Search for Relativistic Magnetic Monopoles with Eight Years of IceCube Data

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We present an all-sky 90% confidence level upper limit on the cosmic flux of relativistic magnetic monopoles using 2886 days of IceCube data. The analysis was optimized for monopole speeds between 0.750c and 0.995c, without any explicit restriction on the monopole mass. We constrain the flux of relativistic cosmic magnetic monopoles to a level below $2.0 \times 10^{-19} \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ over the majority of the targeted speed range. This result constitutes the most strict upper limit to date for magnetic monopoles with $\beta \gtrsim 0.8$ and up to $\beta \sim 0.995$ and fills the gap between existing limits on the cosmic flux of nonrelativistic and ultrarelativistic magnetic monopoles.

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Introduction.—Although not yet experimentally detected, particles with magnetic charge (magnetic monopoles) are explicitly allowed in theories describing the fundamental laws of physics. Maxwell’s equations allow for the introduction of a magnetic current and a magnetic charge density without loss of internal consistency or contradiction with experimental results. Magnetic monopoles were introduced in quantum mechanics by Dirac in 1931 [1] through a mechanism that requires the quantization of both the electric and magnetic charge. The allowed magnetic charges are given by $g = Ne/(2\alpha)$, where $\alpha$ is the fine structure constant, $e$ is the unit electric charge, and $N$ is an integer. The smallest allowed magnetic charge is thus $g = e/2\alpha = 68.5e$, also called the Dirac charge, $g_D$. Magnetic monopoles can also be accommodated in grand unified theories (GUTs) of the known forces in nature, which are based on quantum field theory. GUTs predict the existence of stable magnetic monopoles (‘t Hooft-Polyakov monopoles) that arise when the gauge symmetry of the GUT breaks into the electromagnetic U(1) symmetry, creating a topological soliton that must carry magnetic charge [2–4]. The mass of a monopole depends on the details of the symmetry breaking from the GUT symmetry to U(1). GUT monopoles have masses on the order of $10^{17}$ GeV, but so-called intermediate mass monopoles with masses $\gtrsim 10^5$ GeV can arise if there is a mass scale between the GUT scale and the electroweak scale [5].

Magnetic monopoles could have formed in the early Universe as the temperature of the primordial plasma dropped below the energy scale of the GUT symmetry breaking [6,7]. The expected production rate of monopoles depends on the unknown nature of this phase transition (first or second order), but it can lead to a production comparable to the amount of baryons, predicting a relic density today above current observational limits. This has been dubbed the “monopole problem” [8]. It is through inflation that the primordial density of magnetic monopoles can be brought to a level consistent with observations. Remaining magnetic monopoles will be accelerated along the magnetic field lines of galactic and extragalactic magnetic fields, gaining a kinetic energy given by $E_k = g_D^2 |\vec{B}|L$, where $|\vec{B}|$ is the strength of the magnetic field and $L$ represents the size of the domain where the magnetic field direction remains constant. Even if typical intergalactic and galactic magnetic fields are weak (order of nanogauss) [9], their spatial extensions are large (kilo- to megaparsec), so the total energy gain can be substantial for a monopole crossing several magnetic field domains over the lifetime of the Universe [10,11]. Indeed, energies up to $\sim 10^{14}$ GeV can be expected. Depending on the mass of the monopole, this can result in relativistic speeds in the present epoch. The expected speed range of relic monopoles is an important aspect for their detection, since different techniques are used to search for monopoles of different speeds [10–12].

Relativistic monopoles (defined as those with $\beta \gtrsim 0.750$ in what follows) will induce Cherenkov radiation when traversing a dielectric medium faster than the speed of light in the medium, as electrically charged particles do [13]. Therefore Cherenkov detectors can be used to search for cosmic monopoles through the pattern they would leave when passing through the detector [14–17]. The analysis presented in this Letter uses eight years of data from the IceCube neutrino observatory to search for monopoles with one unit of magnetic charge and speed above 0.750c.

IceCube is a cubic-kilometer array of digital optical modules (DOMs) deployed in 86 strings at depths between 1.45 and 2.45 km below the surface of the glacial ice at the South Pole [18]. IceCube uses the ice both as target and

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diameter (22). A vertically up-going monopole crossing one Earth
mM lower mass limit for the validity of the analysis of
same speed in a medium with refractive index
Cherenkov light as a particle with electric charge
ensure that monopoles reach the detector.

Additional Cherenkov light. The analysis of such speeds
[21,22] are an important and non-negligible source of
production, bremsstrahlung, and photonuclear interactions
particles produced in stochastic energy losses like pair

Mono pole shows that it produces (gn/e2) times as much
Cherenkov light from the products of ionization
is a non-negligible contribution, mainly close to the
Cherenkov threshold. The signature of a magnetic mono-
ole crossing IceCube is therefore expected to be a straight
track with uniform light yield along its path. This will be a
distinctive selection criterion in the analysis presented
below. For ultrarelativistic monopoles (γ ≳ 105), secondary
particles produced in stochastic energy losses like pair
production, bremsstrahlung, and photonuclear interactions
[21,22] are an important and non-negligible source of
additional Cherenkov light. The analysis of such speeds
is beyond the scope of this work.

A sample of 4 × 105 through-going monopole events
was simulated with the standard IceCube simulation soft-
ware, which includes light production and propagation, as
well as the detector trigger response. A uniform speed
distribution between 0.750c and 0.995c at the detector was
adopted, and isotropic arrival directions were assumed.
Relativistic monopoles can lose energy when traversing
matter and they might become nonrelativistic, or even stop,
before reaching the detector. The energy loss of a 1 GeV
relativistic monopole in rock (iron) is ∼10/(100) GeV/cm
[22]. A vertically up-going monopole crossing one Earth
diameter (109 cm) will lose about 1011 GeV, while a
monopole reaching the detector horizontally will just cross
a chord of ∼107 cm and lose 108 GeV. This determines a
lower mass limit for the validity of the analysis of
mM ∼ 108−11 GeV, depending on the zenith angle, to
ensure that monopoles reach the detector.

Backgrounds.—The main background in the search for
relativistic monopoles with IceCube are very energetic
astrophysical neutrinos [23,24]. Muons from astro-
physical neutrino interactions produce enough light in
the detector to mimic monopole tracks. Their distinctive
feature is the stochastic emission of light along the
muon track. The expected number of astrophysical back-
ground events at different levels of the analysis has been
calculated from the measured astrophysical neutrino
flux [25], which can be described by a single power
law Φγ = Φ0 × (Eγ/100 TeV)γ, with Φ0 = 1.01±0.26×
10−18 GeV−1 cm−2 s−1 sr−1, and γ = 2.19 ± 0.10. We
assume no cutoff in the spectrum and a νe:νμ:ντ flavor
eratio at Earth of 1:1:1.

Other backgrounds to this analysis are atmospheric
neutrinos and the much more copious atmospheric muons
produced in cosmic ray interactions in the atmosphere and
that reach the detector depth from above. As explained
below, these backgrounds are removed by either a direc-
tional selection (considering only up-going events removes
atmospheric muons) or by the event characteristics (muons
from atmospheric neutrinos produce relatively dim muon
tracks that do not resemble the much brighter signature of
a monopole).

Data selection.—This analysis uses IceCube data col-
lected between 2011 and 2018, corresponding to 2886 days
of live time [26]. The event selection was performed in two
steps using all the IceCube triggered events. The first
selection (denoted as step I in the rest of the Letter) consists
of applying the exact criteria (“cuts”) that were developed
for a previous IceCube analysis searching for extremely
high-energy neutrinos and described in detail in [27].
Detailed comparisons between data and Monte Carlo
simulations were performed in that analysis to validate
the simulation used to generate the different backgrounds
and evaluate the efficiency of the event selection.

The analysis strategy of step I aims at selecting very
bright events, potentially corresponding to extremely high
energetic astrophysical neutrinos, and is a good base to
further develop a selection for relativistic monopole events,
which would also leave a bright event pattern in the
detector. An online event filter at the South Pole selects
events with more than 1000 photoelectrons (∼PE) to reduce
the amount of data transferred by satellite for further
processing in the northern hemisphere. Additional aggres-
sive brightness cuts, selecting events with a high number of
nPE, are applied off-line in order to drastically reduce the
number of atmospheric background events. At least 104.6
photoelectrons are required for events with a good track fit
quality, increasing linearly with the reduced log-likelihood
of the fit to nPE ≥ 105.2 for events with lower track
reconstruction quality. This cut has been shown to select
muon tracks relative to particle cascades produced by
electron- and tau-neutrino interactions. Additionally, a
zenith-angle-dependent nPE cut is applied to remove high
energetic atmospheric muons that reach the detector from
above the horizon. The black line of Fig. 1 illustrates this
selection. Down-going events registered in coincidence
with two or more pulses in the IceTop surface air shower
array are also rejected as probably induced by an atmos-
pheric shower. One of the effects of the step I cuts is to
reject down-going monopoles, resulting in uniform accep-
tance of the analysis in cos(θzen) for monopoles reaching
the detector from below the horizon and no acceptance for
monopoles coming from above; see the left plot of Fig. 1.
Table I shows the remaining fraction of signal and background events after the step I cut level.

The step I event selection has practically no acceptance for neutrinos with energy below $10^6$ GeV, where the bulk of atmospheric neutrinos lie. Atmospheric muons and neutrinos are reduced to a rate of about $10^{-9}$ Hz after the step I brightness and zenith angle selection, which is well below 0.1 event in the whole analysis live time. We therefore assume a zero background from atmospheric muons and atmospheric neutrinos in what follows.

Since the step I analysis targets all neutrino flavors, it does not reject the typical event pattern induced by electron- and tau-neutrino charged-current interactions, neither all-flavor neutral current interactions. These events are characterized by the full neutrino energy being deposited within a few meters of the interaction point, producing a spherical light distribution in the detector. A second level of cuts (denoted as step II in the rest of the Letter) was developed in a blind manner, using only Monte Carlo simulations of signal and background, aimed specifically at selecting monopole tracks, while rejecting the remaining astrophysical neutrino events accepted by step I. A track reconstruction allowing monopole speeds below the speed of light and characterizing the stochastic energy losses along the track was performed at this level [28]. Nine variables related to the characteristics of the events were used in a boosted decision tree (BDT) classification of the remaining events. The variables describe the expected characteristics of monopole events (through-going tracks with a uniform light emission along their path and a given expected total brightness) and allow efficient separation between signal and background. The BDT was trained on a subsample of the simulated signal and background samples to obtain optimal separation between monopoles and astrophysical neutrinos. Optimal separation was defined by minimizing the model rejection potential (MRP) [29], which provides maximum sensitivity to the signal. Figure 2 illustrates the separation power of the BDT. The left plot shows the event rate as a function of BDT score for the different particle backgrounds and monopole signal, while the right plot shows the MRP as a function of BDT score. The minimum corresponds to the BDT score that defines the best sensitivity of the analysis and determines the choice of the optimal BDT cut at a value of 0.047. We assume no uncertainty in this value since the minimum of the score cut distribution is well defined. Note that the BDT score distributions for electron and tau neutrinos are well separated from the distribution for monopoles, while for muon neutrinos the separation is less pronounced. This reflects the fact that muon tracks can mimic monopole tracks more easily than particle cascades from electron- and tau-neutrino interactions. The last row of Table I shows the remaining fraction of observed, signal, and background

Table I. Number of observed events $n_{\text{obs}}$ at each level of the analysis, along with the corresponding numbers of expected signal and background (astrophysical neutrino) events $n_{\text{sg}}$ and $n_{\text{bg}}$, assuming the model fluxes described in the text.

<table>
<thead>
<tr>
<th>Analysis level</th>
<th>$n_{\text{obs}}$</th>
<th>$n_{\text{sg}}$</th>
<th>$n_{\text{bg}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Online filter</td>
<td>$1.63 \times 10^8$</td>
<td>178</td>
<td>371</td>
</tr>
<tr>
<td>Step I:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial off-line cuts</td>
<td>$3.16 \times 10^4$</td>
<td>89.9</td>
<td>57.2</td>
</tr>
<tr>
<td>Track quality cut</td>
<td>$8.46 \times 10^3$</td>
<td>64.1</td>
<td>20.4</td>
</tr>
<tr>
<td>Down-going cut</td>
<td>3</td>
<td>35.5</td>
<td>10.1</td>
</tr>
<tr>
<td>IceTop surface veto</td>
<td>3</td>
<td>35.5</td>
<td>$10.0^{+10.3}_{-2.1}$</td>
</tr>
<tr>
<td>Step II</td>
<td>0</td>
<td>33.2</td>
<td>$0.27^{+0.27}_{-0.14}$</td>
</tr>
</tbody>
</table>
events after step II. Figure 3 shows the effective area of the analysis as a function of monopole speed, averaged in arrival directions over the full hemisphere, after step I cuts and at final analysis level (step II).

**Systematic uncertainties.**—Uncertainties on the scattering and absorption of Cherenkov photons during their propagation in the ice, as well as of the angular and total sensitivity of the DOMs, limit the sensitivity of IceCube. In order to include these systematic uncertainties in the final result, a study was performed by simulating $10^5$ monopole events for each of ten independent variations of the nominal parameter values used in the standard simulation. Four combinations of the scattering and absorption coefficients of the ice [30] were tested by shifting their nominal values by $\pm 5\%$ and the DOM total efficiency was shifted by $\pm 10\%$ for all DOMs. Four models of the DOM angular sensitivity that bracket the allowed variations in this quantity were used to evaluate the systematic uncertainty induced by this variable. Each of these variations have been extensively vetted by calibration studies in IceCube and represent the current best knowledge of the detector medium and response parameters. For each parameter variation, the monopole events were passed through the full event selection and the effective area was calculated in each case. The variations result in changes of the effective area between $+5\%$ and $-7\%$ with respect to the baseline analysis, dominated by the ice absorption. The angular response of the DOMs has a negligible impact in this analysis due to the high brightness of monopole events. The systematic uncertainties from the ice properties, the DOM efficiency, and the DOM angular response are assumed independent of each other and are added in quadrature, resulting in a total uncertainty on the sensitivity of 8.4\%.

Uncertainties from the intrinsic finite sizes of the Monte Carlo simulated samples used are negligible in this analysis.

An additional source of uncertainty on the magnetic monopole flux limit is the number of expected background events from the astrophysical neutrino flux. The uncertainties in the normalization and spectral index of this flux lead to an uncertainty in the number of predicted background events $n_{bg}$ of about a factor of 2, $n_{bg} = 0.27^{+0.27}_{-0.14}$. The main contribution to this background arises from astrophysical muon neutrinos ($0.24^{+0.23}_{-0.12}$ events remaining), the other flavors being successfully rejected by the analysis due to their different topology ($0.003^{+0.003}_{-0.002}$ and $0.021^{+0.003}_{-0.013}$ electron and tau neutrinos remaining, respectively). However, the low statistics of astrophysical neutrinos with energies above 100 TeV allows for alternative fits to the spectrum that result in a different expected number of background events. Two additional fits were examined in this analysis:
an update to the diffuse high-energy muon-neutrino flux using 10 years of data [31] (yielding a background of $9.4^{+7.9}_{-3.5}$ events after step I and $0.25^{+0.19}_{-0.11}$ events after step II) and an analysis of high-energy starting events using 7.5 years of data [32] (resulting in $1.1^{+1.7}_{-0.6}$ background events after step I and $0.03^{+0.05}_{-0.02}$ background events after step II). These two assumptions represent extremes of the current allowed range of normalization and spectral index of the astrophysical neutrino flux obtained from IceCube data, assuming a one component power-law fit without cutoff. Each of the evaluated fluxes are compatible with data, assuming a one component power-law fit without cutoff. The flux limit has been obtained including systematic uncertainties following the method in Refs. [14,33], and other experiments. Using the background expectation of along with results from previous IceCube analyses and it is shown as a function of monopole speed in Fig. 4, about 10% due to the underfluctuation of the observation with respect to the expected background. Searches for magnetic monopoles have also been performed by RICE [34], ANITA [35], and Auger [36]. These limits are valid in the ultrarelativistic region, $\gamma \sim 10^{-13}$, which would correspond to a single point at the rightmost end of the $\beta$ axis of Fig. 4. The most stringent limit between $\gamma \sim 10^7$ and $\gamma \sim 10^9$ is provided by the RICE Collaboration, at a level of about $10^{-19} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, while the Auger limit reaches down to about $2 \times 10^{-21} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ for $\gamma > 10^{11}$. The limit presented in this Letter is the strictest constraint on the flux of magnetic monopoles above $\beta \gtrsim 0.80$ and up to $\beta \sim 0.995$ for monopole masses above $10^8$–$10^{10}$ GeV (depending on zenith angle) and complements existing limits on the flux of nonrelativistic and ultrarelativistic monopoles.

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![FIG. 4. 90% confidence level upper limit on the cosmic flux of relativistic monopoles as a function of true particle $\beta$ obtained in the present analysis assuming zero background (dark green curve). Also included are previous results of IceCube [14,15], ANTARES [16], and Baikal [17]. The limits are valid for monopoles with the given $\beta$ at the detector. The Parker bound [37,38] is shown as reference.](https://example.com/fig4.png)


[1] P. A. M. Dirac, Quantised singularities in the electromagnetic field, Proc. R. Soc. A 133, 60 (1931).


