Search for Slow Magnetic Monopoles with the NOvA Detector on the Surface

(The NOvA Collaboration)

1Argonne National Laboratory, Argonne, Illinois 60439, USA
2Universidad del Atlantico, Carrera 30 No. 8-49, Puerto Colombia, Atlantico, Colombia
3Department of Physics, Institute of Science, Banaras Hindu University, Varanasi, 221 005, India
4California Institute of Technology, Pasadena, California 91125, USA
5Charles University, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, Prague, Czech Republic
6Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221, USA
7Department of Physics, Cochran University of Science and Technology, Kechi 682 022, India
8Department of Physics, Colorado State University, Fort Collins, CO 80523-1875, USA
9Czech Technical University, Brehova 7, 115 19 Prague 1, Czech Republic
10University of Dallas, 1845 E Northgate Drive, Irving, Texas 75062 USA
11Department of Physics and Astrophysics, University of Delhi, Delhi 110007, India
12Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
13Instituto de Física, Universidade Federal de Goiás, Goiânia, Goiás, 74690-900, Brazil
14Department of Physics, IIT Guwahati, Guwahati, 781 039, India
15Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
16Department of Physics, University of Houston, Houston, Texas 77204, USA
17School of Physics, University of Hyderabad, Hyderabad, 500 046, India
18Department of Physics, IIT Hyderabad, Hyderabad, 502 205, India
19Illinois Institute of Technology, Chicago IL 60616, USA
20Indiana University, Bloomington, Indiana 47405, USA
21Institute of Computer Science, The Czech Academy of Sciences, 182 07 Prague, Czech Republic
22Institute for Nuclear Research of Russia, Academy of Sciences 7a, 60th October Anniversary prospect, Moscow 117312, Russia
23Institute of Physics, The Czech Academy of Sciences, 182 21 Prague, Czech Republic
24Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA
25Department of Physics and Astronomy, University of California at Irvine, Irvine, California 92697, USA
26Joint Institute for Nuclear Research, Dubna, Moscow region 141980, Russia
27Nuclear Physics and Astrophysics Division, Lebedev Physical Institute, Leninsky Prospect 53, 119991 Moscow, Russia
28Universidad del Magdalena, Carrera 32 No 22 - 08 Santa Marta, Colombia
29Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
I. INTRODUCTION

Magnetically charged particles were hypothesized by Dirac in 1931 [1] and are generically predicted by grand unified theories (GUTs) [2]. Although GUT-scale monopoles of \( \sim 10^{17} - 10^{18} \) GeV are often assumed, recent theoretical work suggests possible masses as light as \( \sim 10^7 \) GeV [2, 3]. Searches over the past century for a magnetic monopole component of the cosmic-ray flux have yet to find convincing evidence [4]. Slow-moving (\( \beta < 0.01 \)) GUT-scale monopoles have been ruled out by underground experiments [5]. Weaker limits exist for slow monopoles in the range \( 10^{5} \) GeV < \( m < 10^{12} \) GeV from mountaintop experiments [6]. In this paper, we focus on the possibility that there is a flux of slow cosmic-ray magnetic monopoles. As a large low-elevation surface detector, the NOvA Far Detector is sensitive to a combination of monopole masses and speeds not previously accessible.

The NOvA experiment primarily measures the oscillation of muon neutrinos [7]. The measurement of this oscillation in neutrinos and antineutrinos gives information about the mixing parameters \( \theta_{23} \) and \( \Delta m^2_{32} \), the neutrino mass hierarchy, and the CP-violating phase \( \delta_{CP} \) of the PMNS matrix. NOvA uses two detectors, the 0.3 kt Near Detector underground at Fermilab, 50 km west of downtown Chicago, IL, and the 14 kt Far Detector (FD) near Ash River, MN. A beam of muon neutrinos produced at Fermilab travels through the Earth to the FD. Due to its surface location, monopoles with \( m \gtrsim 10^9 \) GeV can reach the FD without being absorbed by the atmosphere or overburden, while its size and trigger design allow identification of slow tracks. Compared to a dedicated underground monopole detector, NOvA is not optimized for monopole detection and must contend with a large cosmic muon background.

The NOvA FD has been described previously [8]. In brief, the detector is on the surface, with a concrete and barite overburden of 3 meters-water equivalent. It is a large cosmic muon background. Optimized for monopole detection and must contend with a large cosmic muon background.

The NOvA experimental trigger is described in Section III, the offline event selection in Section IV, and we give our results in Section V.
II. SIMULATION

We used simulation to determine the efficiency of selecting monopole tracks across the range of speeds $\beta = 10^{-4}$ to $10^{-2}$. We did not simulate proton decay catalyzed by monopoles [8] and in our analysis we assume it does not occur at a significant rate, leaving instead only an ionization signal. Ahlen and Kinoshita have calculated the energy deposition for non-catalyzing slow monopoles ($\beta < 10^{-2}$) [10]:

$$\frac{dE}{dx} = aN^2/e^2 \left[ \ln \left( bN^{1/3} \right) - \frac{1}{2} \right] \beta,$$

where $N$ is the electron density, which depends on the material. The constants $a$ and $b$ are material-independent and are defined as:

$$a = \frac{2\pi e^2}{hc(3\pi^2)^{1/3}} \quad b = 2(3\pi^2)^{1/3}a_0,$$

where $e$ is the fundamental electric charge, $h$ is the reduced Planck constant, $c$ is the speed of light, and $a_0$ is the Bohr radius. For this search, the monopole charge was assumed to be the Dirac charge, $g = e/2\alpha = hc/2e$, where $\alpha$ is the fine structure constant. The monopole was assumed to have no electric charge. This is not a unique choice; other assumptions would lead to higher or lower predicted detection efficiencies. For instance, a magnetic monopole that also carried an electric charge, or with a multiple of the Dirac charge, would, in general, be easier to detect. An exotic slow particle with only electric charge, e.g. a microscopic black hole, would be detected with higher or lower efficiency depending on its charge.

If, contrary to our assumptions, monopoles were to catalyze proton decay, then this energy deposition estimate would be conservative. Generally, catalysis would slightly increase detection efficiency by causing more hits over threshold. However, should it occur at a very high rate, it could cause reconstructed monopole tracks to be rejected as non-linear (see Section IV). Catalysis would also increase the mass threshold of the search by reducing the range of monopoles in the Earth and in the atmosphere.

A monopole traversing the FD would deposit visible energy in the liquid scintillator. NOvA’s scintillator is mostly composed of mineral oil (solvent) and pseudocumene (scintillant) [11]; its electron density is $2.9 \times 10^{23}$ cm$^{-3}$. Using Eq. 1, this yields $dE/dx = (12$ GeV/cm)$\beta$, which is valid for $10^{-4} < \beta < 10^{-2}$. Although there is substantial theoretical uncertainty on the value of $dE/dx$, we used this nominal value to set limits in this search.

In the absence of information about the directional distribution of monopoles, an isotropic flux was assumed. Geant4 [12] was used to track monopoles through the detector’s geometry. For the mass and speed ranges we considered, the energy lost by a monopole in the detector would be negligible compared to its initial kinetic energy, and it was assumed that its speed remains constant.

The NOvA detectors were designed to measure energy deposition of particles with $\beta$ near 1, which traverse the width of each cell in the detector in under a nanosecond. No consideration was given in the design phase to particles depositing a similar amount of energy over as much as a microsecond, as monopoles at the lower end of our sensitivity would. In order to verify our simulation of the detector response to such slow signals, we performed a dedicated test stand measurement which mimicked the signature of monopole signals by exposing APDs read out by NOvA electronics to light pulses generated by LEDs. The ratio of the measured signal to our simulation of detector electronics was 1.0±0.1. To conservatively account for the possibility that signals from slow energy depositions were overestimated in our detector simulation, we reduced the simulated detector response in the FD by 10%.

Each simulated monopole was combined with 5 ms of zero bias data from the FD (i.e. data with typical running conditions, saved to permanent storage without regard to its content). The trigger operates on data blocks of this length. This results in an event that contains both the simulated monopole and real detector activity. This sample was used to measure how well the search algorithm can identify slow monopoles and differentiate them from the cosmic-ray background.

III. ONLINE TRIGGER ALGORITHM

Using NOvA’s data-driven trigger system [13], the FD is able to isolate interesting physics signals among 150 kHz of cosmic rays. This trigger system operates entirely in software and is able to perform arbitrary analyses of incoming data, although the complexity is limited by CPU time. The event topology in this search is a straight track traversing the FD with a speed that is a small fraction of the speed of light. The trigger was optimized for $\beta = 10^{-3}$ magnetic monopoles.

Pairs of hits coincident in time and in neighboring $xz$ and $yz$ planes are grouped together. These define 3D positions. Each 3D pair that defines a position within six cells or five planes of the surface of the detector (see Fig. 1) is retained for further processing. Using the $xz$ view alone for CPU efficiency, the trigger forms track seeds consisting of two selected hits on different detector faces and a time difference consistent with originating from a particle with $10^{-4.4} < \beta_{2D} < 10^{-2.3}$ in the $xz$ view. The lower speed limit was set based on detector constraints rather than any specific monopole model. This 2D speed can correspond to a 3D speed as large as $\beta \approx 10^{-2.6}$. For each track seed, the algorithm identifies hits that lie on a 20 cell (80 cm) wide “road” with its center along the line connecting the seed hits. It then looks for gaps between adjacent hits on the road and identifies the maximum plane gap (in the $z$-direction) and the maximum cell gap (in the $x$-direction). If there is a plane gap larger than 30 planes (200 cm) or a cell gap larger.
FIG. 1. Hit selection in the trigger algorithm. Cells near the $+z$ edge in the $xz$ view are shown. Filled boxes represent hits in a 5 ms window; size is proportional to signal strength. The dotted red line shows the path of a simulated monopole; hits off this line are zero bias data. Hits above the horizontal dashed line are considered to be on the detector edge.

FIG. 2. Trigger and overall efficiency as a function of angle in the $xz$ view, for monopoles that cross at least 10 m of the detector with $\beta = 10^{-3}$. Efficiency in the $yz$ view has the same form.

IV. EVENT SELECTION

The initial stage of offline event selection was track reconstruction, first of speed-of-light tracks, then of slow tracks. Speed-of-light tracks are primarily cosmic-ray muons. Such a particle takes 50 ns to traverse the height or width of the detector and 200 ns to traverse the length; the hit timing resolution is typically 20 ns. Candidate tracks have hundreds of hits, making speed-of-light tracks easily distinguishable from the slow tracks of interest in this search. To find speed-of-light tracks, hits were clustered using their proximity in time and space. Within these clusters, straight lines consisting of several hits were identified and joined together to form tracks. All hits belonging to such tracks were removed from consideration for monopole track reconstruction. Since removed tracks can overlap a potential monopole track, some true monopole hits may be discarded at this step, reducing the search efficiency.

Hits were then removed if they are separated from all other hits by at least two planes and two cells in their respective views. This removal ensures that sparse tracks are not reconstructed out of stray hits. The remaining hits were reconstructed using the Hough tracking algorithm [14] to identify straight line objects. (Since the monopoles under investigation are so heavy, they do not undergo significant multiple scattering and should appear as perfectly straight lines up to the detector’s resolution.)

A line was fitted to each such collection of hits. A candidate was required to meet the following three basic requirements, as well as others described below. The track must:

1. Have at least 20 hits in each view;
2. Cross at least 10 planes in each view; and
3. Have a reconstructed length of at least 10 m.

The speed, linear correlation coefficient, and time gap fraction (defined below) were calculated for these candidate monopole tracks. As the trigger algorithm searches for monopoles with $\beta < 0.01$, and the analysis strategy is optimized for slow monopoles, any candidate monopole track reconstructed with a speed above this was rejected.

Since slow monopoles are not expected to be highly ionizing, distinguishing characteristics used in this search were the straightness of their tracks and their consistent slow speed. The standard linear regression correlation coefficient ($r^2$) was calculated for hits in $xt$ and $yt$ separately. A true monopole track would have $r^2$ close to unity. The minimum of $r_{xt}^2$ and $r_{yt}^2$ is called $r_{min}^2$.

A potential background was reconstruction failures in which two speed-of-light cosmic rays are identified as a single monopole track. Such a background track would have a cluster of hits occurring early in time, a large time gap, and then another cluster of hits occurring later. To remove such cases, the largest time gap between consecutive hits was required to be small, defined as follows. The

Integrated over all angles, the efficiency for triggering on a monopole with $\beta = 10^{-3}$ that intersects the detector with a true crossing length of at least 10 m is 68% (see Fig. 2). This efficiency is the result of using the conservative lower bound on the efficiency of the readout electronics discussed in Section II. If we did not use the lower bound, the estimated efficiency would be higher: 72% at $\beta = 10^{-3}$. Most of the efficiency loss at the trigger level is caused by the need for the monopole to intersect enough cells in both $xz$ and $yz$ views for its surface hits to be examined.
quantities $f_{xt}$ and $f_{yt}$ were calculated for each track. For each view, $f$ is the ratio of the largest time gap between hits in the track to the total extent of the track in time. A high-quality track has a value of $f$ close to zero, whereas a track built from two unrelated cosmic rays will have a value of $f$ close to unity. The maximum of $f_{xt}$ and $f_{yt}$ is called $f_{\text{max}}$.

The selection criteria were chosen using 1% of the data collected, under the assumption that such samples would contain no monopoles, since it is already known that monopoles, if they exist, are rare. The remaining criteria for selecting an event as a monopole were:

4. $\beta < 10^{-2}$;
5. $r_{\text{min}}^2 \geq 0.95$; and
6. $f_{\text{max}} \leq 0.2$.

Figure 3 shows the strength of $r_{\text{min}}^2$ and $f_{\text{max}}$ in separating signal from background.

Finally, we planned to visually examine any event passing all selections to determine if it appeared to be an unanticipated background.

V. RESULTS

The data set recorded from 5 June 2015 through 12 October 2015 was used for this search. During this period of time the FD was set to a consistent gain setting which was changed for later data taking. In these 129 days, the detector provided good data for $8.21 \times 10^6$ s. The data-driven trigger system was 99.9% efficient during this time period, where the small inefficiency was caused by the available CPU time for the trigger to process incoming data being exhausted. The corrected livetime is therefore $8.20 \times 10^6$ s (94.9 days).

The data set contained 10 447 881 events, none of which fell into the signal region. Figure 3 shows the distribution of the full sample in speed vs. $r_{\text{min}}^2$ and speed vs. $f_{\text{max}}$. All data events are far from the signal region. The two large clusters of background events in the data around $\beta = 10^{-3}$ and $\beta = 0.5$ were caused by electronics effects and speed-of-light muons not removed in the first reconstruction step, respectively. The former, which gives candidate tracks reconstructed within the target $\beta$ range, was confined to modules with recent large energy depositions, which prevents this phenomenon from leading to a reconstructed track passing our criteria. It is caused by a voltage overshoot in the electronics which retriggers most or all channels on a board at a fixed time after the energy deposition. This tends to form rectangular clusters of spurious hits with poor $r_{\text{min}}^2$ values.

The most signal-like events were reconstructed with $\beta$ between $10^{-3}$ and $10^{-2}$ and $r_{\text{min}}^2$ around 0.65. Upon visual inspection, these events proved to be caused either by two speed-of-light tracks in the same location at slightly different times, or by tracks formed out of fragments of high energy showers. In neither case would other events with the same characteristics easily be able to satisfy the requirement of $r^2 > 0.95$.

Since the analysis was background-free, the 90% C.L. flux upper limit is $\Phi_{90\%} = 2.3/L$, where $L = \Omega \epsilon \Delta t$ is the integrated product of acceptance and livetime, $\Omega$ is the solid angle coverage, $\epsilon$ is the efficiency, $A$ is the projected surface area of the FD visible to the monopole, and $t$ is the integrated livetime. Each quantity is detailed below.

Limits are reported for the two major coverage scenarios: half coverage where $\Omega = 2 \pi$, and full coverage where $\Omega = 4 \pi$. The coverage depends on the kinetic energy of the monopole, which is calculated from the monopole’s speed and mass. If the monopole’s energy were sufficient, it could traverse the entire planet. In this case, the FD has $4 \pi$ coverage. The half coverage regime occurs if the monopole had enough energy to make it through the atmosphere from above, but not enough to reach the FD from below. Figure 3 shows the solid angle coverage as a function of monopole speed and mass.

We calculate the detector’s projected area, $A$, for each
simulated monopole’s trajectory. The reconstruction efficiency also depends on this trajectory, so for each monopole speed, the product was determined event by event, $\epsilon_A \equiv (\epsilon_i A_i)$.

The overall efficiency, considering both trigger efficiency and analysis selection, was 53% (see Fig. 2), with most of the loss at the analysis stage arising from non-meson hits being associated with monopole tracks and spoiling their $r^2$ values. As shown in Fig. 4 (top), there are two distinct topologies. Either a small number of non-meson hits are associated with a simulated monopole track, in which case the speed is still reconstructed near $\beta \approx 10^{-3}$, or a small number of simulated monopole hits are associated with a speed-of-light particle, in which case the $r^2$ and speed are both far from the signal region.

Table I shows flux limits as a function of $\beta$. The mass cutoff columns represent slices through the coverage shown in Fig. 5. By taking other vertical slices through this figure, it can be seen that some sensitivity exists for masses as low as $\sim 2 \times 10^7$ GeV, but only for monopoles at the upper end of the speed range, $\beta \approx 10^{-2.1}$. Sensitivity falls off at low $\beta$ as monopole energy deposition drops below the analysis threshold, given the assumption of a monopole with a single Dirac unit $g$ of charge. This assumption is shared by the previous experiments whose limits are displayed in Fig. 6. At high $\beta$, the sensitivity was limited by the trigger design.

These limits are conservative since they use the lower bound on hit efficiency as described in Section II. A higher efficiency would extend the quoted limits slightly towards lower masses. Other detector-based systematic uncertainties were negligible. We considered uncertainties in livetime and solid angle and found that each was well under 1%. However, substantial theoretical uncertainty in slow monopole $dE/dx$ feeds into an uncertainty on translating non-detection into a flux limit. As stated above, these limits use the nominal $dE/dx$ of Ref. [10].

**FIG. 4.** Top: Reconstructed monopole speed vs. $r_{\text{min}}$ for events passing selections 1–3 and 6. Data events are shown as grey circles, and simulation for $\beta = 10^{-3}$ as red squares. Events must be in the dashed box in the lower right to be selected. Bottom: Same for $f_{\text{max}}$ and events passing selections 1–3 and 5. Events must be in the lower left to be selected.

**FIG. 5.** Solid angle coverage as a function of monopole speed and mass. Horizontal dashed lines indicate the boundaries of the search sensitivity in speed. Vertical dashed lines indicate the reference masses used to generate limits shown in Fig. 6 and Table I.

**TABLE I.** 90% C.L. upper limits on the magnetic monopole flux, in units of $10^{-15} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$.

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$m &gt; 5 \times 10^6$ GeV</th>
<th>$m &gt; 2 \times 10^{15}$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-3.6}$</td>
<td>150</td>
<td>74</td>
</tr>
<tr>
<td>$10^{-3.5}$</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>$10^{-3.4}$</td>
<td>23</td>
<td>12</td>
</tr>
<tr>
<td>$10^{-3.3}$</td>
<td>19</td>
<td>9.7</td>
</tr>
<tr>
<td>$10^{-3.2}$</td>
<td>17</td>
<td>8.7</td>
</tr>
<tr>
<td>$10^{-3.1}$</td>
<td>16</td>
<td>7.9</td>
</tr>
<tr>
<td>$10^{-3.0}$</td>
<td>15</td>
<td>7.5</td>
</tr>
<tr>
<td>$10^{-2.9}$</td>
<td>15</td>
<td>7.4</td>
</tr>
<tr>
<td>$10^{-2.8}$</td>
<td>15</td>
<td>7.3</td>
</tr>
<tr>
<td>$10^{-2.7}$</td>
<td>15</td>
<td>7.5</td>
</tr>
<tr>
<td>$10^{-2.6}$</td>
<td>15</td>
<td>7.6</td>
</tr>
<tr>
<td>$10^{-2.5}$</td>
<td>16</td>
<td>8.0</td>
</tr>
<tr>
<td>$10^{-2.4}$</td>
<td>17</td>
<td>8.7</td>
</tr>
<tr>
<td>$10^{-2.3}$</td>
<td>23</td>
<td>11</td>
</tr>
<tr>
<td>$10^{-2.2}$</td>
<td>86</td>
<td>43</td>
</tr>
<tr>
<td>$10^{-2.1}$</td>
<td>360</td>
<td>180</td>
</tr>
</tbody>
</table>
Higher or lower energy depositions would modify the limits in the same way as changes in detector efficiency.

VI. CONCLUSION

By virtue of being a large segmented detector on the Earth’s surface, the NOvA FD is uniquely sensitive to slow monopoles in the mass range below $10^{10}$ GeV which would not have reached previous detectors such as MACRO. We have constrained the flux of this population of monopoles in a large region of speed-mass space which has previously been unconstrained, setting an upper limit on the flux of $2 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ at 90% C.L. for $6 \times 10^{-4} < \beta < 5 \times 10^{-3}$ and mass greater than $5 \times 10^{8}$ GeV.

The results shown here represent less than 10% of the data the NOvA Far Detector has collected to date. The data sets collected beginning in October 2015 have a higher APD gain setting, which allows collection of fainter signals and thus an improved mass reach for magnetic monopoles with $\beta < 0.01$. NOvA also has the capability of searching for monopoles with $\beta > 0.01$ [18].

This document was prepared by the NOvA collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. This work was supported by the U.S. Department of Energy; the U.S. National Science Foundation; the Department of Science and Technology, India; the European Research Council; the MSMT CR, GA UK, Czech Republic; the RAS, RFBR, RMES, RSF, and BASIS Foundation, Russia; CNPq and FAPEG, Brazil; STFC, and the Royal Society, United Kingdom; and the state and University of Minnesota. We are grateful for the contributions of the staffs of the University of Minnesota at the Ash River Laboratory and of Fermilab.

---