Search for Magnetic Monopoles in Deep Ocean Deposits

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High-field magnets and solid-state track detectors have been used in an endeavor to extract and observe magnetic monopoles from ferromanganese pavement that was deposited at the bottom of the North Atlantic Ocean during the last 16 million years. The failure to observe poles sets new and restrictive limits on the abundance of monopoles and upon their production cross sections. For proton-nucleon collisions, the new cross sections are \( \leq 10^{-40} \text{ cm}^2 \) if the monopole mass is one proton mass \( m_p \), and \( \leq 2 \times 10^{-24} \text{ cm}^2 \) at 1000 \( m_p \).

Any magnetic charge up to 60 times Dirac's value of \( \hbar c/m^2 \) could have been detected. The flux of monopoles reaching the ocean floor is less than \( 4 \times 10^{-18} \text{ cm}^2 \text{ sec}^{-1} \) at the 90% confidence level, so that no portion of the cosmic-ray energy spectrum up to \( \approx 10^{16} \text{ eV} \) is composed dominantly of magnetic monopoles.

INTRODUCTION

Nearly four decades ago, Dirac suggested that the existence of free magnetic poles in nature would violate none of the laws of physics but would have the merit of symmetrizing Maxwell's equations and of providing some justification for the quantization of the electron through his relation

\[ g/e = \frac{\hbar}{2m} \left( \frac{e^2}{\hbar c} \right), \]

where \( e \) is the electronic charge, \( g \) is the magnetic pole strength, \( n \) is an integer, and \( e^2/\hbar c \) is the fine structure constant. Although Dirac's statements have never been successfully disputed, repeated searches for free magnetic poles in nature have been fruitless. Rather than attempting to list all previous searches, we refer to our recent work (Ref. 2, hereafter referred to as I) for a terse review. For \( n < 3 \) and hypothetical monopole masses \( m_p \) ranging up to three proton masses \( m_p \), the most restrictive limits on the production cross sections of monopoles have come from accelerator experiments; for \( m_p > 3m_p \), and also for \( n > 2 \), the most restrictive limits have come from I.

Disproving the existence of a hypothetical particle is inherently awkward, and consequently the job of the experimenter is to set limits as restrictive as possible on the existence of such an entity. In this work we lower all of the previous limits; for most conceivable monopoles, the decrease is by a factor of several thousand.

\footnotesize


HYPOTHESIS OF EXPERIMENT

As in I, we depend in this study on the very high energies available in the cosmic radiation to supply monopoles, either by producing monopole pairs through cosmic-ray interactions with the earth's atmosphere or possibly by being composed in part of primary (“cosmic”) monopoles. In either case, the poles are slowed down and thermalized in the atmosphere and the oceans, following which those having the appropriate polarity drift downward under the driving force of the geomagnetic field until they encounter solid material that is sufficiently magnetic to trap and store them.

In this experiment, material was then collected and exposed to high magnetic fields that are sufficient to extract magnetic poles and to accelerate them to energies adequate for detection in suitable solid detectors.

The justification that monopoles would act as we have just described and would have been detected in the device previously used (using solid track detectors and a pulsed magnet to extract monopoles) is given in detail in I and will be discussed further here only when differences in procedure or assumptions make added comments necessary.

MONOPOLE COLLECTOR

One major incentive for this experiment is the finding of material which (1) has been exposed to the ocean water for very long periods of time [and hence can supply a large (collecting area) \times (collecting time) factor] and (2) has grown unusually slowly (so that the area-time factor is compressed within a small volume of material). As in I, the material is a ferromanganese deposit taken from the deep ocean, material which we...
noted satisfies the requirement of being an efficient collector and storer of monopoles over geological time spans. The particular material used here, which comes from a depth of 2.7 km at a position 136 km west of the Mid-Atlantic ridge at 45°N (45°30'N, 29°34'W), was found as a result of a continuing oceanographic program by the Department of Energy, Mines, and Resources, Government of Canada. This ferromanganese crust is unique in that the time at which it began to form can be dated, and is, in fact, known to be 16.0 ± 0.8 million years ago. Since the crust used averages 2.5 cm in thickness, the average growth rate is remarkably slow, nearly a factor of 10^4 less than frequently observed sedimentation rates (10^-4 cm/yr for many pelagic sediments) and a factor of about 10 less than is thought typical for manganese nodules (references quoted in I).

In short, examining a 2.5-cm-thick bit of the crust used is equivalent to processing a 160-m column of ordinary sediment. At 298 K, our measurements on a sample of this material show a magnetic susceptibility of 1.3 × 10^-6 emu/g Oe superimposed on a weak ferromagnetic moment of 4 × 10^-5 emu/g, properties that are roughly similar to those of the previously studied nodules. As in I, such magnetic characteristics assure us that a monopole would be bound to this crust material with an effective field that is much larger than the earth's magnetic field and is sufficient to ensure that it would not be released—ever over geological times.

Since the age quoted is critical to calculating the extent of this search, a description of how it was measured is necessary, even though the details will be given elsewhere. Although the ferromanganese material itself can not be directly and reproducibly dated, it was found to have coated and thereby protected the basaltic glass which constituted the outer skin of a fresh pillow lava. Since such glass would be promptly attacked and hydrated by direct contact with ocean water, and thus destroyed, the fact that it still exists shows that deposition of the crust began very shortly after the pillow lava was formed. The glass was dated by the fission-track technique, for which the principles and techniques are familiar, and include work on closely similar basaltic glass. A favorable aspect of the conceivable errors in this dating technique is that it does not, in contrast to other dating procedures, give ages that are erroneously high. In short, the age of first formation of the crust is at least 16 ± 0.8 million years. Other evidence makes it clear also that the crust has been growing continuously and hence has not been covered up during any significant fraction of its lifetime.

**APPARATUS**

Two separate extraction and detection designs were used: The first was the pulsed-field device used and described in detail in I. This device employs a peak field of 265 kG but can process only 2.3 cm³ of material at a time. It was used in this study to examine 26.5 g of the available material. The second device employs a steady field of 104 kG from a superconducting solenoid, was designed to extract poles from 56 cm³ of material at a time, and was used to process 7.7 kg of material. Since the latter device is new, we now outline its mode of operation with reference to the drawing in Fig. 1.

The magnet surrounds a Dewar that allows direct access from above by the sample holder, which is lowered until the sample has a maximum field of 104 kG at the center—decreasing in either direction to 80 kG at the two ends of the sample. The detector array below is fixed in position during the experiment and consists, as in I, of a sequence of two Lexan polycarbonate and two Daicell cellulose nitrate 250-µ-thick sheets. In this

![Fig. 1. Steady-field device for extraction of magnetic monopoles, drawn with the sample in the fully lowered position. The field at the top and bottom of the sample is 80 kG, that at the center 104 kG. "Plastic detectors" in each case refers to a sequence from the sample of two 250-µ-thick Lexan polycarbonate sheets followed by two 250-µ Daicell cellulose nitrate sheets.](image-url)
case the detectors are shaped into truncated cones, with an additional sequence of detector disks in a recess to observe monopoles which pass through the space where the cones have been cut off. Further down the tube in a low-field region a 25-μ iron sheet acts as a catcher for downward moving monopoles, so that if tracks are found in the detectors the catcher can be used to recycle the monopoles.

In order to establish our efficiency in intercepting the paths of the accelerated monopoles with our detectors, trajectories were calculated for monopoles having magnetic charge-to-mass ratios ranging from $n/(m_e/m_p) = 12$ to 0.01. The inner diameter of the sample holder was specified by requiring that a monopole with $n/(m_e/m_p) = 12$ intercept the detectors if released from the inner radius of the sample holder at the 104-KG position in the magnet. If the above is true then all downward moving monopoles at $n/(m_e/m_p)<12$ will also be accelerated from the sample into the detector. The method and assumptions for calculating the monopole trajectories are given in the Appendix and in that of I.

Although the samples were obtained from 45°N lat, we expect that monopoles of both polarities would be present, since the earth's magnetic field is known to have reversed sign many times in the past. In fact, both direct and inferred measurements show that the "normal", i.e., present, polarity of the earth has obtained over less than half of the time for which we have a record. Direct age and magnetization measurements over the last 3.7 million years give 52% of the time reversed and 48% normal. Inferences based on the hypothesis of uniform ocean-floor spreading is which is surely wrong in detail as noted in Refs. 10 and 16 but is not an unreasonable approximation) implies 53% reversed and 47% normal over the last 16 million years. We shall assume the 52:48 ratio.

Because of the greater expected abundance of south-seeking monopoles, the polarity of the magnet was adjusted to accelerate them in the downward direction, where the detection efficiency is unity and the acceleration path would be generally longer and tracks more readily identifiable. Since north-seeking poles would be driven upwards, a second sequence of detectors plus catcher were positioned above the sample. Just above the sample we placed a thin retarding foil of iron which serves to hold upward moving poles and ensure that they are not released and accelerated towards the detectors until the trapping field is at 50-70 KG is reached. A similar arrangement was used in I and its function is described in greater detail there. The ranges in the detector of the north-seeking poles as a function of pole strength $n$ are approximately 90% of the values given in Table II of I, which applies directly to the present results using the pulsed-field device.

The efficiency for trapping and detecting north-seeking poles is less than unity because of their possible radial migration in the granular ocean-bottom material. As it is lowered into the region of field at which poles are loosened, they can migrate from particle to particle along field lines, which have a radial component. At 17 KG (the calculated trapping field for the most magnetic of minerals) we calculate the efficiency to be 31%; at 0.1 KG (the calculated value for the paramagnetic component of the material used) the value is 56%. For purposes of describing the extent of our search we select 31% as a conservative value. The over-all efficiency is therefore $(1.0\times0.52)+ (0.31\times0.48) = 0.67$.

The ranges of the south-seeking poles will be a function of their position in the magnet at the moment of release from the sample holder, but in no case will the ranges be less than those calculated assuming the holder to be in its fully lowered position. Those ranges are given in Table I. We expect to be able to recognize the track for any pole strength up to 30 $hc/e$.

In the case of the steady-field device, the fields of 80-104 KG are significantly less than the 265 KG of the pulsed-field device. Even so, the minimum field of 80 KG provides 40 eV per atom distance moved by an $n=1$ monopole. As has been discussed earlier, this force is more than adequate to extract a monopole even if it is bound to an atomic nucleus within the sample. If Schwinger is correct in inferring a magnetic charge of $2hc/e$, the energy gain would be a minimum of 160 eV.

<table>
<thead>
<tr>
<th>Magnetic charge ((hc/2e))</th>
<th>Range ((10^{-4} \text{ cm}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2850</td>
</tr>
<tr>
<td>2</td>
<td>1425</td>
</tr>
<tr>
<td>3</td>
<td>950</td>
</tr>
<tr>
<td>4</td>
<td>713</td>
</tr>
<tr>
<td>6</td>
<td>475</td>
</tr>
<tr>
<td>12</td>
<td>238</td>
</tr>
<tr>
<td>48</td>
<td>60</td>
</tr>
<tr>
<td>120</td>
<td>24</td>
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</tbody>
</table>

- Holder assumed to be in its lowered position; range assuming that the trajectory is to the nearest point on detectors.
- Density 1.2 g/cm² assumed, appropriate to Lexan polycarbonate.

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(atom distance), and an even greater margin of safety obtains.

**EXPERIMENTAL PROCEDURE**

We processed 7.73 kG of ~16 million year old ferromanganese crust in these experiments. Of this material, 26.5 g were cut or broken into pieces and processed in the pulsed-field device using a series of 11 separate loadings and 265-kG pulses. The remaining 7.7 kg were crumbled with the aid of distilled water, dried in air at room temperature, and exposed in a series of 147 separate loadings to the steady fields of up to 104 kG in the steady-field device. The detectors were processed using known etching procedures: 4 days in stirred 23° 6.25 NH solution for the Daicell and 2 days at 23° in 50% ethanol: 50% NaOH 6.25 NaOH solution for the Lexan, for which etching was begun 5 days after the magnetic processing of the manganese crust. At the same time we etched a control sample of Lexan polycarbonate from the same sheet of material, a control sample that had been irradiated with fission fragments from a Cf$^{252}$ source. Detectors were subsequently scanned in a stereoscopic microscope at 25X and 50X and in a Leitz Ortholux microscope at 65X. Under all three conditions tracks from the (~18 μ long) fission tracks in the control sample were readily visible, whereas the tracks of a group of three relativistic cosmic-ray nuclei identified by Lexan detectors to be of charge 68 and 69. Such particles have a primary ionization equivalent to that of an energetic n = 1 monopole and hence provided useful guides to the nature of the tracks we were seeking and their visibility under the etching conditions used.

Since the lower detectors could have been at temperatures well below room temperature during the experiment, the following procedure was followed to establish whether particle registration was significantly altered by a low-temperature environment. One Lexan polycarbonate sample was irradiated with Cf$^{252}$ fission fragments while held at 4.2° K, and another was irradiated at 295° K. During etching, tracks lengthened at the same rate in both samples and no differences could be noted between the two samples.

**RESULTS**

No tracks of any particle were seen. The background was zero.

**DISCUSSION**

Table II indicates the (area) x (time) factors for these experiments and I, the preceding most extensive one that has been published. Our final value of 4.9 x 10$^{-16}$ monopoles/cm$^2$ sec is a factor of 2000 greater than that of I. Since that work set a 90% confidence limit of < 8.4 x 10$^{-16}$ monopoles/cm$^2$ sec, the new 90% confidence limit (calculated using Poisson statistics as described by Amaldi et al.) is 4.2 x 10$^{-18}$/cm$^2$ sec or a flux of < 1.3 x 10$^{-18}$/cm$^2$ sec. This result contradicts Porter’s suggestion that the cosmic rays above 10$^{17}$ eV might be monopoles that have been accelerated to very high energies by the galactic magnetic fields. For our results to be consistent with Porter’s hypothesis would require a statistical fluctuation of 100 standard deviations; or, if only poles above 10$^{18}$ eV were assumed to be monopoles, seven standard deviations, or one standard deviation at 10$^{19}$ eV. We conclude that at energies below 10$^{19}$ eV cosmic rays are not dominantly monopoles.

**Note added in proof.** More recent measurements of the cosmic-ray spectrum above 10$^{18}$ eV [see D. Andrews et al. and R. G. Brownlee et al., Acta Phys. Acad. Sci. Hung. (to be published)] show a flux that is a factor of 3 to 6 times the previously quoted numbers, so that we have in effect searched the cosmic rays up to 2 to 3 x 10$^{19}$ eV.

![Fig. 2. Calculated 90% confidence limits, as a function of monopole mass, for the maximum cross section for monopole pair production by nuclear interactions in the upper atmosphere. On the right are given the number of primary interactions sampled and the energy of the interacting cosmic-ray particles.](image-url)
The above result re-emphasizes the problem of the high-energy cosmic-ray particles, which are thought to be dominantly protons\(^{23}\) rather than complex nuclei or lighter particles. If they are protons, their minimum radii of curvature in galactic magnetic fields are so large in comparison to galactic dimensions as to suggest that they are of extragalactic origin. The magnetic monopole was one possible loophole to this inference that is no longer available.

We can use our results, as in I, to set upper limits on monopole cross sections. We use the known flux of cosmic rays as a function of energy and the (area) \(\times\) (time) factor from this search to calculate the number of monopole pairs, each of mass \(M\), which could be created by nucleon-nucleon collisions occurring as the cosmic rays impinge on the earth's upper atmosphere. Figure 2 gives the calculated cross-section limits as a function of monopole mass. It also indicates the cosmic-ray energies needed to create these masses and the number of nucleon-nucleon interactions which could have supplied monopoles to the material we have tested.

A few words of caution should be added with respect to the cross sections at very high monopole masses. We have assumed that the very-high-energy cosmic rays are dominantly protons. In the unlikely\(^{22}\) circumstance that these particles are complex nuclei, a \(10^{19}\) eV particle, which may be an iron nucleus for example, could alternatively be described as 56 nucleons each of \(\sim 2\times10^{17}\) eV. If so, the cross section for the 70,000 \(M\) poles (which would require a single incident particle \(10^{19}\) eV for creation) has in fact not been tested and that of 10,000 \(M\) poles (which require \(2\times10^{17}\) eV) should be correspondingly even lower than we have calculated.

At lower energies, where this ambiguity with respect to cosmic-ray composition is not significant, this work has lowered the cross-section limits below those previously set by accelerator searches\(^{2}\) by a factor of about 200 at \(M = M_p\) and of about 5 at \(M = 3M_p\), which is the present mass limit from accelerator experiments. The preexisting cross sections along with the present ones for \(M = 3M_p\) are listed in the last column of Table II. The limit we have now set at \(M_p = 10m_p\), a mass that will be accessible by the next generation of high-energy accelerators, is roughly at the level set for lower masses by previous accelerator searches.\(^{3}\)

Figure 3 shows that the charge and mass region which was assessed in this experiment is extensive. Virtually the whole domain of Fig. 3 has been assessed in seeking monopoles from upper atmospheric interactions, and only the region above the "\(10^{19}\) eV" line is not included in seeking cosmic monopoles of energy up to \(10^{19}\) eV.

CONCLUSIONS

Subject to the assumptions stated or referred to earlier, the mass-charge limitations given in Fig. 3, and an absolute upper limit on the charge of \(30h\gamma/e\), we conclude the following.


