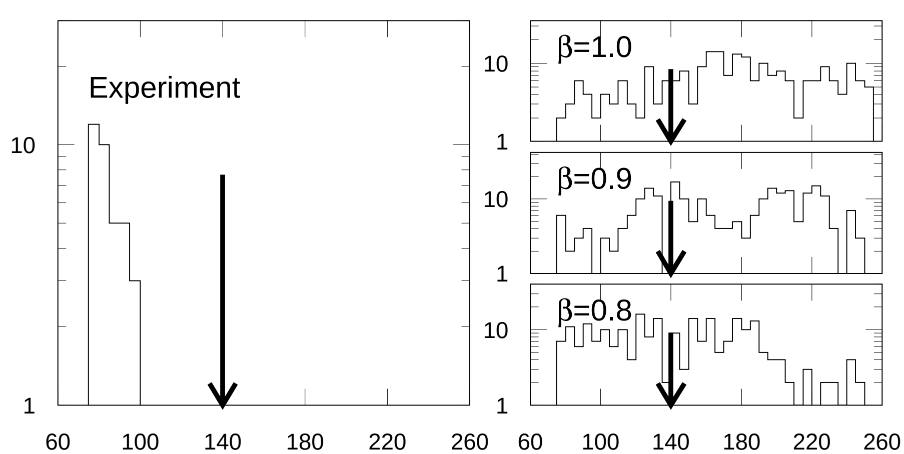


Figure 4: Multiplicity of events after applying the cut shown in fig. 3. Events below a multiplicity of 140 (indicated by the arrow) are rejected.

When comparing experiment to Monte Carlo, one notices that the region given by $0.2 < v < 0.35$m/ns and $v > 0.35\text{m/ns} - 0.15\text{m/ns}/60^\circ \times (\Theta - 60^\circ)$ is mostly unoccupied in experiment but that a fair portion of the signal would lie within these bounds. A monopole within this region would not be confused with a muon. The remaining events (the tail of the atmospheric muon distribution) have multiplicity just below 100 (see fig. 4) and requiring a multiplicity above 140 reliably rejects these events. Given the multiplicity distribution from Monte Carlo, one sees that only a fraction of the signal is removed by this cut.

| $\beta$ | $\frac{\mathcal{A}_{\text{eff}}}{10^9\text{cm}^2\text{sr}}$ | $\epsilon$ | $N_{90\%}$ | $\frac{\phi_{90\%}}{10^{-16}\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}}$ |
|---|---|---|---|---|
| 1.0 | 20.5 | 0.20 | 2.3 | 1.55 |
| 0.9 | 16.0 | 0.22 | 2.3 | 1.88 |
| 0.8 | 9.8 | 0.18 | 2.3 | 3.66 |

Table 1: Acceptances ($\mathcal{A}_{\text{eff}}$), cut efficiencies ($\epsilon$), Poisson expectations ($N_{90\%}$) and upper flux limits ($\phi$) for various speeds ($\beta$) of monopoles.

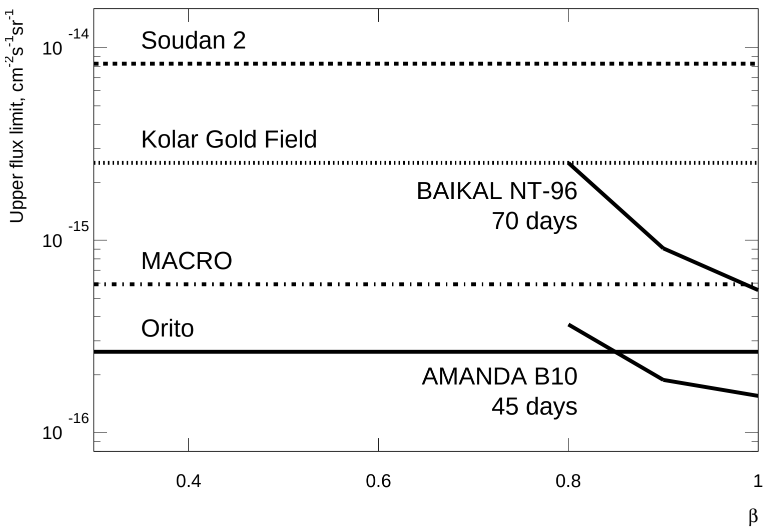


Figure 5: Upper flux limit (90% C.L.) for various experiments. (Taken from Cei 1998)

After having rejected all experimental events, $\epsilon = n_{\text{bounds, mult}>140}/n_{\text{rec}}$ defines the cut efficiency where $n_{\text{bounds, mult}>140}$ is the number of events remaining after the bounds and multiplicity cuts and $n_{\text{rec}}$ is the number of events reconstructed. Now an upper flux limit can be given by $\phi \leq N_{90\%}/(\mathcal{A}_{\text{eff}} \times T \times \eta \times \epsilon)$ where $N_{90\%} = 2.3$ is the 90% confidence level for no events observed, $T$ is the observation time ($3.9 \times 10^6$s) and $\eta = .9$ is the live time of the detector (=1−dead time). The resulting flux limits for the various values of $\beta$ are shown in table 1 and fig. 5. $\beta = 1.0$ e.g. yields an upper flux of $1.55 \times 10^{-16}/\text{cm}^2$s sr. Other limits can be found in Alvarez *et al.* 1970 and Cei 1998. Only one measurement (Alvarez *et al.* 1970) achieves a lower limit, using the current induced in a superconducting coil by monopoles trapped in lunar rocks. Whereas that method makes assumptions on the formation of the moon's surface, our value is based on the direct (non-)observation of a moving monopole.

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