Rocks, Liquids, and Monopoles

H. Kolm, Chairman

Magnetic Monopoles: Where Are They and Where Aren’t They?

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The existence of isolated magnetic charges (monopoles) in nature would require profound rethinking not only in elementary particle physics but also in high-energy cosmic-ray physics and astrophysics. Monopoles, whose possible existence was first suggested by Dirac in 1931 and whose properties were later recalculated by Schwinger, would be intensely ionizing particles similar in their effects in passing through matter to relativistic rare-earth ions (or still heavier nuclei). As Parker has noted, only a very minute abundance of monopoles in the galaxy would be necessary to have removed or at least grossly altered the galactic magnetic field on an astrophysically interesting time scale. Solid-state nuclear track detectors have led to a new series of intensive monopole searches: One of these takes ferromanganese deposits from the deep oceans (as a material which would have magnetically trapped monopoles) and exposes them to high magnetic fields sufficient to loosen monopoles and accelerate them into a detection system; the other experiment is designed to utilize natural detectors (mica and obsidian) to record over geological times the paths of massive, penetrating monopoles. The negative results obtained set new and highly restrictive limits on the abundance of monopoles. These limits are such that the mysterious, high-energy cosmic rays (10^17–10^18 eV) cannot be monopoles as has been suggested, nor can the galactic magnetic fields be seriously altered by the maximum permitted abundance—even over the galactic age. Finally, the flux of monopoles onto the earth over the earth’s entire age is < 1 monopole/cm^2. Qualifications on these claims are indicated in the article.

INTRODUCTION

The reader will recognize that, of the two questions raised in the title, one is at present unanswerable and the other can best be responded to by a series of guarded and carefully worded statements, some of which we will review here. It is perhaps more useful to raise two other questions, one that we can answer.

Do we know whether magnetic monopoles exist or not? Does it matter whether they exist? To each of these questions we give an unambiguous answer: no to the first, yes to the second. The yes answer to the second question has led in recent years to increasingly frequent and intensive searches for free magnetic poles. As we shall see, there are good reasons not only to decide whether they exist or not but also to specify the most restrictive limits possible on their abundance. The purpose of this paper is to summarize the present limits and to describe how they have been set. Major emphasis will be placed on those recent results which have set the most restrictive limits. However, the normal trend of events is such that it can safely be assumed that the future will see new and still more stringent limits set as the means to do so are devised.

WHY MONOPOLES?

Dirac in 1931 gave three reasons for the possible existence of monopoles, reasons that are still valid.1

1. Monopoles would lend symmetry to Maxwell’s equations by allowing the magnetic charge density to appear along with the electrical charge density. (2)

They are forbidden by no law of physics.2 (3) They would explain the quantization of electric charge \( e \) through the relation

\[
g/e = n(hc/2e),
\]

where \( n \) is an integer, \( h \) is Planck’s constant divided by \( 2\pi \), \( c \) is the velocity of light, and \( g \) is the magnetic charge of the monopole. What is commonly referred to as a “Dirac monopole” has \( n = 1 \) although clearly larger integers were permitted by Dirac. Work by Schwinger has led to inferred values of \( n = 2, 4, \) and 12 for free magnetic poles,3,4 so that in seeking monopoles the worker is taking risks if he designs experiments to observe only poles of Dirac’s original minimum pole strength.

Most recently, Schwinger has suggested that the existence of unpaired magnetic poles as dyons, particles having both electrical and magnetic charge, would answer the origin of the bewildering array of “elementary” particles and their groupings.4 They could also explain the observed weak violation of CP symmetry. Since such particles would be observed in virtually all experiments designed to detect purely magnetic particles, we can readily include them in our discussion of monopole searches.

MONOPOLE PROPERTIES

The known, rigorously calculable properties of monopoles stem from the magnetic charges given by Eq. (1). A detailed survey of calculated properties is beyond the

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scope intended for this article, but three properties that will be referred to here are these: (1) By analogy to an electrical charge's attraction to a dielectric material, a magnetic charge is magnetostatically tightly bound to ferromagnetic or paramagnetic matter and can therefore be stored for considerable periods of time. (2) A magnetic field accelerates a monopole with a force $gH$, so that it gains energy at a rate of roughly $20n$ MeV/kG·cm. In moving an atom distance in a 100 kG field, a monopole thus gains a minimum of 45 eV—more than the energy needed to displace an atom from its lattice site—and can therefore be removed from matter under suitable conditions. (3) Fast moving monopoles are heavily ionizing particles, equivalent in their ionization to relativistic atomic nuclei of atomic number 68.5$n$ (an energy loss of $8n^2$ GeV/g/cm$^2$ of matter traversed). We can use this property to understand the slowing down of monopoles and to specify appropriate detection methods. There is no direct theory of what the monopole mass should be.

HYPOTHESES OF MONOPOLE EXPERIMENTS

Monopole experiments have usually been built around the assumption that sufficiently high-energy interactions of particles with matter would produce monopole pairs, which could either be directly observed in flight or slowed down and later accelerated into a detector system. This general hypothesis has many variants.

(1) Accelerator searches are the most direct of those involving interactions. Particles of known energy and trajectory are fired at a target. The particles created in the resulting nuclear interactions have in some cases been looked for by placing detectors down stream next to the beam or in other cases placing a thermalizing and/or trapping medium down stream. A magnetic field is then used to guide monopoles and to accelerate them into detectors that are well removed from interference generated by the particle beam. A summary of the results of such experiments is given in Table I. This table indicates that extremely low cross sections ($<10^{-40}$ cm$^2$) have been set for monopole production, but that the available energies of accelerator particles limit the monopole mass (in terms of the proton mass $m_p$) to $<3m_p$. If the true mass were greater than $3m_p$, the accelerators used so far could not have produced a monopole pair. Similarly, the charge region to which the cross section limits apply has been limited by the detection systems. The limits are good for $n=1$, $n=2$, and in some cases possibly for $n=3$ but surely not for the higher values $n=4$, 6, or 12 that might obtain if quarks exist and if Schwinger's ideas apply.

(2) Searches for monopoles in nature are the other possible route to finding monopoles. Most of the studies in this category attempt to utilize the particle energies of the cosmic radiation, which extend nearly ten orders-of-magnitude above those which have been used in accelerator studies. Figure 1 shows the cosmic-ray spectrum as understood at present. Particles of energies extending up to $2\times 10^{20}$ eV have now been observed so that in principle monopoles of rest mass $>100,000m_p$ could have been produced by nuclear interactions. The problem is that of locating the products of such extremely rare interactions and doing so in such a way as to be able potentially to observe the effects of as many of the highest-energy cosmic rays as possible. A total collecting power of $\sim 10^{14}$ cm$^{2}$ sec represents a critical value since Fig. 1 shows that above that number $n=3$ but surely not for the higher values $n=4$, 6, or 12 that might obtain if quarks exist and if Schwinger's ideas apply.

In Table I. Accelerator searches for monopoles.

<table>
<thead>
<tr>
<th>Study by</th>
<th>Energy (GeV)</th>
<th>Number of protons</th>
<th>Max. monopole mass* (proton masses)</th>
<th>Production cross sections quoted by authors (confidence limit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brander and Isbell$^b$</td>
<td>6.3</td>
<td>$5\times 10^{13}$</td>
<td>1.1</td>
<td>$2\times 10^{-30}$ cm$^2$</td>
</tr>
<tr>
<td>Amaldi et al.$^e$</td>
<td>25-28</td>
<td>$4.5\times 10^{10}$</td>
<td>3.0</td>
<td>$6\times 10^{-31}$ cm$^2$ (95%)</td>
</tr>
<tr>
<td>Fidecaro et al.$^d$</td>
<td>27.5</td>
<td>$4.5\times 10^{14}$</td>
<td>3.0</td>
<td>$10^{-36}$ cm$^2$</td>
</tr>
<tr>
<td>Purcell et al.$^*$</td>
<td>30</td>
<td>$6\times 10^{10}$</td>
<td>3.0</td>
<td>$1.4\times 10^{-4}$ cm$^2$ (86%)</td>
</tr>
</tbody>
</table>

$^a$ Maximum detectible charge $\sim 3 (\hbar c/2e) or less.

$^b$ Reference 11.

$^c$ References 9 and 10.

$^d$ Reference 12.

$^e$ Reference 7.
The new search has three vital features: (1) It used well-dated\textsuperscript{22} ferromanganese deposits from the ocean bottom. This is material [Fig. 3(a)] for which we had measured the relevant magnetic properties, and we knew that it had been in direct contact with the ocean during 16 million years\textsuperscript{22} so that it would have stored all monopoles that had come to thermal velocity before reaching it. (2) We had available high field magnets that could go to fields extending from 100 to 265 kG, fields that should be more than adequate to extract monopoles from solids.\textsuperscript{7,18} (3) We utilized solid-state track detectors, which have the virtue of responding only to highly ionizing particles such as magnetic monopoles, so that only a short length of track (\(>30\mu\)) would have been necessary to give a totally distinctive and identifiable signal.\textsuperscript{23} This last feature has allowed this search to extend to charges 120 times that of the Dirac monopole and roughly 40 times those that would have been observable in the earlier experiments we have involved, such monopoles would either \(\text{[as in Fig. 2(b)]}\) be slowed to thermal velocities and trapped (or ejected into space if they are of the wrong sign) as in Fig. 2(a)\textsuperscript{17b}; or they would be so penetrating as to bury themselves deep within the earth where they would be inaccessible \(\text{[Fig. 2(c)]}\)\textsuperscript{18}.

In the earliest studies based on a model such as that shown in Fig. 2(a), Malkus\textsuperscript{20} used a magnetic coil of the proper polarity as to "gather in" the earth's magnetic field lines, along which thermalized monopoles would drift. In this way the effective area of the coil for receiving monopoles could be greatly enhanced over the geometric area (in a more recent, similar, but scaled-up experiment\textsuperscript{7,19} \(\approx1/7\) m\(^2\) coil was used to collect field lines from an area of 1600 m\(^2\)). The magnet in such an experiment serves also as an accelerator and focusing device so that a detection system, which in both cases has included nuclear emulsions, can be placed at the focus.

In a related type of experiment, Goto, Kolm, and Ford\textsuperscript{4} sought out a magnetite outcrop in the Adirondacks, a site where monopoles would have been trapped throughout the time during which the outcrop had been exposed; they then used a pulsed high field magnet in an attempt to extract and accelerate monopoles into a set of nuclear emulsions.

**THE NEW SEARCHES**

Two complementary sets of searches done by the authors have set limits on monopole abundance that are several orders-of-magnitude more restrictive than existed previously, limits which test the effects of cosmic rays through most of what we noted earlier was a critical energy range above \(10^{17}\text{ eV}\).\textsuperscript{6,18,21}

Part I of these searches\textsuperscript{6-13} utilizes the earlier rationale\textsuperscript{6-17a} for searching the ocean bottom for monopoles.
Fig. 3. Potential monopole trapper and track recorder. (a) Magnetic ferromanganese crust accumulated at the bottom of the North Atlantic Ocean during a 16-million-year time span. (b) North Carolina Muscovite mica that has stored particle tracks for 248-million years.
discussed here. Figure 4 shows what a Dirac monopole track would have looked like in the two detectors used in this study. This bit of control data comes from a high-altitude balloon flight in which we were seeking heavy cosmic-ray particles. Although in principle this track could be from a Dirac monopole, we have, in fact, no reason to doubt that it is merely a relativistic cosmic ray nucleus of atomic number close to $(\hbar c/2e^2)$. These
**Magnetic Monopoles**

**Table II.** Collecting powers of experiments which utilize the high energies of cosmic rays.

<table>
<thead>
<tr>
<th>Method</th>
<th>(area) X (time) factors</th>
<th>Charges detectable ((\text{ke}/2\text{e}))</th>
<th>Maximum mass* (proton masses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic collection from atmosphere(^b)</td>
<td>(10^{10})</td>
<td>&lt;1 to (~3)</td>
<td>(10^4)</td>
</tr>
<tr>
<td>Magnetic collection from atmosphere(^c)</td>
<td>(6.9 \times 10^{10})</td>
<td>&lt;1 to (~3)</td>
<td>(7 \times 10^4)</td>
</tr>
<tr>
<td>Extraction from magnetic outcrop(^d)</td>
<td>(3 \times 10^{22})</td>
<td>&lt;1 to (~3)</td>
<td>(4 \times 10^4)</td>
</tr>
<tr>
<td>Extraction from deep ocean sediment(^e)</td>
<td>(\sim 4 \times 10^{14})</td>
<td>(~\frac{1}{2}) to 220</td>
<td>(4 \times 10^4)</td>
</tr>
<tr>
<td>Extraction from Mn nodule(^g)</td>
<td>(2.8 \times 10^{14})</td>
<td>&lt;1 to 120</td>
<td>(1.3 \times 10^9)</td>
</tr>
<tr>
<td>Extraction from Mn crust(^h)</td>
<td>(4.9 \times 10^{14})</td>
<td>&lt;1 to 60</td>
<td>(1.3 \times 10^9)</td>
</tr>
<tr>
<td>Stored tracks in minerals(^i)</td>
<td>(2.3 \times 10^{14})</td>
<td>2 to (\infty)</td>
<td>(2 \times 10^6)</td>
</tr>
<tr>
<td>Stored monopoles in Apollo 11 soil(^j)</td>
<td>(4.3 \times 10^{14})</td>
<td>&lt;1 to (\infty)</td>
<td>60 to 300</td>
</tr>
</tbody>
</table>

* Set by energy of most energetic cosmic ray sampled. In the first four studies focusing requirements may further limit the masses.

\(^b\) Reference 20.

\(^c\) Reference 13.

\(^d\) Reference 5.


\(^f\) See caution in discussion section in Ref. 19.

\(^g\) Reference 6.

\(^h\) Reference 19.

\(^i\) Reference 21.


Monopole experiments assess the cases depicted in Figs. 2(a) and (b) in which monopoles are brought to thermal velocities before they are recovered and detected.

Part II of our searches\(^{21}\) tested the logical alternative shown in Fig. 2(c)—that monopoles penetrate to great depths into the earth. Here, we cannot hope to collect the monopoles themselves, but we can make use once again of the unique properties of solid state track detectors—track detectors that exist in nature such as mica and obsidian. The two properties are (1) (as noted before) that they ignore lightly ionizing radiation, so that only events of interest would be seen and (2) that they will store tracks over long periods of time. We know this second property obtains because we have shown that a count of the stored tracks from spontaneous fission of uranium-238 allows one to date natural minerals and glasses,\(^{25}\) giving the period of time that we wish to know—the track storage time. For this study, we used micas that we found\(^{21,26}\) have retained tracks over the last 185 to 355 million years and an obsidian that has retained tracks over 32 million years.\(^{27}\) Since we were seeking penetrating monopoles, any candidate for a monopole track was required to traverse the whole sample and hence would have been totally distinct from the short (\(~15-\sim15\mu\) long) tracks used to measure the track storage time. Figure 3(b) is a photograph of a 248-million-year-old mica used in this study.

Figure 5 indicates the mass and charge domains surveyed by our two searches. The areas do overlap, but they also make obvious the unshaded area, a loophole that is unassessed. Because neither mica nor obsidian would record tracks of monopoles with \(n=1\), the possibility remains that monopoles have Dirac's minimum pole strength, mass \(>150m_p\), and that they arrive at the earth solely as cosmic rays of energy \(>10^7\) eV. This possibility has not been tested in our experiments nor in any of which we are aware. No cosmic-ray experiments now in progress remotely approach the collecting power of \(\geq 10^{22}\) cm² sec that is needed in this charge and mass range.

Although there has been no theoretical justification given, the logical possibility exists that monopoles have a magnetic charge that is less than the value allowed by Dirac's and Schwinger's theories. Our deep sea searches would not have revealed monopoles of charge less than \(\frac{1}{2}\) of Dirac's minimum; and as noted in Fig. 5, our fossil track search would not have seen charge 1 monopoles.

Table II indicates some of the relevant accomplish-
ments of the various experiments that attempt to use the cosmic rays as monopole sources. We have added where available results from searches still in progress, or ones which are ended but for which complete details have not been published. For this reason, some of the numbers and limitations are either approximate, or lacking. One of these, whose beginning predates our deep sea study, uses a 150 kG solenoid to extract monopoles from deep ocean sediment.

A second way of evaluating searches for monopoles in nature consists of asking what the concentration of monopoles is in various forms of matter. Table III summarizes results which will be of interest later. Similarly we could use the flux limits quoted in Table II to give limits on the concentration of monopoles in space. The limits set in Refs. 19 and 21 are < 1.7 × 10^{-29}/cm^3.

**DISCUSSION**

*Collapse of magnetic field by monopole flow.* Parker has pointed out that monopole motion in a fluid containing a magnetic field would in time cancel out that field. It is interesting to examine whether our new limits restrict this possibility for either geophysical or astrophysical magnetic fields.

Parker equates the energy dissipation \( J \cdot B \) by the magnetic current \( J = N_s g v \) \( (N_s \) = number of monopoles/cm^3, \( v \) = velocity of motion) to the rate of energy loss \(-d(B^2/8\pi)/dt\) by the magnetic field. For \( v = \) constant and \( v \) parallel to \( B \), one finds the time \( t \) for total decay of a field is
\[
t = B/(4\pi N_s g v).
\]

Monopoles in space will rapidly approach the velocity of light \( c \), so that we can replace \( v \) by \( c \) in Eq. (2), use our limit for \( N_s \), and the current best estimate of galactic fields \( 2 \times 10^{-6} \) G. The conclusion is that the time for total decay of the magnetic field is 300/n billion years.

For all plausible values of \( n \) (1 to 12) this time is large relative to the age of the galaxy. In short, the results do restrict models of the origin of magnetic fields in that they do not permit the magnetic fields of the galaxy to have decayed by monopole motion. These results are consistent with the possibility that the galactic fields pre-existed the formation of the galaxy.

With equal validity we can say that neither the solar nor terrestrial magnetic fields have been importantly altered over the age of the solar system by monopoles arriving from space. As to motion of primordial monopoles that may be trapped within the earth’s core, we have no direct information, the most useful information being the data given in Table III. Although none of the materials examined has the identical history to that of the earth’s core, iron meteorites are thought to be of the same composition and a somewhat similar history. Using the value of \( N_s \) for the iron meteorite in Table III, \( B > 1 \) G, and even with \( v = c \), an obvious overestimate, it becomes clear that within the earth’s core (if it is of the composition of meteorites) we are not even
close to being able to say whether monopoles have ever seriously altered the earth’s magnetism.

Validity of the limits. Our newest limits if taken at face value are highly restrictive indeed. They tell us that on the average less than \( \frac{1}{3} \) monopole/cm\(^2\) has fallen on the earth over its entire \( 4.6 \times 10^9 \) year age, that none of the cosmic rays at least up to \( 3 \times 10^{19} \) eV in energy are monopoles, and that the cross sections for production of free monopoles by nuclear interactions lie below \( 10^{40} \) cm\(^2\) over the whole monopole mass range presently accessible to particle accelerators. It is in order at this time to ask how firmly these statements can be made and whether they rule out monopoles. We have discussed in some detail where the assumptions lie and how restrictive they are; we inferred that the conclusions stated above are highly unlikely to be wrong but that it is impossible to rule out the possibility that some as yet unidentified critical physical assumption was in error.

Rather it appears much more likely that if monopoles exist, they are so rare that we have not yet been able to find them. As we noted earlier, cosmic monopoles of charge \( hc/2e \) and mass \( > 150m_p \) could exist and not have been detected. And equally it may be that monopoles can be produced by nuclear interactions but that the production cross sections are lower than the existing limits.

Although we who have done the most restrictive studies so far would like to believe we have set limits that will be difficult to improve upon, the trend of history is against us. Figure 6 shows the progress over time to higher energies and (as inferred from Fig. 1) to rarer particles as the cosmic rays have been tested for monopoles or monopole creation through interactions. The dangers of extrapolation of graphs such as this are well known, and the temptations great; we merely conclude that the search for magnetic monopoles is by no means ended.

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This reason is particularly relevant if Gell-Mann’s statement is valid that what is not expressly forbidden is “obligatory.”


