

## Search for Tracks of Massive, Multiply Charged Magnetic Poles

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Massive magnetic monopoles of charge  $\geq \hbar c/e$  (twice Dirac's value of the minimum pole strength and half of Schwinger's) would leave tracks in natural minerals, provided they arrive at the earth with sufficient energy. In order to test Porter's hypothesis that the cosmic-ray particles of energy  $> 10^{17}$  eV are (or include) magnetic monopoles, samples of mica and of obsidian have been scanned for the distinctive, long particle tracks which would have been stored over geological times. The failure to find monopole tracks sets an upper limit (90% confidence) of  $1.2 \times 10^{-19}$  monopoles per  $\text{cm}^2$  sr sec for penetrating monopoles incident upon the earth and rules out Porter's hypothesis for the charge and mass range within which poles would have been detected.

### INTRODUCTION

THE suggestion, made in 1931 by Dirac,<sup>1</sup> that free magnetic poles of strength  $n\hbar c/2e$  might exist in nature ( $n$  is an integer,  $e$  is the minimum electrical charge in nature, normally assumed to be the charge of the electron, and  $\hbar$  and  $c$  have their usual meanings) has led to many searches,<sup>2-10</sup> but to no evidence for any monopoles. In most of the searches,<sup>2-7</sup> the assumption was made (tacitly or otherwise) that the value  $n=1$  was to be expected; consequently, most of the detector systems were so designed that poles of  $n>2$  would very likely not have penetrated sufficiently to have been recorded and recognized.

Schwinger, in a pair of papers,<sup>11</sup> has twice come to the conclusion that  $n$  must be at least 4. It has also been noted<sup>7</sup> that if quarks exist, the minimum electrical charge in nature is one-third the electronic charge, from which it follows that  $n$  is at least 3. Hence values of  $n=3, 4,$  and  $12$  are well worth examining. With these possibilities in mind, we previously<sup>9,10</sup> used a detector system designed for values of  $n$  ranging from 1 up to 120 to seek poles that might have been stored in magnetic materials at the ocean bottom. The present search extends to much higher possible monopole masses than could have been collected in the previous experiments.

<sup>1</sup> P. A. M. Dirac, Proc. Roy. Soc. (London) A133, 60 (1931); Phys. Rev. 74, 817 (1948).

<sup>2</sup> W. V. R. Malkus, Phys. Rev. 83, 899 (1951).

<sup>3</sup> M. Fidecaro, G. Finocchiaro, and G. Giacomelli, Nuovo Cimento 22, 657 (1961).

<sup>4</sup> E. Amaldi, G. Baroni, H. Bradner, H. G. deCarvalho, L. Hoffmann, A. Manfredini, and G. Vanderhaeghe, in *Comptes Rendus de la Conférence Internationale d'Aix-en-Provence, sur les Particules Élémentaires, 1961*, edited by E. Cremieu-Alcan et al. (Centre d'Etudes Nucleaires de Saclay, Seine et Oise, 1961), p. 155; Nuovo Cimento 28, 773 (1963).

<sup>5</sup> E. M. Purcell, G. B. Collins, T. Fujii, J. Hornbostel, and F. Turkot, Phys. Rev. 129, 2326 (1963).

<sup>6</sup> E. Goto, H. H. Kolm, and K. W. Ford, Phys. Rev. 132, 387 (1963).

<sup>7</sup> W. C. Carithers, R. Stefanski, and R. K. Adair, Phys. Rev. 149, 1070 (1966).

<sup>8</sup> L. L. Vant-Hull, Phys. Rev. 173, 1412 (1968).

<sup>9</sup> R. L. Fleischer, I. S. Jacobs, W. M. Schwartz, P. B. Price, and H. G. Goodell, Phys. Rev. 177, 2029 (1969).

<sup>10</sup> R. L. Fleischer, H. R. Hart, Jr., I. S. Jacobs, P. B. Price, W. M. Schwarz, and F. Aumento, preceding paper, Phys. Rev. 184, 1393 (1969).

<sup>11</sup> J. Schwinger, Phys. Rev. 144, 1087 (1966); 173, 1536 (1968).

### HYPOTHESES FOR MONOPOLE PRODUCTION

Since the means by which monopoles could have reached the ocean bottom and have been trapped are relevant to this work also, we will now outline the two hypotheses that have been suggested.

One possibility was suggested by Porter<sup>12</sup> as a way to avoid explaining the observed cosmic rays of energy  $10^{17}$ – $10^{20}$  eV as extragalactic rather than galactic in origin. His suggestion is that these cosmic rays are magnetic monopoles, which one can readily show would be accelerated to the extremely high energies of interest.<sup>12,13</sup> Upon reaching the earth, such poles would require large thicknesses of stopping material to bring them to rest. For this purpose the trapping experiments utilized the oceans.<sup>9,10</sup> Not all conceivable monopoles, however, would be stopped. If sufficiently massive (mass enters because the energy loss is primarily by bremsstrahlung, as discussed by Bauer<sup>14</sup> and elaborated in Ref. 9), poles would penetrate the ocean floor and therefore not be trapped there. Figure 1 indicates (by diagonal shading) the region of possible mass and charge that was previously searched,<sup>9,10</sup> leaving the rest of the mass-magnetic-charge domain unassessed. The regions of

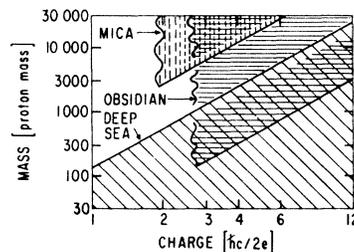


FIG. 1. Mass and magnetic-charge domains that have been searched for cosmic monopoles of  $10^{17}$  eV. Diagonal shading: region covered by deep-sea searches (Refs. 9 and 10); vertical shading: region covered by mica experiments discussed here; horizontal shading: region covered by obsidian experiments discussed here. Note that, as discussed in Ref. 24,  $n=z$  monopoles should be detected in obsidian with an efficiency of 0.2.

<sup>12</sup> N. A. Porter, Nuovo Cimento 16, 958 (1960).

<sup>13</sup> E. Goto, Progr. Theoret. Phys. (Kyoto) 30, 700 (1963).

<sup>14</sup> E. Bauer, Proc. Cambridge Phil. Soc. 47, 777 (1951).

mass charge which we assess in this study are also given in Fig. 1 (horizontal and vertical shading).

Another hypothesis for monopole procurement consists of noting that cosmic rays, whatever their composition, will interact with nuclei in the earth's upper atmosphere, producing monopole north-south pairs, which—given enough stopping material—will come to thermal energies and can subsequently be trapped. Again, the ocean should be a useful stopping material, but, as indicated in Fig. 2, there remains a mass-charge region for magnetic poles such that they would penetrate the ocean bottom at high velocity and hence not be trapped there.

### HYPOTHESIS OF EXPERIMENT

If, for the sake of analysis, one accepts that the assumptions of the previous work were correct and that therefore no measurable monopole flux is moving slowly enough to allow trapping at the ocean bottom, there remains one positive alternative. It is that monopoles are sufficiently massive that they penetrate the ocean bottom and stop only well within the earth. The problem of locating such monopoles is probably insurmountable since they would be dispersed throughout the earth, rather than accumulated at accessible sites.

The problem of detecting their passage, however, is soluble, since moving monopoles are highly ionizing particles<sup>14</sup> whose passage would have been recorded in natural samples over vast periods of geological time. Most nonconducting natural minerals and glasses are solid-state nuclear-track detectors,<sup>15</sup> which record only the tracks of particles that produce damage above a discrete level of primary ionization.<sup>16</sup>

In short, a piece of mica or obsidian would record monopole tracks (provided  $n \gtrsim 2$  for mica and obsidian<sup>17</sup>) over the entire geological time since the sample was last heated to a temperature where tracks would anneal out. A critical question is what that length of time is. Fortunately, there exist other, distinctive, short, straight, randomly oriented tracks from the fission of  $U^{238}$  that are the basis for a method of dating natural minerals<sup>18–22</sup> which gives just the age required<sup>19</sup> and can be used both for micas<sup>20,21</sup> and for natural glass samples.<sup>22</sup>

<sup>14</sup> R. L. Fleischer, P. B. Price, and R. M. Walker, *Science* **149**, 383 (1965); *Ann. Rev. Nucl. Sci.* **15**, 1 (1965).

<sup>15</sup> R. L. Fleischer, P. B. Price, R. M. Walker, and E. L. Hubbard, *Phys. Rev.* **156**, 353 (1967).

<sup>17</sup> R. L. Fleischer, P. B. Price, R. M. Walker, and M. Maurette, *J. Geophys. Res.* **72**, 331 (1967); the value of  $n \geq 2$  quoted there for meteoritic crystals should read  $n > 2$ .

<sup>18</sup> P. B. Price and R. M. Walker, *J. Geophys. Res.* **68**, 4847 (1963); R. L. Fleischer and P. B. Price, *Geochim. Cosmochim. Acta* **28**, 1705 (1964).

<sup>19</sup> R. L. Fleischer, P. B. Price, and R. M. Walker, *J. Geophys. Res.* **70**, 1497 (1965).

<sup>20</sup> R. L. Fleischer, P. B. Price, E. M. Symes, and D. S. Miller, *Science* **143**, 349 (1964).

<sup>21</sup> M. Maurette, P. Pellas, and R. M. Walker, *Bull. Soc. Franc. Mineral. Criet.* **87**, 6 (1964).

<sup>22</sup> (a) R. L. Fleischer and P. B. Price, *J. Geophys. Res.* **69**, 331 (1964); (b) *Geochim. Cosmochim. Acta* **28**, 755 (1964).

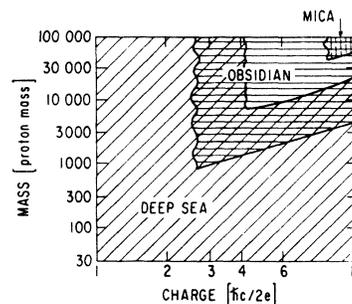


FIG. 2. Mass and magnetic-charge domains in which monopoles produced by cosmic-ray interactions in the earth's atmosphere would have been observed. Shadings as in Fig. 1.

Therefore, a measurable time, the "fission-track age," of a sample is equal to the time over which monopole tracks would have been recorded.

### EXPERIMENTAL PROCEDURE

We have chosen a group of micas and obsidian samples of known or measurable fission-track ages and etched large sheets or disks for times which would display any long tracks such as are to be expected from penetrating monopoles of  $n \gtrsim 2$ . Such tracks would penetrate the entire thickness of samples since the ionization of a monopole exceeds the threshold for detection over practically its entire range. The samples were scanned under a stereomicroscope at a magnification of 10X, which was in fact adequate to identify the short fission tracks which were used for dating and would therefore surely allow detection of the longer tracks which were being sought. Two of the micas<sup>20</sup> and the obsidian<sup>23</sup> had been dated previously; the largest-area mica (from North Carolina) was dated by us for this study. It contained 40 fission tracks/cm<sup>2</sup> and gave an age of  $(248 \pm 27) \times 10^6$  years. Table I lists the samples' ages, sizes, and (area)  $\times$  (time) factors.

### RESULTS

In the obsidian and the two smaller mica samples, no etched particle tracks longer than  $\sim 16 \times 10^{-4}$  cm, the maximum length recorded by fission tracks, were observed. In the North Carolina mica two distinct additional etched features were visible. Over one region of the crystal, dense populations of pits were arrayed along parallel lines. This crystallographic relationship strongly suggests slip bands—arrays of dislocations and dislocation debris. Since (1) the dominant features could not possibly be monopole tracks and (2) the pit density there was so great that a particle track could not have been distinguished, the area involved (3% of the total) was excluded from consideration. The second set of features was occasional groups of 5–10 pits composed of a

<sup>23</sup> C. W. Naeser, U. S. Geological Survey, Menlo Park (unpublished).

TABLE I. Area-time factors for samples used.

Sample (etch)	Time of track storage (years)	Area scanned (cm <sup>2</sup> )	Area × time (cm <sup>2</sup> sec) (90% conf.)	90% Conf. flux limits* (particles/cm <sup>2</sup> sec sr)	Max. cosmic-ray energy tested (eV) (90% conf.)
Muscovite; Batchellerville, N. Y. (49% HF, 147 min, 55°C) <sup>b</sup>	(185 ± 17) × 10 <sup>6</sup>	28.0	1.44 × 10 <sup>17</sup>		
Biotite; Bancroft Ontario (49% HF, 40 min) <sup>b</sup>	(355 ± 40) × 10 <sup>6</sup>	10.75	1.03 × 10 <sup>17</sup>		
Muscovite; from N. C. Pegmatite, CIT sample 2452. (49% HF) <sup>c</sup>	(248 ± 27) × 10 <sup>6</sup>	310	2.09 × 10 <sup>18</sup>		
Mica total:	...	...	2.34 × 10 <sup>18</sup>	3.27 × 10 <sup>-19</sup>	3 × 10 <sup>19</sup>
Obsidian; Hughes, Alaska, USGS sample 67APa9 (49% HF, 1 h) <sup>d</sup>	(32 ± 4) × 10 <sup>6</sup>	34.6	3.24 × 10 <sup>16</sup>	2.92 × 10 <sup>-17</sup>	2 × 10 <sup>18</sup>

\* A unit area of mica reveals tracks over an effective solid angle of  $\pi$  sr; for obsidian the corresponding angle is  $\pi(1 - \sin^2\theta_c)$ , where  $\theta_c$  is the critical angle for track etching, as discussed in Ref. 22(a). For the obsidian used here,  $\theta_c = 26^\circ$ . For  $n = 3$  monopoles, we estimate  $\theta_c$  to be  $45^\circ$ , which would reduce the area-time factor for this case to  $2.0 \times 10^{16}$  cm<sup>2</sup> sec, for  $n = 2$  the numbers would be  $63^\circ$  and  $6 \times 10^{16}$  cm<sup>2</sup> sec.

<sup>b</sup> Reference 20.

<sup>c</sup> This work.

<sup>d</sup> Reference 23

series of terraces descending to a flat bottom, or occasionally to a small, sharp-bottomed pit. Since the terraces were not concentric, and were not matched by pits on the opposite surface, they could not be tracks from penetrating particles.

We conclude that in none of the samples were any tracks detected that can be attributed to magnetic monopoles.

## DISCUSSION

The area-time factors for the mica and obsidian are  $2.22 \times 10^{18}$  cm<sup>2</sup> sec and  $3.05 \times 10^{16}$  cm<sup>2</sup> sec, respectively.

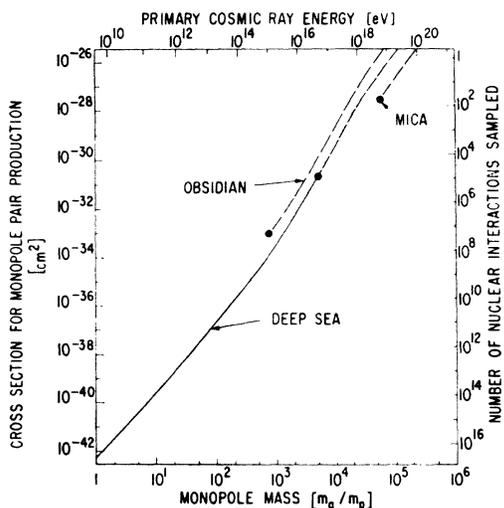


FIG. 3. Calculated 90% confidence limits, as a function of monopole mass, for the maximum cross section for monopole pair production by nuclear interactions in the upper atmosphere. On the right are given the number of primary interactions sampled, and the energy of the interacting cosmic-ray particles is given above. Dashed lines indicate regions in which limits apply only over a portion of the magnetic-charge range in which monopoles could have been detected. Combining the deep-sea search (Ref. 10) with the mica and obsidian results here covers all possible charges from  $\hbar c/2e$  to  $30\hbar c/e$ .

They lead to 90% confidence limits of  $< 3.3 \times 10^{-19}$  and  $< 2.9 \times 10^{-17}$  monopoles/cm<sup>2</sup> sec, using the reasoning described in Refs. 7 and 9. (But see footnote a to Table I for one exception.) These limits are sufficiently restrictive that if, as Porter suggested, the cosmic rays of  $> 10^{17}$ -eV energy were monopoles, we should have seen  $> 6 \times 10^4$  monopole tracks in the micas and  $\sim 700$  in the obsidian.<sup>24</sup>

The reason for considering the limits inferred from obsidian and mica separately is that they apply to significantly different (though largely overlapping) regions of the mass-charge diagram—Figs. 1 and 2. The charge limitations are set by the ionization thresholds for particle registration,<sup>15,16</sup> which place the threshold for muscovite mica just at  $n = 2$  and that for natural glass just below  $n = 2$ . Therefore we could in mica be confident of seeing tracks only of  $n = 3$  and  $n > 3$  monopoles. The mass limit is set by the amount of covering matter that an energetic pole must penetrate, and we must therefore put limits on the depth of burial of the mica and obsidian. From a knowledge of the track-annealing behavior of mica<sup>19</sup> and of the typical geothermal gradient of  $15^\circ/\text{km}$  in eastern North America,<sup>25</sup> a maximum depth of 10 km of rock is estimated under the extreme assumption that the micas spent their entire age at the lowest level compatible with tack retention. What is probably a somewhat more realistic model—uniformly rising material, reaching the surface at the present time—gives slightly greater than 5 km as the average depth of burial. We assume 7.5 km of material with density  $2.7 \text{ g/cm}^3$  for drawing Figs. 1 and 2. Obsidian, by contrast, is discharged at the earth's

<sup>24</sup> In recent work [R. L. Fleischer, P. B. Price, and R. T. Woods, Phys. Rev. (to be published)] we find that the sensitivity of the obsidian used here is such that  $n = 2$  monopoles would be detected with an efficiency of 0.2.

<sup>25</sup> R. F. Roy, E. R. Decker, D. D. Blackwell, and F. Birch, J. Geophys. Res. **73**, 5207 (1968).

surface. We assume covering material of  $10^4$  g/cm<sup>2</sup> for drawing Figs. 1 and 2.<sup>26</sup>

Our failure to find monopole tracks allows us to further restrict the permissible cross sections for monopole production by cosmic-ray interactions in the upper atmosphere. The procedure given in Ref. 9 and the restrictions noted both there and in Ref. 10 apply. Figure 3 shows the limits, both from this study and from the previous deep-sea search.<sup>10</sup> It will be noted that our (area)×(time) factor is such that we have in effect sampled interactions of cosmic rays with energies close to the highest yet reported— $3 \times 10^{19}$  eV—energies adequate to produce a pair of particles with rest masses  $>10^5$  proton masses ( $m_p$ ).

*Note added in proof.* More recent measurements of the cosmic-ray spectrum above  $10^{18}$  eV [see D. Andrews *et al.*, *Acta Phys. Acad. Sci. Hung.* (to be published); R. G. Brownlee *et al.*, *ibid.* (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 to  $\sim 10^{20}$  eV.

In spite of our negative results here and in Ref. 10, can monopoles exist? There are three possibilities. One of these is the as yet inadequately surveyed region<sup>27-29</sup> in the mass-charge domain of Fig. 1 ( $m > 100 m_p$  for  $n = 1$  and  $m > 300 m_p$  for  $n = 2$ ). This region is the subject of work in progress. The second is that some as yet unidentified critical assumption in the monopole searches is in error.<sup>30</sup> Although this possibility can

<sup>26</sup> Note that as long as burial was less than 1 km of crustal material, there is overlap in the regions of Figs. 1 and 2 surveyed by the previous studies (Refs. 9 and 10) and the obsidian in this work.

<sup>27</sup> The exposure of large-area detectors for observing cosmic rays (Refs. 27 and 28) have set limits of  $<1.4 \times 10^{-10}$ /cm<sup>2</sup> sec sr for  $n = 1$  monopoles and  $<5 \times 10^{-12}$  for  $n = 2$ . Such high-altitude flights cannot lower the limits further for  $n = 1$ , because of the difficulty in distinguishing between the track of a monopole and that of a relativistic rare-earth ion.

<sup>28</sup> P. H. Fowler, R. A. Adams, V. G. Cowen, and J. M. Kidd, *Proc. Roy. Soc. (London)* **A301**, 39 (1967).

<sup>29</sup> P. B. Price, R. L. Fleischer, and G. E. Nichols, *Acta Phys. Acad. Sci. Hung.* (to be published).

<sup>30</sup> Two specific examples can be given, all related to our earlier studies (Refs. 9 and 10): (1) Monopoles moving through the

neither be discarded nor established rigorously, the reasoning employs rather straightforward physics and wide margins of safety. Finally, it may be that the cross section or abundance limits set are just not restrictive enough. In the absence of a theoretical prediction, it is hard to know whether a cross section of  $10^{-38}$  or  $10^{-42}$  for producing a pair of monopoles is restrictive or not.

## CONCLUSIONS

Regardless of the possible uncertainties outlined above, the following conclusions can be drawn from this work, subject to the mass-charge restrictions of Figs. 1 and 2.

(a) No significant fraction of the cosmic rays up to  $\sim 3 \times 10^{19}$  eV consists of highly penetrating magnetic monopoles.

(b) Cosmic-ray interactions with the earth's atmosphere produce  $<3 \times 10^{-19}$  penetrating magnetic monopoles/cm<sup>2</sup> sec. This is equivalent to  $<2$ /sec over the entire earth.

(c) The above conclusion supports our earlier statement about the difficulty of locating monopoles within the earth. If they were uniformly dispersed, this work would indicate that there is less than one monopole/4000 m<sup>3</sup> of the earth.

## ACKNOWLEDGMENTS

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oceans might be trapped by suspended particles and therefore not rain down uniformly on the ocean bottom. Since most suspended matter is biogenic and diamagnetic, however, this is unlikely. (2) Monopoles may respond to the  $H$  field rather than  $B$ , and thus they would not be magnetically bound in materials, since  $H$  is continuous. As Purcell *et al.* (Ref. 5) and Goto *et al.* (Ref. 6) have noted, this is not a physically plausible possibility, but has not been rigorously examined.