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Search for cosmic-ray-related magnetic monopoles at ground level

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Magnetic monopoles have been sought at ground level using the large magnetic moment of the Fermilab 15-foot bubble-chamber magnet for collection and acceleration and Lexan polycarbonate for particle detection. The 100 days of operation with proper polarity provides an (area)×(time) factor of 8.4×10^{14} cm^2 sec for slowed north-seeking monopoles. The 3.5 years of exposure also provides 10^{13} cm^2 sec for high-energy directly penetrating monopoles of both polarities. The lack of observable poles sets new limits on monopole mass and charge for experiments that make no assumptions about long-term trapping of magnetic charges.

INTRODUCTION

To explain the quantization of electric charge, Dirac[1] in 1931 hypothesized the existence of particles possessing magnetic charge $g=ng_D$ quantized in discrete multiples of $g_D=e/2\alpha$, where e is the electronic charge and α the fine-structure constant, $\approx\frac{1}{137}$. Since then there have been many null searches for these particles, most of which will be cited later.

In 1975, a possible magnetic monopole was found in the detectors from a balloon flight that was designed to study cosmic rays.[2] Partially motivated by the announcement of this event (which was later[3] concluded to be an unlikely candidate for a monopole) we installed a detector for monopoles at Fermilab's 15-foot bubble chamber. Although located at an accelerator, the apparatus looked primarily for magnetic monopoles created by cosmic rays that collide with nuclei in the atmosphere. Our technique was that pioneered by Malkus.[4] Magnetic monopoles that are sufficiently slowed by the atmosphere can be gathered rather efficiently by the extensive fringing magnetic field of a large dipole. The 15-foot bubble chamber has one of the world's largest dipole moments; field lines from its central region continue into the earth's atmosphere, eventually covering a cross-sectional area of 5×10^4 m^2, as sketched in Fig. 1.

A second mode in which the experiment records monopoles is by detecting cosmic monopoles directly. As Porter[5] noted, in the weak but extensive galactic magnetic fields monopoles will be accelerated to immense energies, from 10^{17} to above 10^{20} eV. Porter proposed that such monopoles might account for the ultraenergetic cosmic rays that are observed in this range. High-energy magnetic monopoles would often penetrate the atmosphere, ignore the magnetic field of the magnet, and cross the detectors. Those that are slowed sufficiently are collected by the magnet over the expanded area defined by the magnetic field distribution.

In short the system we will describe is sensitive to four categories of monopoles.

(1) Monopoles created by nuclear interactions in the atmosphere, slowed, gathered by the magnet, and accelerated into the detectors.

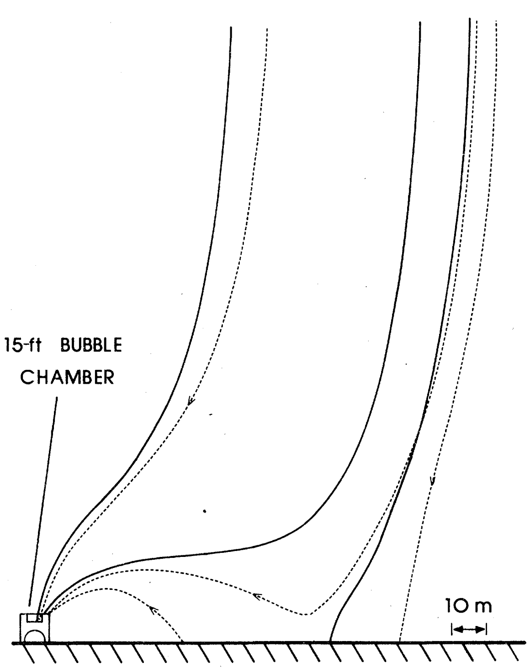

FIG. 1. Magnetic field lines (solid lines) and monopole trajectories (dashed lines) above the 15-foot bubble chamber. Trajectories are calculated for a monopole of magnetic charge 2 ($\hbar c/2e$) and of mass $100m_p$.

(2) Slowed cosmic monopoles that are gathered by the magnet and accelerated into our detectors.

(3) Fast cosmic monopoles that cross our detectors.

(4) Interaction-created monopoles that penetrate our detectors before being slowed.

The experiments reported here improve the gathering power of previous Malkus-type searches for gathered interaction and slowed cosmic poles by a factor of 12. For direct observation of fast cosmic poles and fast interaction poles our experiment improves the previous limit by 33%, providing a check on the previous result and more than doubling the statistics for such searches.

USE OF THE MAGNETIC FIELD OF THE BUBBLE-CHAMBER MAGNET

Any slow monopole of proper polarity within the area of the magnetic field that is gathered by the magnet drifts down the field lines to a surface near the bubble chamber where the magnet's pull exceeds the monopole's ionization loss to air. Then the monopole accelerates. Since our detectors can only register monopoles with speeds exceeding some threshold, we wanted to place the detectors as low as possible within the atmosphere, where the monopoles would be fastest, i.e., as close to the top of the bubble chamber as possible. The closest practical surface was the floor of a room-sized enclosure used in an earlier search for tachyon monopoles.[6] This surface was 6.8 m above the center of the bubble chamber, but was originally beneath the heavy roof of the bubble-chamber building. We replaced the roof above our detector with a movable roof (scuttle), providing an opening through which monopoles could enter and yet which could be closed to protect the bubble chamber in bad weather (Fig. 2). During the following 3.5 years that our detectors were in place, the scuttle was open and the magnet had the proper polarity (complementing the earth's field) for 100 days.

For this long exposure time and large area we needed a detector which was durable, inexpensive, and would not record lightly ionizing background events such as extensive air showers. For these purposes we covered the 9.12-m^2 collection area with multiple layers of clear Lexan polycarbonate sheet, General Electric type 8070-112 ($C_{14}H_{16}O_3$) of thickness 0.010 in. (254 μm).

DETECTION PROCEDURES

The array consisted of two similar portions—the University of Colorado (CU) stacks and the General Electric (GE) stacks. These were treated separately so as to give independent cross checks of the methods used. A total of 18 panels were placed

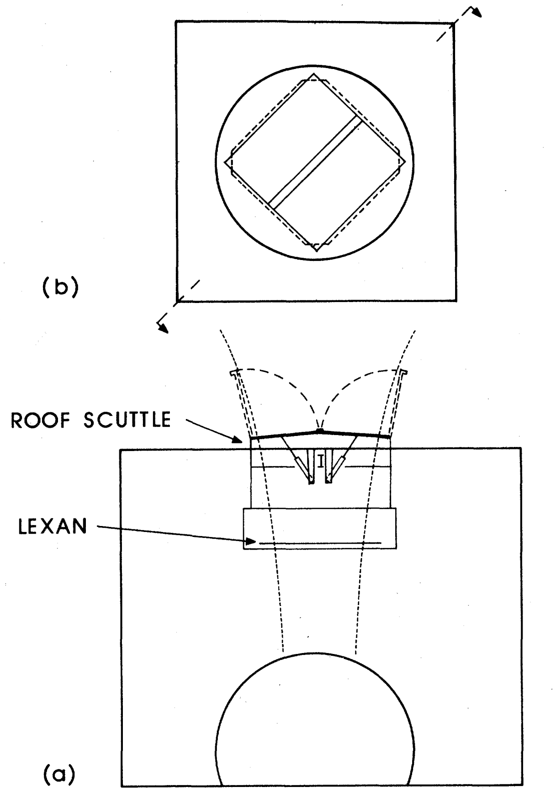

FIG. 2. Sketch of relevant geometry of the bubble-chamber building. The roof scuttle is open during exposures in which slowed magnetic poles are collected. The distance from the center of the bubble chamber to the detector array is 6.4 m.

horizontally over the collection area (Fig. 3). All assembled detectors were transported at ground level so as to avoid interference from heavy cosmic-ray nuclei.

The CU stacks consisted originally of eight sets of 25 sheets, each 2 ft $\times$ 3 ft (4.47 m^2 projected area) mounted on plywood, and wrapped in 0.002-in. aluminized mylar.

Three times in the following 3.5 years we removed the top three Lexan sheets of each panel to look for collinear ionization, the signature of a particle track which at this depth of atmosphere could only be caused by a magnetic monopole or by some other currently unknown, novel heavily ionizing particle. The techniques used for analysis were extremely simple. We bathed the Lexan sheets in aqueous sodium hydroxide (pH 14.5, 54 °C) until they were etched to $\frac{1}{3}$ their original thickness. Along the track of a heavily ionized particle the etch rate of damaged material is higher than the bulk etch rate, and a macroscopic hole is etched through the

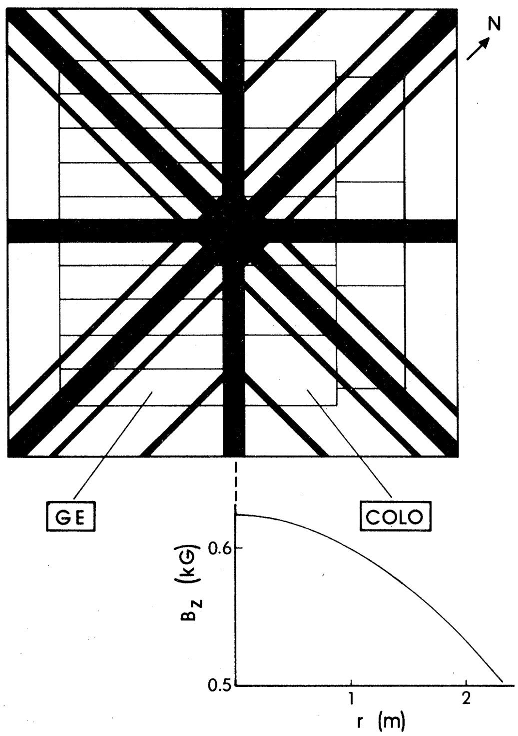

FIG. 3. Detector array, obstructions, and horizontal variations of vertical magnetic field at the elevation of the roof. Beams that obstruct a portion of the area are shown. For slowed monopoles the effective area obstructed is 1.0 to 1.1 times the geometrical area of the obstruction.

sheet along the particle's path.[7] To find these holes we laid the etched Lexan sheet over a sensitive paper and ran the two through an Ozalid blueprinting machine that blows ammonia through any etched hole, leaving an obvious blue spot on the paper.[8] Spots in the same location on the three consecutive blueprints from detectors in one Lexan panel would be the signature of a particle track, and further sheets could consequently have been analyzed for further verification. The background is due to manufacturing irregularities in the Lexan sheets. Upon extended etching such as was used, a portion of these irregularities develop into holes, about 30 per square meter. Each hole's circle of confusion is roughly $(0.5\ \text{cm})^2$ so the chance of accidental overlap in three layers is $[(30 \times 0.25)\ 10^4]^3 \approx 10^{-9}$ per m^2. Furthermore, particle tracks etched through Lexan can be identified by their characteristic conical shape.[7]

The procedures used for the GE stacks were essentially those employed in a previous search for cosmic monopoles.[9] The major differences from the CU procedures are that the stacks were ten 1 ft × 5 ft (4.65 m^2 total area) panels with 20 Lexan sheets in a stack; that each of the times during the experiment the two top sheets were removed for read-out, they were replaced with fresh sheets; that an alcoholic etch was used (1 part 6.25N-NaOH to 1 part ethanol by volume) which allowed etching at room temperature; and that inspection for particle tracks was carried out differently. Each hole through the top sheet (typically $45/m^2$ in these detectors with the etching time and solution used) was visually examined in a stereomicroscope at 30× magnification; and, if a hole could not be rejected with that viewing condition, it would also be viewed in a Leitz Ortholux microscope at 200×. All holes seen were inconsistent with the geometrical properties[7] of etched particle tracks.

For the conditions used we expect that any monopole incident within 64° of the zenith will be detected if it has the Dirac unit charge $\hbar c/2e$ and within 83° of the zenith if its charge is twice the Dirac value.[9,10] In the GE procedure a monopole must penetrate 41.4 mg/cm^2 of material to be detected; in the CU procedure 99.9 mg/cm^2 for penetration of three sheets or 69.4 mg/cm^2 for two sheets (which would probably have been sufficient). For both procedures all plausible accelerated monopoles would traverse the necessary thickness.

At both laboratories samples that were preirradiated with ^{56}Fe nuclei were exposed with the monopole detectors and later etched simultaneously with the monopole detectors to provide control information on the response and extent of etching of the detectors. The Appendix describes the calibration irradiations.

The GE stacks were prepared by 24 November 1976, installed at Fermilab on 5 January 1977, and removed from above the bubble chamber on 26 April 1980 for return to Schenectady. Final etching was begun 27 May for half of the array and 9 June for the other half, giving total exposure times of 1274 days and 1287 days.

Collection area

The area A of the earth's surface over which monopoles are collected is, by magnetic flux conservation,

$$A = (BA)_{\text{detector}}/B_{\text{earth}}$$

$$= (1.6\ \text{kG} \times 9.12\ \text{m}^2)/0.6\ \text{G} = 2.4 \times 10^8\ \text{cm}^2.$$

During the time our Lexan was above the bubble chamber, its magnet had the proper polarity ($\vec{B}$ downward for $T = 2400$ h $= 8.6 \times 10^6$ sec). So ideally our Lexan was exposed to all those positive monopoles collected over an area A of the earth's surface during a time T:

$$(AT)_{\text{ideal}} = 2.1 \times 10^{15}\ \text{cm}^2\,\text{sec}\,.$$

However, after subtracting the monopole trajectories obstructed by the bubble-chamber building (see Fig. 3), we find the actual figure of merit for our experiment:

$$(AT)_{\text{actual}} = 8.4 \times 10^{14}\ \text{cm}^2\,\text{sec}\ .$$

Monopoles incident on this area must be stopped by the atmosphere to be gathered by the magnet and this fact limits the monopole mass for slow monopoles to which our experiment is sensitive. Monopoles that are not stopped can be seen directly [category (2) and (3) particles], but the effective collecting area is reduced to the true area of the detector array.

For the fast monopoles the (AT) factor is given by the stack area 9.12 m^2 times the 1280 days from assembly of the detector arrays up to the average time of development of the last detectors:

$$(AT)_{\text{fast monopoles}} = 1.01 \times 10^{13}\ \text{cm}^2\,\text{sec}\ .$$

RESULTS

No monopole tracks nor those of other penetrating, ionizing particles were observed in either the CU or the GE detectors.

ANALYSIS

We must answer these questions. (A) To what charge and velocity monopoles are our Lexan detectors sensitive? (B) What mass and charge of slowed monopoles will our experiments collect magnetically and record? (C) What monopoles are slowed by the atmosphere? (D) What do we conclude from seeing no tracks? (E) How does our search compare with others?

A. What monopoles can our detectors sense?

Track formation in Lexan has been studied by Fleischer, Price, and Walker.[7] The techniques we used were developed by them for studying high-Z elements in cosmic rays with very similar detectors. To form an etchable track the ionizing particle must eject a minimum number of electrons per unit distance. Their data for Lexan detectors, as shown by Fleischer,[11] fit a primary ionization criterion over a wide range of reduced velocities β (=velocity/velocity of light) ranging at least from $\beta = 0.01$ up to $\beta \approx 0.95$. The empirical formula used to represent the primary ionization J given in Ref. 11 was

$$J = (1.07 \times 10^{-4})\left(\frac{Z^*}{\beta}\right)^2 \left[\ln\left(\frac{\beta^2}{1-\beta^2}\right) - \beta^2 + 15.6\right], \tag{1}$$

where Z^* is the effective charge and the threshold for registration was at $J = 6.5$ in the arbitrary units used. Careful analysis of the existing data shows that 14.3 is a better value for the final constant. For a monopole $(Z^*/\beta)^2$ is replaced by $(n/2\alpha)^2$ and J is therefore given by

$$J = 0.50 n^2 \left[\ln\left(\frac{\beta^2}{1-\beta^2}\right) - \beta^2 + 14.3\right]. \tag{2}$$

The equation tells us that a unit monopole registers an etchable track at $\beta \geqslant 0.34$, a charge-2 pole at $\beta \geqslant 0.0036$ and charge 3 at $\beta \geqslant 0.0015$. Figure 4 shows ionization vs β for a charge-1 and a charge-2 monopole. J is given in the arbitrary units defined by Eq. (1).

Equation (1) implies that monopoles of charge exceeding 1 are recorded by Lexan at very low velocities. However, it should be remembered that the equation has not been tested experimentally for $\beta < 0.01$. The equation clearly fails below $\beta = 0.000\,78$, since it gives negative values. It is a matter of conjecture as to whether a form of etchable damage occurs at low velocities due to an analog of atomic collisons, which produce alpha recoil tracks.[12]

B. What mass and charge of slowed monopoles can we collect magnetically and record?

Of the four categories of monopoles listed in the Introduction, categories (1) and (2) involve the use of the magnet to gather and accelerate monopoles. We discuss these categories before considering the more energetic poles [categories (3) and (4)].

Magnetic collection of monopoles

The two assumptions made in the use of the magnet are derived from the fundamental properties of magnetic poles: Magnetic monopoles are attracted by magnets and they lose kinetic energy

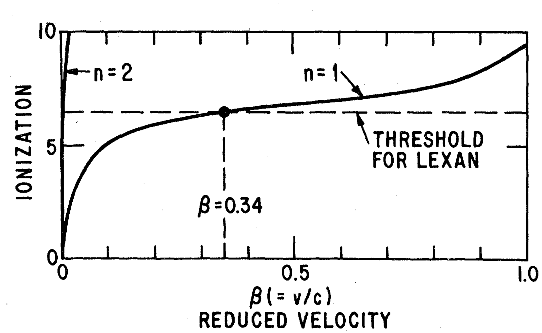

FIG. 4. Relative ionization rate vs reduced velocity (β) for charge-1 and -2 monopoles in Lexan polycarbonate detectors. The threshold for registration is such that $n=1$ poles are recorded at $\beta \geqslant 0.34$ and $n=2$ poles at $\beta \geqslant 0.0036$.

by ionizing their surrounding medium. A magnetic monopole of the proper polarity in the atmosphere above the 15-foot bubble chamber would be accelerated by the chamber's magnetic field through our stacks of Lexan, leaving a track of ionization damage for later analysis.

Magnetic monopoles that are sufficiently slowed by the atmosphere will drift along magnetic-field lines. In the northern hemisphere, where the earth's magnetic-field lines point downward, only positive (north) poles will drift toward our detectors on the ground; to collect these, the magnetic field of the bubble chamber must also point downward. We collect those positive monopoles drifting along field lines which intersect our Lexan detectors above the bubble chamber.

Collection sensitivity

We need next to assess which of the monopoles that would be slowed in the atmosphere sufficiently to be gathered by the magnet [category (1) and (2) monopoles] are accelerated to high-enough velocities to register in the Lexan detectors. An incoming monopole gains an energy $E = ng\int_{z_1}^{z_2} B\,dz$ from the field of the magnet, where z_2 is the height of the detector array (6.4 m above the midpoint of the bubble-chamber magnet) and z_1 is the position where the acceleration provided by the magnetic field exceeds the deceleration due to ionization loss. (This position rises from $z_1 = 10$ m for $n = 1$ to $z_1 = 22$ m for $n = 12$.) From the energy for a given pole strength the upper limit on mass is found at which the velocity just exceeds the critical values for registration that were found in A. Figure 5 shows the results. The maximum mass ranges from 200 proton masses for $n = 1$ to in excess of $10^6\ m_p$ for all poles of higher charge. As noted earlier, for $n > 4$ the critical velocities are not well known, and consequently the thresholds are only approximate.

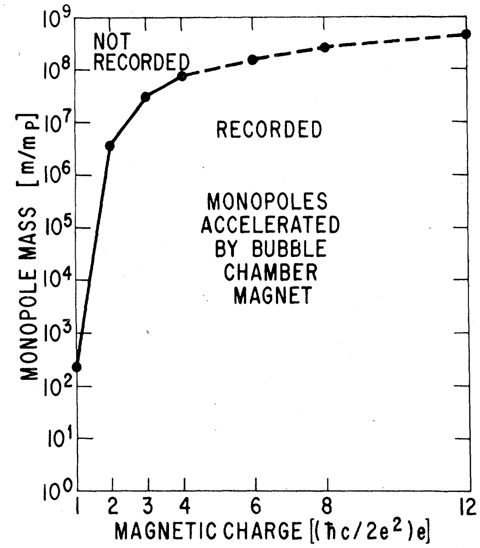

FIG. 5. Detection capabilities for slowed monopoles that are then accelerated by the magnet of the 15-foot bubble chamber. The limit for the most massive monopoles arises because they are not accelerated to high-enough velocities to exceed the ionization threshold.

C. What monopoles are slowed by the atmosphere?

Subject to the limitations given in A and B we now consider the two hypothetical origins of poles that our experiment can record and we describe for each what the applicable charge and mass regimes are and what (area) × (time) factors apply.

Cosmic monopoles

One hypothesis is that free, cosmic monopoles exist in space, are accelerated by the faint magnetic fields there over long distances, and arrive at earth with the very high energies that we noted earlier. These monopoles are either slowed by the atmosphere of the earth to velocities where they can be collected by the magnet and detected [category (2) monopoles] or plunge through the atmosphere directly [category (3) monopoles]. The charge and mass regimes for these two categories are distinct but complementary, the dividing line being derived from the energy-loss properties, which we now describe.

Rates of energy loss

The energy loss of a monopole is given by

$$\frac{dE}{dx} = -\eta E - \zeta\ ,$$

where $\zeta(E)$ is the loss by ionization ($\sim 8n^2$ GeV/$g\,\mathrm{cm}^{-2}$) and ηE is that by bremsstrahlung and pair production. The loss of ionization has recently been calculated by Ahlen, who considered the effects of both near and far collisions.[13] Ahlen finds

$$-\frac{dE}{dx} = \frac{4\pi N e^2 g^2 n^2}{mc^2}\left[\ln(2mc^2\beta^2\gamma^2/I) + K_n/2 - \tfrac{1}{2} - \delta/2 - B_n\right].$$

Here N = number of electrons per unit volume, e = magnitude of the electron's charge, ng = magnitude of the magnetic monopole's charge, $g = \hbar c/2e$, m_e = mass of the electron, $\gamma = (1-\beta^2)^{1/2}$, I = average ionization potential of the medium, K_n = correction for including electron spin, δ = density correction, and B_n = Bloch correction.

When specialized to air as an absorber and extended linearly to low energies,[14] this formula gives

$$\zeta = 1.55n^2(\ln\gamma\beta + 4)\ \mathrm{GeV}/g\,\mathrm{cm}^{-2},\quad \beta > 0.03$$
$$= 860n^2\beta^2\ \mathrm{GeV}/g\,\mathrm{cm}^{-2},\quad \beta \leq 0.03\,. \qquad (3)$$

The contributions for bremsstrahlung and direct electron pair production may be calculated from the standard results for heavy electrically charged particles.[15] A relativistic monopole colliding with a nitrogen nucleus at a large impact parameter radiates the same bremsstrahlung as does an electrically charged particle of charge $ze = ng = 68.5ne$. We assume that this equality holds even at short distances where radiative corrections can be significant. For bremsstrahlung we find

$$\eta_b = n^4\left(\frac{2.56m_p}{m}\right)^2 \frac{1}{X_0}, \quad \gamma > \frac{40m}{m_p} \qquad (4a)$$
$$= n^4\left(\frac{2.56m_p}{m}\right)^2 \frac{1}{X_0}\left(\frac{\gamma\beta^2 m_p}{40m}\right), \quad \gamma < 40\frac{m}{m_p}. \qquad (4b)$$

Here m_p is the mass of the proton, m is that of the monopole, and $2.56m_p = (g^2/e^2)m_e$. X_0 is the usual radiation length (about 40 $g\,\mathrm{cm}^{-2}$ in air), and the reduced contribution in formula (4b) is because the impact parameter for a collision of a relatively soft monopole and a nitrogen nucleus is limited by the size of the nucleus rather than by the usual quantum limit $\nu < E/h$.

In the high-energy limit, the coefficient for the direct production of an electron pair is

$$\eta_p = \frac{10}{\alpha} n^2 \frac{m_e}{m} \frac{1}{X_0}\,. \qquad (5)$$

η_p decreases rapidly as γ is lowered below 10. We shall only need the high-energy limit, however, since the energy lost to pair production is much less than that lost to ionization whenever $\gamma < 700$.

Equations (3), (4), and (5) may be integrated to give the range for monopoles of arbitrary charge, mass, and kinetic energy. Of particular interest is whether a given monopole is slowed to thermal energies by the atmosphere, which we take to be 2000 $g\,\mathrm{cm}^{-2}$, the thickness seen by a monopole incident at the mean zenith angle of 60°. Such a monopole can then be collected over a large area by the fringing magnetic field of the bubble chamber.

Figure 6 shows the results of this integration. Ionization is the dominant energy-loss mechanism for singly charged monopoles. The atmosphere can stop a monopole of approximately 16 000 GeV by ionization alone. More energetic monopoles can only be stopped if their mass is so low that they have an appreciable E/m upon entering the atmosphere and so can be slowed by bremsstrahlung. This feature accounts for the wide separation that is evident between the top two curves as $n \to 1$.

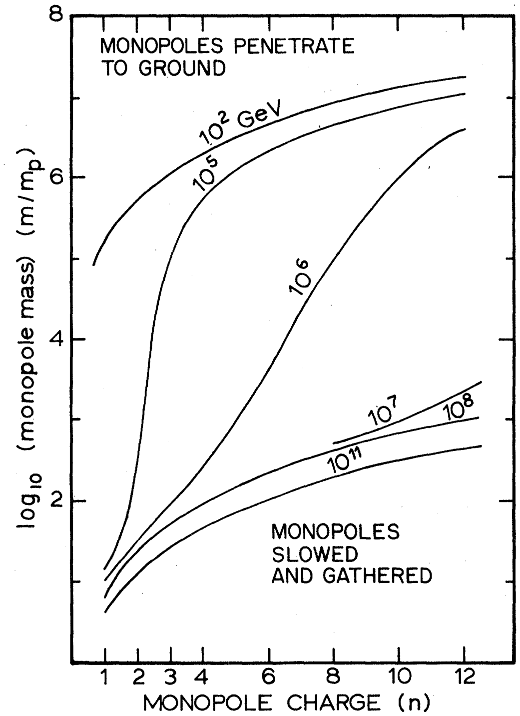

FIG. 6. Mass and charge region of *cosmic monopoles* slowed and gathered by the bubble-chamber magnet. Each curve is parametrized by the kinetic energy of the incident monopole. This energy is the maximum energy which a monopole can have if it is to be stopped by the atmosphere. For instance, a monopole having $n = 10$, $m = 10^6 m_p$ will be stopped if its energy is less than 10^6 GeV. 10^8 GeV is the maximum energy tested here (see text). 10^{11} GeV is the maximum cosmic-ray energy yet observed.

Since all three energy-loss mechanisms increase strongly with n, the curves rise as n increases. By comparing Fig. 5 with Fig. 6, we see that almost any monopole that is slowed by the atmosphere will be detected by the Lexan. The sole exception is a singly charged monopole having a mass $m_g > 100$ GeV.

Practically all cosmic monopoles that are too energetic to be stopped by the atmosphere are still detected directly if they penetrate the Lexan detectors. The sole qualification is that the monopole must have a sufficiently high velocity to leave a track in Lexan. As mentioned earlier, this requirement is fulfilled if $\beta > 0.36$ for singly charged monopoles or $\beta > 0.003$ for multiply charged monopoles. Monopoles which are accelerated by the galactic magnetic field are expected to have an energy of about $10^{10}n$ GeV. Our detectors would be sensitive to such monopoles if their mass were less than 10^{11} GeV for $n = 1$ or 10^{16} GeV for $n > 2$.

Monopoles produced by nuclear interactions

A cosmic-ray proton in colliding with a nucleon of an atom in the atmosphere could produce a pair of monopoles each of mass m_g if its energy exceeded

$$T_{p0}=2m_p c^2\left[\left(\frac{m}{m_p}\right)^2+2\left(\frac{m}{m_p}\right)\right] . \qquad (6)$$

These poles carry the momentum of the incoming proton and hence are moving downward at high velocity. As was the case for the cosmic poles, some are stopped and collected; some move to ground level directly.

Figure 7 shows the mass-charge regime to which the experiment is sensitive. The curved line is the upper boundary of the region in which poles are slowed, gathered by the magnet, and detected. Above that boundary they are detected as directly penetrating particles. The curve is constructed from the data in Fig. 6, assuming that the energy of each monopole $=\frac{1}{2}T_{p0}$. There are upper mass limits near $m_g=10^4 m_p$ established by the low flux of cosmic rays that are energetic enough to produce poles of higher mass.

D. Finding no particle tracks, what can we conclude?

Interactions

To derive an upper limit for the monopole production cross section from nuclear collisions in the atmosphere, we merely divide the cross section σ_p for proton-nucleon collision 30×10^{-27} cm^2 by the number of interactions that could have led to poles that we can observe. Since every cosmic ray will interact in entering the atmosphere, the number of interactions is given by πJAT, where J is the integral flux per unit solid angle and AT is the (area) × (time) factor. J has been found[16] to be $J=1.8E^{-1.67}$ cm^{-2} sr^{-1} sec^{-1}, $E<10^6$ GeV, and $J=180E^{-2}$ cm^{-2} sr sec^{-1}, $E>10^6$ GeV. The flux should be increased by 40% since a primary retains its "useful" energy for more than one collision.[17] For monopoles gathered by the bubble-chamber magnet the effective area should be doubled, since for these monopoles the total area rather than the projected area of the detector is relevant. Also Poisson statistics give the probability of seeing zero events with an average number of events N as e^{-N}; at "the 95% confidence level," $N=3.0$. Thus we can say with 95% confidence that the reaction $pp\to ggX$ has a cross section less than $3\sigma_p/2.8\pi\ JAT$.

Using the known cosmic-ray energy spectrum[16] this quantity can be presented as the cross section as a function of monopole mass for slowed monopoles [Fig. 8(a)] or fast monopoles [Fig. 8(b)], the difference being due to the lower AT factor for the

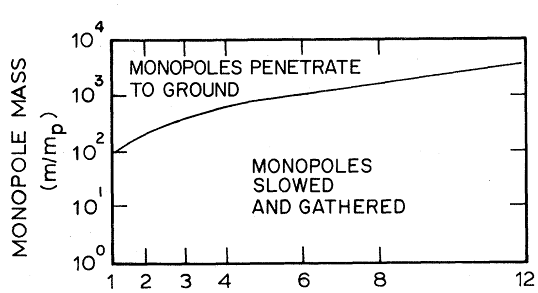

FIG. 7. Mass and charge region of monopoles *produced* by cosmic rays in the upper atmosphere. The curve separates the region of monopoles that are slow enough to be stopped by the atmosphere (light monopoles) from those that penetrate the detectors directly.

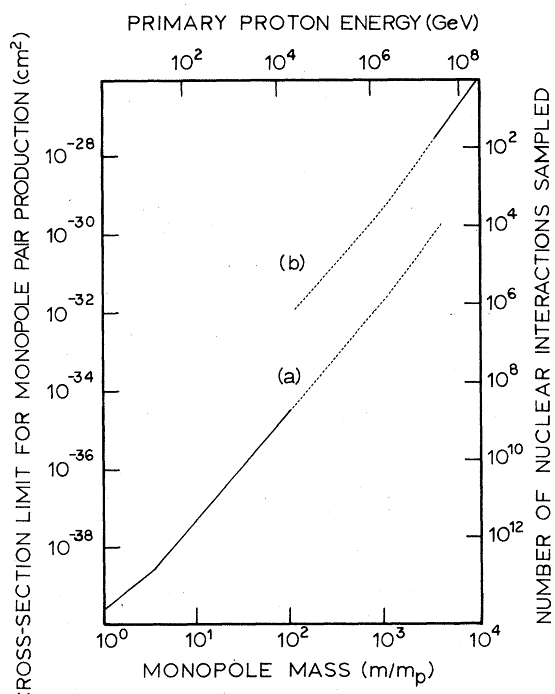

FIG. 8. Calculated 95% confidence limits, as a function of monopole mass, for the maximum cross section for monopole pair formation in the upper atmosphere. On the right are given the number of primary interactions sampled and on top the energy of the interacting primary cosmic-ray particles. In (a), the limits are inferred from lack of tracks from poles that would be gathered by the magnet. In (b) the limits are for energetic poles that would be detected directly without the gathering effect of the magnet.

latter case. The number of interactions leading to the cross-section limits and the associated cosmic-ray energies are also noted on the graphs, the limits range from 3×10^{-40} cm^2 for $m_g = m_p$ poles to $\sim10^{-25}$ cm^2 for $m_g = 10^4\,m_p$. By inspection of Fig. 8, we find that cosmic rays have been sampled by this experiment up to an energy of about 10^8 GeV. It is interesting to note that this is near the energy regime ($T \approx 10^9$ GeV) where the cosmic-ray spectrum achieves its final change of slope, the new slope extending to the highest energies recorded. This change of slope is often interpreted as an indication of the dominance of a different component of cosmic rays, such as an extragalactic contribution. If this component is related to magnetic monopoles, our experiment has not tested this hypothesis thoroughly, since we have only begun to sample this high-energy portion of the cosmic-ray spectrum.

Cosmic monopoles

From the cosmic-ray flux we can conclude with 95% confidence that the flux of cosmic monopoles is less than $\pi J/3$ and that therefore the fraction of cosmic rays that are monopoles is $<3/\pi JAT$ with 95% confidence. This quantity is $\sim10^{-13}$ for an energy of 5×10^9 eV and above and increases to unity at 3×10^{17} eV. This statement is subject to the charge and mass limitations of Fig. 6. For cosmic rays that would be registered directly the statements are less restrictive by a factor of 160, the ratio of effective areas × times.

E. How does this search compare with others?

Other searches for monopoles have examined accelerator targets and ordinary bulk matter which has been exposed to cosmic rays. Accelerator searches have the advantages of high fluxes and predictable monopole trajectories, but cannot yet achieve the high energies of cosmic rays. Conversely, cosmic rays attain high energies but at low fluxes and with the monopole's fate often importantly model dependent.

Accelerator techniques include extracting monopoles produced in targets and beam dumps by high magnetic field,[18-21] surrounding colliding beam intersection regions with plastic ionization detectors,[22] measuring the change of magnetic flux in a SQUID magnetometer as previously irradiated materials are passed through it,[23] measuring the current induced in a coil by the transit of irradiated materials,[24] and looking for photons produced by monopole pair annihilations.[25]

The null results of these searches limit the monopole-pair-production cross sections at low masses as shown in Fig. 9 and listed in Table I.

Many samples of naturally occurring matter have been searched for monopoles. Presumably monopoles, once stopped, would remain in these samples for very long times. The technique of magnetic extraction has been applied to a magnetic outcrop,[26] an iron meterorite,[26] sea sediment,[27] and ocean bottom ferromanganese crust.[28,29] Current-induction techniques have been used for lunar surface material, Arctic rock, Antarctic rock, and meteorites.[24] Tracks from highly ionizing particles have been sought in mica and obsidian.[30] Except for the last search, these searches assume monopole collection, trapping, and stability over geologic time scales. This feature is both their strength and their weakness; it is difficult to predict with certainty the fate of a particle on the earth's surface for millions of years.

Also, previous searches have overestimated monopole ionization losses at low velocities, and

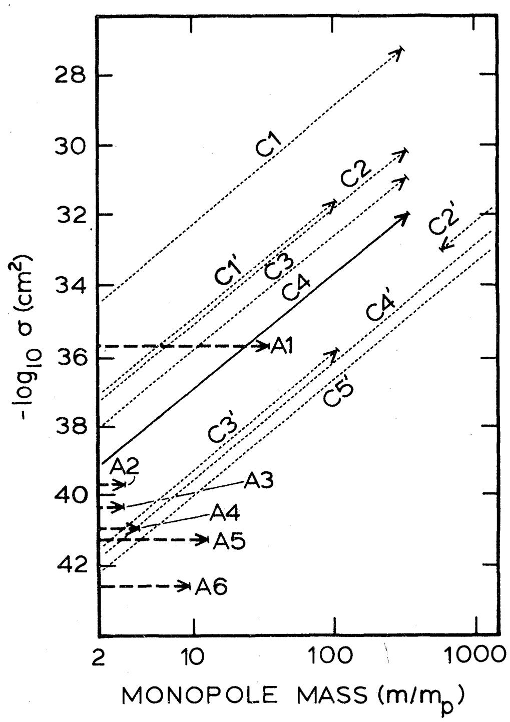

FIG. 9. Cross-section limits of this experiment (C4) compared to those of other studies. Similar cosmic-ray searches: C1 from Ref. 4; C2 from Ref. 9; C3 from Ref. 31. Cosmic-ray searches with monopoles or tracks stored for geological times: C1′ from Ref. 26; C2′ from Ref. 30; C3′ from Ref. 24; C4′ from Ref. 27; C5′ from Ref. 29. Accelerator searches: A1 from Ref. 22; A2 from Ref. 20; A3 from Ref. 18; A4 from Ref. 19; A5 from Ref. 21; A6 from Ref. 23. For masses above $30m_p$ this is the most restrictive study that does not assume monopole trapping (except Ref. 30 which applies to ultrahigh masses and $n>1$).

TABLE I. Searches for cosmic-ray-related magnetic monopoles.

Search	Notation in Fig. 9	Reference number	$g=ng_D$	$(A\times T)$ cm^2 sec	Comments
Malkus (1951)	C1	4	$n\geq 1$	10^{10}	Collecting magnetic funnel
Fleischer *et al.* (1971)	C2	9	$\|n\|\geq 1$	10^{13}	No collecting magnet
Carithers *et al.* (1966)	C3	31	$n\geq 1$	10^{14}	Collecting magnetic funnel
This work (1981)	C4		$n\geq 1$	10^{15}	Collecting magnetic funnel
Goto *et al.* (1963)	C1′	26	?	10^{13}	Pulsed field extraction; would not have detected poles released at low fields
			$\|n\|\gtrsim 2$	10^{18}	Tracks left in mica buried under
Fleischer *et al.* (1969)	C2′	30			5 km of earth; $E_0\geq 10^{10}$ GeV; $m/m_p>10^5$
			$\|n\|\geq 2$	10^{16}	Tracks left in obsidian at earth's surface $E_0\geq 10^6$ GeV
Eberhard *et al.* (1971)	C3′	24	$\|n\|\geq 1$	10^{18}	8 kg of lunar material; quoted results depend strongly on separation of two poles, mixing depth of lunar surface, and dE/dx at low velocities
Kolm *et al.* (1971)	C4′	27	$\|n\|\geq 1$	10^{17}	Barrels of sea sediments; quoted results depend strongly on imperfectly known sedimentation rate
Fleischer *et al.* (1969)	C5′	29	$\|n\|\geq 1$	10^{18}	Monopoles may drift along the ferromanganese crust

thus assumed registration to occur where it might be marginal. So their cross-section limits graphed in Fig. 9 though quite stringent are also model dependent and should be regarded with some caution (see Table I).

Experiments like ours which do not rely on long collection times for adequate cosmic ray fluxes must compensate by using large collection areas, either as large detectors or via magnetic "funnels." Searches have included balloon-borne[2,9] and ground-based[9] ionization detectors, ground-based ionization detectors enhanced by magnetic collection,[4,31] and searches for abnormal ratios of scintillation to Čerenkov light in extensive air showers.[32] For this sort of experiment we have the largest figure of merit (area × time) and can set the most stringent limit on the monopole production cross section.

Theory by 't Hooft[33] led him to suggest that a monopole might have a mass ≈137 M_W, where W is the vector boson. He estimates[34] $m_g\approx 5000\ m_p$, which is within the mass range to which our experiment is sensitive. Grand unified theories have been used to infer masses of the order of that of superheavy gauge bosons, which are estimated[35] to exceed $10^{15}\ m_p$. Even if such massive poles of unit charge are accelerated to the maximum energy found in the cosmic rays, 10^{11} GeV, they still would be too slow to register. All higher-integral charges, however, would register. Use of a more sensitive detector, such as allyl diglycol phthalate, and of much higher area × time factors would be required to assess the existence of such particles in the cosmic radiation.

The search for magnetic monopoles has been long and complex. In principle, one must search over the entire two-dimensional space of mass and charge with only limited guidance as to which portion of this space is most likely. We have made explicitly clear what portion of the mass-charge space we have sampled, and what portion of the energy spectrum of cosmic rays we have utilized. We have set quantitative limits for the existence of poles within this space. These limits (for example, phrased in terms of an area × time factor) can be thought of as a further dimension, whereas the qualifications, or assumptions made in a particular search provide other parameters. If all searches were analyzed in these terms, the composite picture would indicate which portions of this complex space merit further experimentation, and, indeed, which portions have not been searched at all. The question therefore remains: Are magnetic monopoles lurking in an unidentified crevice of mass-charge space?

ACKNOWLEDGMENTS

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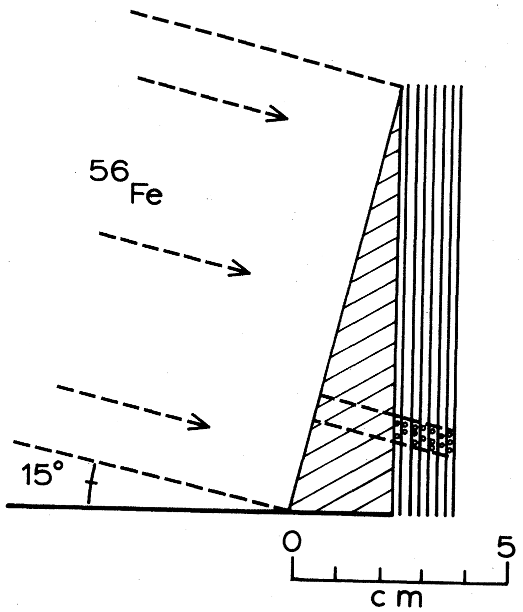

FIG. 10. Geometry of CU calibrations. A lead wedge moderated the broad ^{56}Fe beam before it entered a stack of 50 0.01-in.-thick Lexan sheets. Upon etching holes are formed in the Lexan in the small region indicated. GE calibrations were similar except that a 45° angle of incidence was used.

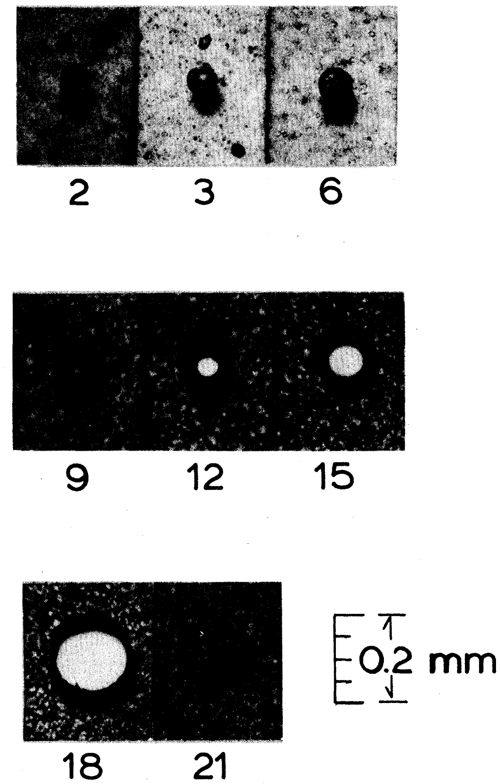

FIG. 11. Photos show variation of track appearance (after etching) with placement of sheets. Lexan sheets are numbered consecutively beginning with the first sheet after Pb wedge. Ionization in sheets 9—18 is sufficient to form a perforation. Nucleus stopped in sheet 21.

APPENDIX: LEXAN CALIBRATION

To determine what ionization rate is needed for track formation, we exposed a sample Lexan detector to a beam of relativistic iron nuclei at the Berkeley Bevatron, then etched and processed it by the Ozalid technique[8] described earlier.

The beam of fully stripped iron ions of 0.59 GeV/nucleon kinetic energy was variably moderated by a lead wedge, spreading out the velocities and hence the ionization rates of the nuclei incident on the Lexan stack (Fig. 10). Knowing the incident beam's kinetic energy and subtracting the energy lost traversing the lead and Lexan before forming a track, we can find the moderated beam's kinetic energy at the start of track formation. The threshold for track formation is the ionization rate at that energy. The range of the fastest iron nucleus which will leave a track in Lexan was measured to be 0.15 cm of lead or 0.45 cm of Lexan, corresponding to a kinetic energy of 0.095 GeV/nucleon. Nuclei forming holes which we can observe with the Ozalid technique have energies of 0.075 GeV as illustrated in Fig. 11. Thus an iron nucleus ($z^* = z = 26$) will just be detected if its velocity $\beta = (0.16)^{1/2}$. Using this value in Eq. (1) confirms the choice of $J = 6.5$ as the threshold value for the primary ionization necessary to leave an etchable hole in Lexan.

For calculating energy losses and ranges of iron nuclei in lead and Lexan we used the standard semiempirical formulas taken from Fano.[36] Similar results are obtained from the range-energy relations of Henke and Benton.[37]

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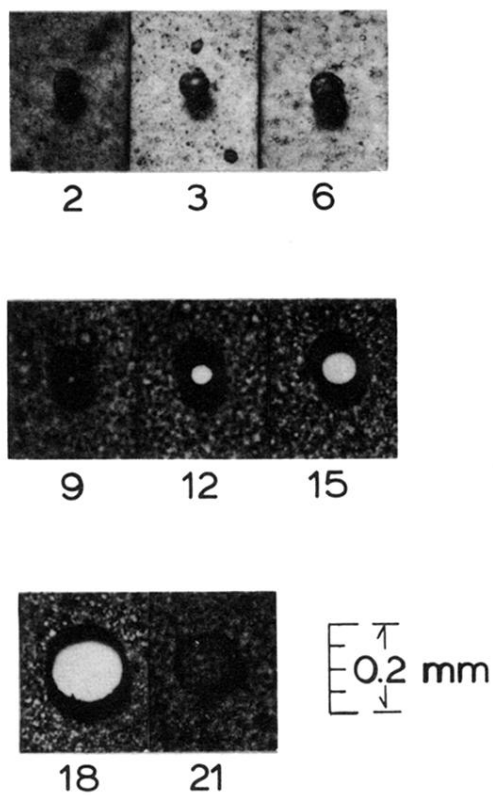

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