Searches for magnetic monopoles with IceCube

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Abstract. Particles that carry a magnetic monopole charge are proposed by various theories which go beyond the Standard Model of particle physics. The expected mass of magnetic monopoles varies depending on the theory describing its origin, generally the monopole mass far exceeds those which can be created at accelerators. Magnetic monopoles gain kinetic energy in large scale galactic magnetic fields and, depending on their mass, can obtain relativistic velocities.
IceCube is a high energy neutrino detector using the clear ice at the South Pole as a detection medium. As monopoles pass through this ice they produce optical light by a variety of mechanisms. With increasing velocity, they produce light by catalysis of baryon decay, luminescence in the ice associated with electronic excitations, indirect and direct Cherenkov light from the monopole track, and Cherenkov light from cascades induced by pair creation and photonuclear reactions. By searching for this light, current best limits for the monopole flux over a broad range of velocities was achieved using the IceCube detector. A review of these magnetic monopole searches is presented.

1 Introduction

The existence of magnetic monopoles, particles carrying a single magnetic charge, is motivated by various theories which extend the Standard Model of particles, such as Grand Unified Theories (GUTs), String theory, Kaluza-Klein, and M-Theory [1]. The elementary magnetic charge g_D is derived from basic principles with a value of $g_D = e/2\alpha$ [2] where α is the fine structure constant and e is the elementary electric charge. Other parameters of magnetic monopoles, such as their mass and predicted flux, depend on the details of the models regarding particle creation.

Relic monopoles are predicted to have been created during symmetry breaking shortly after the Big Bang with a mass of the order of 10^{13} GeV to 10^{19} GeV [3]. The proposed inflationary phase of the early universe leads to a dilution of the monopole density. Intermediate (or smaller) mass monopoles are predicted within intermediate steps of symmetry breaking during or after inflation with masses in the order of 10^{7} GeV to 10^{13} GeV [4, 5]. Monopoles at relativistic speeds are expected to have intermediate masses since only in this mass range they can be sufficiently accelerated in cosmic magnetic fields [4]. Magnetic monopoles can also be introduced by modest extensions of the electroweak theory of the standard model with masses ranging down to a few tera electronvolts [6].

Although the existence of light monopoles may be tested at accelerator experiments (e.g. MoEDAL) [7, 8], for intermediate and heavier masses the cosmic abundance of monopoles is

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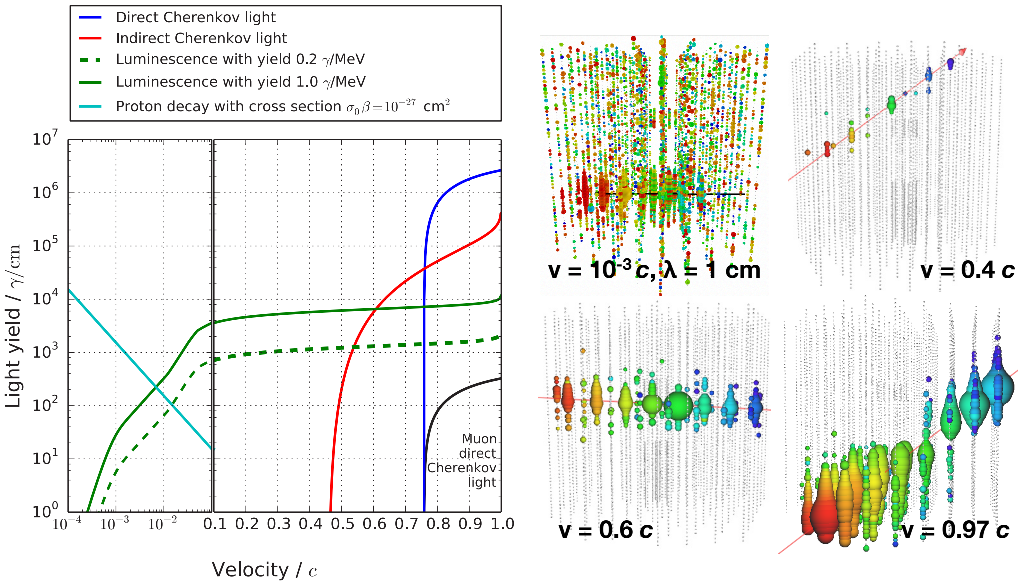

Figure 1. *Left:* Light yield of monopole signatures at different speeds compared to the light yield of a bare muon (black solid). The luminescence yield is varied between $0.2\,\gamma/\mathrm{MeV}$ [11] (green dashed) and $1.0\,\gamma/\mathrm{MeV}$ [12] (green solid). *Right:* Event views of simulated monopole signatures showing light emission due to proton decay (top left) [13], luminescence (top right), indirect Cherenkov (bottom left), and direct Cherenkov radiation (bottom right). The position of the IceCube DOMs are shown with gray spheres. Hit DOMs are visualized with colored spheres, scaling with the recorded charge. The color denotes the time from early (red) to late (blue). The simulated track of the monopole is shown with a solid line. The event view at the top left is simulated using a mean free path of 1 cm for proton decay catalysis and includes hits produced by photomultiplier noise and passing muons during the long event duration over long millisecond event duration.

constrained by astrophysical arguments [9] or by direct searches. Special purpose detectors for monopoles, such as MACRO or MoEDAL [7, 10], use induction, visible damage of plastic targets, and time of flight measurement. Generically, light yield from a monopole is much greater than for particles with electronic charges as shown in Fig. 1 (left). As a result, large aperture general purpose detectors of high energy particles (e.g. IceCube, ANTARES, Baikal) provide the best limits on the flux of monopoles.

2 Monopole signatures

IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole between depths of 1450 m and 2450 m [14]. It consists of 86 strings, each with 60 digital optical modules (DOMs). Neutrino reconstruction relies on the optical detection of Cherenkov radiation emitted by secondary particles produced in neutrino interactions in the ice or the nearby bedrock. The DeepCore sub-array, as used in this work, includes the 8 more densely instrumented strings, optimized for low energies, plus 7 adjacent standard strings [15]. The large volume of IceCube and its generic detection method relying on light production is beneficial for rare event searches, such as magnetic monopole detection. Depending on the monopole mass and arrival direction at Earth, magnetic monopoles can have a range of velocities when penetrating IceCube.

Cherenkov light is produced by charged particles exceeding the speed of $0.76\,c$ in ice. The Cherenkov light yield for magnetic monopoles is $\approx 2 \cdot (g_D/e)^2$ times higher than that of electric charges [16]. The event signature of *highly relativistic* monopoles is therefore expected to be a bright and homogeneous track passing through the entire detector. At *ultra-relativistic* speeds ($\gamma \gtrsim 10^3$), photo-nuclear interactions and pair production take over as the dominant light production processes [17].

Below the Cherenkov threshold magnetic monopoles are energetic enough to ionize the surrounding matter and accelerate the ejected δ-electrons above the Cherenkov threshold. This so-called indirect Cherenkov light can be used for monopole detection down to $\approx 0.5\,c$ [18]. At these *mildly relativistic* velocities monopoles have a comparable light yield as a bare muon.

In some GUT theories protons are unstable particles with a long lifetime [19, 20]. A proton coming close to a monopole's core can decay under baryon number violation. The decay products of a 1 GeV proton induce a small particle cascade in which the secondaries emit Cherenkov light. The catalysis cross section is inversely dependent on the monopole speed. IceCube is sensitive to mean free paths from 1 mm to 10 m [13]. Since IceCube's strings are 125 m apart from each other, the resulting signature of a *non-relativistic* monopole is a slow track. The brightness of the signature depends on the catalysis cross section.

The described detection methods do not cover low relativistic velocities, nor non-relativistic velocities if baryon decay does not exist. Therefore a new approach is followed in order to fill this gap. At *low relativistic* velocities magnetic monopoles produce luminescence light by electronic excitation of the surrounding medium. The luminescence yield dN_γ/dx per path length scales linearly with the monopole energy loss dE/dx. The energy loss can be estimated from the heavy ion energy loss by using an effective charge of $\beta \cdot g_D$. The light yield of pure ice luminescence irradiated with α-particles was recently measured to be on the order of $\approx (1.0 \pm 0.3)\,\gamma/\mathrm{MeV}$ at IceCube temperatures, integrated over the wavelengths to wish IceCube is sensitive [12]. Simulations of monopoles with speed above $0.1\,c$ show, that their signatures can be detected by IceCube [21]. However, the effect of impurities and different charges of the projectile are yet to be determined. The light yield of the described light emissions is shown in Fig. 1 (left) and compared with the light yield of a bare muon. Simulated event views of the expected monopole signatures are shown in Fig. 1 (right).

3 Recent IceCube searches

Searches for magnetic monopoles with IceCube have been executed targeting three of the described signatures. All IceCube analyses are based on simulated signal and background, along with 10% of the recorded data, to avoid experimental bias. After an internal review the analysis scheme is fixed and applied on the remaining 90% of data. Since 2011 the IceCube data acquisition at Pole is running a specialized trigger for the collection of long lasting events produced by non-relativistic (i.e. heavy) monopoles catalyzing proton decay. During the required time, up to several milliseconds, tens of muons pass through the detector and the photomultipliers' dark rates cause almost every DOM to detect a hit. The challenge is to reconstruct the monopole track out of the dominant background. The trigger searches for triplets (three pairs of hit DOMs) which fulfill conditions related to timing and opening angle. The further analysis requests monopole candidates to have at least 26 triplets above a reconstructed speed of $10^{-3}\,c$ or 60 triplets below that speed. With the application of this analysis on one year of DeepCore data no monopole candidate was found. Upper flux bounds were derived for catalysis cross sections $\sigma_0\beta$ from $5 \cdot 10^{-26}\,\mathrm{cm}^2$ up to $2 \cdot 10^{-22}\,\mathrm{cm}^2$ on the order of $2 \cdot 10^{-15}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$

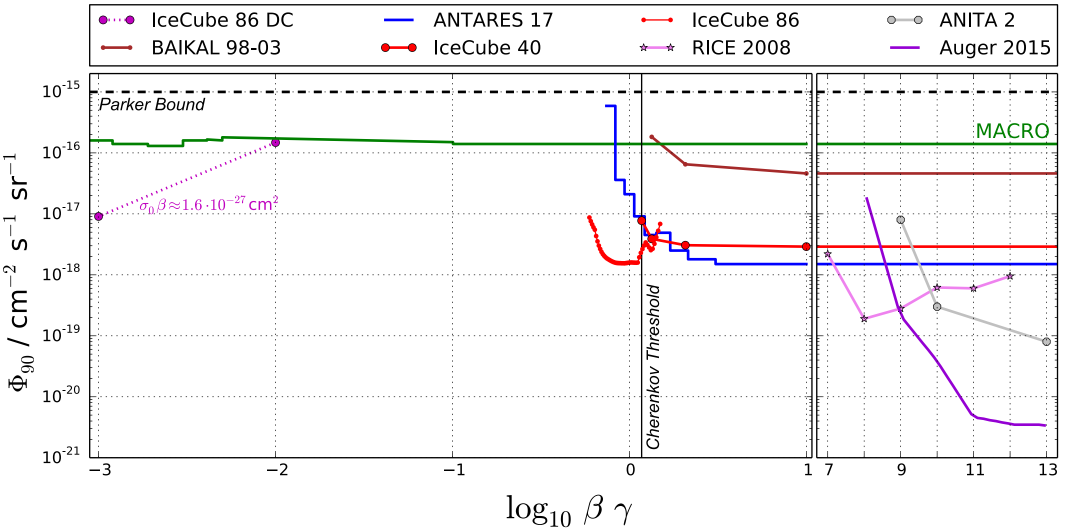

Figure 2. Current upper limits on the flux of magnetic monopoles in dependence on the speed of monopoles at the detector [11, 13, 18, 22–26]. The best limits for cosmic monopoles are achieved by general purpose detectors. However, low relativistic speeds, from $0.1\,c$ to $0.5\,c$, are not covered by them yet so that the latest limit in this region is almost two orders of magnitude higher than for all other speed ranges.

to $2\cdot10^{-18}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ [13]. Assuming dark matter is dominated by magnetic monopoles, these limits require a monopole mass above $1.22\cdot10^{19}$ GeV.

The search for highly relativistic magnetic monopoles of intermediate mass producing direct Cherenkov light [18] used data from 2008 when IceCube was half constructed. Since the monopole signature is as bright as a few hundred tera electronvolt muon, the analysis was based on the extremely high energy filter which is used to select candidate events for astrophysical neutrino searches. Before the detection of astrophysical neutrinos the signature of monopoles would have been distinctive because of its brightness and its upwards going direction. Using this as a main criterion the analysis found three events of which one was an expected muon neutrino and two were of unexpected origin. The latter were identified as partially contained, bright cascades which were possibly early hints of the later detected astrophysical neutrino flux.

IceCube's most recent search for magnetic monopoles targeted mildly relativistic monopoles of intermediate mass emitting indirect Cherenkov light. Data from 2011, when the detector was completed, was used in this analysis. After selecting tracks, reconstructed within the anticipated velocity range and in upwards direction, the main backgrounds were coincident air showers and neutrinos which pass through the 125 m gaps in the geometry of IceCube. Further event selection was done using machine learning algorithms (boosted decision trees). All used variables rely on simple geometrical and timing patterns of the hit DOMs. After the last selection up to 3.61 background events were expected. Three vertical track signatures did pass this criterion. They were identified as muons resulting from neutrino interactions below the IceCube volume. The derived flux bound improves on previous bounds by almost two orders of magnitude [18].

4 Summary and outlook

Due to its unprecedented size IceCube holds the strongest constraints on the flux of non-relativistic and mildly relativistic, i.e. intermediate mass and heavy, magnetic monopoles. Even better sensitivity is expected from further years of data taking with IceCube, or from proposed volume extensions of the detector [27].

Ongoing analyses using IceCube data are expected to improve the current limits and extend over larger velocity ranges. The new analysis searching for slow monopoles introduces a new filter extending data taking to long duration events from DeepCore to whole IceCube. In addition there is an ongoing analysis searching for highly relativistic monopoles discriminating tracks caused by high energetic neutrinos by the homogeneity of the tracks.

Finally there are measurements of light yield from luminescence in ice ongoing, enabling new searches for low and non-relativistic magnetic monopoles. These analyses open a new detection channel enhancing the chance for observation of magnetic monopoles in IceCube.

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