[("$I$","$I_z$")=(1,1) for $K_0$; (1,0) for $\pi^0$]. With respect to the same subgroup, $\pi^-$ has the quantum numbers $(\frac{1}{2},\frac{1}{2})$, $p$ the quantum numbers $(\frac{1}{2},\frac{1}{2})$, and for $\Lambda^0$ one has (0,0). It then follows that the $(K^0\pi^0)$ system in this reaction is uniquely in an "$I$"=1 state, hence, that the reaction amplitude is purely antisymmetric under $K^0 \rightleftarrows \pi^0$. But this means that the differential cross section must be symmetric under interchange of the $K^0$ and $\pi^0$ momentum vectors.

(3) Similarly, consider the reaction

$$\gamma + p \rightarrow Y_1^{-*} + K^+ + \pi^+ .$$

In the octet model of $SU(3)$ one can define a subgroup[13,14] similar to the one discussed under (2). With respect to this subgroup, $K^+$ and $\pi^+$ belong to a common doublet [("$I$","$I_z$")=$(\frac{1}{2},\frac{1}{2})$ for $K^+$; $(\frac{1}{2},-\frac{1}{2})$ for $\pi^+$]; $p$ has the quantum numbers $(\frac{1}{2},\frac{1}{2})$, the 1385-MeV resonance $Y_1^{-*}$, supposedly belonging to the representation ten,[15] has the quantum numbers $(\frac{3}{2},\frac{1}{2})$, and the photon transforms like a scalar (0,0). Therefore, the $(K^+\pi^+)$ system in this reaction is in a pure "$I$"=1 state, hence, the reaction amplitude is symmetric under $K^+ \rightleftarrows \pi^+$.

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# Search for Ferromagnetically Trapped Magnetic Monopoles of Cosmic-Ray Origin*

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Magnetic monopoles, if they exist, should be trapped and accumulated in ferromagnetic materials. Using the high field of a pulsed magnet, we have sought to extract monopoles from a magnetite outcrop on the earth's surface and from fragments of a stony-iron meteorite. In the nuclear emulsions used for detection, no tracks were found satisfying our geometric criteria and having an energy-loss rate compatible with the theoretical expectation for monopoles. The area-time product of the magnetite cosmic-ray exposure is estimated to be about $10^{13}$ cm$^2$ sec. From the negative results, upper-limit monopole production cross sections in the atmosphere are estimated as a function of assumed monopole mass.

## 1. INTRODUCTION

THIS paper describes a search for magnetic monopoles of cosmic-ray origin. The sensitivity to monopoles incident in the primary cosmic radiation or created in the atmosphere by primary particles is about one-thousand-fold greater than in a previous cosmic-ray experiment of Malkus.[1] The total primary proton flux effective in our experiment is two orders of magnitude less than the proton flux in the accelerator experiment of Purcell *et al.*[2] However, our negative results usefully supplement this and other recent accelerator experiments[3,4] because of the possibility that the monopole is present as a primary cosmic-ray particle and/or the possibility that the monopole mass exceeds 2.9 BeV, the maximum that the accelerator experiments could have revealed.

Because of the anticipated scarcity of monopoles, our experiment, like earlier ones, was designed to detect a single monopole. Such sensitivity is not difficult to achieve if the monopole indeed carries the Dirac quantum of magnetic charge, $g_0 = 68.5e$, for in that case the monopole can readily be accelerated to high energy in a moderate magnetic field, and in traversing the

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‡ Work supported in part by the National Science Foundation.

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matter of a counter or emulsion, will experience a characteristic high rate of energy loss.[5,6]

Using a total of $5.7\times10^{15}$ protons of 30 BeV, the Brookhaven group[2] established the following upper limit pole-production cross sections: For poles of mass 2.9 BeV or less, $\sigma$(proton-nucleon) $\leqslant 2\times10^{-40}$ cm$^2$; for poles of mass 2.4 BeV, $\sigma$(gamma-nucleon) $\leqslant 10^{-34}$ cm$^2$, and $\sigma$(gamma-carbon) $\leqslant 10^{-36}$ cm$^2$. Similar limits were obtained by groups at CERN[3,4] and by a Berkeley group[7] working at lower energy (6 BeV protons, monopole mass 1.0 BeV or less). In the only reported cosmic-ray experiment, Malkus[1] scanned an effective area of 8300 cm$^2$ for two weeks—an area-time product of $10^{10}$ cm$^2$ sec—thereby setting an upper limit of $10^{-10}$ north monopoles/cm$^2$ sec in the primary cosmic radiation.[8] The total number of primary protons with energy above 1 BeV incident in $10^{10}$ cm$^2$ sec is about $2\times10^{10}$; of these, $5\times10^8$ have an energy above 30 BeV. Typical upper-limit pole production cross sections from Malkus' work are for poles of mass 5 BeV, $\sigma$(proton-nucleon) $\leqslant 7\times10^{-34}$ cm$^2$; for poles of mass 10 BeV, $\sigma$(proton-nucleon) $\leqslant 5\times10^{-33}$ cm$^2$. Since actual monopole production cross sections less than these upper limits are easy to imagine, Malkus' experiment does not provide convincing evidence against the existence of heavy monopoles. On the other hand, the accelerator experiments are convincing—they make it very difficult to believe in the existence of monopoles less massive than 2.9 BeV.

In order to increase the effective time of cosmic-ray exposure in searching for monopoles, we have taken advantage of the fact that ferromagnetic materials exposed to cosmic rays for geologic periods of time should act as accumulators of monopoles. Our approach was suggested in 1958 by Goto,[9] who showed that monopoles should be trapped in ferromagnetic materials near the surface or near domain boundaries with binding energies such that they could be extracted only by very intense magnetic fields, or by destroying ferromagnetism by heating. In our experiment magnetite outcrop in the northern Adirondacks, and fragments of a stony iron meteorite, were subjected to magnetic fields of sufficient intensity to ensure the extraction of trapped monopoles. These monopoles would have been accelerated to an energy of several BeV in vacuum, allowed to pass through two successive nuclear track emulsions, and then collected in a ferromagnetic target for further experiments. No monopoles have been found, although the area-time product of our search to date is roughly $10^{13}$ cm$^2$ sec for the magnetite, plus an unknown but probably larger figure for the meteoritic material.

After reviewing the theoretical properties of monopoles (Sec. 2), we calculate the magnitude of binding energies involved in ferromagnetic trapping and the intensity of magnetic field required for extraction (Sec. 3). We then describe our experiment (Sec. 4) and examine the implications of the negative result (Sec. 5).

## 2. THEORETICAL PROPERTIES OF MONOPOLES

### A. Intrinsic Properties of Monopoles

Nothing in classical physics prohibits the existence of monopoles. Indeed, nonvanishing magnetic charge would bring a better balance to Maxwell's equations. Attacking the problem of incorporating magnetic charge into the framework of quantum mechanics in 1931, Dirac[10] concluded that quantum physics also failed to prohibit the existence of monopoles, provided the charge carried by each is an integral multiple of $g_0$, defined by $g_0e=\frac{1}{2}\hbar c$. No subsequent theoretical study[11–21] has provided any reason for the nonexistence of monopoles, and in the more than thirty years since Dirac's first paper on the subject, the trend of particle physics— especially the increasingly central role of symmetry principles—has made the existence of monopoles more, not less, credible. The only theoretical argument that makes monopoles somewhat unappealing is that they eliminate the electromagnetic potential. That this is not an objection against their existence, however, has been shown recently by Cabibbo and Ferrari.[21] Dirac's original argument that the quantization of electric charge could be understood if monopoles exist has been unchanged by renormalization theory and other developments of field theory. In fact, the modern developments make it more reasonable that the renormalized values of the elementary electric charge and magnetic charge should not be equal to each other despite the complete electric-magnetic symmetry at the classical level.

The monopole is commonly assumed to have charge $g_0=137e/2=3.29\times10^{-8}$ in cgs units. Our experiment is capable of detecting monopoles of this or any larger charge. (It would also reveal monopoles with charge down to several times less than $g_0$). Its magnetic charge is the defining characteristic of a Dirac monopole, and no other intrinsic property is predicted. The mass is probably "large" because the coupling constant is large. A "canonical mass" may be defined by the Salam-Tiomno rule[22] based on the observation that the ratio

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of the proton mass to the electron mass is the same as the ratio of the square of the strong-interaction coupling constant to the square of the electric coupling constant. This gives a cononical mass of 2.4 BeV $[(137/2)^2 m_e]$ to the monopole, the same as would follow by arbitrarily assuming equal classical radii for monopole and electron. Already experimental evidence seems to rule out this mass value. Nothing can be said about the spin of the monopole, nor about its interactions other than electromagnetic. If monopoles exist at all, there is no reason to suppose them all identical. Rather one would expect to find a family of many different sorts of monopoles, just as there are many different sorts of electrically charged particles, but with the masses of magnetic particles generally much larger than the masses of electric particles.

### B. Acceleration and Deceleration of Monopoles

For the present experiment, we are concerned only with the trapping energy and trapping force of monopoles in ferromagnets (to be dealt with in Sec. 3); with the acceleration of monopoles by magnetic fields; and with the rate of energy loss of monopoles in matter. (An interesting discussion of the behavior of monopoles in liquids and solids is contained in Ref. 2.) In a magnetic field in vacuum, a monopole gains energy at the rate of $2.06\times10^4$ $(g/g_0)$ eV/G cm. Thus, in a field of $10^5$ G, roughly the conditions in this experiment, a monopole of unit charge $g_0$ gains 2 BeV/cm. Since the rate of energy loss in air is not more than 10 MeV/cm, a field of $10^5$ G would produce a runaway situation in air; the partially evacuated chamber we used was not a necessity.

The figures above are relevant also to the question of the behavior of monopoles in the cosmic radiation. In falling from infinity to the top of the atmosphere above the north pole, a north monopole would gain an energy of $3.8\times10^{12}$ eV, and nearly as much at other northern latitudes. The blanket of air is capable of stopping all monopoles with energy less than $8\times10^{12}$ eV. Therefore, unless the primary monopoles are remarkably energetic, most of them should be thermalized in the atmosphere.

There is some chance that primary monopoles might have an average energy greater than the atmospheric stopping power. Magnetic dipole fields in space will be natural accelerators of monopoles. A funneling effect will cause monopole-accelerating collisions with the field to be much more probable than monopole-decelerating collisions. This effect is in addition to any effect from moving fields. Monopoles should, therefore, be accelerated to much higher energies than are protons. Porter[23] has suggested that monopoles may be an important constituent of the extreme high-energy cosmic rays. These considerations suggest that ferromagnetic material on the ocean floor should be examined for possible accumulated monopoles. Monopoles of energy $10^{16}$ eV would be thermalized in traversing about 8 miles of water.

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

Most monopoles produced by proton-nucleon collisions in the air should be thermalized before reaching the earth. If produced not far above threshold (a reasonable assumption in view of the rapidly decreasing intensity of primary protons with increasing energy) and if more massive than protons, a pair of monopoles would carry forward approximately the initial momentum of the primary proton. A monopole of mass 10 BeV, for example, would be created with an energy of about 100 BeV, and would easily be thermalized in the air. The atmosphere could stop proton-produced monopoles up to a mass of nearly 100 BeV.

A relativistic pole passing through matter should behave almost exactly like a minimum ionizing charged particle of charge 68.5$e$, losing energy at the rate of about 8 BeV/(g/cm$^2$).[6,7] This is an energy loss rate of about 18 BeV/cm in a typical emulsion, some twelve times greater than the energy loss rate of a 6-MeV alpha particle, and five times less than the average energy loss rate of a fission fragment. The latter two particles, of course, have short ranges in emulsion, about 25 and 10 $\mu$, respectively; a 10 BeV monopole, on the other hand, would have a range in emulsion greater than 5000 $\mu$. A monopole in an emulsion could not be confused with any particle other than a fast heavy nucleus. This confusion could be eliminated by the study of the tapering end of the track,[24] but we have made no effort in this experiment to stop monopoles in the emulsion, relying rather on geometrical considerations for positive identification, supplemented by the intention of trapping and reusing any monopoles discovered.

### C. Production of Monopoles

The monopole production cross section, even in the simplest case—a gamma ray incident on a proton—is incalculable for two reasons. First, the monopole-photon interaction is strong. Second, the presumably large mass of the monopole causes the production to involve larger momenta (smaller distances within the proton) than have been investigated before. The following arguments are intended to give a very rough order-of-magnitude figure for the monopole pair production cross section.

The cross section for pair production of electrons of mass $m$ and charge $e$ in the field of a heavy charge $Ze$ is proportional to the fundamental area $\sigma_e$ given by (with $\hbar=c=1$)

$$\sigma_e=Z^2e^6/m^2. \tag{1}$$

This may be interpreted as the probability, $e^2$, that the photon exists virtually as an electron-positron pair, multiplied by the cross section, $Z^2e^4/m^2$, for scattering one of the virtual electrons onto the mass shell with

[24] R. Katz and O. R. Parnell, Phys. Rev. **116**, 236 (1959).

momentum transfer $q^2=-4m^2$. The latter factor may, therefore, be written $-4Z^2e^4/q^2$. With this interpretation, it would obviously be incorrect in going over to monopole pair production simply to replace $e$ by $g$ and $m$ by $M$, the monopole mass. Instead, we replace one factor $e^2$ by unity, and hypothesize that the fundamental area $\sigma_m$ for monopole pair production is

$$\sigma_m=-4Z^2e^2g^2/q^2. \tag{2}$$

Just above threshold,

$$q^2=-4M^2M_t/(2M+M_t), \tag{3}$$

where $M_t$ is the target mass. The area $\sigma_m$ must now be reduced because of the weakening of the electric field within the charged target. We postulate a simple form factor reduction, and write for the order-of-magnitude monopole pair production cross section

$$\sigma=\sigma_m|F(q^2)|^2. \tag{4}$$

For the purpose of a numerical estimate, we assume (1) that the nuclear form factor reduction will be great enough to offset the factor $Z^2$, making the gamma-proton cross section dominant; (2) that the monopole has the unit charge $g_0$ such that $eg=\frac{1}{2}$; (3) that production near threshold is dominant because of the shape of the primary cosmic-ray spectrum; and (4) that the monopole is substantially more massive than a proton, so that $q^2\simeq-2MM_p$, where $M_p$ is the proton mass. These approximations lead to

$$\sigma=|F(-2MM_p)|^2/2MM_p. \tag{5}$$

The "theoretical" curve shown in Fig. 5 is based on Eq. (5), using the exponential form factor,

$$F(q^2)=[1-q^2R^2]^{-2}, \tag{6}$$

with $R=0.23$ F. The cross section given by Eq. (5) represents little more than a guess and serves principally to emphasize that monopole pair production cross sections are probably orders of magnitude smaller than electron pair production cross sections, and depend sensitively on the assumed monopole mass.

### 3. FERROMAGNETIC TRAPPING

From the viewpoint of monopole interaction, there exists a fundamental difference between the otherwise indistinguishable magnetic fields of a current loop and a permanent magnet. A monopole is able to extract energy from the source of current by passage through the loop; however, it cannot extract energy by a corresponding passage through the permanent magnet which, without loss of generality, may be thought of as a single magnetic domain in its lowest energy state. A monopole that has been accelerated from the south to the north pole of the permanent magnet along a line of the external $B$ field will conserve energy only if the field it encounters while completing its circuit through the magnet is the oppositely directed $H$ field. Thus, it follows from purely macroscopic considerations of energy conservation that the average force on a monopole in matter must be given by $gH$, not by $gB$ (we use Gaussian units), and that the monopole must experience a potential minimum at the surface of a permanent magnet.

Purcell[25] reached the same conclusion by a convincing microscopic argument. The $B$ field in matter is the space and time average field of the undisturbed matter. In order to feel the $B$ field, the monopole would have to pass near or through the atomic dipoles in a time less than the characteristic Larmor precession time. But the ratio of the time of passage to the precession time is approximately $eg/mcrv$, where $m$ is the mass of an electron, $v$ is the monopole velocity, and $r$ is the distance of closest approach of the monopole to the dipole. For this distance less than the "size" of the electron, $\hbar/mc$, and for $eg=\hbar c/2$, the ratio of time of passage to precession time is greater than $c/2v$. The monopole cannot sample the undisturbed field close to an atomic dipole. The average field it experiences between dipoles is, according to the cavity definition, the $H$ field. The difference between the $B$ and $H$ field is, of course, enormous, amounting for a monopole of unit charge in a typical permanent magnet to about 100 MeV/cm.

When a monopole encounters a ferromagnetic medium that is substantially unmagnetized, it will also experience an attraction, caused by the magnetization it induces. At large distances from the surface the monopole will be attracted by its magnetic image charge. Near or within the ferromagnetic medium, saturation complicates the problem but can be dealt with approximately.

We assume an infinite plane interface at $z=0$ between a ferromagnetic at $z<0$ and vacuum at $z>0$. The ferromagnetic is ideally soft, that is

$$\begin{aligned} &H=0, \quad B=4\pi M \quad \text{when} \quad B<4\pi M_s, \\ &B=H+4\pi M_s \quad \text{when} \quad B>4\pi M_s, \end{aligned} \tag{7}$$

where $M_s$ is the saturation magnetization. This is a reasonably good approximation for most ferromagnetics, those which saturate at low values of $H$. A parameter of interest is $R_s$, the radius of the sphere of saturation surrounding a monopole of strength $g$ in an infinite ferromagnetic medium. It is given by

$$R_s=[g/4\pi M_s]^{1/2}, \tag{8}$$

and has a value of about 120 Å for a unit pole in iron.

We calculate the trapping force on the monopole according to the following model, to be justified below. Let the monopole of strength $g$ be located a distance $z$ from the interface. Pretend that the magnetization in the ferromagnetic is equal to that produced by a single image pole $a(z)g$ at the location of the monopole (See Fig. 1). Then the trapping field at the monopole

[25] E. M. Purcell (private communication).

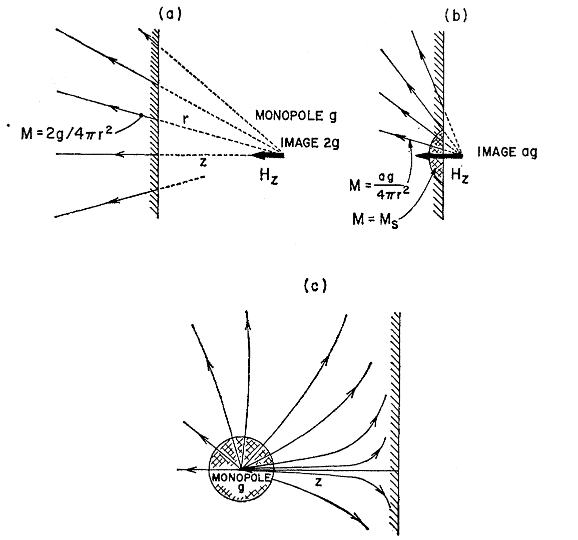


FIG. 1. Model for calculation of monopole trapping force. (a) For the monopole far outside the ferromagnetic, the magnetization is that produced by an image pole $2g$ at the same location as the monopole. (b) For the monopole near the ferromagnetic, the lines of force in the ferromagnetic are assumed to radiate from the monopole; this error is compensated by the adjustable strength $ag$ of the image pole. (c) For the monopole deep inside the ferromagnetic, the lines of force are those produced by image poles $g$ at the location of the monopole and $g$ an equal distance outside the ferromagnetic. There is no force on the monopole.

created by the induced magnetization will be

$$H_z = -a(z)g/8z^2, \quad \text{for} \quad |z| \leqslant [a(z)]^{1/2}R_s \tag{9}$$

and

$$H_z = -4\pi M_s\left[\tfrac{1}{2}\ln\left(\frac{[a(z)]^{1/2}R_s}{|z|}\right)+\frac{z^2}{8a(z)R_s^2}\right], \quad \text{for} \quad |z| \geqslant [a(z)]^{1/2}R_s. \tag{10}$$

The arbitrary parameter $a(z)$ of course permits the model to yield the correct induced field $H_z$ at all $z$. The justification of the model consists in finding suitable approximate values for $a(z)$.

For the monopole in vacuum and for $z > 2^{1/2}R_s$, the model is correct, and $a(z)=2$. In this case, the ferromagnetic is entirely unsaturated, and the field in the ferromagnetic is that produced by an image charge $2g$ at $z$. For the monopole deep within the ferromagnetic, $|z| \ll R_s$, the field within the ferromagnetic is the superposition of fields of image poles $g$ at $z$ and $g$ at $-z$. The monopole feels no force. The model does not correctly give the magnetization; it correctly gives the induced field at the monopole if $a(z)$ is set equal to zero. For a third limiting case, monopole close to the interface, $|z| \ll R_s$, the part of the ferromagnetic near the monopole behaves much the same as a vacuum; consequently, $a(z)$ is close to 1. Qualitative arguments show that in the intermediate regions, where $|z| \approx R_s$, $a(z)$ also does not differ much from 1. Probably $a(z)$ is nowhere greater than the value 2 which it acquires at large $z$. Certainly the peak value of the trapping force occurs for $|z| \approx 0$, where $a(z)$ is approximately equal to 1.

If $a(z)$ were constant, the trapping energy would be given by

$$E = -g\int_{-\infty}^{\infty} H_z dz = a^{1/2}(4g^2/3R_s). \tag{11}$$

For the idealized ferromagnetic described by Eqs. (7), the trapping energy is known[10] to be exactly $4\ g^2/3R_s$. This result is duplicated within 0.3% by the choice, $a(z)=0,\ z<-2^{1/2}R_s;\ a(z)=1,\ |z|<2^{1/2}R_s;\ a(z)=2,\ z>2^{1/2}R_s$. The force curve shown in Fig. 2 is a smoothed version of this model with the correct energy integral.

The image force on a charge near a conductor is strongly divergent (as $z^{-2}$) for $z\rightarrow 0$, indicating the failure of the macroscopic treatment at atomic dimensions. The correct trapping energy of an electron in a conductor is given by choosing a lower cutoff distance of about $10^{-8}$ cm. For a monopole attracted to a ferromagnetic, the saturation property of the ferromagnet weakens but does not eliminate the divergence. Equation (10) retains a logarithmic divergence, and a cutoff is required in order to calculate the maximum trapping force, although not to calculate the trapping energy. We make the reasonable choice of $10^{-8}$ cm for the cutoff distance, the resulting peak field being fortunately insensitive to this choice. Then, taking $a(0)=1$, we find from Eq. (10) the following peak fields for the extraction of a monopole of unit strength $g_0$:

$$H_{\max} = 53 \text{ kG for iron } (4\pi M_s = 22 \text{ kG}),$$
$$H_{\max} = 16.4 \text{ kG for magnetite } (4\pi M_s = 6 \text{ kG}). \tag{12}$$

For the upper limit value $a=2$, these figures are raised only slightly, to 57 and 17.4 kG.

The possibility that strong microscopic attractive fields act on the monopole still needs to be examined. Malkus[1] calculated monopole-atom binding energies of a few eV. Whether nuclei with magnetic moments bind, possibly much more strongly, in unknown, for no

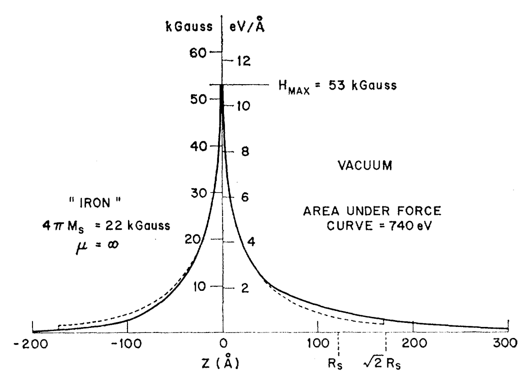


FIG. 2. Trapping force of "iron" ($4\pi M_s = 22$ kG, $\mu=\infty$) on unit monopole, assuming a variable effective image charge and a lower cut-off distance of 1 Å. The dashed lines give the trapping force for $a(z)$ the step function defined below Eq. (11).

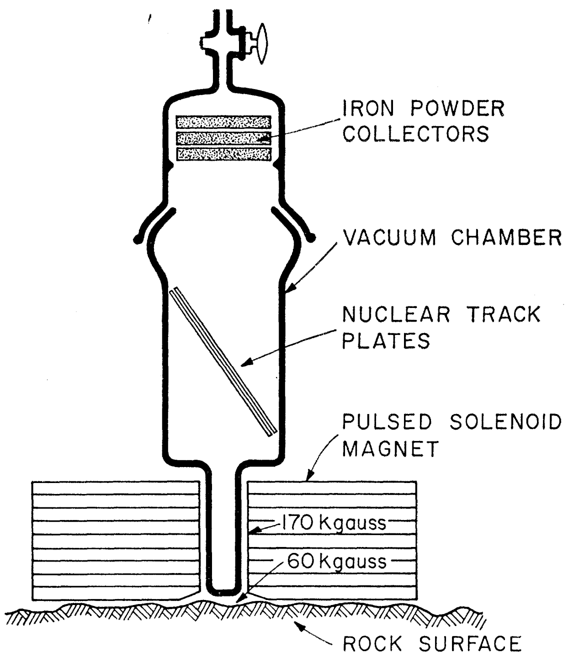


FIG. 3. Schematic diagram of apparatus. Dimensions are given in the text.

calculations with finite nuclei have been reported. In any case, if a monopole approaching closer than $10^{-8}$ cm to the center of an atom continues to be attracted, it is irrelevant to the problem of extraction from a ferromagnetic. A field of 50 kG, for example, exerts on a unit monopole a force of 10 eV/Å, greater than the force of interatomic binding. The atom would simply be extracted along with the monopole. Indeed this field would be sufficient to extract a cluster of atoms, supposing that the monopole polarizes the matter in its neighborhood sufficiently to create a bound cluster surrounding the monopole. A sphere of 10 Å diam containing a unit monopole in a 50 kG field would exert a pressure of $2\times10^{11}$ dyne/cm$^2$$=3\times10^{6}$ psi, which exceeds the yield stress of any known material. An interesting discussion of microscopic effects on a monopole in matter is contained in Ref. 2.

Finally, it should be noted that the required extraction field depends only weakly on the strength $g$ of the monopole. At a cutoff distance $R_0$, and for $a=1$, the upper-limit field is

$$H_{\max}=\pi M_s \ln(g/4\pi M_s R_0^2). \qquad (13)$$

Doubling the assumed pole strength from $g_0$ to $2g_0$ increases the field required for extraction by an increment of only 0.17 ($4\pi M_s$), 3.8 kG for iron, 1.0 kG for magnetite.

### 4. THE EXPERIMENT

There are several kinds of potential ferromagnetic collector of monopoles. Those exposed to cosmic rays for about $10^2$ up to $10^4$ years on the earth include outcrops of ferromagnetic ore, ferromagnetic accumulation on the ocean floor at great depth, old iron meteorites lying on the surface of the earth, and early man-made pieces of iron. Meteorites have, in addition, experienced a much longer cosmic ray exposure in space—$10^8$ to $10^9$ years.[26] A reasonable fraction of monopoles trapped in a large meteorite should be at sufficient depth to survive the meteorite's trip through the earth's atmosphere. We report here a search for monopoles in a terrestrial outcrop of magnetite and in two samples of meteorites. Further meteorite experiments are planned.

#### A. Apparatus

Monopoles could be extracted from ferromagnetics by direct application of a strong field, or by application of a weaker field after destroying ferromagnetism, for example by heating or by chemical dissolution. We have chosen the former method, designing a portable pulsed magnet easily transportable to a site of magnetite outcrop. The strong field approach also has merit in working on valuable meteorite samples, whose nonmagnetic properties can be left undisturbed.

The experimental arrangement is shown schematically in Fig. 3. The magnet is a pulsed solenoid of helical geometry, made by interleaving and compressing 50 suitably slotted and insulated copper and beryllium alloy plates of 6 in.$\times$6 in. outside dimensions; its central hole is 1 in. in diameter. The structure is designed to generate the highest possible field at its bottom surface, which is placed directly against the rock to be searched.

The bore of this magnet is occupied by a glass vacuum chamber whose diameter increases to about 3 in. above the magnet and extends to a total height of 12 in. The enlarged portion is provided with a spherical ground glass joint for access and a stopcock connection for evacuation, as shown in Fig. 3. It houses a pair of nuclear track plates wrapped in black paper, inclined at an angle of about 25° to the axis of the apparatus, as well as a stack of three pellets of iron powder cast in epoxy cement, each about $\frac{3}{8}$ in. thick and 3 in. in diameter, retained against the top of the chamber by suitable protrusions in the glass walls.

Energy to operate this pulsed magnet is supplied through a heavy coaxial cable from a bank of four parallel metallized paper and Mylar capacitors (Sprague type 282 p–15). This bank has an energy capacity of 6400 J (800 $\mu$F at 4 kV) and a total weight of only 140 lb. Highly compact capacitors of this type will not withstand the internal dielectric forces caused by voltage backswing, and since the magnet operates in the underdamped or oscillatory domain, it is necessary to govern the discharge by a circuit comprising two ignitrons which clamps or "crowbars" the voltage after one half-cycle. An oscillogram of two successive pulses is shown in Fig. 4. The peak field is 170 kG at the center

[26] E. Anders, Rev. Mod. Phys. 34, 287 (1962).

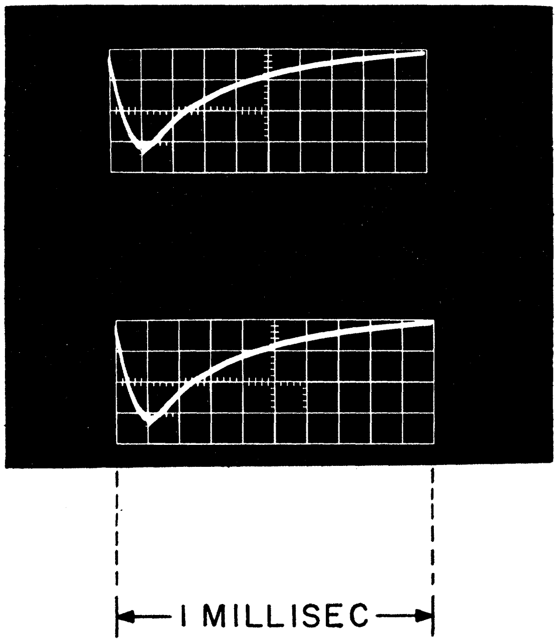


FIG. 4. Oscillograms of field strength versus time for two successive pulses of the magnet. Capacitor voltage is 4 kV; peak field at the center of the magnet is 170 kG.

of the magnet, 60 kG at the surface of the rock, and roughly 30 kG one inch below the rock surface.

Prior to each "shot," the capacitor bank is charged in about 20 sec by a 1.5 kW motor-generator set weighing less than 20 lb. Such high performance was achieved by using a tuned, 2-stroke chain saw engine (McCulloch model MC-30) directly coupled through a centrifugal clutch to an 8000 rpm axial gap, brushless generator (a so-called "alternator") designed for use in jet fighter aircraft (TKM Electric Corporation type A12F) and producing 400-cycle, 3-phase current at 220 V. A separate charging unit containing a suitable transformer and silicon rectifiers converts this output into 4000 V dc.

The entire apparatus is portable in the human sense of the word; it weighs a total of 240 lb, and the heaviest single unit, one capacitor, weighs 35 lb. It was transported on packboards by the three authors in a double portage from a jeep road to the site of the magnetite experiment.

### B. Procedure

#### *1. Brand Pinnacle Experiment*

The selection of a satisfactory site was facilitated by the availability of magnetic anomaly maps covering areas in the Adirondack Mountains.[27] A study of these and comparison with the corresponding topographic maps suggested a number of promising locations, which we then examined in detail from a light airplane at low altitude in early spring 1962, before vegetation had become so prolific as to inhibit vision. Accompanied by Dr. G. Simmons of Harvard University, a field geologist acquainted with the area, we searched for outcrop rock likely to have been exposed since glacial recession and reasonably accessible. One obvious choice was Brand Pinnacle (44°44′ North latitude, 74°6′ West longitude); another was a nameless neighboring ridge just east of Ragged Lake. Our aerial impressions were confirmed by a ground exploration. Brand Pinnacle, having a satisfactory magnetic outcrop, and being the more accessible of the two, was chosen as the site of the experiment.

Upon completion of the equipment in midsummer it was taken to Brand Pinnacle, and an area of about 1000 cm$^2$ of exposed magnetite vein was searched for north monopoles by subjecting it to 200 magnetic pulses. It was obviously important to be doubly sure that the magnetic field was in the correct direction to attract north monopoles from the rock. An ordinary magnetic compass served as the final arbiter on this question. Its south-seeking end was attracted to a spot on the rock that had been directly beneath the magnet, and was attracted also to the upper end of a steel file which had been magnetized in the magnet.

The pulsed magnetic field was measured in the laboratory before and after the expedition and found to retain the time variation depicted in Fig. 4. At the site of the experiment, operation of the magnet was verified before and after each series of shots by observing that a heavy brass washer placed on the upper surface of the solenoid was thrown 30 in. vertically upward, a performance that the magnet duplicated at the time its field strength was measured after the expedition. Only one malfunction occurred when a frayed cable connection was blown off the solenoid.

Our track plate technique followed closely the technique in use at the MIT High-Voltage Laboratory and we are indebted to Dr. Sperduto for help in this regard. It was our original belief that the use of relatively insensitive Kodak NTA plates would minimize background tracks and simplify scanning, and that the existing experience with these plates would permit positive track identification with a minimum of calibration exposures. Both assumptions proved unjustified. The plates were ordered so as to arrive shortly before the experiment, but turned out to have been manufactured six months earlier and stored underground at the factory. There was consequently a considerable background due to radioactive impurities. Moreover, the lack of sensitivity to secondary radiation (delta rays) produced by heavily ionizing particles made it difficult to distinguish readily between the track density of alpha particles and fission fragments. On the basis of this experience we have decided to adopt the present technique of Yagoda of the Air Force Cambridge Research Center for all future exposures, that of preparing a far more sensitive emulsion from Ilford G-5

[27] U. S. Geological Survey, Geophysical Investigations Map GP-191.

gel solution immediately prior to each experiment. As mentioned above, the success of monopole detection did not hinge upon track discrimination, but could have been made on purely geometric grounds. A monopole with energy above 1 BeV would have left tracks of the correct orientation and inclination through corresponding points of both emulsions, which were 50 $\mu$ thick and separated by a glass plate 1.5 mm thick. The tracks would have had at least the density of low-energy alpha tracks, and their length would have exceeded the maximum possible length of such alpha tracks. In addition, the monopole would have been stopped in the iron powder pellets at the top of the chamber, whence it could have been re-extracted and reidentified by a repetition of the experiment.

The Kodak NTA plates with 50 $\mu$ emulsion were 2 in. by 10 in. in size, and identified by lot No. A50C1B2T-S1-51. For each experiment, two 2 in. by 5 in. plates were cut from a single plate; each was subjected to a calibrated exposure of $Po^{210}$ alpha particles (and in some cases also $Cf^{252}$ alphas and fission fragments), and then wrapped in a single layer of black paper. The two plates were superposed for a total of eight days. They were developed three days after the experiment, along with a pair of control plates that had accompanied the expedition in a spare vacuum chamber. A profile photograph was used to determine the angle and position of the plates. The vacuum amounted to roughly $10^{-4}$ atm, and was intended only to reduce the chance of scattering. Development was performed in Kodak D-19 developer (stock solution diluted with two parts of water) for 10 min at 20°C, preceded by 10 min of preswelling in water at the same temperature.

### 2. *Preliminary Meteorite Search*

Two specimens of iron meteorite were made available for search through the courtesy of Professor Frondel of Harvard University. The first of these is a $\frac{1}{2}$-in.-thick slab cut from Carbo meteorite,[26] with one face etched and polished to exhibit the virtually uninterrupted Widmanstätten structure. The specimen is identified as No. 591 g and is about 900 cm$^2$ in size. It was searched with our portable magnet for north monopoles on the unpolished side, and then for south monopoles on the polished side. However, the field of 53 kG at the surface of the iron (less than the 60 kG in the magnetite experiment because of opposing induced currents in the iron) was perhaps not quite sufficient (see Fig. 2). The experiment will be repeated and extended to additional specimens when a larger pulsed magnet installation has been completed.

The second specimen consisted of 50 small fragments of the Estherville meteorite[28] having an average diameter of about $\frac{1}{2}$ in. and a total weight of 447 g, and one sliver of Carbo weighing 116 g. These were exposed to a continuous field of 98 kG inside a 1-in.-diam Bitter solenoid with a track plate chamber extending into each end of the bore to collect monopoles of both polarities. The fragments were sealed into twelve short pieces of 1-in. Tygon tubing, and the magnet was brought to full power for several seconds after the insertion of each of these packages. This technique ensures adequate field throughout the entire volume, but unfortunately is limited to small specimens.

The experimental track plates and control plates were handled in the same way as for the magnetite experiment, except that pairs of plates were superposed for only a few hours.

## 5. ANALYSIS OF RESULTS

### A. Track Plate Analysis

The projected area of the magnet opening on the track plate was about 12 cm$^2$. For safety, a somewhat larger area was scanned, about 20 cm$^2$ on each of the six experimental track plates. Also, a total of 28 cm$^2$ on two control plates was scanned. We decided to cover the remote possibility that the monopole behaved in an unexpected way in passing through matter, and accordingly scanned the plates thoroughly rather than merely searching for heavy tracks of the correct length and orientation. All stars were recorded, all tracks longer than 50 $\mu$ projected length were recorded (the monopole track was expected to appear 115 $\mu$ long), and the number of shorter tracks in each 0.2 cm$^2$ area were counted. All recorded tracks were analyzed statistically as a check on the effectiveness of scanning, and in order to discover any significant deviation from random distribution or orientation, or from the distribution of tracks in the control plates. We are indebted to Mrs. Harald Enge for performing the tedious task of scanning so meticulously that no fluctuations in her attention were reflected in the statistical analysis or in numerous spot checks of her work. The densities of stars (about 25 per cm$^2$ of three or more prongs) and of short tracks (about 200 per cm$^2$) were in fact nonuniform, but varied in a regular way across an entire 10-in. plate, by as much as 3% per cm length of plate. This nonuniformity presumably arises from nonuniformity of cosmic ray shielding or nonuniformity of radioactive contamination in the emulsion. The latter effect is hard to understand, but appears definitely to be present. No nonrandom irregularities of track length, orientation, or number could be found.

All individual tracks longer than 50 $\mu$ were recorded as to position, direction, length, and approximate density. All heavy tracks within about 20° of the correct orientation and within 50 $\mu$ of the correct length were photographed and printed at a magnification of 1000 for detailed comparison with calibration tracks. The number of such tracks (about two per plate) did not exceed what was expected from random orientations. Several were present on the control plates as well as on

[28] B. Mason, *Meteorites* (John Wiley & Sons, Inc., New York, 1962).

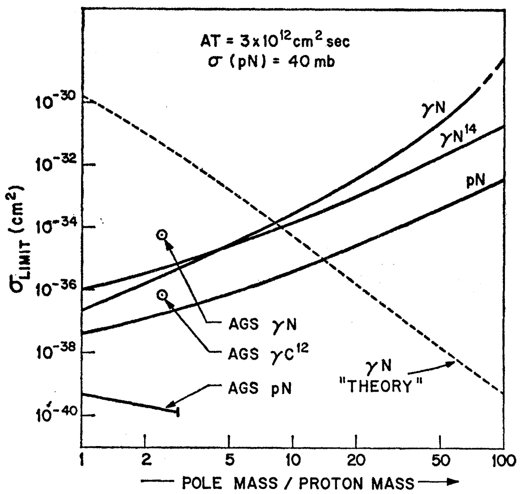


FIG. 5. Upper-limit monopole-production cross sections from negative results of this experiment and of Brookhaven experiment (see Ref. 2). The meaning of the curves is discussed in the text. The "theoretical" curve takes no account of the hard core of the proton, and accordingly is too high at large monopole mass.

the experimental plates. With one exception, the heaviest observed tracks in the experimental plates were consistent with the tracks of alpha-particles of 15 to 30 MeV. The exception was a track of 80 $\mu$ length in one of the Brand Pinnacle plates, showing an energy loss rate substantially greater than an alpha particle. Since its position and orientation on the plate were not what were expected for a monopole, and since it had no companion track in the second plate, we interpret it as the track of a heavy nucleus with $Z>2$. We conclude that there is no evidence that the experimental plates differ in any significant way from the control plates. We believe that the chance that a single monopole track of the expected character—length, orientation, and intensity—could have been missed is extremely small.

### B. Interpretation of Negative Results

The most uncertain parameter in the magnetite experiment is the age of the upper layer of rock. The penetration distance of thermal monopoles into magnetite should be much less than 1 mm. However, the top layer of rock is not pure magnetite. Monopoles should be distributed over a depth at least equal to the mean distance required to reach magnetite. The lifetime of a trapped monopole in the rock surface depends on the penetration depth, the erosion rate of the rock, and the method of erosion. Erosion by dissolving should leave the monopole behind with the more strongly ferromagnetic solid. Erosion by crumbling should carry it away. Conversations with several geologists have led us to believe that at the Brand Pinnacle site, monopoles would remain for 100 to 1000 years, the time required to erode 1 cm of rock. Taking an intermediate figure of 300 years, and using the search of $10^3$ cm, we get an estimated area-time product, $AT=10^{13}$ cm$^2$ sec. The negative results thus at once imply an upper limit rate of arrival of about $10^{-13}$ north monopoles/cm$^2$ sec (of energy less than $8\times10^{12}$ eV) in the primary cosmic radiation.

We may also estimate upper-limit pole-production cross sections in the atmosphere by primary protons and secondary gammas. Figure 5 shows such cross sections as a function of assumed monopole mass, based on a more conservative $AT$ value of $3\times10^{12}$ cm$^2$ sec. We use an energy-independent proton-nucleon cross section $\sigma(pN)$ assuming that in a single collision, a primary proton is degraded below the monopole-production threshold energy. Then the monopole-production cross section limit by protons on nucleons is given by

$$\sigma=\sigma(pN)n/2\pi N(E)AT, \tag{14}$$

where $n$ is the number of monopoles observed, $N(E)$ is the integral primary proton spectrum[29] (protons/cm$^2$ sec sr), and $E$ is the laboratory threshold kinetic energy for monopole production,

$$E=2M(M+2M_p)M_p, \tag{15}$$

$M$ being the monopole mass and $M_p$ the proton mass. The curve labeled $pN$ in Fig. 5 is calculated from Eq. (15) with $n=1$, and $\sigma(pN)=40$ mb.

Putting together the experimental data from several sources[30–32] on gamma rays in the atmosphere, we arrive at the following procedure to estimate the upper limit pole-production cross sections by gamma rays. The integral gamma-ray spectrum $N(E,x)$ [photons/cm$^2$ sec sr at atmospheric depth $x$ (g/cm$^2$)] has a shape approximately independent of depth, that is, it may be written

$$N(E,x)=\bar{N}(E)\alpha(x). \tag{16}$$

Choosing the normalization $\bar{N}(0)=1$ (here "zero energy" means about 50 MeV), we find

$$C\equiv\int_0^\infty \alpha(x)dx=53 \text{ g/cm}^4 \text{ sec sr}. \tag{17}$$

The pole-production cross section is then

$$\sigma=M_Tn/2\pi C\bar{N}(E_0)AT, \tag{18}$$

where $M_T$ is the target mass, $n$ is the number of monopole pairs produced, and $E_0$ is the laboratory threshold energy,

$$E_0=2M(M+M_T)/M_T, \tag{19}$$

and $M$ is the monopole mass. The normalized integral photon flux[30,32] that we used is shown in Fig. 6. The

[29] S. F. Singer, Prog. Cosmic Ray Phys. **4**, 203 (1958).
[30] T. Cline, dissertation, Massachusetts Institute of Technology, 1961 (unpublished).
[31] G. Svensson, Arkiv. Fysik **13**, 347 (1958).
[32] A. Ueda and C. B. A. McCusker, Nucl. Phys. **26**, 35 (1961).

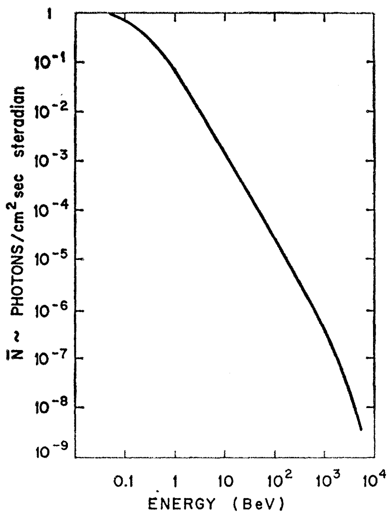


FIG. 6. The energy dependence of the integral photon spectrum in the atmosphere, normalized to $\bar{N}$(50 MeV) = 1. This curve merges data from Refs. 30, 31, and 32.

cross section limits labeled $\gamma N$ and $\gamma N^{14}$ use these data and $n=1$, for the two cases of a nucleon target and a $N^{14}$ nucleus target.

Figure 5 also includes for comparison the cross-section limits determined in the Brookhaven experiment,[2] and a "theoretical" curve based on Eq. (5). If the "theoretical" curve were reliable (it surely is not) our results would not rule out a monopole mass greater than 10 BeV. In any case, the Brookhaven experiment very strongly suggests that monopoles less massive than 2.9 BeV do not exist.

No very meaningful quantitative interpretation can be given to the negative results of the meteorite experiment. If the meteorite in space had been a sphere of radius $R$ large enough to stop all monopoles created within it or incident upon it, and if these monopoles were distributed uniformly throughout the volume of the sphere, the effective area-time product for a given meteorite search would be

$$(AT)_{\text{eff}}=3TV/4R, \qquad (20)$$

where $T$ is the cosmic-ray exposure time in space and $V$ is the volume of meteorite searched. In our experiment with the Bitter magnet, $V=72$ cm$^3$. If we take $T=500$ million years and $R=1000$ cm, we get $(AT)_{\text{eff}}=10^{15}$ cm$^2$ sec. This suggests that the meteorite experiment may be more sensitive than the magnetite experiment. An extension of the meteorite experiment appears to be justified.

## ACKNOWLEDGMENTS

Numerous experts, particularly in geology and in nuclear track plate analysis, have contributed their knowledge and advice to this work. The geologists include Professor P. Hurley, Professor C. Frondel, Dr. G. Simmons, and Dr. K. Emery. The track plate experts include Dr. H. Yagoda, Dr. J. Hornbostel, Dr. A. Sperduto, Professor H. Enge, and Professor J. Schneps. Professor M. B. Sampson kindly supplied calibration exposures to alpha-particles on the Indiana University cyclotron. Valuable engineering work on the pulsed magnet and associated equipment was contributed by D. B. Montgomery and Dr. H. Brechna. Technical assistance was provided by P. Hopkins and D. Sliski. We are indebted to Professor F. Bitter, Dr. B. Lax, and Dr. D. Stevenson for the support of the National Magnet Laboratory; to the Met-a-Mek Corporation and M. Fitch for permission to use the Brand Pinnacle site; and to Professor E. Purcell for advice and encouragement.

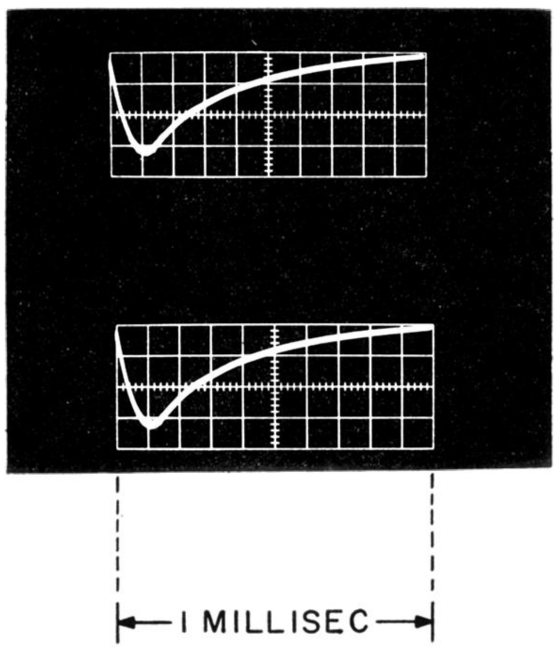


FIG. 4. Oscillograms of field strength versus time for two successive pulses of the magnet. Capacitor voltage is 4 kV; peak field at the center of the magnet is 170 kG.