Search Strategies for Relativistic Magnetic Monopoles with the IceCube Neutrino Telescope

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Abstract: Several models of unified gauge theory predict massive particles carrying magnetic charge. Galactic or cosmic magnetic fields may accelerate these particles to relativistic velocities. Large scale Cherenkov detectors like IceCube or its predecessor AMANDA are novel tools to search for these particles, since they are predicted to emit several thousand times more light than electrically charged particles. Searches have already been performed with the AMANDA, Baikal and 22-string IceCube neutrino telescopes. We present strategies and methods adopted in the 22 and 40 string detector to separate the expected signal from a background that is several orders of magnitude more abundant.

Corresponding authors: Jonas Posselt[2] (*jposselt@uni-wuppertal.de*), Brian Christy[3] (*bchristy@icecube.umd.edu*)
[2] *Dept. of Physics, University of Wuppertal, D-42119 Wuppertal, Germany*
[3] *Dept. of Physics, University of Maryland, College Park, MD 20742, USA*

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1 Introduction

The existence of magnetic monopoles was first suggested by Pierre Curie in 1894 [1]. However, a firm theoretical grounding was not laid down until 1931 when Paul Dirac [2] demonstrated that magnetic monopoles are consistent with quantum mechanics. Dirac found that magnetic charge is given by $g = Ne/2\alpha \approx 68.5e$, where α is the fine structure constant, and e the fundamental electric charge. In 1974 t'Hooft and Polyakov independently described magnetic monopoles that are regular solutions of the field equations in certain groups of Grand Unified Theories (GUT) and match the charge of the Dirac monopole [3, 4]. Within GUT the masses of magnetic monopoles can be estimated to be $M \propto \Lambda/\alpha$, where Λ is the unification energy scale of the theory. This results in a mass range from 10^8 GeV to 10^{17} GeV for various GUT models. Because of these large masses magnetic monopoles are generally assumed to be relics of the early universe where they have been produced via the Kibble mechanism [5].

Analogous to electric charges, which are accelerated along electric field lines, magnetic monopoles are accelerated along magnetic field lines. The kinetic energy gained by a monopole is $E_k \propto gB\xi$, where B is the magnetic field strength, and ξ is the coherence length of the field [6]. During the lifetime of the universe, relic monopoles should have encountered enough accelerators to reach kinetic energies of $\sim 10^{14}$ GeV. Thus monopoles with masses less than $\sim 10^{14}$ GeV should be relativistic. IceCube is able to detect magnetic monopoles travelling through the detector at velocities greater than the Cherenkov threshold ($\beta > 0.76$). The radiation emitted by the monopole is proportional to $(gn)^2$, where n is the index of refraction of the ambient medium [7]. Thus, in ice ($n \approx 1.3$) a monopole will emit ~ 8000 times more light than a bare muon of the same velocity.

2 Detector

The IceCube detector is a cubic kilometer-scale neutrino telescope. In its now completed state, IceCube consists of 86 strings of 60 Digital Optical Modules (DOMs), each spaced out in a hexagonal pattern and deployed between 1450 to 2450 meters below the Antarctic ice surface. For the data presented, we use the configurations of IceCube as of 2007 and 2008 with 22 and 40 strings respectively. Each DOM is configured to detect and digitize photon signals via a Photomultiplier Tube (PMT) and two waveform digitizers, a fast Analog to Digital Converter (fADC) and an Analog Transient Waveform Digitizer (ATWD) [8]. The ATWD has a sampling rate of ~ 300 Megasamples/second with a total of 128 samples and digitizes the incoming waveform across 3 channels representing different gain values. The fADC runs with a sampling rate of 40 Megasamples/second and can read up to 256 samples. This configuration allows the digitalization of short signals with a high dynamic range as well as long signals, although with a smaller dynamic range.

A DOM is triggered when the PMT signal exceeds a certain threshold. However, the data is only read out in the case of a local coincidence with one neighboring DOM on the same string in a time window of 1μs. This serves to reduce background originating from PMT noise. Since the waveforms produced by a monopole are expected to have a long time scale, the fADC provides greaterdistinction between signal and background. Hence, the search strategies in this study mainly rely on the data provided by the fADC.

3 Signal and Background Simulation

The simulation of relativistic magnetic monopoles is done in three stages. Magnetic monopoles are generated uniformly on a disk with their direction perpendicular to the disk. The disk itself is located $\sim$ 1 km from the center of the detector pointing towards it at randomized orientations. The radius of the disk is set to 650 m for the 22 string configuration and 850 m for the 40 string configuration. Datasets were generated for four different speeds, $\beta = 0.995$, $\beta = 0.9$, $\beta = 0.8$, and $\beta = 0.76$, each with isotropic angular distribution at the detector.

Energy loss of the magnetic monopoles as they pass through the ice is modeled using the Bethe-Bloch formula as adapted by Ahlen [9]. The typical energy loss in ice is 6–10 GeV/cm. The light output and propagation is modeled by a version of PHOTONICS [10] specifically generated to work with Cherenkov cone angles associated with the different speeds simulated. The default light amplitude in the simulation is for a muon and this is scaled up using the formula of Tompkins [7].

The principal background to relativistic magnetic monopole searches with IceCube consists of down-going high energy atmospheric muon bundles induced by cosmic rays. Using a 2-component model, which assumes the cosmic ray flux to be composed of only protons and iron, cosmic ray primaries are simulated in the energy range from 10^4 GeV to 10^{11} GeV, where the energy spectra of the components have been fitted to the KASCADE data [11]. The muons are generated with the air-shower simulation package CORSIKA [12] and handed to the detector simulation software.

4 Search Strategies

The general procedure used in the two following magnetic monopole searches is that of a blind analysis. Hence the optimization of the data selection is based on simulated data, and only $\sim 10\%$ of the experimental data, referred to as the burn sample, is used for verification purposes. For the monopole signal, a flux of $5\cdot 10^{-17}$ cm^{-2} s^{-1} str^{-1} is used, roughly representing the lowest limits set by BAIKAL [13] and AMANDA [14].

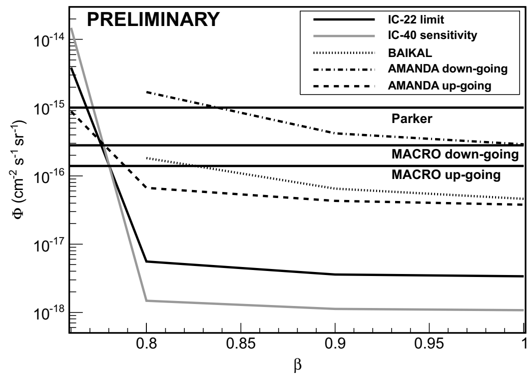

Figure 1: Monopole flux limits set by the 22 string analysis versus beta, shown together with the previous best limits set by AMANDA [14] and BAIKAL [13]. The limits apply to an isotropic flux at the detector. Also shown are the expected sensitivity of the 40 string analysis, limits set by the MACRO [18] experiment and the Parker Bound [19].

4.1 IceCube-22

The first search for relativistic magnetic monopoles was performed on the 2007 data run with the detector operating with 22 strings representing a volume of $\sim$ 0.3 km^3. The selection strategy focused on the brightness of the monopole by first defining a hit with a much higher threshold than the actual DOM, set to be when the fADC waveform reached a saturation level of 1022 ADC counts. This reduced hits from background to be $\sim$ 10 m away from the particle track while signal hits were $\sim$ 10–60 m away from the monopole track. Once the sequence of hits was defined, a simple analytic reconstruction was performed based on a plane wave hypothesis and minimizing the variance relative to the actual hit positions, termed 'linefit'. The result of using the higher threshold for a hit leads to an improvement in angular accuracy from 5–10 degrees for all hits down to $\sim$ 2 degrees.

The analysis aimed to enhance the sensitivity to slower monopoles by binning the data based on speed reconstruction. Unblinding revealed that the background simulation was not reproducing the tail of the speed distribution where the slower signal was expected to be. This resulted in obvious background events surviving into the final sample. Comparisons based on additional characteristics of waveforms and spatial extent of the hits clearly distinguished the events as background muon bundles. After determining no monopole events were recorded, the following analysis was based only on improved simulation rather than the burn sample or other experimental data. The only changes involved a slight tightening of quality cuts motivated by the new simulation and abandoning any speed binning.

The final cut is in the plane of reconstructed zenith direction and the number of bright hits. For up-going events,

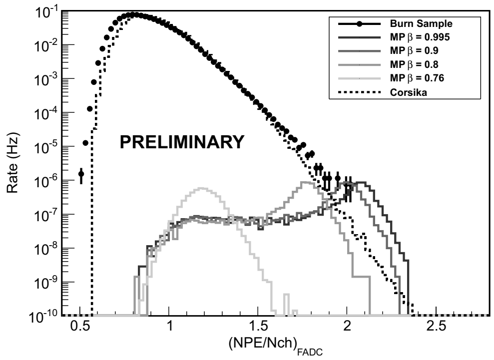

Figure 2: Ratio of the number of hit DOMs and total number of photo-electrons for simulated atmospheric muon background (dashed line), 10% experimental data (black markers) and simulated monopole signal (grey histograms). A precut (Nch > 50) has been applied to reduce the discrepancy between experimental data and Monte-Carlo simulation.

that are largely background free, a simple cut on the number of hits is applied. For down-going directions, where muon bundles produced by high-energy cosmic rays dominate, the cut increases in strength as it approaches the vertical. The cut is optimized on background and signal Monte Carlo by considering the combination that minimizes the model rejection factor [15] for an isotropic and monoenergetic monopole flux.

No data events survived the final cut and upper limits were placed on the flux of magnetic monopoles for speeds of $\beta > 0.8$, which represent a factor of 10 improvement over the AMANDA analysis [16]. Figure 1 shows the limits, as a function of beta, that result for an isotropic flux at the detector. For a complete description of the analysis as well as how these limits transform to an isotropic flux at the Earth's surface, see [17].

4.2 IceCube-40

A relativistic magnetic monopole search is also currently underway using the data taken with the 40-string detector. The selection strategy remained focused on the brightness of the monopoles, however, a different observable was chosen. The primary parameter used was the ratio of the total number of photo-electrons (NPE), which is estimated by unfolding the fADC waveforms, and the number of hit DOMs (Nch). While Nch and NPE are in principle integers, their values are large for bright events and therefore the ratio provides a wider range of values than using the number of saturated DOMs. For bright monopoles NPE/Nch is expected to be larger than for atmospheric muon bundles, since the number of DOMs within a radius r around a particle track is proportional to r^2, while the number of photons decreases as $\exp(-r/\lambda)$, where λ

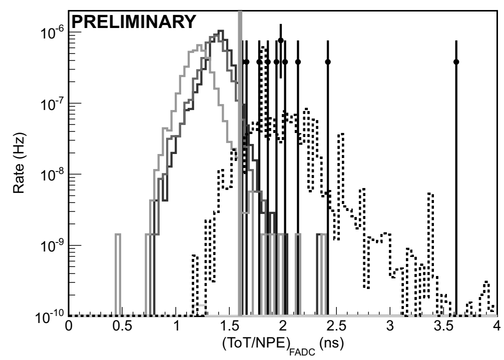

Figure 3: Final cut on time over threshold to NPE ratio. The cut is shown as the thick vertical line at 1.6.

is the effective absorption length. Figure 2 shows the distribution of NPE/Nch after a precut (Nch > 50) has been applied to remove events where a particle track outside the instrumented volume triggers the detector. This also significantly improves the agreement of experimental data and Monte-Carlo simulation in the signal region.

The actual cut was made in the plane of reconstructed direction and the inverse of the NPE to Nch ratio, where direction is reconstructed with the linefit method using all hit DOMs. In analogy to the previous search we made a simple cut on the Nch to NPE ratio for up-going events and a cut increasing in strength toward vertical down-going direction. The downside of choosing these cut parameters is that monopoles with $\beta = 0.76$, i.e. close to the Cherenkov threshold, cannot be effectively discriminated from background. The reason for that is the strong decrease of emitted Cherenkov light as the speed approaches the threshold. This narrows the speed interval where the analysis is sensitive, however, only by a small fraction. As an example figure 4 shows the 2-dimensional distribution of the cut parameters for monopoles with $\beta = 0.8$ and simulated background.

The parameter of the final cut is defined as the ratio of the accumulated time the fADC waveforms stay above a certain threshold (ToT) and again the total number of photoelectrons. Figure 3 shows the distribution of the cut parmeter. The cut value is set so that no data events survive the final cut. The estimated sensitivities to magnetic monopoles with speeds $\beta = 0.995$, $\beta = 0.9$ and $\beta = 0.8$ at the detector are given in Table 1 and are also shown in Figure 1. Though no optimization has been applied to the cut values so far, the sensitivity is improved over the analysis using the 22 string detector by a factor of ~ 4.

Looking to the future, visual inspection of burn-sample events has revealed two classes of background events which are evading the current cut conditions. The first class is events where a single DOM registers a signal much larger than the remaining DOMs. These events are believed to

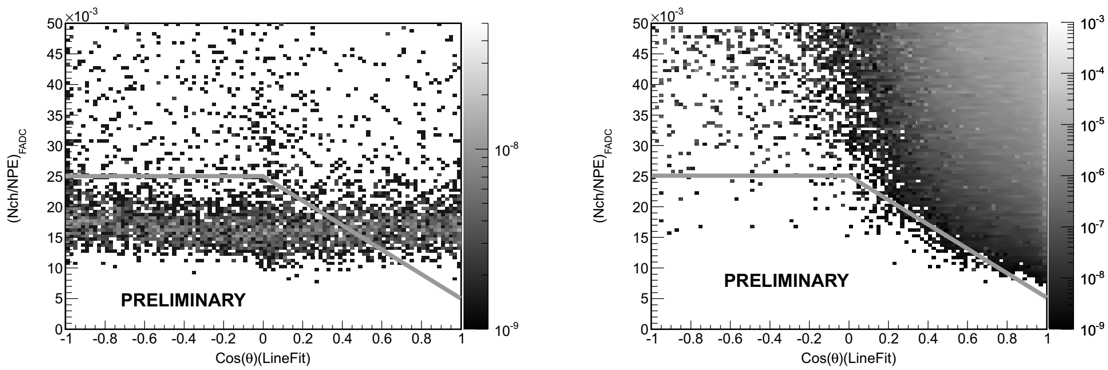

Figure 4: Distribution of Nch/NPE vs Cos(θ) for monopoles with $\beta = 0.8$ (left) and for simulated muon bundles (right). A zenith angle of $\theta = 0^\circ$ corresponds to vertically down going. The cut is shown as a grey line, excluding the upper area.

β	A_{eff} km^2	Exp Signal year^{-1}	Φ_{90} cm^{-2} s^{-1} sr^{-1}
0.995	0.94	185.57	$1.1 \cdot 10^{-18}$
0.9	0.90	178.87	$1.1 \cdot 10^{-18}$
0.8	0.68	134.61	$1.5 \cdot 10^{-18}$

Table 1: Effective area, expected signal and sensitivity (90% C.L.) at the detector for a full year of data.

occur when a particle experiences a stochastic energy loss very close to a DOM. The second and more frequent event class appears to be atmospheric muons with high inclination grazing the corners of the detector resulting in a hit pattern easily leading to misreconstruction. The occurrence of these events may be partially caused by the asymmetry of the 40 string detector. Even though no data events survived the last cut, the final version of the analysis will likely include safety cuts for these event classes.

5 Conclusion

The analysis performed on the data taken with the 22 string IceCube detector has improved the limits on the flux of magnetic monopoles with speeds $\beta > 0.8$ by an order of magnitude. They are presently the most stringent experimental limits. The ongoing analysis of data taken with the 40 string detector will likely improve these limits by another factor of ~ 4. However, these results are preliminary and will be refined.

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