Search for Multiply Charged Dirac Magnetic Poles

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A 265 000-G pulsed magnetic field and plastic track detectors have been used in an attempt to extract and observe magnetic monopoles from manganese nodules formed on the floor of the Southern Ocean. Because of their low growth rate, these nodules compress a long period of possible monopole trapping ($\approx$300 000 years) into small volumes of material, making possible in this search an (area)$\times$(time) factor of $\approx 3\times10^{14}$ cm^2-sec. The detector system has the merit of containing zero background, making possible a sensitivity such that any multiple of Dirac's original charge of up to 120 could have been detected. The absence of monopoles in the material searched sets new limits on the abundance of multiply-charged monopoles and of monopoles that are too massive ($>3m_{\text{proton}}$) to have been produced in previously reported accelerator experiments. The results imply that at no energy up to at least 2×10^{17} eV are the primary cosmic rays dominantly composed of magnetic monopoles.

INTRODUCTION

A CLEAR demonstration of the existence of magnetic monopoles[1] would lead to profound changes in modern physics. First, the presence of monopoles would restore symmetry to Maxwell's equations, which include an electric charge e but no analogous magnetic charge or pole strength g. Secondly, as was also suggested by Dirac,[1] quantization of the electric charge would arise naturally from the existence of a magnetic charge, since Dirac's quantum mechanics requires that

$$eg=nhc/4\pi\,, \tag{1}$$

where n= an integer, h= Planck's constant, and c= velocity of light, so that if both e and g exist, each must have a smallest value. In addition, if monopoles exist, the electromagnetic field will lack some of the symmetry properties commonly ascribed to it—losing its invariance with respect to time reversal and space inversion.[2] Finally, although there is controversy both pro[3] and con,[4,5] it is likely that new theoretical foundations are necessary before the magnetic monopole could be incorporated into a consistent quantum electrodynamics.

PROPERTIES OF MAGNETIC MONOPOLES

Any search for a hypothetical particle is necessarily based on its inferred properties. The behavior of a monopole can be inferred from (a) the previously noted quantum condition ($g=n\hbar c/2e$) and (b) the fact that it acts analogously to the electric charge [e and g are interchanged, E and H (electric and magnetic fields) are interchanged, etc.].

In the past, experiments have been designed primarily to observe monopoles where the quantum number n is unity, corresponding to the lowest magnetic charge given by Dirac[1]; and, as a result, in most of the previous work poles of much higher charges would not have been detected, as we will discuss in more detail later. In a more recent examination of condition (a), Schwinger[5] concluded that n is 4 (two separate factors of 2 being included); and as Carithers *et al.*[2] pointed out, n is at least 3 if quarks exist, since e would be replaced by $\frac{1}{3}e$. A proposal by Schiff[6] would eliminate this factor of 3, but it in turn has been criticized by Peres.[7] At any rate, values of n= 1, 2, 3, 4, 6, and 12 are by no means unlikely, depending on whether quarks exist and on whether none, one, or both of Schwinger's factors of two are appropriate.

The two basic properties of poles listed above lead to three derived properties that are of importance to this work.

By analogy with the electrostatic case, a monopole experiences a magnetostatic attraction to materials of positive magnetic susceptibility and is bound by a force that is proportional to the susceptibility, χ. The binding force may be thought of as supplied by an effective magnetic field $H_e=(n\chi\hbar c/16ex^2)$, where x is the separation of the pole from the substance and saturation effects have been neglected. Although this formula will cease to be valid for small values of x where local approach to saturation will occur in the paramagnet, it is adequate to tell us that for a material of susceptibility $>10^{-5}$ emu/cm^3 a monopole is bound by an effective field that is much larger than the earth's magnetic field. In addi-

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[1] P. A. M. Dirac, Proc. Roy. Soc. (London) **A133**, 60 (1931); Phys. Rev. **74**, 817 (1948).

[2] W. C. Carithers, R. Stefanski, and R. K. Adair, Phys. Rev. **149**, 1070 (1966).

[3] D. Zwanziger, Phys. Rev. **137**, B647 (1965); S. Weinberg, *ibid.* **138**, B988 (1965); A. S. Goldhaber, *ibid.* **140**, B1407 (1965); C. R. Hagen, *ibid.* **140**, B804 (1965).

[4] N. Cabibbo and E. Ferrari, Nuovo Cimento **23**, 1147 (1962); R. A. Carrigan, Jr., *ibid.* **38**, 638 (1965).

[5] J. Schwinger, Phys. Rev. **144**, 1087 (1966).

[6] L. I. Schiff, Phys. Rev. Letters **17**, 714 (1966).

[7] A. Peres, Phys. Rev. Letters **18**, 50 (1967).

tion, the special case of binding to ferromagnetic (or ferrimagnetic) material has been calculated by Goto *et al.*[8] who find that a monopole of strength $n=1$ can be removed from bcc iron by a field of 53 kG; and because the pole strength appears in a logarithmic term, the critical field of a monopole with $n=12$ is only slightly larger, 67 kG. The logarithmic nature of the dependence also has the encouraging effect of rendering the results rather insensitive to changes in the quantitative values derived. In short, the values quoted are unlikely to be more than a few kG in error and therefore give us comfort that a monopole can be caught in a magnetic material and held securely against the magnetic fields usually found in nature and yet will be loosened by fields which we can produce in the laboratory.

A second property of monopoles is that they are accelerated along magnetic-field lines by a force gH (which supplies an increase in energy of $20n$ MeV/kG cm). Thus at a field of 60 kG, a unit pole will gain 2.4 GeV over a 2-cm acceleration distance, while a pole of $n=12$ will gain 29 GeV. The considerable strength of the force provides assurance that poles can be extracted from solids by attainable fields even if poles become bound to atoms. For example, a field of 265 kG such as we have used will supply to a unit pole ≈ 130 eV for each interatomic distance moved through a solid. As has been noted,[8] this is much greater than the binding energies of atoms in solids, and it is also larger than the observed energies for displacement of atoms by atomic knock-ons.[9]

The final property of interest is that a moving monopole is an unusually heavily ionizing particle. A moving magnetic charge creates an electric field that is proportional to the velocity. Cole[10] and Bauer[11] have shown that as long as this velocity is greater than that of the atomic electrons of the medium traversed, the ionization is equivalent to that caused by a minimum ionizing (relativistic) nucleus of charge $(137/2)n$. Thus, a monopole ionizes at least as heavily as a relativistic rare-earth ion; and, if n is greater than unity, it ionizes more rapidly than a relativistic nucleus of any known element. It follows that dielectric track detectors,[12,13] which detect only heavily ionizing particles, are especially appropriate for locating and identifying monopoles. It is also worth noting that the energy-loss rate by ionization for a fast monopole is about $8n^2$ GeV/(g/cm^2). The consequent decrease in range with increasing n sets limitations on how large a value of n is detectible.

[8] E. Goto, H. H. Kolm, and K. W. Ford, Phys. Rev. **132**, 387 (1963).

[9] See review by F. Seitz and J. S. Koehler, Solid State Phys. **2**, 307 (1956).

[10] H. J. D. Cole, Proc. Cambridge Phil. Soc. **47**, 196 (1951).

[11] E. Bauer, Proc. Cambridge Phil. Soc. **47**, 777 (1951).

[12] R. L. Fleischer, P. B. Price, and R. M. Walker, Ann. Rev. Nucl. Sci. **15**, 1 (1965).

[13] R. L. Fleischer, P. B. Price, R. M. Walker, and E. L. Hubbard, Phys. Rev. **156**, 353 (1967).

MASS OF THE MONOPOLE

There is no theoretical basis for assigning a mass to the monopole. The best guidance we have on this subject is a probable lower limit of $3m_p$ ($m_p=$ the proton mass) based on the mass which could have been supplied by proton-nucleon collisions in accelerator experiments.[14–16] This statement applies as long as the cross section for production exceeded 10^{-40} cm^2 and $n<3$.

In some discussions an arbitrary "canonical mass" of g^2/r_ec^2 $(=2.4m_p)$ has been considered, this value being a result of arbitrarily assigning the monopole the classical radius r_e of the electron. For simplicity we choose to discuss possible masses in terms of the proton mass.

PREVIOUS MONOPOLE EXPERIMENTS

Searches for monopoles may be considered in two groups, those where accelerator particles are caused to interact with matter and hopefully to create monopoles,[14–17] and those in which monopoles are sought in nature[2,8,18,19]—either those which might be produced by cosmic-ray interactions with matter,[18] usually imagined to occur in the upper atmosphere, or those which might make up the most energetic part of the cosmic radiation itself.[20,21]

The accelerator experiments have been limited to proton energies of 30 GeV and consequently to monopole masses below $3m_p$. As we indicated earlier, most detection schemes were of doubtful effectiveness for monopole strengths (n) greater than 2, although the precise cutoffs are often difficult to assess. The domain of mass and magnetic charge that has been examined is shown in Fig. 1. Although the area on the mass-charge diagram is limited, the limits on production cross sections that have been set within that region are such that most workers have concluded that poles in the domain where $m<3m_p$ and $n\leq 2$ do not exist.

The monopole searches in nature expand the mass limits by replacing the accelerator beam with the particles of high energy in the cosmic-ray spectrum,[21] which extends[22] up to at least 10^{20} eV. The hypothesis here is that cosmic-ray interactions in the upper atmosphere produce monopole pairs, which are subsequently ther-

[14] M. Fidecaro, G. Finocchiaro, and G. Giacomelli, Nuovo Cimento **22**, 657 (1961).

[15] E. Amaldi, G. Baroni, H. Bradner, H. G. deCarvalho, L. Hoffmann, A. Manfredini, and G. Vanderhaeghe in *Proceedings of the Aix en Provence International Conference on Elementary Particles, 1961*, edited by E. Cremieu-Alcan *et al.* (Centre d'Etude Nucleaires de Saclay, Seine et Oise, 1961), p. 155; Nuovo Cimento **28**, 773 (1963).

[16] E. M. Purcell, G. B. Collins, T. Fujii, J. Hornbostel, and F. Turkot, Phys. Rev. **129**, 2326 (1963).

[17] H. Bradner and W. M. Isbell, Phys. Rev. **114**, 603 (1959).

[18] W. V. R. Malkus, Phys. Rev. **83**, 899 (1951).

[19] L. W. Alvarez, Lawrence Radiation Laboratory, Phys. Notes, Memo 479, 1963 (unpublished).

[20] N. A. Porter, Nuovo Cimento **16**, 958 (1960).

[21] K. Greisen, in *Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965* (The Institute of Physics and The Physical Society, London, 1966), Vol. 2, p. 609.

[22] J. Linsley, Phys. Rev. Letters **10**, 146 (1963).

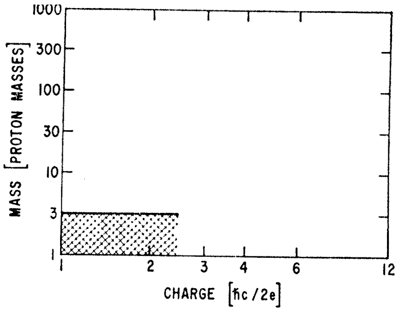

FIG. 1. Mass and magnetic charge region examined by accelerator experiments (Refs. 14–17).

malized after slowing down in the atmosphere.[18] Under the influence of the geomagnetic field those of the appropriate polarity drift to earth, where they can be collected, accelerated by a magnetic field, and detected directly.[2,18] Alternatively, poles could be trapped in matter, stored over geological times, and later extracted[8] or detected *in situ* by other means.[19] Although a wider mass domain is available than in the accelerator experiments, less stringent abundance (or cross section) limits have been set. It is therefore desirable to increase the (collecting area)$\times$(collecting time) factors over those attained in previous studies (7×10^{13} cm^2 sec by Carithers *et al.*[2]).

The mass ranges that can be examined by sea-level collection are determined by the requirement that poles be thermalized before they reach the collection device or trapping object (be it a magnet[2,18] or a magnetic outcrop[8]). The mass domain is indicated in Fig. 2(a), which we have calculated by assuming that a proton-nucleon collision converts the cosmic-ray energy into monopole mass, leaving proton, nucleon, and monopole pair at rest in the center-of-mass coordinate system. The energy in the "lab" (i.e., earth) system is then found, and the monopole range calculated. The slowing down is assumed to be by ionization[10,11] and bremsstrahlung[11,19,23]; for simplicity of calculation ionization loss alone was considered to occur below the energy at which energy loss rates by the two mechanisms are equal and solely bremsstrahlung loss was considered at higher energies.[24,24a] In all of the studies in the literature[2,8,18] the same observation made earlier—that detection systems would not have revealed poles of $n\gtrsim 3$—applies here, so that the domain searched previously lies roughly in the more darkly shaded regions of Fig. 2.[25]

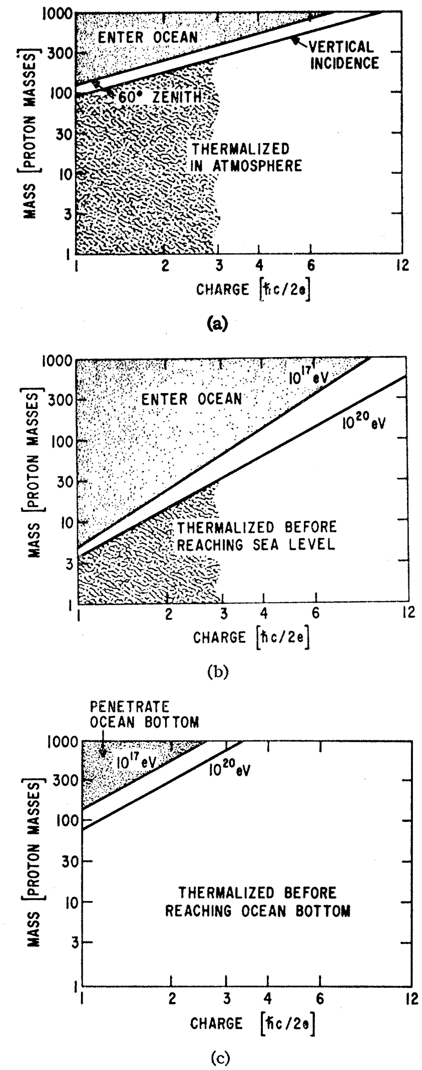

FIG. 2. Mass and magnetic charge domains in which naturally produced monopoles are thermalized at sea level: (a) poles produced by cosmic-ray interactions at the top of the earth's atmosphere, (b) cosmic poles of incident energy 10^{17} and 10^{20} eV, and (c) same as (b) except that a level of 3 km beneath the ocean is considered. The darkly shaded regions in (a) and (b) indicate domains of previous searches (Refs. 2 and 8).

A second hypothesis for a source of monopoles in nature was suggested by Porter,[20] namely the high-energy cosmic rays. Between 10^{16} and 10^{17} eV the cosmic-ray energy spectrum[21] contains a kink which has been interpretated as due to the cosmic rays leaking out of the galaxy as their energies become too high to allow

[23] E. Amaldi, G. Baroni, H. Bradner, H. G. DeCarvalho, L. Hoffmann, A. Manfredini, and G. Vanderhaeghe, CERN Report No. 63-13, 1963 (unpublished).

[24] Bremsstrahlung was calculated following the discussion given in Ref. 23, which uses the method described by B. Rossi, *High Energy Particles* (Prentice-Hall, Inc., Englewood Cliffs, N. J., 1952), pp. 55–57.

[24a] *Footnote added in proof.* We are indebted to P. H. Fowler for pointing out that for sufficiently massive particles energy loss due to pair production will exceed that from bremsstrahlung, since the former is mass independent while the latter decreases as m_g^{-2}. This consideration does not alter any of the figures presented here but could become important for monopole masses greater than $\approx 500n^2$ proton masses.

[25] This limitation does not apply to *in situ* methods of detection such as has been devised by Alvarez (see Ref. 19) and Vant-Hull [L. L. Vant-Hull, Phys. Rev., **173**, 1412 (1968)]. Alvarez's work has never been published, although a report (Ref. 19) is available. Until details of sample size, location (within the pre-atmospheric body of the meteorite examined, etc.) are known the extent of this search is not clear.

confinement by the galactic magnetic fields. In this model the cosmic rays above 10^{17} eV must be predominantly extragalactic. Goto points out that what he considers to be an "awkward" need for extragalactic cosmic-ray sources is eliminated if these energetic cosmic rays are in fact monopoles, which could easily be trapped within the galaxy and would rapidly be accelerated to the high energies actually observed.[26] Because these monopoles are more energetic at the top of the atomsphere, they are more penetrating than those of the same mass created in the upper atmosphere. It follows, as shown in Fig. 2(b), that the mass domain that is accessible in a sea-level collection experiment is more limited than that shown in Fig. 2(a). Goto has shown[26] that, in fact, a more fruitful collection could be made by utilizing the stopping power of the ocean.[27] Figure 2(c) indicates that a usefully wider mass range is indeed accessible by collection from the deep ocean.

HYPOTHESIS OF THIS EXPERIMENT

Ideally, in searching for monopoles in nature, one would wish to find material which contains in a small volume as large and as well-known an area-time collection factor as possible and to seek poles with a detector which both is sensitive to as wide a range of mass and magnetic charge as possible and has a minimum of background from other particles or radiation. In approaching this objective we have subjected manganese nodules taken from depths of about 2000 fathoms (≈ 3 km) beneath the Southern Ocean to magnetic fields of 265 kG in order to extract and accelerate monopoles, and then detect them using solid-state nuclear track detectors of Lexan polycarbonate resin and Daicel cellulose nitrate.

Manganese nodules[28] are small objects, often several cm in diameter, composed primarily of layers of oxides and hydroxides of manganese and iron. Often this material is deposited slowly over a core or nucleus such as a rock fragment, shark's tooth, or sediment lump. The nodules are found over large areas of the ocean bottom and in some regions form a mosaic or even a pavement of ferromanganese material blanketing the ocean floor.

From the point of view of the present work the nodules have the following merits: They are sufficiently magnetic (the susceptibility at the ambient temperature is 20×10^{-6} emu/g superimposed upon a weak ferromagnetic moment of 0.2 emu/g, each averaged over the nodule exclusive of its core) that thermalized poles would be firmly trapped. They can be found at sufficient water depths that most monopoles of plausible mass and charge would be thermalized and hence could be trapped. In short, the domain to the lower right on Fig. 2(c) would be accessible for cosmic monopoles and the whole domain of Fig. 2, extending on to $>1000m_p$ for poles produced by cosmic-ray interactions in the upper atmosphere. Finally, because they may remain exposed on the ocean floor for long periods of time and grow slowly (1–30 mm/million years[29–32]) nodules have high (area)$\times$(time) factors. In addition, the nodules selected for this study were from the Drake Passage and were exposed to the continuous passage of large volumes of water in the circumpolar bottom currents. Table I lists the original locations, dimensions, and area-time factors for the four nodules used in this experiment. Disequilibrium isotope measurements[33] indicate ages of greater than 0.3 million years for nodules from the areas chosen for this study, and we have given values of (area) $\times$(time) calculated using this number. It must be noted, however, that there exists some controversy over the interpretation of such geochemical data (see discussion in Ref. 33), and consequently the numbers we quote must be regarded as subject to some re-evaluation as progress is made in geochronology. However, the lower limit in age derived from the various growth rates given in Refs. 29–32 and Ref. 33 is 0.32 million years, so that from this point of view the value used is a conservative one. The nodules must be younger than 0.7 million years since they lie on sediments which are magnetized in the direction corresponding to the present polarity of the earth's magnetic field,[34] which assumed this polarity 0.7 million years ago.

In summary of the hypothesis used here, we imagine that monopoles rain down on earth—stopping either in the air or the oceans; the south-seeking poles drift downward under the action of the geomagnetic field until trapped by the para- or ferro-magnetism of the nodules on the ocean floor—these being the first solid material to which they are exposed and to which they can be bound; they are extracted by a 265-kG pulse,[35] accelerated, and directed into track-detecting solids whose detection properties are appropriate and are well documented.[36,37]

EXPERIMENT

Figure 3 indicates the monopole extraction and detection system. The sample is placed in the center of a

[26] E. Goto, Progr. Theoret. Phys. (Kyoto) **30**, 700 (1963).

[27] A preliminary description of one such search is given by H. H. Kolm, Phys. Today, October 1967, p. 69.

[28] For a general discussion and additional references see J. L. Mero, *The Mineral Resources of the Sea* (Elsevier Publishing Co., Inc., N. Y. 1965).

[29] E. D. Goldberg, in *Oceanography*, edited by M. Sears (American Association for the Advancement of Science, Washington, 1961), pp. 583–597.

[30] M. L. Bender, T. Ku, and W. S. Broecker, Science **151**, 325 (1966).

[31] B. L. K. Somayajulu, Science **156**, 1219 (1967).

[32] S. S. Barnes and J. R. Dymond, Nature **213**, 1218 (1967).

[33] H. G. Goodell, M. A. Meylon, and J. B. Grant, Amer. Geophys. Union, Atlantic Research Series (to be published).

[34] H. G. Goodell and N. D. Watkins, Deep Sea Research **15**, 89 (1968).

[35] I. S. Jacobs and P. E. Lawrence, Rev. Sci. Instr. **29**, 713 (1958).

[36] P. B. Price, R. L. Fleischer, D. D. Peterson, C. O'Ceallaigh, D. O'Sullivan, and, A. Thompson, Phys. Rev. **164**, 1618 (1967).

[37] P. B. Price, R. L. Fleischer, D. D. Peterson, C. O'Ceallaigh, D. O'Sullivan, and A. Thompson, Phys. Rev. Letters **21**, 630 (1968).

TABLE I. Nodule data.

Nodule No.	Longitude	Latitude	Depth (fathoms)	A_1 Average radius (cm)	A_2 Average radius of core rock (cm)	(Area)×(time)[a] cm² sec
003	67.30°W	59.03°S	1900	2.16	0.81	7.0×10^{13}
029	55.97°W	55.77°S	2330	1.97	1.23	7.8×10^{13}
057	125.03°W	55.88°S	2120	1.97	0.66	7.3×10^{13}
059	99.60°W	59.02°S	2680	1.74	0.92	5.4×10^{13}
					Total	2.75×10^{14}

[a] Assuming linear growth over 0.3 million years of exposure time. The average projected area is calculated from $\pi(A_1^2+A_1A_2+A_2^2)/3$ assuming spherical shapes.

magnet coil which produces a peak field of 265 kG in a half-sine-wave pulse of duration 5.8×10^{-3} sec.[35] During the rise time, the pole will migrate upward (downward were a north-seeking pole present) through a 250-μ-thick sheet of Lexan polycarbonate into a 25-μ-thick "retarder" sheet of iron. There it will be trapped until the critical field[8] of 50–80 kG is reached, at which time the pole is extracted from the iron and accelerated into the detection system, a stack of 4 detectors—two 250-μ-thick Lexan polycarbonate sheets followed by two 250-μ Daicel cellulose nitrate sheets. These sheets are cut to an elliptical shape that allows them to be positioned in the cylindrical Lexan polycarbonate holder at 45° to the vertical. Any pole of charge up to 60 $\hbar c/e$ ($n=120$) would make a detectable track before slowing down to a drift velocity which carries it upward through the Lexan polycarbonate end plate and into an iron "catcher" sheet. There it would be stored, since the field never approaches the critical field for extraction of poles at that position. By later placing the catcher foil in the sample position a monopole could be recycled.

The holder was constructed of Lexan polycarbonate, so that if by some unforeseen behavior an energetic monopole escaped the catcher, its trajectory could be revealed by using the holder (including end plates) as track detectors. Joints that were immersed in liquid nitrogen were made tight by lead gaskets, which effectively prevented liquid nitrogen from entering the spaces between the sample and the detectors.

TABLE II. Expected critical fields, ranges, and track lengths.

Critical[a] field (kG)	Magnetic charge ($\hbar c/2e$)	Range[b] (10^{-4} cm)
53	1	1960[c]
57	2	1050[d]
59	3	730[d]
61	4	560[d]
63	6	390[d]
67	12	206[d]
75	48	58[d]
80	120	25[d]

[a] Calculated from the relation of Goto *et al.* (Ref. 8).
[b] Density 1.2 g/cm³ assumed, appropriate to Lexan polycarbonate.
[c] Etched track length = 31 μ in Lexan, 350 μ in cellulose nitrate.
[d] Tracks etched over entire range in each detector.

In order to insure that all particles leaving the iron retarder foils would be directed into the detectors, the pole trajectories were calculated (as described in more detail in the Appendix) for various values of mass and of magnetic charge.[37a] The diameter of the region holding the sample is accordingly restricted so that a pole leaving the perimeter of the sample would clear the most constricted inner surface of the holder and enter the detector system. From the field at the moment of release the ranges of the poles in the detectors can be calculated. They are given in Table II.

It is appropriate here to describe further the qualities of the detector system since the use of solid-state track detectors is relatively new to physics.[12,38] We have known since 1963 that in a wide range of dielectric solids heavily ionizing particles produce tracks which can be revealed by preferential chemical attack.[39] These

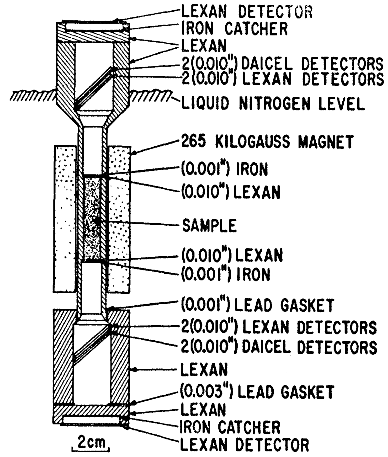

FIG. 3. Device for extracting monopoles from a sample, passing them through a detection system, and collecting them.

[37a] *Footnote added in proof.* J. Schwinger [Phys. Rev. **173**, 1536 (1968)] has suggested that monopoles may carry an electrical charge of either $\frac{1}{3}e$ or $\frac{2}{3}e$. Such poles would be extracted and detected in our system with essentially no difference in efficiency relative to poles with no electrical charge.

[38] R. L. Fleischer, P. B. Price, and R. M. Walker, Science **149**, 383 (1965).

[39] P. B. Price and R. M. Walker, J. Appl. Phys. **33**, 3407 (1962); R. L. Fleischer P. B. Price, *ibid.* **34**, 2903 (1963); Science **140**, 1221 (1963).

etched tracks have been put to diverse uses[12,38] including the first identification of cosmic-ray nuclei more massive than iron.[40] This was accomplished by virtue of the fact that the background track density from lightly ionizing particles in the meteoritic detectors used was undetectably low.

The first space exposures of plastic detectors[41] helped establish that the detection threshold is determined by the primary ionization along the particle path[13] and subsequently led us to a new means of attaining high resolution of cosmic-ray particles utilizing the fact that the etching rate along a track is a function of the primary ionization.[36,37] From accelerator[36] and cosmic-ray[37] studies we now have reliable values of the relation between etching rate and ionization rate in Lexan polycarbonate and cellulose nitrate. These relations show that in cellulose nitrate the entire track length would be revealed by our standard etching treatment. In the Lexan polycarbonate detector a length of 31 μ would be etched away in the case of a unit pole, while for $n > 1$ the entire track length would be etched. From a cosmic-ray study in progress[42] we were fortunate to have a track from a relativistic nucleus of charge ≈ 69, which has allowed us to view directly the sort of track we are seeking, and hence to establish that we would recognize it under the scanning conditions used. Any of the pole strengths listed in Table II would give recognizable and totally distinctive tracks. It should be noted that even though the etched track length from a unit monopole would be only 31 μ in the Lexan polycarbonate, the range is sufficiently great that 350-μ-long tracks would be etched in the two cellulose nitrate detectors that are also present.

EXPERIMENTAL PROCEDURE

The four nodules listed in Table I were pulverized, the core rocks were extracted, and the remaining ferromanganese material was magnetically pulsed in the device diagrammed in Fig. 3 using a series of 31 different loadings. The detectors were removed and etched in stirred solutions under standard conditions: 72 h, 20°C, 6.25N NaOH solution for the Daicel; 24 h, 60°C, 6.25N NaOH solution with 0.4% Benax surfactant for the Lexan polycarbonate. At the same time we etched a control sample of Lexan polycarbonate from the same sheet of material. The control sample was irradiated with Cf^{252} fission fragments while held at a temperature of 77°K, the same as was used for monopole detection. Detectors were subsequently scanned in a binocular microscope at 30× and 60× and in a Leitz Ortholux microscope at 130×. Under the latter two conditions tracks from the relativistic nucleus of charge 69 mentioned earlier[42] were visible as were the ($\approx$18-μ-long) fission tracks in the control sample.

RESULTS

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

DISCUSSION

Table I indicates that the apparent (area)×(time) factor of this experiment is 2.75×10^{14} cm^2 sec. This number is a factor of four greater than that of the previous most extensive study, examining the darkly shaded mass and charge regions of Fig. 2(a) and (2b). In addition we have extended the search throughout the region covered by Figs. 1 and 2, a charge of any value up to $60\hbar c/e$ being detectable in this experiment. The experiment of Carithers *et al.* set a 90% confidence limit of $<3.3\times10^{-14}$ north monopoles/cm^2 sec; our result therefor sets a 90% confidence limit of $<8.4\times10^{-15}$/cm^2 sec. Since we collect over an effective acceptance angle of π sr (not 2π as stated by Carithers *et al.*) the flux limit is

$$<2.7\times10^{-15}/\text{cm}^2 \text{ sec sr}.$$

This result bears directly on Porter's cosmic-monopole suggestion. If the cosmic rays above 10^{17} eV were entirely monopoles, we would have expected to observe south poles from our deep ocean nodules at the 98% confidence level. We conclude that for energies below $\approx 1.5-2\times10^{17}$ eV, the primary cosmic rays are not dominantly monopoles.

Our results also allow us to put upper limits on the production cross sections. If we recollect that a cosmic ray of energy $E>2m_pc^2[2(m_g/m_p)+(m_g/m_p)^2]$ could in principle produce a monopole pair, each of mass m_g, by a proton-nucleon collision, and assume after Carithers *et al.* an interaction cross section for nucleon-nucleon collision of 30×10^{-27} cm^2, we can put limits on the production cross section for monopoles. We use the cosmic-ray spectrum given by Greisen[21] and an enhancement factor of 1.4 (due to higher-energy cosmic rays having more than one opportunity to interact before their energy drops below that of interest).[2] Figure 4 presents the result in terms of the limit on the cross sections versus the monopole mass. For convenience, scales are also given indicating the total number of cosmic-ray interactions and their energy.

For these cross-section data to be immediately useful one would like to be able to compare them with those to be expected theoretically; for the mass range where they are lower than the theoretical values, monopoles could then be concluded not to exist. Unfortunately, there exist in fact no estimates to which even the estimator has been willing to assign a degree of confidence. We, therefore, merely report the data of Fig. 4 and look forward to future theoretical work being of assistance.

[40] R. L. Fleischer, P. B. Price, R. M. Walker, M. Maurette, and G. Morgan, J. Geophys. Res. **72**, 355 (1967).

[41] R. L. Fleischer, P. B. Price, R. M. Walker, R. C. Filz, K. Fukui, E. Holeman, M. W. Friedlander, R. S. Rajan, and A. S. Tamhane, Science **155**, 187 (1967).

[42] Joint General Electric Research and Development Center–Washington University experiment (to be published).

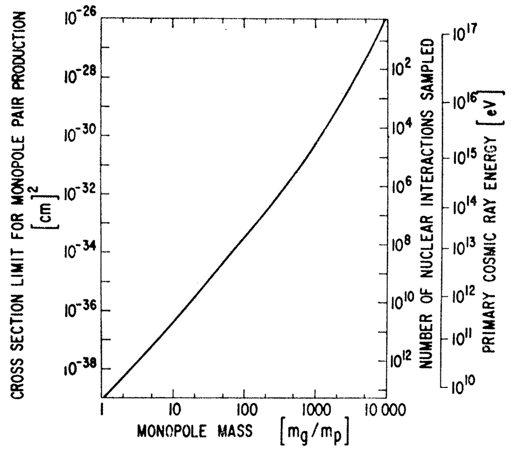

FIG. 4. Calculated 90% confidence limits, as a function of monopole mass, for the maximum cross section for monopole pair production by nuclear interactions in the upper atmosphere. On the right are given the number of primary interactions sampled and the energy of the interacting cosmic-ray particles.

CONCLUSIONS

On the basis of a search for magnetic monopoles in manganese nodules from the deep sea, we conclude that the integral flux of cosmic monopoles of mass less than 130 and charge less than $60\hbar c/e$ is less than 8.4×10^{-15} cm^2 sec (90% confidence).

This result also indicates that cosmic-ray interactions with the entire earth's atmosphere produce less than 40 000 monopoles/sec (90% confidence).

Below 10^{16} eV monopoles form an insignificant fraction of the cosmic rays, and at 2×10^{17} eV they are not the dominant contributor.

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APPENDIX: TRAJECTORY FOR THE MAGNETIC MONOPOLE

The relativistic equations for the trajectory of the magnetic monopole in a magnetic field of cylindrical symmetry are

$$\frac{d}{dt}(mc\beta_R)=gH_R,\quad \frac{d}{dt}(mc\beta_Z)=gH_Z,$$

where g and m refer to the pole strength and the relativistic mass of the magnetic monopole. R and Z refer to the radial and polar components of the monopole velocity and the magnetic field, v and H. $\beta=v/c$, $\beta_R=v_R/c$, and $\beta_Z=v_Z/c$, where c is the speed of light.

Performing the differentiation with respect to time and solving for the components of acceleration, we get

$$\dot{\beta}_R=\frac{g(1-\beta^2)^{1/2}}{m_0c}[(1-\beta_R{}^2)H_R-\beta_R\beta_ZH_Z],$$

$$\dot{\beta}_Z=\frac{g(1-\beta^2)^{1/2}}{m_0c}[(1-\beta_Z{}^2)H_Z-\beta_R\beta_ZH_R].$$

These equations are in the form

$$\dot{\beta}_{R,m}=f_1(\beta_R,\beta_Z),\quad \dot{\beta}_{Z,m}=f_2(\beta_R,\beta_Z),$$

and were solved on the computer by using the Runge-Kutta stepwise integration approximation:

$$\beta_{R,n+1}=\beta_{R,n}+\tfrac{1}{2}(k_1+k_2),\quad \beta_{Z,n+1}=\beta_{Z,n}+\tfrac{1}{2}(l_1+l_2),$$

where

$$k_1=(dt)f_1(\beta_{R,n},\beta_{Z,n}),$$
$$l_1=(dt)f_2(\beta_{R,n},\beta_{Z,n}),$$
$$k_2=(dt)f_1(\beta_{R,n}+k_1,\ \beta_{Z,n}+l_1),$$
$$l_2=(dt)f_2(\beta_{R,n}+k_1,\ \beta_{Z,n}+l_1).$$

Thus, after each interval dt, a new value of the velocity is obtained, and the new position coordinates are found by using the average value of the velocity components over the interval dt.

The magnetic field was assumed to be varying sufficiently slowly to be considered constant over each interval. The field components for a single loop at the coil components are given by[43]

$$H_Z=\frac{I}{2\pi}\frac{1}{[(a+R)^2+Z^2]^{1/2}}\left[\left(\frac{a^2-R^2-Z^2}{(a-R)^2+Z^2}\right)E-K\right],$$

$$H_R=\frac{I}{2\pi R}\frac{Z}{[(a+R)^2+Z^2]^{1/2}}\left[\left(\frac{a^2+R^2+Z^2}{(a-R)^2+Z^2}\right)E+K\right],$$

where K and E are elliptic integrals of the first and second kind and a is the radius of the loop. Approximations[44] to K and E were used.

[43] W. R. Smythe, *Static and Dynamic Electricity* (McGraw-Hill Book Company, New York, 1950), p. 271.

[44] *Handbook of Mathematical Functions*, edited by M. Abramowitz and I. A. Stegun, NBS, Applied Mathematics Series No. 55 (U. S. Government Printing Office, Washington, D. C., 1964), pp. 591–592.